Lecture Notes in Mobility

Ciaran McNally · Páraic Carroll · Beatriz Martinez-Pastor · Bidisha Ghosh · Marina Efthymiou · Nikolaos Valantasis-Kanellos *Editors*

Transport Transitions: Advancing Sustainable and Inclusive Mobility

Proceedings of the 10th TRA Conference, 2024, Dublin, Ireland, Volume 5: Smart Resilient Infrastructure

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Lecture Notes in Mobility

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Preface

We are pleased to publish the Conference Proceedings of the 10th Transport Research Arena (TRA 2024), held on April 15–18 2024 in Dublin, Ireland. The conference brought together 4500 delegates from 57 countries who came together to discuss research findings, the latest innovations in policy, technology and practice, and the future directions of mobility and transport.

The conference tagline was *Transport Transitions: Advancing Sustainable and Inclusive Mobility*, and four primary conference themes were defined, namely:

- Safe & Inclusive Transport
- Sustainable Mobility of People and Goods
- Efficient & Resilient Systems
- Collaborative Digitalization

TRA takes place every 2 years, and TRA2024 featured an array of plenary sessions, ministerial sessions, strategic sessions and special sessions which took place alongside the technical programme. A call for papers was issued in early 2023 which resulted in 1182 submissions. A double blind peer review process was initiated, which ultimately resulted in 784 papers that were chosen for presentation at the conference (66% conversion rate). These papers were presented in a combination of oral or poster presentations over the course of the conference.

All accepted papers presented at TRA 2024 are published in a topical collection of the journal European Transport Research Review (ETRR) or within these proceedings. Both are published in a fully open access format.

TRA is a multi-modal conference that draws on the support of key stakeholders. These include the European Commission, ACARE (Advisory Council for Aviation Research and Innovation in Europe), ALICE (Alliance for Logistics Innovation through Collaboration in Europe), CEDR (Conference of European Road Directorates), ECTP (European Construction Technology Platform), ERRAC (European Rail Research Advisory Council), ERTRAC (European Road Transport Research Advisory Council), ETRA (European Transport Research Alliance), and the Waterborne technology platform. Key Irish supporters of the event were Transport Infrastructure Ireland, Enterprise and Ireland and the Irish Government's Department of Transport.

The editors would like to express their thanks to the presenters, authors, reviewers, session chairs, committee members and sponsors for helping deliver such a successful event. TRA 2026 will take place in Budapest, Hungary.

Páraic Carroll
Beatriz Martinez-Pastor
Bidisha Ghosh
Marina Efthymiou
Nikolaos Valantasis-Kanellos
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Contents

Resilient Infrastructure

Merimbula Airport: Case Study on Sustainable and Resilient Airport Pavement Rehabilitation and Expansion 3
Greg White

Objective Comparison of the Economic and Environmental Costs of Different Rehabilitation Designs for Flexible Local Road Pavements 10
Greg White and Scott Young

Novel Concept for the Security Architecture of Airports Involving Holistic Interpretation via Artificial Intelligence 17
Olaf Milbredt, Andrei Popa, and Friederike-Chantal Doenitz

Analysis and Evaluation of Passenger Flow at the Next Generation Station Using Microscopic Simulations 24
Andrei Popa, Olaf Milbredt, Mathias Böhm, and Florian Glaser

Improving the Planning of Future Track Interventions Using Digital Tools 31
Hamed Mehranfar, Saviz Moghtadernejad, Bryan T. Adey, and Claudia Fecarotti

Automatic Detection of Asphalt Road Distress via Semantic Segmentation 38
Tomislav Dolic, Roland Spielhofer, Andreas Hula, and Matthias Hahn

Bridge-Wind Analysis: Assessing Wind Effects on Long Span Bridges Using Computational Modelling 45
Jennifer Keenahan

Bayesian Modelling for Probabilistic Prediction of International Roughness Index of Flexible Pavements 52
Yiming Zhang, Alix Marie d'Avigneau, Georgios Hadjidemetriou, Mark Girolami, and Lavindra De Silva

Development of European Standards for Surface Characteristics of Bicycle Lanes 58
Anneleen Bergiers, Luc Goubert, and Carl Van Geem

Innovative Condition Monitoring of the Extended Track by Means of LiDAR-Scanner 65
J. Schatzl

Developing a Risk Assessment Methodology for Analyzing the Resilience of Railway Assets to Climate Change 72
Anas Dabaj, Claire Jaffrezic, Anne Petit, Joséphine Boisson Gaboriau, Loïc Saulnier, Fatoumata Bah, and Cyril Cappi

A Geographic Information System (GIS) for Resilience Assessment of Transport Infrastructure 78
Kalliopi Anastassiadou and Stefan Staub

Determining Transverse Properties in Pavement, Using a Traffic Speed Deflectometer with Two Measuring Beams 84
Helene Pehrsson and Marshall Arokia

Detection of Rail Surface Defects Based on Axle Box Acceleration Measurements: A Measurement Campaign in Sweden 90
Wassamon Phusakulkajorn, Jurjen Hendriks, Jan Moraal, Chen Shen, Yuanchen Zeng, Siwarak Unsiwilai, Bojan Bogojevic, Matthias Asplund, Arjen Zoeteman, Alfredo Núñez, Rolf Dollevoet, and Zili Li

Distributed Sensing System Based on FOS Technology for Road Infrastructure Management and Maintenance 97
D. Luceri, I. Ingrosso, A. Largo, C. Solari, and C. Fuggini

SCI_{TSD}: A New Structural Curvature Index for Strain Analysis of Large Road Networks 104
Helene Pehrsson, David Malmgren-Hansen, Marshall Arokia, and Leif Grønskov

Development of a Bio-Based Emulsion for Road Pavement Construction and Maintenance 111
José Neves, Carlos Alpiarça, Margarida Sá da Costa, Ana Cristina Freire, Luís de Picado Santos, Simona Fontul, João Bordado, Rui Galhano, and José Freitas

Serious Game Design for Resilience Enhancement of Transportation Infrastructure to Cyber Threats and/or Flood Hazards 118
Meisam Gordan, Ili Ko, Mona Soroudi, Daniel McCrum, Sandra König, Stefan Schauer, Lorcan Connolly, and Páraic Carroll

Reduction of the Curing Time and Self-healing of Cold Asphalt Mixtures by Means Magnetic Induction 125
Christopher Delafuente-Navarro, Pedro Lastra-González, Irune Indacoechea-Vega, and Daniel Castro-Fresno

Highly Recycled Asphalt Pavement: Recommendations for Producers and Road Owners 132
Martins Zaumanisa, Lily Poulikakos, Lukas Boesiger, Bernhard Kunz, Henry Mazzoni, Peter Bruhin, Dominique Lötscher, Urs Schellenberg, Gion Dosch, and Gabriel-Martin Elekes

Cost of Meteorological Hazards on the French National Railway Network 139
Thaynara Silva, Julien Brunel, and Marc Georges Develter

Exploring the Insights from Transportation Networks: A Multilayer Network Approach to Distribution Systems Onboard Ships 146
Evelien Scheffers and Peter de Vos

Asphalt Pavement Performance Prediction Using Ensemble Learning Methods 153
Tiago Tamagusko and Adelino Ferreira

Comparative Study of Effects of Dolomite and Granite on the Marshall Properties of Asphaltic Concrete 160
Olumide Moses Ogundipe, Ofem Ofem Ubi, James Olugbenga Aribisala, Oluwasegun Oluyemi Aluko, and Daniel Oluwafemi Oguntayo

Evaluation of Marshall Properties of Asphalt Concrete and Stone Mastic Asphalt for Nigerian Roads 167
Olumide Moses Ogundipe, James Olugbenga Aribisala, and Daniel Oluwafemi Oguntayo

A New Hybrid Approach for Identifying Obsolescence Features: Applied to Railway Signaling Infrastructure 174
Elie Saad, Mariem Besbes, Vincent Bourgeois, Victor Czmil, and Marc Zolghadri

Further Development and Implementation of a Mechanistic-Empirical Design and Analysis System for Pavement Structures in Norway 181
Brynhild Snilsberg, Rabbira Garba Saba, and Leif J. Bakloekk

Climate Impact Analysis on Gravitational Mass Movements Along the German Railway and Road Network 188
Sonja Szymczak, Fabia Backendorf, Frederick Bott, Lennart Meine, Miriam Krebs, and Marvin Stell

ML-Based Model for the Estimation of the Pavement Elastic Modulus via Deflection Velocity Measurements 195
A. Abdelmuhsen, J.-M. Simonin, F. Schmidt, and A. Ihamouten

Decision Support for Predictive Maintenance Planning on the Freight Corridor From Rotterdam to Genoa 202
Ute Gläser, Denise Holfeld, and Burchard Ripke

Managing European Railway Traffic Management System Project: Challenges and Lessons Learnt from Denmark 209
Kornpong Mahitthiburin

Recycled Fibers in Asphalt Mixtures as Method to Improve the Mechanical Behavior: ASFIVAL Project 216
Helena Miera-Dominguez, Irune Indacoechea-Vega, Pedro Lastra-González, Christopher DeLaFuente-Navarro, and Daniel Castro-Fresno

Resilience of Transport and Associated Infrastructure to Climate, Cyber and Physical Threats 223
Lorcan Connolly, Caitriona de Paor, Alexandra Micu, and Alan O'Connor

Probability Based Pavement Asset Management on the Irish National Road Network 230
Ray McGowan, Alan O'Connor, and Kieran Feighan

Risk Based Management of Bridges in Ireland 237
Ray McGowan, Liam Duffy, Alan O'Connor, and Kieran Feighan

Cooperation Between a Human Traffic Manager and an AI Assistant for an Improved Railway Infrastructure Resilience 243
Tom Rousseau, Kahina Amokrane-Ferka, Maroua Meddeb, Nicolas Renoir, Mathis Brunat, Mathias Fort, Lucas Schott, Sébastien Mahler, and Hervé Berthou

Improving the Uptake of Climate Change Adaptation in the Decision-Making Processes of Road Authorities; Output of the ICARUS Project 250
Thomas Bles, David Garcia-Sanchez, Alvaro Fonseca, Martin Lamb, Alan O'Connor, Caitriona de Paor, Margreet van Marle, Stine Dybkjaer, Anoek de Jonge, and Ida Bülow Gregersen

Geohazard Susceptibility Mapping Using Publicly Available Datasets for the Irish Road Network 257
Cathal Mac an tSearraigh, John O'Connor, and Miles Friedman

Vision-Based Multi-perspective Road Pre-damage Detection 264
Christos Vlachakis, Alix Marie d'Avigneau, Damian Palin, Georgios M. Hadjidemetriou, Hussameldin M. Taha, Sripriya Rengaraju, Nzebo Richard Anvo, Mark Girolami, and Abir Al-Tabbaa

Advanced Levelling in Road Construction - Development and Site Testing 271
Torsten Schönbach, Alfons Horn, Leandro Harries, and Michael Nosal

Energy Efficient Operations of Railway Switch Heaters and Feasibility of Using Ground Heat 277
Sidharth Kapoor, Siddharth Suresh Sumathi, William Zhendong Liu, and Kristina Canow

Video-Based Object Recognition for Identifying Vehicle Distances Needed in Bridge Load Evaluations 285
Marian Ralbovsky, Michael Aleksa, and Andreas Hula

Assessing Road Repair Materials via Digital Image Correlation 292
Damian Palin, Hussameldin M. Taha, Christos Vlachakis, Sripriya Rengaraju, Georgios M. Hadjidemetrious, Alix Marie d'Avigneau, Nzebo Richard Anvo, Mark Girolami, and Abir Al-Tabbaa

Some Impacts of Traffic Management Decisions on the Residual Life of a Long-Span Bridge 299
Franziska Schmidt and Nisrine Makhoul

An Image-Based System to Improve Freight Capillaries Circulations 304
Claire Nicodeme and Matthieu Leveque

Foamed Bitumen Stabilisation of Basecourse on Brand Highway, Western Australia 310
Anna-Carin Brink and Riaan van Wyk

Experimental Evaluation of the Ageing Effects on Skid Resistance of Bituminous Mixture Pavements 317
Vítor Antunes, José Neves, and Ana Cristina Freire

Improving Real Time Rail Monitoring with EMAT Sensors and Superlets Analysis 324
Quentin Mayolle, Philippe Vanheeghe, Denovan Lampin, and Valentin Vlieghe

Rail Milling: Evolving from A Linear to Circular Infrastructure Asset Management Approach 331
Mick Coen, David Dunne, Cian O'Cinneide, John McEvoy, Tom Ruane, Cathal Mangan, Éamonn Ballance, David Aschauer, and R. Hardwell

Transport Infrastructure Ireland's Approach to Climate Adaptation 338
Oliver Pritchard, Hanna Jordan, Joanne Treacy, Emma Lancaster, and Billy O'Keeffe

Designing Pavements with Waste and Recycled Materials 344
Shafiqur Rahman, Fredrik Hellman, Björn Schouenborg, Erik Simonsen, and Sigurdur Erlingsson

Utilizing GPR and FWD for Pavement Structural Assessment and Moisture Detection 351
Abubeker Ahmed, Magnus Larsson, and Safwat Said

Investigation on Ageing Behaviour of Bio-Extended Bituminous Binders and Asphalt Mixtures for Sustainable Road Infrastructure 358
Jiqing Zhu, Abubeker Ahmed, Yared Dinegdae, and Andreas Waldemarson

Calibrating ERAPave PP with Field Performance Data 365
Yared Dinegdae, Abubeker Ahmed, and Sigurdur Erlingsson

Resilience Assessment and Adaptation for Critical Infrastructure – Modelling Resilient Infrastructure Systems 372
Margreet van Marle, Frederique de Groen, Kees van Ginkel, Thomas Bles, Carles Soriano Perez, and Mike Woning

Indirect Monitoring of Frequencies of a Multiple Span Bridge Using Acceleration Responses Collected From a Passenger Train 379
Abdollah Malekjafarian, Muhammad Arslan Khan, Ramin Ghiasi, Eugene J. OBrien, E. Alexandra Micu, and Cathal Bowe

A Vehicle-Based Sensing Approach for Network-Level Bridge Condition Monitoring 385
Robert Corbally and Abdollah Malekjafarian

Biobased Pavement: Lab Assessment of a Recycling Technique Without Petroleum Bitumen Addition in Irish Context 392
Emmanuel Chailleux, Stéphane Lavaud, Flavien Geisler, Simon Pouget, Amir Tabakovic, Dave Vanvliet, Alan Lynch, E. Winterlich, and Declan O'Pray

Irish Rail Coastal Resilience and Their Response to a Changing Climate and Increased Coastal Erosion 400
Ronan Hallisey, Paul Fish, Damien Keneghan, Jon Denner, Cian Lynch, and Michael Danaher

Quantitative and Qualitative Assessment of European Research and Innovation Initiatives in Transport Resilience 409
Chiara Lodi, Ilias Cheimariotis, Marcin Stępniak, Konstantinos Gkoumas, Fabio Marques dos Santos, Monica Grosso, and Alessandro Marotta

A Programmatic Approach for the Delivery of Public Transport Policy in Ireland 416
Juan Martinez-Covarrubias, Yeonjung Song, Mark Connolly, and Catherine Murray

How do Geopolitical Risks Affect Ship Investment Decisions? 423
Dimitris Georgoulas, Vangelis Tsioumas, Peter J. Stavroulakis, and Stratos Papadimirtiou

Stakeholders' Insights for Development of a Decision Support System (DSS) to Foster Resiliency of Greek Ports Against Climate Change 429
A. Polydoropoulou, G. Papaioannou, E. Bouhouras, I. Karakikes, and G. Vaggelas

Sustainable Approaches to Enhancing Performance and Resilience of Historic Railway Bridges 438
Michal Majka and Cathal Bowe

Railway Train Main Power Converter:Model Predictive Current Control of a Modular Multilevel Converter 445
Vitor Monteiro, Jose Cunha, and Joao L. Afonso

MetProgRé: a Decision Support System to assess Weather Risk for Planning of Railway Renewal Works 452
Camille Morvant, Emmanuel Cieren, Sirine Kahil, Sami El Idrissi Raghni, Rawya Zreik, and Maxime Gueguin

Assessment of Cascading Impacts Across Europe: An Innovative Approach for a Resilient Infrastructure and Society 461
Florencia Victoria De Maio, Saimir Osmani, Paolo Basso, Fabio Bolletta, Rita De Stefano, Marcello Cademartori, and Clemente Fuggini

Health Condition Monitoring Techniques for Traction Transformers Immersed in Oil- A Comprehensive Study 468
Seyed-Saeid Moosavi-Anchehpoli, Smail Ziani, Christophe Parny, Romain Lanselle, Lionel Taunay, Nada Zouzou, and Lokmane Haouchine

Evaluating the Pollutant Removal Efficiency of a New Retrofittable Sustainable Drainage Material 474
Puneeta Sreenivas and Sarah Cotterill

Additive Manufacturing for SNCF Réseau: An Opportunity for Generative Design and Laser Powder Bed Fusion 483
Pascal De Guio, Romain Floquet, Vincent Mahmut, Marie Fischer, and Paul Didier

Additive Manufacturing for SNCF Réseau: Investigation on Material and Process Opportunities for Industrial Purpose 490
Pascal de Guio, Philippe Kuchly, Philippe Pouligny, and Julien Tremblay

Ballasted Track Renewal for High-Speed Mobility: How Recent Technical Innovations Will Allow SNCF to Build a New Model of Track Renewal for Tomorrow 497
Bertrand Avril and Alain Thiébaut

Mitigation of Large Overloads on Road Bridges 503
Bernard Jacob, Roland Abou, and Raphaël Bartolt

Resilient Networks and Operations

Enhancing Ambidextrous and Learning Capacities for the Resilience of Public Infrastructure Administrators 513
Bert de Groot, Hanneke Gieske, Wim Leendertse, and Jos Arts

An Adaptive Supply Chain Stress Testing Framework with Deep Learning 520
Cemalettin Ozturk and Barry O' Sullivan

INFRACOMS Appraisal Toolkit for NRAs to Assess Emerging Technologies in Bridge and Pavement Management 527
Kevin McPherson, Mogens Saberi, Fengqiao Zhang, Anna Arvidsson, Simon Fjendbo, Darko Kokot, Carl Van Geem, and Ali Yeganeh

Increasing the Capacity of Shunting Yards Within the Current Infrastructure: A Computational Perspective 534
Issa K. Hanou, Sebastijan Dumančić, Mathijs de Weerdt, Paul van der Voort, Roel van den Broek, and Marjan van den Akker

Boosting Holistic Railway Infrastructure Monitoring and Health Prediction by Integrated Data Sets and Analysis 541
Thorsten Neumann, Jacques Tiecken, Douwe Buursma, Benjamin Baasch, Javier Camacho de Miguel, Borja Rodriguez-Arana, and Unai Alvarado

Automated Adaptive Traffic Network: Adapting the M50 in Real-Time by Optimizing Speed Limits Using a Proposed Intelligent Agent 548
Amirreza Kandiri, Rui Teixeira, and Maria Nogal

Flight Centric ATC: Reflecting Three Years of Research on an Efficient and Eco-friendly Air Traffic 554
Tobias Finck, Carmo S. Kluenker, and Mara Weber

Impact of the COVID-19 and Russian-Ukrainian War on Rail Freight Transportation – Analysis of Turkiye 561
Hulya Zeybek

Empowering Urban Authorities: Data-Driven Solutions for Effective Public Transport Management 567
Raquel Alario and Antonio Marqués

Railway Assets Resilience to Climate Change Application of the Smarter and Faster Adaptation EU Strategy 573
Hubert Mullard and Philippe Clément

Increase Resiliency Against Extreme Weather Events 580
Rainer Müller, Berit Böttger, and Marija Jović

Water Management As a New Saving Opportunity for Bus Managers: Evidence from the LIFEH2OBUS Project 586
Matthew Robinson and Maria Vittoria Corazza

Review of Transport Network Criticality from a Capabilities Approach Perspective 593
Hrishikesh Dev Sarma, Rui Teixeira, Beatriz Martinez-Pastor, and Helen McHenry

Identifying Infrastructure Demand and Performance Changes Through Agent-Based Modelling Using Fuzzy Logic 599
Sander Mooren, Andreas Hartmann, and Sahand Asgarpour

Simulation Based Infrastructure Critical Boundary Identification for Multi-modal Transport Hubs 605
Simon Collart-Dutilleul, Philippe Bon, Michael Laubrock, and Georges Mykoniatis

On the Capacity of Roadside Communication Networks for Supporting the Delivery of Emerging C-ITS Services 612
Shobanraj Navaratnarajah, Piraba Navaratnam, and David Laoide-Kemp

A Review of Tools and Guidance for Undertaking Climate Change Risk Assessments for the Transport Sector in Britain 619
Áine Ní Bhreasail, Louis Andrews, Matthew Free, Joanna Wooles, Jeremy Clarke, and Laura Stewart

Using Travel Demand Modelling and Traffic Simulation for Crisis Management 629
Marco Marquard, María López Díaz, and Andrea Tundis

Agile Multi-sensor Platform LEONARDO: Evaluation of New Monitoring Technologies in an Operational Environment 636
Henk Samson, Jacques Tiecken, Thorsten Neumann, Benjamin Baasch, Javier Camacho de Miguel, Borja Rodriguez-Arana, and Unai Alvarado

Transport Network Planning and Analysis Decision-Support Tool for South Asia 644
Maria Antoniou, Marianna Loli, Haris Ballis, Rallis Kourkoulis, Bramka Arga Jafino, and Oceane Keou

Value Based Decision Making for Rail: A System of Systems Approach. 651
Jude Carey, Andy Kirwan, Donatella Fochesato, Clara Grajal Marino, Mattias Androls, Richard Mair, Thierry Pulver, and Mikko Sauni

Variable Speed Limit on Motorway: A Feedback Control Implementation 659
Rory Mannion and Bidisha Ghosh

Analysis of Extreme Weather Effects of Travel Time Reliability 666
Dhivya Bharathi, Geraldine Walsh, and Bidisha Ghosh

A Simulation-Based Assessment of the Effectiveness of Vehicular Ad-hoc Networks in Enhancing Transportation Resilience 673
Aihui Hu and Beatriz Martinez-Pastor

Reimagining the Future Ridership of City Bus- A Case of BRTS Bhopal 680
Pragati Goel and Gaurav Vaidya

BIG-Data Handling of Complete and Simultaneously Measured Road Condition Data 687
Bjarne Schmidt, Simon Tetley, and Jerome Daleiden

Healthy Sailing: Prevention, Mitigation and Management of Infectious Disease on Cruise Ships and Passenger Ferries 694
Varvara A. Mouchtouri, Lemonia Anagnostopoulos, Edwin Galea, Prashant Kmar, Niko Siilin, Juergen F. Kolb, Nikolaos P. Ventikos, Vassilis Papataxiarhis, Geogos Vosinakis, Jörn Klein, Dspoina Andrioti Bygvraa, and Christos Hadjichristodoulou

Parameters for Assessing Public Transport Accessibility for Indian Cities 701
Savita Lakra and Mayank Dubey

Optimizing Transit Connectivity: A Synchronization Model Applied to Porto Campanhã 708
Rodrigo Alves, Joana Hora, and Teresa Galvão

Digital Transport Infrastructure

Test Vessel Development for Autonomous Maritime Research 717
Juha Kalliovaara, Jarkko Paavola, Tero Jokela, and Amin Majd

Accelerating the Deployment of Shared and Digital Mobility Hubs Across Europe 724
Franziska Wolf, João Henrique Paulino Pires Eustachio, Walter Leal Filho, Tessa T. Taefi, and Arjen Rodenburg

Assessing the Readiness of European Cities for Distributed Traffic Management: A Smart Infrastructure Readiness Index 732
Konstantinos Katzilieris, Panagiotis Fafoutellis, and Eleni I. Vlahogianni

Improving Data Exchange in Transport and Logistics Through System Federation: Application Evaluation Results 739
Sofoklis Dais and Georgia Ayfantopoulou

Examining the Impact of System Federation on Transport and Logistics: Selected Cases in Greece and Italy 746
Sofoklis Dais, Giulia Renzi, Andreas Kortenhaus, Georgia Ayfantopoulou, Ioannis Kanellopoulos, Angelos Amditis, Godfried Smit, and Hélder Pereira

Railway Switches and Crossings: Identifying and Clustering Passages Using GNSS Measurements 760
Jonas Vuitton, Julian Lohbreier, and Markus Hecht

Frugal Connectivity for Railway Applications 767
Pierre Le Corre, Pierre-Yves Petton, and Rodrigue Fargeon

Improving Cyclist Safety and Infrastructure Planning: A Data-Driven Case Study of Cork City Council Project 773
Gorkem Yetik, Usama Anwar, Ross Foley, and Leonard Goodwin

Operational Obstacles of the Building Information Model in Railway Infrastructures 781
Nassiba Khelladi and Sana Debbech

Fiber-Optic Technology for Monitoring Asphalt Roads-Results of a Feasibility Study 787
Martin Peter Lipus, Johannes Hart, Christopher Wollin, Charlotte M. Krawczyk, Peter Mock, Matthias Breidbach, and Bastian Wacker

Advancing Automated Freight Transport: Unveiling the Requirements and Readiness of Physical and Digital Road Infrastructure 794
Knut Jetlund, Kristoffer Tangrand, and Petter Arnesen

Radar Satellite Observations of Bridge Deformations—A New Method for Monitoring Without Applied Sensors 801
Alois Vorwagner, Maciej Kwapisz, Philip Leopold, and Thomas Moser

Benefits of Radio Coverage Planning of Large-Scale Roadside C-ITS (ITS-G5) Communication Networks 808
Shobanraj Navaratnarajah, Piraba Navaratnam, David Laoide-Kemp, Saul Friedner, and Simon Parsons

A Framework for Road Authorities to Assess Their Readiness to Support Connected and Automated Driving 815
Ianto Guy, Alex Wright, Kevin McPherson, Boris But, Risto Oorni, John McCarthy, Bahman Madadi, Ary P. Silvano, Jeannette Andersson, and Adewole Adesiyun

Framework for Rail Level Crossings Digital Twin Development 822
Boban Djordjevic, Evelin Krmac, Oskar Fröidh, and Behzad Kornejad

AUTOMODAL - Automation of Inland Container Terminal Cranes Solving People Detection in the Operating Range 828
Maximilian Schellert, Agnes Eiband, Tammo Märtens, Felix Kremer, Maximilian Otten, Uwe Clausen, Irfan Yildiz, Michael Herbold, David Bauer, and Moritz Sauter

The 5G-RACOM Project: 5G for Resilient and Green Rail COMmunications 835
B. Holfeld, R. Fritzsche, T. Karabinos, G. Boistault, M. Berbineau, U. Geier, O. Eudes, A. Ende, K. Mößner, T. Bauschert, A. Mitschele-Thiel, A. Sabra, Y. Corre, and P. Pajusco

New Roads Governance Framework Based on Circularity 842
Mª. Antonia Pérez Hernando, Christian Moreno, Rubén Eraña, and David García Sánchez

CEMBOX. Digital Twin Oriented Infrastructure Asset Management Platform 847
Jose Solis-Hernandez, Paula Lopez-Arevalo, Juan Gallego-Gueto, Jose Sanchez-Guerrero, and Noemi Jimenez-Redondo

Using the Analytical Hierarchy Process (AHP) to Prioritize Network Benefits When Applying Novel Traffic Management Strategies 854
Marios Giouroukelis, Eleni Mantouka, and Eleni I. Vlahogianni

Comparing Random Forests and Multinomial Logit Models for Urban Travel Mode Choice Under Innovative Traffic Management Strategies 860
Christos Konstantinou, Eleni Mantouka, Marios Giouroukelis, and Eleni I. Vlahogianni

Data Communication System for Remote Train Operation on Regional Lines, Including Video Integration 867
Patrick Urassa, Øyvind T. Myhrvold, and Nils O. E. Olsson

Modelling Probabilistic Digital Twins of Complex Inland Waterway Transportation Systems Using Bayesian Networks 874
Alexandra Micu, Lorcan Connolly, Alan O'Connor, Eugene O'Brien, and Caitriona de Paor

Using Accelerometers on an In-Service Train to Detect Bridge Damage and Repair 880
E. Alexandra Micu, Cathal Bowe, Vikram Pakrashi, Abdollah Malekjafarian, and Eugene OBrien

Field Validation of Damage Detection in a Railway Bridge in Ireland Using Sensor Redeployment 887
C. Bowe, E. J. OBrien, M. A. Khan, D. McCrum, and V. Pakrashi

Asset Information Management for a Communications Network in Ireland 893
Aonghus O'Keeffe and David Torrado

A Data-Driven Framework for Detecting Railway Maintenance Needs Using Acceleration Data Collected from Passing Trains 899
Ramin Ghiasi and Abdollah Malekjafarian

Enhancing the Performance of Emergency Vehicles Through Reinforcement Learning Based DVSL Control Systems 906
Fatemeh Bandarian, Eric Gyamfi, Evangelos Mitsakis, Evangelos Mintsis, Abdollah Malekjafarian, and Fatemeh Golpayegani

Software Patterns and Architectural Decisions for a Next-Generation Traffic Management System in the TANGENT Project 913
Tiago Dias, Ana V. Silva, and Lara Moura

Tolling Dematerialization Use Cases 920
Ana V. Silva, Tiago Dias, André Amaral Costa, and Lara Trigueiro Moura

Simulating the Effects of Connected and Automated Vehicles on Traffic Management 927
Tamás Attila Tomaschek, Viktor Tihanyi, András Rövid, and Zsolt Vincze

Enhancing Public Transportation Operations Through Service Reinforcement, Bunching Detection and Data-Driven Analysis 933
Andoni Mujika, Iker Arandia, Itziar Urbieta, Harbil Arregui, and Estíbaliz Loyo

Service Orchestration and Network Function Virtualization for Information Systems Maintenance Service in Railway Systems 941
Anna Lina Ruscelli and Gabriele Cecchetti

Dynamic 2D Scene Analysis Inside Train Compartments Using Deep Learning Techniques 948
Youssef Bendraou

Traffic Regulations in the Digital Age 955
Jenny Lundahl, Cilli Sobiech, and Niklas Thidevall

UAV Integration into Airport Infrastructure Inspection Procedures—Case Study Zagreb Airport 961
Irina Stipanovic, Matija Bracic, Marin Tica, Sandra Skaric Palic, Emir Ganic, and Igor Stimac

Author Index 967

Resilient Infrastructure

Merimbula Airport: Case Study on Sustainable and Resilient Airport Pavement Rehabilitation and Expansion

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Abstract. The airport pavements at Merimbula airport (Australia) required strengthening to support larger aircraft. Four structurally equivalent pavement designs were developed, using standard pavement materials, except for an option to use of foamed bitumen to stabilise the existing granular pavement material, prior to surfacing with an asphalt wearing course. The sustainability and resiliency of the four pavement designs were considered and scores assigned. The sustainability score was based on the embodied carbon in the rehabilitated pavements, while the resiliency score was subjectively assigned based on the resistance of the pavement to moisture ingress. It was found that the new rigid pavement and the foamed bitumen stabilised flexible pavement were the most resilient, reflecting the bound nature of these materials. Furthermore, the foamed bitumen stabilised pavement and the structural asphalt overlay of the existing pavement were preferred in terms of sustainability. Because of its high scores in both sustainability and resiliency, the foamed bitumen stabilised pavement was preferred. It is recommended that other airports consider the potential for stabilisation of existing pavements, for sustainable and resilient pavement rehabilitation, whenever the existing pavement materials are suitable.

Keywords: Flexible · Airport · Pavement · Sustainable · Resilient · Rehabilitation

1 Introduction

Merimbula airport is located on the south cost of New South Wales (Australia) approximately halfway between Sydney and Melbourne. Like many regional airports in Australia, it provides a critical link for business, tourism, medical emergencies and natural disaster response (1). Being a regional airport, it has one runway, a single taxiway and a simple parking apron (Fig. 1). Prior to the recent upgrade, the runway was 1600 m long and 30 m wide, and the total pavement area was 55,000 m^2, taking into account the aircraft parking area.

Merimbula airport is located in a flat area between an ocean and mountains, just 2 m above the mean sea level and adjacent to environmentally sensitive oyster farming waterways. As a result, the site has poor drainage characteristics and a high water table,

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Fig. 1. Merimbula airport pre-upgrade airfield layout

and discharging water into the adjacent waterway is environmentally unacceptable. In 2018 the runway at Merimbula airport exhibited a number of isolated structural failures, linked to water ingress into the marginal granular base course layer. At the same time, the airport owners proposed to introduce a new airline that operated larger aircraft. This required a 150 m long extension to each end of the runway and strengthening of the existing pavement structures. In light of the environmentally sensitive site and the high cost of transporting new granular materials to site, a sustainable pavement rehabilitation design was desired, maximising the reuse of the existing material, and minimisation of new granular material demand. It was also necessary to increase the resilience of the existing and new pavements by increasing the resistance to periodic moisture ingress.

This paper presents the design of the Merimbula airport upgrade project as a case study in sustainable and resilient airport pavement rehabilitation. Four pavement design options were considered and the sustainability and resilience of each were compared. The case study provides an example of how airport pavement rehabilitation design options can be assessed, and the associated sustainability and resiliency quantified.

2 Pavement Design Options

Four different, but structurally equivalent, pavement designs for the upgrading of the existing runway pavement at Merimbula airport were developed. The designs included a conventional new flexible pavement, a new rigid pavement, a structural asphalt overlay of the existing pavement, and insitu stabilisation using foamed bitumen stabilisation of the existing pavement followed by an asphalt surface. The structural equivalence of these different pavements was defined by their theoretical ability to support the same aircraft traffic loadings over the 20-year design life (Table 1), for the existing pavement and subgrade conditions.

In airport pavement rehabilitation design, the existing pavement structure and materials are critical (2). Based on geotechnical investigations, it was determined that the existing pavement comprised a thin bituminous chip seal, known in Australia as a sprayed seal (3), over 500 mm of locally sourced marginal, or non-standard, natural gravel, over of a sandy clay subgrade with a characteristic bearing strength of CBR 5%.

Table 1. Design aircraft traffic loading

Aircraft	Mass (kg)	Tire pressure (kPa)	Total departures
Saab 340 B	13,154	379	28,000
Dash 8 Q400	29,347	1565	34,000
Fokker F100	45,813	1076	16,000

The four pavement thicknesses were determined in FAARFIELD (4) and were based on Australian airport pavement design and construction practice (2). The only non-standard material used was the foamed bitumen stabilised base (FBB). FBB is produced by stabilising a new or existing granular material with bitumen that has been foamed by injecting cold water into a stream of the hot bitumen (5). The foamed bitumen has a temporarily lowered viscosity, allowing it to be mixed through granular materials. Once compacted, the FBB cures quickly and provides a semi-bound but flexible and moisture resistant material (6). FBB has been used at a range of airports with the main benefits being compatibility with existing local or marginal gravels, rapid construction, the ability to be produced either insitu with a stabilising machine or exsitu in a pugmil, and the relatively high elastic modulus compared to the unstabilised granular material (5). Based on the mixture design results (7) the FBB at Merimbula airport was characterised in FAARFIELD as a user defined layer with a modulus of 800 MPa and no fatigue performance criterion, which is consistent with other airport pavement rehabilitations in Australia (8). The resulting pavement rehabilitation designs are shown in Fig. 2.

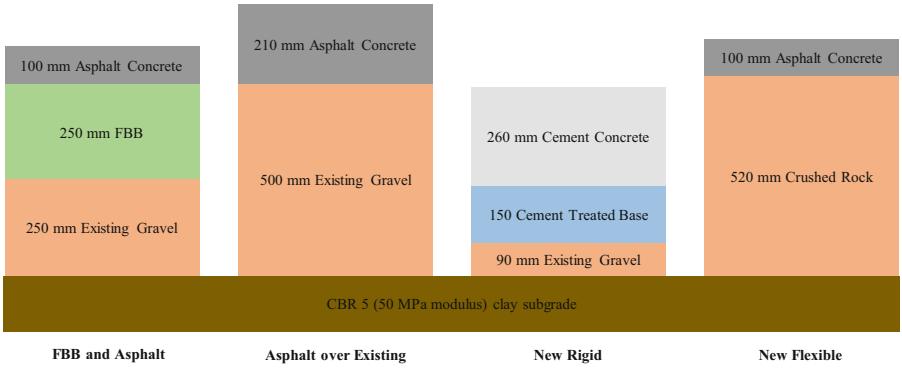


Fig. 2. Pavement rehabilitation design options

The new rigid pavement was the thinnest and the structural asphalt overlay of the existing pavement structure was the thickest, when the existing pavement was also included. The FBB and asphalt surface option, as well as the new flexible pavement option, were of similar thickness, because the high modulus of the FBB offsets the low modulus of the existing granular material, resulting in a similar structural contribution to that of the comparable thickness (just 20 mm greater) of new fine crushed rock. However,

because the different materials used in the four pavements have different embodied carbon and moisture resistance characteristics, the thickness of the four pavements cannot be considered as an indicator of pavement sustainability and resiliency.

3 Pavement Design Sustainability and Resiliency

3.1 Pavement Sustainability

Sustainability of different pavement options can be expressed as the embodied carbon in the new pavement materials (9). The weight of embodied carbon was expressed as the equivalent mass of carbon dioxide associated with the production, transportation, processing and construction of each material (8). The sum of the material thicknesses, when combined with the material compositions and embodied carbon rates, allowed the calculation of an environmental cost for each pavement design option. The lower the mass of embodied carbon, the higher the sustainability score for that pavement. This approach has previously been used to compare the environmental cost of different airport pavement designs and materials (10–12).

The embodied carbon rates for the various materials were determined elsewhere (9) but are summarised in Table 2, along with the density used to convert between material mass and volume. The resulting environmental cost, over the full pavement area, is shown in Table 3, along with the sustainability score for each pavement design option.

Table 2. Material environmental costs

Material	Density (kg/m^3)	Environmental cost (kg.eCO_2/m^3)
New asphalt concrete	2450	356.5
New Portland cement concrete	2600	324.0
New crushed rock	1900	144.4
New cement treated crushed rock	2250	194.1
Retained existing gravel	1800	0.0
FBB produced from existing gravel	2100	77.4

Table 3. Pavement environmental cost

Pavement	Environmental cost (tonnes.eCO_2)	Score (out of 10)
FBB and asphalt overlay	3024	10.0
Asphalt over existing	4116	7.3
New rigid pavement	6244	4.8
New flexible pavement	6090	5.0

3.2 Pavement Resiliency

In contrast to the sustainability, there is no measurable or calculatable indicator of pavement resilience. Therefore, relative resilience was considered subjectively, based on the risk of moisture related pavement failures during periods of moisture exposure. Table 4 summarises the pavement resilience assessment. The rigid pavement and stabilisation with foamed bitumen design options were considered to be highly resilient, and the new flexible pavement was rated as having medium resilience. Although retaining the existing pavement and overlaying it with asphalt would better protect the existing gravel base course, the risk of further wetting of the retained marginal gravel, and failure of the base layer, is significant without replacement or treatment of this material.

Table 4. Pavement resilience

Pavement	Assessment	Score (out of 10)
FBB and asphalt overlay	FBB is moisture resistant and only a moderate thickness of margin gravel is retained, under the 350 mm thickness of asphalt and FBB, so the retained gravel would be well protected by the surface asphalt and the FBB	9
Asphalt over existing	The asphalt provides protection to the retained existing gravel, but lateral water movement and the water table remain a high risk without improvement of the existing granular material	4
New rigid pavement	Concrete are cement treated crushed rock sub-base are effectively waterproof and the clay subgrade is not prone to shrink-swell, minimising the risk of surface unevenness	10
New flexible pavement	New crushed rock imported to standard material requirements, including low moisture susceptibility, and protected by new asphalt surface	7

3.3 Combined Sustainability and Resiliency

Whether the sum or the product of the sustainability and resiliency scores was considered, the FBB and asphalt surfacing option was preferred (Table 5). This generally reflects the high moisture resistance and low embodied carbon associated with insitu FBB production and demonstrates the benefits that can be achieved by stabilising an existing granular pavement structure, rather than replacing it with a new pavement.

Table 5. Combined sustainability and resiliency scores

Pavement	Sustainability	Resiliency	Sum	Product
FBB and asphalt overlay	10	9	19	90
Asphalt over existing	7	4	11	28
New rigid pavement	5	10	15	50
New flexible pavement	5	7	12	35

4 Conclusion

The new rigid pavement and the FBB and asphalt surface pavement were the most resilient design options, based on the bound nature of the all the materials in the pavement, making them resistant to the effects of water ingress. Furthermore, the FBB and asphalt surface pavement, as well as the structural asphalt overlay option, were the most sustainable design options, because they retained the existing granular pavement material, which was effectively environmentally free. Because of its good performance in terms of both resiliency and sustainability, the FBB and asphalt surface design was preferred as the most sustainable and resilient pavement rehabilitation option. This reflects the high moisture resistance and the low embodied carbon associated with FBB. It is recommended that other airports consider foamed bitumen stabilisation of existing granular pavements in the future, whenever the existing pavement materials are suitable.

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Objective Comparison of the Economic and Environmental Costs of Different Rehabilitation Designs for Flexible Local Road Pavements

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Abstract. Low traffic local roads are often comprised of a marginal gravel base course with a thin bituminous surfacing. These pavements commonly require rehabilitation at the end of their life. The economic (financial) and environmental (embodied carbon) cost of three typical pavement rehabilitation designs were estimated and objectively compared. The rehabilitation treatments included full depth granular reconstruction with new material, an insitu cementitious stabilisation of the existing pavement to form a lightly bound gravel base, and an insitu foamed bitumen stabilised existing gravel base, each with a sprayed seal surface. The full depth reconstruction with new granular materials had the highest economic and environmental costs, by a significant margin. It is recommended that stabilisation be the preferred rehabilitation option for local roads, and that pavement reconstruction using new materials only be considered when stabilisation of the existing pavement is determined to be unviable.

Keywords: Flexible · Pavement · Local road · Financial · Environmental · Cost

1 Introduction

Low traffic local roads make up the majority of pavement networks in many countries. For example, in Australia 75% of the 876,000 km of road pavements are considered local [1]. These roads are often constructed with pavements that incorporate lower quality materials than typically used in highway and heavy-duty pavement construction. Consequently, they often require partial of full depth rehabilitation.

Rehabilitation can take many forms [2] and local experience and estimated cost have traditionally been the primary selection criteria for determining the preferred rehabilitation approach. However, as society places more emphasis on the environmental impact of infrastructure, the environmental cost, expressed as the mass of embodied carbon, is also becoming an important criterion for comparing different pavement rehabilitation design options [3]. This research objectively compared the economic (financial) and environmental (embodied carbon) costs of flexible pavement rehabilitation options for local roads comprised of an existing 250 mm thick marginal granular base course and a thin bituminous surface.

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2 Methods

The computer software Circly [4] was used to design three different flexible road rehabilitations. The rehabilitation designs were based on local road practices in Australia [5] and are shown schematically in Fig. 1. Each rehabilitation option was designed for three levels of traffic and for four typical subgrade bearing capacities (Table 1). All rehabilitated pavements included a non-structural sprayed seal surface [6].

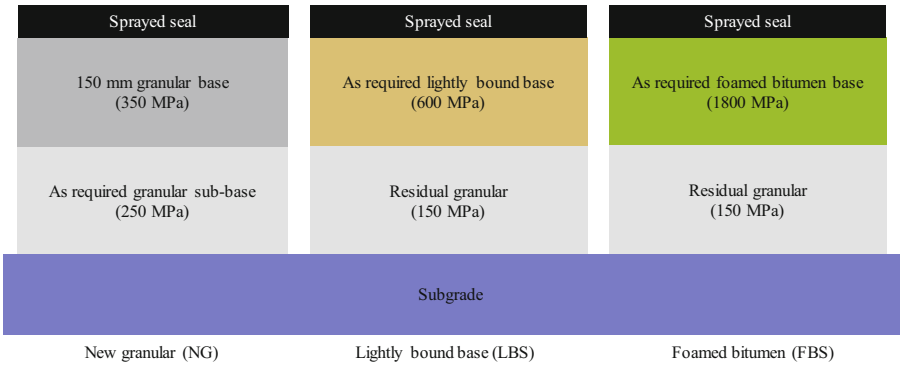


Fig. 1. Schematic of pavement rehabilitation design types (values in brackets are elastic moduli)

Table 1. Traffic loadings and subgrade conditions

Traffic loadings		Subgrade conditions	
Input value	Represents	Input value	Represents
$5x10^4$ ESALs	Light traffic	CBR 3%	Weak clay
$5x10^5$ ESALs	Medium traffic	CBR 5%	Drained silt
$5x10^6$ ESALs	Heavy traffic	CBR 9%	Natural gravel
-	-	CBR 15%	Compacted sand

Standard or normal material characteristics were assigned to each layer in Circly and most materials would be familiar, with the exception of the sprayed seal, lightly bound insitu stabilised base (LBS) and foamed bitumen insitu stabilised base (FBS). Sprayed seals, also referred to as surface dressing or chip seals, comprise a sprayed film of hot bitumen followed by a single particle thick layer of pre-coated aggregate [6]. This is a common surface for local roads in regional Australia, New Zealand and South Africa.

FBS improves a marginal granular material by producing a bound but flexible material at ambient temperature [7]. The liquid bitumen is foamed by injecting a stream of water and air and then the foamed bitumen is mixed into the granular material, using a specialised stabilising machine [2]. The same process can also be performed in a pugmil, but this is less common for local road pavement rehabilitation. FBS provides a moisture resistant and crack resistant material, with a relatively high structural modulus, and is well suited to the improvement of existing marginal granular pavements [8]. FBS generally includes 3.0–3.5% bitumen and 1.0–2.0% lime or cementitious supplementary binder.

LBS is also a stabilised material, produced either insitu or in a pugmil, by mixing typically 1–4% cement or blended cementitious binder into an existing granular material, resulting in a semi-rigid and semi-bound product [2]. The target unconfined compression strength of LBS is usually 1–2 MPa and the structural modulus is higher than for a granular material, but not as high as for FBS or asphalt concrete.

3 Pavement Designs

The rehabilitated pavement thicknesses ranged from 150 mm to 758 mm (Fig. 2). Some of the LBS and FBS pavement designs include a granular overlay, to be incorporated into the stabilised layer, due to the design thickness exceeding the existing 250 mm of granular pavement. The granular overlay ranged from 50 mm to 150 mm and was rounded up to the next 50 mm, reflecting common Australian practice.

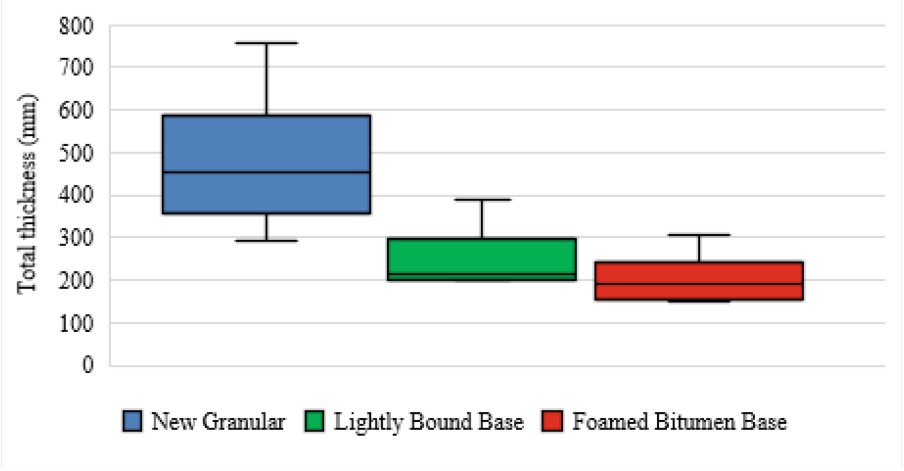


Fig. 2. Comparison of pavement thickness for rehabilitation options

Thinner pavements were required for the lower traffic loadings and the higher subgrade CBR values. Furthermore, the new granular pavements were associated with the highest average thickness and the greatest range in thickness (Fig. 2). This reflects the lower structural modulus associated with granular materials, compared to LBS and

FBS, as well as the high influence of subgrade CBR on the required thickness of granular pavements. In contrast, the FBS pavements were the thinnest pavements, reflecting the relatively high modulus of FBS.

4 Economic Costs

The economic cost of the different pavement options was calculated from the thickness of each pavement, as well as typical cost rates (Table 2) from experience rehabilitating local roads in Australia. For the LBS and FBS, the construction process was estimated on a m^2 basis, while the material cost was estimated based on the depth, because the binder cost is a function of the layer depth, whereas the cost of the construction processing is generally not affected by the thickness of the stabilised layer.

Table 2. Economic cost rates of materials (A$ /m^2)

Material/Activity	Financial cost	Notes
Excavation	100 /m^3	Assumed no disposal cost
Two coat sprayed seal	11 /m^2	Material supply and placement
Fine crushed rock	60 /tonne	Material supply and placement
Lightly bound stabilised base	8 /m^2	Construction only, plus binder
Foamed bitumen stabilised base	10 /m^2	Construction only, plus binders
Cement	250 /tonne	Supply only
Unmodified C170 bitumen	1400 /tonne	Supply only
Hydrated lime	450 /tonne	Supply only

The economic costs were all expressed in Australian dollars (A$) and ranged from 22 /$m^2$ to 170 /m^2 (Fig. 2). For the same type of rehabilitation design, the thicker the pavement, the higher the cost. On average, the LBS pavements had the lowest economic cost at just 26.21 /m^2, followed by FBS at 47.37 /m^2, and the highest average cost was associated with the NG, at 110.54 /m^2. The high cost of the NG pavement reflects the excavation activity and cost of new fine crushed rock, with the latter also reflected in the LBS and FBS rehabilitations that required a granular overlay prior to stabilisation. The difference in economic cost for the LBS and FBS reflects the high cost of the bitumen in FBS, compared to the lower cost of the cementitious binder in LBS.

At the time of writing, one Australian dollars was equivalent to approximately €0.65.(Fig. 3)

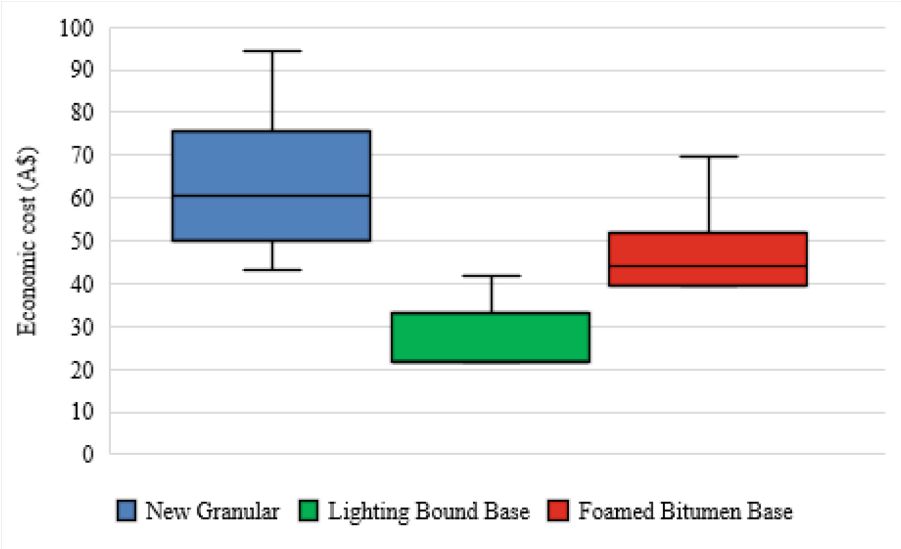


Fig. 3. Comparison of financial cost of rehabilitation options

5 Environmental Costs

The environmental costs were estimated in a similar manner to the economic costs, except the embodied carbon rates were extracted from literature (Table 3). All environmental costs were calculated as equivalent kilograms of carbon dioxide (e.CO_2), based on international standards for estimating and comparing greenhouse gas emissions embodied in infrastructure construction [9]. The calculated environmental costs ranged from 17 kg.e.CO_2/m^2 up to 274 kg.e.CO_2/m^2 (Fig. 4).

Table 3. Material embodied carbon rates (kg.e.CO_2) [10]

Material/Activity	Embodied carbon	Notes
Excavation	2 /m^3	Removal and disposal
Two coat sprayed seal	6 /m^2	Calculated from crushed rock and bitumen
Fine crushed rock	160 /tonne	
Lightly bound base	7 /m^2	Construction only, plus binder
Foamed bitumen stabilised	8 /m^2	Construction only, plus binders
Asphalt surface	345 /tonne	
Cement	365 /tonne	Supply only
Unmodified bitumen	840 /tonne	Supply only
Hydrated lime	315 /tonne	Supply only

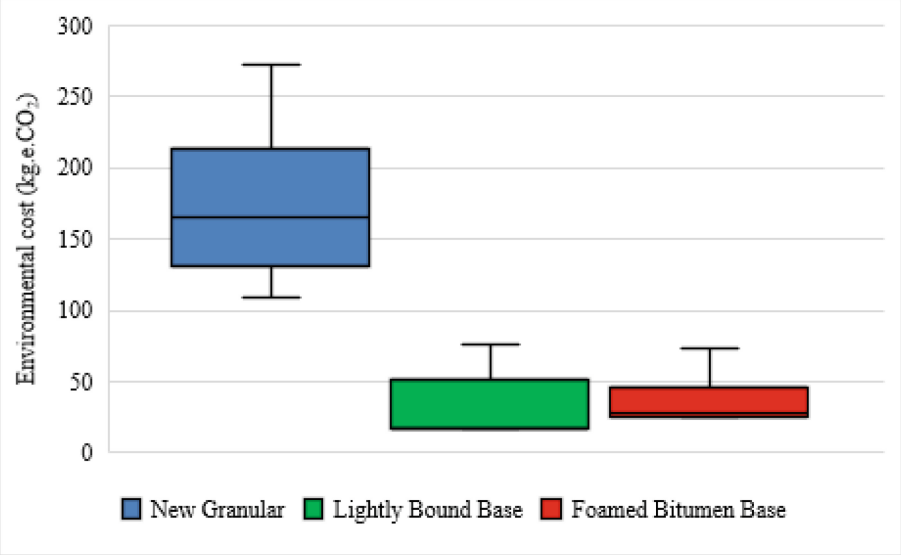


Fig. 4. Comparison of environmental cost of rehabilitation options

The lowest average environmental cost was associated with LBS, at 30.2 /m^2, compared to the slightly higher 36 kg.e.CO_2//m^2 for FBS and the significantly higher 173.8 kg.e.CO_2/m^2 for NG. This again reflects the high cost of new fine crushed rock for the NG pavement. This also partially offset the higher cost of bitumen in the FBS rehabilitations, relative to the LBS pavements, because the LBS pavements required thicker granular overlays for some of the traffic and subgrade combinations.

6 Conclusion

Based on the comparison of three different local road pavement rehabilitation options, across 12 combinations of traffic loading and subgrade support condition, the NG pavement had the highest economic cost and the highest environmental cost, by a significant margin (Table 4). This primarily reflects the high cost associated with new granular materials. This was also reflected in the significant increase in cost associated with LBS and FBS rehabilitations, whenever a granular overlay was first required to increase the granular material thickness.

The relatively low financial and environmental costs associated with LBS and FBS demonstrates the significant benefit of stabilising existing pavements, particularly for local roads comprised of a marginal granular base and a thin bituminous surface. It is recommended that stabilisation be the preferred rehabilitation option for existing local road pavements, and that pavement reconstruction with new granular materials only be considered when stabilisation of the existing pavement is determined to be unviable.

Table 4. Summary of average economic and environmental costs (/m^2)

Rehabilitation Type	Economic cost (A$)	Environmental cost (kg.e.CO_2)
NG	110.54	173.8
LBS	26.21	30.2
FBS	47.37	35.3

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Novel Concept for the Security Architecture of Airports Involving Holistic Interpretation via Artificial Intelligence

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Abstract. The Airport security touches a core value of society: Moving freely without fear, since at any time an airport can be the target of an attack. A constant evolution of airport security lies at the heart of defending such a core value. The attackers' approaches and technological devices changed, as did those of aviation security, in response to each attack. Digitalization and automatization offer the possibility to counter the attackers' approaches. An enhancement based on the combination of digitalization and automatization comprise Artificial Intelligence which is nowadays broadly used in airport security. An analysis of the existing areas of application of AI at the airport security revealed a lack in information exchange leading to the necessity of collecting and construing of security-related data to derive an overview of the overall security situation at the airport. In this paper, we describe a concept that centrally interprets and adequately acts on security-relevant information with the help of AI. Since an overall interpreting security system based on AI needs to be adapted to on airports security infrastructure, we present a way to perform this adaption.

Keywords: Airports · Security · Automation · Artificial Intelligence

1 Introduction

Since the beginning, commercial aviation has been the target of criminal and terrorist operations. Both, aircrafts and airports are affected, where aircrafts were even used as weapons. During this time, the attackers' approaches and technological means changed, as did those of aviation security, in response to attacks.

In the field of aviation security, the following methods are increasingly used, namely video recognition and analysis as well as profiling. In addition, these methods are extended by using Artificial Intelligence (AI) potentially offering added value for the operation enhancement of airport security.

Nowadays, Artificial Intelligence is broadly used in airport security, ranging from intelligent video surveillance through border control to monitoring of high-security areas. An analysis of the existing areas of application of AI at the airport security revealed a lack in information exchange. Therefore, a timely and adequate overview of the holistic

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airport security situation may be a difficult task. This leads to a time-delayed response in the event of a security-related incident such as identifying an unattended baggage and its originator, and initiating the appropriate measures. The centrally interpreting AI described in this paper overcomes this drawback.

2 Automatization of Security Processes

In this section, we examine the automatization level of the various types of security processes present at the airport (see Fig. 1). Our examination starts from passenger processes through baggage processes to security processes of room surveillance.

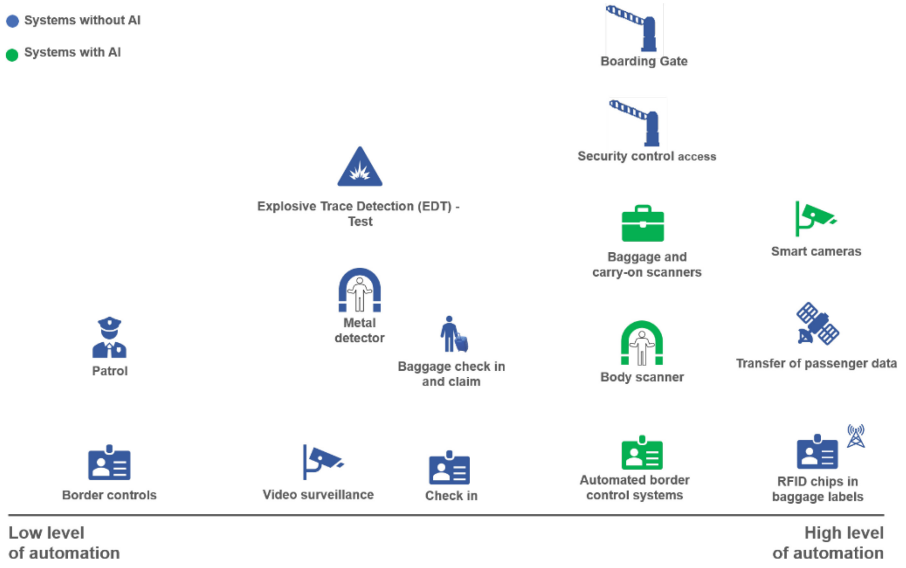


Fig. 1. Assessing the level of automation of security processes at airports based on current market offerings rather than system deployment

The passenger security process starts by purchasing the ticket [1]. The passenger name is sent to authority and compared with several databases [1]. Transmitting the data is highly automated [1]. The various types of check in (online, self-service and counter) are culminated by taking the arithmetic mean yielding a medium level. The security check solely by metal detector features a lower level than medium. Besides the metal detector, an explosives trace detection is conducted by personal using a wiping test. In the case of a manual check, due to e.g. an alarm, the level is low. An example for the application of AI is the body scanner [2]. Such AI-driven types of the security are displayed in Fig. 1 by a green icon. Checking the carry-on baggage is conducted by CT-scanners using AI to detect dissembled forbidden items [3]. Access to security check and gate is granted by scanning the boarding pass. In some cases, this procedure is not fully automatic leading to a high level of automation. The border control is undertaken by biometric scanners

and automatic door [4]. The presence of the security officer is mandatory and therefore the level is high. The automation level of baggage check is comparable to the passenger check in. Transportation and routing of baggage is fully automatic employing barcode or RFID [5, 6]. Checking baggage is comparable to the checking of carry-on baggage. The room surveillance is realized by security officer patrol and cameras [1, 7]. Additionally, cameras can be equipped with intelligent analytic software interpreting e. g. the behavior of persons using AI [7].

3 The Usage of Artificial Intelligence Within Airport Security

The processes described above are complex, involve human resources and need to be able to adapt to changing threat situations in the future. At the same time, quality, convenience and efficiency need to be increased at a high security level. Due to the high cost pressure, the design of the processes needs to make economic sense.

The use of AI offers an approach to address these challenges. Unlike humans, AI can make faster decisions, solve problems with less uncertainty in less time, and is constantly available [8]. In addition, human decision making is subject to errors. These errors can be reduced by using AI [9]. A disadvantage is the lack of flexibility under changing conditions.

Currently, AI is used independently in certain areas. One of these is intelligent video surveillance interpreted by AI. Here, the system independently learns to detect and report irregularities in the security area [10]. The project iBorderCtrl as another example represents an AI-based system for psychological profiling. This involves the automatic detection of deception in real time by analyzing people's nonverbal micro-expressions [11].

Another AI-based system is the monitoring of high-security areas accessible only to authorized personnel. This system uses electronic gates in conjunction with motion sensors and various types of cameras [12].

These and the previously described examples act independently of each other and thus represent stand-alone solutions. There is no exchange of information between the individual AI systems. Thus, no overall picture of the security situation can be created. To overcome this drawback, an AI solution is proposed below that has access to all security-relevant systems.

4 Holistic Interpretation via Artificial Intelligence

Figure 2 shows a scheme of the AI information flow. Different areas of the airport are shown with sensors (in blue) and actuators (in green). In the upper half are the above-mentioned security processes. By including safety (in the lower half), the AI is able to detect mutual ramifications.

Safety (accident prevention) and security (crime prevention) are by definition two separate areas. However, safety can have an impact on security and vice versa. For this reason, an overall concept is needed that covers both areas in the context of management—Especially of critical infrastructures such as an airport. Our proposal for such a

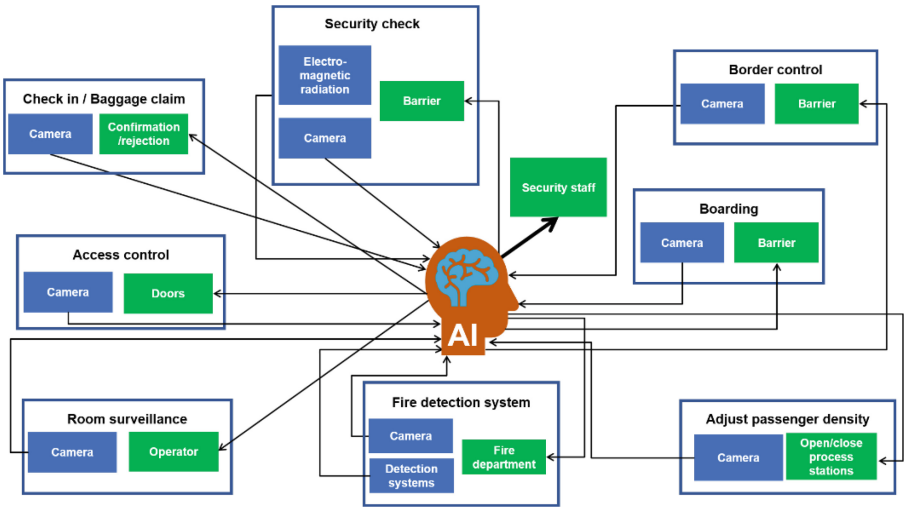


Fig. 2. Schema for the use of AI in different areas of security and safety

concept consists of a centrally managing and interpreting AI system. In contrast to existing AI systems, such an overall interpreting AI system is able to detect the intertwining of safety and security.

An example of the need to include safety is the false activation of a fire alarm with subsequent evacuation to an area at risk from attackers.

Smoke detectors offer the possibility to react to traces of fire in the air by means of laser sensors, temperature measurement and cameras or video technology. This automatically opens emergency exit doors and smoke vents in the event of a fire, closes key doors, and deploys emergency lighting [13].

However, the sensors can trigger a false alarm, for example, if the sunshine is at an unfavorable angle [14].

Thus, the possibility exists for terrorists to trigger an alarm by manipulating these sensors and exploit the response for an attack. This exploitation may consist, for example, of the deliberate placement of an explosive device—Disguised as an unattended item—Along the evacuation route of passengers. An AI having that has access to information from the smoke detectors can detect possible tampering by matching data from various sensors. In addition, such an AI can detect a coincidence in time between the occurrence of a fire alarm and an unattended item in the evacuation route by accessing information from the room monitoring system. Based on this detection, the responsible authorities are alerted with recommendations for action.

Another advantage of this overall system is the correlation of different security aspects. For example, the AI-enriched room monitoring can relate an unattended item in the terminal to the behavior of the originator. The originator is detected by the system using room monitoring, and at the same time, the AI detects suspicious behavior of the originator. The central AI system detects a critical situation and per-forms face recognition of the originator. With the help of the data determined by the face recognition, similarities are searched for in available databases. An image of the causer together with

the results serves as the basis for the action recommendation for the actuators, in this case the security personnel.

Such an overall system must be tailored to each airport, since each airport is individually designed, e.g., in terms of layout and security architecture. Those responsible for the security of an airport can thus realize an overall system by centralizing both the evaluation and the control. In order to obtain a system that takes care of the interpretation of the data, we propose an AI system adapted to the security architecture. In order for this AI system to detect and adequately respond to any threats, a learning process is necessary. This can be done, for example, with the help of scenarios. The German Aerospace Center (DLR) project E^2S^2AI (Evaluation and Evolution of Safety and Security with Simulation Based Artificial Intelligence) employs a different approach. The AI system learns by performing different factions within the security architecture. Feedback to the AI system on the success or failure of the action enables it to learn. To realize the potential of this learning method, it is beneficial to establish symmetry so that the system can compete against itself. For this reason, another system is introduced to test the weaknesses of the first's response. Both systems learn by responding to the other's action (see Fig. 3). Because both AI systems are adapted to an airport's security architecture, they can provide valuable advice on how to improve an airport's safety and security.

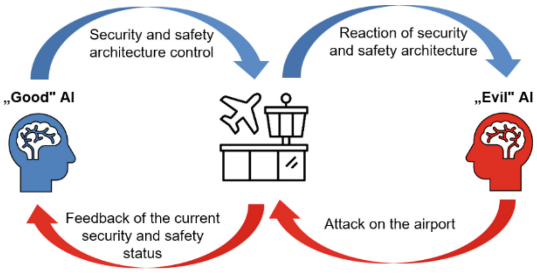


Fig. 3. E^2S^2AI method, two AI systems compete against each other to improve security at the airport

5 Conclusion and Outlook

The analysis of security processes shows an advanced level of automation and widespread use of AI in many areas. However, these are isolated solutions for specific tasks, such as facial recognition. The systems used do not provide for any exchange of information between the individual AI applications.

In this paper, we present a concept that centrally interprets and adequately acts on security-relevant information with the help of an AI. Such a system combined with adequate devices has the potential to speed up the reaction time to security incidents. In contrast to currently deployed AI systems, our concept presented in this paper is capable of detecting coordinated attacks and responding adequately. AI-enhanced room monitoring, for example, can establish a link between an unattended item in the terminal and the behavior of the originator. The identified information and corresponding recommendations for actions are immediately made available to the responsible parties.

The German Aerospace Center (DLR) project E^2S^2AI is investigating the methodological basis for this concept and its feasibility. In the process, an AI system is being developed that is intended to increase safety and security at the airport. This system consists of two components challenging each other. This approach leads to learning unforeseen types of attacks and the appropriate response. Subsequently, the aim is to test the method developed in E^2S^2AI with a real-world airport's security landscape. In addition, the data protection and acceptance of such a system will be evaluated.

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Analysis and Evaluation of Passenger Flow at the Next Generation Station Using Microscopic Simulations

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Abstract. The impact of mankind's change of climate system and ecosystem is evident. Nonetheless the society's need for mobility is still growing. Having these points in mind a transformation of mobility from fossil fuel based to renewable energy based is required. The German government is giving great hope on railways as a mode of transport implementing one aspect of this transformation. A growing number of passengers poses a tremendous challenge of the railway infrastructure, since nowadays train stations already reach their capacity limit at peak times. A train concept developed by the German Aerospace Center called Next Generation Train is one answer to this challenge. In this paper, we evaluate the performance regarding passenger flow of the corresponding station called Next Generation Station. To this end, we implemented a microscopic simulation of the Next Generation Station with input parameters such as expected number of passengers, walking speed distribution and dimension of passengers. The transfer time of passengers serves as key performance indicator during the simulation. We compare this transfer time with the reference value for train stations adopted by the German Rail. The methodology developed in this paper can be transferred to existing train stations.

Keywords: Next generation station · Next generation train · Passenger simulation · Passenger transfer time · Key performance indicator

1 Introduction

The society's growing need for mobility and the associated burden on the environment and climate pose enormous challenges worldwide. The German government is giving great hope on railways as one mode of transport. It schedules a doubling of transport performance in passenger rail transport by 2030 [1]. This ambitious goal represents a huge challenge for the entire rail infrastructure. In addition to control and safety technology, track network and rolling stock, train stations need also to be able to handle the significant increase in passenger numbers [2].

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However, some train stations are already reaching their capacity limit at peak times or their load limit as passenger numbers increase [3, 4]. In addition to enormous investments in station infrastructure, new concepts are necessary to ensure comfortable and efficient transfers in the future despite increasing passenger numbers.

The concept Next Generation Train (NGT) developed by the German Aerospace Center (DLR) is an answer to the challenge of increasing passenger capacity. This concept comes along with some paradigm changes, such as double-deck multiple-unit vehicles, missing stairs inside the wagon, simultaneous boarding and alighting of passengers, both on the lower and upper level, to reach the goal [5, 6]. Therefore, a new train station concept is necessary. Having this in mind, the DLR is researching the station concept Next Generation Station (NGS) which represents a multimodal hub station of a metropolis [6].

In this paper, the performance of the NGS concerning passenger flow is evaluated. To this end, a microscopic simulation is used making it possible to represent the complexity and the interaction of passengers. We use the transfer time as key performance indicator for the evaluation. The inputs consist of the geometric layout of the NGS, characteristics of passengers and an underlying timetable for train departure and arrival.

2 Simulation Model

In this section, we describe the train station concept Next Generation Station (NGS), the input parameters for the simulation model and the basis for the evaluation of the performance of the NGS.

2.1 Next Generation Station

The NGT concept comes in two vehicle concepts, the high-speed train (NGT-HST) will operate mainly between metropoles and an intercity train (NGT-LINK) will carry passengers from the surrounding areas to the high-speed line's hub stations [5]. The current design of the NGS has 14 platforms on four levels enabling the NGT HST to stop in double traction (approx. 1600 seats) or the NGT LINK to stop in triple traction (approx. 1425 seats). The lowest level is developed for regional traffic (NGT LINK). The intermediate level has an access and distribution function for passengers and the two upper levels are reserved for the second and first class of the high-speed train NGT HST allowing simultaneous boarding and alighting on both levels (see Fig. 1). Direct transfer between the comfort classes of the NGT HST is not provided, nor is direct transfer between the high-speed trains.

In the NGS concept analysed, a passenger on the LINK level intending to board the HST has to go to the intermediate level and then use the corresponding elevator or escalator.

2.2 Input Parameters

Building dimensions and data from literature were considered as input parameters for the simulations of the NGS model, namely

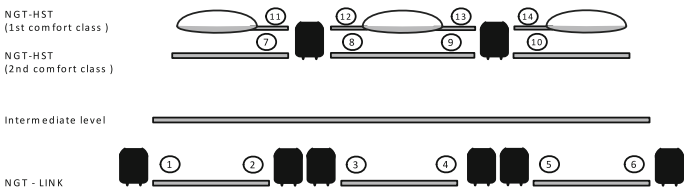


Fig. 1. Scheme of the NGS with corresponding levels and platforms

- geometric layout of the NGS,
- characteristics of passengers (e.g. walking speed distribution [7], body proportion [8]),
- properties of mechanical equipment (e.g. escalators [9–11], passenger elevators [12, 13]) and
- timetable distribution based on the peak load of the Berlin central station combined with the peak hour of London [14, 15].

We used a load factor of 100% for both vehicle concepts and a passenger change rate of 50% for the NGT HST and 100% for the NGT LINK.

2.3 Key Performance Indicators for Evaluating the Performance of a Station

We use three performance indicators. The first is the transfer time, defined by the period that is necessary, according to the timetable, for passengers to change from an arriving to a departing train [10]. The Deutsche Bahn AG (DB) employs the guideline "Transfer times in the working timetable" [10] to determine a specific transfer time for each station in Germany. According to [10], the transfer time for the NGS is 10 min. That time represents a reference value for the evaluation.

Within the simulation, the beginning of the transfer time is represented by leaving the train or entering the intermediate level of the NGS via access from private transport or public transport. The time of taking a waiting position at the platform marks the end of the transfer time.

The traffic performance is assessed by comparing the simulated transfer time with the calculated transfer time (reference value).

The evaluation of the passengers' perception of quality based on the so-called traffic quality split in quality walking area and waiting area are the second and third key indicator, respectively. It is also known as level-of-service (LoS) [11, 16]. Traffic load cases based on passenger density are assigned to six quality levels (A-F). Quality level A represents the largest comfort of movement and quality, and level F means a breakdown of the traffic flow.

3 Simulation Results

The objective of this paper is to evaluate the performance of the NGS in terms of passenger flow. For this purpose, 12 operating hours were simulated and the key performance indicators were evaluated.

The arithmetic mean values of the simulated transfer times of all relations including the standard deviation range from 0.66 to 8.94 min. Thus, they are all below the reference value of 10 min.

The proportion of transfers with a duration greater than the reference value is listed for each transfer relation in Table 1. It is used to determine the transfer relations for which there is an increased risk of the transfer time exceeding the reference value. To provide a clearer overview, the values have been color-coded: Green $< 2\%$, Orange $\geq 2\%$–$< 5\%$, and Red $\geq 5\%$.

Table 1. Total number of transfers (italics) and proportion of transfers (bold) whose duration exceeds the reference time of 10 min, color coding of the proportion: Below 2% green, between 2% and 5% orange, above 5% red.

from\to		LINK						HST 2st comfort class		HST 1st comfort class		Private transport	Public transport
		1	2	3	4	5	6	7	10	11	14		
LINK	1	**0.20%** *3421*	**0.29%** *3396*	**2.46%** *3461*	**3.44%** *3433*	**4.86%** *3479*	**4.31%** *3390*	**0.08%** *3992*	**0.43%** *3945*	**0.72%** *2625*	**0.69%** *2596*	**0.58%** *8999*	**0.54%** *8927*
	2	**0.43%** *2300*	**0.17%** *2317*	**5.18%** *2316*	**8.06%** *2319*	**3.91%** *2325*	**8.83%** *2322*	**0.26%** *2659*	**0.77%** *2655*	**1.30%** *1696*	**1.58%** *1708*	**0.97%** *6059*	**0.57%** *6008*
	3	**3.91%** *3400*	**2.97%** *3305*	**0.15%** *3366*	**0.81%** *3315*	**4.10%** *3265*	**2.97%** *3402*	**0.26%** *3798*	**0.22%** *3713*	**1.92%** *2243*	**0.89%** *2471*	**0.52%** *8637*	**0.44%** *8696*
	4	**5.09%** *2279*	**10.08%** *2342*	**0.40%** *2275*	**0.21%** *2346*	**2.00%** *2300*	**3.63%** *2317*	**0.36%** *2531*	**0.16%** *2561*	**1.19%** *1679*	**1.48%** *1753*	**0.49%** *6133*	**0.62%** *6082*
	5	**6.68%** *3413*	**6.69%** *3332*	**7.03%** *3439*	**5.00%** *3400*	**0.39%** *3356*	**0.85%** *3401*	**0.45%** *3770*	**0.10%** *3817*	**1.32%** *2652*	**1.15%** *2514*	**0.91%** *6800*	**0.44%** *9143*
	6	**4.23%** *2267*	**5.86%** *2302*	**4.98%** *2287*	**5.90%** *2442*	**0.34%** *2373*	**0.04%** *2312*	**0.53%** *2637*	**0.20%** *2608*	**0.77%** *1691*	**1.40%** *1787*	**0.61%** *6077*	**0.82%** *6076*
HST 2st comfort class	8	**2.27%** *3176*	**2.41%** *3814*	**2.08%** *3126*	**2.33%** *3129*	**1.64%** *3169*	**3.07%** *3061*					**0.09%** *7668*	**0.22%** *7655*
	9	**3.86%** *3292*	**3.58%** *3181*	**2.90%** *3167*	**1.77%** *3166*	**2.60%** *3110*	**1.37%** *3282*					**0.28%** *7543*	**0.10%** *7756*
HST 1st comfort class	12	**5.00%** *2079*	**4.97%** *2151*	**3.74%** *2086*	**4.19%** *2074*	**2.93%** *2082*	**4.76%** *2120*					**0.53%** *5115*	**0.30%** *5076*
	13	**6.45%** *2093*	**5.29%** *2172*	**4.23%** *2106*	**2.52%** *2144*	**3.27%** *2077*	**2.35%** *2087*					**0.34%** *5256*	**0.54%** *5017*
Private transport		**3.28%** *8681*	**4.74%** *6093*	**2.12%** *9153*	**7.06%** *5994*	**1.59%** *9106*	**4.77%** *5886*	**0.06%** *7950*	**0.00%** *7827*	**0.45%** *5287*	**0.41%** *5144*		
Public transport		**2.90%** *8862*	**4.82%** *6135*	**3.85%** *9212*	**10.18%** *6023*	**1.43%** *8911*	**5.51%** *6026*	**0.01%** *7015*	**0.06%** *7735*	**0.39%** *5176*	**0.33%** *5200*		

In 0.08% to 1.92% of all transfers with long-distance transport or private transport and public transport as destination have a transfer time greater than the reference value. In contrast, passengers having a platform served by the NGT LINK as their destination take longer than 10 min, i. e. longer than the reference value, for their transfer in at least 5% of a total of 15 transfer connections.

To find the reason for these high values, we examined several transfer relations with a high percentage of passengers needing longer than 10 min for their transfer. First, we evaluated the residence times of the passengers on different levels. It is notable that the passengers on the destination platform LINK level have a higher residence time than the reference time for the way from the escalator or elevator to the waiting area. Consequently, we investigated the passenger density on the LINK level. The results correspond to Level D of the LoS for walking areas during 40% of the simulation time. Such a quality level leads to high obstruction and temporary standstill of the passenger flow. High passenger density on the destination platform leads to low walking speeds and an uncomfortable stay for the passengers. Also, it encourages safety-critical situations such as passenger standing in the marked danger zone at the edge of the platform.

The high passenger density on the destination platform is caused by the use of the nearest escalator/elevator in this simulation model. Consequently, the randomly selected waiting area on the destination platform may be far away from the escalator or elevator and blocked by passengers.

To prevent a long residence on the destination platform, we designed and examined a new scenario. We evaluated the effect of passenger paths shifting from the destination platforms to the intermediate level. Therefore, each passenger is assigned to the escalator or elevator closest to his or her waiting position, which is also close to the boarding door of the booked train at the destination platform. Thus, a minimum distance on the destination platform can be guaranteed. The input parameters for the simulation of this scenario are not changed to obtain a comparable result.

The results of the simulations show a slight improvement in the mean values of the transfer times: They now range between 0.67 and 7.49 min including standard deviation. This measure significantly reduces the proportion of transfer relations exceeding the reference value. It is less than 2% for all relations. In contrast to the first scenario, passengers have a shorter path and consequently spend less time on the destination platform. For this reason, the traffic quality on the regional platforms is evaluated by the criteria LoS for waiting areas. Thus, the passenger density on all platforms can be assigned the traffic quality LoS A in more than 99% of the simulation time. In the intermediate level, the passenger density in both scenarios corresponded to LoS A for walking surfaces during the whole simulation time.

4 Conclusion and Outlook

The DLR is researching a new type of rail transport concept for the future to meet the growing mobility needs of the population and the increasing demands in terms of comfort and travel time. An important aim of this project is to connect major cities by high-speed rail connections as an alternative to short haul flights. This involves the use of a high-speed train (NGT HST), which has special demands on the station infrastructure due to simultaneous boarding and alighting of passengers, both on the lower and upper levels. To fulfill these demands, a new type of station concept was developed with the NGS. Some train stations are already reaching their capacity limits during periods of high passenger volume. Therefore, it is important to investigate the performance of the NGS in terms of passenger flows. This procedure involved the development of a simulative method to illustrate complex passenger movement behavior at a train station. Also, it contains the identification of appropriate key performance indicators for evaluating the passenger flow within a train station and the development of recommendations for improvements by using simulations.

The results of this simulation provide approaches for improving traffic quality for NGS passengers. These need to be further investigated and evaluated in future work.

Due to a complex system, we made simplifications and assumptions for the simulation structure. An example for a future research topic could be the extent to which a specific operating concept for the NGS, assuming a doubling of passenger numbers, affects the simulation results. Other factors that should be considered include baggage drop-off and pick-up on long-distance travel, retail stores, food and service facilities. Also, changes in passenger decision-making behavior regarding escalators and elevators should be considered.

The method developed in this study allows not only the evaluation of the NGS, but also the performance of existing stations in terms of passenger flow. The method can

also be used to assess the impact of future structural and operational changes of existing stations.

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Improving the Planning of Future Track Interventions Using Digital Tools

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Abstract. This paper proposes a methodology to capitalise on the recent advances in technology to efficiently estimate the required condition-related track interventions, possession times and their expected costs for a railway network early in the intervention planning process. Having such estimates not only helps track managers effectively plan and allocate resources, but it also enhances the communication between different stakeholders within the intervention planning process, e.g., asset managers, line planners, capacity managers, and network developers. The methodology uses data of different levels of detail, probabilistic discrete state modelling of the condition of components, and component-level intervention strategies. It also uses fault trees to connect potential losses in service with the likelihood of corrective interventions that may occur due to sudden events as a function of the condition of the components.

The methodology is used to estimate the required condition-related interventions, possession times and expected costs for a 25 km railway network in Switzerland. The results indicate that the methodology has the potential to help track managers early in the intervention planning process. Once implemented in a digital environment, the methodology will lead to improvements in the efficiency of the planning process, improvement in the timing of preventive interventions and the reduction in corrective intervention costs.

Keywords: Infrastructure management · Railway systems · Digitalization · Deterioration modelling · Maintenance planning · Intervention strategies

1 Introduction

Currently, track managers estimate interventions using a relatively qualitative approach including the integration of historical and recent inspection data by a group of experts in initial phases of intervention planning. This approach requires significant time, effort, and cooperation from experts. Additionally, the experts' subjectivity can result in interventions being scheduled earlier or later than required. This can induce additional costs and service disruptions. Track managers, therefore, would benefit from a systematic

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approach that can efficiently estimate a complete and detailed overview of future intervention requirements. The use of digital tools can address the gap in current intervention planning by enabling track managers to effectively exploit the vast and growing data on network track assets, their condition over time, and the costs and impacts of interventions on service.

There are multiple methodologies aimed at improving the intervention planning for different assets by addressing different asset managers' concerns such as determining optimal track intervention strategies [1]. Although these methodologies generate an overview of intervention requirements, they need to be further improved to become more useful. Improvements include detailed estimates at the component or element level, incorporating the risk of serviceability failure, and approximating track possession times. An example of methodologies focused on the component level is found in [2]. An example of methodologies focused on risks associated with track failure is found in [3]. An example of works that include estimation of intervention costs and/or possession times is found in [4].

This paper proposes a methodology to estimate component-level interventions, costs, and possession times systematically and efficiently for future planning periods at early stages of intervention planning. The methodology considers the condition evolution subject to multiple deterioration processes, failure risks connected to the component condition states, possible preventive interventions, and associated costs and effects on service through allocated possession times. The methodology can use both qualitative and quantitative information from different sources, such as visual inspections, approximate and detailed estimates of failure risks, and approximate and detailed estimates of the intervention costs and impacts on service. An application of this methodology is demonstrated by estimating a complete overview of component-level intervention requirements for track assets on a 25 km railway network in Switzerland.

2 Methodology

An overview of the proposed methodology for estimating the type, costs, and possession times of component-level interventions over future planning periods is shown in Fig. 1. This methodology includes the following steps:

- Step 1: Select all track assets for which the estimates are to be made. Do not include the tracks that have undergone preliminary studies by engineering offices.
- Step 2: Estimate the condition of all components for all track assets at $t = 0$.
- Step 3: Estimate the condition of all components for all track assets at $t = 5$.
- Step 4: Estimate the failure risk at $t = 5$.
- Step 5: Estimate the probability that each component requires an intervention according to component-level intervention strategies.
- Step 6: If no intervention is needed, set $t = t + 1$ and update the condition state of the components.
- Step 7: Estimate the required interventions: If the intervention requirement probability of a component or the failure risks exceeds the threshold, an intervention is needed. Indicate possible and most likely intervention types, costs, and possession times.

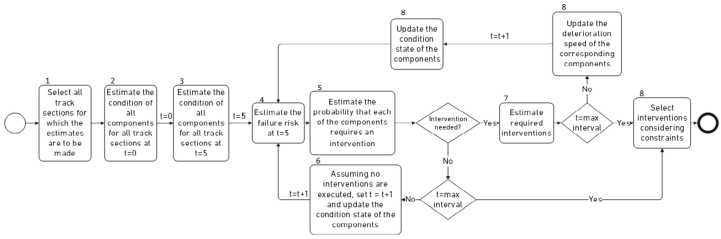


Fig. 1. The proposed methodology for implementation in a digitalized intervention planning process

- Step 8: Suggest intervention postponements: If the execution of all interventions is not possible within the planning period, prioritize based on failure risk. Postpone lower-risk track assets until intervention costs are within the budget.

3 Example Railway Network

The example railway network includes eight stations that stretch over 25 km located in Switzerland. This double-track network has 45 daily passenger trains on each track side. The conditions of tracks and switches are regularly checked. Track geometry, i.e., twist, cross-level, gauge, curvature, and alignment, is measured by SBB coaches twice a month [5]. Tracks with high demand also undergo yearly semi-automatic and manual checks for other issues, e.g., sleeper cracks or ballast loss [6].

Figure 2 shows a summary of the latest inspection records for the example railway network, based on the database associated with track and switch conditions. The figure indicates that switches are mostly good, while most of the track assets are in damaged condition.

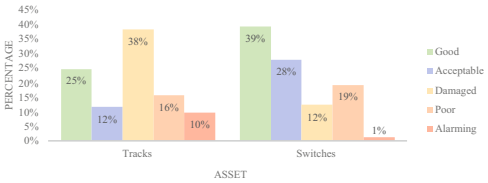


Fig. 2. The latest condition distribution of the example railway network

3.1 Components

While switches are considered as one component, railway tracks are decomposed into five main components, made of different materials, i.e., rails, fastenings, sleepers, ballasts/sub-ballasts, and subgrades. Ballasts and sub-ballasts are considered as one component since they deteriorate similarly [7].

A component-level track analysis helps plan and coordinate track interventions and train schedules earlier on by providing more insights into interventions, e.g., likely possession time and costs.

3.2 Condition State of the Track Components at t = 0 and t = 5

Five discrete states are defined to describe the condition of components, ranging from 1 to 5 such that Condition State 1 (CS1) represents a situation where there is no or minor damage and CS5 represents an alarming situation with severe damage that is unsafe. The states in between show increasing levels of damage. For example, switches are in the CS1 if they have no issues, and in CS5 if the settlement is too high, or the cross nose is deformed. Similar to switches, such condition states are defined for other components. The condition state of all components is then estimated using the definitions and information from the latest inspection reports.

Probabilistic discrete state modelling is used to estimate how CSs change over time, which is similar to the modelling used in existing Bridge Management Systems [8]. Table 1 shows an example of transition probabilities for switches for one-year periods, which is the average time between observations. Here, deterioration rates increase as a function of the maintenance interventions on the component. This is because maintenance activities do not always restore the physical and chemical properties of the components [9]. It is assumed that after the first maintenance, the deterioration rate increases by 2% after each intervention. The maintenance count resets after component replacement. The same logic is used for other components.

Table 1. Example transition probabilities for switches

CS	1st maintenance intervention					2nd maintenance intervention				
	1	2	3	4	5	1	2	3	4	5
1	0.84	0.16	–	–	–	0.82	0.18	–	–	–
2	–	0.72	0.28	–	–	–	0.70	0.30	–	–
3	–	–	0.56	0.44	–	–	–	0.54	0.46	–
4	–	–	–	0.32	0.68	–	–	–	0.30	0.70
5	–	–	–	–	1.00	–	–	–	–	1.00

Figure 3 shows the estimated condition state of the components at t = 5, based on their initial CS at t = 0 multiplied by their transition probability for the next 5 years.

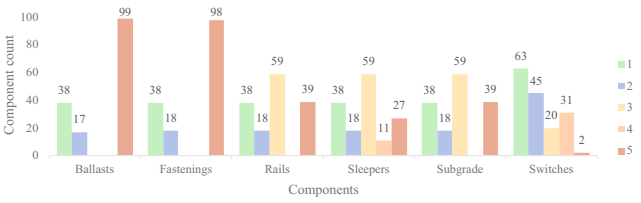


Fig. 3. Overview of the condition state of the track components at t = 5

3.3 Component-Level Interventions and Intervention Strategies

Different interventions are needed to maintain components' expected serviceability which varies according to the component type and damage severity. This includes rehabilitation, renewal and replacement [9].

The intervention costs are divided into owner and user costs. The owner costs are based on a reference price index [10]. The user costs are the value of the added travel time, i.e., 6′524 mu/day, calculated as in [11]. Table 2 shows intervention costs for switches, which increase with the complexity and labor demand of activities [9]. The intervention costs for other components are calculated similarly to switch intervention costs.

Table 2. Example switch intervention costs

Intervention type	Unit cost (mu/quantity)	Duration of the service disturbance (h)	Service disturbance costs (mu)	Total costs (mu)
Rehabilitation	3′110	4	260′496	263′606
Renewal	3′930	4	260′496	264′426
Replacement	14′110	8	520′992	535′102

Intervention strategies and effectiveness for components are estimated using different sources such as [9, 11]. For example, the switch intervention strategy indicates no intervention is needed in CS1 and CS2, while a replacement is needed in CS5. For CS3 and CS4, rehabilitation and renewal are applied, respectively. The effectiveness indicates the probability of a component being in CS1 or CS2 after the intervention [9].

3.4 Failure Risks Between t = 6 and t = 10 and t = 11 and t = 15

Fault trees are developed to estimate track failure risks, connected to the severity of components' failure. Top events are restricted service (rehabilitation at night) and interrupted service (replacement with total closure) defined for each track section. The basic events are gradual or sudden deterioration due to external loads, such as traffic or natural hazards. Failure probabilities of components are estimated based on the occurrence probability of basic events. These events depend on the external loads and the component resistance. The external loads are independent from CSs of components and based on expert opinion, while the resistance of components varies with components' CS. This means occurrence probabilities of basic events varies for different CSs, with a lower value for CS1 and a higher value for CS5. The consequences of each top event depend on how much work is needed to restore the level of service. These are estimated using information from Sect. 3.3. The failure risks are then estimated depending on the components' CS. These estimates enable obtaining a meaningful overview of interventions and avoiding intervening on different components every year. These also help plan interventions using a predefined failure risk threshold in case there are no component-level intervention strategies defined. This threshold is defined as the value of failure risks when all components are in CS4.

3.5 Most Likely Interventions

The interventions are estimated for the next planning periods, i.e., t = 6 to t = 10, and t = 11 to t = 15 considering deterioration rates and intervention strategies discussed earlier. Interventions are scheduled to be executed on a component when the failure risks approach the defined failure risk threshold in each planning period. After knowing which interventions are needed, detailed information regarding the most likely interventions such as the expected costs and possession times are estimated.

4 Conclusion

This paper proposes a methodology to estimate interventions, possession times, costs, and failure risks for track assets. It is demonstrated on a 25 km railway network in Switzerland. The novelty of the method includes the focus on components, instead of assets, and the use of fault trees to estimate condition-dependent failure risks. The method accounts for the factors that track managers care about. It uses a five-state probabilistic model to estimate the current and future CSs and intervention requirements. It uses fault trees to estimate the failure probabilities and consequences for two top events related to traffic disruption. The consequences include owner and user costs. To comprehensively assess the advantages of this methodology, future studies should conduct testing on both real-world and simulated networks.

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Automatic Detection of Asphalt Road Distress via Semantic Segmentation

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Abstract. We address the problem of automating the previously manual inspection of asphalt distress and damage, which is time-consuming and subjective. With the help of a semantic segmentation neural network, we automate this process and make a pixel perfect detection. Our method is based on a previously published approach, validated for detecting distress symptoms in asphalt surfaces, for highway road data. The main challenge with the previous approach was, that the original training material did not yet contain significant samples of classes like foliage, drainage and additional types of road surface damage relevant to smaller secondary roads. Upon trying to retrain the underlying neural network it was discovered that methodological improvements were necessary to accurately detect these new classes. For now, we tried a new combination of a momentum-based Adam-Optimizer and a Cosine based learning Rate scheduler with restarting epoch also called Cosine Annealing. In theory, this should evade local minima of the error function, compared to the previously used polynomial decay without restarting epoch. The combination of both should yield a better minimum of the error function and higher accuracy rate.

Keywords: semantic segmentation · pixel perfect detection · cosine annealing · automatic distress detection · asphalt distress detection

1 Introduction

We explore the ability of a neural segmentation network to accurately and precisely predict distress of roads utilizing a pixel perfect detection. The neural network was trained on labeled road image data with high resolution, containing 25 different classes. The images were taken by a 2D laser scanner and were labeled by domain experts. The research conducted within this paper is based on an already pretrained neural network architecture introduced in [1]. During inference time we observed that the network still performed quite poor. The pretrained network was trained by use of a stochastic gradient descent optimizer (SGD) [2] in combination with a polynomial learning rate decay. Therefore, we took the opportunity to try a new combination of gradient optimizer and learning rate scheduler in order to find a better minimum of the error function concerning the neural network architecture. It should be mentioned that we also trained on new data generated by a 2D laser scanner, probably giving us better results on the validation data

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set, representing the same type of data as the training data set. In this work we will present the application of the momentum-based Adam optimizer [2] in combination with a cosine annealing learning rate scheduler [3] in order to effectively avoid local minima of the error function.

2 Data and Methodology

2.1 Data

We trained the segmentation network on two different datasets covering the most important distress classes, resulting in an overall of different 25 classes. The following Table 1 gives a detailed summary the classes present in each dataset and further to what amount they were present. The data was labeled by domain experts, using the framework Scalabel [4]. For training purposes those datasets were split into 80 percent of training data and 20 percent of validation data.

As we can see from Table 1, there is a high imbalance between the classes. Usually this is not good for a segmentation or classification task. This circumstance is counteracted by using an error function for unbalanced training datasets, namely the sparse categorical cross entropy function balanced with class weights. In the following Eq. (1), we introduce the SoftMax function for K variables in a vector z corresponding to K possible classes. In our setting, the function is applied to the network output for each pixel, calculating the probabilities for each of the K classes. The class with highest score wins the vote and therefore determines the final class of the corresponding pixel.

$$\sigma(z)_i = \frac{e^{z_i}}{\sum_{j=1}^{K} e^{z_j}}, \quad i = 1, .., K. \tag{1}$$

2.2 Model

We trained a neural segmentation network, which consists of a ResNet18 [5] backbone working as the encoder, a Spatial Pyramid Pooling (SSP) context module [6] pooling most important features from the encoder and lastly, a two-dimensional linear up sampling module as the decoder. In the following the network is explained in more detail (see Fig. 1).

Table 1. The first column depicts the names of the classes present in the labeled dataset. The second and third column show the cardinality of instances for each dataset which we will call D1 and D2 respectively. One instance is defined as a closed labeled polyline within one of the many road surface images present in that specific dataset. D1 contains 1130 images with a resolution of 900 × 675 pixel and 739 images with a resolution of 2019 × 2250 pixel. D2 contains 1205 images of 2D laser scanner data, from which 194 are with a resolution of 2692 × 3000 pixel and the other 1011 images have a resolution of 3000 × 1903 pixel. To get an idea on how much of area is covered by each class we will give magnitudes in parentheses for the first dataset.

Classes	D1	D2
Drill core	6 (~0.01 m^2)	0
Marker	480 (~50 m^2)	161
Single crack SG1 (sealed)	1237 (~50 m^2)	1054
Single crack SG2	5387(~10 m^2)	3956
Single crack SG3	923 (~1 m^2)	721
AFLI	24 (~1 m^2)	0
Chipping/detachment	82 (~0.1 m^2)	0
Grain outbreak	71 (~1 m^2)	0
Emaciation	172 (~10 m^2)	
EFLI	23 (~1 m^2)	0
Binder enrichment	24 (~1 m^2)	0
Bridge transition construction	2 (~1 m^2)	0
Road gully	10 (~1 m^2)	0
Banquet	739 (~500 m^2)	468
Biomass	3786 (~5000 m^2)	1963
Borde	34 (~1 m^2)	16
Plaster	50 (~10 m^2)	4
Shaft	27 (~1 m^2)	2
OBJ mobile	2 (~0.001 m^2)	0
OBJ Stationary	11 (~0.1 m^2)	2
Seam intact	261 (~1 m^2)	1
Seam tear	79 (~1 m^2)	2
Normal	- (~10,000 m^2)	–

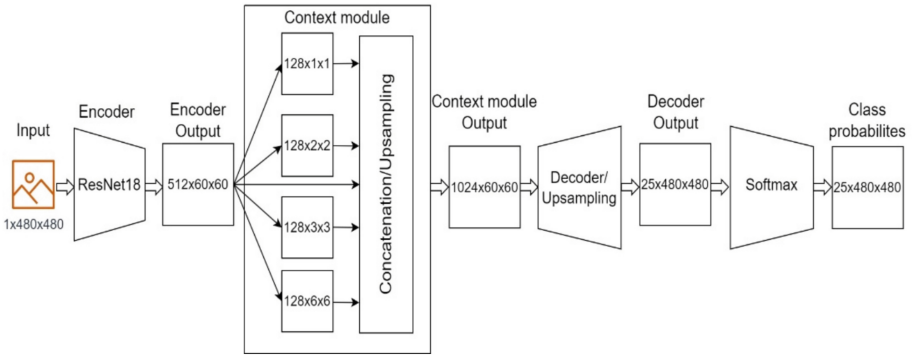


Fig. 1. The input shape to the ResNet18 encoder is a $1 \times 480 \times 480$ greyscale image with only one channel. Since the ResNet18 has an overall output stride of 8, the resulting encoder-output has the dimensions $512 \times 60 \times 60$ with 512 layers channel depth. The subsequent SSP context module applies four two-dimensional average pooling kernel filter on that same encoder-output. After further processing and concatenation of those four strands together with a shortcut connection, the up-sampling decoder module is applied, finally resulting in a $25 \times 480 \times 480$ output. After applying the SoftMax function (1) onto the first dimension, we get the class probabilities for each pixel.

2.3 Methodology

In our approach we tried to improve the methodology of network training by avoiding local minima of the error function during training which was achieved by use of a cosine annealing learning rate scheduler [3]. Further we used a momentum-based Adam optimizer, which should be more robust regarding local minima compared to the SGD optimizer, which does not incorporate momentum information of the computed gradient.

2.4 Implementation and Hardware

The procedure was implemented in python using the TensorFlow library [7].

It also had to be considered that it was not possible to label every single pixel of each image contained within the training datasets. This circumstance was counteracted by introducing one more "VOID" class in the work of [1]. When comparing true and predicted data, labeled pixels which contained the VOID class where just omitted and ignored in the training procedure. Furthermore, to make the network size acceptable, each of the images was divided into 480×480 patches, allowing for acceptable training time and manageable memory consumption. After prediction, those patches were composed back together to the overall image. Training was conducted on a NVIDIA GeForce RTX 3060 GPU. Both datasets were trained for approximately 40 epochs, resulting in a training time of almost 5 days for each of the datasets.

3 Results

The detection accuracy was measured by the Intersection over Union coefficient (IoU) defined by

$$IoU = \frac{TP}{\mathrm{TP} + \mathrm{FP} + \mathrm{FN}}. \tag{2}$$

In formula (2), TP defines the amount of true positive detected pixels by the segmentation network. FP and FN describe the amount of false positive, respectively false negative amounts of detected pixels. Table 2 applies this formula to the validation dataset split, for each of the datasets D1 and D2 respectively. Both datasets were trained for 44 epochs. The training accuracy and loss are shown in Fig. 2, showing converging behavior on the validation dataset. Converging loss on validation data jointly with converging loss on training data is a quality measure, showing that no overfitting occurred during the training procedure and that the trained network has good generalization abilities. We must bear in mind that the training was started from a pre-learnt network. Still, no layer weights of the old network were fixed, which means that no real transfer learning occurred. This also wasn't necessary since we had a whole bunch of newly labeled high-resolution data and high overall coverage of classes. From this point of view, the 40 epochs of training leading to an optimal solution are quite good, compared to the 300 epochs for which the pre-learnt network was trained.

Table 2. We split the datasets into 80 percent data for training purposes as well as to a standout dataset of 20 percent for validation purposes. The second and fourth column depict the IoU values using the pretrained network from [1] for both datasets respectively. mIoU denotes the mean Intersection over Union over all occurring classes. The third and fifth column depict the results after training. We can clearly see that the network output improves tremendously, giving us better results and usability for automated detection purposes.

IoU of Validation Dataset	D1_score_0	D1_score_1	D2_score_0	D2_score_1
All classes (mIoU)	0.21	0.5	0.24	0.67
Drill core	0	0.59	–	–
Marker	0.82	0.87	0.9	0.9
Single crack SG1 (renovated)	0.34	0.61	0.37	0.79
Single crack SG2	0.03	0.1	0.03	0.16
Single crack SG3	0.06	0.2	0.05	0.3
Chipping/detachment	0.02	0.42	–	–
AFLI	0.01	0.31	–	–
Grain outbreak	0	0.4	–	–
Emaciation	0	0.32	–	–
EFLI	0	0.37	–	–
Binder enrichment	0	0.54	–	–

(*continued*)

Table 2. (*continued*)

IoU of Validation Dataset	D1_score_0	D1_score_1	D2_score_0	D2_score_1
Bridge transition construction	0.32	0.32	–	–
Road gully	0.1	0.38	–	–
Banquet	0.12	0.83	0.14	0.75
Biomass	0.59	0.99	0.51	0.95
Borde	0.17	0.63	0.046	0.76
Plaster	0.38	0.89	0.2	0.79
Shaft	0.57	0.67	0.02	0.68
OBJ mobile	–	–	–	–
OBJ Stationary	0	0.6	0	0.89
Seam intact	0.06	0.26	0	0.77
Seam tear	0.13	0.4	0	0
Normal	0.94	0.99	0.89	0.99

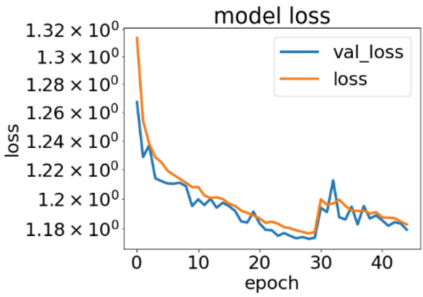


Fig. 2. The graph depicts the learning loss during training of dataset D1. The y axis denotes the loss, while the x axis denotes the epoch. One epoch is defined as one feed through of the whole dataset, during the training procedure. The label "loss" defines the loss for the training dataset and "val_loss" that of the validation dataset respectively. At epoch 30, the learning rate scheduler made a restart of the learning rate to higher values, accounting to the nature of the cosine annealing methodology, avoiding local minima. The high fluctuation of the validation loss metric is owed to the fact that it represents only a small fraction of the whole dataset, namely 20 percent

4 Discussion

In the present work we detected the usability of the Adam based optimizer together with the cosine annealing learning rate scheduler used in training of a segmentation network. It shows that with this setting; the training procedure doesn't overfit and generalizes quite well. Furthermore, we achieved quite fast convergence of the loss function during the first 40 epochs. In the future, the output of the network could be improved by using 3D information and feeding them together with the 2D greyscale image to the network. Such data is available from 3D scans of the road surface.

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Bridge-Wind Analysis: Assessing Wind Effects on Long Span Bridges Using Computational Modelling

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Abstract. Bridges are a critical element of any transportation network, and their safe and reliable operation is paramount. Bridge closures have major economic impact; Therefore, it is important that decisions that affect the operation of bridges are based on reliable data. The forces that bridges and the vehicles on them experience in high wind are poorly quantified. The accepted state of the art for designers and operators is that decisions about the bridge design are largely based on wind tunnel testing, with bridge operation plans arrived at separately based on experience and ad-hoc assumptions. This paper attempts to reframe the design process by considering computational modelling of wind-bridge interaction. Two case studies are considered: The Rose Fitzgerald Kennedy Bridge in Ireland and the Queensferry Crossing in Scotland. Results of computational models are presented, which have been validated using field data generously provided by Transport Infrastructure Ireland and Transport Scotland. This builds confidence in the use of such methods in the design and prediction of wind effects on long-span bridges.

Keywords: Bridge · wind · modelling · safety

1 Introduction

Long span bridges cost billions to construct, millions to operate and enable regional and national economic growth. However, they are not intrinsically adapted to deal with the effects of the wind flows surrounding them because (1) they are very flexible, with large deflections resulting from modest forces and (2) they are bluff bodies, despite efforts to make the designs more streamlined. Thus, aeroelastic analysis is pivotal in their design [1]. Wind-bridge problems are two-fold (a) the fatigue life of the bridge may be reduced as well as (b) diminished driving controllability increases the risk of accidents [2]. The majority of major natural disasters are caused by windstorms [3, 4], which resulted in over 500 bridge collapses between 1989 and 2000 [5] and over 1062 bridge failures between 1980 and 2012 [6] in the US alone. Globally, wind-induced problems for long-span bridges (total collapses, as well more minor issues) are widely documented [7]. Wind-induced accidents of high-sided road vehicles travelling on bridges (particularly when they are unladen) also occur frequently worldwide [8] and are of major concern. An

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overturned truck, due to wind, blocked three lanes of the Burlington Skyway 4 bridge in Canada in March 2022, resulting in a 6-hour closure of the bridge [9]. A similar disruption happened on the Golden Gate Bridge in January 2023 [10]. Rollover accidents are found to be the most common (47%), followed by rotating accidents (19%) [11]. Since the opening of the Storebælt Link in 1998, the owner has recorded 56 wind-induced accidents, of which 33 happened adjacent to the towers [12], suggesting that wake conditions at towers are a particular risk for vehicle safety [12, 13]. Safety precautions in high winds such as speed restrictions and bridge closures are required [14] and setting the thresholds for these criteria can be challenging; speed limits can be too high to be safe or too low to be efficient [2, 15]. Therefore, it is essential that they are based on reliable data.

It is hypothesized that climate change has the potential to further exacerbate these scenarios through an increase in the prevalence of stronger, more variable, and more extreme wind speeds [3, 4, 16, 17]. Arctic Amplification is likely to cause changes in atmospheric circulations which will increase storm frequency and intensity in Europe. Where evacuations due to incoming typhoons are commonplace, closing bridges to traffic will totally obstruct the evacuation [2]. Therefore, a rational prediction of the performance of vehicle–bridge systems under strong wind is of utmost importance [2]. Ultimately, bridge closures, whether it is a short closure due to a wind-induced traffic accident, or a longer one due to wind-induced fatigue damage, have major direct and indirect costs. For example, a closure of the Forth Road Crossing (FRC) cost the Scottish economy £50 m [18] and a closure of the Haringvliet bridge in the Netherlands cost the transport sector alone €53 m [19]. This paper discusses the state-of-the-art in analyzing wind effects on long span bridges, in the form of wind tunnel testing and highlights the opportunities of using computational methods. An introduction is given to two long span bridges, as case studies for bridge-wind analysis. Results are then presented from computational fluid dynamics models of these bridges, with reference to data collected from the field.

2 Bridge-Wind Analysis

The accepted state of the art is that decisions about the bridge design and operation are largely based on wind tunnel testing, including the development of the actual guidelines themselves [20]. Although wind tunnel testing offers data, it is often insufficient for the structural engineer, due to limitations in the assumptions of stationarity, normality and scalability, particularly of Reynolds and Strouhal numbers [21] when the geometry is scaled down to the prototype. Wind is non-stationary and non-normal [22, 23], however; most wind tunnel tests are carried out in smooth flow (~ 1% turbulence) due to difficulty in the experimental reproduction of the turbulence spectra [24]. Furthermore, rather than modelling the complete structure, bridge aerodynamics are studied using cross-sectional models that represent the short, mid-span cross section of the deck. While this approach has been accepted in the past [25], differences can arise when compared to the full bridge as a result of not being able to capture the true bridge dynamics [26]. It is likely that the assessment of the forces over a freely vibrating body in large scale turbulence is not in the scope of the wind tunnel for the immediate future [20]. Additional challenges with

wind tunnel testing include the potential risk of sensors disrupting the flow field [26], the need to decide the location of sensors a priori and that attempts to visualize the flow field are complex and expensive [21]. More recently, the use of Computational Wind Engineering (CWE), i.e., the application of computational methods to wind engineering problems, is coming to the fore [21], owing to the significant improvements in numerical methods and computational capacity.

3 Bridge Case Studies

3.1 Rose Fitzgerald Kennedy Bridge, Wexford, Ireland

The Rose Kennedy Fitzgerald (RFK) Bridge (Fig. 1) serves as a second river crossing to bypass the town of New Ross, Co. Wexford, Ireland. It is an extrados bridge, i.e., a hybrid type of the box girder bridge and the cable-stayed bridge. It has a main span of 230 m, which is the longest extrados bridge with a concrete box girder in the world. In addition, it is currently the longest bridge in Ireland, with a full length of 887 m.



Fig. 1. Rose Fitzgerald Kennedy Bridge (Google images CC BY-SA 4.0)



Fig. 2. Queensferry Crossing, Scotland, UK (Google images CC BY-NC-ND 2.0)

3.2 Queensferry Crossing, Scotland, UK

The Queensferry Crossing (QFC) (Fig. 2) is a road bridge which carries the M90 motorway in Scotland, United Kingdom. It connects the traffic across the Firth of Forth between Edinburgh, at South Queensferry, and Fife, at North Queensferry. The bridge was opened in August 2017, and it is the longest three-tower cable-stayed bridge in the world with a total length of 2.7 km. It also has the highest tower in the UK and the height of the central tower is 210 m. In October 2016 during construction the balanced cantilevers which extended 322 m north and south from the central tower were the world's longest free-standing balanced cantilevers. The bridge deck carries two lanes of traffic in each direction alongside hard shoulders. Overall, it is the biggest infrastructure project in Scotland in over a generation.

4 Results of Computational Models

Computational Fluid Dynamics (CFD) models were created of both the RFK bridge and the QFC and results were compared to short samples of the field data collected by the Structural Health Monitoring (SHM) systems, and wind tunnel testing data.

Figure 3 is a plot of the drag coefficient estimated at various angles of attack determined from the CFD simulations designed to replicate the wind tunnel conditions for the Rose Fitzgerald Kennedy bridge, in Ireland. The maximum relative difference is 29.6% at the angle of attack of -7degrees, which is similar to studies in the literature (who reported differences of 30%) [27]. The full results of this work are published in [28]. A similar study with similar results was completed for the QFC, with results published in [29].

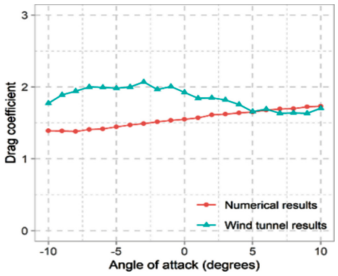


Fig. 3. Drag coefficient at various angles of attack determined from CFD models designed to replicate wind tunnel conditions for the RFK bridge

Figure 4 is a plot of wind velocities over a six-hour period on 23rd December 2020 at the Rose Fitzgerald Kennedy bridge (during which time the maximum one-minute mean wind velocity in the 12 month period occurred, at 23.7 m/s at 46.4 degrees to the main span of the bridge). The green curve is the raw data recorded by sensor B at the top of the central tower, and the blue curve is the 10-minute average value of the raw data. The red curve is the result from a full-scale 3-Dimensional CFD simulation model designed to replicate wind conditions at the bridge site. Non-time varying inflows were configured based on wind profiles provided by a full-scale Weather Research and Forecasting (WRF) model [30]. The calculated time-averaged wind velocities are shown to have relative differences of less than 10% to the measured wind velocities by anemometers 90% of the time. The underlying behavior within the time history of the wind velocity is generally predicted by the CFD simulations, demonstrating that the modelling approach has good potential. The simulations in this study used 256 cores and completed in an average of 20 h per simulation. The full results of this work are published in [31]. A similar study with comparable results was completed for the Queensferry Crossing over a one-hour period on 25th August 2020, with results published in [32]. In this case, each simulation had a wall-clock time of 33.7 h. It is noteworthy that even when using simple models with lots of assumptions, promising results can be obtained from computational models of wind-bridge interaction.

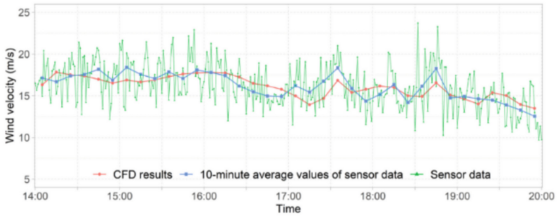


Fig. 4. Comparison of CFD results and field data for the RFK Bridge

5 Conclusion

This paper presented a comprehensive background and context for the importance of considering bridge-wind analysis carefully. Two case studies were presented: The Rose Fitzgerald Kennedy Bridge in Ireland and the Queensferry Crossing in Scotland. Results from computational bridge-wind analysis of these bridges are presented, which supports the proposition of great use of computational modelling of these problems in the future.

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Bayesian Modelling for Probabilistic Prediction of International Roughness Index of Flexible Pavements

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Abstract. Performance prediction is a crucial step in the predictive maintenance of pavements, which could affect working plans and budget allocation of transport authorities. The International Roughness Index (IRI) is a widely adopted performance index that reflects the pavement condition at some level and the ride quality. Machine learning algorithms, which have the capacity to handle nonlinear problems, have been extensively used to predict pavement performance. However, such methods usually suffer from the issues of hyperparameter optimisation and the lack of interpretation ability. Pavement deterioration involves inherent uncertainty in material properties, measurement accuracy, and environmental and operational conditions. It is thus critical to characterise the predictive uncertainty so that rational maintenance decisions will be made. Nevertheless, most existing approaches focus on single-value prediction of pavement performance and fail to consider this inherent uncertainty. In this study, a reduced-order Gaussian Process Regression (GPR) is proposed for the probabilistic prediction of the IRI of flexible pavements. The Long-Term Pavement Performance (LTPP) dataset is used to illustrate its feasibility. These datasets are collected from the LTPP Specific Pavement Studies located in different climatic zones in the US. The proposed method is then compared with the traditional GPR. The comparison results indicate that the reduced-order GPR model exhibits higher predictive performance and better uncertainty quantification ability than the traditional one.

Keywords: Road pavement performance · probabilistic prediction · Bayesian inference · Gaussian Processes

1 Introduction

Age-related deterioration is challenging for pavement subjected to highly varying dynamic loadings and accelerated material degradation [1]. The international roughness index (IRI) is commonly used to reflect the functional condition of pavements. Its prediction enables optimal maintenance and rehabilitation plans, highlighting the need for developing accurate and efficient predictive models.

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The pavement performance prediction models can be generally classified into deterministic and probabilistic models [3]. The main drawback of the deterministic models is that they only generate the mean value of each time step [4]. The pavement deterioration is highly influenced by uncertainties in data acquisition and working environments. As opposed to deterministic prediction, probabilistic models allow for the quantification of uncertainty by offering not only the predictive mean but also the associated variance, which is important in making rational maintenance decisions.

Bayesian models have been extensively used for probabilistic pavement performance prediction, such as Bayesian neural networks (BNNs) [5] and Gaussian process regression (GPR) [6]. The BNNs provide a probabilistic alternative to regular neural networks by specifying the prior distributions over the weights. Their advantages could be more pronounced for the small data set for probabilistic prediction. However, the fundamental problem of the BNN is the intractable computation of the posterior distribution, and it lacks interpretability as the regular neural networks. As a nonparametric Bayesian model, the GPR model has a variety of applications in time-series modelling and uncertainty quantification and exhibits better robustness compared to neural networks. Unfortunately, its application in pavement performance prediction is still limited.

From a statistical perspective, pavement performance is a dynamic process that evolves. Such time-varying characteristics can be regarded as concept drift in machine learning that induces the predictive models to be a valid approximation only in a certain period. In this regard, online learning that does not require large amounts of training data and updates the best predictor for future data at each step is beneficial for tracking such concept drift. It is also likely to have a better performance than offline models. Hence, an online learning algorithm is introduced to GRP to deal with the time-varying characteristics of the pavement performance in this study.

2 Reduced-Order GPR Methodology

The GPR modelling process starts by establishing a Gaussian prior that is determined by a prior mean and covariance function [7]. Given the training data with n observations denoted as $D = (\mathbf{X}, \mathbf{Y})$, where $\mathbf{X} = \left[\mathbf{x}_1^{\mathrm{T}}, \mathbf{x}_2^{\mathrm{T}}, \cdots, \mathbf{x}_n^{\mathrm{T}}\right]^{\mathrm{T}}$ and $\mathbf{Y} = \left[y_1, y_2, \cdots, y_n\right]^{\mathrm{T}}$. The observation model can be written by

$$y = f(\mathbf{x}) + \varepsilon_{\text{noise}}, \quad \varepsilon \sim N\left(0, \sigma_{\text{noise}}^2\right) \tag{1}$$

where $f(\mathbf{x})$ is the latent function, and σ_{noise}^2 is the variance of the noise. The distribution of the latent function can be specified by $f \sim N(0, \mathbf{C})$, where $\mathbf{C} = C(\mathbf{X}, \mathbf{X})$.

Suppose f_* is the prediction value for an unobserved point $\mathbf{x}_*$. According to the assumption of GP prior, the combination of f and f^* follows a joint Gaussian expressed as [7]

$$p(\mathbf{f}, f_*) = N\left(\begin{bmatrix}\mathbf{0} \\ 0\end{bmatrix}, \begin{bmatrix}\mathbf{C} & \mathbf{C}_* \\ \mathbf{C}_*^{\mathrm{T}} & \tilde{C}\end{bmatrix}\right) \tag{2}$$

with $\mathbf{C}_* = C(\mathbf{x}_*, \mathbf{X})$ and $\tilde{C} = C(\mathbf{x}_*, \mathbf{x}_*)$.

According to Bayesian inference, the posterior distribution of the target prediction f^* conditioned on the training set is expressed as

$$p(f_*|\mathbf{Y}) = N\left(\mu_{f_*}, \sigma_{f_*}^2\right) \tag{3}$$

with the mean and variance of

$$\mu_{f_*} = \mathbf{C}_*\mathbf{K}^{-1}\mathbf{Y} \tag{4}$$

$$\sigma_{f_*}^2 = \tilde{C} - \mathbf{C}_*^{\mathrm{T}}\mathbf{K}^{-1}\mathbf{C}_* \tag{5}$$

where $\mathbf{K} = \mathbf{C} + \sigma_{\text{noise}}^2\mathbf{I}_n$, and $\mathbf{I}_n$ is the identity matrix of $n \times n$.

The GPR requires a computation scale of $\mathrm{O}(N^3)$. It thus becomes computationally demanding when dealing with large training data sizes [8]. Furthermore, continuously building the time-varying GPR model for forecasting purposes can be time-consuming, even if the training data set is not excessively large. To overcome above issues, a reduced-order GPR is developed by using only nearby local datasets and a moving window strategy. The consecutive training data in the moving window with a fixed length of w are denoted as $D_t = (\mathbf{X}_t, \mathbf{Y}_t)$, where $\mathbf{X}_t = \left[\mathbf{x}_{t-1}^{\mathrm{T}}, \mathbf{x}_{t-2}^{\mathrm{T}}, \cdots, \mathbf{x}_{t-w}^{\mathrm{T}}\right]^{\mathrm{T}}$ and $\mathbf{Y}_t = \left[y_{t-1}, y_{t-2}, \cdots, y_{t-w}\right]^{\mathrm{T}}$, which changes with time t rather than time-unvarying in the standard GPR.The squared exponential (SE) covariance function with the extensive application is used to define the GPR due to its explicit interpretation and high flexibility. The time varying covariance function is written as [8].

$$C_t(\mathbf{x}, \mathbf{x}') = \eta_t^2 \exp\left[-\frac{1}{2}\sum_{k=1}^{d_t}\left(\frac{x_k - x_k'}{l_k}\right)^2\right] \tag{6}$$

where η^2 is the signal variance, l is the characteristic length scale, and d is the input dimensionality.

The posterior distribution of the reduced-order GPR with mean and variance prediction becomes

$$\mu_{f_*,t} = \mathbf{C}_{*,t}\mathbf{K}_t^{-1}\mathbf{Y}_t = \mathbf{C}_{*,t}\mathbf{K}_t^{-1}\left[y_{t-1}, y_{t-2}, \cdots, y_{t-w}\right]^{\mathrm{T}} \tag{7}$$

$$\sigma_{f_*,t}^2 = \tilde{C}_t - \mathbf{C}_{*,t}^{\mathrm{T}}\mathbf{K}_t^{-1}\mathbf{C}_{*,t} \tag{8}$$

where $\mathbf{C}_{*,t} = C(\mathbf{x}_*, \mathbf{X}_t)$, $\mathbf{K}_t = \mathbf{C}_t + \sigma_{\text{noise},t}^2\mathbf{I}_w$, $\mathbf{C}_t = C(\mathbf{X}_t, \mathbf{X}_t)$, and $\mathbf{I}_w$ is the identity matrix of $w \times w$.

3 Probabilistic Prediction of Pavement Performance

In this study, the Long-Term Pavement Performance (LTPP) Standard Data Release (SDR) Number 36, released in August 2022, was used as the data resource. Specifically, data from Specific Pavement Study (SPS) programs for flexible pavement sections in

four climate regions was used to develop the predictive models. To build an accurate model, it is important to identify the predictor variables that have a high correlation with IRI. Based on the previous research, nine factors, including initial IRI, age, (HPMS) alligator cracking percentage, alligator cracking percentage, transverse cracking length, longitudinal cracking length, transverse cracking number, patching area, and wheel path cracking length, are considered as the important factors for IRI modelling and used as the main inputs (Fig. 1).

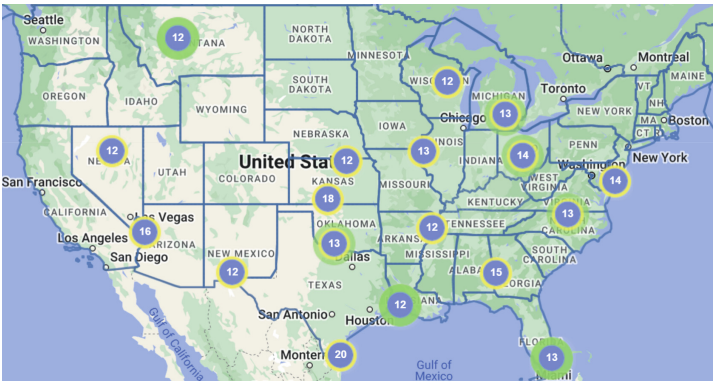
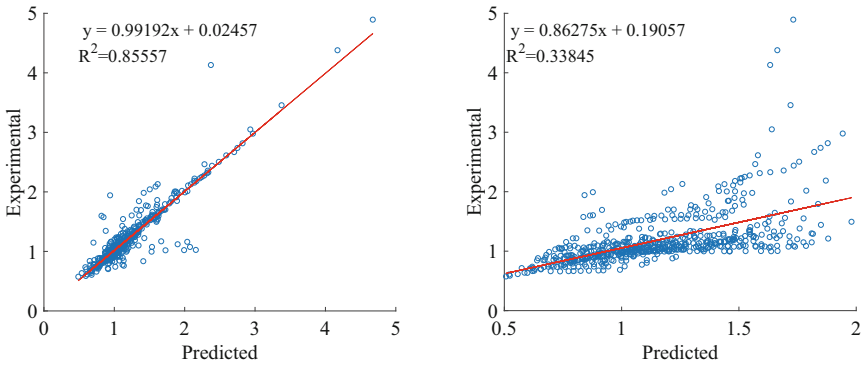


Fig. 1. SPS-1 locations for IRI prediction. Map generated using the Infopave mapping tool (https://infopave.fhwa.dot.gov/Media/LTPPSectionMapping#), based on Google Maps.

The collected raw data involve outliers and missing data, which should be pre-processed to ensure the data quality and completeness. In the LTPP module, the amount of cracking and patch are stored with three categories, i.e., low, medium and high. In this study, the values of these three categories are summed as the input variables for each type of distress. As the variables usually were not measured at the same time interval, their values are interpolated to match the measured time of IRI.

The reduced-order GPR is employed to predict the IRI measurements. The data are normalized to [0, 1] to overcome the different ranges of input variables. It is compared with the traditional GPR to further demonstrate its performance. The dataset is divided into 70% training data and 30% testing data. The prediction results of various models are shown in Fig. 2. The R2 of the reduced GPR (0.856) is much higher than that of the static GPR (0.338). This result demonstrates that the proposed moving window strategy can efficiently improve the prediction performance of GPR models by considering the time-varying characteristics of IRI.

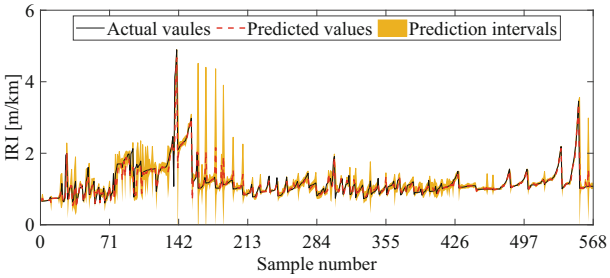
The prediction intervals of different GPR models are shown in Fig. 3. The prediction intervals of GPR models fluctuate dramatically. It illustrates the large uncertainties in the predictions mainly resulting from the data quality. The dynamic GPR has much narrower prediction intervals than the traditional one, and most predictions fall in this interval. This finding indicates the excellent performance of reduced-order GPR in quantifying the prediction uncertainty. It also reveals that the moving window strategy can efficiently improve the models' ability to quantify prediction uncertainty. In conclusion,



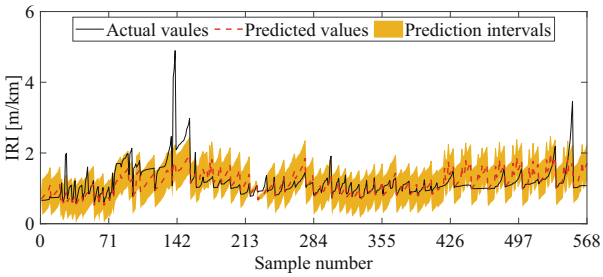
(1) dynamic GPR (2) static GPR

Fig. 2. Prediction results of GPR modelling methods.

this proposed method exhibits better forecasting accuracy and uncertainty estimation ability than the traditional GPR model.



(a) reduced-order GPR



(b) static GPR

Fig. 3. Prediction intervals of various Bayesian modelling methods.

4 Conclusions

A reduced-order GPR is developed for probabilistic prediction of the IRI of flexible pavements in this study. This method allows us to quantify the prediction uncertainty in addition to generating predictive means. In practice, the traditional GPR model is computationally expensive and fails to adapt to the time-varying characteristics efficiently. To mitigate such issues, a moving window strategy is employed to shrink the size of the training data, which results in a reduced GPR. The proposed reduced-order GPR model is verified by data collected from the LTPP SPS-01 project. Four measure criteria are used to evaluate the prediction accuracy and uncertainty in a quantitative manner. The reduced-order GPR method is compared with the traditional one. It exhibit much better performance in prediction accuracy and uncertainty quantification, demonstrating the effectiveness of the proposed moving window strategy.

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Development of European Standards for Surface Characteristics of Bicycle Lanes

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Abstract. In the frame of the pre-normative research project "SuChar-BiLan", partially financed by the Belgian national standards body (NBN) and the Belgian Federal Public Service (FPS) for Economy, the Belgian Road Research Centre (BRRC) investigates various parameters that are important for safety, comfort and energy consumption of users of bicycle lanes: longitudinal and transverse evenness, macro- and mega-texture, skid resistance and rolling resistance. The results of the project will be transmitted to working group CEN/TC227/WG5 of the European Committee for Standardization (CEN) that has been developing and reviewing the standards for surface characteristics for roads and that soon will cover bicycle lanes as well. After a literature study on existing technologies that have potential for measuring surface characteristics of bicycle lanes, three surveys were designed and respectively addressed to technology providers, bicycle lane owners and managers, and bicycle lane users. This contribution reports the analysed results of the surveys. Then a measurement and appraisal campaign was set up. The assessments by the users and the measurement data were compared to determine which surface characteristics influence users' perceptions. This contribution also reports on the first results of the campaign.

Keywords: Data collection · Condition monitoring · Active mobility

1 Towards European Standards for Surface Characteristics of Bicycle Lanes

A shift from car to bike kilometres has numerous advantages: it contributes to the urgent decarbonisation of road traffic, reduces our dependency on fossil fuels, cuts down on air and noise pollution, increases road safety, and it contributes to a fitter and healthier population through exercise. The latter increases general well-being and has a positive economic impact by lower sickness expenditure and less absence through illness. To get people to cycle more, a number of conditions must be met, and one of the most important of these is the availability of safe and comfortable cycle tracks. The surface characteristics of a cycle track (in addition to other characteristics such as lighting, adequate signing, safe crossings with cars, etc.) play an important role: good skid resistance, so cyclists can brake and turn without falling, is indispensable. Sufficient evenness is important for the comfort of the cyclist. Rolling resistance - the force a cyclist has to overcome

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to keep moving at the same speed - has been an underexposed aspect of cycle tracks up to now, but it is important for the comfort of the cyclist and the range for the rider of an electric bicycle. Moreover, a diversification of the users of cycle tracks has been noticeable in recent years: electric bicycles, also other vehicles, such as electric scooters, monowheels, cargo bikes, etc..

Standards for measurement methods for surface characteristics of roads exist ([1, 2]) and are drafted and regularly revised within the European group CEN/TC227/WG5, in which BRRC is also represented and plays an active role. Standards for measuring the surface characteristics of cycle tracks do not yet exist. The methods for road surfaces for cars can sometimes, but certainly not always be used. In addition to adapted measurement methods for cycle tracks, there is also a need for the corresponding threshold values to be included in the standard tender specifications (as already exists for longitudinal evenness in Flanders, Belgium: [3]). The SuChar-BiLan project aims to contribute to the development of European standards for surface characteristics of cycle tracks.

2 Surveys

As a start, three surveys were conducted. One survey was addressed to users of cycling infrastructure in Belgium. The second survey targeted managers of cycling infrastructure in Belgium (mainly the Regions and the local authorities). The third survey was sent to technology and service providers in Europe and beyond, whose methods and tools potentially should confirm with any prescriptions in future European standards.

2.1 Results of the Users Survey

The 1189 respondents, users of different types of vehicles, of wide variety of age, cycling in various regions of Belgium, all genders represented, gave their opinions on their expectations of cycle lanes.

Respondents consist of 771 male, 402 female and 16 x-gender participants. 59% of respondents use the cycling infrastructure daily, 30% weekly, 7% monthly and 4% almost never. 23% of these respondents cycle only when the weather is pleasant.

Figure 1 (p. 3) shows which means of transport respondents use mainly on the cycle tracks (blue). It also reveals which means of transport they use secondary (orange). Most of the respondents use several means, depending on the purpose of the ride. In order of occurrence: city bike, racing bike, mountain bike, folding bike, cargo bike, longtail bike, speed pedelec, bicycle with trailer, step, …

Participants were asked to give a score to several aspects from 1 (least important) to 5 (most important). In Fig. 2 (p. 3) the different aspects are ranked for the category “all users” from most to least important. Top 5 average result for all respondents: safety, surface damage, separation from other road users, skid resistance/slipperiness, free from vegetation. Specific vehicle categories (as presented in Fig. 1) are then looked at more into detail and compared to the result of the mean category “all users”. Some results are shown here for folding bike, cargobike two-wheeler and tricycle, mountain bike, speed pedelec and step.

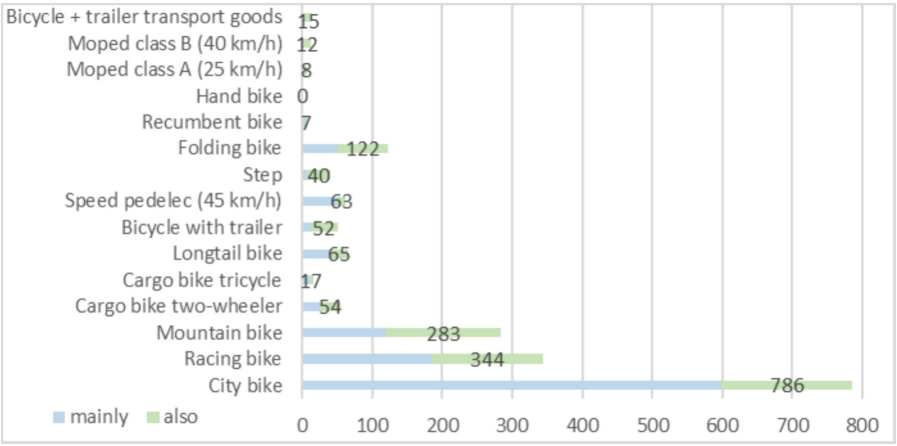


Fig. 1. Various means of transport used on cycle tracks. The numbers show the number of respondents. A distinction is made between main (blue) and secondary use (orange).

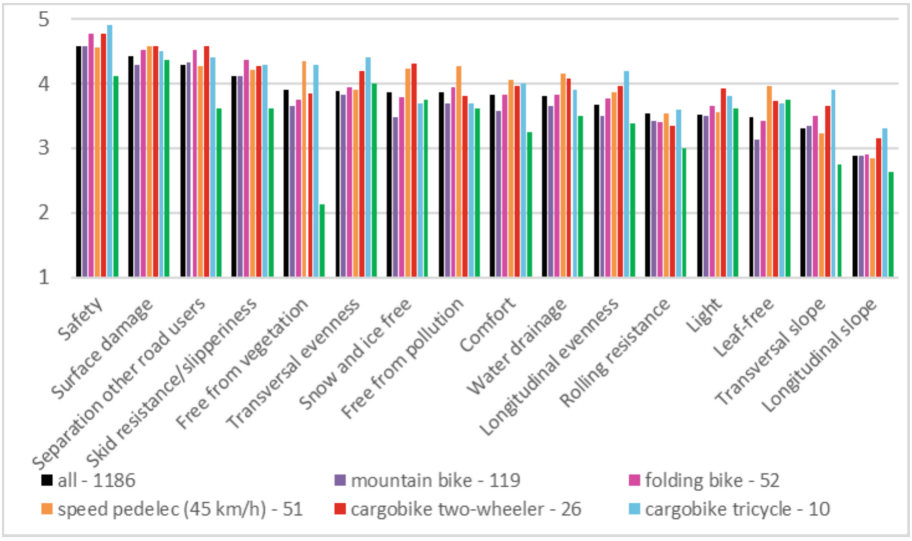


Fig. 2. Ranking of various aspects from most important (5) to least important (1) for the category "all users". Results for some other vehicle categories are shown.

Only respondents which mainly use this vehicle are considered, not the secondary users. The graph reveals that the order of importance is different for the various vehicle categories. Some examples are given here:

– Mountain bike and folding bike users rank "free from vegetation" and "snow and ice free" as less important. "Free from pollution" and "water drainage" are ranked as

more important. An explanation may be that these vehicles are used/conceived for specific purposes: off road - in the forest and in the city.
- The ranking for speed pedelec users is very different from the mean category. Top 5: surface damage, safety, vegetation free, separation other road users, pollution free. As they are cycling at higher speeds (up to 45 km/h) they are more easily disturbed by surface degradations and obstacles than others.
- Two-wheeled cargobikes rank "snow and ice free" as fourth important aspect. Water drainage and longitudinal evenness are more important. As they are transporting children the risk of an icy road is higher than for other users. By carrying more weight evenness becomes more important.
- Tricycle cargobikes rank transversal evenness as third important aspect. In contrary to the two-wheeled cargobikes snow and ice are less important, probably because of the stability that is offered by the three wheels. These wheels are however a disadvantage on uneven paths. Longitudinal evenness and transversal slope are ranked as more important than the other categories.
- Steps reveal a different ranking for most aspects. Top 5: surface damage, safety, transversal evenness, snow and ice free, leaf-free. Free from vegetation is the least important This can be explained by the difference of the vehicle itself (small wheels, driver standing) and the specific use in cities.

Other parameters than vehicle category are investigated, such as influence of age, gender, region, frequency of use on the ranking of the aspects. Some influences are found but not all presented here, for example "light" is found to be more important for women and youngsters.

Safety and comfort are the most important expectation of cycle path users. This outcome of the users survey confirms what was reported in the literature. The results of the literature study can be found in [4].

People were asked about their level of satisfaction when driving on several road surfaces. This is the ranking from most to least satisfied for the category "all users": asphalt pavement, concrete pavement, concrete stone pavement, clay pavers, natural stone pavement.

2.2 Results of the Managers of Cycling Infrastructure Survey

A small group of 17 managers of cycling infrastructure gave their views: 3 national road authorities, 1 province, 3 cities, 8 municipalities and 2 private owners. Respondents are responsible for 11 to 7700 km of cycling paths.

Especially for surface characteristics like rolling resistance, skid resistance, com-fort score, transversal and longitudinal evenness, transversal and longitudinal slope, there is a desire to obtain the information, while it is not yet the case.

These are the triggers to decide on maintenance (out of 17 managers): complaint (14), accident (8), time (8), condition measurement (6), others (financing, budget, opportunity e.g. sewage system works).

Most attention is given to: safety (11), comfort (11), continuity (5), more cycling paths (2), space (2), other (experience, light, skid resistance, pollution, social control).

2.3 Results of the Technology and Service Providers Survey

Not so many companies provide technology or services for the inspection of surface characteristics of cycle paths. The third questionnaire was answered by 10 companies.

These characteristics can be measured by the technology/services offered by the respondents (out of 10 companies): surface degradation (8), comfort (5), longitudinal evenness (5), longitudinal slope (5), transversal slope (5), macro- or megatexture (5), transversal slope (3), geometry 3D digital twin (3), skid resistance (2), rolling resistance (1), others (photos, GPS, geometry, …).

Technology and service providers already offer a wide variety of data sets and data types but for the moment the actual request for data collection by managers is still quite limited. They encounter difficulties to commercialise new developments because of the lack of specific standards and normative references.

3 Test Panel Field Test on Comfort, Evenness and Rolling Resistance

3.1 Goal and Set up of the Experiment

An extensive field test with a test panel is foreseen in this project in order to link the subjective experiences of bicycle lane users (not only cyclists) to surface characteristics such as macro and mega texture and evenness and the outcome of a selection of measurement devices. The three parameters considered in this experiment are comfort, evenness and rolling resistance.

A set of 23 test sections on cycle paths with a typical length of 100–500 m (some shorter) are selected in such a way that a variety of textures and degrees of unevenness is included, as well as several pavement materials (bituminous, cement concrete, cobble stones, setts, cold plastic material) and in varying degree of wear. A panel of volunteers was recruited to ride on the sections with vehicles suitable to be used on a bicycle lane and to assess each section (0 “very poor” – 10 “excellent”).

Surface characteristics are typically measured with dedicated measurement tools and devices ([2, 3]). A trial with several measurement devices for determination of comfort, longitudinal and transversal evenness and texture was carried out, also on some other, wider sections. Participating devices were, a.o. the FPP of BRRC [5].

A typical result of the measurement campaigns, the average score of the panel test participants as a function of the evenness coefficient for wavelength 0,5 m ($EC_{0,5m}$, see [6] for a definition of $EC_{0.5m}$) as measured with the FPP, is shown in Fig. 3 (p. 6).

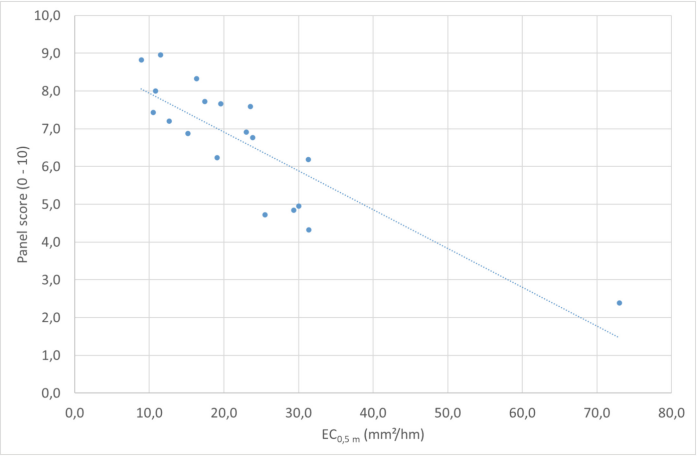


Fig. 3. Panel score for "comfort" as a function of the $EC_{0,5m}$ parameter as measured by the BRRC FPP.

4 Conclusions

Safety and comfort are the main expectations of the users of cycling infrastructure and managers of this infrastructure are aware of that. Surface characteristics (evenness, skid resistance, texture, rolling resistance) contribute to safety and comfort but European standards must still be developed and now is the right time. The SuChar-BiLan project provides robust data, obtained from surveys and field tests. Interesting technologies exist, giving results that express expectations of users and/or quality levels of some surface characteristics. In the second year of the project the results of these and additional field tests will be analysed further and give rise to more and better suggestions, and more support to the European group CEN/TC227/WG5 for the development of new standards specifically on surface characteristics of bicycle lanes.

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Innovative Condition Monitoring of the Extended Track by Means of LiDAR-Scanner

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Abstract. Track condition monitoring and component assessment is of high importance for the railway system. It forms the basis for maintenance planning and thus enables for guaranteeing a high track quality. A wide variety of technologies are used to describe track condition being continuously improved. The LiDAR (Light Detection And Ranging) technology is not yet a key part of the applied measurement methods but provides great potential. This paper analyses the boundary conditions and system properties of the LiDAR technology. Based on the findings, a potential analysis of the LiDAR technology for evaluating the condition of the extended track and in particular of ditches is carried out. For this purpose, a methodology is developed describing different factors of the extended track. It is further verified with GPR (ground-penetrating radar) data and in-situ observations. The correlation analysis between the GPR data and the LiDAR assessments shows slight correlations only. The observation of condition development over time for specific track sections shows that the LiDAR assessment method provides reliable and plausible results.

Keywords: LiDAR · Data Analytics · Condition Assessment · Extended Track

1 Introduction

Rail transport is one of the most sustainable and environmentally friendly forms of passenger mobility and freight transport. This is a major reason why railways are predicted to have increasing transport volumes. Although this is gladly welcomed, it also poses difficulties and challenges. Increasing traffic on railways causes an increased load on the track and, in turn, denser timetables with limited options to carry out monitoring, maintenance and renewal activities. However, these activities are essential to maintain high track quality and to ensure optimal service lives. Therefore, we need to find efficient but also reliable monitoring and maintenance methods that only have a minor impact on the availability of the railway infrastructure. With state-of-the-art measuring vehicles, most components of the track can already be described metrologically. However, one element of the track that has received little attention so far is the dewatering and drainage system, even though a non-functioning drainage system can counteract the economic benefit of long-lasting track components. Thereby, water can occur in various forms in

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the track system: Above the surface as surface or slope water and below the surface as seepage water, capillary water, groundwater or water running along sediment layers [8, 9]. To minimise any negative effects by the water on the track system such as mud spots, surface ditches and subsurface drainage systems are used. According to Zaayman [9], the hydraulic functionality of surface ditches depends on the structural conditions, such as the formation of the bed and the inclination, and on the contamination and vegetation within the ditch. Therefore, it is of great importance that open drainage systems are maintained condition-based. However, the decision-making basis is largely provided by visual inspections still. A measurement methodology directly aimed at describing the condition of surface drainage systems is not yet known. With the help of fractal analysis of the longitudinal level, it is at least possible to conclude which component of the track is causing the track failure based on the analysis of the wavelengths [5]. GPR uses electromagnetic waves to draw conclusions about moisture and contamination parameters as well as geometric parameters such as the evenness of the layers, the design of the profile and the transverse slope of the layers [4]. In this way, the effects of a non-functioning drainage system can be assessed, but not the condition itself, which opens a field of research that addresses the description of the condition of dewatering systems.

2 The LiDAR-Technology

LiDAR technology is not unknown in the transport sector; it is already used in the field of autonomous driving in road traffic as part of the perception system [1, 6]. But LiDAR technology has also been used in the railway sector for mapping [3] and risk assessment of tree falls in the Austrian railway network [7]. The operating principle of a LiDAR scanner is based on the time-of-flight method and is similar to RADAR technology. In contrast to RADAR technology, the LiDAR scanner emits beams in the infrared, ultraviolet or visible light range. These beams are reflected by one or more objects. Depending on the time between emitting and receiving the beam, the one-dimensional distance between the scanner and the target object can be inferred, considering the speed of light [6]. For the investigations carried out, a 2D laser scanner with a 360° field of view and laser beams in the infrared range was used for profile measurement. Due to the continuous movement of the track measurement vehicle, a depiction of the terrain located near the track is created (Fig. 1).

The LiDAR-data set includes the distances of the measurement points to the reference point, which represents the intersection of the rail surface and the track axis, and the reflection intensities. In addition, a pre-classification, which distinguishes between surface and vegetation points, can be made with LAS software. To be able to assess trends, only data provided by the ÖBB-Infrastruktur AG recorded in autumn from 2016 to 2021 is used.

3 Methodology

3.1 Ditch Detection

In a first step, the algorithm determines if a ditch exists at the analysed cross-section by means of geometrical circumstances. Thereby, the lowest surface point and its location is decisive for detecting a ditch. If the defined conditions are met, the surrounding surface

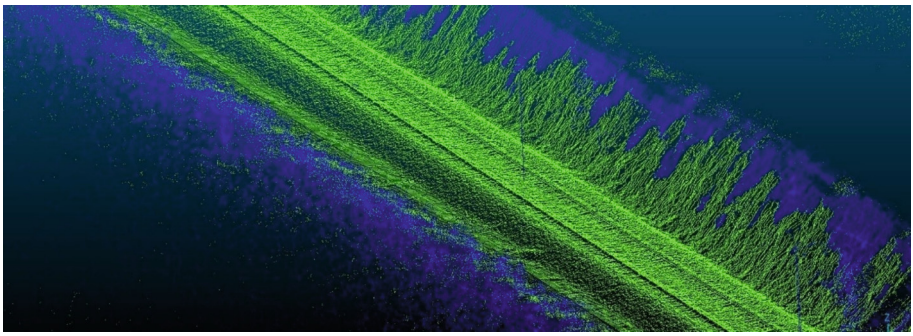


Fig. 1. Visualisation of the input data on an exemplary track section

points not higher than 0.07 m above the lowest surface point are defined as points part of the ditch. This assumption is based on the trapezoidal shape with a flat sole which most ditches have. Thus, the horizontal difference of the lateral end points of this area can be used to calculate the width of the ditch. Furthermore, the vertical position of the lowest point in relation to the rail surface and the horizontal position in relation to the track axis can be determined. To eliminate falsely detected ditches, minimum and maximum widths and minimum lengths in longitudinal extension are defined. Thereby, problems can occur with noise barriers or very flat terrain.

3.2 Ditch Condition

In cross-sections with detected ditches, possible vegetation is determined by the frequency of vegetation points lieing within the lateral ditch end points and minimum 0.15 m above the ditch sole, exemplary shown in green in Fig. 2. Furthermore, vegetation overhanging into the ditch is excluded by filtering.

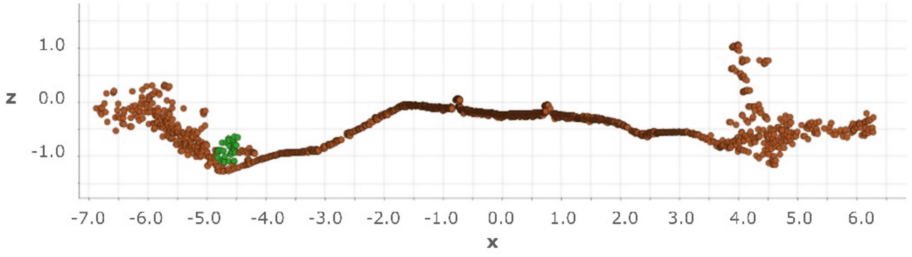


Fig. 2. Detected vegetation in the ditch

To assess the unevenness within the ditch and thus the condition of the ditch profile, the detected ditch is divided into 0.05 m subsections. Thereby, a high deviation of the difference between the ditch sole and the surface points in these subsections infer an uneven profile. To be able to assess any contamination in the ditch, both surface and vegetation points are considered as a further criterion. Analogous to the assessment of the

unevenness, the ditch is again divided into 0.05 m subsections, whereby not the standard deviation but the mean value of the differences between the ditch sole and the data points is calculated. The joint consideration of all subsections forms a condition index, whereby this index is related to the ditch width to generate a relative evaluation index. This ensures that narrower ditches, which may already be overgrown, are not incorrectly given a better rating. This method is also applied to the detection of vegetation and the unevenness.

Non-floating water in ditches indicates in most cases a non-functioning dewatering. This can have serious consequences for the quality and longevity of the track. For detection, the algorithm searches for data gaps in the order of 0.2 m to 0.5 m within the ditch, as stagnant water does not create reflection points.

In addition, not only cross-sectional assessment but also longitudinal assessments is performed, considering that the functionality of the dewatering system depends on the drainage possibility and thus the longitudinal inclination of the ditch. This can be calculated by lining up the sole points in longitudinal direction, assuming a linear gradient with kinks at high and low points. To model the ditch, a regression line of the ditch sole points is calculated between the high and low points. To estimate the discharge possibility of the water, the sliding standard deviation of the differences between the measured ditch sole and the regression line is considered (Fig. 3). However, it is not possible to check the minimum longitudinal fall in absolute values, as the individual data points represent relative values to the rail surface. To be able to assess the longitudinal gradient, either the information about the rail gradient would be required, or the data points would have to be available as GPS-coordinates.

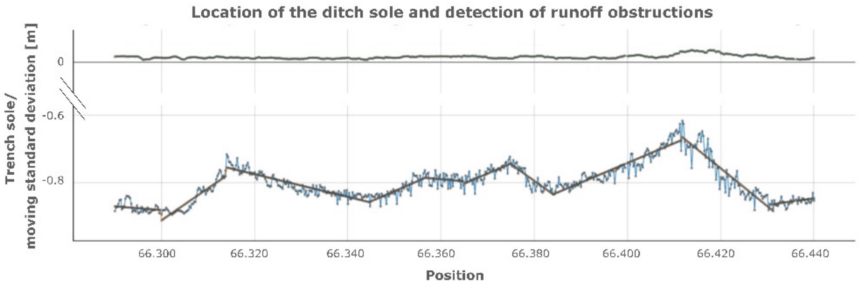


Fig. 3. Location of the ditch sole and detection of runoff obstructions

4 Correlation Analysis

In the next step, the plausibility of the results is checked. For this purpose, a correlation analysis with ground penetrating radar (GPR) data is executed. Due to the ordinally scaled data structure of the GPR data and the robustness of the method against outliers, Spearman's rank correlation coefficient is used for the correlation analysis. The results of the calculations predominantly show the expected positive correlation between the GPR and LiDAR assessments, but also negative correlations and non-significant correlations

can be seen (Fig. 4). Most of them are correlation pairs including either claying (assessment is a specification of the type, not a scale) or the ditch width (negative correlation expected). Furthermore, it must be stated that the condition assessment with GPR does not assess the same factors as with the LiDAR scanner, although there are interfaces and overlaps. A narrowing down of the examined correlation pairs could provide more reliable results here. Due to this, further analyses are required for validation.

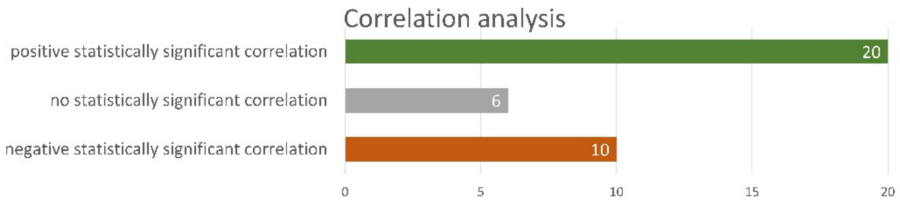


Fig. 4. Results from the correlation analysis between the LiDAR- and GPR-parameter

5 Case Study and Time-Series

For validating the results above, the next step is to analyse short track sections in more detail. In doing so, two features become apparent. On the one hand, the LiDAR data assessments provide comprehensible results in sections with continuous ditches, but the data analysis does not provide reliable results for ambiguous cross-sections. On the other hand, a post-synchronisation of the data must be carried out to make it comparable. Analogous to existing synchronisation algorithms [2], the LiDAR data can be synchronised by the ditch sole signal. The methodology is based on the search for the minimum sum of the vertical differences between the individual measurement runs, with the most recent measurement signal forming the reference case. In an exemplary section of about 130 m, a continuous ditch can be detected by the detection methodology. The deterioration of the condition of the ditch is among others evident in the unevenness in the transverse direction of the ditch (Fig. 5).

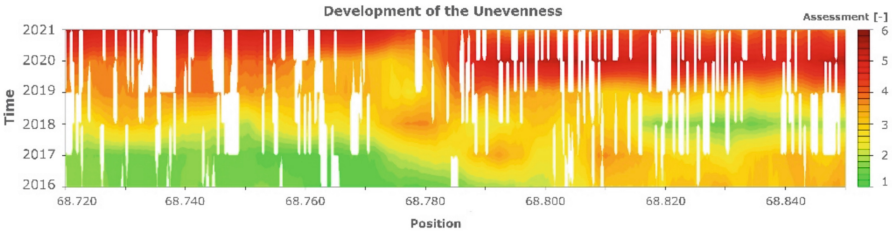


Fig. 5. Development of the unevenness at one exemplary section

Starting from a good initial condition in 2016, the unevenness increases continuously until 2021. The LiDAR assessment results and the statements made can be supported with the help of track videos from the years 2016, 2018 and 2021 (Fig. 6).



Fig. 6. Validation of the LiDAR results by track videos

6 Conclusion and Outlook

The presented article shows the possibility to describe the condition of surface ditch systems with LiDAR technology. This is shown by the correlation analyses and the case study. However, the methodology relies on a correctly detected ditch. Thereby, the method of determining a ditch via geometric analysis proved to be the most accurate approach. Anyway, further in-depth analyses are needed to validate the assessment results. Here, fractal analysis and punctual failure investigations could provide information and knowledge, as well as the link between asset data and measurement data. In addition to the methodologies presented, information could also be obtained from the reflection intensity and a holistic vegetation assessment could be carried out. However, the overall aim should be to implement an efficient maintenance concept for dewatering systems to optimise the overall maintenance demand and quality of track.

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Developing a Risk Assessment Methodology for Analyzing the Resilience of Railway Assets to Climate Change

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Abstract. In this article, we develop a risk assessment methodology for analyzing the resilience of railway assets to climate change. The methodology relies on climate projections, asset data, and hazard modelling to identify areas of highest risk and vulnerability. The latest climate projections in France are used to identify potential changes in extreme weather events for different time horizons and different climate change scenarios. The results of this approach enable to make informed decisions about the most effective ways to reduce the potential impacts of climate change on railway assets.

Keywords: Climate Change · Resilience · Railway Assets · Adaptation · Damage · Decision-Aid

1 Introduction

Railway infrastructures are facing significant impacts from climate change, as extreme weather events like floods, wildfires, and high temperatures cause significant damage to assets [1–3]. As a result, there is a growing need for methodologies that can accurately assess the impact of climate hazards on the railway system [4].

To this end, this paper introduces a new risk assessment framework developed within MINERVE Project, that aims to quantify the potential impact of climate change on railway infrastructures. The methodology relies on a risk-based approach [5, 6], which involves identifying the hazards associated with climate change, assessing their likelihood, and potential impact, and developing appropriate mitigation strategies.

In the upcoming sections, we will first provide a global overview of our methodology, followed by an in-depth presentation of each one of its building blocks. We will then illustrate our approach with a practical example and conclude with some perspectives of our work.

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2 Methodology for Assessing Climatic Risks on the French National Rail Network

2.1 Overview of the Methodological Approach

Our methodology is organized into five main building blocks (see Fig. 1). The first two preliminary steps involve selecting the future climate scenarios to be considered (1) and the relevant natural hazards threatening the network (2). The next three steps allow the assessment of the climate risk projection for each railway assets:

– Step three (3) involves choosing indicators that assess the current and future hazards trends and characteristics. These indicators are processed to obtain a hazard score.
– The fourth step (4) consists in assigning hazard sensitivity scores to the railway assets. These sensitivity scores reflect the damage susceptibility of the assets if exposed to each natural hazard.

The last step (5) consists of combining the hazard scores and the sensitivity scores of the assets according to their level of exposure. By combining these scores, our methodology helps in quantifying the climate vulnerability evolution of each asset with respect to each hazard.

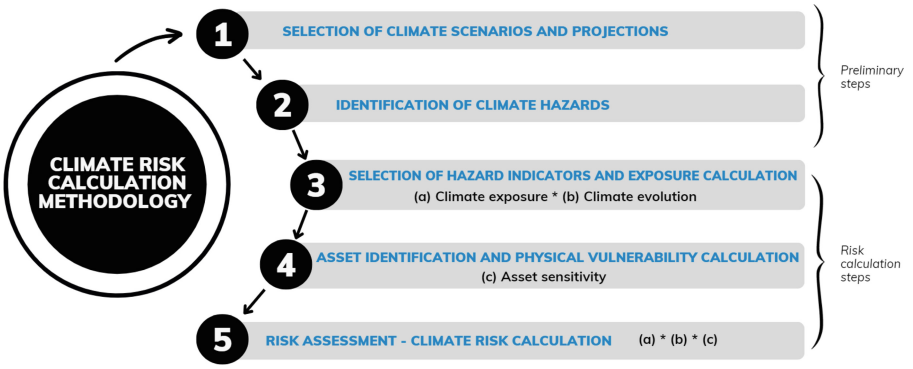


Fig. 1. Methodology for evaluating the vulnerability of railway assets

These building blocks (see Fig. 1) are explained more in detail in the following sections.

2.2 Focus on the Framework

Selection of Climate Scenarios and Projections

The developed methodology relies on the simulation of future changes in hazards and their impact on the network. Relevant climate scenarios and projections were thus selected.

In this regard, a recent public consultation has defined the reference warming trajectory for adaptation to climate change in France [7]. In line with the results of this

consultation, two trajectories were chosen for this study, IPCC RCP4.5 (corresponding to a stabilization of GHG emissions) and RCP8.5 (corresponding to an increase in GHGs at the current rate, without integration of climate policies). For each of these scenarios, available median climate models were used to project trends in climate hazards over time horizons of 2050, 2070 and 2100.

Identification of Climate Hazards Threatening the Rail Network

The EU taxonomy for sustainable activities has defined a classification of chronic and acute hazards to be considered when assessing climatic risks and vulnerabilities [8]. Based on this classification and a detailed study of the hazards that have impacted the SNCF network in recent years, 14 hazards have been defined as threatening the French railway assets (see Fig. 2).



Fig. 2. 14 Climate hazards threatening the SNCF network. Image courtesy of SNCF, reproduced with permission

To assess the evolution of these hazards and their impacts on the railway assets, our framework proposes to examine these climate hazards on a comparative basis, considering their **relative evolution** in respect to the **reference period**.

Selection of Hazard Indicators and Exposure Calculation

The relative evolution of these hazards is assessed across time and space using regional climate models [9]. To ensure the analysis is up to date, the latest projections of these hazards are retrieved from official climate databases like Drias and Copernicus[1].

These projections provide raw indicators which are processed using geomatic tools to calculate their evolution in relation to the reference period. This approach enables the quantification of the relative evolution of each hazard across space and time for each RCP scenario.

Asset Identification and Physical Vulnerability Calculation

As a complex system, the railways are inherently vulnerable because of the diversity of their components **(electrical, mechanical, civil engineering**) and their dependencies. In

[1] The DRIAS and Copericus platforms are managed by the French national authorities and the European Union respectively and provide regional and global climate models.

our methodology, vulnerability is considered as the physical damage an asset could suffer when exposed to a specific hazard. To evaluate this vulnerability, sensitivity scores are assigned to each asset based on expert opinions and the analysis of past events incidents.

Climate Risk Calculation and Evaluation
Once exposure, hazard trends, and asset sensitivities have been calculated (as explained in the previous sections), the scores are weighted to perform the climate risk calculation and projection. This process allows the overall risk to be assessed by combining hazard factors and asset sensitivities.

3 Application of the Methodology: Example of the Landslide Risk in the Maurienne Valley in France

3.1 Landslide Hazard Assessment in a Critical Area

The methodology was applied to the entire French railway network. The preliminary findings indicate that the railway system is highly vulnerable to high winds, overflowing floods, and landslides - mainly the south-west and east of France, and Ile de France. To illustrate the practical implementation of our methodology, the remainder of this section will illustrate the evolution of the landslide risk in the Maurienne Valley, located in eastern France, in the Savoie region.

According to the Pan-European landslide susceptibility map [10], the actual region's exposure (score "a") to landslides reveals an average score of 4.3/5 corresponding to a strong to very strong risk. Moreover, heavy rainfall is frequently identified as one of the main triggers for landslides, particularly in relation to the impacts of climate change [11, 12]. To assess the evolution of this hazard (score "b"), we combined the actual exposure score (score "a") with an indicator derived from DRIAS climate database, which simulate variations in intense rainfall: daily fraction of intense precipitation in percent (NORPFL90). This analysis reveals an average increase in landslide intensity in Savoie of +9% by 2100 for RCP8.5.

3.2 Sensitivity of Earthworks and Tunnels to Landslides

Assets sensitivity can vary significantly based on their characteristics and location. In the railway system, two distinct asset categories have been identified in our framework: linear and punctual ones. To illustrate the implementation of our methodology to these two types of assets, we focus here on earthworks (linear assets) and tunnels (punctual assets) as examples.

For landslides, both tunnels and earthworks were given a maximum sensitivity score by field experts, which corresponds to an extreme risk of damage (see Fig. 3).

3.3 Vulnerability of Earthworks and Tunnels to Landslides in the Maurienne Valley

The detailed calculation of the landslides impact on these two assets is illustrated in Fig. 3. The weighting of the three scores reveals that tunnels and earthworks are at extreme risk of damage by 2100 for an RCP8.5 scenario.

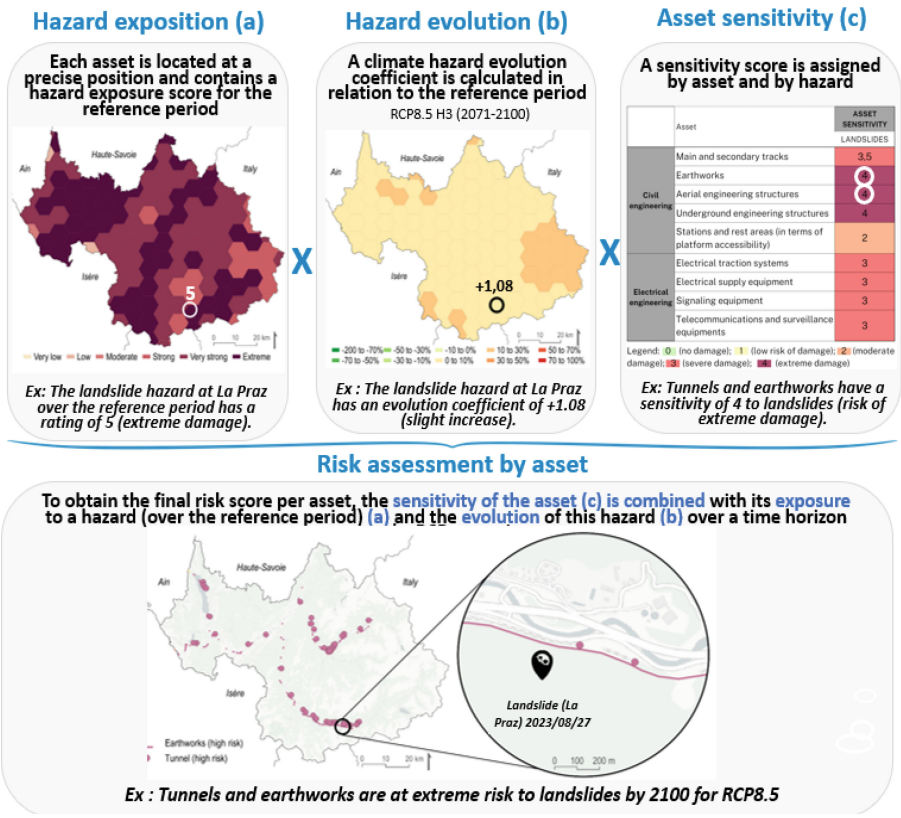


Fig. 3. Risk assessment on the Lyon-Turin line

Very recently, in August 2023, a landslide occurred in the Maurienne valley (on the Lyon-Turin line), dragging in 15,000 m3 of rocks. The landslide ruptured catenary and signaling systems and damaged the tunnel of La Brèche. This incident occurred in an extreme-risk area for tunnels and earthworks towards landslides (see Fig. 3). This example demonstrates the relevance of our methodology.

4 Conclusion and Future Research

In this paper, we have proposed a methodology for assessing the impact of climate change on railway assets. Our risk-based approach focuses on the areas and the assets of the highest risk and vulnerability.

The results of this risk assessment can be used to engage adaptation plans to improve the resilience of the railway system. These plans can consider the future impacts of climate change on network assets and other considerations like financial constraints. These issues will be addressed in future works.

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A Geographic Information System (GIS) for Resilience Assessment of Transport Infrastructure

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Abstract. The paper presents a concept for the integration of resilience assessment aspects into a life cycle management for transport infrastructure. A subsequent assessment of the resilience of the road infrastructure allows appropriate measures to be applied at the critical locations, thereby ensuring the availability and safety of the transport infrastructure. To promote the practical application of the assessment procedures, the development of a web based geographic information system (GIS) tool is proposed to enable the linking of all relevant data at network and object level. In this way, available information on potential hazards (e.g. through flood hazard maps) in combination with a criticality assessment of the road network and the associated function of the bridge and engineering structure can support the prioritization of resilience measures. For owners and operators of road infrastructures, such a GIS tool would offer the possibility to combine all relevant information for the assessment of the considered road infrastructure - on object and network level. Starting on network level with a criticality analysis in order to identify the critical infrastructure objects which can be better protected according to the result of a resilience assessment on object level. As a result, appropriate measures are proposed in order to increase the resilience of the road infrastructure. All the available data can be quickly analysed and visualized as well as redundant data storage can be avoided or at least reduced.

Keywords: Extreme weather · flooding · resilience · critical infrastructure · road transport · GIS

1 Overview and Motivation

1.1 Disruptive Events

The flood events in July 2021 led to severe damage to the transport infrastructure in Germany. Engineering structures, especially bridges, were severely damaged or even completely destroyed. Considering the increase of extreme weather events due to climate change and the unfavourable age distribution of transport infrastructure in Germany, more efforts are required to optimise and coordinate maintenance, upgrading and replacement of existing transport infrastructure. Increasing age of structures and changing impacts are reducing their structural reliability over the years.

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1.2 Resilience

Resilience can be described as the inherent capability of a system to absorb changes and disruptions of various kinds, to adapt to them and to retain its characteristic functionality. In the present paper, the following definition of resilience by Scharte et al. (2014) is used: "Resilience is the ability to repel, prepare for, take into account, absorb, recover from and adapt ever more successfully to actual or potential disruptive events. Disruptive events are either catastrophes or processes of change with catastrophic outcome which can have human, technical or natural causes."

The resilience of a system can be assigned to five different sequential phases represented in the form of a resilience cycle in Fig. 1.

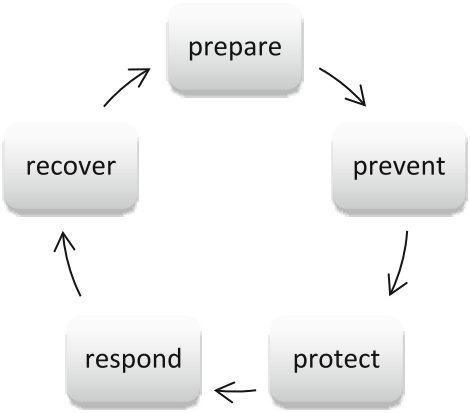


Fig. 1. Resilience cycle showing the five leverage points to increase the resilience of the system. (Scharte et al. 2014).

The first phase covers the preparation for disruptive events for example by implementing early warning systems (prepare). By reducing the underlying risk factors, the probability of occurrence of a disruptive event is decreased (prevent). If a disruptive event occurs, it is important that existing protective systems operate without defect and the negative impacts are minimized as far as possible (protect). By rapid, well-organized immediate measures, the extent of the damage resulting from the incident is reduced, and the functionality of the system retained as far as possible (respond). Finally, a resilient system is characterized by its ability to recover and adaptively learn from the event to be better equipped for future disruptive events (recover) (Anastassiadou et al. 2020).

Resilience measures can be assigned to one of the five phases of the resilience cycle shown in Fig. 1. Measures of the phase prepare are temporally decoupled, their purpose is to increase the understanding of the system and thus only have an indirect effect on the system's resilience as they reinforce the impact of measures in the other phases. E.g. the knowledge gained by advanced weather forecast models (prepare-measure) can improve the emergency planning (respond-measure). Measures, which can be assigned to the phases prevent, protect, respond and recover unfold their effect in a chronological order (Deublein et al. 2021).

Resilience measures are understood to be those technical, planning and organizational measures on the individual structure (e.g. bridge or tunnel) or for the entire infrastructural network that exceed the specifications of regulatory texts in force (standards, design, codes etc.). For example, the use of high-performance concrete in bridges where only conventional types of concrete are actually specified in the standards for the planning situation (Deublein et al. 2020).

2 Methodology, Results and Main Contributions

2.1 Methodology and Data

Authorities and infrastructure managers already use a wide range of data. But often the data are in different databases, are in different formats and cannot be easily merged. The spatial reference can be used to bring this information together. Geographic Information Systems (GIS) offer the possibility to combine, analyse and visualise this data. Coordinates, condition scores and other characteristics for engineering structures for example are kept in the Road Information Bank for Structures (SIB-BW). The positions of the permanent counting points are also known and can be located accordingly on a map in order to retrieve additional information on network utilization. Risk maps, terrain models, satellite images, information from monitoring and other data can be combined with the data from the resilience assessment.

An implementation-oriented methodology was developed in a previous study (Deublein et al. 2021) in order to ensure the functionality of the road infrastructure during and after disruptive events. In order to establish the usability of the methodology, a resilience assessment software tool for practical implementation was also developed (Anastassiadou et al. 2022). The resilience assessment software tool is intended to help managers and owners of transport infrastructures to apply the developed methodology and assess the resilience of their infrastructure. In the tool, the definition of the system to be assessed, the net screening and the hazard analysis serve as essential fundament for the resilience screening, the evaluation of resilience improving measures and the resilience optimisation. Different infrastructure elements can be assessed on an object level (e.g. bridges, tunnels). The results of the procedure give an overview of possible resilience measures (Anastassiadou et al. 2020) and show their potential to be implemented easily and where more an in-depth analysis should be considered.

Figure 2 presents the step of resilience screening. The investigated network includes a tunnel and a road section. The results of the screening (criticality and vulnerability analysis) indicates that a further investigation for the tunnel is needed/proposed. After the selection of possible measures, a resilience optimisation can be proposed.

2.2 Results and Main Contribution

Main result of the research is a concept for the development of a web-based geographic information system (GIS) for the resilience assessment of transport infrastructure for the modes rail, road and waterway. In addition, a specification sheet based on the concept is developed, which allows a technical implementation of the theoretical concept. For this

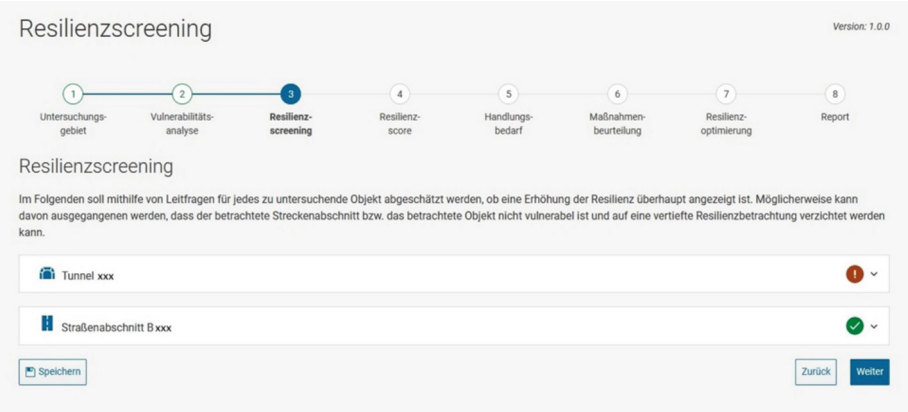


Fig. 2. User interface of the web-application for resilience assessment (step: resilience screening). Image generated using the web-application by the Federal Highway and Transport Research Institute (BASt), available at https://www.bast.de/DE/Ingenieurbau/Fachthemen/Resilienz/B3-Resilienz.html?nn=1816396.

purpose, the existing concept for resilience assessment was extended and prepared for the transfer into a web-based GIS.

The vulnerability analysis is extended by additional functions. The existing information on criticality (e.g. traffic volume, functionality level) and vulnerability (e.g. gravitational and meteorological hazards, sabotage) are automatically displayed to the operators and not entered manually by operators themselves as was the case until now. A large part of these data (e.g. traffic volume) are stored in the Federal Information System for Roads (BISStra). Therefore, the concept provides a connection to the BISStra. In addition to the data from BISStra, further data with spatial reference from other sources shall be integrated and evaluated. The identification of suitable data is also part of the project.

On a next step, the tool is planned to offer the possibility to evaluate different measures and to display their effects on the resilience. An example of the intended extension is a map view that is to be integrated into the user interface (Fig. 3). It shall allow an interactive selection of structures (on object level). Further information on these structures (e.g. structure condition notes) and on the traffic networks (e.g. traffic volume) are also stored in the map view and are automatically transferred to the corresponding fields of the tool when an object is selected. In this way, operators and managers of transport infrastructure are provided with all relevant, up-to-date data without having to laboriously compile it from different sources.

The tool offers the possibility to visualise geodata and perform spatial analyses. The integration enables seamless interaction between the tool and BISStra to exchange and share data.

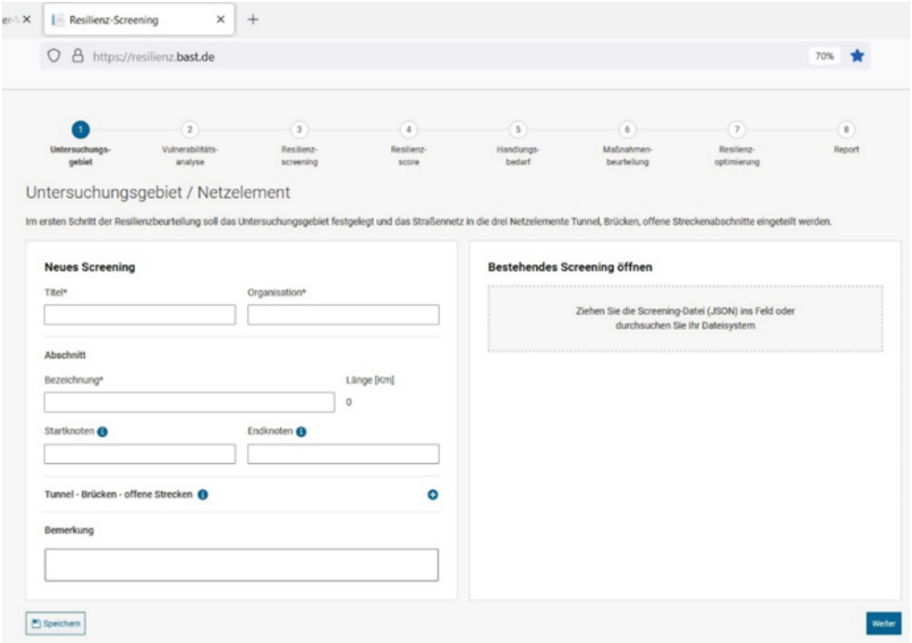


Fig. 3. User interface of the web-application for resilience assessment (step: definition of the investigation area). Image generated the web-application by the Federal Highway and Transport Research Institute (BASt), available at https://www.bast.de/DE/Ingenieurbau/Fachthemen/Resilienz/B3-Resilienz.html?nn=1816396.

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Determining Transverse Properties in Pavement, Using a Traffic Speed Deflectometer with Two Measuring Beams

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Abstract. The condition of road is currently assumed to be homogeneous across the width of a lane, when measuring using both Falling weight deflectometer (FWD) and Traffic Speed Deflectometer (TSD). It is however a well-known fact that the condition of a road can vary drastically even over short distances, in the longitudinal direction. Based on this fact, the assumption that the conditions do not vary in transverse direction seams a little crude. The goal of this paper is to show that there in fact is significant variations in the transverse direction of pavements. Using a TSD with measuring beams in both wheel paths, has helped to form a better understanding of what happens in the transverse direction of the road, as well as providing a more accurate picture of where weaknesses occur. This article will focus on the significance of measuring with two beams at once and how this can help provide a clearer picture of what happens in the transverse direction of the pavement.

Keywords: TSD · Maintenance prediction · Bearing capacity · Road survey

1 Introduction

Roads are the most valuable state property in most countries in the world. The condition of the road is preserved through monitoring traffic, estimating road performance, road maintenance and rehabilitation. The asphalt pavements of roads and streets deteriorates without regular road maintenance [1]. The road pavement construction and maintenance requires assessment and evaluation of various options and alternatives. Pavement management system (PMS) was introduced to describe the different types of operational decision-making and pavement maintenance. In Denmark,"Belman" PMS is used for 3 functions: road network diagnostics, road maintenance budget optimization, forecasting and the list of pavement repair contracts [2]. Traffic Speed Deflectometer (TSD) along with Ground Penetrating Radar (GPR) provides comprehensive data for the diagnosis of the road at the network level. One of the issues with the road network diagnosis is that the road is assumed to be homogeneous across the width of a lane. Transverse cracks are one of the pavement deterioration that ruins the assumption. It is commonly believed that transverse cracks are reflective cracks, propagated from cracked hydraulic-bound

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base [3]. Another reason could be low-temperature cracking on flexible pavements with asphalt layers laid over unbound base course material. The latest generation of TSD is equipped with measuring beams on both wheel paths to understand the transversal variation on the road pavement.

2 Theory

The TSD is a measuring devices developed to mimic the pavement response of a cargo truck [4]. It measures the response to a 10 ton axle, while still moving at traffic speed, i.e. it can measure hundreds of lane miles in a day. It uses 11 Doppler lasers, mounted on a beam placed on a line in the driving direction. The lasers measure the vertical velocity of the pavement at specific points and will pick up the a small component of the driving speed [4]. Using an odometer mounted behind the rear axle of the trailer to measure the driving speed, the Doppler signals can be translated to deflection slopes [5], that can be used to estimate the bearing capacity of the road.

Along with TSD data this article uses output from the Greenwood ViscoElastic Back Calculation model, a model developed by C. P. Nielsen in 2019 [4]. This model works by combining the Cauchy equation of motion with the relation between stress and strain [4]. It takes into account the viscous properties of the pavement, when measuring with a rolling wheel, using the Huet-Sayegh model to calculate the complex modulus of the asphalt layer [6].

$$E(\omega) = E_0 + \frac{E_\infty - E_0}{1 + \delta(i\omega\tau)^{-k} + (i\omega\tau)^{-\mathrm{h}}} \tag{1}$$

where ω is the angular frequency and E_0 and E_∞ are the elastic moduli at vanishing and infinite frequency, respectively, i is the imaginary unit, τ is a time constant, and δ, k, and h are model parameters.

The unbound layers in the pavement are described using hysterectic damping model [4].

$$E(\omega) = E_0 + isign(\omega)\eta, \tag{2}$$

where η is the damping coefficient.

3 Experiments

A TSD with dual measuring beams has measured a loop around Roskilde lake. The loop is around 50 km with variations in pavement structures and traffic flow. This loop has been measured with TSD and FWD for many years with different measured pavement temperatures and thus the physical properties of the section is well known. The raw data used for this paper has been specifically collected for this study, but has been varied by other studies prior to processing.

The TSD data is exported with 1 m interval. A section of 500 m in the Roskilde loop was chosen for further analysis. An asymmetrical numerical deflection model [7] was used to calculate the deflection basin. Surface Curvature Index SCI_{300} [8] was plotted for

both measuring beams. In Fig. 1, blue color denotes the left hand side and orange color denotes the right hand side. From the top plot in Fig. 1 it is observed that the right hand side has a higher SCI_{300} than the left hand side in a small area (22,195 m–22,230 m) and the rest of the section it has a good correlation. There are a lot of spikes in SCI_{300} on the right side, pointing towards more weaknesses on that side.

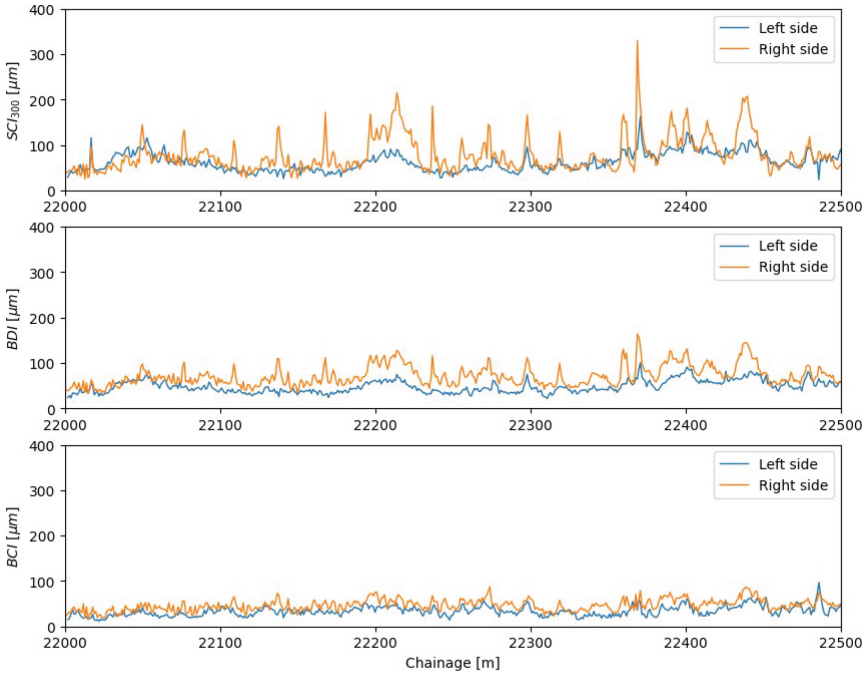


Fig. 1. Deflection indices (SCI_{300}, BDI and BCI) from the test section at Roskilde loop in Denmark. In blue: left hand side beam, in orange: right hand side beam.

Base Deflection index (BDI) [8] is calculated from the deflection on the two sensors positioned at 300 mm and 600 mm from the trailer's rear axle.

$$BDI = D_{600} - D_{300}. \tag{3}$$

From the middle plot in Fig. 1, it is evident that the right hand side has higher BDI value (71.712 μm in average) than the left hand side (47.95 μm in average) throughout the entire section. Base Curvature index (BCI) [8] is calculated from the deflection on the two sensors positioned at 600 mm and 900 mm from the trailer's rear axle.

$$BCI = D_{900} - D_{600}. \tag{4}$$

In the bottom plot in Fig. 1, it can be seen that the two sides have the same BCI throughout the section. The difference in the BCI values is around 10 μm which is very low.

Figure 2 shows the deflection bowls and deflections slopes for both measuring beams at chainage 22,215 m. The dots represent the slopes measured from each Doppler sensors in the TSD. The continuous line represent the slope curve and the dashed line represents the deflection bowl. Blue color represents right hand side and orange color represents the left hand side. The zero point on the X-axis is the location of the trailer's rear axle center. The variation in the deflection bowl near the trailer's rear axle correlates to the big variation in SCI_{300}. There is still variation in the deflection bowl at 600 mm in front of the trailer's rear axle and this correlates to the variation in BDI. The deflection bowls converge towards the farthest point from the trailer's rear axle proving that there is not a lot of transversal variation in the deepest layer of the pavement.

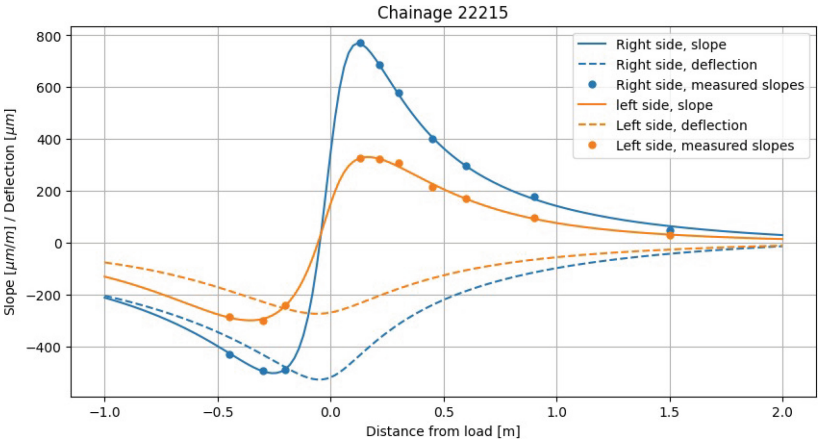


Fig. 2. Slope and deflection curves comparison between two measuring beam at chainage 22,215 m, from Fig. 1. The dots represent the slopes measured from each Doppler sensors in the TSD. The continuous line represent the slope curve and the dashed line represents the deflection bowl. In orange: left hand side beam, in blue: right hand side beam.

Figure 3 shows the E-moduli for the three layers, calculated using the Greenwood Visco-Elastic Back Calculation model [4]. The back calculation was done with 1 m resolution and is plotted with a running average of 10 m, to limit the variation of discontinuities. It shows a very clear difference in base layer, with a clearly stiffer layer in the left side of the lane. In the Asphalt layer the difference is less noticeable and the subgrade does not show a lot of variation throughout the section.

The quick and easy way of calculating information about different layers is deflection indices (SCI, BDI and BCI) through a numerical asymmetrical model fit. The quality of the numerical model fit is checked by both goodness of fit and looking at the slope curve fit. With the help of visco-elastic back calculation the E-moduli for each pavement layer is calculated. For the visco-elastic back calculation, the structural properties of the pavement layers were taken into consideration. There is good correlation between SCI_{300} with Asphalt layer E-moduli, BDI against base layer E-moduli and BCI against subgrade E-moduli. From the core samples measured in the Roskilde loop, the first layer is asphalt, the second layer is stone or gravel aggregate base layer and the third layer is

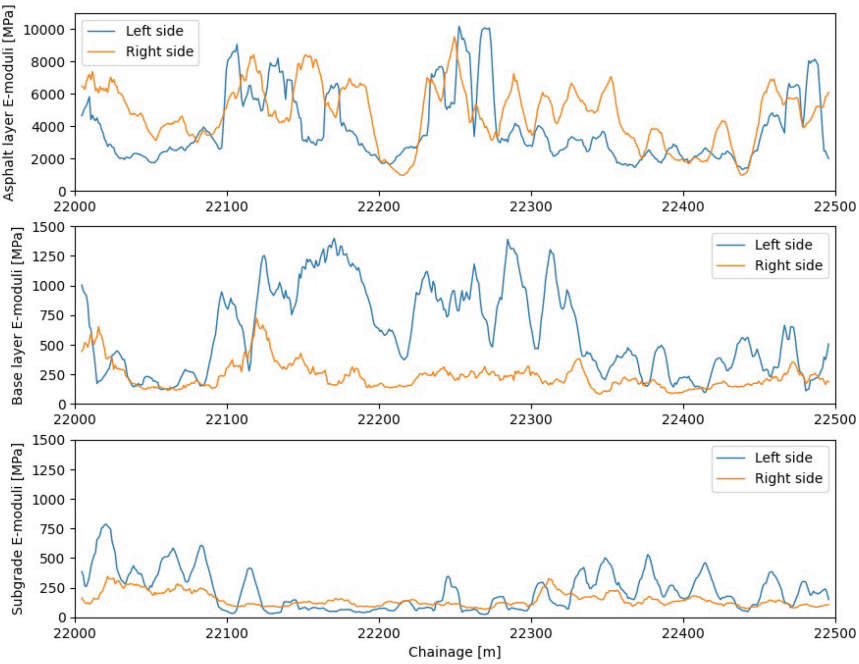


Fig. 3. Back calculated E-moduli [4] from left and right beam, for asphalt layer, base layer and subgrade.

unbounded clay subgrade layer. The E-moduli of the 3 layers from the viscoelastic back calculation is reasonable to the materials identified with the core samples.

4 Conclusion and Future Work

A TSD with dual measuring beams challenges the traditional assumption of homogeneity across the width of the lane and from the experimental results, the following things are have successfully been determined:

- Identifying transversal variation of structural properties in deeper layers that is not visible through surface distress (crack) measuring equipment.
- Bearing capacity variation across the width of the lane is captured at a single run, with the dual beam TSD.

The methods used shows good promise with regards to better project and network level road performance analysis, thereby helping in the road maintenance decision-making process.

A related project in the pipeline involves combing the measurements from the dual beam TSD along with subsystems such as GPR, Surface Imaging System (SIS) and Right of Way (ROW) imaging. The hope is that this will provide an overall picture of the pavement structure in the longitudinal as well as transverse direction. SIS provides information on surface distresses and it can be cross verified with SCI_{TSD} from TSD

data, a TSD specific curvature index comparable to SCI_{300} [9], that can be used to located cracks and other weaknesses down to 5 cm precision.

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Detection of Rail Surface Defects Based on Axle Box Acceleration Measurements: A Measurement Campaign in Sweden

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Abstract. This work presents the results of a measurement campaign to demonstrate the effectiveness of the axle box acceleration (ABA) technology for detecting rail defects. The measurements were conducted along the Iron Ore line between Sweden and Norway for the IN2TRACK3 project. This line is mostly single-track with passenger-freight mixed traffic and heavy axle load. Historical data and track information data were not considered in this study. By analyzing data acquired from the accelerometers in vertical and longitudinal directions, rail defects were detected in near real-time using big-data analytics. For our validated sections, 100% of rail defects (including squats) were detected using time-frequency analysis and an outlier detection approach. The methodology also allows for identifying priority locations, e.g., defective welds, joints, transition zones, etc., and its use for prescriptive maintenance recommendations is being explored in the framework of the IAM4RAIL project.

Keywords: Rail defect detection · Rail monitoring · Rail surface defects · Axle-box acceleration · Intelligent railway infrastructure

1 Introduction

Rail surface defects require great maintenance efforts, typically rail grinding, repair welding, or rail replacement. For light defects, grinding with a sufficient depth has the potential to remove them completely from the rail surface [13]. For severe defects, rail replacement or repair welding is needed as multiple grinding passages might not entirely remove them, leading to the re-appearing of the defect due to residual damages. As grinding is more cost- and performance-effective than rail replacement and repair welding, the effective management of light defects (those that can completely be removed by grinding) is needed to reduce maintenance costs. Further, managing defects (particularly severe defects) is also required to keep safety at adequate levels. To achieve adequate management, having an effective technology that is capable of timely detecting and frequently monitoring rail defects is of the utmost importance [9].

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Various measurement technologies have been used for the detection of rail defects. Most of these technologies are suitable for reactive maintenance because, for instance, they detect defects when their crack length is rather high. In this work, we focus on axle box acceleration (ABA) technology, which allows frequent monitoring of the infrastructure as it can be mounted on trains in operation (without the need for dedicated measurement vehicles) and has reported capabilities for early-stage defect detection [1,3,6,8].

The ABA technology has been tested in various countries by different infra-managers. The system used in this paper has been successfully tested in The Netherlands, UK, and Romania by TU Delft to assess the conditions of various railway components, e.g., fasteners [1], rails [2,3,5,6,8,10], insulated joints [7], transition zones [11], and crossings [12]. As the ABA system has increased its technology readiness level, at this stage of development, assessing the robustness through extensive measurement and validation campaigns in different locations and under different measurement conditions is crucial for evaluating, improving, and achieving its large-scale application in Europe and worldwide.

2 Measurement Campaign for Rail Defect Detection

The measurement campaign was conducted on the Iron Ore Line between Lulea in Sweden and Narvik in Norway, from which five locations were selected to conduct track inspections and validation for the detection of the ABA measurements. A total of approximately 400 km of tracks were measured and analyzed almost in real-time for rail defect detection. The line is (mostly) single-track with passenger-freight mixed traffic and heavy axle load (up to 31 t). The measurement train ran two round trips along the line. No prior information about the location of defects and the type and location of railway assets was required.

The ABA measurement system can be implemented on various types of vehicles, including passenger trains. New generation trains are already equipped with smart sensing technologies, so it is expected in the near future to have massive amounts of condition data for the monitoring of the whole infrastructure. Within the same train, a localized acquisition system is installed for storing monitoring data, including ABA signals and positioning information. And, a wired connection based on cables is used for the data transmission.

3 Methodology

This campaign used the ABA measurements from the vertical and longitudinal directions to detect rail defects (including squats). The basic principle is to use a train as a moving load that excites the infrastructure and to detect defects by evaluating the time-frequency characteristics of the dynamic response measured by accelerometers installed on axle boxes. As small defects in their early development stage generate a rather short-duration impact on the wheel-rail interface, their characteristics are related to high-frequency responses. The sampling frequency of ABA measurements considered in this work was 25.6 kHz. A higher

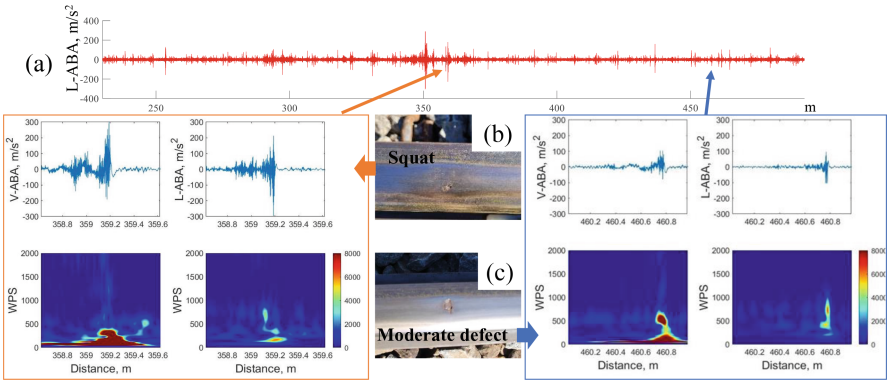


Fig. 1. Example of the ABA measurements of a rail portion from Location 1.

sampling rate is also needed because this is a moving sensor setup that requires a good set of data samples at each monitored location.

Figure 1 illustrates an example of the measurement of a rail portion from Location 1 in which relatively high energy is observed in the signal, from which Fig. 1(b) shows a location of a squat, while Fig. 1(c) shows that of a rail defect. The figure shows vertical (V-ABA) and longitudinal (L-ABA) ABA signals of the first axle on the left rails and their corresponding wavelet power spectrum (WPS) energy. The WPS is obtained from the time-frequency analysis using the Morlet wavelet function to extract characteristic frequency responses. For this work, the frequency responses considered are between 200 and 2000 Hz. Based on the obtained variations of the WPS energy, the location of defects is determined by the automated detection algorithm. This algorithm is an outlier detection approach detecting energy variations beyond local average values.

In the field inspections, various measurement techniques are used, including visual inspection using cameras and geometry profile measurements using Rail-Prof. Other measurements were conducted for future analysis, such as impact hammer tests, falling weight tests, pass-by measurements of track vibrations, and geometry measurements using a 3D scanner. You can see the demonstration campaign and a webinar at https://youtu.be/1Hw5Nqmmc0Q and https://youtu.be/8a362ghI_5A.

4 Results

We evaluate the effectiveness of the ABA method by comparing the results of the field inspections to the ABA data. Results indicate that the ABA system detects all squats and other moderate and severe defects in the five validated locations, demonstrating the capability of ABA for the detection of rail defects. All insulated joints are also detected. Photographs of some of the rail defects can be seen in Fig. 2.



Fig. 2. Photos of some squats and other defects from validated locations.

In the first two locations, a total of eight rail defects were found over a length of over 2 km. At the last three locations, 51 rail defects were found over a length of approximately 1.5 km. These differences occurred because locations 1 and 2 were selected without prior analysis of the ABA measurements, whereas locations 3, 4, and 5 were selected based on the first round of ABA measurements. As the ABA detection method can indicate locations with an impact excitation energy higher than average values with a certain threshold, it detected all insulated joints and some locations of welds and small defects. Healthy welds ideally should remain undetected to the ABA system or exhibit a subtle response. Detected welds suggest an existing deteriorating condition that is typically associated with the presence of rail defects. Thus, to differentiate between faulty welds and rail defects themselves is not required. The ABA method can then be used as an indicator for weld quality control.

Figure 3 illustrates an example of a small defect located within the running band. Due to the nature of the defect, the ABA signals obtained from four different wheelsets of the two measurement runs do not always show a pronounced energy content in the ABA responses. This presents us with a dual challenge. On the one hand, we can adjust the threshold to a lower setting in order to detect small defects like the one shown in Fig. 3. On the other hand, it is important to consider that these small defects may be of a benign nature, implying that some of them are likely to be naturally eliminated through natural wear [4]. Therefore, there is a trade-off between setting the threshold and the number of benign defects detected. Some small defects may be expected to wear away naturally over time, while others that are consistently detected over time can be indicated as defects that are becoming more severe.

After the first ABA measurement is conducted, new measurements of defects and track components will update their condition and allow for assessing their growth rate. Also, new measurements can indicate the presence of new defects

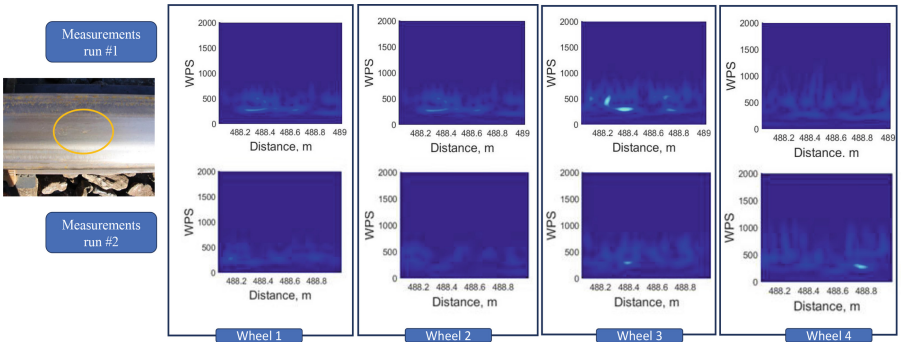


Fig. 3. Example of the ABA measurements at an undetected small defect, shown are the WPS obtained from the ABA signals in the vertical direction from all four wheelsets and two measurement runs.

or can be used to evaluate the effectiveness of maintenance actions, for instance, to determine the grinding depth that is effective for defects of certain severity.

5 Conclusion and Outlook

In this paper, we report a demonstrator campaign for rail defect detection in a freight-dominated line. The ABA measurements have been evaluated with field measurements in a total of 5 locations in Sweden. Using time-frequency analysis and an outlier detection approach, 100% detection of squats and other moderate and severe defects is achieved. In the locations selected without using the ABA results, a total of 7 squats were found over a length of over 2 km. In the other locations that were selected for analysis, 46 squats were found over a length of approximately 1.5 km in total. This shows the potential of the use of ABA data to identify priority locations in track for maintenance actions. Moreover, the detection of moderate and severe defects was almost obtained in real-time. The evolution from early squats to moderate/severe ones is a slow process with low dynamics, and moderate and severe defects tend to grow faster due to the higher impact forces involved. Therefore, a real-time detection solution is recommended for severe defects as it is crucial to prevent rail breaks.

In this demonstrator campaign, we assumed that no information on railway assets and defects was available. As a suggestion for implementation and further research and development, the ABA system can be embedded into existing railway track information systems to continuously monitor the ABA energy at defects and components such as welds, S&Cs, insulated joints, transition zones, bridges, etc. With data analytics, information from those different data types can be extracted and integrated to synergize with the physical understanding of the ABA signals. The integrated information can then enhance the effectiveness and interpretability of the continuous monitoring of assets, particularly to update the status of rail surface defects.

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Distributed Sensing System Based on FOS Technology for Road Infrastructure Management and Maintenance

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Abstract. In the context of European road transport, where safety is paramount, this paper presents an innovative approach to road infrastructure management and maintenance, exploiting Fiber Optic Sensors (FOS) technology for asphalt-paved roads. The work integrates autonomous robotized solutions and modularization techniques, developing a real-time monitoring system using FOS embedded in the road wear layer. Extensive laboratory tests verified FOS parameters and performance, reporting a 100% success rate in surviving to asphalt realization process; functionality tests showcased real-time monitoring capabilities, detecting residual stress during the pavement realization. The already available results indicate the technology's potential to revolutionize road maintenance, enhancing safety and minimizing maintenance costs, representing a significant stride toward proactive and efficient road infrastructure management.

Keywords: Monitoring · Fiber Optic Sensors · Road Infrastructure · Asphalt

1 Introduction

In today's European landscape, road transport is the predominant mode of inland passenger travel [1, 2], playing a pivotal role in both social and economic advancement. The need for effective road infrastructure management and maintenance is essential, alongside the imperative of ensuring network capacity and safety within construction zones (where approx. 4% of accidents occurs [3] on a country-wide average).

Within this overarching context, the InfraROB EU Project aims for a transformative mission. Its primary objective is to reduce workers' exposure to live traffic and construction machinery while simultaneously reducing the expenses associated with repetitive tasks and strengthening the road users' safety as well as the network availability.

In pursuit of these ambitious goals, the Project supports innovative solutions to automate, robotize, and modularize road infrastructure construction, enhancement, and maintenance, with focus on asphalt-paved roads and cracks and potholes repairing.

In the InfraROB Project RINA-C combines its expertise in roads and highways with those on structural monitoring, integrity management, and digitalization of services. Central to RINA-C's role in this Project is the development of the future-oriented system

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that continuously monitors the condition of the road over a long period of time through the embedding of distributed FOS in the asphalt. The integration of FOS technology into road surfaces holds the potential to revolutionize how we detect and respond to pavement damage, enhancing safety and infrastructure longevity.

In this paper, solutions, details and the preliminary results achieved by RINA-C are described. Specifically, methods, which encompass the formulation of precise specifications for the sensor system, the requirements and procedures necessary for its integration within the asphalt as well as the rigorous testing phase, including small and midscale laboratory tests to assess parameters and validate FOS technology.

Through these comprehensive efforts, RINA-C aims to make a substantial contribution to the advancement of road infrastructure management, offering innovative solutions that combine expertise in road engineering, digitalization, and SOA technology.

2 Methodology

In the frame of InfraROB EU project, a remote real-time monitoring system based on FOS was designed to be embedded in the road wear layer, by means of an automated laying down process during pavement realization with the aim of detecting damages (i.e. cracks), and validated at lab scale and relevant environment. A commercial scouting of suitable strain sensors for the specific application was carried out and sensors produced by SOLIFOS AG resulted in the best option to be considered. In particular, two different typologies of strain sensors were identified: BRUsens DSS 3.2 mm V9 grip [ID: SS], a distributed FO strain gauge cable with metallic tight buffered tube and a structured PA outer sheath for strain measurement up to 1%; BRUsens DSTAS V13 [ID: MFS], a distributed FO sensing cable for Strain and Temperature with four temperature and two strain-sensing cables to measure strain up to 1%. These sensors can both resist up to 30 MPa of hydrostatic pressure and for short periods (about 15 min) can operate at very high temperature (180 °C), but they differ in the outer final diameter (SS Φ 3.2 mm; MFS Φ 5.9 mm) which can influence the performance of the cables in the automated laying down process. For this reason, both the sensors were considered in this preliminary phase of validation. Moreover, to enable the uncoupling of temperature and strain effects [4], a FO temperature sensing cable (BRUsens DTS STL PA, [ID: TS]), extra small, armored with stainless steel loose tube, stainless steel strength members and PA outer sheath with two sensors was chosen to be paired with SS sensor, while MFS sensor has already a Temperature sensor inside.

2.1 Laboratory Tests

Two different experimental campaigns were planned to assess the feasibility of the selected FOS to the specific application: survival tests and flexural tests.

Survival tests were considered to verify the capability of FOS to survive to asphalt setting process, which is characterized by high temperature (180 °C) and high pressure (0.23 MPa) values. Cylindrical samples of 10 cm diameter and 10 cm height were realized in laboratory through a two steps process where on a first layer of 3.5 cm thick asphalt FOS were laid down and covered with another asphalt layer of 6.5 cm thickness.

Temperature and compaction pressure were set the same as the values for road pavement realization. Once FOS were embedded in the samples, they were connectorized and checked by means of Visual Fault Locator (VFL). A visible ray of light emitted by the VFL was let into the FOS and its exiting was checked, the passing through of light meaning the integrity of the FOS.



Fig. 1. Survival campaign samples: in the blue box SS Samples; in red box TS samples; in purple box MFS samples.

Flexural tests were considered to evaluate the resolution and accuracy of FOS in this application. Beams of 50 × 10 × 10 cm dimensions were realized in laboratory through a two steps process where on a first layer of 3 cm thick asphalt FOS were laid down and covered with another asphalt layer of 7 cm thickness (temperature and compaction pressure were set the same as the values for road pavement realization). Seven different typologies of samples were realized: I. Reference beams without FO; ii. Reference beams without FO and with a Flat Steel Bar (FSB) inserted on the free surface of the mold (which should act as an activator of crack in the beam); iii. Beams with SS; iv. Beams with MFS; v. Beams with SS and FSB; vi. Beams with MFS and FSB; vii. Beams with SS, TS and FSB. The samples will be tested by means of three points bending test to verify the ability of FOS to detect the crack formation and, eventually, the resolution of the FOS respect to the position of the cracks (Fig. 1).

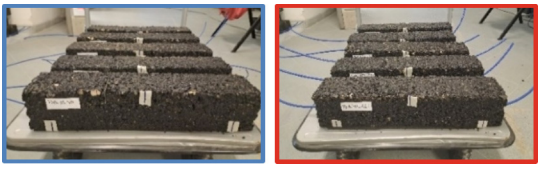


Fig. 2. Example of Flexural test samples: in blue box fifth set; in red box sixth set.

2.2 Functionality Test

A functionality test to validate the monitoring system in relevant environment was planned. A 25 m long stretch of road pavement was paved with FOS embedded in the road wear layer on a private road in the Brussi Costruzioni Srl plant where many passages of heavy vehicles occur every day. FOS were laid down following two lines in the lane: on one side SS and TS sensors, on the other side MFS sensor. To promote

crack formation on the pavement in a short time, steel plates of different geometries were inserted in the pavement. For realizing the demo four different work phases were necessary: first the FO cables were laid down on the stretch of road; thus the asphalt was poured on the road; hence the steel plates were stitched in the asphalt and finally the asphalt was compacted (Fig. 3).



Fig. 3. Demo realization.

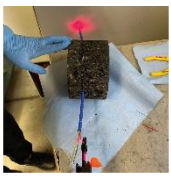
3 Results and Discussion

3.1 Laboratory Tests

As reported in methodology section the laboratory tests were two different typologies of tests: survival tests and characterization tests. Currently survival tests have been completed, while characterization tests are underway and results are not available yet.

The results obtained for the survival tests are reported in Table 1. The obtained survival rate of 100% of tested cables demonstrated the suitability of chosen FOS for the specific application of the project (Fig. 2).

Table 1. Survival tests results – in the last column the survival test performed on a sample

	Number of tested samples	Number of tested cables	Survived cable (%)	
SS	6	6	100	
TS	5	9	100	
MFS_Strain	6	10	100	
MFS_Temperature	6	11	100	

3.2 Functionality Test

After each phase of the realization process of the stretch of road pavement, acquisitions from FOS were collected by means of an Optical Backscattering Reflectometer (OBR4600 by Luna Inc.) with the aim of verifying the survival of the FOS during upscaled asphalt realization process and defining baseline for future monitoring campaigns.

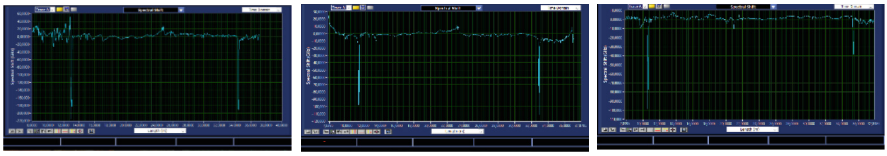


Fig. 4. Location of initial and final points of interest of FO cables: left: referred to SS sensor; middle: referred to TS sensor; right: referred to MFS sensor.

In particular, once the cables were laid down, acquisition were taken to locate the initial and ending points of the segment of FO cables that were stretched and positioned along the road way (Fig. 4). The peaks reported in each graph, where spectral shift is reported as function of length, represent the positions of these points on the FO cables indicated as the distance in meter from the OBR port.



Fig. 5. Signal acquired at different times the pouring phase: four minutes after starting (cyan line); ten minutes after starting (red line); twenty-two minutes after starting (green line); thirty-five minutes after starting corresponding to the final time of pouring phase (yellow line).

During the realization process the SS sensor was continuously monitored to be sure that no particular events occurred to the FOS. Figure 5 shows the spectral shift values as a function of the length of the FOS in acquisitions made in different moments during the pouring process. In the circles it is possible to see the length where the spectral shift value returns to zero value, indicating the position of asphalt front at the time of acquisition. Figure 5 also gives evidence of the ability of FOS to monitor events in real-time.

Acquisitions were acquired for all the FOS also once the compaction process was finished and repeated the day after (16 h after finishing the pavement compaction). In Figs. 6, 7, 8 and 9 the measured spectral shift as function of length of FOS is reported after the laid down phase (cyan line), the compaction (red line) and 16 h after the compaction

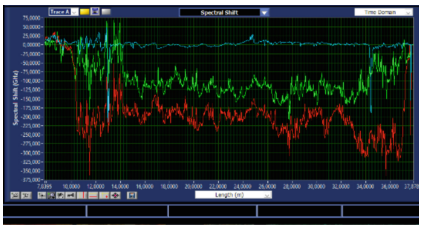


Fig. 6. Acquisition for SS sensor once laid down (cyan line); just after the complete pouring of asphalt (red line); 16 h after finishing the pavement (green line).



Fig. 7. Acquisition for TS sensor once laid down (cyan line); just after the complete pouring of asphalt (red line); 16 h after finishing the pavement (green line).

(green line) for the different FOS. It is possible to see how the red lines showed for all the FOS the highest spectral shift variation, because of high temperature of asphalt. After 16 h from compaction, the strain sensors (Figs. 6, 7 and 8) showed still relevant values of spectral shift, while temperature sensors (Figs. 7, 8 and 9) showed values almost near zero. This means that the asphalt achieved the environmental temperature and the spectral shift value in strain sensors is due to residual stress imposed to the FOS by the pavement realization.



Fig. 8. Acquisition for MFS_Strain sensor once laid down (cyan line); just after the complete pouring of asphalt (red line); 16 h after finishing the pavement (green line).



Fig. 9. Acquisition for MFS_Temperature sensor just after the complete pouring of asphalt (cyan line); 16 h after finishing the pavement (red line).

4 Conclusion

In the present work the preliminary activities performed for the design and realization of a real-time remote monitoring system based on FOS embedded in the road wear layer by means of an automated laying down process during pavement realization were reported. The monitoring system aims to detect damages (i.e. cracks) at their initial phase of formation to prevent severe consequences in terms of maintenance costs and road safety.

The reported preliminary results demonstrate the suitability of chosen technology to be applied to the described application.

Survival tests validated selected FOS robustness during the asphalt setting process, reporting a 100% success rate and the demo realization on a 25 m road stretch showcased real-time monitoring capabilities, detecting residual stress during the pavement realization. The already planned flexural tests will enable to analyze FOS resolution.

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SCI_{TSD}: A New Structural Curvature Index for Strain Analysis of Large Road Networks

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Abstract. Efficient maintenance of road networks requires data surface, subsurface and structural conditions. One device for providing structural data on network level is the Traffic Speed Deflectometer (TSD). The TSD measures pavement response at traffic speed, using Doppler lasers installed in a semi-trailer. While providing the user with a large amount of information, indices to evaluate the roads in a simpler manner are needed in practice, e.g., for selecting the worst conditioned roads in a network. In this article, a new index named the SCI_{TSD} is formally derived from plate bending theory which is proportional to strain in the bottom of the top layer. As opposed to indices such as SCI_{300} which is developed for stationary instruments, like the Falling Weight Deflectometer, SCI_{TSD} also works on asymmetric deflection bowls, which are common due to visco-elastic properties of asphalt. Results from comparisons of back-calculated top layer strain on real-life data with SCI_{TSD} are shown to have high agreement. SCI_{TSD} is calculated directly on TSD measurements and can therefore be calculated fast. It is therefore highly suitable for helping road authorities select sections of interest and can thereby increase the efficiency of road maintenance.

Keywords: Curvature · Deflection index · TSD · Maintenance prediction · Bearing capacity

1 Introduction

In order to maintain roads efficiently, structural measurements are carried out for road authorities. Traditionally, these measurements has been done with the Falling Weight Deflectometer (FWD), which performs load response measurements with geophones placed on the pavement while a weight is dropped. Due to the instrument being stationary during a measurement, FWD measurements are expensive to perform in large scale. The introduction of devices that measures structural response at speed, such as the Traffic Speed Deflectometer (TSD), has enabled network wide measurements with high resolution data. The TSD uses Doppler lasers to measure the response of a trailer axle loading on the road in high resolution at traffic speed. The TSD provides deflection-slopes, i.e., the first

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derivative of the deflection, at 10 longitudinal positions from the loading wheel. This will provide a discrete curve that describes the road's response.

In practice, having such high-resolution data available for entire networks poses a challenge of how to select relevant sections. Different approaches to describe the condition of the road structure has been used, [1]. One could use the maximum deflection, which would tell how stiff the road is, but it is not given that all roads must be equally stiff as they are designed for different traffic loads. Another popular index is the Surface Curvature Index SCI, explained e.g. in [2], which is the difference in deflection directly under the load with deflections at distance, S, from the load. A common value for S is 300mm (SCI_{300}) as it was practical for the FWD instruments it was originally applied on. Assumptions for SCI_{300} include,

1) The deflection bowl is symmetrical, as for a purely elastic road structure. 2) The deflection bowl approximates well a circular curve from −300 mm to 300 mm. Neither 1) or 2) are always the case in practice.

The surface curvature indices are of general interest, as we from simple plate theory can deduct a proportional relationship between the curvature under plate bending with strain in the plate (elaborated in next section), [3–5]. Since 2018, the TSD has sensors behind the load as well to capture visco-elastic effects, observed in some pavements at dynamic loading. Since we base SCI_{TSD} on a sensor in front and after the load, it is not restricted by 1) and further, S can be smaller which means assumption 2) is less critical. In this paper, a formal adaption of the traditional SCI parameter to the TSD setting, SCI$_{TSD}$, is presented. It contributes with novel enhancements such as,

1. proportionality with strain in the top layer, see explanation in Sect. 2,
2. represents asymmetric deflections bowls, i.e., with visco-elastic roads.
3. has a less strict assumption on 2) due to a smaller S.
4. it is calculated directly on slopes without the need of integrating to get deflections.
5. for discontinuities where plate theory no longer relate curvature to strain, it provides a good indicator for relative movements. This makes the TSD able to find concrete slabs with poor load transfer and cracks, even below intact asphalt layers.

In the experiments, Sect. 3 SCI_{TSD} and back-calculated top layer tensile strain is well aligned, confirming the strength of this index for structural screening of roads.

2 Theory

2.1 Plate Bending

Radius of curvature states that the curvature of a point P on a horizontal tangent is the curvature of the circle touching P, see Fig. 1a. With a circle given,

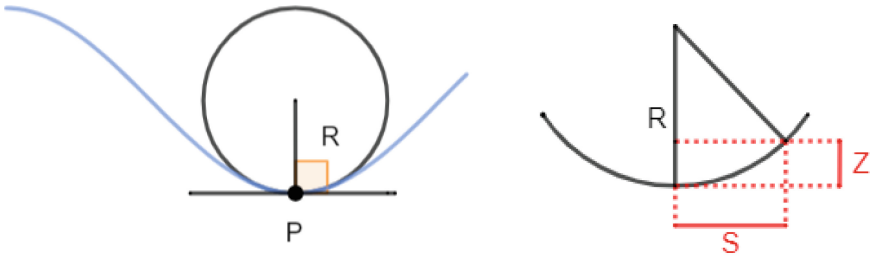
$$y = \pm\sqrt{R^2 - x^2}. \tag{1}$$

The curvature is defined as the second derivative [6], hence for a circle, Fig. 1a, the curvature is

$$\ddot{y} = \frac{1}{\sqrt{R^2 - x^2}} + \frac{x^2}{\left(R^2 - x^2\right)^{\frac{3}{2}}}. \tag{2}$$

Evaluating this for $x = 0$ gives the following solution for the curvature at P:

$$\ddot{y}(x = 0) = \frac{1}{R} \tag{3}$$



(a) (b)

Fig. 1. (a) Circle with radius R that describes the curvature at point P. (b) Circle approximation of a deflection basin with radius R. Here, z is the difference in height at two points and S is the distance between.

2.2 $\mathbf{SCI_{TSD}}$

Figure 1b shows the deflection of a plate and the radius of curvature of the deflection. R can be formulated using the distances S and z in Pythagoras theorem

$$R^2 = (R - z)^2 + S^2 \Rightarrow \frac{1}{R} = \frac{2z}{z^2 + S^2} \tag{4}$$

since $z^2 << S^2$ the Eq. 2.2 can be simplified to

$$\frac{1}{R} \simeq \frac{2z}{S^2}. \tag{5}$$

z can be described directly from TSD slopes and therefore the index is named SCI_{TSD}. As curvature can be estimated from the numerical derivative of slopes, then,

$$\frac{1}{R} = \frac{Slope_f - Slope_b}{l}. \tag{6}$$

Here $Slope_f$ and $Slope_b$ are the slope values measured in front and behind the load respectively and l is the distance between the measurement points. f and b do not need to lie symmetrically around P for Eq. 2.2 to be true but S should

be small for $1/R$ to represent curvature. In order to make an index similar to traditional curvature indices we define it as z in 5 and substitute $1/R$ with the expression from 6 in Eq. 5. Further, it simplifies if we choose $S = l$, although it is not strictly necessary, and we get,

$$\begin{aligned} \frac{Slope_f - Slope_b}{l} &= \frac{2 \cdot SCI_{TSD}}{l^2} \Rightarrow \\ SCI_{TSD} &= \frac{(Slope_f - Slope_b) \cdot l}{2} \end{aligned} \tag{7}$$

This index is an approximation of the curvature at the point of the load, thus SCI_{TSD} is proportional to the strain in the bottom of the top layer

$$\varepsilon = \frac{H}{2} \frac{\partial^2 w}{\partial x^2}, \tag{8}$$

where H is the layer thickness. For the deflections close to the load it is known that the second derivative is $\frac{1}{R}$, meaning that Eq. 6 can be used to find the strain directly. The reason this is not the index used is that SCI_{TSD} (Eq. 7) can more easily be related to already existing SCI_{300} measurements. Thus combining Eqs. 6 and 7 gives the following solution for the strain in the bottom of the top layer

$$\varepsilon_{xx} = \frac{H}{2} \frac{2 \cdot SCI_{TSD}}{l^2} = \frac{H \cdot SCI_{TSD}}{l^2}. \tag{9}$$

As plate theory assumes homogeneity, surface curvature indices do not relate to strain when calculated over a discontinuity, e.g. on each side of a concrete slab. Instead, the SCI_{TSD} will be the difference of a positive and negative velocity component, resulting in a high value in the exact moment the load cross the discontinuity. This signal will instead relate to the load transfer between two plates, [7].

3 Experiments

In order to validate the relevance of the index to analyze roads for structural weaknesses, SCI_{TSD} is compared to the output of a mechanistic model. The model presented in [8] is used here, which models the steady state response of a road with up to four layers, where layers can exhibit visco-elastic properties. From back-calculation, the layer properties can be estimated by minimizing the difference between the measured slope values and the model's response. This provides the user with E-moduli and strains for all layers in the model.

In this study a 2.3 km section of a highway in Denmark was measured by a TSD. This section is designed to have a 20 cm top asphalt layer. The typical TSD sensor configuration, also used in below experiments, has,

$$Slope_f = Slope_{0.13\,m}\ , \quad Slope_b = Slope_{-0.2\,m} \tag{10}$$

Table 1. Mean, Standard Deviation, Minimum- and Maximum value for top layer thickness, measured in GPR radargrams.

Mean	Std.	Min.	Max.
18.5 cm	2.1 cm	14.4 cm	24.6 cm

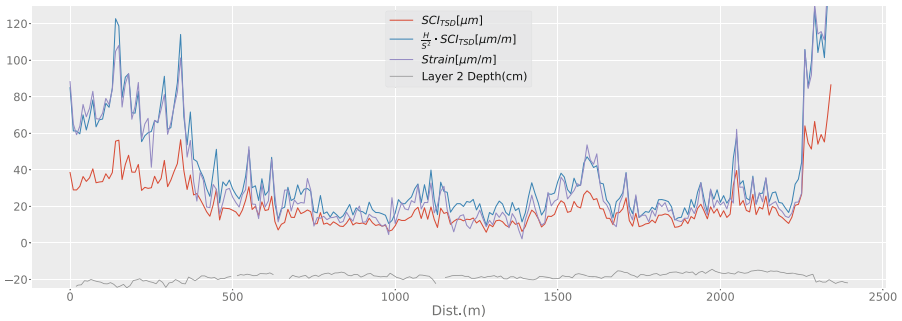


Fig. 2. Measurements for a 2340 m section, with a 10 m reporting interval. Red line: SCI_{TSD}, purple line: Tensile strain in the bottom of the asphalt layer, from the model in [8], blue line: strain according to Eq. 9, grey line: layer depth extracted from GPR.

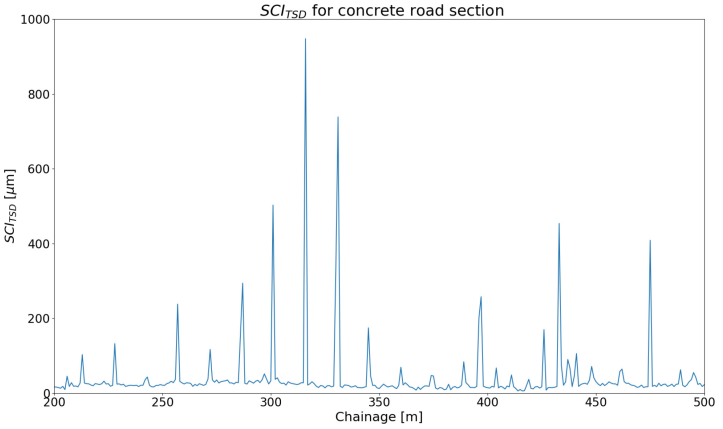


Fig. 3. SCI_{TSD} from measurements in an airport consisting of concrete plates.

with a sensor measuring 0.13 m in front of and one measuring 0.2 m behind the load, $l = 0.33$ m. The TSD used here has a 2 GHz Horn antenna based Ground Penetrating Radar (GPR) for recording subsurface layer reflections in 10 cm scan-spacing. The data were analysed to find the layer thickness, see Table 1.

In Fig. 2 a high agreement between modelled top layer strains and strains obtained from SCI_{TSD} is seen. It is also seen that SCI_{TSD} correctly captures the variation in strain.

In Fig. 3 SCI_{TSD} is reported on measurements from an airport with concrete slabs. Some of the joints exhibit higher values indicating a poorer load transfer.

4 Conclusion and Future Work

SCI_{TSD} derived from traditional curvature- and strain theory using the advantages that the TSD offers, has been shown to be a good condition indicator. Without the need of using a model to assess the road, SCI_{TSD} is a fast and reliable index to monitor large networks. An advantage of SCI_{TSD} is that even when the assumption of homogeneity breaks the relation to strain, the index offers useful description of discontinuities. The mathematical framework is easily extendable to e.g. a Base Curvature Index BCI_{TSD} or a Base Damage Index BDI_{TSD}, [9]. Here, the reformulation would offer to calculate these indices directly from deflection-slopes as well.

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Development of a Bio-Based Emulsion for Road Pavement Construction and Maintenance

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Abstract. The paper presents the development of two bio-based emulsions composed of bitumen and a heavy fraction of bio-oil from the thermochemical liquefaction – bio emulsion – and destinated for road pavement construction and maintenance. The bio-oil was extracted from wood residues (biomass) through an innovative liquefaction process. The process involves depolymerizing lignin, cellulose, and hemicellulose, transforming wood residues into an oligomeric mixture. The liquefaction is an alternative to the pyrolysis process, demonstrating greater efficiency and product stability. The bio emulsions were formulated in the laboratory and applied on two full-scale pilot to validate the production technology at the pre-industrial level. The paper presents the experimental work carried out in the laboratory to develop the bio emulsions, based on rheological and mechanical tests. The paper describes the full-scale road section construction and monitoring through structural tests to validate the performance of the bio emulsion application in the case of track coat to promote adherence between bituminous layers. The experimental results confirmed the adequation of the heavy bio-oil from the liquefaction process for further developments on sustainable road pavement bio-based products. The conclusions highlight the viscoelastic behavior of this type of bio emulsions. The paper presents part of the main outputs of the research project BioRoadPAV®.

Keywords: Bio-oil · Bitumen emulsion · Road pavement

1 Introduction

Current trends in pavement research include developing of composite materials from biomass, contributing to the Sustainable Development Goals (SDG) [1, 2].

Research and development of bio-based materials are increasing to overcome the environmental impacts of non-renewable resources (e.g., petroleum-based materials) and contribute to the circular economy [3] and the SDG. Biomass includes all residues of vegetal or animal nature that can serve in various industrial processes, namely as

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a source of energy or raw material. Bio-oil has excellent potential for application in road pavements, namely through its use in the production of bituminous mixtures and bio emulsions, due to the similarity of its saturated, aromatics, resins and asphaltenes fractions. Bio-oil origins from biomass were diverse, such as rice husk, sunflower, cotton, soy, linseed, and wood (oak, pine). Intensive research and practice are being conducted on the use of bio-based materials in transport infrastructures [4].

Pyrolysis is the most used process to obtain bio-oils [4]. However, this process has a lower yield, resulting in structures with high thermal degradation. An alternative process is the thermochemical liquefaction of biomass with higher yield and stability than pyrolysis [5, 6]. The BioRoadPAV® project – New Biobinders for Application in Road Pavements – was ongoing in Portugal between 2021 and 2023 [7, 8]. The project aimed to develop bio emulsions composed by a bio-oil extracted from biomass (pine wood residues) through an innovative thermochemical liquefaction process patented at Instituto Superior Técnico (IST) [5, 6]. The heavy fraction of the bio-oil, obtained after sugars extraction and light fraction distillation, was used to produce the bio emulsions by mixing with neat bitumen. The paper's main objective, as part of the BioRoadPAV® project, is to present the innovative bio emulsions and their characterization in laboratory tests and the application as a tack coat on a real-scale road test section.

2 Methodology

2.1 Research and Development of Bio Emulsions

Two types of bio-based emulsions (bio emulsions) were developed in BioRoadPAV® project, with the characteristics presented in Table 1 and according to EN 13808:

- Bio emulsion for tack coats promoting the adherence between bituminous layers (equivalent to C60B3 type cationic bituminous emulsion) (Bio C60B3).
- Bio emulsion used for surface treatments (equivalent to C69B2 type cationic bituminous emulsion) (Bio C69B).

Manufacturing the bio emulsions began by adapting the proportions of incorporation of the heavy fraction of the bio-oil into the bituminous binders, to obtain a final product compatible with the standard specifications of 70/100 and 160/220 bitumen grades. These are the preferred bitumens to produce bituminous emulsions and allow for a reduction in additives.

The main problem to solve in formulating of the bio-emulsions was the thermal degradation. It was overcome with the immediate use of a heavy fraction of the bio-oil and a reduction in the temperature of emulsion manufacture (138 °C). The bio emulsion consists of an organic phase (bitumen and heavy fraction of bio-oil) and an aqueous phase (emulgent). It is a colloidal mixture in which molecules from the organic phase are agglomerated and suspended in the continuous aqueous phase. In general, the stability of the mixture is guaranteed by surfactant agents (emulsifiers). However, in the case of the bio emulsion, the organic phase changed composition, resulting in the need to add additives to guarantee the stability of the final product.

Table 1. Properties of the bio emulsions.

Characteristics (units and standards)	Bio C60B3	Bio C69B2
Original emulsion		
Breaking value (EN 13075-1)	70-155	< 110
Binder content (per water content) (%) (EN 1428)	58-62	67-71
Binder content (%) (EN 1431)	≥ 58	≥ 67
Oil distillate content (%) (EN 1431)	≤ 3,0	≤ 2,0
Efflux time (4 mm; 40 °C) (s) (EN 12846-1)	15-70	40-100
Residue on sieving (0.5 mm) (%) (EN 1429)	≤ 0,1	≤ 0,1
Setting tendency (7 days storage) (%) (EN 12847)	≤ 10	≤ 5
Recovered binder		
Penetration (25 °C) (0,1 mm) (EN 1426)	≤ 330	≤ 330
Softening point (°C) (EN 1427)	≥ 35	≥ 35
Stabilized binder		
Penetration (25 °C) (0,1 mm) (EN 1426)	≤ 220	≤ 220
Softening point (°C) (EN 1427)	≥ 35	≥ 35

The emulsion manufacturing was firstly evaluated through the stability of the mixture and whether phase separation occurred in the reservoir. Initially, it was observed, that the colloidal mixture separated, and a solid organic phase was obtained at the bottom of the beaker and an immiscible aqueous phase. Secondly, once the question of phase separation was solved, the rupture of the bio-emulsion was controlled, particularly in the case of bio emulsion for the tack coat (Bio C69B2), with higher percentage of binder in its composition. Once this instability was overcome, through readjustments in the calibration of the colloidal mill and the replacement of some additives and emulsifiers, all current standard tests were carried out to ensure the characteristics specified in EN 13808 for cationic bituminous emulsions. The final bio emulsions were composed of 11% of a heavy fraction of bio-oil.

The transition to the industrial scale was prepared using the formulations with the best results obtained to produce a tack coat for bituminous layers bonding (Bio C60B3) and for surface treatment (Bio C69B2). The heavy fraction of the bio-oil, previously mixed with conventional bitumen, was fed to the emulsion production mill and the final bio emulsions were stored in 200 L drums to be sent to the construction sites.

2.2 Construction of Full-Scale Pavement Sections

The bio emulsions were tested in two full-scale pavement sections. In the case of applying tack coat to promote the adhesive bond between bituminous layers (Bio C60B3), the experimental test section was carried out on a national road with T1 heavy traffic category (ESAL = 100×10^6, 80 kN), during rehabilitation works (IC2 itinerary, located at Rio

Maior, Portugal). The bio emulsion C60B3 was applied between the bituminous base (90 mm) and binder layers (70 mm) of dense hot asphalt concrete (AC 20). The spreading of the bio emulsion was manual, and the final aspect is shown in Fig. 1a. The application of the bio emulsion was done in one of the lanes, along 20 m, and all the rest of the rehabilitation works, a conventional (C60B3) and reference bituminous emulsion was used (Bio C60B3). For both emulsions the application rate was 0,5 kg/m^2. The tacking surface was clean and free of dust before emulsion application.



a) b)

Fig. 1. Pavement section of the tack coat: a) after manual spreading of the bio emulsion; b) after the construction of the overlay.

After allowing the tack coat to break and set, the overlay of binder bituminous mixture was spread and compacted (see Fig. 1b). After 24 h, Falling Weight Deflectometer tests (FWD) were carried out to confirm the bearing capacity of the pavement structure. Additionally, cores of the bituminous layers (150 mm) were extracted to confirm the layers thickness and to provide specimens for laboratory tests.

2.3 Laboratory Tests

An extensive experimental study was performed in the laboratory concerning the rheological characterization of the bio emulsions developed in the project, before and after Pressure Ageing Vessel (PAV): properties according to the EN 13808 (see Table 1); Linear Viscoelastic behavior (LVE) (EN 14770); Multiple Stress Creep and Recovery tests (MSCRT) (EN 16695); Fourier Transform Infrared Spectroscopy – Attenuated Total Reflectance (FTIR-ATR); and Thermogravimetric Analysis (TGA).

The Shear Bond Test (SBT) was performed on two sets of cores extracted from the pavement of the test section (Fig. 2a), according to EN 12697-48. The tests were carried out after the conditioning of the specimens for 5 h at a temperature of 20 °C. Figure 2b shows the specimens after testing.



a) b)

Fig. 2. Shear Bond Test: (a) Equipment in operation; (b) Specimens after being tested.

3 Results and Discussion

It was possible to produce bio emulsions that comply with European specifications, both in terms of intrinsic and rupture properties and consistency of the stabilized binder, which represents the bitumen that will be applied to the pavement in an earlier service phase. The stabilized binders from bio emulsions were significantly softer than those obtained from conventional bituminous emulsions of the same type. The rheological characterization of the stabilized binders resulting from the bio emulsion and the conventional bituminous emulsion showed differences between their viscoelastic behavior, which become more accentuated with increasing temperature. It revealed that the conventional emulsion is less soft and has a more pronounced elastic component. Therefore, it can be concluded that the heavy fraction of bio-oil played an active role in the behavior of the bio emulsion contributing to viscosity reduction. The heavy fraction of bio-oil did not have a negative effect on the aging resistance of the emulsion. It means that the aging of the bio binder was not more pronounced than that of the conventional emulsion. When applying bio emulsions on full-scale experimental sections, a different viscosity of bio emulsions was observed in comparison to the reference bituminous emulsion. During spreading, the bio emulsions exhibited a more viscous behavior for identical application conditions, with a notable influence on the spreading duration (for the same application rate).

Table 2 presents the main results of SBT, in terms of mean and coefficient of variation (CV): maximum force, displacement at maximum shear stress, maximum shear stress, shear stiffness modulus, shear energy, and post-peak shear energy. The mean maximum shear force obtained for the bio emulsion cores is higher than the value obtained for the traditional emulsion cores. The cores of bio emulsion presented a mean value of post-peak shear energy that was half the value obtained for the traditional emulsion set cores indicating a different answer to the applied shear load, after failure.

Table 2. Results of shear bond tests.

Parameters (units)	Mean		CV (%)	
	Bio C60B3	C60B3	Bio C60B3	C60B3
Maximum shear force (kN)	32.3	27.1	18.1	6.2
Displacement at maximum shear stress (mm)	2.2	2.3	12.1	9.4

(*continued*)

Table 2. (*continued*)

Parameters (units)	Mean		CV (%)	
	Bio C60B3	C60B3	Bio C60B3	C60B3
Maximum shear stress (MPa)	1.6	1.3	18.1	6.4
Shear stiffness modulus (MPa/mm)	0.7	0.5	11.7	8.8
Shear energy (Nm)	39.3	36.0	27.6	14.2
Post-peak shear energy (Nm)	4.3	8.3	28.8	15.0

The experimental sections were successfully constructed following the current construction methods, under real conditions. The quality control carried on the experimental sections confirm the suitability of the applications of bio emulsions, when in comparison with identical conditions of application of the conventional bituminous emulsions (without addition of bio-oil).

4 Conclusion

The paper presented the results of part of the research developed under the scope of the BioRoadPAV® project – New Biobinders for Application in Road Pavements – consisting of the manufacturing and application of bio emulsions composed of 11% of heavy fraction of a bio-oil extracted from pine wood residues by the innovative process of liquefaction. Two full-scale road test sections were constructed regarding the application of the bio emulsions as tack coat to promote the adhesive bond between bituminous layers and for surface treatments. After construction, the experimental sections revealed promising results, but they will be monitored over time, regarding the durability of the application of the bio emulsions.

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Serious Game Design for Resilience Enhancement of Transportation Infrastructure to Cyber Threats and/or Flood Hazards

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Abstract. It is challenging to predict the precise location and severity of flood events, which can cause major disturbance to different public services, such as disruption to and the closure of critical transportation infrastructure. Therefore, approaches to enhance the resilience of these infrastructures are required. Serious games are new computing tools that have been applied in various fields with a combination of gameplay, learning and training. However, the application of serious games in intelligent transportation systems remains underutilized. As a result, the concept of a serious game is developed in this study to significantly improve transportation infrastructure resilience in an example of a flooding event. The serious game concept presented in this paper is being developed as part of the H2020-funded PRECINCT project (www.precinct.info).

Keywords: Serious Game · Transportation Infrastructure · Flood · Resilience

1 Introduction

The main aim of Intelligent Transportation Systems (ITS) is to enhance transportation mobility and safety, as well as improve the integration of advanced technologies into the transportation infrastructure [1]. Critical Infrastructures (CIs) in transport include airports, bridges, tunnels, roadways, ports, etc. can be subjected to damage induced by different causes such as fatigue, aging, environmental effects, overloading, flood, earthquake, wind excitations or terrorism and criminal activities during their service life which can critically disturb their integrity, serviceability and safety [2]. CIs within urban environments, such as transportation networks, energy networks, communication networks, etc. are influenced by each other due to their interdependencies. These interconnections result from the integration of smart infrastructure and the reliance of each infrastructure on other infrastructures to function, i.e. a transport network needs the energy network and communication network to function. As mentioned above, these interdependent CIs can be damaged due to physical threats or hazards, e.g. a flood. In this context, the

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frequency and severity of climate-driven natural hazards seem to be rising in the European Union's countries [3]. In addition to the increased severity, hydro-meteorological events such as storms, floods, and landslides have a significant impact, and account for 64% of the reported damages due to natural disasters in Europe since 1980 [4]. The knowledge and experiences of Critical Infrastructure Operators (CIOs) when dealing with such hazards, are primarily limited to the sectoral CIs for which they work. ITS are not only susceptible to physical hazards such as flooding, they are also susceptible to cyber threats, e.g. denial of service attacks. However, understanding the interdependency and cascading effects of CIs to complex cyber-physical threats is essential for improving the resilience of ITS. The resilience assessment of CIs is challenging due to the various influencing elements as well as the complex mechanisms in the interlinked smart systems of CIs. It is a challenge to have an overview of the influence of all interdependent CIs. Consequently, this paper presents a novel serious gaming approach, incorporating the interdependency, cascading effects, and resilience scores of CIs to address the current deficiencies. Additionally, the serious game aims to prepare CIOs better to respond to such hazardous events within an 'edutainment' environment. The serious game concept presented in this paper is being developed as part of the PRECINCT project (www.precinct.info). PRECINCT stands for Preparedness and Resilience Enforcement for Critical INfrastructure Cascading Cyber-Physical Threats, a European Union's Horizon 2020 funded ongoing project.

It is worth noting that serious games are relatively new technology-enhanced simulation tools developed for a purpose other than entertainment, such as teaching a specific knowledge or skill. Unlike traditional approaches, they are often considered to provide a more interactive learning environment, a motivational approach to learning, and safe training for patients and students [5]. In recent years, research on serious games has increased significantly. They have recently emerged in the educational game market with the combination of play and learning [6]. A wide range of serious games has been used in various fields such as psychology, medical, dental, energy, language learning, etc. However, the application of serious games in intelligent transportation systems remains underutilized.

2 Effects of Floods on Infrastructure

A complex combination of factors, including climate change, land-use change, poorly implemented regulation, and a lack of integrated planning, has often resulted in environmental degradation and disproportionate impacts of natural disasters affecting millions worldwide [7]. Flooding events (surface or coastal) can destroy buildings, roads, bridges, and trees, devastate agriculture, cause mudslides, and threaten human life [8]. Flooding hazards account for almost half of bridge failures for a range of factors, i.e. (1) scour at the foundation, (2) hydrodynamic loads and pressures on the deck, piers and/or foundations, (3) overtopping, and (4) debris accumulation [9]. Therefore, in the recent decades, several strategies have been introduced, developed, and implemented to manage the environmental effects of floods as well as control the safety of transportation infrastructure. For example, a wave monitoring system was installed on the National Highway in Japan in order to detect the direct and indirect impact of floods on the transportation sector [10]. Moreover, different flood detection systems have been proposed, accordingly [11].

3 Background and Overview of Serious Games

Gamification can be defined as "using game-based mechanics and theory to engage people, motivate action, and promote learning" [12]. In 1987, the term "serious game" was introduced by researcher Abt [13]. In 2002, the US Army developed a serious game in the form of a video game named America's Army. Then, the Serious Game Initiative was founded in 2002 by the Woodrow Wilson Center for Scholars in Washington, D.C [14]. They described serious games as "games that do not have entertainment, enjoyment, or fun as their primary purpose" [15]. In other words, a serious game is a computer-based simulation that merges knowledge and skills development with video game-playing aspects to enable active, experiential, situated and problem-based learning. Nevertheless, "entertainment" has been considered a significant factor of serious games in other definitions, e.g. "serious game is a mental contest, played with a computer in accordance with specific rules, that uses entertainment to further government or corporate training, education, health, public policy, and strategic communication objectives" [16]. Serious games can explore entertainment for different purposes, such as training, education and skills development [17]. Since 2002, serious games have been successfully introduced for different domains such as education, scientific research, environmental science, healthcare, government, politics, military, entertainment, religion, security, marketing, culture and art [18]. The serious game presented in this paper aims to improve the resilience of transportation infrastructure in an example of a flooding event.

4 Interdependency Graphs, Cascading Effects and Resilience

CIs are increasingly at risk from various intentional cyber-physical attacks and risks from natural hazards, such as floods. However, assessing and managing the impact of cascading effects arising from the interdependencies between different types of CIs and different types of hazard/threats and their resilience for 'rapid recovery' is becoming increasingly pertinent and is highly challenging, especially in the context of delimited geographical areas (e.g. districts, cities or regions). The vulnerability of urban centres points to the need for public-private solid coordination to mobilize a response from different sectors and an improved level of protection for associated CIs [19]. Understanding the various effects of an incident such as a flood requires knowledge about the hazard, the area and infrastructures that will be affected. Modern CIs (e.g. water, transport, electricity) are strongly interconnected, and the reduced operation of one or more may affect others. Therefore, a holistic threat analysis includes awareness of the relevant CIs and their interdependencies. In this paper, these interdependencies are modelled through a graph where nodes represent CIs (or relevant parts of CIs), and edges represent dependencies, such as exchanging of resources or providing services.

In recent years, CIs have seen significant advances in resilience. The PRECINCT project focuses on a Resilience Methodological Framework (RMF) and Resilience Index (RI) using monetary evaluations of CI service disruptions [20]. Resilience indicators categorise CI's aspects as Infrastructural, Environmental, or Organisational, and assess them based on their baseline state, impacting service measures during triggering events. The RMF, aided by an interdependency graph simulation. It quantifies resilience through

service measures, feeding into the serious game for users to explore action effects before, during, and after threats. Cost-benefit assessment, combined with machine learning, aids in predicting optimal strategies within budget constraints.

5 Serious Game Architecture, Components and Process

The proposed serious game uses initial pilot data and concepts from flooding events in a city PRECINCT, which offers interactive decision support and scenario specification/building user interface that the player interacts with when gaming. Figure 1 and Table 1 summarise the flowchart, interface, principal components, and elements of the proposed PRECINCT serious game, respectively. The serious game's concept design can be seen in Fig. 1. Firstly, a registered user logs in by entering their username, email, and password, then selecting a character, either the Game Director, an Attacker or Defender. Once a user is logged in, the game will present the qualified director with a director's dashboard to select the type of physical or cyber-attack, the location, and the budget for the attacker and the defender for each CI. The attacker's dashboard enables the attacker

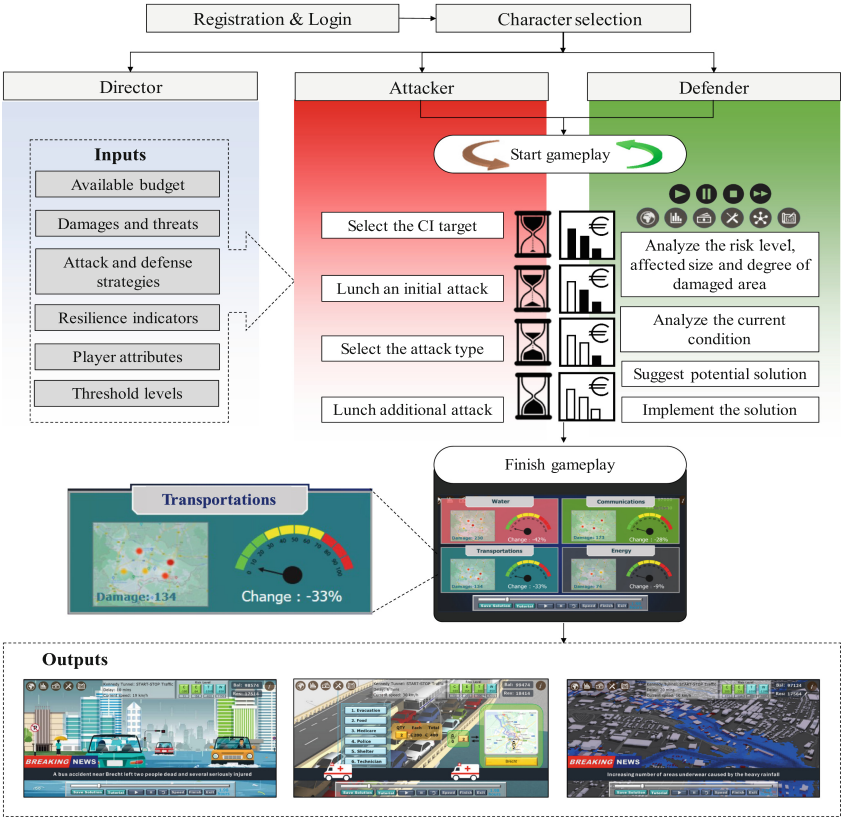


Fig. 1. Flowchart of the proposed serious game along with game interface.

to select tools for the initial attack, use upgrade tools for changing the severity of the hazard or threat, and utilise noise to generate small attacks aiming to confuse the player. The Defender will be presented with the serious game's initial budget balance, the player's ranking, the attack type and the level set by the director. Next, the Defender must enter his or her job role and the number of years of experience in this position. The game Director will be a trusted member of staff from the CIO or else emergency response coordination team.

Table 1. Library of components of the proposed Serious Game.

Characters	Dashboards and Roles
Director	• Setup damage scenario(s), i.e. type of attack and location (Damage identification) • Define budget for defender and attacker for each CI
Attacker	• Select the CI target (Damage location) to lunch an initial attack • Select the attack type (Damage severity) • Can lunch additional attack by selecting destructive option(s) or increasing the severity of damage
Defender	• Provide the player's information, i.e. the initial budget balance, ranking, type of threat, job role, years of experience • Select gameplay options to play, pause, restart, speed or quit the game • Use the provided tutorial, control elements, time slider and play buttons • Finish the game and get the report (game score)

Next, the Defender is presented with the opening attack scenario: for example, a flood is set by the Director using the rainfall selected by the Attacker to launch the initial attack. The serious game provides a set of analysis tools to help the Defender understand the impact of the hazard, through geospatial visualization, the CI's resilience rating, and traffic data, for example. The serious game uses the interaction of the Attacker and the Defender to simulate an attack's cascading effect. After the Defender implements a solution to counteract the attacker's first attack, the Attacker can intensify the attack by increasing the severity of a rainfall event, for example. Consequently, the transportation infrastructure is damaged due to the additional attack. The size of the affected area, the resilience rating for each CI, the links of affected CIs, and the detailed cascading effect between different CIs can also be displayed using the proposed serious game. Additional attack scenarios can be set, such as a cyber-attack on the transportation network.

6 Conclusion

In this study, a serious game concept design has been developed focusing on enhancing the resilience of transportation infrastructure. The gameplay starts with user registration and login. Then, the gameplay was presented, and finally, the analysis of the gameplay was briefly discussed. The serious game presented in this paper allows players to

realistically and accurately represent their transportation infrastructure within a gaming environment. A geospatial analysis of the urban area under consideration in the game enables players to visualise the problem's domain and all interconnected / interdependent CIs. The role of the game Director is to select the type of attack, the location and the budget for the attacker and the defender for each CI (e.g. transportation, energy, or telecommunications network nodes). The game players (Attacker and Defender) can investigate the impact of different severity of flood events or different types of cyber-physical threats on the transportation infrastructure as well as their interdependencies and cascading effects through different game metrics, particularly resilience. The focus of the proposed serious game is to help CIOs understand their current resilience to cyber-physical threats, improve their response and recovery processes and prepare for unseen events, thereby improving the resilience of CIs and their operators to unforeseen attacks or natural events. PRECINCT has implemented the proposed serious games within four living lab urban areas to perform vulnerability assessments both at individual CI and at the command & coordination level.

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Reduction of the Curing Time and Self-healing of Cold Asphalt Mixtures by Means Magnetic Induction

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Abstract. This research evaluates the feasibility of using magnetic induction to reduce the curing time and for the self-healing of cold asphalt mixtures. For this purpose, the traditional oven curing method was compared with two novel magnetic induction protocols for fast curing in terms of water evaporated, time and energy used; the resulting mixtures were evaluated mechanically. Then, by means of a rupture-healing-rupture test, the feasibility of healing the cold asphalt mixtures by magnetic induction was determined. In addition, the impact of healing by magnetic induction on the service life of the mixtures in the face of particle loss was evaluated. With the developments of this research, it is possible to conclude that fast curing by magnetic induction is a feasible option, which improves the resistance to particle loss but decreases its stiffness and indirect tensile strength of the samples. In addition, it is possible to heal the mixtures by magnetic induction, having an optimum healing temperature, which allows the increase of durability against particle loss.

Keywords: Porous asphalt · Cold asphalt mixture · Magnetic induction · Curing time · Virgin steel fibers · Healing process

1 Introduction

Cold asphalt mixtures are manufactured at room temperature with asphalt emulsion, so they require less energy [1] and generate fewer greenhouse gas emissions than hot asphalt mixtures [2, 3]. Despite their advantages, cold asphalt mixtures have been relegated to a second place because of their longer curing time and lower durability.

To date, [4, 5] have addressed the problem of long curing time of cold asphalt mixtures by applying magnetic induction. Both presented promising results, but both investigations used virgin steel fibers as magnetic aggregate, which increases the cost and emissions of cold asphalt mixtures [6].

On the other hand, regarding the lower durability of cold asphalt pavements, the same magnetic induction technology employed by [4, 5] has been used to increase the

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service life of hot asphalt pavements [7, 8], so it is interesting to verify whether the advances obtained to date can be replicated in cold asphalt mixtures.

Due to the above, the objective of this research is to determine the feasibility of reducing the curing time and to evaluate the curing capacity of cold asphalt mixtures by magnetic induction using industrial by-products.

To meet the objective of this research, 3 asphalt mixtures were designed: 1 reference mixture without magnetic aggregate, a control mixture with virgin steel fibers and an experimental mixture with industrial by-product.

In this research, 4 phases were developed: in the first, a novel magnetic induction curing protocol was evaluated with respect to the traditional method established by U.S. asphalt [9]. In the second phase, the mechanical properties of the three cold asphalt mixtures were studied. Then, thirdly, the healing ability of the cold mixtures at different temperatures was determined by means of a breaking-healing-breaking cycle. Finally, fourth, the temperature at which the highest percentage of healing was achieved in the previous phase was applied every 100 cycles in the Cantabro test (EN 12697–17) to determine its impact on the durability of the cold mixtures in the face of particle loss.

2 Materials and Methods

2.1 Materials

Cationic emulsion CP60BP4 MIC type, modified with polymers, and typical aggregates used in northern Spain were used. The properties of the natural aggregates are summarized in Table 1.

Table 1. Aggregate properties

Aggregate	Property	Value	Limit	Standard
Ophite	Los Angeles coefficient (%)	13	≤ 20	EN 1097–2
	Specific weight (g/cm^3)	2.787	–	EN 1097–6
	Polished stone value (PSV)	60	≥ 56	EN 1097–8
Limestone	Los Angeles coefficient (%)	24	–	EN 1097–2
	Specific weight (g/cm^3)	2.705	–	EN 1097–6
	Sand equivalent (%)	78	> 55	EN 933–8

For this research, virgin steel fibers were considered for the manufacture of a control mixture and steel shot blasting (industrial by-product) for the manufacture of an experimental mixture. The density and granulometry are summarized in Table 2.

Table 2. Density and granulometry of magnetic aggregates

Aggregate	Density	Sieve (%)						
	g/cm3	8	4	2	1	0.5	0.25	0.063
Steel shot blasting	7.435	100	100	100	100	67	14	0
Virgin steel fibers	7.800	100	100	100	100	0	0	0

2.2 Methods

This research was divided into 4 phases. In all of them, three porous asphalt mixtures were used. The first one was the reference mixture, which did not contain magnetic aggregate in its dosage (Ref. mixture). The second was the control mixture, with 1% magnetic content of virgin steel fibers (Control mixture). The third mixture was the experimental mixture containing industrial by-product, which had 1% of steel shot blasting as magnetic material (Exp. Mixture).

Phase 1. Curing Evaluation. To determine the feasibility of curing asphalt mixtures by magnetic induction, the percentage of evaporated water, time required and energy used by the method employed for the reference, control and experimental mixtures were compared.

The reference mixture was cured as established by the US. asphalt [9] that is, 48 h in an oven at 60 degrees Celsius. Regarding the control mixture and the experimental mixture, two induction protocols were fabricated, each protocol was designed according to the characteristics of the magnetic particles with the objective of increasing the power and achieving the target temperature of 100 °C (boiling point of water).

Phase 2. Mechanical Evaluation. In order to perform a complete evaluation of the curing process, the three types of mixtures were evaluated mechanically. Initially, the voids were calculated (EN 12697–8), then the cohesion was evaluated by the Cantabro test (EN 12697–17), the modulus of rigidity (EN 12697–26) and the indirect tensile strength (EN 12697–23).

Phase 3. Determination of Healing Temperature. To evaluate the healing capacity, the control and experimental mixtures were submitted to a bending test until fracture, then subjected to magnetic induction until they reached different temperatures and finally subjected to the bending test. The remaining strength was compared with the initial strength and the optimum healing temperature was determined.

Phase 4. Evaluation of the Impact of Healing. In order to study the real impact of healing on the service life of the mixtures, the healing process was applied every 100 revolutions in the Cantabro test to the control and experimental mixtures. These were compared with the reference, control and experimental mixtures without healing within the same test.

3 Results and Discussion

3.1 Phase 1. Curing Evaluation

Figure 1. shows the results of the different curing processes.

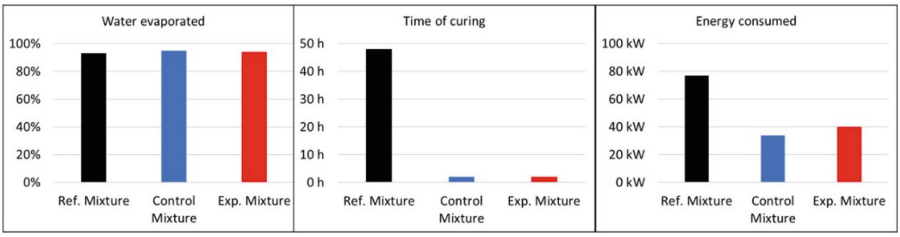


Fig. 1. Results of curing process

Magnetic induction technology appears as a viable option to reduce curing time since it allows a similar percentage of water to be reduced in much less time, implying less energy expenditure at the laboratory level.

3.2 Phase 2. Mechanical Evaluation

Regarding the mechanical analysis of the mixtures cured with the different procedures, the results are summarized in the Fig. 2.

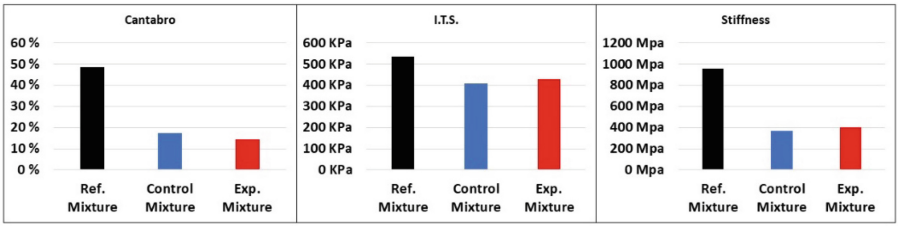


Fig. 2. Results of mechanical tests

Samples cured by magnetic induction significantly improved the performance of the mixture against particle loss. However, they showed inferior performance with respect to tensile strength and stiffness. In the three tests, there were no significant differences in the performance of the control mixture and the experimental mixture, so the use of industrial by-products is a viable option for the curing of cold asphalt mixtures by magnetic induction.

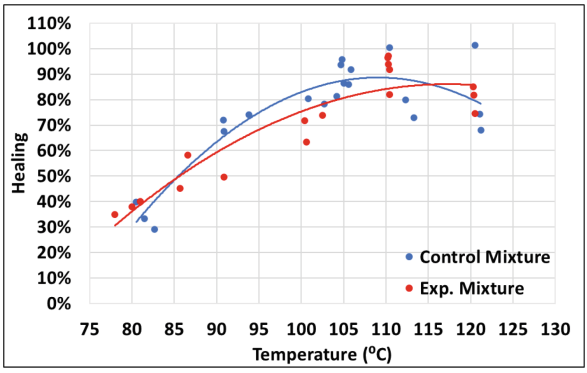


Fig. 3. Results of healing process

3.3 Phase 3. Determination of Healing Temperature

Figure 3 shows the results of cold asphalt mixtures healing by magnetic induction.

In both the control mixture and the experimental mixture, a plateau in the trend curve is observed, which means that the healing capacity increases with temperature, reaching an optimum point above which the healing performance begins to decrease. It is probable that this decrease in the healing capacity is produced by a softening and rearrangement of the particles due to an excess of temperature.

3.4 Phase 4. Evaluation of the Impact of Healing

The results of the Cantabro test with different healthy cycles are summarized in Fig. 4.

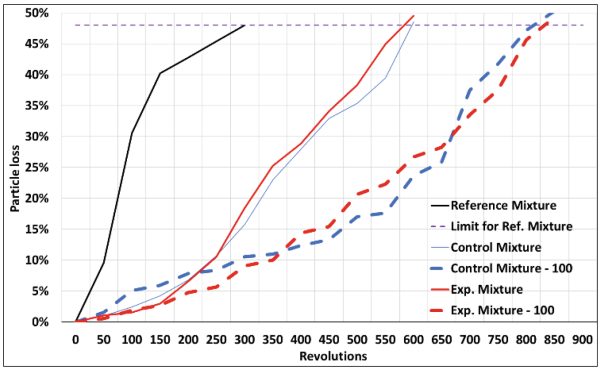


Fig. 4. Cantabro test with different healthy cycles

As in the mechanical analysis, the mixtures healed by means of magnetic induction without healing in the test performed better than the oven-cured mixture. In addition to the above, the mixtures that were healed every 100 revolutions in the Cantabro test

showed significantly superior performance to their unhealed counterparts. Therefore, it is possible to conclude that the magnetic induction healing process is a feasible option to increase the raveling life of cold porous asphalt mixtures.

4 Conclusions

In this research, it has been possible to conclude the following points:

-By means of magnetic induction it is feasible to reduce the curing time of cold asphalt mixtures, producing mixtures with better particle loss performance, but lower stiffness and tensile strength.

-It is possible to heal cold asphalt mixtures by magnetic induction. This process presents an optimum temperature, above which it is possible to increase the useful life of porous asphalt mixtures against particle loss.

In the future, harder asphalt emulsions should be used to improve the mechanical performance of the mix in terms of stiffness and indirect tensile strength.

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Highly Recycled Asphalt Pavement: Recommendations for Producers and Road Owners

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Abstract. While recycling of asphalt is increasing, there is still lack of practical solutions for processing and homogenizing reclaimed asphalt, and designing mixtures for maximum Reclaimed Asphalt Pavement (RAP) use. This paper briefly summarizes the *HighRAP* research project conducted in Switzerland. The findings and the developed recommendations can be used by asphalt producers and road owners to increase the RAP use in the production of new asphalt mixtures. The recommendations include a method for quantitative evaluation of RAP processing, rejuvenator selection methodology, criteria for balanced mix design, suggestions for performance-based test methods, and the maximum content of RAP for various mixtures, including polymer-modified and wearing courses.

Keywords: Reclaimed asphalt pavement · RAP · Performance · Asphalt recycling

1 Introduction

There has been a considerable progress in Reclaimed Asphalt Pavement (RAP) use for hot mix asphalt production. However, multiple practical hindrances prevail in each of the RAP use stages, including material preparation, mix design, and production. These problems limit the maximum RAP content and can lead to mixture performance issues.

The objective of the *HighRAP* project was to develop recommendations for increasing RAP content in hot-mix asphalt without compromising mixture performance.

Within the *HighRAP* project, individual studies addressed six specific problems that limit RAP use as summarized in Table 1. The activities that were undertaken during the project to attempt solving each problem are outlined in the table as well. The findings

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from each activity are presented in this paper under separate headings and the key recommendations are summarized in the last section. To download full report, please visit https://www.empa.ch/web/s308/highrap .

Table 1. Summary of problems with RAP use and the corresponding *HighRAP* project activities.

***HighRAP* project study**	**Problems with RAP use**	**Activities during *HighRAP* project**
 RAP milling & processing	RAP material properties and inhomogeneity limit maximum RAP content in asphalt production.	-A full-scale experiment to evaluate the effect of milling. -A full-scale experiment to develop a method for quantitative assessment of RAP crushing and screening procedure.
 RAP characterization	RAP characterization is time consuming, and involves hazardous solvents.	-An experiment to evaluate the suitability of two methods for characterization of RAP without extraction of binder.
 Aging & Rejuvenators	Appropriate rejuvenator selection and good aging resistance are crucial for high content recycling.	-Laboratory-aging of asphalt to compare with plant produced mixes and road cores. -Development of a procedure for evaluation of rejuvenator aging resistance.
 Performance-based design	Volumetric designs can not be relied upon for high recycling due to lacking empirical evidence.	-Use performance-based mixture design with cracking and rutting test. -Develop acceptance criteria for semi-circular bend and cyclic compression tests.
 Test section in high traffic intensity pavement	High RAP use in polymer-modified pavements and wearing courses may deteriorate theirs performance.	-Construction of a test section in high traffic street to validate the performance of polymer-modified mixtures with RAP between 30-60 %.
 Test section in high altitude pavement	High RAP use in high altitude increases the risk of low temperature cracking.	-Construction of a test section in Swiss Alps to validate the performance of foundation and base course mixtures with RAP content between 60-85 %.

2 RAP Material

Inhomogeneity of RAP is caused by variability of the milled pavement, blending of RAP from various sources, various pavement aging states, various damage states, milling of multiple layers, etc. Furthermore, RAP often has high filler content. This is partially due to the milling and subsequent crushing operations, where filler (dust) is generated as a result of mechanical impact. To evaluate the potential to improve the homogeneity and properties of RAP, the following experiments were performed.

2.1 Processing

Using gradation analysis of RAP before and after binder extraction, three indexes (CBF indexes) were developed that allow evaluating crushing and screening of RAP (Fig. 1):

- Chunk Index demonstrates the size of RAP agglomerations.
- Breakdown Index demonstrates the reduction of RAP aggregate particle size during processing.
- Filler Increase Index reflects the amount of generated filler content during RAP processing.

A spreadsheet for determining the indexes: https://doi.org/10.5281/zenodo.5500154 .

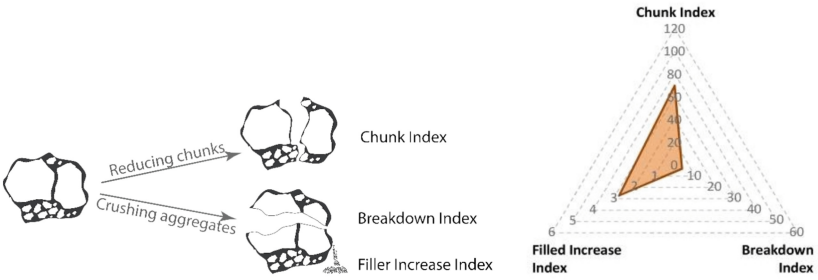


Fig. 1. Logic for the CBF indexes (left) and a result for one processed material (right) [1]

To validate the CBF indexes, a case study was performed using four different full-size crushers. The results showed that the indexes offer quantitative means to characterize RAP procession operations. In particular, the indexes allow optimizing the crushing and screening process, they permit comparing different RAP crushers, and they can help to select RAP management techniques for maximum recycling.

2.2 Milling

A milling experiment was performed by varying the milling parameters in four full-scale jobsites [2]. The results on CBF indexes shown in Fig. 2 demonstrate that the properties of milled RAP can be affected by the milling parameters, most notably—Milling machine moving speed. Optimizing the milling process to minimize aggregate breakdown and filler generation is possible but further research is needed before recommendations for any changes in milling practice can be suggested.

2.3 RAP Characterization

An important practical factor prohibiting implementation of procedures for increasing RAP stockpile homogeneity is the effort and time needed to test the RAP properties. To attempt developing practical and rapid RAP characterization methods, the Cohesion and Fragmentation tests were explored as recommended by RILEM [3]. The following findings arouse from the study:

- The Fragmentation test results had a high repeatability and showed a potential to characterize the RAP depending on the processing method that was used for preparing the RAP. However, a relationship between the test result and RAP aggregate toughness and RAP agglomerations could not be established.

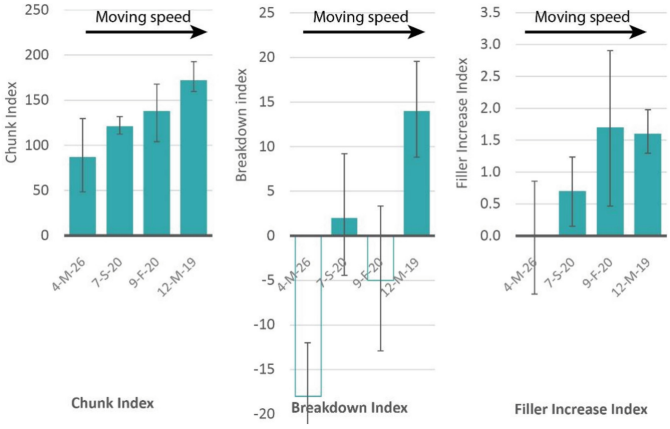


Fig. 2. Milling machine moving speed affects the CBF indexes

- The Cohesion test was intended for characterization of RAP binder content and binder properties. The test results were found sensitive toward binder softening point and binder aging but not toward binder content.

3 Design of Mixtures with High RAP Content

The traditional mixture design methods do not allow to capture some of the challenges related to designing high RAP mixtures, including cracking resistance, rejuvenator use, and blending of all materials. Performance-based test methods can allow to capture these effects and thus increase the confidence in paving of high-RAP mixtures.

3.1 Aging and Rejuvenator Selection

The rejuvenator dosage for the test sections was selected to reach target binder penetration. The binder, rejuvenated with an additive based on crude tall oil, was tested for aging resistance. The results showed that the rejuvenator used in this research can fulfill all the conventional binder test requirements and does not exhibit accelerated aging.

3.2 Performance-Based Mix Design

The mixtures for test sections were optimized using performance-based test methods. The following steps were implemented:

- Optimize the rejuvenator content for the mixtures based on target penetration results.
- Use semi-circular bend (SCB) cracking test and cyclic compression (CC) plastic deformation test to balance the design binder content and other design parameters. During the research, acceptance criteria for the SCB and CC tests were developed for various layers and mix types.
- As needed, perform additional binder and mixture tests before approving the final designs.

4 Performance of Highly Recycled Mixtures

4.1 RAP use in High Traffic Volume Roads

Four *HighRAP* mixtures, including two polymer-modified mixtures, with high RAP content were paved in Aathalstrasse, Uster, Switzerland. Three reference mixtures were also placed. A video from the test section construction is available here: https://youtu.be/MvyCwyrMNOs .

The test section results demonstrated that by following a performance-based mix design procedure, it is possible to produce polymer-modified mixtures (including a wearing course mixture) with at least 30–50% RAP content, without sacrificing mixture performance. Figure 3 provides the most informative performance-based test results of the *HighRAP* mixtures with respect to with the reference mixtures.

Mixture	Binder grade	RAP content	Crack propagation resistance		Rutting resistance			Stiffness	Fatigure Resistance	
			SCB	G-R	CC	FRT	MSCRT	ITT	ITT	MMLS3
AC 8 H HighRAP	45/80-80	30%	→	→	↗	↗	→	→	→	-
AC 8 H reference	45/80-80	0%	●	●	●	●	●	●	●	-
ACB 22 H HighRAP	45/80-65	60%	→	↗	↓	↘	↘	↘	↘	↓
AC B 22 H reference	45/80-80	30%	●	●	●	●	●	●	●	●
AC T 22 S HighRAP 65%	50/70	65%	↘	↗	↑	-	↘	↗	→	-
AC T 22 S HighRAP 75%	50/70	75%	↓	↓	↑	-	↗	↑	↓	-
AC T 22 S reference	50/70	65%	●	●	●	-	●	●	●	-

Legend:

- ● reference mixture result
- ↑ significantly better performance
- ↗ slightly better performance
- → similar performance
- ↘ slightly worse performance
- ↓ significantly worse performance

SCB Semi-circular bend test (mixture)
G-R Glover-Rowe test (binder)
CC Cyclic compresstion test (mixture)
FRT French Ruting Tester (mixture
MSCR Multiple stress creep recovery test (binder)
ITT Indirect tensile test (mixture)
MMLS3 Model mobile load simulator (mixture)

77

Fig. 3. Summary of the performance of the Uster test section mixtures

4.2 RAP use in Pavements at High Altitude

Five *HighRAP* mixtures having high RAP content were paved in Lukmanierpass, Switzerland at an altitude of above 1900 m along with the respective reference mixtures. Based on the test results, it was concluded that by following a performance-based mixture design, it is possible to produce base course mixtures having 60–85% RAP content with similar properties compared to the mixtures conventionally paved at high altitudes. Figure 4 compares the most informative performance-based tests results of the *HighRAP* mixtures with respect to the reference mixtures paved in the Lukmanierpass test section.

Mixture	Binder grade	RAP content	Crack propagation resistance		Rutting resistance		Thermal Cracking resistance	Stiffness	Fatigure Resistance	
			SCB	G-R	CC	BTSV	TSRST	ITT	ITT	MMLS3
ACT16N 125 HighRAP	100/150	60%	→	→	→	→	→	↗	↗	-
ACT16N 125 Reference	100/150	50%	●	●	●	●	●	●	●	-
ACT16N 85 Reference	70/100	50%	↗	→	↘	→	→	↗	↗	-
ACT22N 85 HighRAP	70/100	70%	→	→	→	→	→	↑	↗	-
ACT22N 125 Reference	100/150	50%	●	●	●	●	●	●	●	-
ACF22 85 HighRAP	70/100	85%	↗	↗	↑	↘	↑	↗	↘	↗
ACF22 125 HighRAP	100/150	85%	↗	↗	→	↓	↑	→	→	→
ACF22 35 Reference	20/50	85%	●	●	●	●	●	●	●	●

Legend:

- ● reference mixture result
- ↑ significantly better performance
- ↗ slightly better performance
- → similar performance
- ↘ slightly worse performance
- ↓ significantly worse performance

SCB Semi-circular bend test (mixture)
G-R Glover-Rowe test (binder)
CC Cyclic compresstion test (mixture)
BTSV BTSV temperature (bitumen)
TSRST Thermal stress restrained specimen test (mixture)
ITT Indirect tensile test (mixture)
MMLS3 Model mobile load simulator (mixture)

Fig. 4. Summary of the performance of Lukmanierpass test section mixtures

5 Conclusions and Recommendations

Based on the *HighRAP* research project results, the following recommendations for increasing RAP use in hot mix asphalt are proposed (for full conclusions and recommendations visit https://www.empa.ch/web/s308/highrap):

- At least 30% RAP can be added in polymer-modified wearing courses for high traffic intensity roads (binder grade PmB 45/80–80) and at least 50% RAP can be added in PmB base/binder course (binder grade PmB 45/80–65). High polymer modification is required for the added virgin binder.
- Up to 85% RAP can be used in high altitude base and foundation courses.
- High RAP use should only be permitted if high RAP homogeneity is ensured.
- Performance-based mix design should be used for mixture approval.
- Rejuvenator dosage can be optimized based on target penetration.
- Rejuvenator/soft binder should be approved by testing aging resistance after RTFO and 2xPAV cycles by determining mass loss & penetration change.
- Correspondence to conventional extracted binder test requirements should be ensured even if performance-based mix tests are used.
- CBF indexes can be used to optimize RAP crushing and screening.
- These recommendations should be implemented only after local validation.

Acknowledgements. The authors would like to thank the following entities for financial and in-kind contribution to the *HighRAP* project: FEDRO, FOEN, AWEL, ANU, Ammann Schweiz AG, BHZ AG, Reproad AG, and Catram AG.

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Cost of Meteorological Hazards on the French National Railway Network

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Abstract. The increasing average annual temperature and the intensification of extreme weather events are placing significant strain on national infrastructures, particularly railway networks. This paper examines the vulnerability of the French national railway network to meteorological hazards, focusing on weather-related train operations incidents and associated costs from 2001 to 2019. The study aims to provide insights for optimizing crisis management strategies and enhancing resilience to future climate conditions.

Keywords: weather hazards · climate change · adaptation · rail infrastructure · operating incidents

1 Introduction

The European railway network comprises 234,000 km of lines, with diverse assets that have varying lifespans, making it vulnerable to weather hazards (Palin et al., 2021). Despite this, European rail infrastructure and operators are often unprepared for extreme weather, leading to severe disruptions (Ludvigsen and Klæboe, 2014). CEDR (2012) projects a rise in average temperatures and an increase in precipitation intensity, which could exacerbate disruptions if no mitigation strategies are implemented.

While the number of studies and funded projects about the weather hazard impacts has increased significantly across Europe (EEA, 2020), there is a notable lack of research specific to the economic analysis of climate adaptation in the rail sector (European Commission, 2020). This paper seeks to address this gap by analyzing the effects of weather hazards on French train operations and the associated costs for SNCF Réseau.

2 Weather Hazard Impact Across Europe

In the United Kingdom, Ferranti et al. (2018) documented severe disruptions during a heatwave on July 1, 2015, costing the national economy an estimated £16 million. Similarly, the London Underground experienced increased delays during extreme heat periods (Greenham et al., 2020). (Ochsner and Palmquist, 2022) found that adverse weather conditions accounted for 5–10% of infrastructure failures and 60% of delays in Sweden. In the Netherlands, critical events included high temperatures and snowfalls (Oslakovic et al., 2013).

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3 Methodology

This study uses empirical analysis, following Greenham et al. (2020), to examine the effects of weather-related disruptions on the French rail network from 2001 to 2019. Data were sourced from SNCF Réseau's BREHAT monitoring tool, which details train delays and cancellations due to nine specific weather events. The study also analyzes maintenance costs associated with weather damage to assess both direct and indirect impacts on the rail network.

3.1 Data Analysis

The BREHAT tool (Base de Résultat de l'Exploitation Habile à d'Autres Taches) records extensive data on train operations, including delays (over 5 min at arrival), cancellations, and the number of affected trains. Weather-related disruptions are categorized as:

- Fog
- High heat
- Rain
- Flooding
- Rime/glaze ice
- Snowfall/snowdrift
- Thunderstorms/hail
- Strong winds/storms
- Unidentified hazards

From 2001 to 2019, about 170,000 weather-related incidents were documented, accounting for 1.5% of all train operation disruptions.

Maintenance costs from these incidents were gathered from the insurance claims database (2013–2019). This data helps evaluate the network's vulnerability and performance. Maintenance costs, eligible for insurance claims, include direct consequences (e.g., asset damage, safety risks) and indirect consequences (e.g., revenue losses).

3.2 Modelling

To assess the financial impact of weather-related train cancellations, a simplified model for train access charges was created. This model estimates revenue loss based on:

- The nature of the train route
- The number of cancelled trains
- Access charges associated with different train categories using the network.

According to Article 31 of Directive 2012/34/EU, SNCF Réseau charges for the use of the national rail network. However, when trains are cancelled due to weather hazards, these charges are not collected, leading to potential revenue loss. The model quantifies this financial impact for SNCF Réseau.

4 Results and Discussion

4.1 Description of the Weather Hazards

The number of disruptions has stabilized since 2010, potentially due to improved data collection or significant weather events like the Xynthia storm (2010) and the 2018 heatwave (Fig. 1). Ile-de-France, the region with the highest traffic, experienced the most weather-related incidents (geolocation of weather hazards analysis from BREHAT tool).

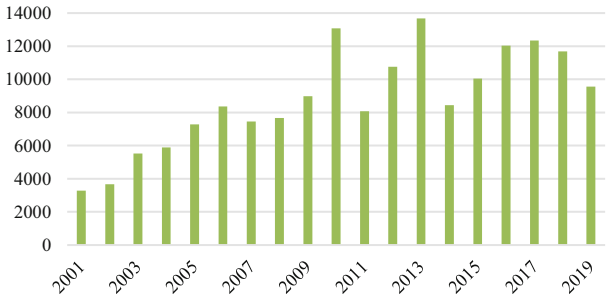


Fig. 1. Number of disruptions caused by weather hazard, from 2001 to 2019 (Source: BREHAT, SNCF Réseau)

Nearly a quarter of weather-related incidents occur around Paris in the highly trafficked Ile-de-France region, indicating a high sensitivity to weather hazards. Autumn accounts for half of all weather-related disruptions, with November alone contributing 25% (Fig. 2). Around 50% of autumn disruptions are due to rain. Winter disruptions are mainly caused by frost and snow, with only 30% due to rain. There were nearly 90,000 disruptions in autumn, while summer saw around 25,000, primarily due to thunderstorms, heavy rains (40%), and high temperatures (16%).

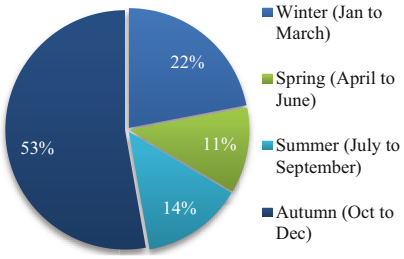


Fig. 2. Percentage of weather disruptions, from 2001 to 2019 (Source: BREHAT, SNCF Réseau)

4.2 Asset Damage Analysis

Seven main asset categories have been analyzed: Tracks (including switches), signaling (including level crossings), civil engineering, rolling stock, catenary (including substations), passengers and unknown (Fig. 3). As in the conclusions of (Ochsner and

Palmquist, 2022), tracks and switches are the most affected, especially in autumn, correlating with high rain and fog incidents. Rolling stock issues are more prevalent in winter, aligning with snow-related disruptions. Signaling and catenary are more sensible during spring and summer.

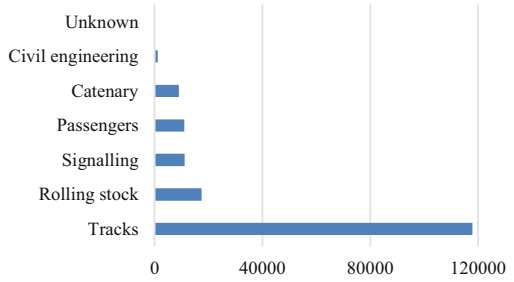


Fig. 3. Assets damaged causing train disruption due to weather hazard, from 2001 to 2019 (Source: BREHAT, SNCF Réseau)

The proportion of disruptions due to track and signaling failures has decreased since 2010 and 2001, respectively, while catenary-related issues have risen since 2016.

4.3 Magnitude of Disruptions

Rains, while frequent (49% of disruptions), result in fewer delays and cancellations compared to heat-related incidents and thunderstorms, which, despite being less frequent, cause significant disruptions (40% of delays and cancellations) (Fig. 4). The southeastern and western regions are particularly vulnerable to high heat and thunderstorms (50% of the disruptions geolocated), with Ile-de-France also heavily impacted, related to the high traffic volume passing through this very dense region.

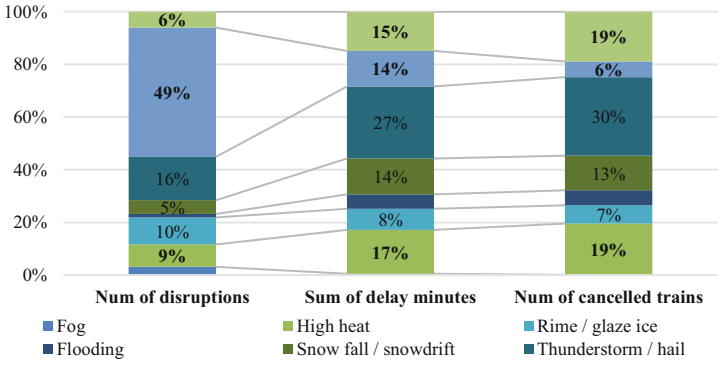


Fig. 4. Magnitude of the weather hazards on disruption, from 2001 to 2019 (Source: BREHAT, SNCF Réseau)

4.4 Costs of Weather Hazards

The French railway network, managed by SNCF Réseau, faces significant maintenance and operational costs due to weather-related damage. After any weather hazard, SNCF Réseau undertakes refurbishment to maintain network performance. These maintenance costs, associated with various weather hazards, are often eligible for insurance claims. The analysis of recent years reveals the following average annual claims and associated costs (Table 1):

Table 1. Average yearly claims and cost per weather hazard (Source: Insurance claim database SNCF Réseau)

Weather Hazard Category	Average Number of Yearly Claims	Mean Cost per Claim (€)
High heat	15	26,000
Rime/glaze ice	2	27,000
Flooding	40	55,000
Snow fall/snowdrift	4	43,000
Thunderstorm/hail	133	20,000
Rain	21	25,000
Strong wind/storms	100	40,000

Based on these claims, the financial losses related to weather events average around €ten million per year for SNCF Réseau. In addition, approximately 5000 trains are canceled annually due to weather hazards, as recorded from 2001 to 2019. This cancellation leads to a significant loss in train access charges, estimated at around €five million per year. Table 2 shows that these charges, which are proportional to the number and type of canceled trains, vary by route and weather condition. Thunderstorms and hail account for the most significant percentage of canceled trains, followed by strong winds and storms:

Table 2. Percentage of train access charges from cancelled trains per weather hazard (Sources: Insurance claim database SNCF Réseau, SNCF Réseau Network Statement, 2023)

Weather Hazard Category	% Train Access Charges Lost due to Weather Hazards
High heat	13%
Rime/glaze ice	4%
Flooding	7%
Snow fall/snowdrift	17%
Thunderstorm/hail	36%
Rain	4%
Strong wind/storms	19%

In total, the combined costs of network refurbishment and lost train access charges due to weather hazards average around €15 million annually for SNCF Réseau. Although this amount represents only 0.2% of SNCF Réseau's 2022 turnover, it provides an initial understanding of the economic impact of weather-related disruptions. Notably, 30% of these costs are concentrated in the Ile-de-France region.

This analysis serves as a preliminary threshold to guide SNCF Réseau in prioritizing resilience investments by identifying specific weather hazards, their impacts, and affected regions.

5 Conclusion

The findings highlight the economic impact of weather hazards on the French railway network, underscoring the need for robust mitigation strategies. Further research should focus on long-term trends and econometric analyses to refine the understanding of these impacts. Prioritizing investment in resilience measures is crucial for managing future risks.

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Exploring the Insights from Transportation Networks: A Multilayer Network Approach to Distribution Systems Onboard Ships

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Abstract. Creating resilient and multi-layered transportation networks is of paramount importance for modern society, particularly considering the need to respond to a diverse array of risks. These resilient multilayer transport networks appear to share comparable properties with vital multilayer distribution systems found onboard large and complex ships. However, little is currently known regarding the similarities and differences in the design of multilayer networks found in various contexts, such as transportation infrastructure and shipboard distribution systems. This study introduces several multi-modal networks and elucidates their similarities and differences and their design processes. A case study details a typical topology of integrated onboard distribution systems, represented abstractly as a multilayer network to showcase said similarities and differences. The study concludes with the lessons learned from comparing transportation networks with vital onboard distribution systems and provides an outlook for future research into resilient shipboard systems.

Keywords: Onboard distribution systems · Transportation networks · Ship systems' design · Resilience · Transfer of technology

1 Introduction

Network theory can be used to quickly evaluate system performance, system vulnerability or the level of system interconnectedness during the design or operational phase of a system. This 1) allows for a better understanding of the design space because a higher number of options can be calculated [1] and 2) it can prevent mishaps in the system re-design or operation [2]. It is common knowledge amongst ship designers that main and auxiliary systems do not operate in isolation but are, in fact, interrelated and should be designed as such. These relations and interdependencies strengthen further with higher levels of integration. Currently, the level of system integration increases due to higher levels of autonomy required and more complex power, propulsion and energy systems. Multilevel networks, containing multiple types of connections or nodes, form a means to perform system vulnerability analysis of combined systems in early-stage ship design.

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Multilayer networks (see [3] for a comprehensive review) have been used in several applications, such as electrical engineering (see land-based power grids in Table 1), architecture, urban engineering and various (public) transport disciplines [4–6]. This study provides a comparison between multilayer network applications in various disciplines, most notably between specific transportation networks and vital onboard distribution systems. The case study focuses on the similarities and differences between a city public transport (PT) network and a topology of integrated onboard distribution systems supporting a single functional end-user. For this study, it was hypothesised that metro networks, due to their comparable size and number of different lines (considered as layers from a multilayer perspective), would prove to be very similar to integrated onboard distribution systems from a network theory perspective and that it would thus be possible

Table 1. Multilayer network applications and their characteristics

Network	Design Freedom	Design Boundary Conditions	Layers
Integrated Onboard Distribution Systems	Full design freedom in ship design phase. Capacity and topology remain constant if design is completed or change at high expenses. Design based on maximum capacity requirements.	Limited volume and weight freedom. Minimal costs.	Cooling water, HVAC, electricity, sensor data, fuel, lubrication oil, etc.
City metro network	Topological architecture remains constant or changes at high expenses over a long time. Capacity can be adjusted, design for mean capacity.	Existing infrastructure, predicted passenger numbers.	Metro lines
PT network	Rail-based transport remains constant. Road-based transport can be dynamically adjusted in route and capacity. Design based on mean capacity.	Existing infrastructure, predicted passenger numbers.	Tram, train, bus
Land-based power grid	Topological architecture and capacity remain constant or change at high expenses	Existing infrastructure, predicted capacity requirements.	High voltage, medium voltage, low voltage

to consider metro network resilience metrics and measures as potential improvements for on-board distribution systems as well.

Integrated Onboard Distribution Systems. Integrated onboard distribution systems are systems consisting of components (machines, equipment, other apparatus) that convert/transform an energy flow (or some other form of generalised flow) and connections/links between them that transport different forms of energy/generalised flow from suppliers to users [7]. Some examples are the cooling water system, HVAC system and the electric power grid. Two of the main challenges in onboard distribution and distributed system design are that 1) the distributed system design from ship type to ship type is vastly different in that it cannot be captured using a small set of parameters describing the spacings and 2) the complexity of distributed systems lies not only in their individual structures but also into the interactions of different systems [8]. Table 1 presents some characteristics of integrated onboard distribution systems and comparable-sized multilayer network applications.

2 Case Study—PT Networks Compared with Integrated Onboard Distribution Systems

This study compares metro networks and integrated onboard distribution systems on some of their key properties: Number of nodes, number of edges and mean degree. Metro networks and, more generally, transport systems, have been studied extensively in previous years [4, 9]. A major focus lies on the resilience of these systems, both in relation to manmade attacks/failures as well as naturally caused failures/disasters. This focus makes transport networks a relevant application to study for the improvement of onboard networks' resilience. Figure 1 shows, for a selection of metro networks [10], the number of stations (nodes), connections (undirected edges), tracks (directed edges) and the mean degree. Note that the number of directed edges (tracks or rails) is exactly twice the number of undirected edges (tunnels or connections between stations).

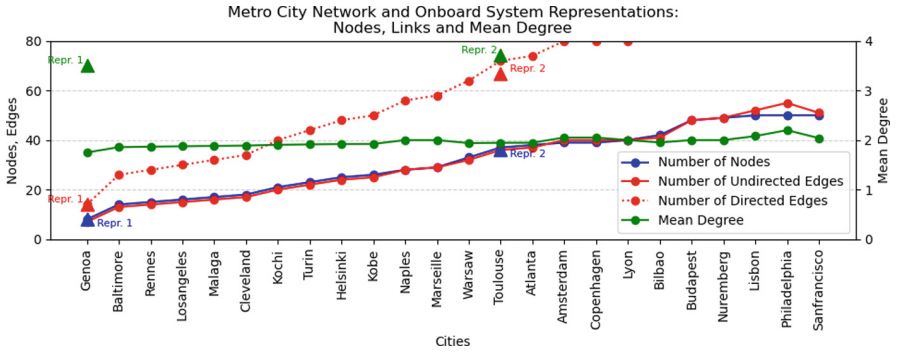


Fig. 1. Metro networks [10] (lines) and onboard system representations (triangle markers) compared on number of nodes, edges and mean degree. The triangles show, in corresponding colors to the lines, the relative location of the onboard system representations

The separate markers (triangles) refer to the case study of integrated onboard distribution systems representations 1 and 2, which are explained in more detail later. The figure shows that the mean degree of the metro networks is close to the lower bound mean degree, which follows an asymptotic increasing line in infinity to 2. Therefore, the structure of the metro networks is either close to a path network or a tree network. It is common for smaller metro networks to have a linear, diametrical, x-shaped or circular network [11, 12], the first three being variants on path or tree graphs.

Comparison in L-space and P-space. A second comparison is based on PT network representations: The L-space (physical infrastructure with edges representing lines) and the P-space (service space; two nodes are linked if they are served by at least one common route [13]). Figure 2 shows two networks with eight nodes: A low-detail representation (representation 1) of integrated onboard distribution systems and the metro network of Genoa in L-space and P-space. Here, the metro network consists of a single line (a single layer), therefore, the P-space is a complete graph.

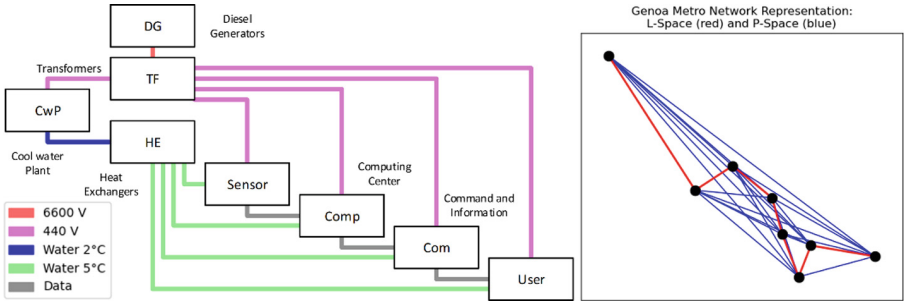


Fig. 2. A network comparison of networks with eight nodes: A) High-level representation of integrated onboard distribution systems and their interrelations. B) The L-space (red) and P-space (blue) metro network representation of Genoa showing stations and physical connections between stations. (Color figure online)

Figure 3 shows the same integrated onboard distribution systems (representation 2) at a higher level of detail and the metro network of Toulouse, which contain respectively 36 and 37 nodes. Since Toulouse contains two metro lines (two layers), the P-space contains two fully connected subgraphs. Whereas the integrated onboard distribution systems contain five layers in both representations, i.e. the "smaller" PT networks contain a lower number of metro lines.

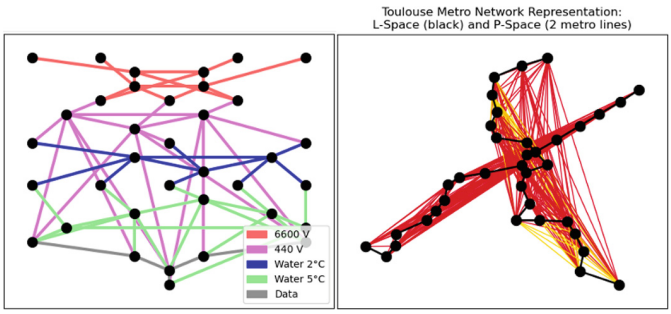


Fig. 3. A network comparison of networks with 36 and 37 nodes: A) More detailed representation of the integrated onboard distribution systems and their interrelations of Fig. 2A [1], B) The L-space (black) and P-space (red, yellow) metro network representation of Toulouse. (Color figure online)

3 Conclusions

Based on the case study, we have drawn the following conclusions regarding the comparison of multilayer network applications.

Sparse networks. Both the integrated onboard distribution systems as well as the metro networks can be considered sparse networks, e.g., they contain significantly less links than the maximum possible number of links. However, due to the inherent property of onboard systems of having supplier nodes and user nodes, this network is closer to a tree-graph, whilst metro networks are closer to path graphs. The tree structure can be found on both the lowest and highest level of detail, however, in-between the supplier and user nodes of each layer we see a more cyclic-based graph between the hub nodes or distribution nodes. The higher mean degree of the onboard networks in comparison to PT networks, as noticeable in Fig. 1, originate from these hub nodes.

Hierarchical reliability. In the early stages of onboard system design, the current focus is on the reliability of separate systems. Future research should take the interaction between these levels regarding the robustness and reliability of the system into account.

Flow layers versus mode layers. When a multilayer network model is used as a tool to understand or improve a system, the definition of the layers is of the utmost importance. We found that there are two main groups within the transport or distribution networks: Heterogenous flow networks and multimodal transportation networks, respectively networks in which the layers represent a different flow, such as a combined cooling water and electricity grid, and networks in which the layers contain the same flow, but the transport or distribution mode depends on the layer. PT networks and cargo transport networks are part of the second group, while power grids and integrated onboard distribution systems are part of the first group. More research is required in determining the differences in reliability and robustness estimations of the different network groups.

Table 2 shows the previously introduced multilayer networks with the characteristics that followed from this study.

Table 2. Multilayer network applications and their characteristics

Network	Type	Interlayer Structure	Intralayer Structure
Integrated Onboard Distribution Systems	Heterogenous Flow Network	Cyclic distribution with tree-like connection to supplier and user nodes	Tree-like
City metro network	Multimodal transportation network	Some shared nodes (hubs), but rarely shared lines and hardly circular structures	Path-like with a rare circle
PT network	Multimodal transportation network	Some shared nodes (hubs), but rarely shared lines and hardly circular structures	Path-like with a rare circle
Land-based power grid	Heterogenous Flow Network	Cyclic distribution with tree-like connection to supplier and user nodes	Tree-like at low voltage levels, circular at high voltage levels

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Asphalt Pavement Performance Prediction Using Ensemble Learning Methods

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Abstract. Ensuring road quality is crucial for the safety and comfort of all road users. The International Roughness Index (IRI) is a fundamental index for assessing the performance of flexible pavements. However, many conventional methods to gauge this index often fall short in accuracy and reliability. To address this, the present research harnessed ensemble machine learning methods, incorporating data from 55 asphalt pavement sections from the Long-Term Pavement Performance InfoPave database. The models were trained using pavement structure, age, traffic, and climatic factors to predict IRI values. Results indicate that ensemble learning methods effectively predict pavement performance, recording R^2 values ranging from 0.82 to 0.87. Notably, the initial IRI emerged as the most significant predictor. Moreover, models showed heightened precision for pavements displaying IRI values under 2.0 m/km, indicating their aptness for early-stage flexible road pavements. These findings underscore the potential to refine these models further and the necessity for more diversified datasets.

Keywords: Pavement Quality · Performance Prediction · Ensemble Learning · International Roughness Index · Long-Term Pavement Program

1 Introduction

A well-functioning Pavement Management System (PMS) is fundamental to maintaining high-quality road networks, with the pavement performance model playing a central role in assessing pavement quality [1, 2]. Likewise, a key metric in this evaluation is the International Roughness Index (IRI), an established benchmark for measuring pavement quality [3]. Sayers et al. [4] defined roughness as road undulations causing vehicle oscillations, with the IRI capturing a standard vehicle's typical response to such surface variations.

Therefore, predicting pavement performance remains challenging, prompting exploration into Machine Learning (ML) approaches. Thus, ensemble algorithms have gained attention for their proficiency with structured data [5]. While decision trees represent decisions and potential outcomes hierarchically [6], they can be prone to overfitting, potentially performing sub-optimally on new data. Ensemble models, like Random Forest (RF), overcome this by amalgamating multiple decision tree predictions, enhancing accuracy and robustness [7].

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The Long-Term Pavement Performance (LTPP) program, introduced by the Federal Highway Administration, offers an extensive dataset for pavement performance research, with its InfoPave portal featuring data from over 2500 monitoring stations [8]. Nevertheless, identifying optimal algorithms and features for improved prediction remains an open challenge.

This study delves into the potential of ensemble learning methods for IRI prediction, discerning key features and best-performing algorithms. The paper unfolds four sections: Introduction, methodology, experimental results, and conclusions.

2 Materials and Methods

The methodology adopted to develop this research can be divided into three main parts: Data collection, data preparation, and model training (Fig. 1).

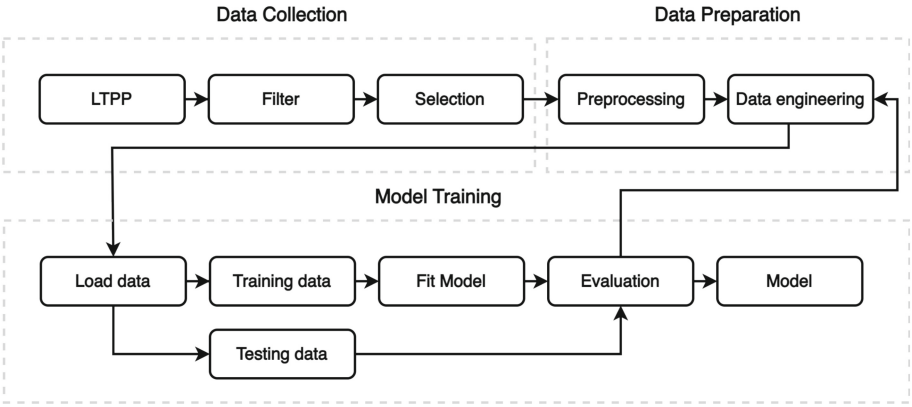


Fig. 1. Methodology adopted for the development of models.

Data from LTPP undergoes filtering, feature selection, preprocessing, and data engineering before being utilized to train and evaluate ML models. The process concludes with the selection of the optimal model based on its performance.

2.1 Data Collection

The ML model was trained using InfoPave's data from LTPP (2023), targeting sections classified as asphalt concrete on granular base and on bound base. The variables included pavement structure (Structural Number, SN), age, traffic (Annual Average Daily Truck Traffic, AADTT), performance (IRI), and climatic conditions (precipitation and temperature). Furthermore, the variable IRI_0 was created, representing the initial IRI of the section upon joining the LTPP program.

To simplify the models, sections with maintenance or rehabilitation were excluded to eliminate uncertainties from these actions. This resulted in a dataset of 55 sections from the United States and Canada (Fig. 2). Notably, many of these sections are near the east coast, which may introduce biases in the models. Consequently, Table 1 outlines the statistics of the selected ML models.



Fig. 2. istribution of sections of the LTPP program used [8].

Table 1. Descriptive statistics for the features used to train the models.

Feature	Mean	SD	Min	25%	50%	75%	Max
SN	4.6	1.5	2.0	3.6	4.2	5.5	8.3
Age	16.1	7.4	1.0	10.0	15.5	21.0	38.0
Accumulated AADTT	2998	4019	11	668	1554	3666	27,470
Precipitation (mm)	1058	458	92	701	1141	1445	2091
Temperature (°C)	15.4	6.1	2.7	10.0	16.2	19.5	25.9
IRI_0 (m/km)	1.22	0.47	0.64	0.89	1.06	1.52	2.52
IRI (m/km)	1.39	0.61	0.62	0.91	1.19	1.74	4.00

Table 1 showcases the dataset statistics, detailing 612 entries from various survey years across the 55 LTPP monitoring sections used for training.

The dataset's IRI distribution leans towards lower values, limiting its representation for values above 2.00 m/km. This distribution can be viewed in Fig. 3.

2.2 Data Preparation

Data was sourced from the LTPP and adjusted. Due to missing yearly data in some sections, steps were taken to fill the gaps:

- Section identification: Distinct sections were grouped.
- Year range determination: Each section's earliest and latest years were pinpointed.

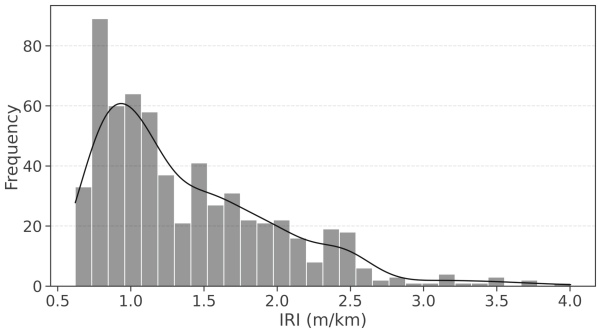


Fig. 3. IRI distribution in the dataset.

- Yearly dataset consolidation: All missing years were created.
- Data imputation for missing years data:

  – Consistent data entries like traffic open year and SN were populated with constant values.
  – Gaps in AADTT and IRI data were linearly interpolated to maintain data trends.
  – Missing precipitation and temperature data were filled in with average values to avoid one-off events.

Subsequently, the following data engineering was performed:

- Pavement age calculation: The pavement section's age was calculated by subtracting its opening year from the current year.
- Traffic accumulation: The accumulated AADTT for each section was determined by summing the AADTT from all previous years and the current one.

Lastly, the year and section were deleted. The variables used for training were SN, age, accumulated AADTT, precipitation, temperature, and IRI_0, with IRI as the target.

2.3 Model Training

Five ML models were chosen to predict IRI, specifically RF, Gradient Boosting Decision Tree (GBDT), eXtreme Gradient Boosting (XGBoost), Categorical Boosting (CatBoost), and Light Gradient-Boosting Machine (LightGBM). Furthermore, the dataset was divided into two subsets: 75% of the data was used for training, while 25% was reserved for testing. Likewise, all models' training parameters were identical; "random_state = 42" and "max_depth = 4" were adopted. For the other parameters, the default values were used.

In conclusion, following the model training, its predictive performance was evaluated using R-squared (R^2) and Root Mean Squared Error (RMSE).

3 Results

The trained models demonstrate reliable IRI predictions with R^2 values ranging from 0.82 to 0.87. Table 2 shows that IRI_0 significantly influences most models' predictions, except for LightGBM, which exhibits less reliance on IRI_0 and maintains a balanced feature importance for robustness. Likewise, features such as SN and Age have minimal impact on the models. The models' effectiveness is confirmed by both their R^2 values and RMSE, highlighting high accuracy and reliability, as illustrated in Fig. 4 and detailed in Table 3.

Table 2. Feature importance.

	SN	Age	Ac. AADTT	Precipitation	Temperature	IRI_0
Random Forest	1.9%	1.3%	8.8%	2.5%	2.3%	83.2%
GBDT	2.7%	2.6%	10.4%	4.2%	3.8%	76.4%
XGBoost	3.9%	1.9%	6.1%	2.7%	2.0%	83.5%
CatBoost	5.7%	4.6%	11.6%	6.9%	5.0%	66.3%
LightGBM	8.5%	13.9%	20.2%	18.0%	14.3%	25.0%

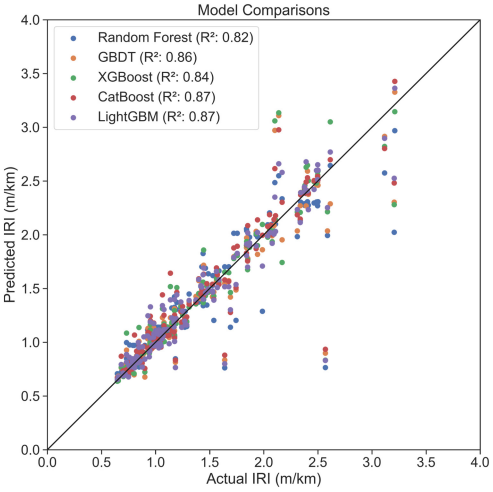


Fig. 4. Results for the models evaluated on the test data.

This analysis underscores the robust predictive power of the models, with LightGBM standing out due to its comprehensive feature sensitivity and minimal dependence on IRI_0. This model's performance, along with others, solidifies our methodology's capability to forecast IRI effectively across diverse conditions, as supported by the high R^2 and low RMSE values.

Table 3. Models' metrics

	R-squared	RMSE
Random Forest	0.82	0.25
GBDT	0.86	0.22
XGBoost	0.84	0.24
CatBoost	0.87	0.21
LightGBM	0.87	0.21

4 Conclusions

In conclusion, this study developed a predictive module to assess the IRI, considering factors like SN, age, AADTT, precipitation, and temperature. The models showcased predictive solid capabilities, with the initial IRI (IRI_0) as the most influential variable. Notably, predictions were more accurate for IRI values below 2.0 m/km, reflecting the dataset's emphasis on well-preserved pavements, as seen in Table 1.

This study's primary constraint is its dataset's focus on low IRI values, mainly under 2.0 m/km. Nevertheless, the research highlights ML's potential in optimizing infrastructure management and the need for quality input data to achieve optimal outputs.

Looking ahead, research should focus on improving datasets to include degraded pavements and incorporate pavement interventions. The final objective is reliably forecasting the IRI for extended periods like 5, 10, and 20 years. The associated codes, datasets, and models are available at github.com/tamagusko/predict-iri-ensemble.

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Comparative Study of Effects of Dolomite and Granite on the Marshall Properties of Asphaltic Concrete

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Abstract. Aggregates are an important component of asphalt concrete and their properties control its performance to a large extent. It is important to consider the parent rocks from which the aggregates are produced. This study examines the properties of granite and dolomite aggregates and the Marshall properties of asphalt concrete produced from the aggregates. The tests conducted on the mineral aggregates include aggregate abrasion value (AAV); aggregate impact value (AIV); aggregate crushing value (ACV) and water absorption. Marshall test was carried out on the asphalt concrete produced using the two aggregates. The results showed that the AAV for granite and dolomite were 26.0% and 65%, respectively. The AIV values were 6.72% and 31.1% and the ACV values were 7.5% and 22.3%, respectively for the aggregates from granite and dolomite. The AAV, AIV, and ACV results indicate that the dolomite aggregates are weaker than the granite. The Marshall stability values for granite and dolomite are 13.39 kN and 13.24 kN and flow values at the maximum stability are of 2.64 and 2.14 mm, respectively. This indicates that they are suitable for use as aggregates for asphalt concrete.

Keywords: Asphalt Concrete · Dolomite · Granite

1 Introduction

Asphalt concrete is commonly used as surfacing material for road construction. However, due to the larger proportion of mineral aggregates in asphalt concrete, its performance is greatly influenced by the properties of the aggregates (Yaseen et al., 2021). These aggregates help resist the significant stresses developed in the pavement structure due to vehicle loading and help to withstand the wear and tear due to abrasion that may arise due to the combined effect of traffic and climatic changes. Golalipour et al., (2012) stated that the aggregates characteristic is the factor that is usually noticed as the most influential parameter causing rutting in the bituminous pavement. The ability of the aggregate to develop resistance against rutting and fatigue cracking relies mainly on their source.

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Therefore, a proper selection of aggregates is required to obtain an acceptable pavement performance (Yaseen et al., 2021). Reclaimed asphalt pavement (RAP) has been used in asphalt concrete as aggregates to avoid depletion of the natural aggregate deposits. Ogundipe (2020) investigated the use of reclaimed asphalt pavement in asphalt concrete and found it suitable. Furthermore, researches were carried out to use waste polyethylene terephthalate and waste glass in asphalt concrete (Ogundipe and Nnochiri, 2020).

Andrzejuk et al. (2019) reported that the dolomite structure is very compact with no visible pores, scratches, or cracks. It was found from EDS analysis that calcium oxide (47.06%) and magnesium oxide (24.02%) are predominant in dolomite and the SiO_2 content is 16.44%, which qualifies dolomite to alkaline aggregates (Andrzejuk et al., 2019). Vaganov et al. (2016) looked at the possibilities of creating sustainable concrete compositions from local dolomite raw materials. It was observed that by-products of dolomite quarry (fine fractions) could be successfully used as micro-fillers in self-compacted concrete and as effective micro-fillers in lightweight aggregate concrete. Agrawal et al. (2022) studied the use of stockpiled dolomite quarry waste for sustainable and cleaner production of concrete. The test findings revealed the concrete mix made with 10% dolomite quarry waste displayed mechanical strength comparable to the control concrete mix (Agrawal et al., 2022).

This study focused on the use of dolomite in asphalt concrete. Several researchers have investigated the effects of numerous aggregate types on the properties of asphaltic concrete. Šernas et al., (2016) evaluated the effect of high-quality dolomite as aggregates in the asphalt wearing layer. Designed asphalt mixes were tested using empirical and performance-based tests, which showed promising results for asphalt mixes with high-quality dolomite aggregates. They stated that resistance to permanent deformation could be achieved by optimizing the quantity of binder and granular composition of the aggregates. Haritonovs et al. (2012) found that mixes with steel slag and local limestone in coarse portions and dolomite sand waste in sand and filler portions had high resistance to plastic deformations and good resistance to fatigue failure.

The aggregate used in the production of asphalt concrete in Nigeria is mainly granite from igneous rock. However, dolomite is available in commercial quantities. Therefore, the possibility of using dolomite in asphalt concrete production in Nigeria must be examined. This will go a long way in reducing the cost of producing asphalt concrete by using it in areas where they are available in commercial quantities. Therefore, this study conducts a comparative analysis of the effects of dolomite and granite on the Marshall properties of asphalt concrete.

2 Materials and Methods

2.1 Materials

Coarse aggregates (dolomite and granite) of single sizes of 25 mm and 20 mm were used. The fine aggregate used was river sand. Crushed stone dust passing the 75-micron sieve was used as filler. The grading curves for the aggregates are shown in Fig. 1. Their properties are given in Table 1. The Table shows that the granite meets all the specifications while the dolomite does meet the specifications for Aggregate Abrasion and Aggregate impact values (FMPWH, 2016). This confirms the concern about the use

of dolomite for asphalt production. Bitumen of 60/70 penetration grade was used. It meets the specifications (FMPWH, 2016) as shown in Table 2.

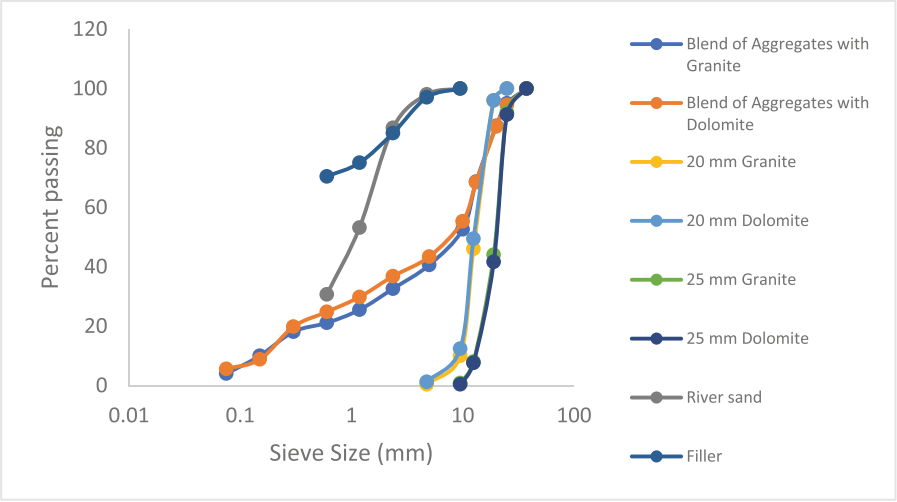


Fig. 1. Grading curves for the aggregates

Table 1. Comparison of aggregate properties

Parameter	Code	Granite	Dolomite	Specifications (FMPWH, 2016)
		Measured value	Measured value	
Abrasion Test	BS 812–113 (1990)	26%	65%	<40%
Aggregate Crushing Test	BS 812–110 (1990)	7.5%	22.3%	<30%
Aggregates Impact Test	BS 812–112 (1990)	6.73%	31.7%	<30%
Water Absorption		0.74%	0.30%	<3%

Table 2. Bitumen properties

Parameters	Value	Specification
Penetration @25 °C (mm)	61.3	60–70
Ductility @ 25 °C	121	100 Min
Solubility	107	99.5 Min
Viscosity (cP)	2753	2400 Min

(*continued*)

Table 2. (*continued*)

Parameters	Value	Specification
Flash Point (°C)	287	≥ 250
Softening Point (°C)	55	55–65
Specific gravity @ 25 °C	1.02	1.01–1.06

2.2 Mix Design and Testing

The mix consists of 40% 25 mm, 20% 20 mm, 30% river sand and 10% filler. The aggregates were measured and mixed. The Marshall samples were prepared at 160 °C and 140 °C mixing and compacting temperatures, respectively with bitumen content ranging from 4.5 to 6.5 at 0.5 interval. The Marshall test was conducted in accordance with British Standard (BS EN 12697–33, 2012). Thereafter, the volumetric properties: volume of voids (VTM); void in mineral aggregates (VMA) and the void filled with bitumen (VFB) were calculated and analysed.

3 Results and Discussion

The Marshall stability result is shown in Fig. 2. The maximum Marshall stability values for granite and dolomite are 13.39 kN and 13.24 kN. Although, the stability obtained for dolomite is slightly lower than granite, it satisfies the specifications of the Federal Government of Nigeria (FGN) for roads and bridges (FMPWH, 2016). This could be attributed to the higher aggregate crushing value (ACV) and aggregate impact value (AIV). Figure 3 shows the plot of flow against bitumen contents. The flow of asphaltic concrete is its deformation at maximum load. From the Figure, it could be seen that the maximum flow value for the aggregate type occurred at 6.5% bitumen content with a value of 3.24 mm for granite and 3.2 mm for dolomite. The flow values at maximum stability are 2.64 mm and 2.14 mm. These values fall within the range of 2-6 mm as specified by FGN (1997) general specifications for the binder course. The flow values for the samples having dolomite was generally higher than for samples produced with granite. Also, this could be attributed to higher ACV and ACV.

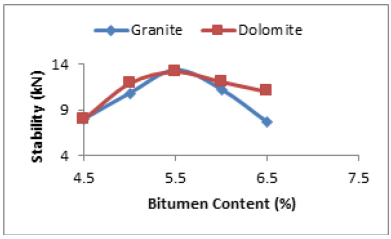


Fig. 2. Stability versus bitumen content

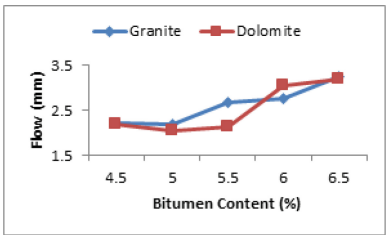


Fig. 3. Flow versus bitumen content

A properly designed and compacted mix will contain enough air voids to prevent rutting due to plastic flow and ingress of water. The bulk density curves with respect to bitumen content for all asphalt samples produced with the granite and dolomite aggregates are presented in Fig. 4. The Figure shows that for the asphalt concrete produced from dolomite, the bulk density increases until 5% bitumen content and afterwards decreases slightly. In contrast, the bulk density increases gradually to 6% for granite in the binder content and decreases afterwards. However, the bulk densities of the samples with dolomite were generally higher those of granite for all the bitumen contents. The percentages of air voids obtained for the aggregates are shown in Fig. 5. It can be seen from the Figure that there is a decrease in the percentage of air voids in the mix as the bitumen content increases. The samples with dolomite were found to have higher air voids at 4.5, 5, 5.5 and 6.5% while the value was lower at 6.0%. The air void content of the asphalt concrete has effect on its resistance to fatigue with higher void content indication lower resistance to fatigue. However, asphalt concrete containing dolomite was found to have higher stability at 5, 6 and 6.5% bitumen contents. Generally, the air voids values for asphalt concrete produced from both aggregates (granite and limestone) are within the specifications.

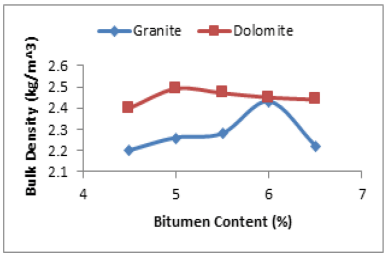


Fig. 4. Bulk density versus bitumen content

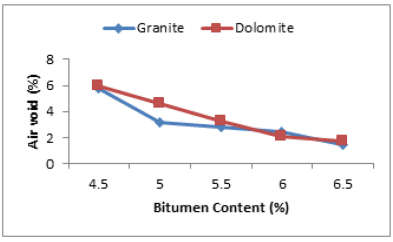


Fig. 5. Air voids versus bitumen content

It is expected that the Marshall mix should possess maximum void spaces for future compaction under traffic to avoid bleeding of the binder content in hot ambient. The void filled with bitumen (VFB) obtained for the aggregate types is shown in Fig. 6. The VFB of the aggregate types gradually increases as binder content increases; however, the value obtained for dolomite is higher than that of granite. The increment observed in the VFB could be attributed to the fact that more effective bitumen content was present in the mix to fill the available void spaces. Higher values obtained for the dolomite samples indicate that it has more affinity for bitumen, which could be the reason why the stability values were generally higher. The VFB values were greater that the specified values for the bitumen contents of 5.5 to 6.5% for both. Figure 7 shows the voids in the dolomite aggregate are general more than in the granite.

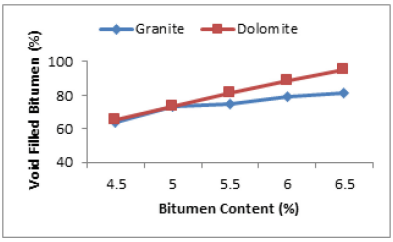


Fig. 6. Voids filled with bitumen versus bitumen content

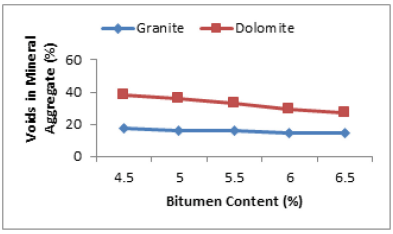


Fig. 7. Voids in mineral aggregate versus bitumen content

4 Conclusion

Aggregates play a significant role on the performance of pavements. Therefore, a proper selection of aggregates is required to obtain an acceptable pavement performance. This study conducts a comparative analysis of the effects dolomite and granite on the Marshall properties of hot mix asphalt (HMA). The findings indicate that the two aggregate types (granite and dolomite) satisfy the specifications in terms of stability, flow and the air voids. The mix from dolomite aggregates has greater bulk density than granite aggregates, which is due to the fact that it has greater affinity for bitumen. Lastly, the dolomite aggregate can be used in the asphalt concrete production in Nigeria, thus, avoiding the depletion of granite aggregates being used currently. However, it is essential that the skid resistance be evaluated because of the high aggregate abrasion value.

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Evaluation of Marshall Properties of Asphalt Concrete and Stone Mastic Asphalt for Nigerian Roads

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Abstract. Asphalt concrete is mainly used for the surfacing layer of road pavements in Nigeria. It has been reported to fail prematurely, and the early failure has been attributed to the fact that the road is the main transportation mode in Nigeria, thus exerting pressure on the transportation facilities. It is important to evaluate the properties of stone mastic asphalt as an alternative pavement surfacing material for flexible pavement in Nigeria to address the problem. Therefore, this study involves a comparative analysis of the conventional asphalt concrete and stone mastic asphalt using the Marshall mix design, the main method used to design bituminous mixtures in Nigeria. The asphalt concrete was prepared following the specifications in the General Specifications, Road and Bridges prepared by the Federal Ministry of Works and Housing, Nigeria, while the stone mastic asphalt was prepared following the British standard. The aggregates used were examined, and the aggregate abrasion value (AAV), aggregate impact value (AIV) and aggregate crushing value (ACV) were found to be within the values specified. The 60/70 penetration grade bitumen commonly used in Nigeria was used for both mixtures. Marshall test was carried out on the asphalt concrete and stone mastic asphalt, and the stability, flow, density, air voids, voids in mineral aggregates and voids filled with bitumen were determined. The results indicated that the values obtained were within the acceptable limits in the specifications. Also, it was found that the stone mastic asphalt has slightly higher stability, indicating its better fatigue resistance compared to conventional asphalt concrete. Again, the stone mastic asphalt has a lower flow value, implying it possesses better resistance to permanent deformation than asphalt concrete. However, further investigation, such as the skid resistance test, indirect tensile fatigue test (ITFT), indirect tensile stiffness modulus (ITSM), and repeated load axial test (RLAT) will be carried out to establish the performance of the stone mastic asphalt.

Keywords: Asphalt concrete · Stone mastic asphalt · Marshall

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1 Introduction

Any region's economy depends on shipping and receiving goods and commodities at ports and harbours (Oguntayo et al., 2020). These goods are, after that, conveyed using the road mode of transportation, whose material composition for its surfacing layer is mainly asphalt concrete (AC). Heavy trucks are currently the primary means of moving products in Nigeria, and their impact on the condition of the pavement can be significant (Oguntayo et al., 2020; Ogundipe, 2016). This increasing number of trucks imposes great stress and strain on the pavements through traffic loadings and axle loads (Syamsunur et al., 2013). The AC pavement can bear the imposed loads to some extent; exceeding the limit leads to pavement distress (Mashaan et al., 2013; Oner, 2023). However, Syamsunur et al. (2013) believe developing new pavement material types and construction methods can lessen these distresses. Various techniques can be applied to reduce pavement discomfort and increase its useful life. However, a typical pavement suitable for enhancing the performance of the pavement against early failure is stone-mastic asphalt (Baha, 2015; Syamsunur et al., 2013; Oner, 2023).

The mid-1960s saw the development of stone mastic asphalt (SMA) in Germany, and its use has grown significantly due to improved pavement serviceability. This particular asphalt mixture contains a greater proportion of coarse than fine particles. Kar et al. (2019) show that SMA comprises 8–12 per cent filler, 6–7 per cent asphalt binder, and 70–80 per cent coarse aggregate. These SMA skeleton combinations reduce traffic noise, help prevent permanent deformation, and create an incredibly strong pavement. (Chegenizadeh et al., 2021; Qiu and Lum, 2006). Additionally, SMA benefits from exceptionally robust surfacing and produces less tyre noise (Sengul et al., 2013). SMA is a highly rut-resistant bituminous course for heavy traffic roads, both for wearing and intermediate courses. However, using SMA mixes is not widespread despite the overwhelming evidence supporting their superiority. In Nigeria, for example, road surfacing for pavement still uses AC mixtures. Therefore, this study evaluates the Marshall properties of stone mastic asphalt using the Marshall mix design for Nigerian roads. Furthermore, a comparative analysis of conventional and stone mastic asphalt concrete was conducted.

2 Materials and Methods

2.1 Materials

The following materials were used in this study: crushed stone dust (CSD), 60/70 penetration-grade asphalt, coarse aggregates, and fine aggregates. These materials were obtained from local quarry in Ado-Ekiti, Nigeria. The material properties (aggregates and bitumen) and the aggregate gradation for the asphalt mixtures are shown in Table 1 and Fig. 1, respectively. The aggregate gradation also fits well within the stipulated envelope by the Federal Ministry of Works and Housing, Nigeria (FMPWH, 2016), and the material qualities are within the range suitable for bituminous mixtures.

Table 1. Material properties

Property	Results (%)	Specification (FGN, 2013)	Status
Aggregate			
Aggregate Impact Value	14.3	30% Maximum	Pass
Aggregate Crushing Value	13.02	30% Maximum	Pass
Aggregate Abrasion Value	18.00	40% Maximum	Pass
Flakiness index	18.83	30% Maximum	Pass
Elongation Index	21.5	30% Maximum	Pass
Water Absorption	0.1	4% Maximum	Pass
Bitumen			
Penetration at 25 °C (mm)	67.7	60–70	Pass
Softening Point (°C)	48.5	47 Minimum	Pass
Specific gravity	1.02	1.01–1.06	Pass

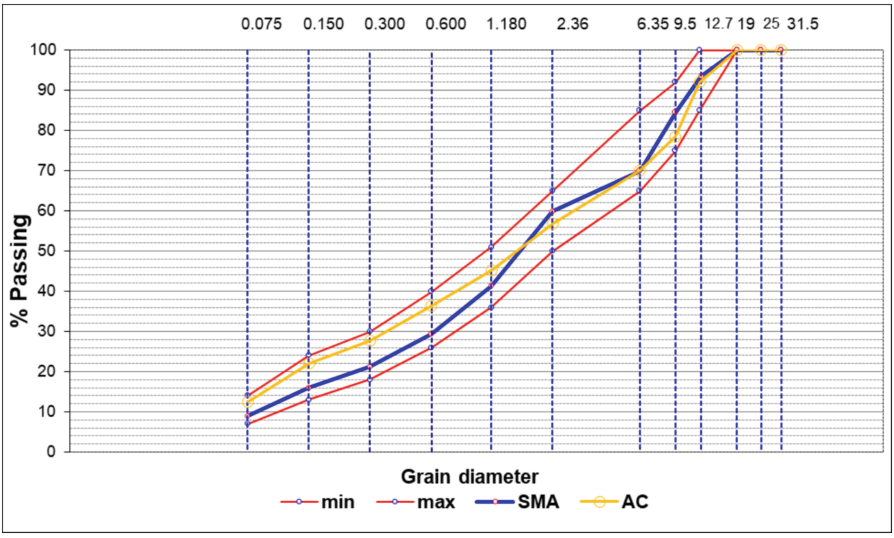


Fig. 1. Combined aggregate gradation for the asphalt mixtures

2.2 Sample Preparation and Testing

Using the mix proportions provided in Table 2, the bituminous mixture was produced using AC and SMA graded aggregates and 60/70 penetration-grade bitumen. The crushed granites were dried and sieved. The dry blending approach was used in this study. The AC was prepared in accordance with the General Specifications (FMPWH, 2016) and the SMA was prepared in accordance with the British Standard (BS EN 13108–5, 2006). Each sample received 75 blows at the top and bottom of the specimen, resulting in 75

compactions. According to Fig. 2, the compacted mixtures was subjected to Marshall testing (BS EN 12697–34, 2012) to determine their stability, flow, bulk density, voids in minerals aggregate (VMA), volume of bitumen (Vb), and air voids.

Table 2. Mix proportion for the bituminous mixtures

Material	AC	SMA
12.7 mm aggregate (%)	45	60
10 mm aggregate (%)	25	21
Fine aggregate (%)	25	10
Filler (%)	5	9

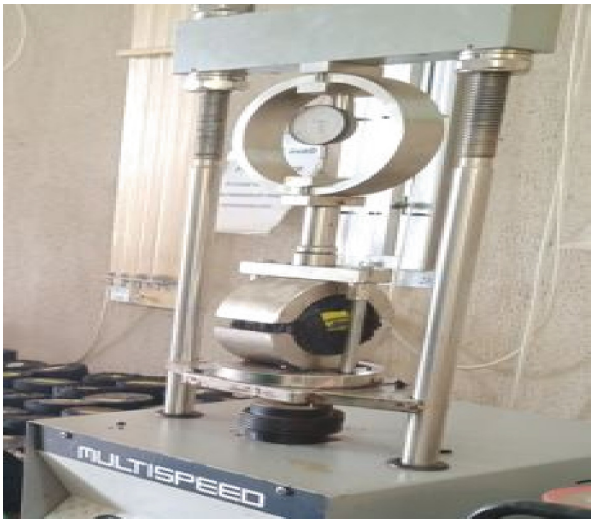


Fig. 2. Specimen in Marshall equipment

3 Results and Discussion

The Marshall properties of AC and SMA mixtures are shown in Fig. 3. In Fig. 3a, as the bitumen content increases, the stability value for SMA and AC mixtures increases to 6.10 kN and 5.91 kN, respectively, decreasing after that. Also, the stability of the SMA mixtures was slightly greater than the AC mixtures. The greater stability values obtained for the SMA mixtures indicate the better performance of the SMA mixtures. The increase in stability can be attributed to the proportion of coarse aggregates in its skeleton. The stability values for both combinations can be observed to meet the Federal Government of Nigeria's requirement of not less than 3.5 kN.

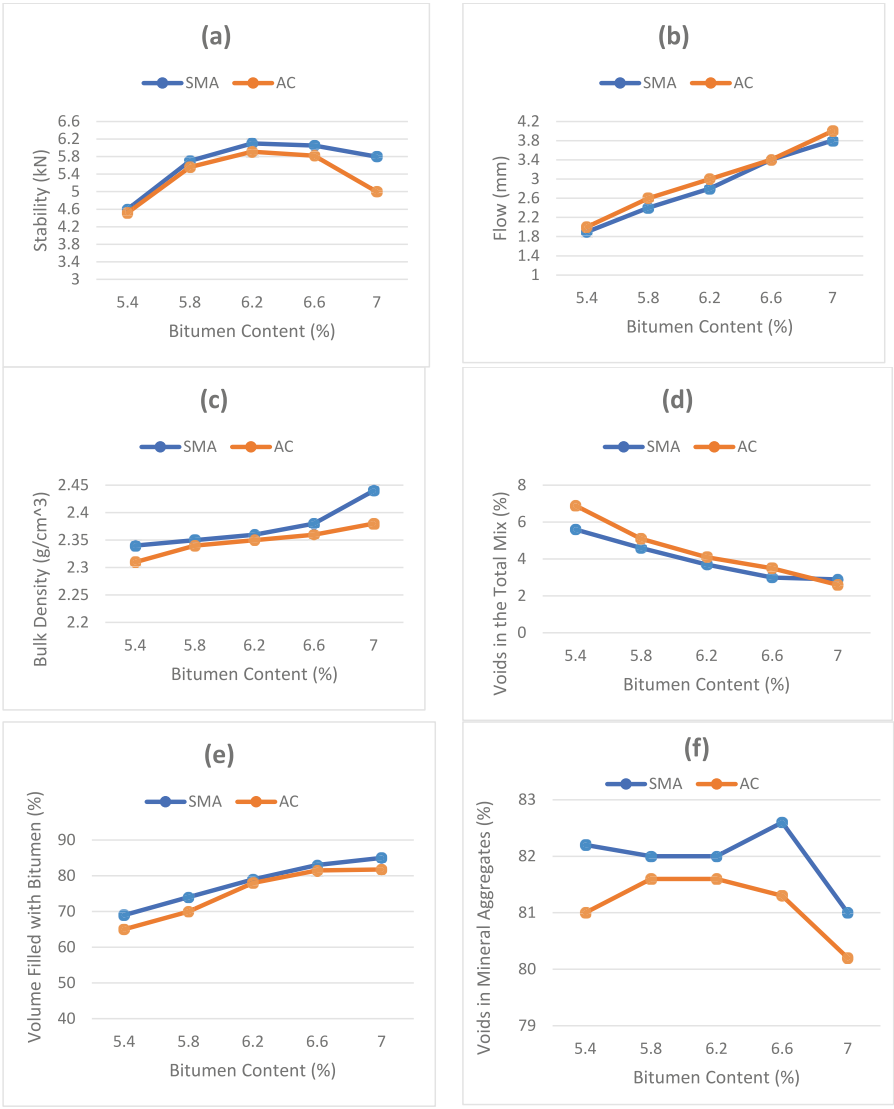


Fig. 3. Marshall properties of AC and SMA mixtures

Flow is a factor that affects how the pavement responds to traffic loads as well as how flexible and plastic it is. Figure 3b compares the SMA and AC mixtures' flow values to the bitumen amount. The data show that when the bitumen content rises, the flow also rises. The flow value of the SMA mixtures ranges from 1.9–3.8 mm, while that of AC mixtures was 2.0–4.0 mm. The flow values of the SMA mixtures were found to be slightly lower than the flow values of the AC mixtures. However, in both SMA and AC mixtures, all the specimens performed within the acceptable flow value specified by the Federal Government of Nigeria for roads.

Figure 3c shows that whilst the bulk density increases with bitumen content for the SMA and AC mixtures, the bulk density of SMA mixtures is slightly greater than that of the AC mixtures.

Figure 3d shows voids in the total mix (VTM) for the SMA and AC mixtures. For both mixtures, the VTM decreases with the increase in the bitumen content. Also, less VTM was observed in the SMA mixtures than in the AC mixtures. The lower air void content leads to better fatigue resistance of the SMA mixtures (Hainin et al., 2012).

Figure 3e shows the void filled with bitumen (VFB) for the SMA and AC mixtures. It can be seen that the VFB increases with increasing bitumen content for both mixtures. Also, more voids were filled with bitumen for the asphalt mixtures with SMA than for the AC mixtures.

The voids in the mineral aggregates (VMA) for the SMA and AC mixtures are shown in Fig. 3f. The VMA of the SMA mixtures was observed to be greater than the AC mixtures. The orientation of the interspace made available for the fine aggregates by the coarse aggregates, according to Qiu and Lum (2006), is one reason for the increase in the VMA.

4 Conclusion

Stone mastic asphalt (SMA) is a highly rut-resistant bituminous course for heavy-traffic roads, both for wearing and intermediate courses. However, using SMA mixes is not widespread despite the overwhelming evidence supporting their superiority. This study compared the Marshall properties of SMA and AC mixtures for Nigerian roads. It was found that the stone mastic asphalt has slightly higher stability, indicating its better fatigue resistance compared to conventional asphalt concrete. Again, the stone mastic asphalt has a lower flow value, implying it possesses better resistance to permanent deformation than asphalt concrete. It was also observed that the VMA of the SMA mixtures was greater than the AC mixtures. Hence, SMA can be utilized as a pavement course in Nigeria to mitigate early pavement failure and increase its useful life. Nonetheless, the study recommends further tests, such as the skid resistance test, indirect tensile fatigue test (ITFT), indirect tensile stiffness modulus (ITSM), and repeated load axial test (RLAT) be carried out to establish the performance of the stone mastic asphalt.

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A New Hybrid Approach for Identifying Obsolescence Features: Applied to Railway Signaling Infrastructure

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Abstract. Electrical component obsolescence poses a major issue especially within systems with large life cycles. Thus, finding the optimal management solution for each obsolescence case is as crucial as knowing what to consider when faced with an obsolescence case. In this paper, a novel hybrid approach for identifying features affecting electrical component obsolescence management is introduced, which combines features engineering techniques and expert knowledge. The method then uses machine learning to predict obsolescence resolution techniques in order to find the optimal resolution. The motivation behind this research is driven by the imperative need for SNCF RESEAU to optimally address and mitigate the challenges posed by electrical component obsolescence in railway infrastructure.

Keywords: component obsolescence · obsolescence management · feature selection · feature extraction · machine learning · hybrid approach

1 Introduction

Obsolescence, pertains to the process of becoming non-available, non-adequate, and/or non-suitable [Zolghadri et al., 2021]. Obsolescence poses a problem as it renders previously functional components obsolete, leading to waste, inefficiency, and the need for constant adaptation. One of the major causes of obsolescence is the difference between the component life cycle (≈ 18 months or less) and the systems within which it is contained (30 years or more) [Renaud et al., 2018], e.g., planes, trains, railway infrastructures, etc.

The difference between the component and system life-cycles triggers component obsolescence that requires a response, sometimes incurring costs rarely acceptable. For instance, the decades-old railway infrastructure of SNCF RESEAU constantly grapples with issues related to the obsolescence of electrical components, resulting in significant and unplanned annual expenditures.

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For that reason, multiple approaches have been proposed for obsolescence management strategy selection focused on minimizing the cost [Porter, 1998, Zheng et al., 2015, Singh and Sandborn, 2006]. But various features beyond cost, including the number of suppliers, time constraints, solution reliability, and multiple stakeholder opinions from design, operations, manufacturing, sales, and service, can significantly influence the determination of the optimal decision for obsolescence management [Pingle, 2015].

The contribution of this work is twofold: proposing an approach for deriving the set of features affecting the decision-making process for obsolescence management, and proposing an analysis method for determining the contribution of each feature within the decision-making process through the use of machine learning. The remainder of this paper is separated as follows: starting with the dataset formation and methodology description in Sect. 2, followed by the presentation of the results in Sect. 3, and finally ending with a brief conclusion and discussion in Sect. 4.

2 Contribution

The section starts off by tackling the dataset formation methodology from the process described in Fig. 1 (shown in blue), afterwards the models used are discussed in Sect. 2.2 (shown in red), and finally the analysis method is tackled in Sect. 2.3 (shown in green).

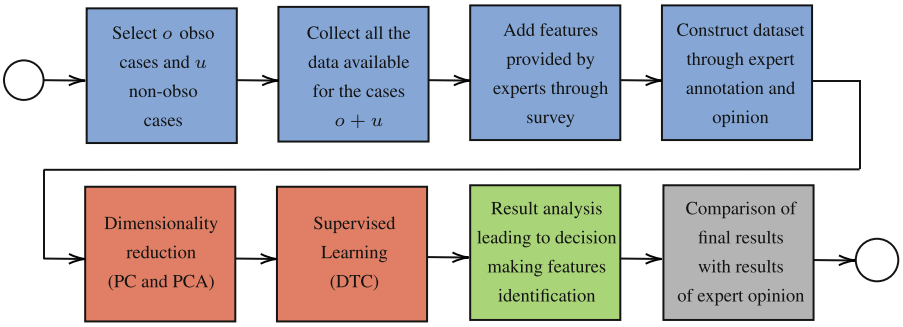


Fig. 1. Methodological Approach Process

2.1 Dataset Formation Methodology

Data Acquisition. A survey has been conducted regarding the features affecting obsolescence management solution selection of electrical products, e.g., blinkers, power supplies, etc. The survey was sent out to the obsolescence management team of SNCF RESEAU, who monitor, detect, and decide on the appropriate resolution for each obsolescence case. These personnel come from various backgrounds

and domains of work, including the supply chain, technical management, technicians, engineering, and purchasing departments. For each obsolescence case, a set of features is recorded, but the knowledge is held by the experts of the team.

The dataset was constructed from numerous internal databases within the company following the formation of the set of features obtained from the survey conducted, the literature, and an internal company data visualization interface. The quality of the data varies depending on the database source. The data regarding the features referring to the technical properties of the various units and components are not always digitized, and thus the knowledge of the personnel as well as the archives of the company was accessed to be filled.

Dataset Formalization. The dataset is formalized in what follows. Given the dataset of obsolescence and non-obsolescence cases $\mathcal{D}$ such that $\mathcal{D} = \{(x_i, y_i) \in \mathcal{X} \times \mathcal{Y} | i = 1, ..., N_{o+u}\}$, where each case x_i is a D-dimensional vector comprised of D features $x_i \in \mathbb{R}^D$, and each class label, i.e., obsolescence management solution (e.g. replacement, repairing, etc. [Rust et al., 2022]), is represented by an integer $y_i \in \mathcal{Y} \equiv \{1, ..., N\}$ resulting in N distinct classes. Let $\mathcal{X} \equiv \mathbb{R}^D$ for generality. The set $\mathcal{X}$ is divided into two subsets: the obsolete set containing obsolete units, and the non-obsolete set containing non-obsolete units. The obsolete set is given by $\mathcal{O} = \{(x_i^o, y_i^o) \in \mathcal{X} \times \mathcal{Y} | i = 1, ..., N_o\}$, and the non-obsolete set is given by $\mathcal{U} = \{(x_i^u, y_i^u) \in \mathcal{X} \times \mathcal{Y} | i = 1, ..., N_u\}$. The obsolete and non-obsolete sets are disjoint $\mathcal{O} \cap \mathcal{U} = \emptyset$. Each of the sets above are represented by their corresponding matrices where $\mathcal{O}$, $\mathcal{U}$, and $\mathcal{X}$ are represented by the matrices $O \in \mathbb{R}^{o,D}$, $U \in \mathbb{R}^{u,D}$, and $X \in \mathbb{R}^{o+u,D}$ respectively such that $X = \begin{pmatrix} O \\ U \end{pmatrix}$

The dataset $\mathcal{D}$ is composed of $o = 316$ obsolete instances, and $u = 10$ non-obsolete instances. The instances are labeled with one of the following classes of obsolescence remediation: existing stock (7 instances), Last-time Buy Order (30 instances), minor redesign (28 instances), major redesign (124 instances), and substitution (126 instances). The labeling process was conducted through expert annotation.

2.2 Model Methodology

As a preliminary process, and in order to combat the restrictive nature of binary values, all the binary fields are normalized on a scale from $[1, 5]$ following the normal distribution as follows $1 + 4\frac{(x-\bar{x})}{\sigma}$ where x is the row feature vector and σ is the standard deviation.

Step 1: PC. Highly correlated features pertain to variables that exhibit a strong linear relationship with one another, i.e., they convey nearly identical information. Consequently, this phenomenon can give rise to a predicament referred to as multicollinearity [Montgomery et al., 2021], wherein the independent impact of each variable on the target variable becomes arduous to ascertain. Thus, to address this problem, the Pearson Correlation (PC) coefficient is calculated for

X^T [Mei et al., 2022]. Any vector with a correlation above an arbitrarily selected α is removed following the backward elimination method [Kotu and Deshpande, 2014] from the matrix X^T, i.e., to reduce redundancy, thus reducing its dimensionality $X \in \mathbb{R}^{o+u,h}$ such that $h \leq D$.

Step 2: PCA. When confronted with a large number of features and a small dataset, the model may inadvertently fit the noise within the data rather than discerning the underlying patterns. Consequently, the ability of the model to generalize effectively diminishes [Goodfellow et al., 2016]. By reducing the number of features the complexity of the model diminishes as well, thereby reducing the likelihood of overfitting the training data which leads to better generalization and higher accuracy on novel data [Sammut andWebb, 2011]. Ergo, the Principal Component Analysis (PCA) algorithm is used which computes the orthonormal ℓ-dimensional subspace $X^* \in \mathbb{R}^{o+u,\ell}$ of X forming $\mathcal{X}^*$, and by consequence $\mathcal{D}^*$ such that $\ell < h$.

Step 3: DTC. The next and final step is to harness the knowledge that the experts possess through learning a function f that takes in the expert provided instances and maps them to the expert classified class labels $f : \mathcal{X}^* \longrightarrow \mathcal{Y}$. The aim of this step is to mimic the reasoning behind the decisions made by the experts. For the reason of ease of interpretability, the Decision Tree Classifier (DTC) algorithm is used to learn the decision conditions of each class $y_i \in \mathcal{Y}$, i.e., obsolescence management solution.

2.3 Analysis Methodology

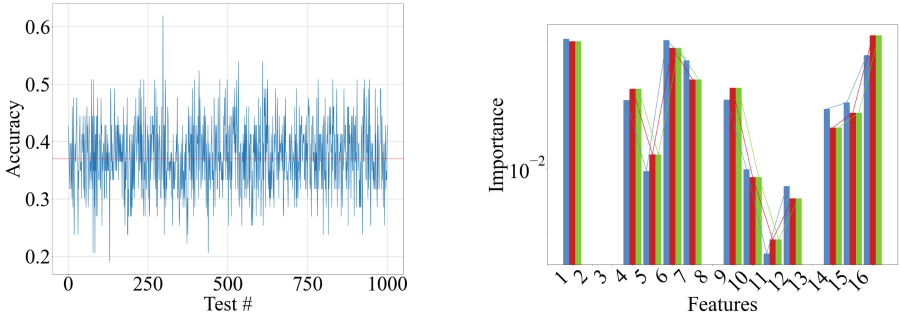
The first step of the analysis involves analyzing the mean decrease in Gini impurity within the learned DTC model f, which can be used to determine the importance of each feature: the higher the mean decrease in impurity, the more important the feature is considered [Sandri and Zuccolotto, 2010]. The second step is to determine the features that contribute the most to the formation of the orthonormal subspace X^*. This is done by taking the sum of the highest ℓ elements of the vectors of the column space of X^*, where each vector corresponds to a feature present in X [Goodfellow et al., 2016].

3 Experimentation and Discussion

The number of initial features $D = 16$ was reduced to $\ell = 7$ principal components. The correlation threshold, set at $\alpha = 0.15$, was determined by identifying the optimal value within the range $\alpha \in [-1, 1]$ that maximizes the average accuracy of the DCT model while minimizing the dimensionality of $\mathcal{D}$, resulting in $D = 12$. Similarly, the number of principal components $\ell = 7$ was determined using a similar optimization method and objective. The optimal parameters were

derived by selecting the values corresponding to the model with the highest accuracy among the 500 tests conducted.

Afterwards, an additional 1,000 tests were conducted on the proposed model using the obsolete set $\mathcal{O}$, which is shuffled before every test to reduce bias and evaluate its generalization. The maximum and minimum accuracy values of DCT are reported as 61.90% and 19.05%, respectively. The standard deviation, arithmetic mean, and geometric mean of the accuracy measurements are 5.95%, 37.48%, and 37.00%, respectively. These values suggest a balanced spread, indicating that the accuracy measurements are not skewed and are symmetric. This implies a degree of inconsistency in the model's behavior, as illustrated in Fig. 2a, but it is not considered erratic. The top-performing model attained a 40% accuracy on the non-obsolete set $\mathcal{U}$ suggesting a potential application for monitoring using the model.



(a) Model accuracy measurements.

(b) Feature contributions.

Fig. 2. Obtained results displaying feature contributions on a logarithmic scale, following the methodology outlined in Sect. 2.3. Blue bars indicate mean contributions, red bars show values from the best model, and green bars represent contributions from the top-performing model on non-obsolete instances.

The sorted list of highest average feature contributions aligns closely with the model achieving the highest accuracy on both $\mathcal{O}$ and $\mathcal{U}$. In both lists, the top three elements include "repair complexity," "several components are involved," and "supplied as new, no longer supply, no longer newly supply, reparable only." However, it contradicts the list derived from the combined options of experts "existing stock quantity," "existing substitution product," and "security block/product"), highlighting a lack of consensus on the subject. For detailed lists, refer to the GitHub repository: https://github.com/Inars/A-Hybrid-Approach-for-Identifying-Obsolescence-Features.

The results shown display a discrepancy within the decision making process of the SNCF RESEAU obsolescence management team. They emphasize the need of a unified decision making model that attempts to deduce consensus by

optimally finding a resolution to a given obsolescence case using the features that are most relevant.

4 Conclusion and Perspective

This paper presents a hybrid methodology designed to identify feature contributions that influence decision-making in obsolescence management resolutions. The proposed method highlights the divergence of expert opinions on the subject. During the dataset formation process, a noticeable discrepancy in the number of class instances was observed, necessitating a substantial increase in instances. Two key research areas emerge: data generation techniques to address data scarcity and k-shot learning models for resolving class imbalances.

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Further Development and Implementation of a Mechanistic-Empirical Design and Analysis System for Pavement Structures in Norway

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Abstract. Design of pavement structures has a great impact on life cycle cost (LCC) and environmental effect of pavements. At present pavement structures in Norway are designed with use of empirical based tables and requirements described in the Norwegian design guideline for pavement structures. The current design procedure does not allow prediction of performance and evaluation of the effect of changes in material, climate, and traffic, which makes it difficult to accurately calculate the LCC and environmental impact. Mechanistic-empirical (ME) systems can overcome these shortcomings since they allow prediction of performance based on realistic material, climate, and traffic data. Therefore, a research and development program was initiated by the Norwegian Public Roads Administration (NPRA) to further develop and implement a ME design and analysis system for Norwegian conditions.

The work involved evaluation of existing ME systems around the world to find a system that can be adapted to Norwegian conditions. Based on this evaluation a system called ERAPave PP (Elastic Response Analysis of Pavements –Performance Predictions) which was under development by The Swedish National Road and Transport Research Institute (VTI) in collaboration with the Swedish Transport Administration (STA) was selected. NPRA and STA established a cooperation program to further develop and implement the ERAPave PP in Norway and Sweden. The objectives of the project were to further develop ERAPave PP by adding models for climate and frost heave, as well as to establish databases for implementation of the system in each country.

This paper describes the process with selection, further development, calibration, and implementation of ERAPave PP for Norwegian conditions.

Keywords: ME-design, Analysis · Performance prediction · Calibration · Implementation

1 Introduction

Pavements represent a significant part of the road infrastructure asset, and the design of the pavement structure has a great impact on life cycle costs (LCC) and environmental impact for pavement structures. Traditionally, pavements have been designed using

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empirical methods. Such methods do not allow prediction of performance and evaluation of the effects of changes in material, climate, and traffic, which makes it difficult to accurately calculate the service life, and hence the LCC and environmental impact in terms of life cycle assessment (LCA).

Since the advent of Burmister's elastic multilayer theory, efforts have been made by many researchers in various countries to develop rational methods for design of pavement structures and overcome the limitations of the empirical methods. These methods are based on the calculation of stresses and strains in the pavement structure under wheel loading using mechanistic methods and prediction of performance using empirical equations, for which the calculated stresses and strains will be input parameters. Such methods are called mechanistic-empirical (ME) pavement design methods and are being utilized in many countries.

Most of the existing ME pavement design methods use elastic layer theory to calculate stresses and strains under wheel loading. However, these existing systems vary in their approach to performance prediction and in how they use the predicted performance to carry out the design. Based on their approach to performance prediction, the existing ME design systems can be grouped into two: those that directly predict performance in the form of distress development (such as rut depth and cracking) over the design period and those that predict the allowable number of load repetitions based on predefined failure criteria.

This paper describes the selection, further development, calibration and implementation of a ME system called ERAPave PP (Elastic Response Analysis of Pavements –Performance Predictions) to Norwegian conditions.

2 The Need for ME Design and Analysis Systems

At present, pavement structures in Norway are designed with use of a purely empirical method using index values and load distribution coefficients. The design requirements are described in the design guideline for pavement structures [1]. This method was developed in the 1960ies and has been adjusted and improved several times since based on experience and new knowledge. The goal of the design method is to obtain a technically and economically optimal pavement structure both for new construction and maintenance. The current design procedure is easy to use and conservative to take care of uncertainties involved in planning and construction of the road. However, the method has several shortcomings: it does not allow prediction of performance and evaluation of the effect of changes in material, climate, and traffic, difficult to adapt to local conditions, manual design (not digitalized), and requires experience in pavement engineering. Since it does not allow performance prediction, i.e. calculation of service life, it is difficult to accurately calculate LCC and environmental impact (LCA) for pavement structures. ME systems can overcome these shortcomings since they allow prediction of performance based on realistic material, climate, and traffic data. This will provide larger flexibility and the possibility to optimize the pavement design based on LCCA and LCA, and digital documentation of the design and future need for maintenance.

3 Selection of System

Several countries have or are in the process of developing and implementing ME systems. The existing ME systems are developed and calibrated to certain conditions (materials, building methods, climate, and traffic) for a specific country or area. These systems must be adjusted and calibrated if used elsewhere and can therefore not directly be implemented in Norway. An evaluation of different systems was conducted to find the best system that can easily be adapted to Norwegian conditions as described in [2]. The selection criteria were focused on the following questions:

1. Does the system predict pavement performance?
2. Are the pavement performance models relevant to Norwegian conditions?
3. Does the system have flexibility for further development?
4. Does the system have a frost model to calculate frost penetration and frost heave, or is it possible to include this?
5. Does the system allow the use of axel load spectrum as traffic input?
6. Does the system have a climate model?
7. Can the system be calibrated and adjusted to other conditions?
8. How can the system be acquired/procured?

According to these criteria, the Swedish system called ERAPave PP was chosen since it was the best fit for our needs: it predicts pavement performance, the performance models are relevant to the most important Norwegian deterioration mechanisms, and it can be used both as a design and analysis system for pavement structures. ERAPave PP is under development by the Swedish National Road and Transport Research Institute (VTI) which makes it easy to further develop and adapt to Norwegian conditions. The conditions in Sweden and Norway are comparable regarding traffic, climate, and building materials & methods, which provides the basis for cooperation between the road administrations in both countries in further development of ERAPave PP. Consequently, a cooperation program was established between the Swedish Transport Administration (STA) and the Norwegian Public Roads Administration (NPRA).

4 Further Development and Calibration of ERAPave PP to Norwegian Conditions

ERAPave PP is a ME pavement design and analysis system. It uses elastic multilayer theory to calculate response, i.e., stresses and strains. The calculated stresses and strains are used in the performance prediction models to predict the development of rutting in the various layers and fatigue cracking in the bound layers. ERAPave PP has also in-built performance model for prediction of rutting caused by studded tire wear. A new model for calculation of frost heave and a climate model for calculation of temperature have been developed in this project. A more detailed description of ERAPave PP is given in [3, 4]. In the following sections, work done in Norway to adapt and calibrate ERAPave PP to Norwegian conditions is described.

4.1 Establishment of Input Databases to Facilitate Implementation

The input data to ERAPave PP include material, traffic, and climate data. To facilitate the implementation and use of ERAPave PP in Norway, databases of the basic data required are established and connected to ERAPave PP.

Material data

Elastic moduli and Poisson's ratios for materials in the layers of the pavement structure are the most important material property data required by ERAPave PP. In addition, wear resistance property of the aggregate in the surfacing layer and frost properties of subgrade materials are required. An extensive laboratory testing of the commonly used asphalt mixtures in Norway was conducted at the Norwegian University of Science and Technology (NTNU) to establish dynamic modulus master curves for the various mixture types. The dynamic modulus master curves were established using the sigmoidal model described in Eq. 1.

$$\log\left(\left|E^*\right|\right) = \delta + \frac{\alpha}{1 + e^{\beta - \gamma \log(f)}} \tag{1}$$

Where |E*| is the dynamic modulus, f is the frequency, δ and δ + α are the dynamic moduli at the infinitesimal and infinite frequencies, respectively, and β and γ are the model parameters. The William, Lindel and Ferry (WLF) equation (Eq. 2) is used to shift measured values at a reference temperature of 15 °C.

$$\log(\alpha(T)) = \frac{-C_1\left(T - T_r\right)}{C_2 + \left(T - T_r\right)} \tag{2}$$

Where α(T) is the shift factor, T is the testing temperature, T_r is the reference temperature and C_1 and C_2 are the model parameters. A more detailed description of the work done to establish dynamic modulus master curves for Norwegian asphalt mixtures are given in [5].

The stiffness moduli for coarse crushed rock materials used in base, subbase and frost protection layers are estimated using back-calculation from deflection measurements conducted on some test sections. Laboratory testing is underway to determine the stiffness modulus of fine-grained subgrade materials (clay and silt). For unbound granular materials the stiffness modulus at the optimum moisture content is adjusted for the effect of varying moisture content using the model shown in Eq. 3.

$$\log \frac{M}{M_{opt}} = a + \frac{b - a}{1 + e^{\left(\ln \frac{-b}{a} + k_m (S - S_{opt})\right)}} \tag{3}$$

Where M is stiffness modulus at degree of saturation S, M_{opt} is the stiffness modulus at the optimum degree of saturation S_{opt}, and a, b, k_m are model parameters.

A material database, which contains the required material properties, is built in ERAPave PP and when a user chooses a material the program automatically picks the required properties from the database.

Climate data

It is well known that temperature and moisture content in the pavement structure have significant effect on performance of pavements. Temperature affects deformation in asphalt layers as well as low temperature cracking and frost heave during winter. Moisture content affects the stiffness of unbound layers specially during the spring thaw period. ERAPave PP uses a temperature model to calculate temperature at different depths within the pavement structure. The temperature model is based on the finite-volume method and is described in detail in [6]. The temperature model uses data for air temperature, wind speed, and solar radiation as input data and calculates temperature at required depths in the pavement structure. The calculated temperatures are used in conjunction with dynamic modulus master curve for asphalt materials to calculate stresses and strains, and the development of deformation rutting in the asphalt layers. To obtain the input data for the temperature model (air temperature, wind speed and solar radiation), ERAPave PP uses a map-based solution, which allows the user to choose the project location or specify the project coordinates. The program then picks the required data from the nearest weather station for a specified period of time. In ERAPave PP frost heave is calculated using the SSR-model (Seppo Saarelainen Routanousu) [7], using data for frost index and frost properties of materials for the project location.

Traffic data

ERAPave PP allows two ways of inputting data for traffic loading. The first approach is to use AADTT (average annual daily truck traffic) and convert it to number of equivalent single axle loads. The second approach is to use traffic load spectra, i.e., axle load distribution data from weigh-in-motion (WIM) or Bridge-WIM measurements. In Norway, there is currently lack of data on axle load distribution. However, there is an ongoing work to install and use WIM measurements as part of implementation of ERAPave PP. The aim is to establish a traffic loading database and connect it to ERAPave PP for use in design and analysis of pavements.

4.2 Calibration of ERAPave PP to Norwegian Conditions

As mentioned earlier in this paper ERAPave PP contains empirical models that are used for prediction of performance over the design period. The performance prediction models that are currently implemented in ERAPave PP include rutting models for bound and unbound layers, fatigue cracking model for bound layers, studded tire wear model for surfacing layer and a frost heave model. These empirical models need to be calibrated to Norwegian conditions using measured performance data such as field measured rutting data.

Several reference road sections were selected for the purpose of calibration of the performance models and an extensive work to gather data for these sections is ongoing. The data being collected include the original construction data (layer thicknesses, material types) and deflection measurements, which are being used to back-calculate stiffness modulus for the unbound layers. Core samples were taken from the asphalt layers and tested in the laboratory to determine the dynamic modulus master curve.

In Norway pavement condition data (rutting, roughness, etc.) is measured every year on major roads. The condition data is stored in a road data bank. The data collected for

the refence sections will be used in conjunction with the condition data from the road data bank to calibrate the performance models.

4.3 Implementation of ERAPave PP in Norway

There is ongoing work to implement the new system in the Norwegian pavement design guideline. The implementation process includes development of a Norwegian web-application and setting of design requirements in the guideline. In addition a training program is being developed to train potential users, both in the road administrations and in consulting companies.

5 Summary and Conclusions

A work being conducted to select, adapt and implement a ME pavement design and analysis system in Norway is described in this paper. The work includes establishment of input databases for materials, climate, and traffic, as well as calibration of ERAPave PP to local conditions. The adaption of ERAPave PP will give greater flexibility in the choice of both materials and layer thicknesses compared to today's practice. The transition to a ME design system will allow consideration of local conditions (locally available materials, climate) and provide a better understanding of the pavement deterioration mechanisms. We believe that the new system will contribute to improved planning and management of the road network because it enables prediction of the service life of pavement structures. It could also lead to lower environmental impact in terms of energy and GHG reduction in construction and maintenance of roads. Performance prediction will also enable documentation of consequences of different choices (standard materials, quality, layer thickness, change in traffic etc.).

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Climate Impact Analysis on Gravitational Mass Movements Along the German Railway and Road Network

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Abstract. Climate change is visible in the measurement series of various climate parameters, and its consequences are already clearly noticeable today. Since parts of the permanent consequences can no longer be averted, adaptation to changing climate conditions and extreme weather events is mandatory. This is especially crucial for land-based transport infrastructure (railways and roads), as transport structures usually have long life cycles up to several decades. The integrated climate impact analysis, a tool developed by the BMDV Network of Experts from the German Federal Ministry for Digital and Transport (BMDV), serves to assess the current and future climatic influences and the resulting climate impacts on the transport sector based on a three-step procedure (exposure, sensitivity and criticality analysis). In this contribution, we present the exemplary application of the climate impact analysis in a case study for the risk of gravitational mass movements along the federal railway and trunk road network based on a rockfall event near Kestert in the Upper Middle Rhine Valley. The case study shows that the same process can have different impacts depending on the mode of transport.

Keywords: Climate resilience · Climate impact analysis · Hazard indication map · Geohazard · Railway infrastructure · Road infrastructure

1 Introduction

Current climate change is one of the greatest challenges of our time and is already having a significant impact in several fields of action, e.g. transport infrastructure, human health, agriculture. In addition to a change in mean values, climate change is also characterized by a change in the probability of occurrence of extreme events. In Germany alone, the damage caused by extreme weather events since 2000 amounts to a total of 144.7 billion euros [1]. Taking regional climate models into account, Germany is likely to experience an increase in extreme climatic events in the future, especially more intense heat waves and droughts, heavy rainfall events and violent storms [2]. Since long-term consequences can in part no longer be averted, adaptation to changing climate conditions and extreme

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weather events is the second important building block in dealing with climate change, alongside the reduction of anthropogenic greenhouse gas emissions. Hence, adaptation is an important goal of international climate policy [3]. In Germany, a political framework for action has been created with the German Strategy for Adaptation (DAS) to Climate Change, which is underpinned with specific measures through the Adaptation Action Plan (APA) [4]. Most recently, the German government adopts a first nationwide climate adaptation law for seven thematic clusters, including (transport) infrastructure [5].

Adapting railway and road infrastructure to climate change is crucial for maintaining operations under future climate conditions, but is a major challenge. As land-based transport infrastructure is expected to be in service for long periods of time, it is necessary to integrate climate change adaptation into long-term planning, design and life cycle management of rail and road infrastructure. Therefore, the mechanisms by which climate change becomes a threat to railways and roads must not only be understood but also concretely located in a short period of time. Only in this way the scope of the necessary measures can be reliably estimated.

One main goal of the BMDV Network of Experts, founded by the German Federal Ministry for Digital and Transport (BMDV) in 2016, is to address this issue [6]. This network is a cross-modal format of departmental research and consists of seven departmental research institutes and specialist authorities within the portfolio of the BMDV. The objective of the network is to address pressing and future-oriented questions in the field of transportation and to enable a resilient and environmentally sound organization of the transport modes. Concerning the topic of climate change impacts and climate change adaptation, an important objective is the development and application of an integrated climate impact analysis for the rail, road and waterway transport [7].

In the following chapters, we present (1) the concept of the climate impact analysis developed by the BMDV Network of Experts, (2) its application in a case study for the risk of gravitational mass movements along the federal railway and trunk road network, and (3) give an outlook on forthcoming research activities.

2 Climate Impact Analysis

Climate impact refers to the potential or realized consequences of climate risks on natural and man-made systems [8]. The integrated climate impact analysis from the BMDV Network of Experts serves to assess the current and future climatic influences and the resulting climate impacts on the transport sector [7]. It is intended (1) to identify the transport elements that are more affected by and vulnerable to climate change, (2) to prioritize adaptation needs and (3) to serve as a communication tool. The climate impact analysis is a three-step procedure based on an exposure, sensitivity and criticality analysis. The exposure analysis aims at detecting the spatial and/or temporal distribution of transport infrastructure that is potentially at risk due to a specific climate impact. The results of this analysis are hazard information maps. At the hazard information map level, an overview of a possible hazard due to a hazard process is provided for a larger area on the basis of area-wide information on topography, land use and geology. The maps can be created for the current situation and, under consideration of climate change scenarios, also for the future hazard potential. The sensitivity analysis investigates

the vulnerability of transport infrastructure by climate impacts, depending on object- and route-specific infrastructure characteristics. For instance, in the case of tree fall events the presence or absence of overhead lines on railway lines is a valuable indicator because if a tree damages an overhead line the restoration is more complex and time- and costconsuming. The criticality analysis evaluates the traffical or, in the case of waterways, also ecological importance of route sections. Possible criticality indicators are, for example, the amount of goods, the value of goods or the availability of alternative routes. A schematic representation of the integrated climate impact analysis is given in Fig. 1 with the networks of transport on the left, the hazard information maps in the middle and on the right hand side the potentially affected route sections.

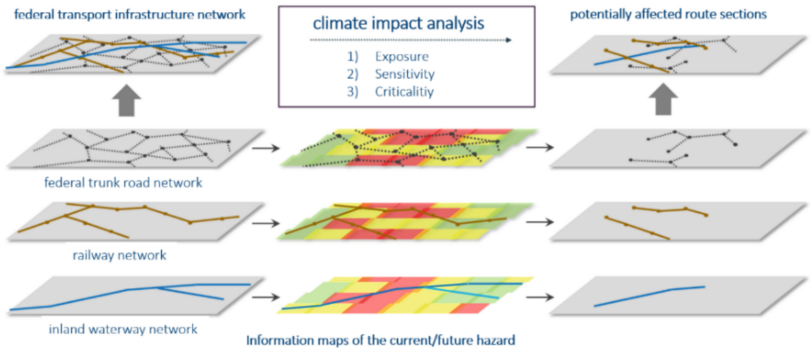


Fig. 1. Schematic representation of the integrated climate impact analysis for three modes of transport [7]

Within the framework of the BMDV Network of Experts, the climate impact analysis is carried out for 12 climate impacts (among others river floods, tree falls, gravitational mass movements) and for the three modes of transport (rail, road and waterway). If two or all three modes of transport are affected by a climate impact, a cross-modal consideration is sought. For rail and road, for example, the climate impact of gravitational mass movements plays an important role, because, on the one hand, they often result in relatively large damages, which can lead to long outages and repair costs. On the other hand, the risk of gravitational mass movements is expected to increase under the aspect of climate change due to changed precipitation regimes with simultaneously increasing heat and drought.

3 Application of the Climate Impact Analysis

3.1 Gravitational Mass Movements and Their Impact on Land-Based Transport

Gravitational mass movements are defined as downslope, fracture-free and fracture-like displacements of rock and/or loose rock under the effect of gravity. These diverse processes can be classified according to various criteria such as material type, movement mechanism, movement speed or water content. They are triggered by a complex interplay of various natural (e.g. climate, geology, vegetation) and anthropogenic factors [9].

Although only 10% of the area of Germany are classified as endangered by gravitational mass movements [9], the largest direct and indirect damages can occur along traffic infrastructure. In terms of transport routes, gravitational mass movements most often result in the blocking or destruction of transport infrastructure. They can cause damage to the substructure and superstructure and destabilize dams and embankments. Rapid, sudden gravitational mass movements can also endanger rail and road users.

3.2 Climate Impact Analysis for Gravitational Mass Movements

To conduct the climate impact analysis for the climate impact gravitational mass movements, the exposure analysis has to answer the question, which sections of the rail and road network are at risk. In the scope of two research projects [10, 11] hazard information maps for slope and embankment landslides for rail and road traffic were developed based on an engineering geological model. Based on the input parameters slope gradient, rock fracture and vegetation cover, each 20 m x 20 m pixel in the rail and road vicinity was assigned a hazard level ranging from 1 (very low hazard) to 15 (very high hazard). This map can be used to identify areas in the vicinity of the transport network having an increased risk for slope and embankment landslides. As sensitivity element, the presence or absence of slope stabilization structures was chosen. This information was derived from data sets provided by DB Netz AG for the rail and BASt for the road network. The criticality of each route segment of the rail and road network was determined in a project [12] where a set of 15 (rail) respectively 16 (road) indicators was combined to a single criticality indicator.

3.3 Case Study: Rockfall Event Near Kestert in March 2021

A recent example of a particularly large gravitational mass movement event along the traffic network in Germany occurred on 15th March 2021 in the Upper Middle Rhine Valley near the village of Kestert (close to the famous Lorelei). A rockfall with a volume of approximately 16.000 m^3 [13] occurred, damaging the road and railway line that run along the base of the slope. Because of the extensive restoration work to stabilize the instable slope and install new protection measurements a full closure for seven (rail) and five (road) weeks respectively was necessary. The economic costs of this event amounted to between 20 and 30 million euros. While the affected road is only important for local traffic, the affected railway line is part of the important European freight corridor Genoa – Rotterdam with usually 114 freight trains and 56 local passenger trains per day [13].

Figure 2 shows the three sub-steps for the climate impact analysis for the Kestert case study. The exposure analysis shows that the hazard information map identifies both rail and road as at risk in the area where the event occurred (exposure within 50 m buffer zone). Thus, the model underlying the map correctly identified the slope as an area where gravitational mass movements could potentially occur. The sensitivity analysis indicates that the corresponding rail section is protected by slope stabilization structures. This also protects the road because the two modes of transport run parallel to each other at this point. However, the safety structure was not sufficient to protect the modes of transport from an event of the dimensions of the rockfall event in March 2021. This is

because safety structures are built only for events of certain dimensions, not for every potential particularly large and very rare event. The criticality analysis shows that, in terms of impact, an event can have quite different effects on the two modes of transport. The affected road section is partly of medium relevance because it is not part of a supra-regional transport route and, due to the high redundancy of the road network, the additional time required or the additional travel kilometers due to the route closure are low. However, the affected rail line is an important international freight corridor with a high relevance, so that the weeks-long closure of the line resulted in massive economic impacts and long detours of freight trains or a shift of freight transports to other modes of transport. The different impact of the rockfall event on the two mode of transport is mostly based on the function and alternatives available rather than the effects of the process itself.

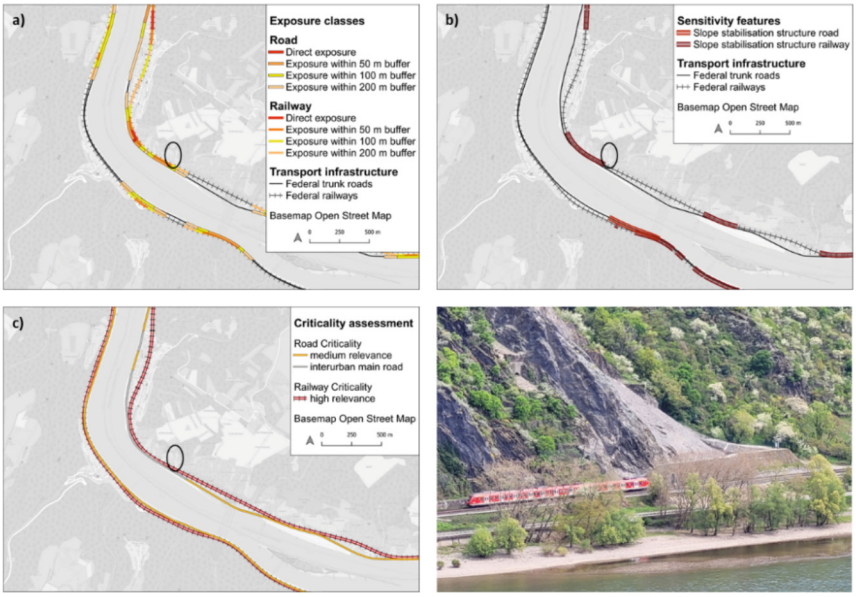


Fig. 2. The three steps of the climate impact analysis for the Kestert case study: a) exposure analysis, b) sensitivity analysis and c) criticality analysis. The location of the rockfall is marked with the black oval. The photography gives an impression of the site after the rockfall event and the installation of the new protection measures. Source photography: Enno Nilson

4 Conclusions and Outlook

The study has shown the applicability of the concept of the climate impact analysis as a valuable tool to identify regions at risk correctly. Similarly, the study has shown that the impact of a single event can be completely different for two modes of transport. As the rail network generally has a lower network density than the road network, incidents of the same size often cause greater economic damage to the rail than to the road mode.

The next steps include the extension of the climate impact analysis for the climate impact gravitational mass movements to the nationwide rail and road network as well

as the implementation of the climate impact analysis for further climate impacts in the scope of the BMDV Network of Experts, such as river floods or embankment fires. The focus will be on both cross-modal and cross-hazard approaches.

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ML-Based Model for the Estimation of the Pavement Elastic Modulus via Deflection Velocity Measurements

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Abstract. Nowadays, the urgency to appraise the structural deteriorating condition of road pavements and ascertain their remaining operational lifespan is more paramount than ever. The limitations of conventional computational methods and measurement techniques such as the Falling Weight Deflectometer (FWD) have paved the way for the emergence of the Traffic Speed Deflectometer (TSD), enabling continuous bearing capacity evaluation without traffic disruption. Given the large amount of data generated by TSD, this paper introduces an innovative Machine Learning (ML) based model for the estimation of the pavement elastic modulus (E_1) using vertical deflection velocity (D_v) measurement. The research formulates a robust estimation model by employing Support Vector Machine (SVM) techniques, that subsequently validated through rigorous performance metrics. This research significantly advances pavement assessment by offering promising data-driven approaches and ML prospects for monitoring road durability and safety.

Keywords: Pavement Elastic Modulus (E) · Deflection Velocity (Dv) · Machine Learning (ML)

1 Introduction

The progressive deterioration of road pavements state necessitates urgent, efficient and automated structural assessment in order to evaluate the residual life of the pavement. The accurate estimation of the pavement elastic modulus (E_i) plays a pivotal role in this process, serving also as a fundamental factor for designing resilient pavements, optimizing maintenance strategies, and improving overall road safety [1]. However, traditional methods and devices like the Falling Weight Deflectometer (FWD) face limitations when it comes to estimating (E_i), particularly when evaluating an entire network of pavements. These limitations stem from operational and security constraints, as well as the need for traffic control during measurement data collection [2]. To tackle these obstacles, the Traffic Speed Deflectometer (TSD) has emerged as an innovative solution for

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continuous assessment of pavement bearing capacity, eliminating the need for traffic control. By measuring the vertical deflection velocity (D_v) of the pavement caused by a rolling wheel, the TSD provides valuable information about the pavement's condition at specific locations [3,4]. Although the TSD holds considerable potential for pavement analysis, effectively processing the substantial amount of data it generates presents another sort of challenges. However, these challenges can be overcome by employing specialized techniques, such as Machine Learning (ML) [5]. Therefore, the aim in this research paper is to present an efficient and effective ML-based model for the estimation pavement elastic (E_1) using (D_v) measurements. The study progresses from explaining the experimental setup and data collection process for the supervised learning classification and regression phase. Support Vector Machine (SVM) techniques is well advanced model that are employed to construct an estimating models for pavement elastic modulus, with accurate results validated by performance metrics [6]. Ultimately, this work contributes to enhancing pavement assessment by utilizing deflection velocity data and ML for precise property estimation.

2 Forward Model: Data Acquisition and Processing

- **Experimental Setup:** The research took place at the University Gustave Eiffel Nantes as part of (I-Street) project [7], where a fatigue carousel, serving as an advanced outdoor road traffic simulator, was employed [8].
- **Pavement Structure:** The characteristics data of the employed pavement structure were obtained through bearing capacity tests [7,9], presented in (Table 1). Whereas, (L_1), the uppermost layer, constructed with third Hot Mix Asphalt (HMA) material with broad range of (E_1), indicating that both traffic loads and temperature play a key role in its fatigue behavior. (L_2) and (L_3) consist of Unbound Granular Material (UGM), chosen with specific fixed attributes for the sake of analysis simplicity. (L_4), which corresponds to the third platform (Pf_3), features a comparatively lower modulus value than others. Additionally, uniform deformation is evident in this structure due to consistent Poisson's ratio, aided by strong bonded interfaces that enhance structural integrity. Furthermore, the temperature ranges related to measurements taken at specific depths.

Table 1. Characteristics of the Forward Model Pavement Structure

Layer (L_i)	Thickness (m)	Material	E_i (MPa)	ν	Interface	Temperature (°C)
1	0.10	**HMA**	**2000 - 18000**	**0.35**	**(1) bonded**	**4 - 29.5**
2	0.05	UGM	126	0.35	(1) bonded	5.5 - 29
3	0.25	UGM	126	0.35	(1) bonded	5 - 28.5
4	∞	Pf_3	104	0.35	(1) bonded	6 - 28

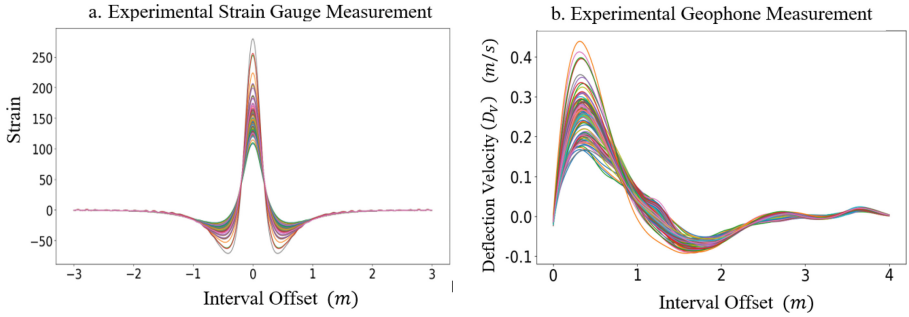


Fig. 1. Forward Model Components: a) Strain Gauge, b) Geophone Measurement.

- **Measurement Instruments:** Pavement instrumentation comprised strain gauges, temperature sensors, and a geophone. Dynatest PAST-IIA strain gauges were situated 9 cm deep in the bituminous layer for deformation measurement [10]. Temperature sensors at depths of surface, 2.5, 10, and 30 cm captured real-time temperature. A surface geophone measured deflection velocity from carousel arms motion [11].
- **Load Configuration:** For consolidation simulation, 30,000 spinning charging cycles were executed after pavement construction, totaling 120,000 loadings across four carousel arms. Maintaining a constant speed of approximately 22.5 m/s and utilizing a dual-wheel load of 65 kN, these parameters align with France's pavement load limit [8].
- **Data processing:** Ninety-eight (98) deformation data points were simultaneously collected from strain gauges (Fig. 1a) and a geophone (Fig. 1b). The strain gauges data was input for Alize software [12], to extract the equivalent Modulus value (E_1) for each measurement. These (E_1) values served as labels for the SVM algorithm. Additionally, seven features were extracted from geophone measurements, corresponding to the TSD sensor position on the deflection velocity curve[3]. These features, combined with the Alize (E_1) labels, were used for SVM learning.
- **Data Augmentation:** Since 98 datasets weren't sufficient for the learning prcesses, data augmentation was applied. Geophone data was simulated by varying the (E_1) value between 2000 and 18000 MPa in intervals of 50 MPa, resulting in a dataset of 320 case (98 measurement and 222 simulated one).

3 Classification Analysis

This study developed a classification model to categorize data based on (E_1) values, divided into four classes (C_1 to C_4) with values (2000–6000 MPa, 6000–10000 MPa, 10000–14000 MPa,14000–18000 MPa, respectively). The dataset was split into 70% for training and 30% for testing the SVM model. Model performance

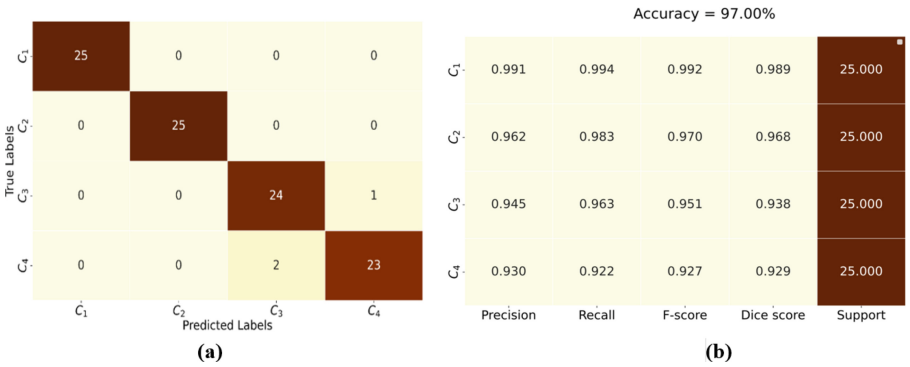


Fig. 2. Classification Analysis: a) Confusion Matrix, b) Evaluation Metrics.

was evaluated using a confusion matrix [13], which primarily demonstrated accurate predictions, with some misclassifications attributed to overlapping features and measurement noise (Fig. 2a). The model achieved an accuracy of approximately 97%, indicating strong predictive capability across instances. A comprehensive set of evaluation metrics in (Fig. 2b), including Precision, Recall, F-score, Dice score, Accuracy, and Support [5,14], further illuminated the model's performance dynamics for identifying true positives and actual positives.

4 Regression Analysis

This analysis employed Support Vector Regression (SVR)[6] to estimate (E_1) values based on deflection velocity (D_v) measurements. Despite noise in the experimental data, SVR exhibited robust performance, with high (R) and (R^2) values as shown in (Fig. 3a). The (R^2) value of 97% indicated a strong correlation between predicted and actual (E_1) values. A ($RMSE$) value of 7.9 suggested reasonable predictive accuracy, though within literature acceptable limits [15].

To assess the model's uncertainty, a variance analysis was conducted in (Fig. 3b) by comparing predicted and actual test values. This analysis revealed a range of ±5%, deemed acceptable given inherent data variability and current domain standards [15].

Table 2. SVR Grid search Hyperparameter Tuning

Index	SVM Parameter	Value
1	Kernel	RBF
2	ϵ precision	0.95
3	C tolerance parameter	1500
4	γ kernel scale factor	80

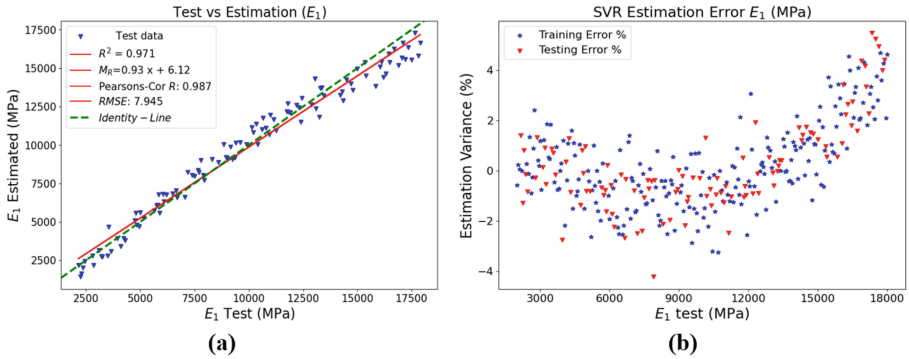


Fig. 3. Regression Analysis: a) SVR Performance Analysis, b) Variance Analysis.

For SVM, meticulous hyperparameter calibration was crucial. Grid Search (GS) systematically explored combinations [16], leading to optimized settings in (Table 2): Radial Basis Function (RBF) kernel, (C) tolerance parameter set to 1500 for error emphasis, and gamma (γ) set at 80 for smoother decision boundaries. This fine-tuning achieved an accuracy of approximately 97%, highlighting the effectiveness of this approach for accurate modulus estimation.

5 Conclusion

This study presents an innovative fusion of Machine Learning (ML) and deflection velocity measurement (D_V) techniques, offering a pioneering solution for accurately estimating pavement elastic modulus (E_1) in road pavements. The forward model combining a limited experimental dataset with numerical simulations of deflection velocity (D_v), the research effectively augments the size of the database, enabling a more comprehensive analysis. The methodology encompasses various phases, ranging from forward modeling and data processing to the incorporation of Support Vector Machine (SVM) model and the application of advanced validation techniques.

According to the results, the SVM model showcases remarkable performance in both classification and regression analyses the classification analysis attains an accuracy of 97%, with relatively high evaluation metrics values. The regression analysis demonstrates as well an efficient performance with an R^2 value of 97%, underlining the model's capability in predicting (E_1) values. Furthermore, the variance analysis between estimated and tested (E_1) values ranges around $\pm 5\%$ MPa, which is falling within literature acceptable limits.

As perspective, future endeavors could involve the exploration of alternative ML models for refined feature engineering and dimensionality reduction, aimed at optimizing overall performance.

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Decision Support for Predictive Maintenance Planning on the Freight Corridor From Rotterdam to Genoa

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Abstract. The central task of any rail infrastructure manager is to maintain the track properly and make it available for operation. To achieve this, maintenance management must meet both safety and economic challenges. The assessment criteria to be applied for network maintenance are defined in regulations and standards. In detail, the considered limit values for the superstructure are defined by the standard EN13848 [1] at European level and by DB Group Guideline (KoRil) 821.2001 [2] at the national level. On this basis, the condition assessment of the superstructure is determined by the measured values obtained during prescribed regular inspections (e.g., of the track geometry).

Due to the nature of the underlying optimization problem, which is characterized by a high complexity due to the individual development of the condition of each 25 m segment, the diversity of the machine types, the variation on the effect of maintenance and the large range of possible train free time windows an exact solution of the resulting linear mixed-integer program would require a high numerical effort and thus an infeasible computation time. Therefore, we present a heuristic solution approach to solve the described optimization problem with sufficient accuracy in a significantly lower runtime. The solution approach is based on a branch and bound algorithm, where the local optimization is limited by the respective machine characteristic.

Keywords: Predictive maintenance · Decision support · Scenario based

1 Problem Description

"Good" planning of maintenance activities does not just mean that a lot of interventions are realized during a shift, resulting in high utilization, but rather that the right things are done at the right time.

Therefore, we present in this paper a planning approach that enables the infrastructure manager to create a predictive maintenance plan for different scenarios and to compare and validate them with respect to costs and achieved network quality. By different scenarios we mean, on the one hand, different ownership conditions and, on the other hand,

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different planning parameters. Here, an accurate prediction of the track condition forms the basis for reliable operational planning. In this context, an accurate prediction of the track condition forms the basis for reliable operational planning. Therefore, in the first section we explain the necessary data basis of the planning approach, before we come to the explanation and analysis of the algorithm itself in the second section.

1.1 Prediction of Track Geometry

A valid prediction of the track geometry degradation is one of the most important building blocks for a reliable planning and scheduling of maintenance. Only the prediction paves the way from reactive or preventive to predictive maintenance planning to extend the service life of components and improve the reliability of infrastructure.

It is analyzed in [3] that the amplitude of individual faults can reach the threshold that triggers maintenance before the standard deviation reaches this value, resulting in the need to maintain the individual fault before planned maintenance. At the same time this approach implies two requirements that are essential for reliable prediction:

- High quality of historical data in terms of reliability and reproducibility and
- high positional accuracy as a function of the calculation grid

The used DB database fulfills these requirements, so that the model is able to predict the deterioration of the track geometry for single defects or standard deviations.

To predict track degradation, the track is divided into sections of 25 m length. For each section, the measurement data is pre-processed to remove anomalies. The results of the developed degradation model, which is based on historical inspection and monitoring data, are visualized in Fig. 1. The historical values are illustrated by a time less than or equal to zero whereas the predicted track geometry is represented by a time greater than zero. Figure 1 shows the modelled degradation of a 20 km section of the rail freight corridor as contour plot. The color from blue to red illustrates the track quality where red means that the track geometry needs to be maintained.

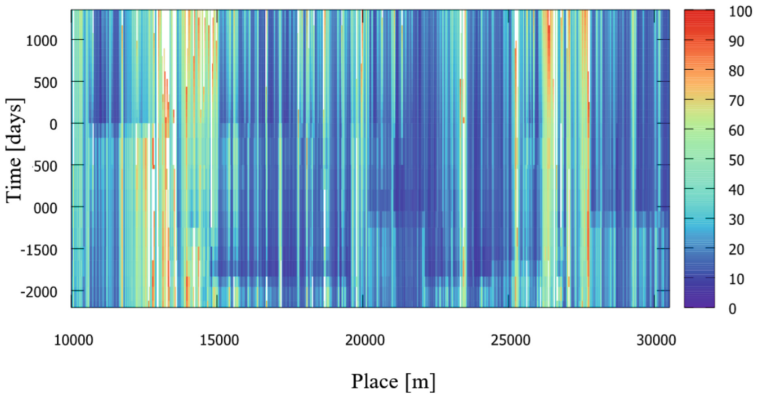


Fig. 1. Historical and predicted values of the normalized longitudinal level with maintenance thresholds (colour code)

The contour plot clearly shows the different local behavior of the track and the time when maintenance is required. An average value for the track geometry degradation, which is often used for simplification, leads to significantly lower efficiency in planning. Thus, the planning model presented in this paper considers the individual states of the 25 m sections to bundle maintenance activities and related works into shifts.

1.2 Data Base

A comprehensive database is essential for predictive maintenance planning. The database required for the development of the decision support tool can be subdivided as follows:

Asset register. The network under consideration must be defined in terms of its structural characteristics (type of asset, type of structure, and substructure) and geographic location to enable effective and cost-efficient planning. To plan the detour traffic, data is needed on both the routes to be maintained and the available secondary routes. This requires information on the maximum permissible speeds, the maximum load, and the available capacity of the individual route sections.

Prediction data base. For each 25 m segment an accurate and reliable prediction of the track geometry parameter with respect to the maintenance threshold is provided. As an example, the prediction is shown in Fig. 1, where 100% means that the track geometry parameter reaches the threshold.

Historic data regarding executed interventions. In order to predict the effect of an intervention in the simulation phase of the maintenance planning process, a reliable database of already executed interventions is required.

Possessions data base. Depending on the track condition and the available capacities, various scenarios can be defined for maintenance. For example, the infrastructure manager can schedule short periods (<4 h) several times during the nights or a maintenance corridor, where a certain track section is closed for a longer period (>12 h).

Definition of the considered interventions. The interventions considered here are grinding and tamping activities. Both activities have to be defined in terms of their costs and the expected duration per unit of length processed. In addition, the expected effect on the quality parameters is to be determined by a prior data analysis.

Definition of the available machine pool. The grinding and tamping machines differ in terms of their working speed and the expected quality improvement. The user can set these parameters and also vary the number of machines to be available.

2 Solution Approach

The aim of this planning is, on the one hand, to maximize the quality and thus the reliability of the network and, on the other hand, to minimize the costs of maintenance execution. The latter consists of the machine costs and the costs for the possession installation. It must be noted that, in a possession not only the working time itself but also the preparation and travel time needs to be considered to generate a reliable shift

plan. Consequently, the underlying optimization problem must take into account a variety of restrictions related to safety, scheduling, or technical constraints. To name a few, the following aspects are considered in the shift design: To name a few, the following aspects need to be considered in the shift design:

- Use of the most appropriate tamping machine (differ in speed, achieved quality)
- Selection of a suitable possession (differ in duration, start date and length) taking into account the predicted status of the 25 m segments
- Optimal usage of tamping machines with respect to their type and location
- Consideration of obstacles (e.g., a switch can only be tamped by a special tamping machine and the installation of a ramp)

The consideration of the multi-layered planning criteria and the size of the network leads to a high complexity of the optimization problem. The exact solution of the resulting linear mixed-integer program would require a high numerical effort and thus a long computation time. Therefore, we present in the following a heuristic solution approach to solve the described optimization problem with sufficient accuracy in a significantly lower runtime.

2.1 Heuristic Solution Approach

Figure 2 shows the main steps of the developed modular decision support system. Shows the main steps of the developed modular decision support system.

Define scenarios. The infrastructure manager defines the different planning scenarios, i.e., he defines what kind of possessions are available for the considered planning horizon. The extreme cases here are on the one hand long maintenance corridors (a certain section is closed for a long period, e.g., a weekend) or on the other hand many very short maintenance periods resulting from the respective timetable. Of course, scenarios between these extreme cases are also conceivable.

Evaluate available possessions. The defined possessions must then be monetized, i.e., it must be evaluated how many costs are caused by the closure and the associated establishment of detours or train cancellations.

Data Analysis. As described in Sect. 1.1 a valid prediction of track geometry degradation is one of the most important building blocks for reliable maintenance planning. In addition, the planning algorithm requires the following analysis steps:

- Analysis of the effect of an intervention using historical data.
- Integration of a route optimization to choose the optimal tamping machine.
- Analysis of combination possibilities of interventions (e.g., grinding and tamping) and the corresponding update of technical and safety-related criteria.

Planning From the previous step, we obtain a graph-theoretical model of the network which is underpinned with asset and prediction data. During the initialization phase the infrastructure manager must define which machines are available and set certain planning parameters like e.g., planning horizon, maximum shift length, condition thresholds etc.

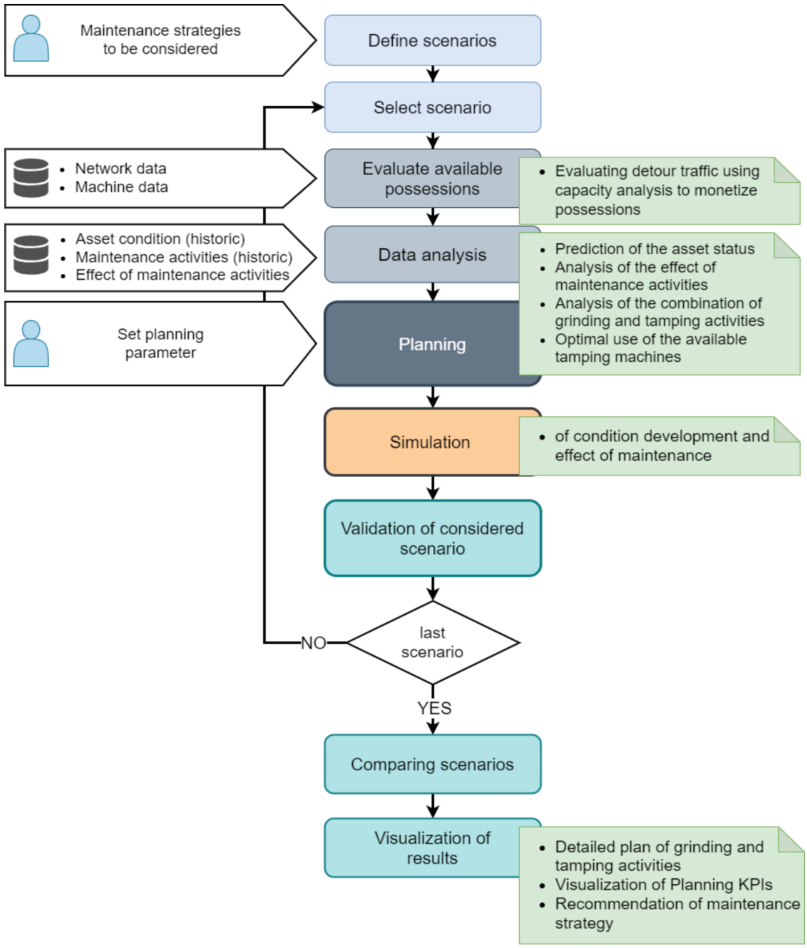


Fig. 2. Flow chart of the solution approach

Note, tamping machines differ in their processing speed and in the assets, they are able to tamp. In detail, track tamping machines can only tamp track segments, whereas switch tamping machines can tamp both switches and the surrounding track assets but at a slower speed compared to the track tamping machines. The planning procedure itself starts with the determination of all critical segments, i.e., with the determination of all segments that exceed the predefined maintenance threshold. The critical segments are divided into switch and track assets. Since switches cannot be processed by all available tamping machines, the critical segments that contain a switch are considered first. Thus, the planning procedure starts by allocating the fastest, suitable and available tamping machine to the most critical switch. Based on the speed of this tamping machine, the local optimization area is defined. In this local optimization area, the segments to be processed are now selected in such that, on the one hand, the objective functional is maximized and, on the other hand, the various planning criteria are fulfilled, such as, for

example, the first and last 80 m of a planned intervention must be uncritical (in order to enable the construction of the ramp) or critical segments with a distance of less than 500 m must be combined. The corresponding segments are marked as blocked for this possession and finally, all critical segments (that are solved by this shift) are removed from the list of to be planned critical segments.

After the planning of all possible critical segments, the same algorithm is applied to plan all critical track segments. This approach results in a uniform quality development of the network. I.e., in general, the algorithm ensures that not individual spots but connected areas are maintained. Finally, the planning algorithm terminates if:

- all critical assets are planned for the next time horizon
- no suitable tamping machine is available in the planned time horizon
- the end of the planning horizon is reached

This planning strep results in is a schedule of tamping activities, with other words in a list of work shifts, where each shift is assigned a specific time (or possession), a specific machine, and a list of sections to be tamped during that shift. In addition, a list of critical sections that cannot be processed during the planning period due to capacity constraints is provided.

Simulation/Validation of considered scenario To validate the computed plan the costs for maintenance and the achieved network quality are computed. To obtain a prediction for the latter, the results from the data analysis step are used.

Comparing Scenarios/Visualization of results The different scenarios are compared on the basis of predefined KPIs. The results are displayed in a web interface.

2.2 Summary and Outlook

The creation of plans for maintenance tasks usually requires a lot of human resources. This tool offers the possibility to quickly create a plan under the given capacity constraints and to effectively compare different plan configurations and their impact on the quality of the network and efficiency of maintenance activities. However, it must be emphasized that by considering tamping activities alone, we have made some simplifying assumptions. The developed tool can therefore be seen as a proof of concept. In the next development steps, a more refined planning process will be mapped.

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Managing European Railway Traffic Management System Project: Challenges and Lessons Learnt from Denmark

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Abstract. The European Rail Traffic Management System (ERTMS) represents a critical infrastructure project dedicated to the digitalisation of railway transportation services within the European Union. Nevertheless, the ERTMS deployment has experienced a gradual pace, falling behind the EU ERTMS implementation schedule. Under this premise, this study investigates the schedule performance of ERTMS projects across the EU region, and the prevailing project management practices employed in managing the ERTMS project through a qualitative case study of the Danish ERTMS deployment. The findings reveal that ERTMS projects are inherently more susceptible to risks than their initial estimates, with the actual schedule exceeding initial estimation by 1.75. The qualitative analysis has identified fourteen prominent causes contributing to project delays and eleven distinct solutions to mitigate these underlying challenges. The study reveals that addressing specific challenges requires a combination of solutions across three levels of project management: technical, strategic, and institutional.

Keywords: ERTMS · Megaproject · Railway Digitalisation

1 Introduction

The European Rail Traffic Management System (ERTMS) is a pivotal digital innovation driving the railway sector into Industry 4.0. Unlike conventional analogue or electromechanical control systems, ERTMS relies exclusively on real-time wireless communication between trains and local control centres. The overarching goal of ERTMS is to replace the existing signalling systems within the EU, primarily due to the lack of interoperability among the legacy ATP systems [1, 2]. However, despite the EU's commitment of deploying ERTMS across all member states, the journey towards interoperability encounters several difficulties. Many infrastructure managers and train operators remain apprehensive about transitioning from legacy systems to ERTMS, contributing to a sluggish deployment process [3]. To accelerate this transformation, various supporting mechanisms have been enacted; however, these supports do not comprehensively encompass the entirety of the deployment, leaving pressure on infrastructure managers [3].

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Each ERTMS deployment can be viewed as megaproject due to its nature, which is large-scale, costs more than one billion, takes many years to complete, involves a wide range of stakeholders, and contains a high degree of complexities and innovations [4–6]. The fundamental rationale behind pursuing megaprojects is to create impactful societal changes while minimising uncertainties and associated costs [7]. This sheer ambition to enact massive transformative change seduces a wide array of stakeholders, which [4] described as megaprojects sublimity.

However, reality often falls short; most megaprojects end up in disappointment, where schedule and cost overruns can be expected [8]. This due to the nature of megaproject which often involved with extended project timeframes, and this invites a plethora of uncertainties including market, technological, and policies uncertainties, rendering conventional project management tools ineffective, which leads to improvisation when it comes to practice [4, 9, 10].

Against this backdrop, the study addresses the current state of schedule performance and the multifaceted challenges and solutions in managing ERTMS projects. The initial phase of our investigation relies on quantitative analysis to assess the schedule performance of ERTMS projects across the EU. Subsequently, the second phase delves into a qualitative case study to identify the challenges and current solutions for managing ERTMS project. This study only includes the analysis of the ERTMS wayside project as it reflects the digitalisation of the rail transport infrastructure.

2 Descriptive Statistics

The assessment of the schedule performance of the ERTMS project within the EU is collected following the political sublime of megaprojects [4]. This analysis includes three categories of schedule overruns: (1) Schedule overruns resulting from technical complexities leading to interruptions. (2) Delays arising from the absence of approval letters after the kick-off contract, resulting in project inactivity. (3) Delays when all project components are completed, but the system waits for activation, causing delays in commissioning.

As of 2023, 160 ERTMS wayside projects have been initiated across the EU. Commencement dates for these projects were sourced directly from the official ERTMS website. Google searches were conducted for planned and actual commissioning years. This involved collecting project documents, newspaper articles, and related publications. Out of the 160 ERTMS wayside projects, 95 completed projects with completed information were found. The empirical data reveals that only 16 of these 95 projects (16.8%) adhered to their initial commissioning plans. On average, projects experienced a schedule overrun of 2.05. Table 1 provides the descriptive statistics of the ERTMS wayside project schedule performance.

Table 1. Descriptive statistics

	Estimated duration	Actual duration	Overrun ratio
Mean	3.24	5.68	2.05
Median	3	5	1.75
SD	1.74	3.58	1.18
1st Q	2	4	1.31
3rd Q	4	7	2.29

3 The Case Study

A representative case study method is used to identify the underlying factors contributing to poor schedule performance of ERTMS projects. Purposive sampling for case selection is based on the following criteria: 1. An ERTMS wayside deployment in the EU; 2. Accessibility of data; and 3. Contextual representation. Following these criteria, the case study chosen to address this inquiry is the Danish ERTMS deployment. Moreover, the deployment represents the nationwide deployment of ERTMS level 2 Baseline 3 which is the system the is commonly installed. Semi-structured interviews were conducted to capture the perspectives and experiences of project stakeholders concerning the challenges faced and the solutions employed to address them. The interview process and analysis adhered to the three project management levels from [11]. Qualitative content analysis was used to synthesise the findings from six interviewees, including project director, two IM project managers one IM project planner, one chief consultant, and one project manager from one of the suppliers, project documents, monthly progress reports, and other secondary data sources.

The Danish ERTMS rollout was inaugurated in 2009, stemmed from the obsolescence of the legacy signalling system, The project was strategically designed to optimise value for the system while affording suppliers the opportunity to leverage the project's scale. In 2017, the project organisation officially acknowledged that the project had encountered unforeseen challenges, followed by a significant extension of the project's commissioning deadline of nine years and a reduction of the project's scope. However, as of 2023, the project progress went according to the replanned project plan.

4 Result and Discussion

In total 14 challenges and 11 solutions were extracted. Table 2 shows all of them. The challenges and solutions are ordered according to the level of project management, causes are colour-coded from light to dark orange, while solutions are colour-coded from light to dark green. The most prevalent approaches involve the incorporation of schedule buffers and the facilitation of information sharing among stakeholders to address the encountered challenges.

Table 2. Challenges and solutions of Danish ERTMS project

ID	Challenges	Solutions										
		S11	S12	S13	S14	S21	S22	S23	S24	S31	S32	S33
		Adding buffer	Early preparation	Adaptive project plan	Loading IM resource for project control	Technical based negotiation	Trust building	Information sharing	User involvement	Knowledge management framework	Joint organisation culture	Compliance verification framework
C11	Live environment	x						x				
C12	Repetitive tasks							x	x			x
C13	Dependencies	x				x		x				
C14	Incomplete infrastructure information	x	x					x				
C15	Uniqueness of scope	x										x
C21	Many change requests			x								x
C22	Supplier as system integrator			x	x							x
C23	Overambitious project scope			x	x							x
C24	Coordination among stakeholders					x	x	x	x		x	
C31	Loss of knowledge						x			x		
C32	Inefficient human resources	x			x							
C33	Differences in organisation culture						x				x	
C34	Operational change management								x	x		
C35	Changes in approval process	x	x					x				

Macroscopically, the nationwide Danish ERTMS rollout has some homogeneity of challenges and solutions to other brownfield ERTMS projects. But upon closer examination of how the challenges were handled, the approach was widespread in term of the level of solutions in project management that the project organisation used to tackle the challenges which is complicates to pinpoint the most effective solution, highlighting the constraints of conventional project management methodologies within the ERTMS domain.

Transitioning from the legacy signalling system to ERTMS level involves a prolonged period of track possession, causing disruptions to current train services. To secure long possession, the project organisation must request it a year in advance, due to the track capacity agreement. However, uncertainties related to the design lead time for hardware and software applications prevent the creation of a detailed installation plan a year ahead. Once established, the plan is shared and negotiated with train operators and relevant authorities, leading to smaller possessions, some included in the schedule buffer and others not. Dependency issues arise as the modernisation of Denmark's signalling system is a brownfield project, requiring concurrent update of civil and electrification systems. To address this, Denmark proceeds all works simultaneously, meaning delays in track or electrification could delay the signalling work. Shared small track possessions were allocated to all three projects, resolved through schedule buffers and close monitoring of progress to ensure a seamless handover.

"First thing when we are doing ETCS level two, there should be a minimum speed of 200 km/hr. Do you think that all the tracks in Denmark have the ability to go at 200? My

answer is no. So, the track needs to be maintained, the tamping needs to be done, and then the speed profile of the of the track needs to be increased. Denmark is also purchasing new trains, and the new training is only operated in electrical, so Denmark needs to also upgrade not their signalling system, but also need to upgrade their electrification system." (Interview quote from IM's project planner)

Regarding the strategic level of project management, at the early phase of the project, the system integration tasks belonged to the project supplier giving a supplier full control of project. However, after the project replanning and reorganisation in 2017, this responsibility was transferred to the infrastructure manager, minimising the unreasonable claims and delays from the suppliers.

"We believe in the beginning of the signaling program that we could give system integration task to the suppliers, but we realised that that was not the case…. You can write a contract and then you face unforeseen things, and then you have claims from suppliers, that's fair enough. But you can say some suppliers have a business model that, begin with cheap proposal, and then send a lot of claims." (Interview quote from Senior chief consultant)

Moreover, the initial project plan from 2009 was designed to explore all the available paths to go through. But the plan struck back with massive numbers of change requests and claims from suppliers, as they need the detailed requirements to develop specific applications of all ETCS subsystems. Moreover, the railway packages benefit the Danish project through the reduction of the need for establishing an exhaustive requirement specification.

"The project needs to scout for the easiest way to go through. You can plan, but you should try to see how it fits into reality. It's like in military, you can have a plan, and the first minute you start the war, you need a new plan…. "But since 2017, you have very precise specification of ECTS, you have a very strong model how to verify the compliance, and you have a very strict change control management of ECTS. So, the institutional support is much better today." (Interview quote from Senior chief consultant)

In managing the project at institutional level, a key challenge involved securing Danish validators for approving interfaces between the legacy infrastructure and the new signalling system. Another significant challenge was the operational change for the infrastructure manager and train operators due to the transition to ERTMS. This shift rendered existing employee competencies obsolete, leading to resistance to change. However, the project organization anticipated this challenge and integrated the concept of user involvement during design and commissioning. This collaboration between the project and the operation departments ensured a smooth transition to the new operational norms. At the institutional level, a structured knowledge management framework was established to facilitate the know-how between the project and operation organisations. The framework documented lesson learnt from early deployment lines, new operational norms, and prior successful rollouts, fostering a continuous improvement of ERTMS rollout in Denmark.

"We had people from operation who allocated to the project 50% of their time. They were continuously bridge the operation and the project. Being 50% each on each side, they could continuously tell their colleagues you know, this is what's coming, and this

will be working like this in the future. So, they were very very strong ambassadors and advocates for the new solution." (Interview quote from IM's project manager)

*"Ministry said that what the **** is going on for years that you're not completing this on time. Then we had some pictures showing that these are the problems that we need to create new norms. So, new rule came in, so the ministry provided the approval for the new norms and implemented those norms."* (Interview quote from IM's project planner)

5 Conclusion

ERTMS deployment is a one of a transport megaproject at a continental scale. The analysis of the current ERTMS project schedules showed that the actual project schedule surpasses the initial estimates by a considerable median of 75%. This observation underscores the inherent risks embedded within ERTMS projects. In-depth investigation of this phenomenon was conducted through the case study from the Danish ERTMS project. The analysis showed that there is no singular effective project management solution to address each encountered challenge. Instead, it is necessary to combine the current project management solutions from several project management levels to cure a specific challenge. Our findings run counter to the improvisation theory in project management claiming that in high complexity project, pure improvisation is required [9].

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Recycled Fibers in Asphalt Mixtures as Method to Improve the Mechanical Behavior: ASFIVAL Project

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Abstract. Extending the life cycle of roads involves improving their environmental and economic impact. Various types of fibers have been presented as an innovative solution to improve the mechanical performance of hot asphalt mixtures and increase its durability. However, their use has not been widespread, mainly because of their high cost compared to other materials commonly used in road construction. Reinforcing asphalt mixtures with recycled fibers could be a viable alternative to overcome the cost disadvantage and ameliorate the environmental impact of both the asphalt mixture and the industry from which the fibers originate. This paper presents the mechanical performance of different recycled fibers added to an asphalt concrete (AC) mixture and a porous asphalt (PA) mixture as part of the ASFIVAL project. The results were compared with a reference mixture made with conventional bitumen and a control mixture made with polymer modified bitumen (PMB) in order to evaluate their mechanical performance and to see if the improvement was as effective as the use of PMB. The three fibers showed good mechanical performance compared to the reference and even matched the control values in some properties.

Keywords: Asphalt mixture · recycled fibers · mechanical performance

1 Introduction

Escalating growth in traffic volumes and the effects of climate change are leading to a soaring need for road network maintenance, which has social and environmental impact in terms of resource consumption, congestion, and noise and pollutant emissions. Innovative solutions, such as the use of fibers, have been proposed over recent years to extend the life of the road.

An advantage of this technology is that it does not require any special equipment, as the fibers can be easily added without increasing the temperature and with almost the same productivity, since the amount of fibers is generally small, making it feasible on a large scale [1, 2]. Fiber reinforcement acts as a barrier to prevent crack initiation and propagation and good results have been achieved in terms of rutting, cracking, moisture sensitivity and tensile strength [3–5]. Most studies have been carried out on the use of

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virgin fibers, but to improve cost and sustainability, some studies have started to look at recycled fibers [6–8].

The main objective of the project related to this work is to reduce the environmental and economic impact of transport infrastructures by optimizing the design of new bituminous mixtures incorporating recycled fibers from industrial processes to improve their mechanical performance. The aim of this paper is to present and discuss the results obtained so far on the mechanical performance of asphalt mixtures reinforced with three different types of recycled fibers.

2 Materials and Methods

2.1 Materials

Almost all the materials used were typical in the manufacture of asphalt mixtures: a 50/70 penetration grade binder or PMB 45/80–65 in combination with ophite as coarse aggregate, limestone as fine aggregate and filler. The aggregates and bitumen properties are listed in Table 1 and Table 2, respectively.

Table 1. Characteristics of aggregates.

Characteristics	Results	Standard
Ophite		
Specific Weight (g/cm3)	2.794	EN 1097–6
Los Angeles abrasion (%)	15	EN 1097–2
Flakiness Index (%)	< 1%	EN 933–3
Polishing Value	60	EN 1097–8
Limestone		
Specific weight (g/cm3)	2.724	EN 1097–6
Sand equivalent	78	EN 933–8

The alternative material used in this work was recycled fiber. Availability, homogeneity and possible alternative applications were considered when selecting the most suitable fibers. Based on these considerations, three recycled fibers were selected for this study: Indigo (I), Ecofibra (E) and Pulp (P). Each comes from a different company and has a different composition. Figure 1 shows their physical appearance.

Table 2. Characteristics of bitumen.

Characteristics	Results	Standard
50/70		
Specific weight (g/cm^3)	1.035	EN 15326
Penetration at 25 °C	57	EN 1426
Softening point (°C)	51.6	EN 1427
Fraass brittle point (°C)	−13	EN 12593
PMB 45/80–65		
Specific weight (g/cm^3)	1.028	EN 15326
Penetration at 25 °C	55	EN 1426
Softening point (°C)	74.1	EN 1427
Fraass brittle point (°C)	−16	EN 12593
Elastic recovery at 25 °C (%)	92	EN 13398



Fig. 1. Illustration of the recycled fibers used. From left to right: Indigo, Ecofibra and Twaron(R) 0705 Pulp.

2.2 Mixture Design and Sample Preparation

A reference mixture, a control mixture and three AC and PA mixtures were designed with a maximum aggregate size of 16 mm. Table 3 shows the bitumen and recycled fiber content of the mixtures.

Table 3. Experimental AC and PA mixtures

Mixture	Binder type	Binder content (%)	Recycled fiber	Fiber content (%)
AC-REF	50/70	4.4	–	–
AC-CONTROL	PMB 45/80–65	4.3	–	–
AC-I	50/70	4.4	Indigo	0.08
AC-E	50/70	4.4	Ecofibra	0.4

(*continued*)

Table 3. (*continued*)

Mixture	Binder type	Binder content (%)	Recycled fiber	Fiber content (%)
AC-P	50/70	4.7	Pulp-0705	0.08
PA-REF	50/70	4.5	–	–
PA-CONTROL	PMB 45/80–65	4.5	–	–
PA-I	50/70	4.8	Indigo	0.1
PA-E	50/70	5	Ecofibra	0.6
PA-P	50/70	5.3	Pulp-0705	0.1

A conventional procedure was used to manufactured the specimens. The production temperature was provided by the supplier of the bitumen, so the reference and experimental mixtures were produced at the same temperature (150 °C), while control mixtures were produced at 165 °C.

The only difference in the production process was the addition of the fibers in the experimental mixtures, which was carried out by adding the fibers at room temperature together with the aggregates into the mixing drum (dry process). This method was selected because it is a simple and easily replicable alternative for any asphalt plant without the need to acquire new equipment. Besides, the experimental mixtures showed a homogeneous distribution of the fibers without clusters.

2.3 Experimental Work Plan

It was necessary to conduct a mechanical performance evaluation of the selected recycled fibers, as there is little information available on their use as reinforcement in AC and PA mixtures. The aim of the results presented here was to optimize the mixtures containing the fibers by modifying various parameters, such as bitumen content, particle size distribution and fiber content. This would allow the most promising fibers to be selected. Previously, several tests had been carried out on different mixtures, varying only the type and quantity of fibers incorporated.

To this end, different laboratory tests were performed depending on the type of mixture being tested. On the one hand, voids content (EN 12697–8), Marshall test (EN 12697–34), water sensitivity test (EN 12697–12) and wheel tracking test (EN 12697–22) were performed for AC mixtures. On the other hand, voids content (EN 12697–8), particle loss (EN 12697–17), water sensitivity test (EN 12697–12) and binder drainage test (EN 12697–18) were conducted in PA mixtures.

3 Results and Discussion

For AC mixtures, all mixtures showed a voids content between 4% and 6% (Fig. 2 left) with small variations due to changes in fiber and bitumen content. The results of the wheel tracking test (Fig. 2 left) showed a large difference between the reference and control specimens, with the experimental mixes falling between these values. The resistance against plastic deformation obtained with the experimental mixtures significantly

improved compared to the reference mixture, being remarkable the one obtained with the P fiber, which is close to control values. In addition, the water sensitivity results (Fig. 2 right) showed good performance against water damage. AC-P was the one with the lowest ITSR value, but it presented a high dry strength, keeping the wet strength similar to the reference. All the dry strength values were better than the reference mixture and some were even better than the control.

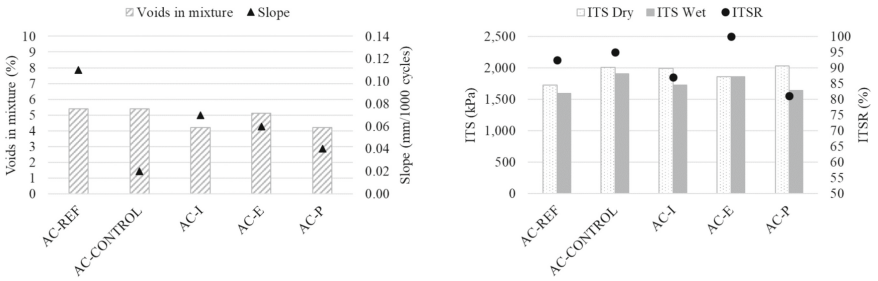


Fig. 2. Results of AC mixtures. Left: voids content and slope from wheel tracking test. Right: indirect tensile strength and moisture sensitivity test.

Taking into account all the tests carried out, the mixtures show good mechanical performance, improved resistance against plastic deformation and an increase in strength with respect to the reference.

For the PA mixtures, all mixtures had a voids content above 20% (Fig. 3 left), with the control mixture having the highest voids content. In terms of particle loss, the results presented in Fig. 3 show that the experimental mixtures had a particle loss similar to the control, thus improving the reference. On the other hand, the ITSR value improved with respect to the reference (Fig. 3 right) and the resistances were similar to the reference and the control. These characteristics seem to be little affected by the modifications made. Finally, the results of the binder drainage test showed that the experimental mixtures had no runoff.

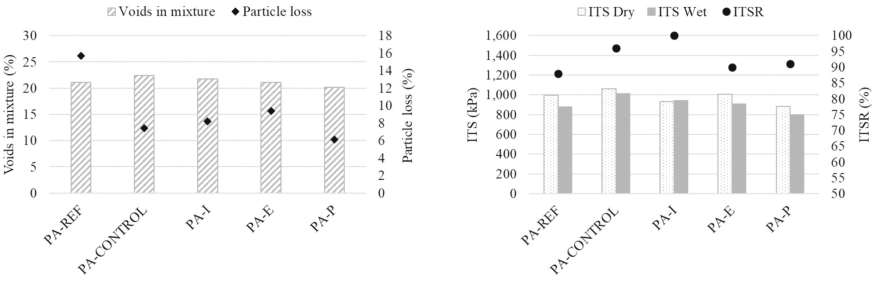


Fig. 3. Results of PA mixtures. Left: voids content and particle loss test. Right: indirect tensile strength and moisture sensitivity test.

Considering the set of tests, all mixtures achieve better mechanical performance than reference mixture; they had around 20% void content and had a good performance against particle loss obtaining values lower than 10%. Resistance was maintained in both dry and wet conditions.

4 Conclusions

This paper presents the results of tests carried out to evaluate the mechanical performance of recycled fiber reinforced mixtures. The three fibers studied are potentially suitable for use in mixtures. Their environmental or economic impact could be the variable that determines which is the most efficient. In AC mixtures, the plastic deformation performance was significantly improved, as well as the dry strength. On the other hand, in PA mixtures there was a significant reduction in particle loss but had no effect on water sensitivity results.

The activities currently being carried out in the ASFIVAL project are aimed at determining the recyclability of the mixtures and their economic and environmental feasibility.

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Resilience of Transport and Associated Infrastructure to Climate, Cyber and Physical Threats

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Abstract. The effects of climate change regularly impact the performance of transport networks. In the case of road transport, climate change has various impact drivers such as heat, cold, wind, snow, ice etc. which hamper safe and reliable operation. Due to the interdependent nature of critical infrastructures (CI), resilience assessment requires a whole stakeholder approach which engages not only transport operators, but also the various other infrastructures within a geographical area. This paper initially outlines the ICARUS project which aims to deliver a common approach for National Road Authorities (NRAs) in addressing the resilience of road infrastructure to Climate Change. Results of the PRECINCT project are presented subsequently, where the influence of other infrastructure systems on transport was investigated. There is a clear link between how resilience is currently addressed within one transport sector and across various interconnected CIs. The results of the paper show the importance of effective stakeholder engagement across the value chain of Critical Infrastructure.

Keywords: Resilience · Climate Change · Transport · Infrastructure · Hazard

1 Introduction

The European internal market is heavily dependent upon the CI therein, which provides key services to the users while also facilitating trade and movement of goods and people within and throughout the market. The myriad of threats to which CI is exposed to pose a significant threat to the efficient operation of the internal market, as well as pose threats to the personal safety of users. The threats posed by natural disasters such as flooding, earthquakes and extreme temperatures have been historically well documented and dealt with in the literature [1]. In the era of climate change, these hazards are occurring more frequently to the extent where CI owners are forced to take action. More recently, CIs have also become exposed to man made threats such as physical terrorist attacks and cyber hazards [2]. This combined cyber-physical threat has added another dimension to the problem, which requires a coordinated response at both the local authority / city level, as well as a cooperative approach.

In order to address these issues, the concept of CI resilience has evolved recently to address all aspects of the Disaster Management Cycle [3]. Resilience is generally

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considered as the capacity of a system, community or society potentially exposed to hazards to adapt, by resisting or changing to reach and maintain an acceptable level of function and structure. This may be in response to a climate hazard (e.g. flooding, hurricane), natural hazard (e.g. earthquake), or a man-made hazard such as a cyber-attack or terrorism. Recent EU directives [4] require CI operators and city managers alike to respond to these hazards through consideration of Resilience.

This requirement to consider a holistic resilience perspective has led to funding of various research projects in the area. This paper will describe two such projects, as illustrated in Table 1.

Table 1. Project focus

Acronym	Full Title	Focus
ICARUS	Improve the uptake of Climate change Adaptation in the decision making processes of Road aUthoritieS	Building Climate Change Resilience to National Roads through consideration of service levels
PRECINCT	Preparedness and Resilience Enforcement for Critical INfrastructure Cascading Cyberphysical Threats and effects with focus on district or regional protection	Resilience of multi-modal CI networks through resilience quantification

2 ICARUS

2.1 Aim of the ICARUS Project

In the face of the ever-changing climate, the ICARUS project aims to build and implement the business case for resilience via adaptation, balancing the service levels that the road network needs to achieve with the costs and benefits for enhancing resilience. The three primary work packages of the project include:

1. Impacts and Operational Risks
2. Adaptation and resilience measures to achieve minimum viable service levels
3. Appraisal Methodologies, Benefit and Costs

The project further elaborates these ideas through investigation of international case studies and development of Terms of Reference for demonstrator projects. As part of work package 2 above, two stakeholder engagement workshops were carried out in order to establish the baseline in resilience assessment / minimum viable service levels, as well as to characterise mitigation measures to climate impact drivers.

2.2 Findings from Stakeholder Engagement

Baselining current practice. To get an understanding of the current State of the Practice in the use of service levels for climate adaptation and resilience, the ICARUS consortium

undertook a workshop engaging key stakeholder groups including Department of Transport, Local Council, NRAs, Infrastructure Owner, Infrastructure Company and National Infrastructure Authority.

The State of the Practice demonstrates little or no formal quantification of resilience. The process of risk assessment is much more commonly used to indirectly enhance resilience. On the side of minimum service levels, it was found that while service level metrics exist (see Fig. 1), they are applied more for investigating the past or present performance of the infrastructure and are not used to evaluate and project the resilience of infrastructure against an uncertain future of climatic disruption. The primary barrier to resilience assessment and application of service levels appears to be in lack of data, lack of funding / resources for application, as well as the difficulties associated with an ever-changing environment, both physically and bureaucratically.

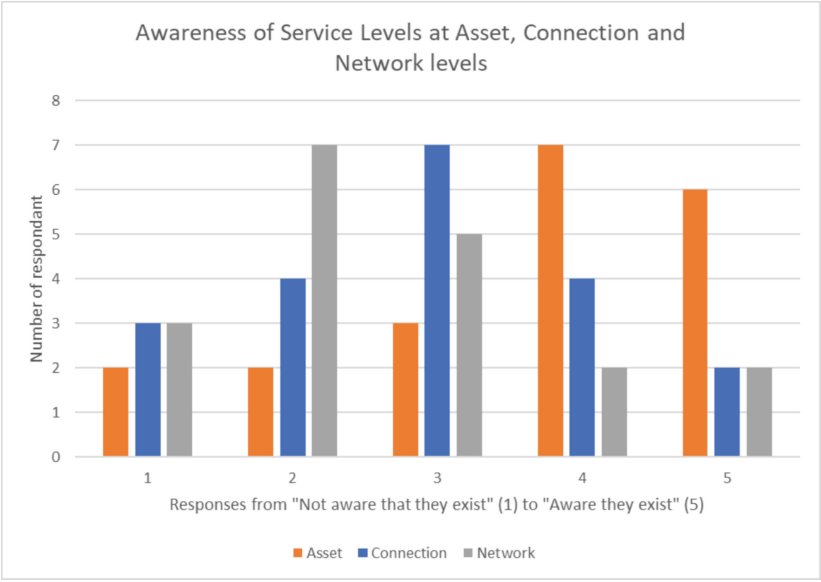


Fig. 1. Awareness of service levels at the asset, connection and network level

Characterisation of adaptation measures. To get an understanding of how adaptation measures are characterised and mapped to different climate impact drivers. This workshop was attended only by members of NRA member. In general, the stakeholders were familiar with how to implement climate change adaptation within their organisation. However, this adaptation was generally focussed on internal guideline development rather than actual implemented results. According to the stakeholders, the barriers to implementation were primarily internal, and related to:

1. Costs/funding.
2. Inability to determine long term needs.
3. Defining risk of a network on a strategic level.

4. Incomplete asset information/data.
5. Lack of engagement across the NRA.

The findings of the ICARUS stakeholder workshop will be used to develop guidelines for implementation of climate change adaptation and making a business case for mitigation measures. The wider stakeholder approach was found to be essential in order to obtain actionable results.

3 PRECINCT

3.1 Project Introduction

PRECINCT aimed to connect private and public CI stakeholders in a geographical area to a common cyber-physical security management approach which yields a protected territory for citizens and infrastructures, a 'PRECINCT' that can be replicated efficiently for a safer Europe. The project quantified resilience through a stakeholder engagement approach to gather relevant data and data sources.

3.2 Resilience and Cascading Effects

A key aspect to the PRECINCT project was the Resilience Methodological Framework (RMF) which provides a quantitative value for the Resilience Index (RI) for a CI system as well as the Return on Investment (ROI) for specific investment strategies. The steps involved in the RMF are as follows:

- **Step 1—Define Infrastructure System:** Environment, hazards, governance etc.
- **Step 2—Quantify Service:** What is the purpose of our Critical Infrastructure (€)?
- **Step 3—Estimate Losses in Service:** How do hazard impact services per state?
- **Step 4—Identify Resilience Indicators:** How can we change our response?
- **Step 5—Investigate Investment Strategies:** Impacts on Resilience and ROI

The RMF was programmed within a Cascading Effects Simulation (CES). The CES uses a directed interdependency graph to describe the involved Cis nodes and how they depend on one another in the sense that limitations in one CI may affect the other. More details are available in [5].

In order to calculate the RI, the Service must be quantified. This involves quantifying the overall value of the infrastructure in terms of all the relevant services represented. Examples might include the revenue of a motorway through tolling, or ticket revenues from a passenger train. The service should always be quantified in monetary terms to allow cross optimisation across different CIs.

Once the service has been quantified and attributed to nodes within the interdependency graph, the CES is run (i.e. the cyber-physical impact on the CI network is simulated) and the outcome state probabilities are evaluated. This allows calculation of the total losses in service. The baseline RI (before mitigation) is then given as:

$$RI = \frac{Total\ Service - Service\ losses}{Total\ Service} \tag{1}$$

It should be noted that the service must be calculated over an appropriate time period, considering the duration of the event and the recovery phase. In order to investigate actions which can be taken to enhance resilience, the PRECINCT project developed "Resilience Indicator" nodes within the CES. Deterministic state changes in these nodes have a direct impact on the nodes to which they have an edge. In this way, various different combinations of mitigation actions may be made across one Living Lab. In order to make decisions on optimum enhancement strategies, information is needed relating to not only how resilient the new CI is, but also, whether the strategy used will be the optimum from an investment perspective. For this reason, the ROI is defined by comparing the service value before investment (referred to as Stage 0) to the service value after the investment (referred to as Stage 1) as follows:

$$\mathrm{ROI} = \frac{\left(V_S^1 - V_S^0\right) + \left(V_{RS}^1 - V_{RS}^0\right)}{V_{CIP}^1 + V_{CInv}^1} \tag{2}$$

where,

Vs = Value of service,
$\mathrm{V_{RS}}$ = Value of Resilient service (services after losses due to hazard)
$\mathrm{V_{CIP}}$ = investment in infrastructure (no change in service).
$\mathrm{V_{CInv}}$ = investment in infrastructure (with change in service).

3.3 PRECINCT Living Labs

The PRECINCT RMF and CES was demonstrated in 4 Living Labs, as highlighted in Table 2.

Table 2. PRECINCT Living Lab CIs and hazards

Living Lab	CIs involved	Hazards investigated
Ljubljana	Telecoms, power supply, emergency response, rail transport, road transport	Cyber hacks and bomb (terrorism)
Antwerp	Water distribution, power supply, road transport, telecoms, healthcare	Flooding
Athens	Road transport, rail transport, airport	Cyber terrorism
Bologna	Power supply, telecoms, road transport, rail transport, airport	Rain and wind

Figure 2 illustrates a plot of resilience increase vs. ROI for various investigated resilience enhancements within the Athens Living Lab, which were assessed through the aforementioned resilience indicator nodes. Quantification of resilience in this manner across multiple CI sectors is a complex task which can only be logically carried out through stakeholder engagement and expert judgement. It was found throughout the project that development of a framework for resilience calculation for each Living Lab through engagement provided a platform to later apply more objective data to the

problem, such as ticketing information for service levels, monitoring data and historic cost information related to mitigation activities.

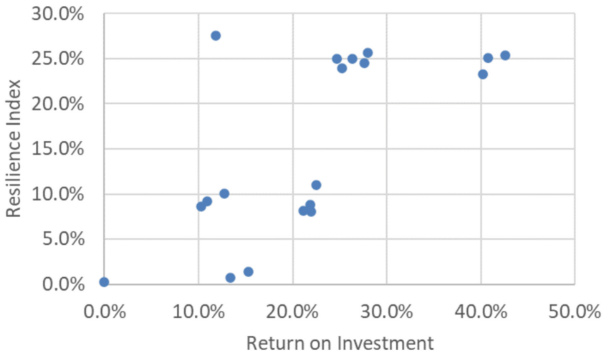


Fig. 2. Resilience increase Vs ROI for various mitigation actions for LL3 - Athens

4 Conclusions

This paper presented a snapshot of the PRECINCT and ICARUS projects, both of which are focussed on resilience calculation for Infrastructure. Although there are major differences in the approach to resilience, the results show the benefit of early stakeholder engagement in the resilience calculation in order to develop meaningful and actionable results.

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Probability Based Pavement Asset Management on the Irish National Road Network

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Abstract. The paper provides a research investigation focused on applying Markov Processes to ascertain the most effective approach for managing the lifecycle of a pavement network. It provides an extensive examination of condition data collected from the Irish national road network, overseen by Transport Infrastructure Ireland (TII). The study develops Transition Probability Matrices (TPMs) for various condition indicators, taking into account factors like Annual Average Daily Traffic (AADT). Additionally, it discusses the merits of using homogeneous versus non-homogeneous chains. In conclusion, the paper underscores the pivotal role of probabilistic techniques in the realm of pavement asset management.

Keywords: Pavement · Probability · Asset Management · Markov Processes · Transition Probability Matrices · Ireland

1 Introduction

Deterministic Pavement Deterioration models are widely employed due to their simplicity, user-friendliness, and widespread recognition. These modeling techniques encompass straight-line extrapolation, S-shaped curves, polynomial constrained least squares, and logistic growth models. However, deterministic models come with certain drawbacks, such as: (i) they do not consider the uncertainties associated with pavement behavior under varying traffic loads, (ii) their development necessitates an accurate and comprehensive dataset and (iii) ideally, deterministic models should incorporate all variables that influence pavement deterioration.

In the conventional approach, pavement deterioration models typically forecast either an absolute condition value for a given pavement age or the year-to-year incremental change in condition. When dealing with modeling uncertainties, probabilistic methods become necessary. Among these probabilistic models, the Markov model stands out as the favored method for modeling pavement performance. Markov probabilities can be derived from as few as two years of pavement condition data collection. A vital element within the Markov model is the transition probability matrix (TPM), which encapsulates the likelihood that a segment will remain in a particular condition for a given year. Generally, the TPM is calculated based on the historical pavement condition data.

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There are large variations in construction type, pavement condition and traffic volumes across the Transport Infrastructure Ireland (TII) network (McGowan et al. 2023). Accordingly, TII have broken the network into sub-networks based on construction (engineered or legacy) and traffic volumes to more effectively manage the network overall. This approach has led to 5 Sub-networks being established, enabling different levels of service, treatment strategies, intervention effects, intervention costs etc. to be applied as appropriate. The 5 sub-networks are: Subnetwork 0 (1200 km) —Motorway and dual carriageway; Subnetwork 1(1200 km)—Engineered Single Carriageway; Subnetwork 2 (700 km)—Urban Pavements; Subnetworks 3 (1300 km) and 4 (1000 km)—Legacy Single Carriageway. TII consider Key Performance Indicators (KPI's) using the qualitative descriptors of Very Good, Good, Fair, Poor and Very Poor. Currently these condition classes are defined separately for the key pavement performance parameters of International Roughness Index (IRI), Rut Depth (RUT) and Longitudinal Evenness (LPV3). Estimations obtained using Markov transition probabilities are used to evaluate, probabilistically, the relative condition of a network as a function of time. Individual TPMs are developed for each sub-network, reflecting the very large difference in pavement response across sub-networks. The process makes possible the evaluation of the implication of alternative maintenance scenarios on network condition and to optimise budget spend as a function of time to maximise the condition of the network or to maintain the condition of the network above a prescribed limit, i.e. no more that 25% in Fair condition by Year X. Furthermore, alternative thresholds for condition states are analysed. TPMs are presented in the context of either homogenous and/or inhomogeneous chains, i.e. TPM's varying as a function of the considered time step. The results of the work provides TII with an extremely powerful asset management tool for optimal lifecycle management of its >5000 km pavement network.

2 Markov Chain Modelling of Pavement Deterioration

Markov chain modelling is a probabilistic method that is used in a variety of pavement management systems (Kulkarni, 1984, Carnahen et al., 1987, Thompson et al., 1987, Butt et al. 1987, Butt, 1994, Corotis et al., 2005, Costello et al., 2005, Hassan et al., 2015) to build probabilistic models that predict pavement degradation. Markovian models require an initial condition state vector and a TPM. The number of TPM's is conditional on the system's homogeneity; if the degradation of the network is constant throughout time, one TPM suffices for the model, but variability in network degradation requires more than one TPM. The future state of pavement intervals depends on the present state of the intervals, not the past state/s, which is a feature of Markov models.

In applying Markov chain modelling to the problem of pavement degradation, the condition states of the pavement segments are assumed to range from State 1, which represent the proportion of the pavement segments in near-perfect condition, to State n, which represent the proportion of the pavement segments in very poor condition, i.e. the pavement segment is completely damaged/degraded. The present/current condition of the pavement segments is represented as a vector and it is named the Initial condition state vector with notation a_0:

$$a_0 = (State\ 1, State\ 2, \ldots, State\ n) \tag{1}$$

In the context of Markov chain modeling, TPMs are utilized to anticipate the forthcoming condition of pavement segments as they deteriorate over time. These transition probabilities are organized within a matrix, where the rows signify the current state, and the columns signify the future state. The elements within the TPM are denoted as p_{ij}, where 'i' designates the row and 'j' signifies the column of the matrix element. Table 1 showcases the typical structure of a 5 × 5 transition matrix.

Table 1. General form of a Transition Probability Matrix, P.

Moving from State ***i***	To State ***j***				
	State 1	State 2	State 3	State 4	State 5
State 1	p_{11}	p_{12}	p_{13}	p_{14}	p_{15}
State 2	0	p_{22}	p_{23}	p_{24}	p_{25}
State 3	0	0	p_{33}	p_{34}	p_{35}
State 4	0	0	0	p_{44}	p_{45}
State 5	0	0	0	0	$p_{55} = 1$

The following six rules must be considered when developing transition matrices:

1. Transition probabilities, p_{ii} (p11, p22, p33, p44)—main diagonal denote the proportion of the pavement segments remaining in condition i after one time step (e.g. 1 year) has passed.
2. Values below the main diagonal are generally represented with zeros, suggesting that the pavement segments condition cannot improve without treatment (pij = 0 for i > j). Where improvements/repairs are modelled the lower diagonal is non zero.
3. Values above the main diagonal indicate the probability of the pavement segments in condition i moving to a lower condition within one time step.
4. The element p55 equal to unity suggest that the pavement segment has reached its worst state of degradation and cannot deteriorate further.
5. All elements of the matrix should be positive.
6. The sum of elements in each row should be equal to 1.0.

The elements of a TPM may be calculated based upon survey data using Eq. 2 (Ortiz-García et al. 2006):

$$p_{ij} = N_{ij}/N_i \tag{2}$$

Where *Nij* signifies the total count of pavement segments transitioning from state *i* to state *j* following one time step, and *Ni* represents the total number of pavement segments in state *i* at the beginning of the time step.

Table 2 provides a numerical example of a TPM. The table considers the following condition states: Very Good (VG), Good (G), Fair (F), Poor (P), and Very Poor (VP). The defined threshold values for each performance indicator's condition state adhere to the specifications of the managing authority. In Table 3, the classification system adopted for each subnet by TII can be observed.

Table 2. Numerical Example of a Transition Probability Matrix.

Moving from State *i*	To State *j*				
	VG	G	F	P	VP
VG	0.9	0.08	0.01	0.005	0.005
G	0	0.8	0.1	0.07	0.03
F	0	0	0.7	0.2	0.1
P	0	0	0	0.6	0.4
VP	0	0	0	0	1

The top row in Table 2 displays the probabilities of pavement segments in very good (VG) condition transitioning to any of the good, fair, poor, and very poor conditions. Specifically, there is a 0.90 probability that pavement segments in very good condition will remain in the same very good condition, signifying that 90% of these segments will not deteriorate after one time step. Among them, 8% are expected to degrade to good condition, while only 1% will downgrade to a fair condition. Additionally, a combined 1% will transition from very good to poor and very poor conditions.

The third row represents the transition probabilities for pavement segments in fair (F) current condition. In this case, there is a 0.70 probability of staying in the same fair condition. However, without repair works, pavement segments cannot move to a better condition (good or very good), resulting in values of 0 (zero) in the columns associated with these two conditions. Instead, there is a 0.20 probability of transitioning from fair to a poor condition and a 0.10 probability of moving from fair to a very poor condition.

By utilizing Eq. 2 in conjunction with the survey data collected on TII's network at 100-m intervals from 2010 to 2019, taking into account parameters such as IRI, LPV, and RUT, TPMs were established for Subnets 0, 1, 2, 3, and 4. The distribution percentages across the network are thus determined.

Moreover, when formulating the TPMs for different Subnets, the consideration of traffic volume, specifically AADT (Annual Average Daily Traffic), played a significant role in distinguishing between TPMs. To illustrate this, for Subnet 0, TPMs were created for three distinct AADT categories: AADT <20,000, 20,000 < AADT <40,000, and AADT >40,000.

After defining both the initial vector and the TPM, Eq. 3 can be employed to determine the probability distribution of the condition states at any particular time, t:

$$a_t = a_0 P^t \tag{3}$$

Where a_0 is the initial condition vector, P^t trepresents the TPM raised to the power of t, t is time in years, and a_t depicts the distribution of pavement segments condition at time t.

Markov chain modelling can be used in this way in evaluating the condition of an asset or a network of assets throughout their lifespan. Estimations obtained using Markov transition probabilities can be used to evaluate, probabilistically, the relative condition of a network and its assets as a function of time. Evolution of individual indicators can

be analysed or combined indicators can be developed. The process makes possible the evaluation of the implication of alternative maintenance scenarios on network condition and to optimise budget spend as a function of time to maximise the condition of the network or to maintain the condition of the network above a prescribed limit, i.e. no more that 25% in condition X by Year Y. Furthermore, alternative thresholds for condition states can be analysed. Significantly, TPM's may be developed for either homogenous and/or inhomogeneous chains, i.e. TPM's varying as a function of the considered time step and condition state (Butt et al., 1987).

TPMs were constructed for three condition indicators (IRI, RUT, LPV3) using data collected from 2010 to 2019. The data used for TPM development was gathered in alternating odd and even years on opposite sides of the roadway, specifically with surveys conducted in direction 1 during even years and direction 2 during odd years. To validate the TPMs created, several alternative validation scenarios were taken into account.

3 Pavement Management Strategies

With the TPMs developed and validated for the Irish network, it is now pertinent to utilize them in defining the most effective maintenance strategy for the network, subnet by subnet, over a designated time frame, such as 20 years. In this process, it is imperative to identify potential treatment options, assess the costs associated with these options, and establish suitable thresholds for their application.

In the temporal analysis subsequent to repair actions, two strategies were employed to model inhomogeneity: (a) TPMs were formulated to depict the behavior of enhanced segments, and these were applied after an intervention and (b) when a reconstruction was executed on a non-engineered pavement (specifically Subnet 3 or 4), the performance was reclassified to be represented by the TPM corresponding to an engineered pavement.

Based on this treatment trigger strategy and by utilizing the probabilistic deterioration models associated with AADT, as derived from recorded data and validated as previously described, it becomes feasible to determine the set of optimal interventions for a pavement network within a specified time frame, as illustrated in Fig. 1. Additionally, it's worth considering whether a 'hybrid' indicator, combining various individual indicators, should be employed, as suggested by COST 354 (2008).

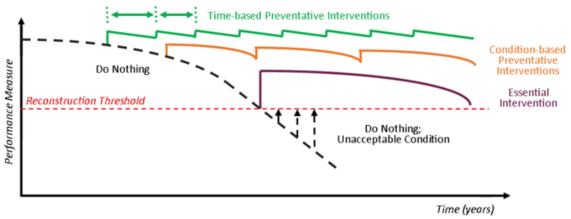


Fig. 1. Optimising Pavement Lifecycle Strategy.

As an illustrative example, Fig. 2 illustrates the network's condition as influenced by an optimized set of interventions for (a) a Do-Nothing scenario and (b) a Budget A intervention scenario. This optimization was carried out using the dTIMS software, which is

TII's Pavement Asset Management (PAM) system. In the Do-Nothing scenario, it's evident that the network experiences substantial deterioration over the specified time horizon. Conversely, in the budget intervention scenario, the network tends towards a more stable condition. It's important to note that an additional constraint on the optimization may pertain to the percentage of the network in a "Good" or better condition.



(a) Do Nothing (b) Budget Scenario A

Fig. 2. Analysing Altergative Budget Scenarios.

4 Conclusions

The objective of this paper is to introduce the calibration of TPMs for three pavement characterization parameters. These matrices, which represent the likelihood of transitioning between different condition states, are fine-tuned using survey data collected over a span of several years. Subsequently, these TPMs are incorporated into a Markov Process to forecast how condition states evolve over time and predict condition as a function of time. When coupled with various pavement management strategies, this process can be employed to anticipate the network's condition under different budget scenarios. Moreover, the methodology finds applications in Risk-Based Asset Management initiatives, facilitating the optimal management of network performance.

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Risk Based Management of Bridges in Ireland

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Abstract. The purpose of this paper is to present an overview of the state of the art in terms of Bridge Management Systems (BMS's) and the application of risk-based approaches to the management of bridges. In this regard a review of international best practice in the development of BMS's is presented along with the types of functionality which they can offer and the direction they are taking in state-of-the-art asset management. Significantly, the enhanced functionality of BMS's is demonstrated to build upon existing/traditional information and data set structures to facilitate decision making around intervention strategies and budgeting. It is demonstrated that at their core, BMS's make use of processes such as Markovian Processes (which can be homogenous or non-homogeneous) to predict condition as a function of time horizon. This has been the case for the past couple of decades with many international examples of successful implementation documented. Indeed, one such example is presented in an Irish context where the Markovian formulation is developed using available datasets. As such it is demonstrated that there are no operational barriers to implementing these processes formally to enhance BMS functionality and facilitate decision making around optimal intervention strategies and budgeting. Best practice internationally is demonstrated to be moving to asset lifecycle management which has risk evaluation at its core. Current examples are presented from international organisations to highlight this move. Risk based decision frameworks offer the possibility to work with the enhanced functionality of a BMS to provide for consideration of inspection frequencies for bridges/structures in different risk groups, and moreover for budget allocation decisions to be made based on risk from safety, economic, sustainability and resilience perspectives.

Keywords: Bridge Management Systems · Risk Based Approaches · Resilience · Markov Models · Probabilistic Modelling · Asset Management · Lifecycle Optimisation

1 Introduction

Bridge Management Systems (BMS) are used by Authorities to ensure the safety and performance of the bridge stock at minimum cost. The NCHRP (The National Cooperative Highway Research Program) Report 300 was the first BMS framework published in 1987 [1]. Since then, BMS methodologies have been continuously evolving [2, 3] to satisfy the needs and requirements of the transportation agencies worldwide.

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The traditional structure of a BMS includes four main features as follow: *inventory*; *inspection*; *maintenance, repair, and rehabilitation (MR&R)*; and *optimisation.* The Inventory feature consist of bridge stock data. The Inspection feature comprises of inspection data used to determine the bridge condition state. The Maintenance, Repair and Rehabilitation (MR&R) feature monitors short and long-term action plans. Finally, the Optimisation feature integrates the previous three features for optimal budgetary allocation.

The EIRSPAN BMS, employed by Transport Infrastructure Ireland (TII), [4, 5], is an online platform designed for the purpose of prioritizing maintenance requirements for road bridges in Ireland and optimizing the utilization of available funds, managed by TII. The foundation of the EIRSPAN system lies in routine bridge inspections and maintenance. Bridges are ranked on a scale from "0" indicating the best condition, to "5" signifying the worst condition. The initial ranking of a bridge is automatically computed, taking into account the overall condition of the bridge and the volume of traffic it handles. The final ranking can be adjusted manually based on additional factors, including but not limited to alternative routes or prospective plans to bypass the bridge, which are not factored into the initial ranking. The EIRSPAN system generates outputs that include the condition rating of the bridge and its individual components, along with personalized reports for specific components or all components of the bridge.

The latest BMS methodologies consider factors like safety, mobility and environment sustainability in their predictions and budget allocation for bridge stock management [2]. These factors gained consideration as a consequence of functional characteristics of bridges and the risk that hazards could cause service disruption. Thompson et al. [6] declares that a BMS that includes the factors mentioned above has the potential to assist the bridge owner in determining the inspection frequencies for bridges/structures in different risk groups. Moreover, budget allocation decisions may be made based on risk.

According to FHWA, risk management is the *"process and framework for identifying, evaluating, and managing potential (threats)"*. The New York DOT defines risk management as the *"identification, assessment, and prioritization of risks followed by coordinated and efficient application of resources to monitor risk, mitigate threats and maximize the realizations of opportunities"*.

The World Road Association (PIARC) recommends in the *Risk-Based Management of the Bridge Stock* [7] a simplistic risk-based analysis approach be adopted in the management of bridge networks that is based on a three-criteria assessment: *hazard*, *vulnerability* and *consequences.*

2 Markovian Based Bridge Management

Markovian based maintenance management is used in practice as part of existing BMS such as PONTIS and BRIDGIT. A Markovian model can be used to predict the deterioration of a structure from one condition state to another over time. With the development of Markov chains predictions can be made on the level of future deterioration of structures. A Markov process has the property that the probability of an event occurring (i.e. moving to the next condition state) is independent of past states and only depends on

the condition state it is in at the present point in time and the action applied to it. This is known as the Markovian Property. Also, using a Markov process, the deterioration is modelled as discrete condition states rather than a continuous deterioration process. Although the condition of the structure is recorded using discrete states and at discrete times using a Markovian based methodology, the physical process of deterioration of a structure is relatively stable, and inspections and maintenance are carried out at discrete times, therefore the state of a structure is only required at these discrete times. This approach is applicable in Ireland as the inspection regime is well established and there is time-based condition data available for almost 20 years.

According to Markov theory:

$$P(t) = P_0 \times P^t \tag{1}$$

where

$P(t)$ is the probability of being in a particular state i at time t.

P_0 is the initial state vector.

P^t is the Transition probability Matrix (TPM).

Figure 1 illustrates an example of a TPM. Six rules must be considered when developing TPM's:

1. Transition probabilities, p_{ii} ($p_{11}, p_{22}, p_{33}, p_{44}$)—main diagonal, denote the proportion of the bridge elements remaining in condition i after one time step (e.g. 1 year) has passed.
2. Values below the main diagonal are generally represented with zeros, suggesting that the bridge elements condition cannot improve without treatment ($p_{ij} = 0$ for $i > j$). Where improvements/repairs are modelled the lower diagonal is non zero.
3. Values above the main diagonal indicate the probability of the bridge elements in condition i moving to a lower condition within one time step.
4. The element p_{55} equal to unity suggest that the bridge element has reached its worst state of degradation and cannot deteriorate further.
5. All elements of the matrix should be positive.
6. The sum of elements in each row should be equal to 1.0

TPM's may be developed for either homogenous and/or inhomogeneous chains, i.e. TPM's varying as a function of the considered time step however this requires detailed temporal information regarding interventions.

$$P = \begin{bmatrix} p_{11} & p_{12} & p_{13} & \cdots & p_{1n} \\ 0 & p_{22} & p_{23} & \cdots & p_{2n} \\ 0 & 0 & p_{33} & \cdots & p_{3n} \\ : & : & : & & : \\ 0 & 0 & 0 & \ldots & 1 \end{bmatrix}$$

Fig. 1. Example of a TPM

[5] used cross-entropy based optimization as a viable alternative to traditional optimization solvers in estimating transition probabilities for bridge deterioration on the network operated by TII. Families of structures were created from the EIRSPAN database to extract subsets such as reinforced and prestressed concrete structures, steel structures etc. The geographic proximity to the coast was also considered in developing the subsets. Working with these datasets [5] successfully predicted evolution in condition as a function of time as a basis to determine optimal intervention strategies considering specification of minimum performance/condition criteria for the network/subsets of the network. The approach facilitates a multiple step risk-based management system for bridge structures on the network employing the Markov transition matrices to assess condition at a point in time and as a function of time.

Agrawal et al. [8] employed the Weibull distribution and Markov Chain approach to model approximately 30 years of bridge inspection data to estimate the degradation rates for various elements of bridges in New York State. The NYSDOT uses these estimations in their 5- and 10-year budget prioritization plans [9]. proposed a budget optimization model for a cost-effective management strategy for the bridge stock in France. Risk Based Bridge Management

A *Guideline for Risk Assessment for Bridge Management Systems* was developed under NCHRP Project 20–07, Task 378, authorized by AASHTO [6]. demonstrates that the risk assessment integrated with the bridge management system framework (Fig. 2) represents a significant advance to assist life cycle cost analysis in determining the project benefits.

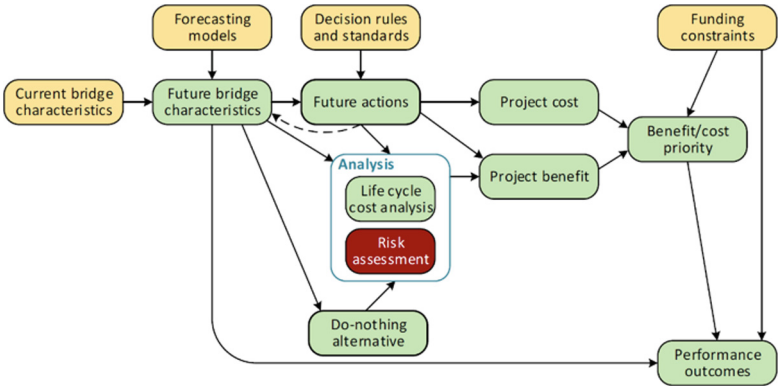


Fig. 2. Risk Implication in a BMS [6]

The Guideline proposes a risk analysis methodology that bridge management agencies could customize depending on their needs and the hazards to be considered in the BMS analysis—Fig. 3. It is suggested that the agency shall be consistent across all bridges when defining the hazard scenarios and performance criteria.

Internationally the move is towards the development of risk based asset management frameworks, which at their heart incorporate the advanced functionality which modern BMS's have to offer. In this context they do not seek to replace or remove the need

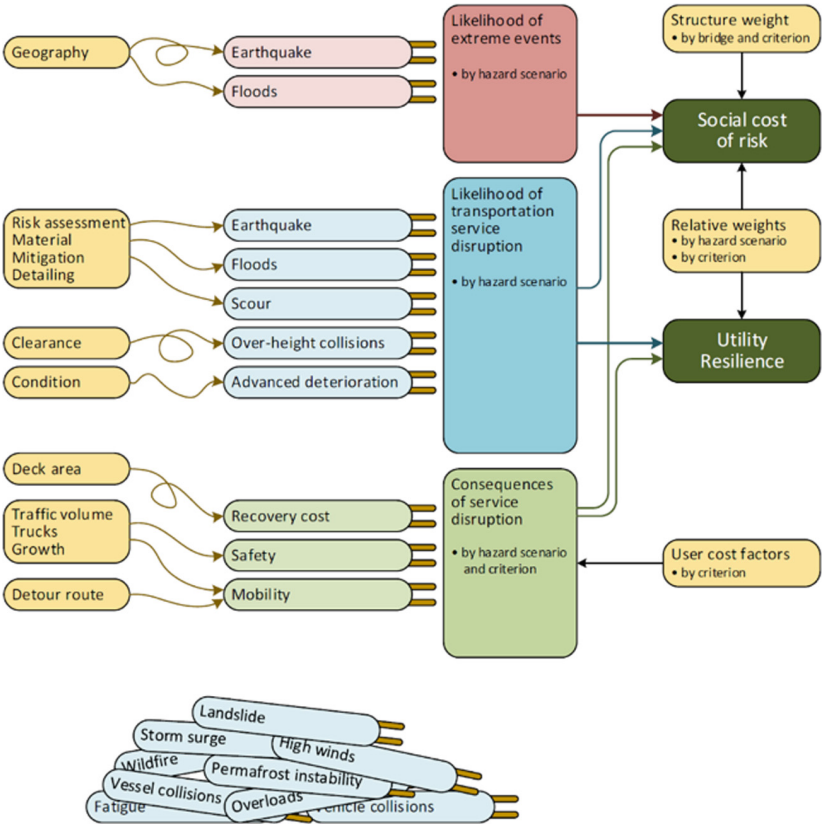


Fig. 3. Risk Implication in a BMS [6]

for BMS's but rather to augment them, by incorporating the outputs of their developed functionality into decision making process around optimal lifecycle asset management which consider risk and risk acceptance thresholds as the decision metric both from a safety and economic perspective.

3 Conclusions

The state of the art in terms of BMS's and the application of risk-based approaches to the management of bridges in Ireland is presented. The enhanced functionality of BMS's builds upon existing information to facilitate decision making around intervention strategies and budgeting. BMS's make use of processes such as Markovian Processes to predict condition as a function of time. This has been the case for the past couple of decades with many international examples. There are no operational barriers to implementing these processes to enhance BMS functionality and facilitate decision making around optimal intervention strategies and budgeting. Best practice internationally is moving to asset lifecycle management which has risk evaluation at its core.. Risk based decision

frameworks offer the possibility to work with the enhanced functionality of a BMS to provide for consideration of inspection frequencies for bridges/structures in different risk groups, Markovian processes and budget allocation decisions to be made based on risk both from safety and economic perspectives. The stages are clearly identified whereby enhanced functionality of BMS's becomes the foundation stone for a risk-based asset management process.

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Cooperation Between a Human Traffic Manager and an AI Assistant for an Improved Railway Infrastructure Resilience

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Abstract. This article deals with railway traffic management, which includes tasks such as traffic planning, resource allocation, service adaptation and passenger information. Operators monitor the real-time movement of trains, passengers and resources, mitigate unexpected events and ensure safety. Human operators currently perform these complex tasks using their expertise. However, technical aspects of railways and concurrent disturbances increase cognitive load and biases, affecting traffic management and passenger satisfaction. To address these challenges, we propose an AI-based railway traffic manager assistant that combines Machine Learning (ML) and Human-Machine Interaction (HMI) to support operators in their daily tasks and assists them to make decisions when facing critical situations. This article outlines the design approach and introduces the initial assistant version. User-centred evaluation yields preliminary results from limited-scale experiments.

Keywords: Railway Operations · Resilient Systems · Decision Support · Reinforcement Learning · HMI · Cognitive Workload

1 Introduction

Operational rail supervision consists in monitoring traffic, anticipating disruptions and reducing their impacts. It aims at ensuring the resilience of the railway operations and the quality of passenger information. In this project, we are particularly interested in the supervision of passenger train movements. Trains, resources and passenger information must be monitored in real-time over a large area. Services must be adapted when disruptions occur. To carry out this activity, operators: (i) utilise situational awareness tools (e.g. real-time train location, passenger information); (ii) ponder various mitigation scenarios (e.g. delaying or canceling some trains, transferring passengers to another train); and (iii) make collaborative decisions regarding the ultimate course of action. According to [6], performance depends on the complementarity between operators, operational

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tools, and the working environment. In France, the current work environment design relies on verbal exchanges and numerous tools (see [9]). Human operators must then aggregate and digest large amounts of information. While the process is time-consuming and mentally demanding, decisions must be taken rapidly. Furthermore, incidents tend to propagate. In this context, the mental load may hamper operators in understanding the overall situation [5] and act [1,7].

Operational disruptions cannot be solved following a pre-established plan: mitigation rather involves exploring a set of strategies and balancing their characteristics (e.g. impact on passengers, delays). Tools based on operational research have already been developed, but fail to match completely the needs of the operators. For instance, the strategies automatically suggested are not always understood by an operator, who may reason differently. Moreover, these algorithms rarely capture human expertise and seldom allow to share experience feedback when similar situations occur [12].

For these reasons, user-centred design seem more relevant to create efficient decision support tools. Following the progress of ML on cognitive tasks, we decided to create an AI-based assistant that leverages state-of-the-art RL algorithms and includes bidirectional features. In this paper, we introduce an AI-based assistant for railway traffic management that should (1) provide the user with comprehensive insights on the situation; (2) quickly process the most demanding parts of the decision-making; (3) learn both from real-life samples and from the experience of the operator it assists; (4) investigate unexplored contingency plans.

2 Related Works

Several studies have been conducted in the field of railway supervision, such as research on real-time rescheduling [2] and rescheduling through stop-skipping [3] in densely populated railway systems. In other studies, the promise of AI, especially Deep Reinforcement Learning (DRL), in the context of railway planning and scheduling was acknowledged. In general, DRL merges the capabilities of deep learning (DL), able to handle complex and vast problems, with reinforcement learning (RL) a generic and flexible framework for making sequential decisions. This integration introduces a new and potent AI tool that is increasingly gaining traction in the domains of autonomous decision-making and operational control. In particular, DRL can be highly beneficial in the domain of transportation systems, specifically in traffic management systems by automating numerous road control strategies, such as speed limit control, ramp metering, lane pricing, etc., which in turn enhances highway safety and mitigates congestion [4]. Other methodologies demonstrated that DRL agents excel at dynamic real-time rescheduling. In [8], the authors proposed a multi-agent deep reinforcement learning-based approach with different state representational choices to solve the real-time railway rescheduling problem by comparing three environment representation methods and three different solutions. In [11], Ning et al. proposed a solution to minimise the average total delay for all trains along

the railway line where an agent is responsible for adjusting running time and generating instructions of departure sequences, aiming to maximise passenger satisfaction and minimise the average total delay for all trains along the railway line. The learning agent is responsible for adjusting train travel times, waiting times and departure sequences, and conflicts are resolved simultaneously.

3 Research Background

In this section, we focus on defining the main research topics of our study, i.e. Bidirectionality and Reinforcement Learning.

Bidirectionality. Our design approach aims to (1) promote collaboration between the AI assistant and the human operator, (2) centralise expert knowledge for sharing and training. We explore the concept of *bidirectionality* to favor mutual learning between the AI assistant and its user. A literature review revealed two core features: *bidirectional learning* and *knowledge transfer*. Figure 1 depicts how we have implemented bidirectionality using RL.

Bidirectional learning enhances collaboration through a simultaneous exchange of behaviors and mental models. It involves two phases: communication and interaction. In the former, each agent explicitly shares its understanding, state and intentions [13]. In the latter, agents adapt their behavior to each other based on ongoing interaction and dynamic mutual understanding.

Knowledge transfer explores how a neophyte agent can absorb the experience of an expert agent [14]. This concept extends to human-machine interactions, regardless of who acts as the expert. Scenarios include distilling domain expertise to an AI that shares it back to untrained operators.

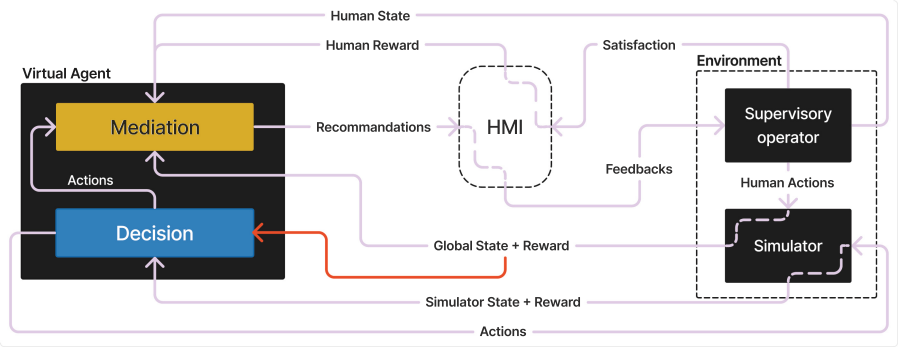


Fig. 1. Bidirectional interactions between our assistant and a human operator. The decision block ensures knowledge transfer. The mediation block enables bidirectional learning. Both components are trained using RL.

Reinforcement Learning (RL) [15] is a type of machine learning paradigm where an agent learns by interacting with its environment to achieve a specified

goal. The foundational principles rest on the agent making sequences of decisions, receiving rewards or penalties as a feedback, and refining its strategies or exploring others to optimise future rewards.

At its core, RL involves the agent observing the current state s of the environment, choosing an action a, based on a policy, and then receiving a reward r from the environment. The goal of the agent is to find an optimal policy that maximises the expected cumulative reward over time.

Function approximation – particularly using deep neural networks (often referred as Deep Reinforcement Learning or DRL) – has made RL applicable to complex tasks involving large state and action spaces. Our model, which includes a railway environment simulator, uses DRL to capture intricate patterns and relationships, allowing our AI assistant to generate nuanced strategies, tailored to the specificities of traffic management.

An RL agent can leverage the expertise of the human operator as additional knowledge during its training phase. By observing the actions and decisions made by the human operator, the agent can derive insights into efficient strategies. Conversely, the strategies discovered by the RL agent can enrich the decision-making of the human operator. This reciprocal learning encapsulates the core of bidirectionality.

4 An AI-Based Bidirectional Assistant

The assistant we designed relies on a multi-services platform fed in real-time by Flatland simulator [10]. Figure 2 shows the main services of our assistant: (1) connectors to receive events and context from Flatland; (2) a service that notifies about failures, real-time train positions and statuses (3) an event and context tracker, that feeds our training dataset; (4) a recommender that provides mitigation strategies based on RL.

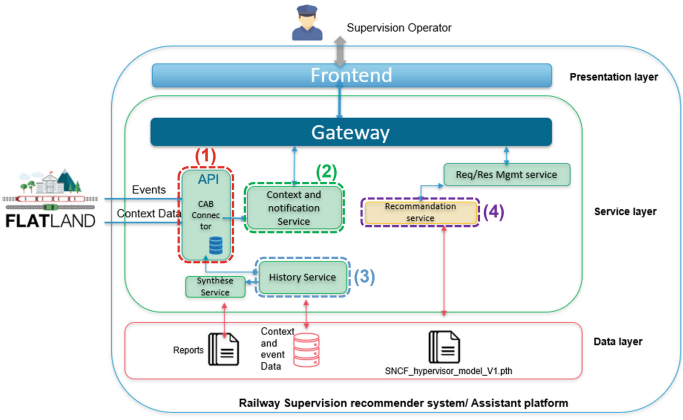


Fig. 2. Assistant architecture.

To favor bidirectional interactions, we designed our user interface following the user-centred approach [16]. Workshops were organised to involve operators in the design process. As a guidance, we proposed to split the user interface into four zones (see Fig. 3): (1) a list of the pending events pushed by Flatland; (2) a spatial visualisation of the context with the position of the trains; (3) a panel of mitigation strategies for a given event and their performance (e.g. delays, costs); (4) a temporal visualisation of the events. Through zone (3), the operator can request recommendations to the assistant, and choose or amend them. The proposal guidance is approved by end-users at a validation workshops.

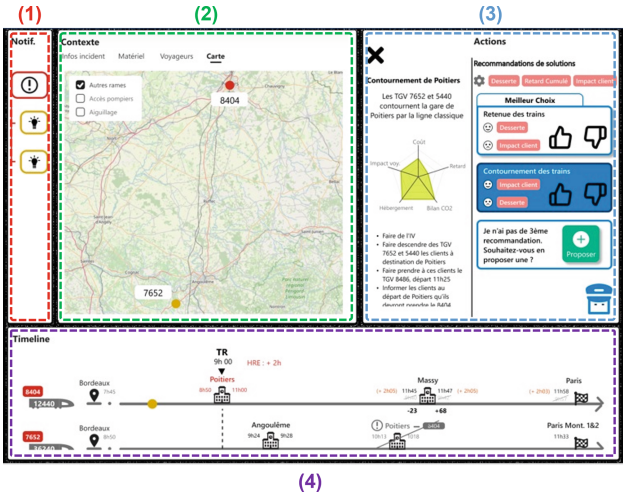


Fig. 3. Assistant HMI.

5 Conclusion

In this paper, we described a virtual assistant we have designed to help traffic managers mitigate disruptions more efficiently and more rapidly. We presented the specific needs of the human operators and proposed guidelines to match them. The tool we designed leverages the most recent progress in RL and is inspired by the concept of bidirectionality. As a result, it allows (1) to learn from experts, (2) to distillate knowledge to neophytes, and (3) to adapt its policy recommendations to the human operator it interacts with.

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Improving the Uptake of Climate Change Adaptation in the Decision-Making Processes of Road Authorities; Output of the ICARUS Project

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Abstract. The integration of climate change and resilience considerations into the decision-making processes of National Road Administrations (NRAs) represents a delicate balancing act between ambition and pragmatism. A critical question is how to establish and execute a decision case for resilience through adaptation, finding equilibrium between service level requirements for the road network and the costs and benefits associated with enhancing resilience.

The ICARUS project, funded by the Conference of European Directors of Roads (CEDR) emphasizes the importance of striking the right balance between service levels and costs, analogous to the mythologic figure Icarus flying neither too high nor too low.

While European NRAs acknowledge the impact of climate change on their assets and operations, the full integration of adaptation strategies remains a formidable challenge. The ICARUS project aims to bridge this gap by advancing the state of the art in climate change resilience assessments, impact evaluation, cost-benefit assessments, and the implementation of nature-based solutions, while providing practical guidance on how to use these methods for building the decision case and use in the daily processes of road authorities.

Keywords: Resilience · climate change adaptation · roads · decision case

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1 Climate Change Adaptation by Road Authorities

1.1 Current State of the Art and State of the Practice

Many European NRAs have long recognized that climate change will have a significant effect on their assets and operations, as well as on the services that the road network provides for society. Consequently, significant progress has been achieved by research conducted in the past decade (named are [1–5]). Conducting a resilience assessment has become relatively common practice and the forthcoming development of adaptation strategies has also been undertaken in many cases (named are [6–8]). However, the step to full implementation in all processes and across all organizational levels of the NRAs poses a significant challenge [9].

1.2 Aim of the ICARUS Research Project

Recognising the challenge for the implementation of climate change adaptation in National Road Authority (NRA) processes, the Conference of European Directors of Roads (CEDR) funded a transnational research call on the topic in 2022. The ICARUS project (2022–2024) is addressing these needs with the following key objective: to provide guidance on how to build and implement the decision case for resilience, by balancing service levels that the road network needs to achieve with the costs and benefits for enhancing resilience.

The ICARUS project will produce results that progress the current State of the Art and will be of immediate benefit to Road Authorities:

- An overview of the baseline for climate change resilience assessments, resilience evaluation and the use of cost benefit assessments for climate change adaptation
- A report on using impact chains to better understand direct and indirect impacts
- Guidelines on how to define and use minimum viable service levels for evaluating resilience and adaptation options based on quantification and valuation of associated costs and wider benefits and considering a whole life perspective
- Guidelines providing an overview and characterization of measures, aided towards implementation in the various NRAs processes (planning, design, construction, maintenance, procurement)
- Demonstration report showing how adaptation measures can be evaluated
- Report with success factors on implementing Nature Based Solutions,
- Resource training pack for different target audiences

This paper focusses on two outputs of the ICARUS research: (1) the understanding of climate change impacts and (2) guidance on how to make the case for adaptation.

2 Understanding Climate Change Impacts

2.1 Causal-Effect Relationships Between Assets and CIDs

Within the road sector, “impact” is almost always referred to as a negative consequence for the infrastructure due to a hazard or extreme weather event. Within ICARUS it is proposed to use the term impact-drivers that have another meaning. The concept of

Climatic Impact-Driver (CID) was developed in the IPCC Sixth Assessment Report (AR6). CIDs are physical climate system conditions (e.g., means, events, extremes) that affect an element of society or ecosystems [10].

In a first approach, IPCC classifies Climate Impact Drivers (CIDs) in extreme and slow-onset processes and trends. To establish the causality-effect relationships between CIDs and assets, it is mandatory to clarify the following concepts: (1) target area and road strategy, (2) direct damages and (3) indirect damages. These concepts are applied in the definition of impact chains presented in this paper (Fig. 1), which are based on four pillars: hazard, exposure, vulnerability, and impact. The target area and road strategy should be clear for assessing the vulnerability and exposure. Distinguishing between direct and indirect damages is key for the impact assessment.

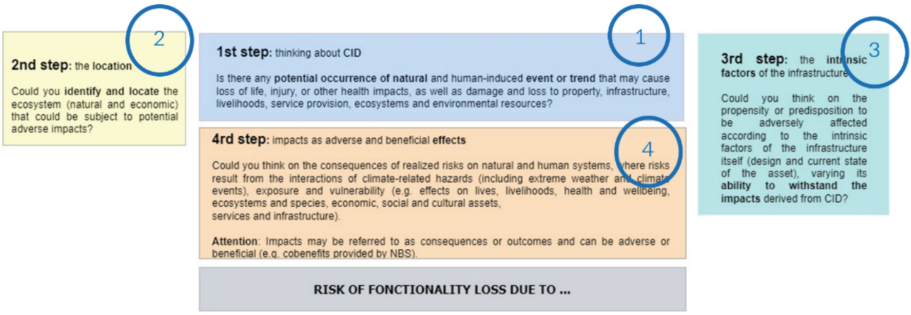


Fig. 1. General impact chain graph for hazards and road infrastructure, with steps referring to (1) hazard, (2) exposure, (3) vulnerability and (4) impact) [13].

2.2 Impact Chains for Road Assets

An Impact chain is an analytical concept to better understand, systemise and prioritise climate factors as well as environmental and socio-economic factors that drive climate related threats, vulnerabilities, and risks in a specific system. Impact chains serve as the backbone for an operational climate vulnerability assessment with indicators based on quantitative approaches (data, models) combined with expert assessments [11].

ICARUS proposes [12] the use of impact chains as a methodology to understand how the various climate hazards can impact the roads including, also, the opportunity for adaptive responses (grey and green solutions). In this regard, it's necessary to be aware that adaptive response to the impact chains may well have impacts of their own, for instance responses may drive up the carbon impact of the road.

The graph above shows the structure that is recommended to define impact chains. The methodology consists of answering the questions posed in each of the steps. It is a flexible methodology and should be adapted to the needs of each NRA. Although in ICARUS only the conceptual part is developed, the impact chains are the basis for the development of more sophisticated quantitative studies (e.g. Bayesian networks).

3 Making the Case for Adaptation

While the significance of resilience and climate change adaptation is well understood, practical implementation remains a challenge. Integrating climate change adaptation into decision-making processes can be complex, often resulting in a gap between knowledge and action. To bridge this gap, it is essential to determine how resilience and adaptation options can be effectively expressed to facilitate decision-making. Furthermore, it is key to understand how decisions are being made at road authorities.

3.1 Existence of a Tactical Gap

The decision-making process at NRAs is multidimensional and is done via different steering mechanisms; sometimes decisions are made via guidelines and design standards (often at asset scale), whereas other decisions are made based on Key Performance Indicators (which are described mostly at a network scale). These two levels often are referred to, as respectively input and output based steering mechanisms. The challenge of implementing climate change adaptation options within these decision-making processes of NRAs is complex due to the existence of a tactical gap [14]:

- It is not well understood how changes in guidelines and standards lead to different performance in terms of KPIs.
- The effect of climate hazards and climate change on KPIs is not well understood, further complicated by external factors like societal changes.
- There is limited understanding of how the effectiveness of adaptation options can be measured in terms of performance and changes in KPIs.

This tactical gap is further complicated by the fact that the metrics used at a network level to measure performance (KPIs) are different from the metrics used at the asset level for design and maintenance.

3.2 Use of Benefits and Co-benefits

Given the tactical gap identified, it is concluded that a translation is needed from the decision-making context (including the KPIs, other policies and other decision criteria) to an assessable metric for measuring resilience and effectiveness of adaptation options. This translation is done by applying the concepts of benefits and co-benefits. We distinguish between these two concepts by using the following rational:

- A benefit is directly linked to a KPI. For that purpose, the NRA needs to determine the benefits associated with achieving each KPI. For example, increased safety leads to fewer deaths on the road network.
- A co-benefit is a benefit that is not linked to a KPI. Co-benefits are the additional benefits that are achieved as a result of achieving the primary benefit. NRAs should identify the co-benefits associated with achieving each KPI, as much as possible linked to other policies that the NRA thrives for like environmental effects or road user needs. For example, a co-benefit of increased safety is less demand on emergency services.

The ICARUS guidelines [14] provide a list of benefits and co-benefits that NRAs may consider and provides guidance on how these benefits and co-benefits can be appraised for use in a resilience assessment as well as for valuation of adaptation options.

3.3 Three Approaches to Make the Case for Adaptation

In general, NRA's base decisions both on output steering via KPIs and input steering via guidelines. Many guidelines and policies are generally in place for organising the work. However, the budgets for these activities are likely to be determined via KPI performance. Hence, to be able to make the case for climate adaptation, the ICARUS guidelines [14] recommend three approaches as depicted in Fig. 2.

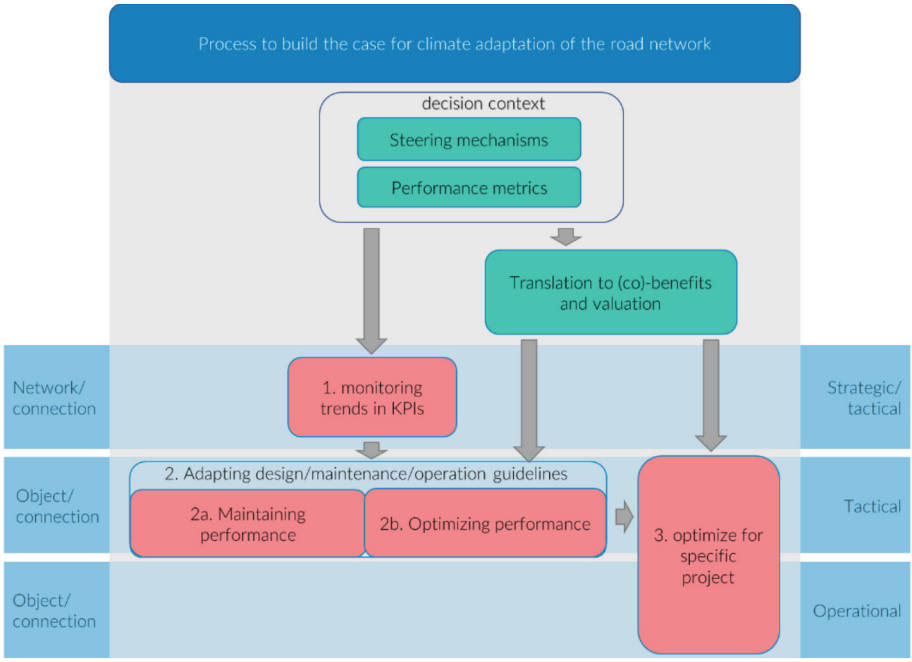


Fig. 2. Process to build the case for climate adaptation with 3 approaches in pink. The blue bars show the applicable road level, as well as the level of decision making at NRAs on the right.

Approach 1 involves gaining insight in the effects of climate hazards on road performance by analysing trends in KPIs and their correlation with climate threats. This helps to determine the need for adaptation and future performance changes.

Approaches 2a and 2b focus on changing guidelines and standards to incorporate climate adaptation. The former aims to maintain the current performance in the future, while the latter involves optimising performance by evaluating costs, benefits, and co-benefits associated with guideline changes.

Approach 3 addresses the need for adaptation on a project-specific basis, also addressing an optimum service level, while considering factors such as political concerns, past

climate events, and stakeholder involvement. It can also serve as a basis for optimising guidelines via approach 2b.

4 Conclusion

The ICARUS guidelines provide specific recommendations regarding using the concept of impact chains and the three approaches to build the case for decision making. This includes recommendations regarding cost benefit and multi criteria analyses, linked to using benefits and co-benefits that are important in the decision-making context of the road authority at hand. Future ICARUS guidelines will further elaborate on the implementation of the approaches in specific processes of NRAs.

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Geohazard Susceptibility Mapping Using Publicly Available Datasets for the Irish Road Network

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Abstract. To optimise the resilience and future sustainability of a road network, effective asset management is necessary to facilitate the safe working condition of a road network and its users. While asset condition and deterioration are key contributors for informing effective asset management, other external factors, such as natural adverse geological processes (i.e. geohazards), can also influence the approach to proactive management. However, significant financial investment and time is required to acquire accurate datasets to inform on natural factors which influence the susceptibility of a geohazard across a study area. Transport Infrastructure Ireland (TII) commissioned research to proactively use publicly available datasets to create generalised susceptibility maps across the Irish Road Network, and aid in the identification of critical areas which may require further investigation. This paper outlines the process developed for the creation of generalised susceptibility maps for three geohazards relevant for the Irish Road Network, namely compressible soil, karst landforms and slope instability. The process, applied to three counties (Cork, Dublin and Galway), included the selection of natural factors which could be informed through publicly available datasets and the application of multi-criteria analysis to develop susceptibility maps.

Keywords: Resilience · Geohazards · Asset Management

1 Introduction

Transport infrastructure is vital to support economic growth, distribution of goods and services and providing daily mobility to people. However, the risk to infrastructure is increasing due to various hazards, particularly natural hazards which are exacerbated by climate change. According to the European Commission Joint Research Centre [1], annual damage to Europe's critical infrastructure could be ten-fold by 2100 under business-as-usual scenarios due to climate change alone, from €3.4 billion to €34 billion.

Transport Infrastructure Ireland (TII) has a vision to lead in the delivery and operation of sustainable transport, including strengthening the resilience of the network and continuing to prioritise safety. Effective asset management is a critical component of that

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vision to facilitate cost-effective intervention on the transport network and withstand various hazards and risks. TII recognise that the performance of an asset management strategy, particularly proactive management, is strongly dependant on the quality and availability of asset data and information [2], including external hazards.

To support this objective, TII commissioned the review of existing publicly available data which could support the development of a robust asset management strategy (with respect to geotechnical assets), isolate hazard areas for further investigation and facilitate proactive management and intervention where required.

2 Geohazards Relevant to the Irish Road Network

Various hazards exist in Ireland which have the potential to interact with linear infrastructure. National Highways outline relevant hazards in the UK in CS641 [3], where hazards are summarised in categories of natural (*e.g.* solution features, soft ground, landslides, groundwater rise), and man-made (*e.g.* mining, landfill, unstable engineered slopes, defective drainage). Many of these hazards are also relevant to both the natural landscape of Ireland and the activities/assets which exist along the Irish Road Network.

For the purpose of this research, three geohazards, considered most relevant to the Irish Road Network, were selected and in this context are defined as:

- Compressible Soil (C)—Presence of soil and/or ground conditions susceptible to long-term compaction and/or consolidation (*e.g.* compression of saturated soils).
- Slope Instability (S)—Natural and man-made characteristics which could induce destabilisation of engineered or natural slopes along the network.
- Dissolution Features (D)—Dissolution of sub-surface rock (i.e. karst), causing collapse or subsidence of surface soil, resulting in an open surface void (doline) or depression.

The objective of this research was to use publicly available data as part of a simplified process to inform key hazard factors associated with the selected geohazards. While publicly available data is unable to inform all relevant factors and is often coarse in terms of resolution, its proposed use in this case is aimed at providing an initial overview of potentially susceptible areas which can then be used in a strategic manner to isolate areas for further investigation.

A comprehensive literature review was completed to identify factors and characteristics which influence the susceptibility of the geohazards selected, including statistical analysis of characteristics documented in the following hazard inventory sources:

- 40 no. compressible soil sites (*e.g.* alluvial clays, post-glacial lake clays, estuarine silts) documented in 'Geotechnical Properties of Irish Compressible Soils' [4]
- 2778 no. historical landslide events documented in the Landslide Events Database available from the Geological Survey of Ireland (GSI) [5]
- Karst Landform Database available from the Geological Survey of Ireland (GSI) [5]

Following a subsequent review of applicable hazard factors against available datasets, the following hazard factors were selected:

- Soil / Subsoil—The underlying material has relevance to all the selected geohazards.

- Dissolution Features: Characteristics such as particle size, thickness, permeability and chemical composition can influence the degree of dissolution [6, 7] and/or the susceptibility of doline development [8].
- Slope Instability: Characteristics such as strength, stiffness, thickness, soil moisture can influence the stability of natural slopes (*e.g.* transitional slip on cutting) or engineered slopes (*e.g.* toe destabilisation of embankment).
- Compressible Soil: Material such as peat, alluvium, estuarine, lake and post-glacial deposits are troublesome in terms of road design and performance [4, 9]. Over 80% of the sites assessed by Long [4] were located within 100 m of the sediment classifications categorised (for this study) as 'compressible'.
- Bedrock—The underlying bedrock has significant relevance to dissolution features. Characteristics such as mineral content (*e.g.* concentration of calcium carbonate), purity, porosity, geological structures (*e.g.* faults, fractures) and depositional history can influence the degree and rate of dissolution [7, 10–13].
- Elevation—Nearly 50% of the sites assessed by Long [4] were located at an elevation less than 10 m Ordnance Datum (OD), while over 80% of the sites were at an elevation less than 50 mOD. However, not all 'compressible' soils required low-lying areas to form (*e.g.* peat); therefore, this factor is assigned a smaller influence than the soil classification.
- Slope—Slope angle has been regarded as the single most effective geo-environmental variable for susceptibility modelling of landslides [14]. Almost 70% of the historical landslide events documented in Ireland [5] had slope angles greater than 15°, while almost 50% of those events had slope angles greater than 30°.
- Rivers & Waterbodies—Approximately 70% of the sites assessed by Long [4] are within 250 m of a river or stream, with almost 25% within 50 m.

The datasets associated with the factors above are outlined in Table 1.

Table 1. Hazard Factors and Associated Datasets for selected Geohazards.

Factor	Dataset	Source	Scale
Soil	Quaternary Sediments	GSI	1:50,000
Bedrock	Hydrostratigraphic Rock Unit Groups	GSI	1:100,000
Elevation & Slope Angle	LiDAR (where available)	TII & GSI	2 m (± 0.15 m RMSE)
	European DEM (v1.1)	CLMS	25 m (± 7 m RMSE)
Rivers	River Network Routes	EPA	1:50,000

3 Susceptibility Analysis

The use of a multi-criteria decision analysis (MCDA) process was required to analyse the quantitative and qualitative factors in a semi-quantitative manner which incorporates both types of data. The Analytical Hierarchy Process (AHP) was selected (developed

by T.L. Saaty in 1971–75 [15]), which provides the mathematical structure, expressed as a matrix, to rank the subjective and objective aspects of a decision using pairwise comparisons.

The initial pairwise comparison matrices were developed by assigning a relative importance or significance to each factor/criteria using the 1–9 fundamental scale of Saaty. Priority vectors were then be computed. The consistency of the approach was checked using the consistency ratio (*CR*), which is defined using Eq. (1),

$$CR = CI/RI \tag{1}$$

where *RI* is the random index, and *CI* is the consistency index, expressed as Eq. (2),

$$CI = (\lambda_{max} - 1)/(n - 1) \tag{2}$$

where λ_{max} is the principal eigenvalue of the matrix, and n is the order of the matrix. According to Saaty, the consistency ratio must be $\leq$10%. The susceptibility weight (S_i) was then be calculated using Eq. (3),

$$S_i = \sum_{(i=1)}^{n} W_i{}^* R_i \tag{3}$$

where W_i is the weight for each criterion and R_i is the weight for each factor, both associated with a particular geohazard.

A comprehensive and iterative review process was undertaken during the selection of the relative importance of each factor/criteria. This was further reviewed and refined following development of the susceptibility maps. Table 2 provides a summary of the final weights selected for each criterion and factor, while Fig. 1 provides an example of the outputs generated.

Table 2. Criterion and factor weights for susceptibility analysis, with consistency ratio (*CR*) for criteria weighting shown in brackets ().

Factors	Criteria	$W_{i,C}$	$W_{i,S}$	$W_{i,D}$	$R_{i,C}$	$R_{i,S}$	$R_{i,D}$
Soil	Peat	0.31	0.25	0.05	0.59 *(0.02)*	0.25 *(0.03)*	0.19 *(0.04)*
	Alluvial, Estuarine	0.31	0.17	0.05			
	Variable	0.15	0.16	0.17			
	Till	0.06	0.06	0.23			
	Sand	0.06	0.04	0.08			
	Gravel	0.06	0.04	0.08			
	Building	0.02	0.02	0.02			
	Outcrop / Subcrop	0.03	0.26	0.32			
Bedrock	Pure Limestones	–	–	0.37	–	–	0.81 *(0.03)*
	Impure Limestones	–	–	0.26			
	Dolomitised Limestone	–	–	0.18			

(*continued*)

Table 2. (*continued*)

Factors	Criteria	$W_{i,C}$	$W_{i,S}$	$W_{i,D}$	$R_{i,C}$	$R_{i,S}$	$R_{i,D}$
	Namurian	–	–	0.10			
	Igneous & Metamorphic	–	–	0.03			
	Other Sedimentary	–	–	0.03			
	Unknown	–	–	0.03			
Elevation	0 to 10 (mOD)	0.65	–	–	0.32 *(0.02)*	–	–
	10 to 50	0.25	–	–			
	>50	0.10	–	–			
Slope Angle	>45 (degrees)	–	0.43	–	–	0.75 *(0.02)*	–
	30 to 45	–	0.28	–			
	20 to 30	–	0.18	–			
	10 to 20	–	0.07	–			
	0 to 10	–	0.04	–			
Rivers	0 to 10 (m)	0.58	–	–	0.09 *(0.01)*	–	–
	10 to 50	0.23	–	–			
	50 to 250	0.12	–	–			
	>250	0.07	–	–			

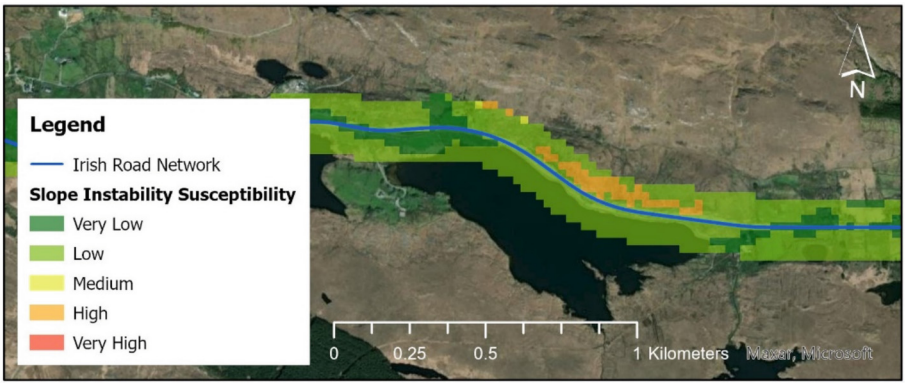


Fig. 1. High Susceptibility Area for Slope Instability on N59 in Co. Galway (beside Derrylea Lough), where rock slope stability measures had previously been implemented.

Desk-based validation of the susceptibility maps was conducted using Receiver Operating Characteristics (ROC), a highly adopted metric in susceptibility analysis [14], which relies on the sensitivity and specificity derived from a confusion matrix. The Area Under the Curve (AUC) was used to interpret the model. Using the inventory datasets referenced earlier as True Positive, an average AUC of 0.85 was obtained, which is considered 'very good' [16].

4 Conclusions

This paper presented a simplified process of using publicly available data to develop susceptibility maps of selected geohazards to aid in the identification of potentially hazardous areas along the road network for further proactive investigation. The following are key conclusions drawn from this work:

- The process can be expanded to consider additional factors (where they can be reasonably informed by available datasets), geohazards and geographical areas.
- The accuracy of the process is highly dependent on the selection of the appropriate hazard factors and the importance ranks/weights assigned to the associated criteria. This is directly related to the level of technical experience of the team regarding both the ground conditions of the target area and the associated geohazards.
- Validation is a critical component to successful modelling. Limitations exist for the validation options available and employed. ROC can contain insensitiveness to imbalances between positive and negative instances of datasets [17], and incomplete or limited inventory datasets.
- The analysis and validation process would significantly benefit from information on asset condition and/or deterioration throughout the network to allow cross-reference and refinement of susceptibility classes.
- The susceptibility output relates solely to natural hazard and not the risk to the asset. The degree of risk is influenced by aspects such as asset condition (e.g. mitigation during or post construction), network criticality or other.
- The process developed could also be used by other asset owners/managers (e.g. Local Authorities) to explore possible hazard areas along secondary routes, particularly heavily trafficked or critical routes.

Given the limitations associated with available data to inform both the process and validation, it is evident that the process outlined should only be used as an initial step in the overall geotechnical asset management strategy. However, the outputs can be used in a strategic manner for proactive investigation and intervention where required.

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Vision-Based Multi-perspective Road Pre-damage Detection

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Abstract. Road condition evaluation is essential for selecting maintenance strategies to prevent road failures. However, current road evaluation methods are subjective, manually performed and time-consuming, while road maintenance is mostly reactive with associated risks, such as possible network disruptions. Presented herein is a vision-based methodology for road inspection and evaluation. For this purpose, we couple digital image correlation (DIC) with perspective warping to measure material displacement or strain that can be an early warning of pavement failure. Our results show that perspective warped images were able to be successfully used in DIC analysis and obtain strain values within 19% of the images taken at a direct angle to the sample. Perspective warping enables us to bypass the limitation of fixed DIC applications and allows for the collection of images from mobile cameras such as everyday cars in motion. This provides new opportunities for the effective prediction of road damage formation and consequently predictive maintenance.

Keywords: Pavement Defect Detection · Material Strain · Predictive Maintenance · Digital Image Correlation · Computer Vision · Perspective Warping

1 Introduction

Road networks are critical for any country's social development and prosperity by facilitating the mobility of people and goods. However, road pavements are subject to constant deterioration over their lifetime, which can be accelerated by heavy traffic, weather conditions or inadequate maintenance [1]. This deterioration will impose risks on road users' health and safety, as well as leading to economic consequences. Transport authorities expend significant effort to monitor and maintain the networks to decrease the possibility of failures and ensure that road networks continue to serve the needs of society. Road pavement monitoring consists of detecting and classifying defects, as well as evaluating defects' severity and extent. Pavement monitoring has been traditionally manual, subjective, and time-consuming. Thus, there has been tremendous interest from academia and industry in automating pavement monitoring using artificial intelligence [2].

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Digital image correlation (DIC), which is a photogrammetry-based methodology technique, has the potential to be used for early detection of road pavement failures. DIC involves pixel correlation between images, used for measuring the displacement of structural elements subjected to stress [3]. Road pavement videos and frames can be collected via cameras and laser scanners on vehicles moving at highway speeds and from angles. However, applications for implementing DIC for detecting strain and distress in road pavements in frames collected at different angles are limited. This work aims to fill this gap of knowledge by developing a method for detecting strain or damage using images taken at different angles. This allows us to bypass the limitations of standard DIC applications and enables the use of images captured by moving vehicles at oblique angles for strain detection. The wide range of images captured provides a more accurate and robust method of road assessment. Understanding where deterioration is about to happen will allow predictive maintenance, increase road safety, and reduce disruption and associated CO_2 emissions.

In this paper, 100 mm concrete cubes are tested under compression in which strain was measured with DIC. Images were taken with a camera positioned firstly normal to the specimen face (standard setup) and secondly at an angle to the specimen face (non-standard setup), simulating images taken at angles from a moving vehicle. The images taken at an angle are pre-processed via perspective warping, to reconstruct the view of the specimen from the standard setup. Then both sets of images are processed using DIC software to measure the strain in the specimens. The images taken normal to the specimen's face act as the ground truth.

2 Methodology

2.1 Sample Preparation

Ordinary Portland cement concrete was used for the experimental procedure of this study. The fabrication process of concrete samples was the following. Cement and fine aggregate were dry-mixed in a rotary drum mixer for 2 min. Water was then poured into the rotary drum and mixing continued for another 3 min. Coarse aggregate with a maximum size of 12 mm was then added along with the remaining water and mixing continued for 5 min until a homogenous mix was achieved. Concrete was then cast into oiled 100 mm stainless-steel cubic moulds, covered with plastic sheets and demoulded after 48 h. The specimens were cured in water for another 26 days, which thereafter were stored in sealed plastic containers. Prior to testing, the surface of the concrete specimens was coated with white paint and sprayed with black paint at a random speckle pattern for displacement tracking in DIC.

2.2 Loading Scheme

To simulate road traffic conditions, the specimens were tested under cyclic compression at a peak load of 10 MPa at 0.4 MPa/s for 5 loading cycles as depicted in Fig. 1. Loads were kept within the elastic zone to avoid damaging the specimens.

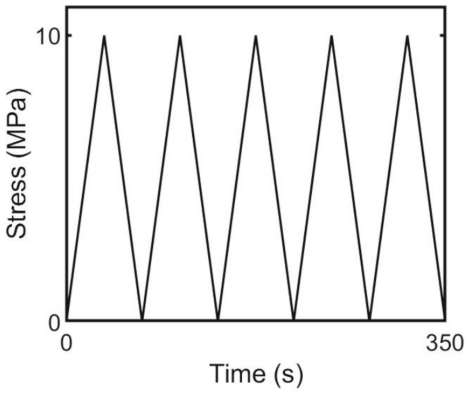


Fig. 1. Loading sequence for DIC analysis

2.3 Perspective Warping

The images taken from the angled camera were perspective warped via four-point transform using OpenCV [4]. This approach consists of selecting four reference points that form a parallelogram once the perspective transform is applied (see Fig. 3b-c for an illustration). The first image of each frame set was chosen, and the four reference points were manually selected as the corners of the concrete cube. Since the camera was static for the duration of the experiment, the same transformation was then applied to the rest of the captured images.

2.4 Digital Image Correlation

Strain was measured by using DIC. Images were taken at two locations, one at a direct angle to the specimen and the other at 35°; the images were captured by a Raspberry Pi High-Quality camera with a resolution of 12 Megapixels and an Android Phone with a 50 Megapixel camera at a 1 s interval. The images captured at an angle were perspective warped following the process outlined in Sect. 2.3 to allow for in-plane deformation analysis of the specimens. Strain at both locations was calculated with the image analysis tool GeoPIV-RG [5]. The subset size was set as 30 pixels and the step between the subsets was chosen as 20 pixels. An illustration of the setup is portrayed in Fig. 2.



Fig. 2. DIC setup with two cameras capturing images at different angles.

Figure 3a displays the image of a typical sample taken at a direct angle, Fig. 3b displays the original image taken at a 35° angle, including the four reference points selected for perspective transformation and Fig. 3c displays the perspective warped image.

3 Results and Discussions

Figure 4 displays the strain propagation obtained from the DIC analysis for both the direct angle and perspective warped images. As it can be seen, the strain pattern from the perspective warped images was similar to that obtained from the direct angle. Perspective warped images led to a slightly higher strain value, by 19%, compared to the direct images. The additional image processing for the perspective warped images led to a lower standard deviation of subset pixel intensities and the sum of the square of subset intensity gradients (SSSIG) compared to the direct images which can induce greater error in the DIC analysis [6]. The slight phase shift between the strain plots is due to synchronization issues between the two cameras.

While the current application focuses on concrete specimens, the same technique could be applied to asphalt pavements which are more common in roads [7]. Moreover, this work focused on strain in the x and y planes, to understand the behaviour of rough road surfaces, multiple cameras can be used for 3D measurements [8]. Overall, it has been shown that perspective warping is a viable process that could be employed in DIC. This opens up new opportunities in the field of DIC expanding beyond conventional fixed setups. Images could be taken from moving vehicles which could be post-processed and used for road inspection and maintenance purposes.

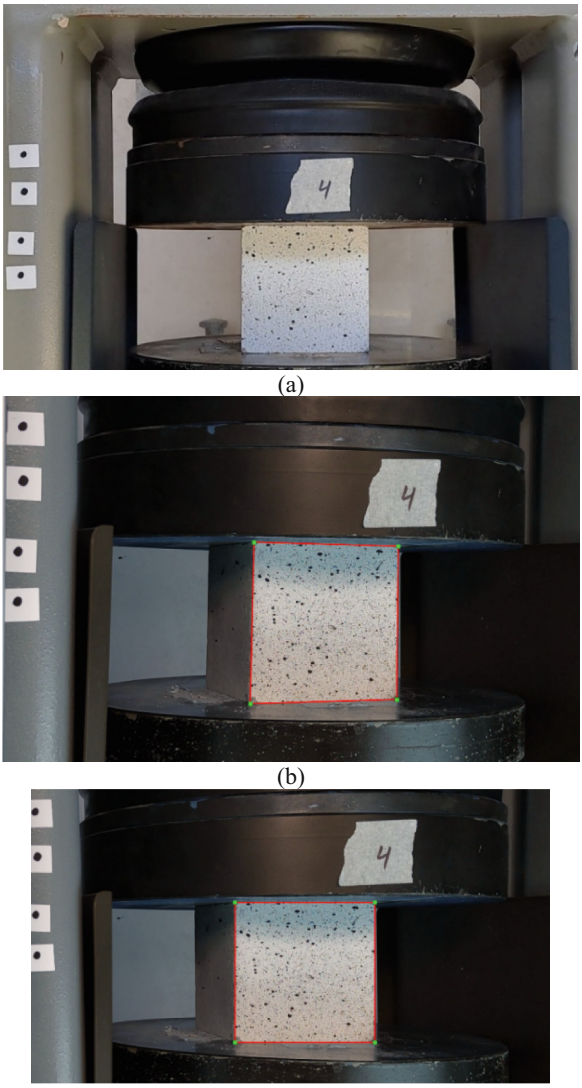


Fig. 3. Images of typical sample captured for DIC at (a) image taken normal to the sample, (b) original image at an angle, (c) perspective warped image at an angle.

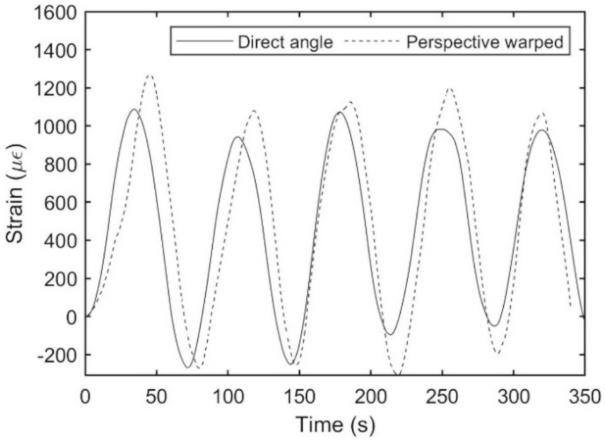


Fig. 4. Strain vs. time for images taken at a direct angle and perspective warped images.

4 Conclusions

In this work DIC was used to measure strain in concrete specimens; cameras were positioned at two locations—one normal to the specimen and the other at a 35° angle. The images taken at an angle were perspective warped to convert the face of the specimen normal to the camera which made them possible to be used in DIC analysis. The perspective warped images were able to display strain values within 19% of the ground truth to the normal position. The primary contribution of this work is the ability to measure material strain outside of fixed DIC conditions by using frames captured at angles, which is a real-world requirement of predictive road maintenance. This opens up new avenues in road and infrastructure monitoring and predictive maintenance, thereby improving safety and allowing significant cost savings and efficiency gains. Future work would involve field trials by mounting multiple cameras on a moving vehicle and measuring 3D strain in asphalt pavements.

Acknowledgements. This work is supported by the UK Engineering and Physical Sciences Research Council (EPSRC) [grant number EP/V056441/1].

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Advanced Levelling in Road Construction - Development and Site Testing

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Abstract. In asphalt road construction, pavement thickness is crucial for both structural integrity and cost-efficiency. Insufficient thickness compromises load-bearing capacity, leading to premature failure, while excessive thickness incurs unnecessary expenses. Uniformity across the pavement layer is equally essential. The existing levelling method, although reliable, has room for enhancement, relying heavily on constant monitoring by paving crews. This study introduces an Advanced Levelling System functioning as a high-level height control system. It incorporates an additional control loop to monitor the rear edge of the screed's height. To support this expansion, improvements were made to grade and slope sensors, along with the development of new sensors like Super Ski, Line Reader, rear-edge screed height sensor, optimized slope sensor, and layer thickness sensor. Extensive testing was conducted at MOBA Automation AG and TPA GmbH test sites, as well as real construction projects in Bielefeld and Hamburg, Germany. Emphasis was placed on joint paving, precise layer thickness control, superimposed grade control, and scanning the rear edge of the screed from the curb. The system's ability to respond to rapid changes in paving conditions was assessed using planned disturbance variables. The Advanced Levelling System's effectiveness was successfully validated. Optimizations in grade and slope control, along with sensor enhancements, ensured precise layer thickness during paving. This system seamlessly transferred many grade and slope control tasks from the paver operator, streamlining the process.

Keywords: Asphalt · Paving · Automation · Advanced Levelling

1 Introduction

In asphalt road construction, the achievable quality when using road pavers largely depends on the experience and expertise of the operating personnel. At the same time, increasing traffic density is placing ever higher demands on the stability of asphalt pavements and thus on the quality of laying. This underlines the importance of quality assurance and optimization of paving processes in asphalt road construction. In addition to the mixing ratios and compaction properties of the material, the machine and process parameters of the road paver, as well as the associated leveling properties of the control system, also play a decisive role in the achievable paving quality [1].

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Increased automation would not only reduce the dependency on individual experience values, but also ensure that the paving quality is maintained at a consistently high level regardless of individual operator knowledge. A further increase in automation in the area of grade and slope control systems would thus also meet the increased demands of modern traffic standards [2].

2 Leveling in Asphalt Construction

Leveling in Asphalt Paving involves an automatic screed control system for placing a uniform mat of desired thickness, grade, and shape. It includes a controller and various sensors selected based on installation needs. Operators set a target height relative to a reference and chose a levelling system based on surface condition, precision, and mat thickness. String lines are still used for reference, with the paver screed aligning itself using scanning systems like ultrasonic sensors (Sonic Ski). These sensors can also measure heights of existing asphalt layers or curbs. For surfaces with appropriate longitudinal but unsatisfactory transverse grade, a traveling reference using a mechanical beam can provide the desired mat thickness. The beam is either connected directly to the paver or fixed to the tow-arm. In the latter setup, multiple sonic sensors measure the distance to the ground and continuously supply the measured grade values (Big Ski). Single or dual grade control systems can be used, with systems on each side or a single system on one side and a cross-slope sensor on the other [3, 4]. Advanced automation includes 3D leveling systems with a digital terrain model reference and total station for precise control, eliminating subsurface waves.

3 Advanced Levelling

To ensure level paving, the paver's grade and slope control systems use a control loop to compensate for disturbances. One problem is the measurement of screed height, which is not captured close to the rear edge of the screed. This can lead to tilting, resulting in constant unwanted thickness changes. An additional control loop will therefore be developed to monitor the screed's rear edge in order to operate autonomously. The leveling sensors, including Super Ski, Line Reader, Height Sensor, Slope Sensor and Layer Thickness Sensor, will be optimized as part of this research. The leveling control loop will be improved to perform the following paving tasks autonomously: lane to lane, layer thickness control, superimposed cross slope control, optimized drive off, scanning of the screed's rear edge from the curb, optimizations in the 3D range. The following sections will focus on lane to lane and layer thickness control with SuperSki and Layer Thickness Sensor.

3.1 Super Ski

In contrast to a measuring system with a continuous measuring beam, where the height sensors are mounted on the measuring beam, the Super Ski uses single measuring beams with integrated distance sensors, i.e. the sensor technology is coupled with the mechanics and is therefore part of the measuring beam.

As Fig. 1 shows, the distances are not measured sequentially with the aid of the respective measuring heads, but in parallel, i.e. all measuring heads transmit an ultrasound packet at the same time, which is in turn received by all measuring heads.

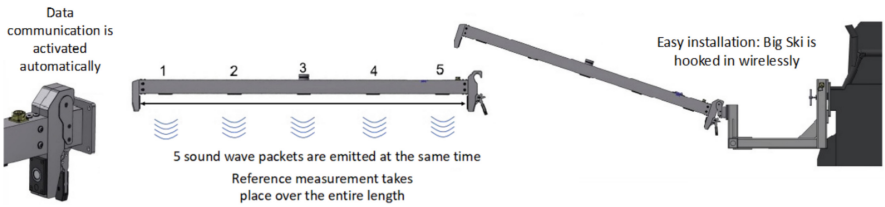


Fig. 1. Super Ski System/Setup

If the Super Ski system is divided into measuring ranges, there is a measuring range behind the screed and a measuring range in front of the screed. During each measuring process, 15 measurements are thus taken synchronized for one side by the paver. This setup results in the following improvements: Increased accuracy of measured values through optimized digital evaluation algorithms, improvement of flatness results, easy installation of the sensors (simple hook in), lower weight compared to the Big Ski, no wiring, compatibility with existing leveling computers.

3.2 Thickness Measurement and Thickness Control

Layer thickness measurement is of crucial importance for autonomous grade and slope control, as the grade and slope control system itself only temporarily ensures that the set layer thickness is maintained. The measuring principle itself is based on two grade sensors a and b, which are arranged in the longitudinal axis of the paver and symmetrically to the rear edge of the screed in such a way that they measure the corresponding distances to the asphalt pavement and the carriageway (cf. Figure 2, closeup on the right side). The distance C in the symmetry point S is necessary for the calculation to compensate the offset heights of the sensors. For the accuracy of the measured value, it is necessary to calibrate the layer thickness measuring system on a surface that is as flat as possible. Finally, Fig. 2 shows the structure and the associated main components for the autonomous operation of the paver as it was also used for site testing (cf. Section 4). For a correct control of the layer thickness, a distance information, which can be determined by a Global Navigation Satellite System (GNSS), is mandatory. If the road design is available in digital form, the GNSS system can replace a total station, thus eliminating the moving and maintain of the total station and achieving a higher degree of autonomy.

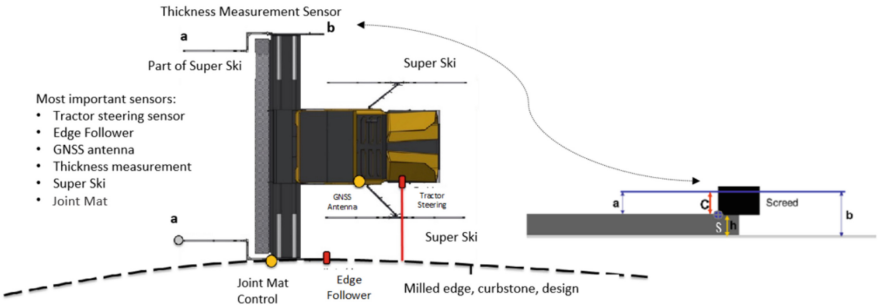


Fig. 2. Paver components for Autonomous Asphalt Paving with Thickness Sensor System

4 Site Testing and Results

At the beginning of the InfraROB research project, a relative thickness measurement system was tested. This means that the thickness of the pavement cannot be determined absolutely due to the construction or the subsequent mounting on the paver. For a precise measurement of the layer thickness, it is necessary that the position of the sensor system is known exactly and that it does not change due to twisting in the mechanics. After successful calibration, the thickness can be calculated during the paving process. Most of these tests were carried out at MOBA AG's test site in Limburg, Germany. Figure 3 shows the continuous and direct calculation of the layer thickness. The results of the first test show us that we need a filter to avoid short-term measurement failures. It is also easy to see that the system is still error-prone at this stage of development. In this test, the layer thickness was increased from 5 cm to 8 cm. The measuring system reproduces this jump with small deviations.

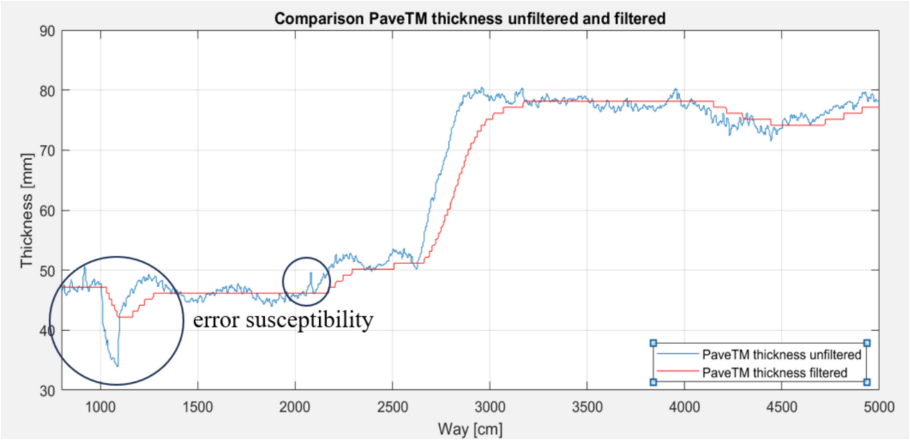


Fig. 3. Results from a first measurement with a relative system

Since the system has a certain error susceptibility due to the calibration during installation, an absolute system was used in the following. In this design, there is a rigid

connection between the front sensor and the rear sensor. The calibration takes place during the installation of the system and has not taken place at work site.

The first test was again carried out at the test site in Limburg. The system was tested in which the layer thickness was deliberately changed in short sections. It was shown that despite the major changes, the layer thickness follows the target layer thickness well. This test was repeated with Hot Mix Asphalt (AC 16 BS according to TL Asphalt-StB [5]) in Bad Hersfeld, Germany and verified with manual measurements. The demonstration showed that the layer thickness system and the associated layer thickness control are of great benefit to the user even in the case of atypical paving behavior in road construction.

In order to document the control behavior of the layer thickness control, an additional test was performed by changing the working parameters during the paving process. At the position marked in Fig. 4, the paving speed was reduced from 6 m/min to 3 m/min. Typically, the layer thickness should increase due to the lower paving speed. This effect can be seen in the overshoot in the middle of the diagram. After a short time, however, the control mechanism of the layer thickness controller comes into action and reduces the layer thickness to the set point. Since the paving parameters, such as temperature, material properties, paving speed, etc., change slowly in normal paving situations [6], the overshoot shown in the diagram will not occur. Nevertheless, it can be seen noted that the system adjusts the required layer thickness with different parameters.

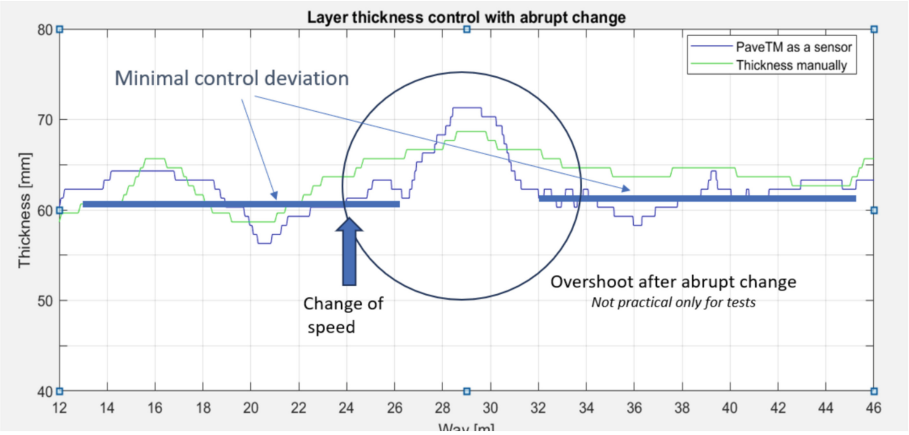


Fig. 4. Results from the layer thickness control with untypically abrupt changes during the paving process

5 Conclusion

After testing for the different applications, it can be noted that the Advanced Leveling Algorithms for Layer Thickness Control work well. Verification of the system for longer paving distances and under normal paving conditions will take place in the scope of the EU-Project InfraROB at the final demonstration site in Austria.

Another function of Advanced Levelling will be the Cross Overlay Control function. Here, both the evenness of the road surface and the cross slope are monitored. A combination with the cross slope and the layer thickness is also possible. The tests for these

algorithms will be tested at the MOBA test site in the near future and will then be shown at one of the next demonstration set-ups. When all the systems and algorithms are taken together, a large number of applications should be covered, so that nothing stands in the way of semi-autonomous paving and automation of the screed workplace.

Acknowledgments. This paper was carried out in the framework of the InfraROB project (Maintaining integrity, performance and safety of the road infrastructure through autonomous robotized solutions and modularization), which has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 955337. It reflects only the author's view. Neither the European Climate, Infrastructure and Environment Executive Agency (CINEA) nor the European Commission is in any way responsible for any use that may be made of the information it contains.

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Energy Efficient Operations of Railway Switch Heaters and Feasibility of Using Ground Heat

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Abstract. A railway switch is a vital component for its safe, reliable, and time-bound operations. Faults in switches are common in locations experiencing winters due to snow or ice buildup, despite using heating systems. The majority of switches are electrically heated, and guidelines for their efficient operations have been studied in this work. A computational model has been created to understand the temperature distributions in switch heating systems, and it has been verified from the annual heating data of an operational switch in Sweden. The results from a parametric study by varying ambient temperature, wind load, and heating element power can be used to implement heating control strategies in existing heaters, which will support their sustainable operations. In addition, the feasibility of using ground-source borehole renewable energy is also investigated for different bedrocks. The results of the temperature drop in the borehole for a constant winter heating load over 15 years give insights on the potential usage of ground heat in switch heating.

Keywords: Switch heating · ground heat · borehole heating · CFD · numerical modeling

1 Introduction

A railway switch consists of a pair of switch blades and stock rails. The switch motor, coupled to the switch rod, re-orients the switch blade and directs a train to the selected track. In locations experiencing severe winters, snow or ice buildup between the switch rail and the stock rail can block the movement of the switch rail, which prevents its operation. Thus, different types of heating systems are used to keep switches free from snow. E.g., the majority use electric resistance heating, but open flame heating, hot or cold air blowing, etc. are also used worldwide, consuming a large amount of energy and leading to huge CO_2 emissions.

Various attempts have been made towards 'Green Switch' operations, e.g., efficient and durable resistance heaters can vary heating power along their length

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due to their self-regulating heating cores. Non-conventional options, e.g., suspended contact-less switch heaters between switch and stock rail or induction heaters operating at different frequencies, are not popular yet [1,2]. The feasibility of using ground heat for switch heating is also a fairly new concept.

In Sweden, the Swedish Transport Administration (Trafikverket) manages approximately 12000 switches, out of which 6800 electric heating systems with a rated power of 10–30 kW for each of them annually consume 130–200 GWh of electricity. [3] Failure of switches due to switch blade position and switch heating is responsible for more than 1000 faults annually. [4]. Furthermore, it is imperative to adopt ways to reduce energy consumption, both from a sustainability and operational expense perspective. Since the switch is related to operational safety, access to it is restricted for any field experiments. With the help of Trafikverket, a detailed design of a switch heating system and its annual heating data are acquired for analysis, which is used to build a numerical model to understand heat transfer in a railway switch operation using computational fluid dynamics (CFD). Since not much work on CFD studies of switch heating has been done in the past, barring a few [5], a parametric study on the impact of ambient factors, e.g., temperature, wind load, and heating element power, can be used to determine and implement heating control strategies in existing heaters. Also, the feasibility of using ground heat from boreholes in different bedrocks has been studied.

2 Modelling

2.1 Analysis of Switch Heating Record

Trafikverket has provided the annual measurement data & rated specifications for a resistance-heated switch that is located in an undisclosed location. Switch heating is turned on if the air temperature $\leq$5 °C and the rail sensors detect a temperature $\leq$8 °C. It has approximately 300 W/m of maximum heating power, totaling 17.2 kW per switch. Data comprises hourly measurements for rail temperature, which are measured at two points on the rail, ambient temperature, and energy consumed. This data is also used in the verification of CFD results.

From the data, the maximum heating power per switch is found to be 17.875 kW, which is close to the rated power.

In Fig. 1, classification of the data based on rail temperature, it has been observed that heater operation control tries to maintain rail temperature in a range of 8 °C to 8.6 °C. Since more data on weather like wind speed, rainfall, snowfall, frost, etc. is not available, it is not possible to attribute these points to a specific condition. In Fig. 2, upon filtering and performing linear regression on the data for rail temperature equals 8 °C, the relationship is established to predict hourly energy consumption from the air temperature. Still, some dispersion in the data can be attributed to unknown weather data like the presence of water or snow and wind speed, which strongly influences the heat transfer rates. Thus, R-square, which represents the fitness of the curve, has a value of 0.795 for

linear regression. It can be improved if variables like air speed are known and multiple-variable regression is performed.

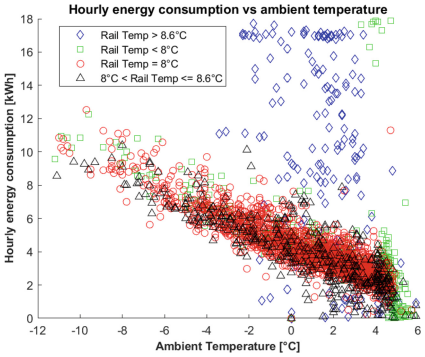


Fig. 1. Classification on rail temperature.

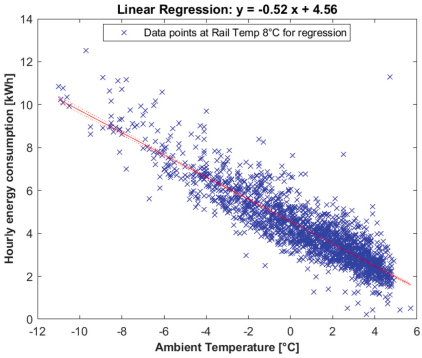


Fig. 2. Ambient temperature vs energy use.

2.2 Modeling Switch Heating

A CFD numerical study to model conjugate heat transfer in switch heating is performed, followed by verification of the model against the measurement data. Finally, a parametric study for various combinations of ambient temperature, wind load, and heating power.

Geometry: A cross section of a switch blade is an asymmetric section that is smaller in height than the stock rail. The horizontal gap between the stock rail and switch blade gradually increases away from the switch point till it reaches the heel block, where another segment of rail, i.e., the closure rail, starts. Closure rails are the straight or curved rails that are positioned in between the heel of the switch and the toe of the frog. For this study, the geometry of the stock rail and switch blade cross section near the heel block is chosen. A 2D geometry based on *UIC60* rail geometry cross section resting on two metal plates 275 mm wide & total 30 mm thick have been constructed in *SpaceClaim* of *ANSYS Fluent*.

A heater element sized 5 mm × 10 mm is also drawn as a separate face. In reality, when the heater is clamped to the rail using track clips, there is thermal contact resistance due to the imperfect joint and a thin air gap. Thus, a 2 mm-thick element is also drawn in between the heater wall and rail, which shall represent the contact resistance. Further, the computational domain is created with 750 mm upstream and 2250 mm downstream to ensure domain independence in the solution, and using 'face split', local sizing is ensured, as shown in Figs. 3 and 4.

Meshing: Various meshes have been constructed to check for mesh independence with face sizes ranging from 2–5 mm along with an inflation layer of first element thickness of 0.2–0.75 mm to achieve a y^+ of 1,2 and 3. y^+ is a non-dimensional parameter that decides how well the flow field is captured near the

wall. A final mesh with an element count of 0.29 million and $y^+ = 1$ has been selected for the study, which is recommended for the k−ω viscous model.

Solver Settings: Solver Type: Pressure-based. Air: In-compressible ideal gas. Rail: Hot rolled steel. Spatial discretization: Second Order (Upwind). Transient Formulation: First Order Implicit. Viscous method: k−ω SST along with 'Production limiter', 'Curvature correction', and 'Low Re correction'. Residuals convergence: 10^{-6}. Pressure-velocity coupling: SIMPLE.

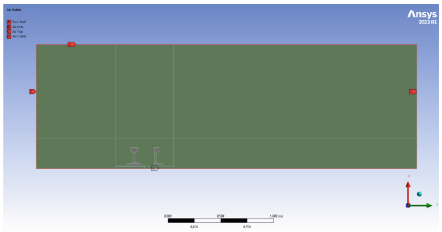


Fig. 3. 2D CFD fluid domain.

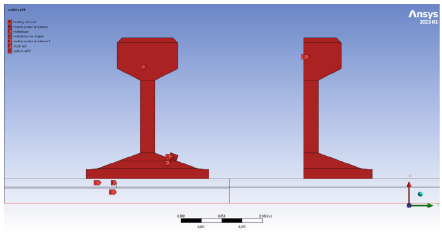


Fig. 4. Switch geometry in fluid domain.

The transient solver is selected as the cross-flow over rail can't be solved in a steady state due to the oscillating and periodic nature of the flow field at low speeds close to the ground. E.g., 0.5 m/s is calm wind and 1.5 m/s is light breeze at the rail height. [6] A time step of 0.001 s to 0.02 s can be used for simulations. The higher-time steps have convergence issues, while the lower ones have the least discretization error but take a long time. Finally, simulations are run at a 0.01 s time step. An independent time for the solid conduction rail is selected using the 'Solid time step', which can be significantly higher than the flow time step, to fast-track the CFD simulations. Simulations are run to simulate one hour of heater operations.

2.3 Simulating Borehole Heat Extraction

Crystalline rocks are generally granite, which is the most common bedrock in Sweden and is quite stable for drilling up to 300 m. The geothermal gradient of more than 16 °C/km in crystalline rocks proves to be a good heat source. [7] The change in temperature of the borehole field has been modeled using FLS_{III} solver of the open-source tool *GSHPsDesigner*, which was developed at KTH. It models the borehole as a finite-line heat source with heating loads uniformly distributed over its depth. [8] A 2×2 configuration of U-boreholes, which are 4 m apart and 300 m deep, are withdrawing two-thirds of the 15 kW hourly thermal load, which is half the value of the maximum heater load in Sweden. The heating load repeats over a period of 15 years, from November 1 to March 31, and zero load for the rest of the days. The borehole temperature at any location equals the difference between its annual average air temperature and the temperature change results obtained from the FLS_{III} solver after extracting the heat from

ground. The heat can be extracted from a borehole before brine starts to freeze, i.e., around −8 °C [7].

3 Results and Discussion

Since thermal contact resistance is an uncertain parameter, the density and heat capacity of contact element are assumed to be one-hundredth of the heater. Its thermal conductivity has been estimated by running various CFD simulations over a range from 0.24 to 4.8 W/mK at the maximum heater power of 300 W/m, which is equivalent to its maximum rated power. Maximum operating heater temperatures for different commercial products vary from 100–150 °C and a thermal conductivity of 0.96 W/mK is selected such that the heater temperature reaches close to 100 °C as seen in Fig. 5. Also, from the same figure, it's interesting to note that if the air gap increases, which corresponds to lower thermal conductivity, the local temperature can reach beyond 150 °C which can lead to premature failure of the heating element.

The validity of the CFD model can be verified against some of the experimental data taken from Fig. 2, where heater power is used to deduce equivalent linear heater power. The results in Fig. 6 show that the CFD results predict the rail temperature to be around the rail threshold temperature of 8 °C, which is true especially at higher air temperatures and the wind speeds do not greatly influence the deviation in the rail temperature. But, for lower air temperatures, it is more sensitive to the air speed and hence it is difficult to accurately predict rail temperature. Overall, the CFD model results can predict correct rail temperatures for non-snowfall cases if air speed is known. Thus, it is highly recommended to record air speed.

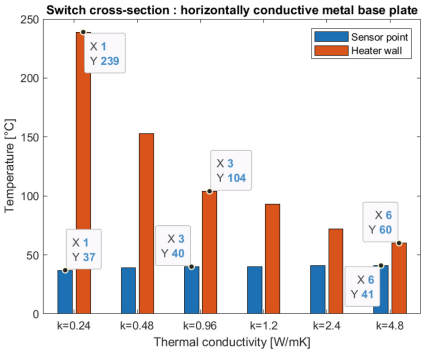


Fig. 5. Varying 'k' of resistance element.

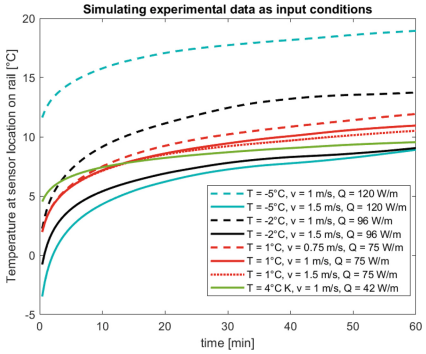


Fig. 6. Field measurements for CFD inputs.

Many switches operate in dual power modes, i.e., normal mode at lower power and boost mode at higher power, while some switches can only operate at single power, but their switching on-off cycle is based on a threshold rail

temperature. By utilizing real-time weather, rail temperature monitoring, and a voltage control strategy, a wide range of heating power ranges can be adopted. At higher ambient temperatures and lower wind speeds, the rail temperature is fairly predictable, especially in non-snowing conditions. But for other boundary conditions, like sub-zero temperatures with different wind speeds, the rail temperature can deviate much from the threshold temperature. Thus, it's imperative to understand the thermal inertia and response time to reach a reference temperature when the boundary conditions change.

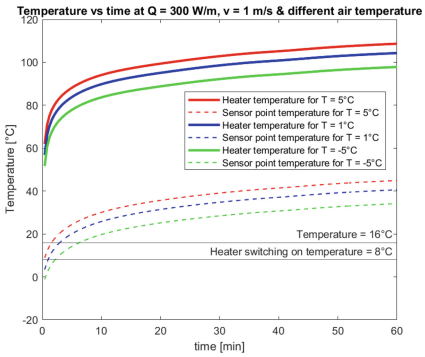


Fig. 7. Different ambient temperature.

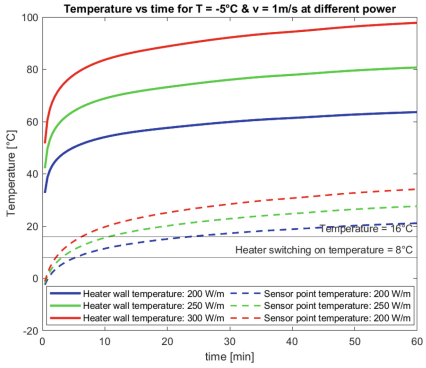


Fig. 8. Different heater power.

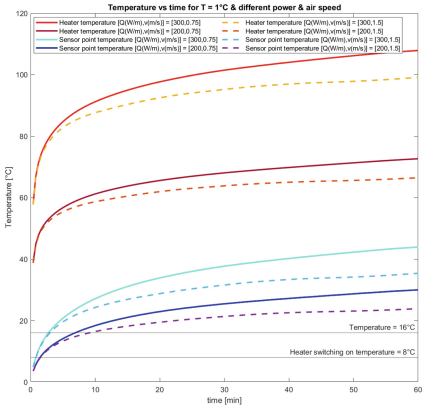


Fig. 9. Different heater power & air speed.

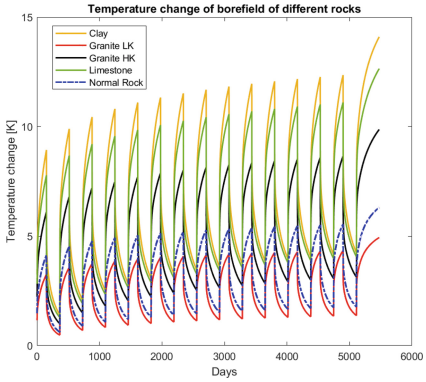


Fig. 10. Borehole temperature response.

The variations in rail temperatures by changing ambient temperature, heater power, and wind speed are shown in Figs. 8, 7, and 9, which can guide in deciding heating control strategy for different boundary conditions. It's important to know that the response time is generally less than 10 min to raise temperature from 8

°C to a reference value of 16 °C for the boost mode operations, e.g., potentially before snowfall or scheduled operations of the switch or to tackle excessive wind gusts. This gives an indication of the built-up thermal inertia due to elevated temperature levels. Hence, the results shown above can be used to operate the heaters at prolonged lower power and shift to higher power modes when required. Finally, for meeting a 15kW winter heating demand with two-thirds coming from boreholes over 15 years, there is more than 10 °C temperature change for clay and limestone rocks, but it is much less for the most common in Sweden, i.e., granite, as seen in Fig. 10.

4 Conclusion

A CFD model for switch heating has been closely validated by taking into account the uncertainty in thermal contact resistance. The simulations agree closely with the measurement field data. The deviations can be attributed to unknown values of the wind speed, especially at lower temperatures. The simulations also help us to understand the response time for the rail temperature increase at different boundary conditions, which can be used to develop a predictive control for switch heating under varying conditions. A further challenge is to develop an advanced CFD model with snow and water films as boundary conditions. Finally, the long-term feasibility of using ground-source heat is promising for certain bedrocks and invites further investigation. Also, another design challenge will be the transfer of heat from ground to rail, which is recommended for future work.

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Video-Based Object Recognition for Identifying Vehicle Distances Needed in Bridge Load Evaluations

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Abstract. To evaluate the reliability of a bridge, the maximum traffic load that is expected to occur during bridge operation needs to be known. The distribution of vehicle distances in congestion is an important parameter that co-determines the expected maximum traffic load effect. However, up to now only very few data exist that address this issue.

In the presented study, measurement of vehicle distances was performed using an innovative camera solution called "Mobility Observation Box" (MOB). Video data acquired at two highway sites was processed to detect vehicle trajectories and evaluate vehicle distances. This data served to determine probabilistic distributions of vehicle distances. To separate behavior in congestion from the flowing traffic, the evaluation was executed in several velocity ranges. A bimodal distribution was fitted to describe the vehicle distances in particular velocity ranges.

The presented paper describes methodology of acquiring more accurate data on distances of vehicles in congestion and shows first results of an application. The applied methodology seems useful – after performing more measurements at different sites – to provide vehicle distance distributions for the assessment of traffic loads on bridges.

Keywords: Bridge · Traffic load · Congestion · Vehicle distance · Video-based recognition

1 Introduction

Bridge infrastructure is essential for keeping the flow of goods around Europe going. The operating freight vehicles produce considerable loading of bridge structures. New bridges are designed to withstand traffic loading events that have a statistical return period of 1000 years, or a 5% probability to be exceeded within 50 years [1]. The appropriate traffic loading is usually adopted from the EuroCode [1], which was derived from traffic measurements on highways with heavy traffic in the 1980s. Alternatively, in presence of more accurate data about the actual traffic composition at the bridge site of interest, traffic flow simulations can be performed and applied to a model of the bridge. This paper focuses on measurement method that provides data for the vehicle distance distribution, which is an important input parameter to traffic flow simulations. Since the evaluation

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of bridge reliability in terms of Ultimate Limit States (ULS) depends on the maxima of traffic load effects, which often occur in congestion, the distribution of vehicle distances is one of the key input parameters.

While older studies assumed in congestion constant vehicle distances of 2.5 m or 5 m, most later studies adopted the approach of using a probabilistic distribution. Uniform distributions with bounds (5 m, 15 m) or (5 m, 25 m) were among the most widely used approaches. Koshini [2] proposed in 1985 four different beta distributions for describing vehicle distances in congestion between pairs of vehicle types: car-car, car-truck, truck-truck, and truck-car. Freundt et al. [3] used besides constant distances and uniform distribution also a normal distribution with lower and upper bounds.

Kraus [4] cites a study finished in 2018, where vehicle distances were measured on a congested highway in Germany using a video-based approach. From the dataset of ca. 410 measured distances, lognormal distribution was used to describe the axle-distances, i.e. distances between last axle of a vehicle and the first axle of the following vehicle. He presented also additional measurements (approx. 140 measured distances) that were done using a laser distance sensor.

A recent study [6] used Gaussian distribution to describe the vehicle distances, which appear to describe traffic in flowing condition. Video-based vehicle recognition was also applied on a suspension bridge in Scotland [5], where the camera was mounted on the top of bridge tower, 95 m above road surface. The authors used statistical correlation of vehicle weights and lengths to infer the weights from lengths determined from video.

The present work adopts the video-based approach to determine vehicle distances in flowing traffic and in congestion. Recent advances in video-based techniques made this technology more available and suitable for wider application. The purpose of this work is to contribute to enlargement of the still quite small datasets described above, on which the current traffic simulation assumptions rely.

Studies that use video-based traffic analysis were done with different objectives. The range of applications includes statistics for policy makers and regulators [7], traffic safety [8], or assessment of bridge load effects [5, 9].

2 Mobility Observation Box

The measurement unit (Fig. 1) includes a camera, hardware for capturing and storage of video streams and a battery that ensures more than 7 days of self-sustained operation.

The Mobility Observation Box (MOB) was originally developed to measure the safety of transport infrastructures according to objective criteria and thus make them comparable. The system is compact and allows quick and uncomplicated installation and deinstallation without the need for specialized personnel. Machine learning algorithms and artificial intelligence developed for MOB applications are able to automatically recognize different groups of road users (trucks, cars, pedestrians, cyclists, e-scooters, etc.) and track their movement for each video frame. While the system's original purpose is the analysis of traffic conditions, behavior, conflicts which is normally used for traffic safety, within this work its capabilities were used to identify inter-vehicle distances per speed class based on vehicle trajectories.



Fig. 1. Mobility Observation Box: application in urban traffic (left) and installation at a highway (right).

3 Video-Based Identification of Vehicle Distances

Following the detection of road users in the video files obtained from the MOB, trajectories of all detected road users were identified and analysed. Based on the per-frame information of the object detection bounding box (see Fig. 2 left), movements and distances were determined. The evaluation method used at site 2 associated the right and left bounds of the bounding box with a meter value on the driving lane (Fig. 2 right). The distance between front and rear of two vehicles in that lane (detected based on bounding box data) was then calculated through a simple difference. If two vehicles following one another were not detected simultaneously, the time distance between their respective appearance was used to calculate an "outside the image distance", based on their average driven speeds. An additional correction had to be applied for the rear position (end of vehicle) of trucks, as they can hide parts of following passenger cars. Amount of that was manually estimated for the concrete view given this site.

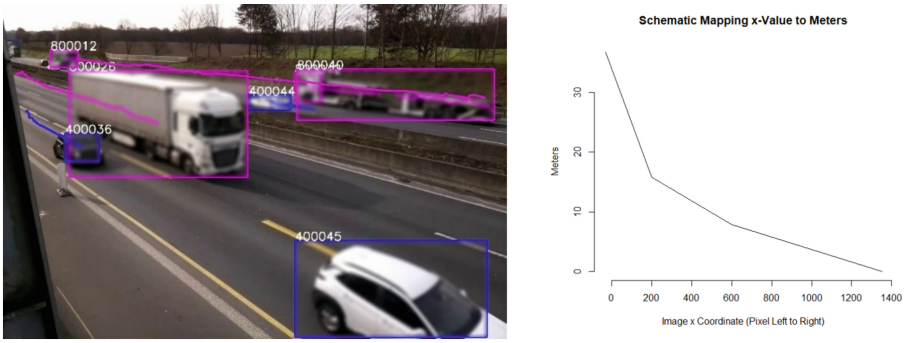


Fig. 2. Object detection in MOB data (left); Scale associating box position to meter value (right).

The evaluation method used at site 1 was slightly different: the time of crossing a reference line was detected and vehicle length was estimated, based on the bounding box size near that line. Both methods produced similar outputs.

The reason for using two evaluation methods lies in the different camera angles that were used. At site 2, more detailed vehicle size information was available from that angle, while on site 1 this was not the case, therefore alternative method was applied.

4 Results

Results from two different measurement sites are presented here. The sites are located on different highways and feature different traffic characteristics. While comparable vehicle counts were captured on both sites (70,424 vs. 101,306), the site 2 features larger portion of trucks in the right lane (Fig. 3 left). This is largely caused by different velocity profiles at the sites. While site 1 features predominantly free-flowing traffic with vehicles travelling mostly with a speed larger than 80 km/h and with small portion of congestion situations (vehicle velocity < 30 km/h), the site 2 features mostly slow-moving traffic with a lot of congestions (Fig. 3 right). In such traffic conditions, cars tend to move out of the right lane, thus increasing the portion of trucks.

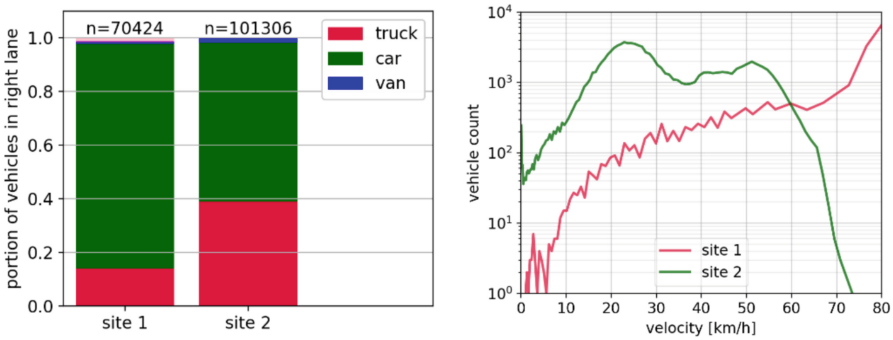


Fig. 3. Comparison of traffic at the two measure sites: composition of identified vehicle types in the slow lane (left) and distribution of measured velocities (right).

The traffic-flow simulations for evaluation of bridge loading assume a constant velocity of vehicles. Vehicle distances are generated by the sampling of a uniform, lognormal, or beta distribution. The evaluation of identified vehicle gaps at site 1 showed that the vehicles tend to use roughly the same time gaps independent of the speed, in conditions where the road is saturated and traffic is slowly flowing ($v = 30$–80 km/h), which is visible in Fig. 4 left from the similarity of the curves. For this reason, we adopted description of vehicle spacings in flowing traffic using time gaps [s], rather than distances [m]. In congestion ($v < 20$ km/h), the description using distances [m] was kept. Figure 4 left shows the identified net time gaps (i.e. passing time between rear edge of a vehicle and the front edge of the following vehicle) at site 1. This data was used to fit distributions shown in Fig. 4 right. Thin dashed lines show fits using a single lognormal distribution, which is the usual modelling approach. Thick solid lines show fits that use a bimodal distribution, consisting of one Weibull and one lognormal distribution. The fitted bimodal distributions match better the underlaying data; the difference to using single lognormal

distribution is noticeable but not drastic. At higher speeds (v > 70 km/h) the traffic becomes less saturated and the distribution of time gaps changes toward larger time gaps.

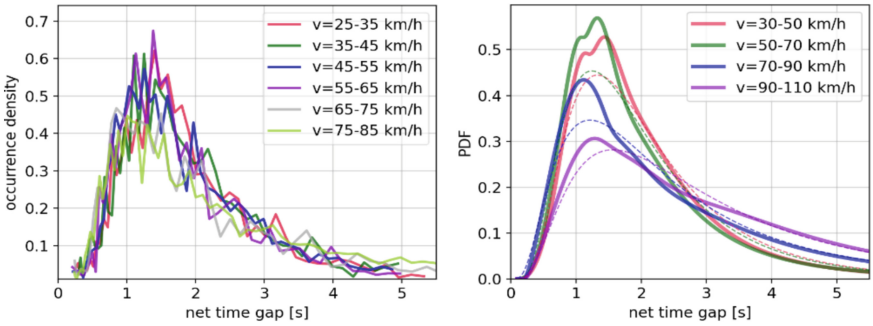


Fig. 4. Identified vehicle net time gaps [s] at site 1 in different speed ranges (left). Fitted bimodal distributions (solid) and fitted lognormal distributions (dashed) at site 1 (right).

For evaluation of vehicle distances in congestion, data from site 2 was used. Figure 5 right shows fitted distributions of net vehicle distances (i.e. distance from the back of a vehicle to the front of the following vehicle). In here, again bimodal distributions consisting of one Weibull and one lognormal distribution were used (solid lines in Fig. 5). A single lognormal distribution was also used for comparison (dashed lines). The difference between using single and bimodal distribution was minor for v < 10 km/h. Low amount of congestions at site 1 did not allow to split the velocity range 1–20 km/h (Fig. 5 left) further.

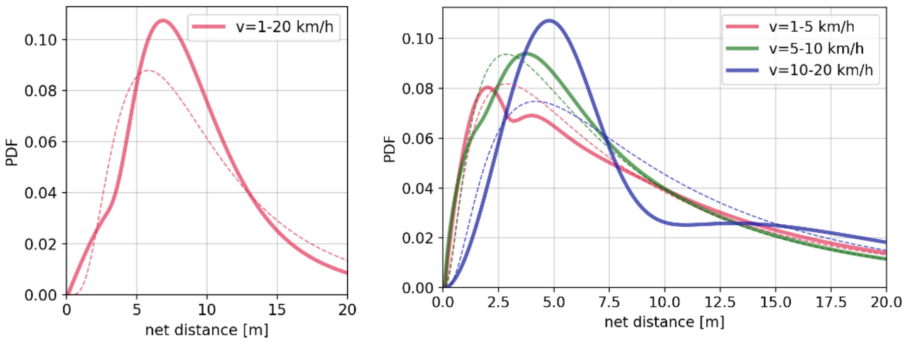


Fig. 5. Identified vehicle net distances in congestion at site 1 (left) and site 2 (right). Fitted bimodal distributions (solid) and fitted lognormal distributions (dashed).

5 Conclusion

The presented method of video-based recognition of vehicles and identification of vehicle distances from the video stream proved to be a feasible method for the given purpose: identification of vehicle distances in congestions. The hardware “Mobility Observation

Box" (MOB) mounted 6–8 m above the road and facing the traffic stream at an angle of around 45° allowed a reliable evaluation of the slow lane; the other lanes get often shadowed at this perspective.

The identified vehicle spacings were used to fit distributions of net time gaps [s] for velocities above 30 km/h and of net vehicle distances [m] for congestion situations ($v < 20$ km/h). In contrast to previous suggestions from the literature, the vehicle distances in congestion seemed to have a roughly lognormal distribution. The used bimodal (Weibull + lognormal) distributions were able to achieve a better fit than single distributions.

In order to derive general recommendations on modelling of vehicle distances in traffic simulations of bridge loading, evaluation of video streams at more sites will be necessary. The presented work shows that the video-based method works well and can be applied on a wider selection of road sites.

Acknowledgements. This work was conducted within the project REAL-LAST (Real load models for bridge structures) funded by FFG (Austrian Research Promotion Agency) within the call "DACH 2021" as project No FO999889387.

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Assessing Road Repair Materials via Digital Image Correlation

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Abstract. This study investigates the performance of road repair materials using digital image correlation (DIC). Cementitious mortar prisms were produced for slant shear testing and repaired using a commercial belitic calcium sulfoaluminate (BSCA) mortar or polyurethane-based repair material. The repaired prisms were subjected to a slant shear test under repeated loading and unloading, and DIC was utilised to measure and compare the strain developed across the repaired prisms. The DIC-generated strain maps show clear differences in the strain between the two repair materials: the prisms repaired with the BCSA mortar showed less pronounced strain under loading across the prisms until the final loading, whereas the prisms repaired with the polyurethane-based materials exhibited a pronounced but consistent positive and negative strain. These differences in the strain across the samples are attributed to the difference in the elastic modulus of the two repair materials. This work highlights the potential of using DIC to assess the performance of road repair materials for their development in the laboratory and contributes to the longer-term objective of digitising road networks towards safer and longer-lasting roads.

Keywords: Pavements · maintenance · strain · and elastic modulus

1 Introduction

Roads represent invaluable public assets; however, a substantial portion of these assets have either surpassed their planned service life or are approaching this point. To guarantee the long-term functionality and safety of our road networks, it is crucial to implement effective maintenance and repair strategies. Despite the increasing availability of road repair materials, the repairs often exhibit heightened susceptibility to damage when compared to the integrity of the parent road material [1]. Failed repairs necessitate frequent maintenance and repair activities, resulting in significant economic, social, and environmental impacts. Traditionally, road inspection, including repair inspection,

D. Palin and H.M. Taha—Contributed equally to this work

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relies on human observation, which is subjective and lacks quantitative information on the mechanical performance of road repair materials and their interaction with the surrounding parent material. This limitation highlights the need for easy-to-use techniques to provide such information in laboratory and field settings. Such techniques would enable the design and delivery of more durable and cost-effective road repair and maintenance strategies.

Digital image correlation (DIC) is a non-contact optical technique that employs tracking and image registration methods to measure displacement and strain on the surface of materials. DIC is relatively simple to use, cost-effective and provides quantitative or objective data. The first instance of DIC being used for construction applications is perhaps Choi et al., who used it to measure the strain in cementitious material specimens [2]. Since then, DIC's utility in construction has been expanded to diverse applications, including the structural health monitoring of large infrastructure projects [3, 4], for evaluating the performance of repairs [5–7] and the validation of computational models [7]. More recently, DIC has been used to assess the strain on the surface of road materials and pavements in the laboratory under various loading configurations [8]. Despite DIC's applicability, it is yet to be used for analysing road repair materials performance.

Here, we use DIC, for the first time, to measure the surface strain in cementitious materials repaired with two commercial road repair materials under loading. Briefly, we (1) cast cementitious mortar specimens, (2) split the specimens for slant shear testing, (3) repaired the specimens with a belitic calcium suphoaluminate (BCSA) mortar or a polyurethane-based repair material, (4) performed slant shear testing using cyclical loading on the repaired prisms, and (5) measured the surface strain in the parent and repair materials using 2D DIC. This work represents an important step in the assessment of road repair material performance and towards digitising the road network from a material performance perspective.

2 Materials and Methods

2.1 Mortar Sample Preparation

Mortar prisms (40 x 40 x 160 mm^3) were cast from ordinary Portland cement (OPC; CEM I 52.5R, White Star Cement) following EN 1015–11 [9]. The mortar was produced with a cement-to-sand ratio of 1:3 and a water-to-cement ratio of 0.5. The prisms were removed from the moulds after 24 hours, tightly sealed in polyethylene bags and kept at room temperature for 28 days. Following curing, the mortar prisms were split at a 30° angle (from and across the centre of the longitudinal axis of the specimens) using a force-controlled testing machine (Controls Testing Equipment Ltd). We decided to split the prisms rather than the generally used saw cut method [10], to generate more realistic crack surfaces. The two split surfaces were separated from each other by ~5 mm, creating an artificial crack and three sides of the specimens were sealed (the bottom and two sides) with adhesive tape.

The mortar prisms were then repaired by filling the cracks with either a BCSA mortar (Korodur, Rapid Set Cement All) or polyurethane-based repair material (Road Mender, 10 min Road Mender) until the repair material became level with the top surface of the respective specimen. The BSCA mortar was prepared with a water-to-mortar mix ratio

of 0.18, and the polyurethane repair material was prepared by mixing part A with part B in equal proportions (w/w). The tape was removed once the repair materials were set (around 30 min). The front face of each specimen (a diagonal crack facing outwards) was sprayed with an even coat of white paint and then speckled with black paint with a random pattern (Fig. 1).

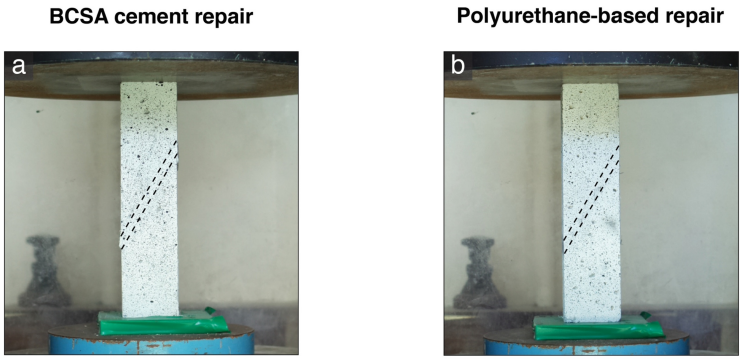


Fig. 1. (a, b) Images of mortar specimen repaired with (a) a belitic calcium sulphoaluminate (BCSA) cement and (b) a polyurethane-based repair material. The dashed lines in (a, b) delineate the location of the repair materials beneath the white paint and black speckle pattern

2.2 Slant Shear Test

Figure 1 displays photographs taken of two representative mortar prisms repaired in a slant shear configuration with the BCSA mortar (Fig. 1a) and the polyurethane-based repair material (Fig. 1b). Both repaired prism types were compressively loaded under compression following EN 1015–11 (Fig. 1) [9], reaching a maximum load ($_{Max}$) of 0.28 MPa and unloaded ($_{Min}$) for 10 cycles (Fig. 2). The value of 0.28 MPa was selected based on previous slant shear tests of the prisms repaired with the repair materials as it is below their bond strength of both materials (data not shown) to avoid debonding/failure of the repairs in the current work.

2.3 DIC

Images were taken normal to the specimen face with a Raspberry Pi camera with a 12-megapixel resolution and a frame interval of 1 image per second. The strain in the materials was calculated using the image analysis tool GeoPIV-RG [11]. The subset size was set as 20 pixels, and the step between the subsets was chosen as 10 pixels.

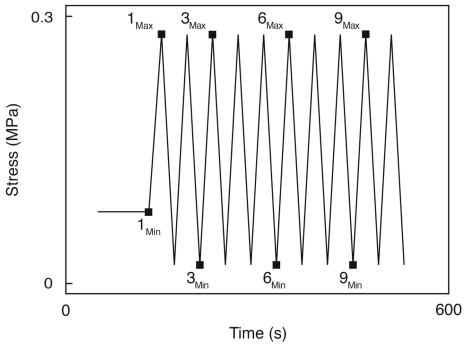


Fig. 2. Plot of the loading scheme for the slant shear test. The black squares in the plot represent the points in the loading cycle that correspond to the strain maps in Fig. 3. Note: $_{\text{Min}}$ is the minimum load and $_{\text{Max}}$ is the maximum load in the cycle

3 Results and Discussion

Figure 3 displays the strain maps of representative repaired mortar prisms during loading and unloading. The prism repaired with the BCSA mortar maintains a similar strain across the prism when loaded ($_{\text{Max}}$) and unloaded ($_{\text{Min}}$; Fig. 3b) until the ninth loading (Fig. 3a; 9_{Max}), where there is a distinct bimodal pattern in the strain map whereby the centre of the specimen demonstrates a negative strain and the top and bottom display a positive strain. In contrast, the prims repaired with the polyurethane-based repair materials demonstrate pronounced yet consistent negative strain (i.e., expansion) when loaded ($_{\text{Max}}$) and positive strain (contraction) when unloaded ($_{\text{Min}}$) in the location of the repair material (Fig. 3b).

The differences in the strain maps between the two repaired prism types can be explained by differences in the mechanical properties of the repair materials. The BSCA mortar having a comparable modulus of elasticity, E, or stiffness to the OPC (BCSA: $E = 31.7$ GPa [12]; OPC mortar: $E = 31.5$ GPa [13]) will have a similar behaviour when loaded and unloaded (Fig. 3a). In contrast, the polyurethan-based repair with a lower E (the polyurethan-based repair material: $E = 1$ GPa [14]), when loaded will expand outwards and, when unloaded, contract back (Fig. 3b). Furthermore, because the BSCA mortar is stiff and not elastic it is less strained until at some fatigue limit the material demonstrates a bimodal strain pattern and is likely permanently damaged (Fig. 3a; 9_{Max}), while the polyurethane-based material being relatively elastic is strained but is able to withstand repeated loadings and unloading's and is relatively undamaged (Fig. 3b).

4 Possibilities and Limitations

DIC offers promising nondestructive technique for assessing surface strains on road repair materials and potentially roads. However, several considerations and challenges need to be addressed in its application. Significant limitations lie in the fact that DIC is a surface technique, capturing strain on the road surface and not in the depth of the

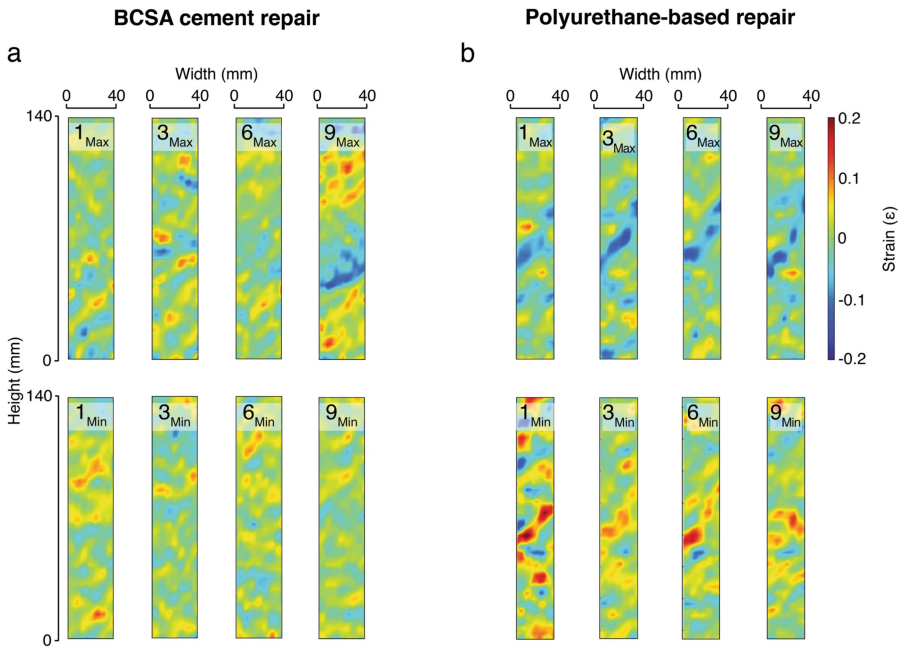


Fig. 3. (a, b) Strain maps of (a) the specimens repaired with the BCSA cement and (b) the specimens repaired with the polyurethane-based repair material. Note: $_{\text{Max}}$ represents the maximum load, and $_{\text{Min}}$ is the minimum load in the cycle

road. To overcome this limitation, DIC could be integrated with complementary below-ground techniques, such as ground-penetrating radar (GPR) [15]; and/or efforts could be directed towards integrating DIC data into models that consider boundary conditions, aiding in the modeling of strain distribution in road layers for a more holistic assessment of pre-damage detection. Additionally, DIC will encounter challenges in real-world road surface conditions, including debris, oil, variable light quality, and environmental factors like rain impacting the reliability of the strain measurements. Effective data processing and cleaning protocols will be essential to mitigate these challenges and ensure the reliability of the acquired surface strain data.

5 Conclusion

In this study, DIC has shown that prisms repaired with the BCSA mortar repair material demonstrated similar strain across their surface, while the prisms repaired with the polyurethane-based materials exhibited a pronounced positive and negative strain when loaded and unloaded. Notably, the prisms repaired with the BSCA mortar showed signs of fatigue damage at the end of the loading cycle, while those repaired with the polyurethane-based material did not. The differences between the repair materials can be attributed to differences in their mechanical properties, with the BCSA mortar being stiff and non-elastic and the polyurethane-based material being less stiff and elastic. A

better understanding of the strain in road repair materials and the surrounding repaired parent materials would offer quantifiable data and valuable insights into the performance of road repair materials. This work highlights the potential of using DIC to assess the performance of road repair materials in the laboratory and, if combined with other advanced non-destructive techniques, such as GPR [15], could provide comprehensive information on road repair for maintenance in the field.

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Some Impacts of Traffic Management Decisions on the Residual Life of a Long-Span Bridge

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Abstract. Bridges are important links in our road infrastructure network, making it possible to carry all types of goods and creating economic growth. This is particularly the case for (some) long-span bridges that cross main rivers, and for which there exist no alternative. These long-span bridges are often composed of high concrete piers, and steel orthotropic decks, which permit big crossings. These types of bridges are sensible to specific parameters of the traffic, possibly reducing their residual lifetime when introducing new traffic management procedures. This is the case for platooning, where vehicles are closer to each other than regular traffic and whose lateral positions are aligned in the lane. After presenting the context, this paper will show the assumptions and boundary conditions for our work. Without big emphasis on the calculations themselves, we will give some results in terms of modification of the residual lifetime of these bridges.

Keywords: Traffic impact · residual life · management decisions

1 Influence of Platooning on Specific Bridges

The issue of the introduction of platoons on bridges can be summarized by three impacts.

1.1 Closer Vertical Loads

Even if convoys are being observed on European roads currently [1], this practice is forbidden, and a 2-second gap is the minimum distance to be found between two vehicles.

The fact that platooning will bring the vertical axle loads closer, up to $0.3s$, will have an effect on long span bridges: for non-local effects with influence lines longer than 20 meters, more loads will have to be taken into account.

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1.2 Aligned (in Lateral Position) Vertical Loads

Currently, a variability of the position of the trucks in the lane is observed in traffic measurements [2], it is therefore expected and taken into account in the calculations [3]. This is not the case for platooning as it is currently foreseen, where trucks would drive closer behind each other, in the same lateral positions, in order to maximize the aerodynamic drag and minimize fuel consumption.

This could be an issue for bridges with local, lateral localized effects: for example, for steel bridges with longitudinal stiffeners (for example, bridges with steel orthotropic decks), the fatigue life of some steel elements might be decreased a lot.

1.3 Higher, Closer Braking Forces

The current design of bridges to horizontal forces is linked to the number of trucks on the bridge.

With platooning, at a given time, there might be more trucks on the bridge, meaning that the design loads might have a lower safety margin when compared to actual braking forces developed by platoons on a bridge.

On the other hand, platooning and CACC may reduce the brake forces as vehicles can better anticipate on the behaviour of the preceding vehicle. The shock-wave damping/string-stability CACC offers avoids late braking and therefore large brake force amplitudes.

2 Assumptions and Methodology of the Assessment of Bridges to Platoons

2.1 Asumptions

Several assumptions that simplify the problem and therefore the calculations have been made:

– First, the dynamic impact of the moving loads has been neglected in the calculations. If a gross value of the effect of a vehic

2.2 Methodology

Assessment of Effect of Axle Loads on Bridges. These effects are calculated through the convolution of the effect to be considered, with the vertical, moving axle loads of the traffic: this leads to the time series of effects (strains, stresses, ...) in the bridges due to the traffic loads.

In particular, a moving vehicle with N axles would be considered as N moving loads, with given axle loads and given distance between the axles. If $I_i(x)$ is the value of the influence line of effect i at coordinate x and we consider truck j,

the global effect at coordinate x, $E_i(x)$, is given by the sum of the effects of all axles:

$$E_{(i,j)}(x) = \sum_{n=1}^{N} P_{(j,n)} I_i(x - d_(j,n)), \tag{1}$$

where $P_{(j,n)}$ is the axle load on axle n of truck j, $d_{(j,n)}$ is the distance between axle 1 and axle n for truck j (so by definition, $d_{(j,1)} = 0$).

The values of $P_{(j,n)}$ and $d_{(j,n)}$ are given by the vehicle configurations and the function $I_i(x)$ is representative of the chosen infrastructure.

This time series is then studied in terms of fatigue and extreme loads.

Assessment of Extreme Loads. By computing this effect $E_{(i,j)}(x)$, its maximum value can be assessed for the various traffic configurations. Two traffic configurations can then be compared in terms of extreme effects by calculating the ratio of the effect $E_(i, j)(x)$.

More precisely, in this work we have compared the "new" traffic with platoons to the current traffic (as measured).

Fatigue Assessment. Fatigue is a well-known issue for steel bridges, or steel elements in composite bridges [5]. It is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading. Therefore, it is linked to the GVW of the vehicles, but also the axle loads.

The fatigue life of the structure is given by the stress cycles exerted by the moving load on the structure. The aggressivity of the vehicle configurations is given by the following equations, that correspond to the S-N Wöhler curves [5]. The fatigue life is then calculated using Miner's law, by reducing the complex loading (of variable amplitude) to a series of simple cyclic loadings (histogram of cyclic stress).

This makes it possible to assess the fatigue life of a structure based on the time series of the effects.

3 Example of Assessment and Corresponding Results

As a first step, we define a fully loaded, an average loaded, an empty truck, and we compare their effect when driving alone to driving in platoons.

These trucks are of type 5-axle semi-trailer (2-axle truck followed by a 3-axle semi-trailer, where the tridem is located at the end of the trailer).

The introduction of platoons in the traffic will not have an impact on effects with influence lines longer than the vehicle length, namely around 16.50 m - 18.75 m. A set of 19 influence lines have been chosen.

Using these combinations of influence lines and trucks/convoys of trucks, assessments about the influence the multi brand platooning on bridges can be made (see Fig. 1 as an example).

But some general conclusions can be drawn:

- If the length of the influence line is longer, the increase in aggressivity of the traffic on this effect will be higher. In particular, if the convoy/platoon is composed of more than 2 trucks, this will have to be calculated. On the other side, for a span length of 25 meters, there is no need to consider more than 2 trucks (and even this case is only interesting in the case of very small gaps between trucks).
- The increase of aggressivity will be maximal for the longer influence lines, especially those linked to the supporting cables of suspended bridges (type F). This is especially negative for older cable-stayed bridges, which already have issues to carry the current traffic loadings. The bridges with limitations in terms of acceptable GVW are generally not part of highway (more of secondary roads), so there should be no safety issues. Nevertheless, for older cable-stayed bridges on highway, a site-specific assessment would have to be performed.

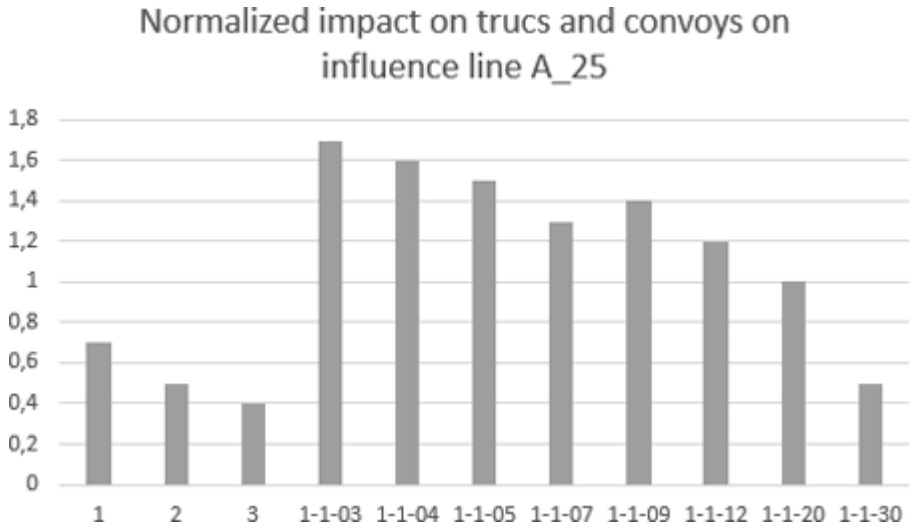


Fig. 1. Normalized effect of trucks 1, 2 and 3, and convoys of trucks 1 (gap between 0.3 s and 3.0 s) on influence line A of length 25 m.

4 Conclusion

Introducing new types of traffic (truck shapes, truck loads, driving conditions) leads to changes in the effect of traffic on infrastructures. It is therefore important to assess rationnaly these effects, by agreeing on assumptions and assessment metholodgies.

Afterwards, the effect of traffic on the infrastructure, but also on the surrounding traffic, economical issues, other externalities (noise, emissions), ..., can be optimized.

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An Image-Based System to Improve Freight Capillaries Circulations

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Abstract. To date, many freight capillaries are limited or degraded. They are called "Voie Unique à Trafic Restreint » (VUTR). There is no security engagement there, which restrict traffic to one train on the track. To increase circulation, the freight line is separated into sections. For a train in section S, sections S-1 and S+1 must remain empty. To confirm the wholeness of the convoy in S, drivers must confirm the presence of rear red lights by checking visually. The procedure is time-consuming and does not bring as many improvements as expected. This paper presents a system to improve divided VUTR. On each side of the subsections, visual sensors are installed. They bring remote surveillance, easily understandable by a human agent. The video stream starts recording when the train arrives and stops when it leaves. The system also has an option to plan data acquisition on specific times, for example theoretical timetables. Data are sent on a central server, accessible to control centers, drivers, and station's agents. This first use of this application is a human monitoring. In case of system failure, the drivers would go back to their original missions. The second use is an algorithmic processing of the data. Image processing and machine learning are considered. In both cases, the detection of red lights in section S allows to say "section S-1 is free and safe".

Note: *no SIL is attributed to this system.*

Keywords: Freight · Image Processing · Traffic Improvement · Artificial Intelligence

1 Introduction

In addition to providing better security for the transported goods, freight trains are also more efficient, energetically and ecologically speaking. About two thousand tons of merchandises may be shifted with a single train. This means that one train can move as many goods as about fifty trucks. So, even powered by fossil fuels, freight trains are more consistent with climate change adaptation than road transport. Furthermore, most countries are actively exploring more ecofriendly alternatives such as electric, hybrid or battery trains [1, 2] to reduce diesel-railway carbon footprint. Hence railway freight has an important impact for green transportation.

Given this fact, it is important to maintain and strengthen railway transportation for goods. Unfortunately, maintenance is expensive, especially nowadays with the increase

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of raw material prices. Many freight capillaries are impacted by the lack of resources and grow limited and degraded. Those tracks are often limited to the sole use of freight, and their exploitation is transformed to be as economical as possible.

The most impacted tracks are called «Voie Unique à Trafic restreint» (VUTR) [3] or Unique Tracks with Restricted Traffic (UTRT). They refer to single and isolated tracks. Due to the absence of security engagements, traffic is restricted to a single train on the track at a time. Train operation is handled by line managers and service agents, according to the specific operation regulations, in particular strong safety requirement. The driver must acknowledge and respect the line peculiarities, wait for the line manager to authorize departure, and most importantly apply the speed limit (40 km/hour or less). Given this set-up, it is 2 to 4 trains that may run per day. This situation is suboptimal, and many clients have to turn to road transport due to lack of train's availability.

In order to increase circulations, a new process called "divided UTRT" was tested. The principle copies railway cantoning: the line is divided into sections. For a train in section S, sections S-1 and S + 1 must remain empty to ensure security. In addition, each section is separated from its neighbor by "clearance portions" SD. On the latter, poles are erected with additional signaling, to indicate the demarcation of the area.

Stopping in those areas is mandatory: there the train drivers must check the completeness of their convoy. They leave the cabin, walk alongside the train, look for and confirm the presence of the rear red lights, and walk back to the driving console to resume their journey.

This process allows multiple trains on the line while maintaining security requirements. However, the complete path is about 1.5 km, in the ballast, which can be grueling and dangerous for agents. It often takes around one hour to complete the patrol and lines frequently have three SD or more along the way. In these conditions, the procedure is time consuming. Hence it does not bring as many improvements as expected, and it is economically unpractical (Fig. 1).

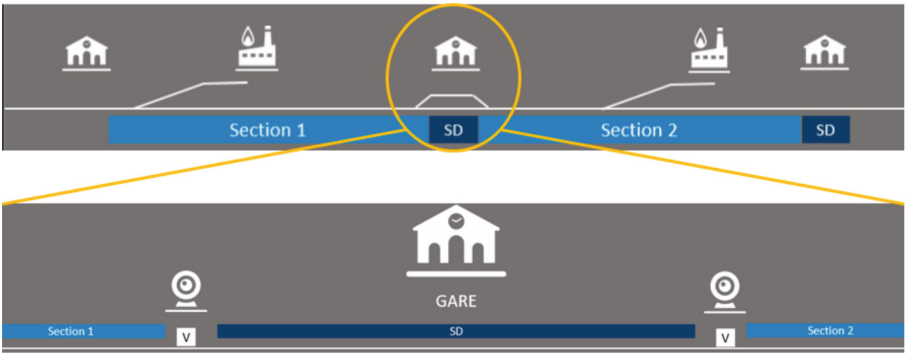


Fig. 1. Sketch of the divided UTRT. Sections are separated by SD areas. Initially, they are marked by signaling on poles. Sensors may be installed to solve the limitations.

The issue is the duration of convoy integrity verification. Human check is the most trustable one but also the most wasteful in resources, without any benefits for the agent.

Hence, automation of the monitoring task seems the natural lead to transform the divided UTRT into a viable system.

The Shift2Rail Project for example has included the "on-board train integrity" block. Its main goal is to autonomously verify the completeness of the train, while train is in operation. If the distance and speed between the first and the last wagon of rolling stock remains unchanged, then all is working correctly. Otherwise, the on-board system will detect the loss of train integrity [4].

However, the affected lines must answer limited budget, the solution must be frugal. Moreover, given that freight cars are not necessarily the property of the operator, the railway company may not be able to equip all wagons. Hence, installing IoT sensors or RFID tags on wagons [5] is not conceivable, as it also requires immobilization of rolling stocks and lots of maintenance costs. Last but not least, there are only a limited number of places where the system integrity must be checked.

This work presents a system to improve the divided UTRT. It is based on remote observation of the SD, though visual sensors. The system is rather cheap, easy to put in place and takes advantage of previously installed equipment. It also has a strong impact on agents and their daily tasks, reducing mental workload and optimizing decision making processes.

The paper is organized as follow. Section 2 presents our methodology, the system that was put in place and its different configurations. Section 3 exposes the experimentation and results, highlighting requirements and limitations. Section 4 concludes the paper.

2 Methodology

By copying the human eye, visual sensors provide information that are naturally understood by human agents. In particular, using cameras, integrity evaluation is a simple matter of red lights detection [6, 7]. Two configurations emerged.

First, with the installation of cameras on the SD poles, the video stream may be sent to a global server. Then, the users (exploitation or station agents) would access the video and monitor in real time the environment. When the train arrives, they would be capable of visualizing the tail of the train and its lanterns.

Here again, relying on human verification is expected by regulation organizations. However, people working in stations or control centers already have many tasks and missions to attend to. They cannot be asked to stay in front of a video and do nothing until the freight train passes in the camera's field of view. That brings up the other arrangement.

This second configuration makes use of Image Processing and Artificial Intelligence to automatically detect the train's arrival and its rear red lights. In this way, the agent receives a notification with a single screenshot and the recommendation of the algorithms: train integrity ok or not ok. When available and without engaging the security of other tasks, the agent validates the tool's output or refute it. They would then contact the driver and confirm departure from the SD zone.

3 Experimentation

The system described in this section has been installed on-site. It uses a Bosch camera, of HD resolution (1920x1080pixels). It provides 30 frame per second and allows scrshots, both with a dynamic range of 120 dB. The hardware is power and controlled through POE protocol, no nearby power outlet is need.

To create the data processing system, there is a first step of tracks detection using a pre-trained and finetuned YoloV7 [8]. Then a "corridor" is created (Fig. 2), corresponding to the half-height train's gauge. The aim is to limit the search of the lanterns to the possible area and reduce processing time.



Fig. 2. Illustration of the camera, installed as a remote eye (Left). On the right, the track is segmented and an example of half-height train's gauge, the area to search for the lights.

The second step consists in detecting the lights. It may be done when the train passes in front of the camera, with a validation on several images. Since stopping in the SD is mandatory, a confirmation may also be conducted by analyzing the picture of the parked train. Knowing the shape of the lights, their precise number (two) and the distance between them (about 1.4meter), the search for the light is strongly reduced.

On every selected images, both the Red-Green-Blue (RGB) and the Hue-Saturation-Value (HSV) color spaces are used and pre-processed to highlight the "pure" red color, main component of lanterns' light. As it may not be robust enough, YoloV7 is applied, to detect and recognize the rolling stock. Given the type of wagon, the algorithm also output the position of the lanterns. These coordinates are compared to the ones extracted from the pre-processing to confirm the detection (Fig. 3).



Fig. 3. Highlights of queue red lanterns using pre-processing in RGB channels and HSV color space. From left to right are displayed the original image, the processed red channel and the processed saturation channel.

Note that because of frugal requirements and to reduce telecommunication footprint, the camera does not send streams continuously. It is triggered by movements and the arrival of the train, on the same principle as event cameras [9]. A batch of images is kept and renewed. The first image is compared to the last: if the number of different pixels is above the defined threshold, then the recording starts. It is made easier by the a priori knowledge about the train's arrival speed, direction and localization.

Last but not least, a study has been conducted concerning the lightning conditions. The best detection results occur at night, when the lanterns are about the sole light source. In addition, the visibility of the peculiar red of the beacon is conversely proportionate to darkness. During the day, the most difficult condition is when the sun is low, aligned with the tracks, facing the camera. The sensor may be blinded. Even if the detection still occurs, the confidence rate may decrease by several points.

4 Conclusion

Freight trains are the most efficient way of transporting goods. However, many capillaries are difficult to look after, hence specific and restrictive regulation for those lines. A new operation process is proposed, using canton and clearance portion. This paper introduces an image-based system to monitor the arrival of trains in specific areas. It also focuses on detecting the two red lanterns at the rear as they ensure the train integrity. Both classical image processing tools and deep learning algorithms are used to achieve that goal. Results are promising.

Future work will make use of the Infrared beam offered by the selected camera. Indeed, European consortium established the future beacon to signal the convoy integrity. The material is responsive to those wavelength and should be easily identifiable.

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Foamed Bitumen Stabilisation of Basecourse on Brand Highway, Western Australia

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Abstract. Brand Highway (H004) forms part of a major road network linking Perth with the regional centre of Geraldton and the North-West of Western Australia. The Highway is a strategic restricted access vehicle (RAV), Category 7 freight route, as well as a local access between town sites and rural access areas. Brand Highway has been constructed in various stages from 1962 using a variety of locally-sourced materials such as crushed limestone, laterite and crushed granite in the subbase and basecourse layers. The section that was investigated as part of the initial project is situated between SLK 4 and SLK 50, directly north of the Muchea Road Train Assembly Area. The posted speed of this section of road is 110 km/h and it consisted of a two-lane, two-direction bituminous sealed surface with 3.5 m lane widths. Sealed shoulder widths varied from 0.5 m to 1.5 m. Apart from the geometric improvements required to widen the surface width to include a 1.0 m wide median strip for riding quality and safety reasons, one of the project objectives was to increase pavement life expectancy with a cost-effective rehabilitation design. In situ recycling of 250 mm of the existing basecourse and subbase layers together with 50 mm imported crushed rock to facilitate shape correction and improve drainage, using foamed bitumen and lime proved to be the optimum solution. This paper will give an overview of the pavement rehabilitation design conducted, describe the construction methodology followed and quality control testing conducted on site.

Keywords: Brand Highway · Pavement Rehabilitation Design · Falling Weight Deflectometer (FWD) Analysis · Foamed Bitumen Stabilisation · In Situ Recycling

1 Introduction

Brand Highway forms part of the road network linking Perth in Western Australia with the regional centre of Geraldton and the North-West of the State. This portion of Brand Highway has been constructed in various stages from as far back as 1962. The aim of this paper is to provide an overview of the pavement investigation conducted for SLK 4 to SLK 50 of Brand Highway (H004) and the methodology used for in situ recycling of the existing basecourse, with incorporation of crushed rock to facilitate road widening, shape correction and improved drainage.

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2 Pavement Investigation and Rehabilitation Design

2.1 Visual Observations

Visual observations of the condition of the pavement were made during a drive-through inspection of the road on 8 February 2021. Defects observed included flushing, stripping, and bleeding of the bituminous seal (Photograph 1), with cracked asphalt in intersections. Rutting of up to 40 mm, was measured in the wheelpaths. There was a significant amount of damage (and repairs) at side roads (Photograph 2 and Photograph 3) with poor drainage (refer Photograph 4). Shallow drains and blocked culverts were also common through the site.



Photograph 1. Rutting in wheelpaths



Photograph 2. Stripping and general pavement failure



Photograph 3. Significant cracking and pavement failure



Photograph 4. Water ponding with no runoff opportunity

2.2 Geotechnical Investigation

Twelve (12) test pits were excavated, and material sampled to enable characterisation of all granular and bituminous materials to a depth of 1.2 m beneath the road surface. Dynamic Cone Penetrometer (DCP) testing to a depth of 1.5 m (or refusal) from the road surface was also conducted at each test pit.

The quality and type of the pavement materials along this road section is highly variable. It includes different thicknesses of crushed rock, laterite gravel and bitumen stabilised limestone in the basecourse, and crushed rock, crushed limestone and laterite gravel at subbase level. The subgrade mostly consists of sandy materials.

2.3 FWD Testing

Falling weight deflectometer (FWD) testing with the plate load set at 40 kN (566 kPa) was conducted at 25 m intervals, staggered left-wheel path to right-wheel path along both lanes. Average maximum deflections per lane were less than 500 microns.

2.4 Design Life and Design Traffic

The 2020/21 traffic count data was obtained from the (Main Roads Western Australia (MRWA) website and the traffic load distribution of the Muchea weigh-in-motion (WIM) site was used. The design traffic for a design life of at least 12 years was calculated to be between 6.5 and 7.3 million design equivalent standard axles (DESAs).

2.5 Data Analysis

2.5.1 Identifying uniform pavement sections

The cumulative difference (CD) approach [1] was used to identify uniform pavement sections. Figure 1 shows CD plots produced for the maximum deflection (D_0), base layer index (BLI), middle layer index (MLI) and lower layer index (LLI); calculated in accordance with the benchmarking technology developed by Horak and Emery [2]. Data points are shown as "markers" with the plotted lines representing the CD analyses. A uniform section is based on a marked change in grade of the slope of the plot. SLK 32 and SLK 33 are at the same location and there is no missing data.

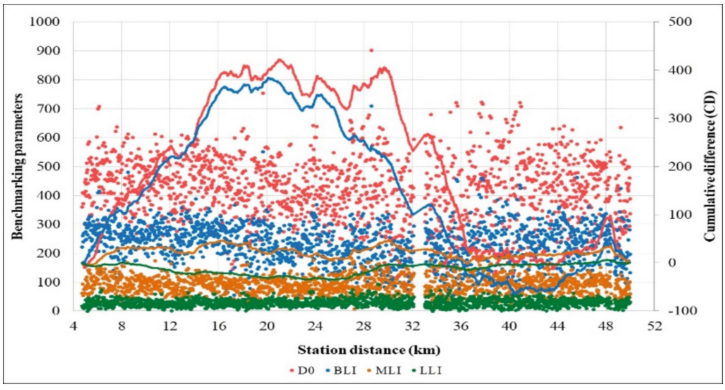


Fig. 1. CD of benchmarking analysis

From the CD graphs it is obvious that the greatest variability in data is in the basecourse (D_0 and BLI), while the subbase (MLI) and subgrade (LLI) appear to be more uniform. This is typical of a pavement that has been in service for several years where the subbase and subgrade have consolidated under traffic.

2.5.2 Backcalculation of Layer Moduli from FWD Results

The Rubicon Toolbox [3] software package was used to conduct backcalculation of pavement layer moduli and determine the remaining life of the various pavement sections.

Based on materials test results, and the fact that it is known that laterite (ferricrete) and limestone set up over time, the backcalculated basecourse and subbase moduli were capped at 700 MPa and 500 MPa, respectively. The average upper subgrade moduli were consistently around 250 MPa.

2.6 Pavement Rehabilitation Design Option

Several rehabilitation design options were considered. The option chosen that satisfied the design life involves in-situ recycling of the existing basecourse with the addition of foamed bitumen to construct what is typically called a Bitumen Stabilised Material (BSM) [4] layer. There are several advantages in doing so:

- Existing wearing course materials need not be milled off, but can be directly mixed in.
- Where required, additional material can be added and mixed in at the same time.
- A BSM provides an improved granular layer with very good waterproofing, durability and fatigue properties.

3 Stabilization Design

After determining the optimum active filler type, the percentage foamed bitumen required was determined by obtaining the Indirect Tensile Strength (ITS) [4] of various blends of existing pavement materials with at least three percentages of foamed bitumen added. The lime and foamed bitumen percentages specified were:

- 1% Hydrated Lime; and
- 2.5% Foamed Bitumen.

4 Construction

4.1 Background

Construction works commenced in February 2022 and the project was completed in May 2023. In total 26.4 km of Brand Highway was rehabilitated for this project using insitu foamed bitumen stabilisation with a Wirtgen WR250 [5].

Arup Australia Pty. Ltd. was requested to provide technical construction support after initial construction related concerns were identified in the first 6 months of the construction period that could negatively impact the design life of the foamed bitumen stabilised basecourse and ultimately the full pavement. The sections below report on the most relevant construction processes assessed and the guidance on best practise guidelines to mitigate variability in the final foamed bitumen stabilised layer constructed.

4.2 Best Practice Construction Methodology

4.2.1 Pre-start Check List and Daily Records

The in-situ recycler used consists of many moving parts, mixing bitumen at temperatures up to 180 °C with water in the mixing chamber to facilitate the foaming process. This necessitates that the recycler be checked and cleaned before works start as well as at the end of the working shift to prevent bitumen solidifying in the spray nozzles and build up in the mixing chamber. Not maintaining the recycler will directly impact the quality of the final foamed material placed and the subsequent performance of the layer constructed.

4.2.2 Cold In Situ Recycler (Stabiliser)

Understanding the equipment used to conduct recycling and foamed bitumen stabilizing at the same time is critical to ensure the product meets the design intent. Having an experienced recycler operator is crucial.

The recycler operator in turn needs a supervisor at the back of the recycler to visually monitor the consistency of the foamed bitumen material as it exists the recycler, providing feedback to the operator if he needs to adjust water content or increase advancing speed. Specific things to be aware of are:

- Inconsistent mixing/ distribution of bitumen – spraybar/pumps of recycler could have airlocks or blockages preventing continuous flow to the individual spray nozzles. This is visually identified by lighter or darker strips of stabilised material at the back of the stabiliser.
- Tactile check – Sampling material freshly stabilised across the width of the stabilised section and checking if the material is too wet or too dry and communicating that back to the stabiliser operator to make the necessary adjustments.
- Poor dispersion of foamed bitumen – This can be visually identified by lumps of bitumen or stringers in the stabilised layer. Photograph 5 taken during the construction phase provides an example of a stringer.



Photograph 5. Lump (stringer) of bitumen identified at the back of the recycler

Typical causes of stringers are:

- Insitu moisture content being too high or too low and therefore impacting the fluff point of the material which is usually around 70% of OMC

- Material grading has changed and most likely a reduction in fines
- Advancing speed of stabiliser could be reduced to allow more agitation of the material in the mixing chamber

4.2.3 Compaction and Trimming

One of the critical items to consider is managing the risk of differential compaction behind the stabiliser. The drum of a steel-wheel roller typically spans the compacted strips left by the rear wheels of the recycler. This is commonly known as "bridging". Using a padfoot roller as the primary compaction plant behind the stabiliser prevents this bridging action by compacting deep into the layer and subsequently developing density from the bottom of the layer. The pads further assist in disturbing the surface and therefore moving material transversely and reducing the risk of bridging. A vibrating padfoot roller is recommended if the layer compacted exceeds 150 mm.

4.2.4 Deflection Testing after Construction

FWD testing was conducted after completion of the construction works. A comparison of the overall maximum deflections before and after construction, showing the large reduction in deflections are summarised in Table 1.

Table 1. Comparison of average maximum deflections before and after construction

Parameter	Northbound		Southbound	
Year	2021	2023	2021	2023
Average deflection (micron)	424	204	429	237
Improvement in average deflection (%)		76		81

5 Conclusions and Recommendations

Insitu foamed bitumen stabilization is a proven technology with significant benefits in rehabilitation works where existing pavement materials can be reused to significantly extend the pavement life. This has been validated by FWD testing conducted 1 year after construction was completed to compare the improvement in measured deflections. Experienced operators and strict quality control during construction are imperative.

Acknowledgements. The Authors wish to thank Main Roads Western Australia for their collaboration while Arup provided technical support during construction.

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Experimental Evaluation of the Ageing Effects on Skid Resistance of Bituminous Mixture Pavements

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Abstract. The objective of the paper is to present the results of an extensive experimental work carried out in field weather conditions to study the ageing effects on skid resistance of a bituminous mixture for road pavement wearing course. A set of prismatic roller compacted specimens were aged using two laboratory ageing methodologies: 1) short- and long-term oven ageing (LTOA); 2) TEcnico accelerated AGEing methodology (TEAGE); 3) and an experimental section was exposed to real climatic conditions (Field), as reference. A bituminous mixture for wearing courses with a maximum aggregate size of 14 mm and a neat bitumen 35/50 was evaluated. To assess the evolution of surface characteristics with the environmental effects, both micro- and macrotexture properties were evaluated in laboratory and in the field over the time using the Pendulum test value (PTV) and mean texture depth. Measurements were performed before the ageing starts and after six months until the specimens reach the pretended age. In terms of microtexture was possible to verify that no significant impact was observed for LTOA ageing method. However, the evaluation performed on the samples aged under real conditions and using the TEAGE method showed considerable increases in PTV in first 12 months. After this period, the results presented a tendency to a constant P TV. After 18 months, the samples under real environmental conditions showed a slightly decrease of PTV. This decrease can be associated with the removal of the aged film of bitumen that covers the aggregates by the action of the rainfall.

Keywords: Ageing · Bituminous mixture · Macrotexture · Road pavement · Skid resistance

1 Introduction

The surface characteristics of a road's wearing course hold paramount importance when it comes to ensuring the safety and comfort of road users. Every year, road accidents pose substantial risk to people's lives on a global scale. Among the key determinants impacting road safety, the skid resistance of the pavement stands out as a critical factor [1, 2].

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The bitumen can be considered as the most susceptible component in the bituminous mixture as result of ageing and its subsequent deterioration. This susceptibility exerts a significant influence on the overall performance and quality control of bituminous mixture courses, and by extension, on the service life of road wearing courses. Therefore, accurate and reliable tests and methods are necessary to evaluate the bitumen's rheological behaviour and to provide solid basis for the evaluation and application of bitumen in bituminous mixture roads.

The bitumen ageing results in hardening (stiffening) of the mixture, which modifies its performance. This may be beneficial since bituminous mixtures have improved load distributions properties and are more resistant to permanent deformation. However, ageing may also impact the embrittlement and loss of durability in terms of water resistance and moisture susceptibility. Furthermore, the ageing conducts to changes in macro- and micro- textures of the pavement surface, which have direct impacts on skid resistance. In fact, the ageing of bituminous mixture impacts the skid resistance evolution during pavement lifetime.

The ageing hardening can be quantified by means of ageing indicators. These correspond to several physical grading tests. The hardening severity can be specified in terms of increased numbers of ageing index, softening point, viscosity, mass loss and decreasing penetration. There is general consensus about the detrimental impact of environmental effect and traffic loading on bituminous mixtures in roads. The age hardening factors that can be hold accountable for these bitumen performance changes are related to origin, traffic and environmental loads and exposure time, this is the phenomena that can be related to temperature, periodicity, oxygen, UV-light, water, diffusion rate, film thickness, void content, acids, etc. These factors are directly responsible for hardening and activation of ageing mechanisms [3, 4].

The objective of the paper is to present the results of extensive experimental work carried out in field weather conditions to study the ageing effects on the skid resistance of a bituminous mixture surface road pavements. The field results were compared with two laboratory ageing methodologies to evaluate to assess the rehabilitation of laboratory methods to simulate real ageing conditions.

2 Materials and Testing Methodology

A set of prismatic roller compacted specimens were aged using two laboratory ageing methodologies: 1) short- and long-term oven ageing (LTOA); 2) TEcnico accelerated AGEing (TEAGE) methodology [5]; 3) and an experimental section was exposed to real climatic conditions, as reference (Field).

The studied dense graded bituminous mixture for wearing courses had a maximum aggregate size of 14 mm and was produced with a neat bitumen 35/50 (AC14 surf 35/50). The bituminous mixture was designed according to European standards EN 13108–1. The optimum bitumen content was selected using the Marshall method (EN 12697–34). The mixture was produced in-plant and compacted using the roller compacter (EN 12697–33). The bituminous mixture was designed according to EN 13108–1 with basalt aggregates and a binder content of 5%. The bituminous mixture presented the following characteristics: voids in mineral aggregate 15.5%, voids filled with bitumen 79.5%,

porosity 3.2%, Marshall stability 14.8 kN, Marshall flow 3.0 mm and filler/binder ratio of 1.4.

The bituminous mixture specimens were laboratory aged considering two different methods: 1) short- and long-term oven ageing by conditioning loose mixture at 135 °C by 2 h, and after compacted specimens at 155 °C by 5 days in a ventilated oven, respectively; 2) the TEAGE method that combines the application of UVB radiation and the subsequent temperature, and watering/drying cycles during a specific period adjusted to Lisbon conditions to closely reproduce the in-field conditions, regarding temperature and precipitation. It was reproduced the conditions equivalent to 6, 12, 24, 36, 48 months in field considering an average of 36 W/m^2 reaching the pavement surface and 40 days per year with a precipitation >5 mm. The third method was under real condition in a test field located at the National Laboratory for Civil Engineering campus (experimental test section) in Lisbon, Portugal. Table 1 shows the field ageing data and the TEAGE conditioning parameters defined in this study.

Table 1. Field ageing and TEAGE conditioning parameters

Field ageing (years)	Accumulated solar UVB radiation (Wh/m^2)	Precipitation > 5 mm (accumulated number of days)	TEAGE parameters w/d cycles per day	Immersion time (min.)	TEAGE conditioning (days)
0.5	1256	20	4	40	1.45
1	2512	40	4	40	2.90
2	5024	80	4	40	5.81
3	7536	120	4	40	8.71
4	10,048	160	4	40	11.62

To assess the evolution of surface characteristics with the environmental effects, both micro- and macrotexture properties were evaluated in laboratory and in the experimental campus over the time. Measurements were performed before the ageing starts and after six months until the specimens reach the pretended age. For the specimens aged in laboratory the measurement of initial surface properties and after ageing were also performed. The initial properties were evaluated on specimens that were not subjected to any type of load that allows the removing of the bitumen film.

The macrotexture was evaluated using the volumetric patch technique according to EN 13036–1 to obtain the mean texture depth (MTD). The microtexture was indirectly evaluated by the skid resistance measured by the pendulum test method accordingly EN 13036–4, to determine the Pendulum test value (PTV).

3 Results and Discussion

Figure 1 and Fig. 2 present the specimens in two distinct sets of conditions: environmental conditions and TEAGE conditions, each subjected to varying ageing periods. A noticeable visual change was evident throughout ageing the ageing process. In both

cases, i.e., laboratory and field conditioning, the bituminous mixture surface exhibited a transition from initial black hue to a more pronounced greyish or whitish tone. This alteration in coloration serves as a conspicuous indicator of surface ageing in the bituminous mixture. Conversely, the specimens aged through the oven method (LTOA) did not manifest any changes in color of surface appearance.

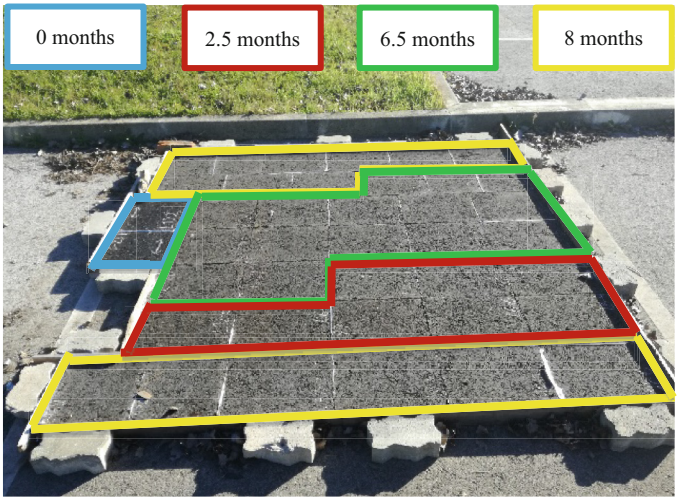


Fig. 1. Environmental ageing conditions (Field ageing)

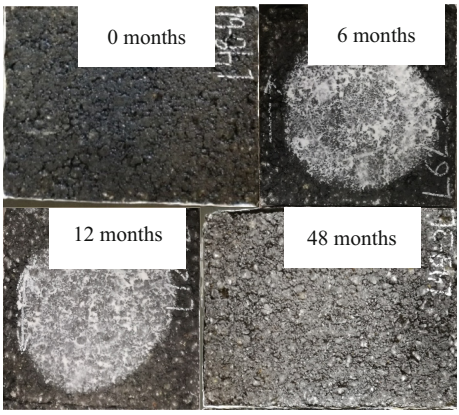


Fig. 2. Laboratory ageing conditions (TEAGE)

Figure 3 and Fig. 4 illustrate the assessment of macro- and micro-textures, respectively, along the different ageing periods. In the initial 24 months of real and TEAGE ageing, macrotexture exhibited a decrease, followed by a slight increase, in the case

of TEAGE ageing method, and an increase with some fluctuations for the real ageing conditions, that can be attributed to the cleaning effect of rainfall. For the long-term oven ageing (LTOA), only the first 24 months were considered for result representativeness, as there is no consensus on the real ageing it simulates. This method solely considers the effect of temperature in the ageing process. Thus, the macrotexture reduced after ageing and is equal for 12 and 24 months.

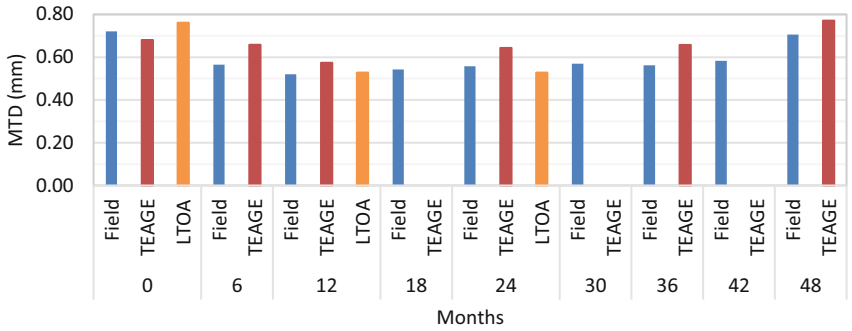


Fig. 3. Macro texture ruth depth

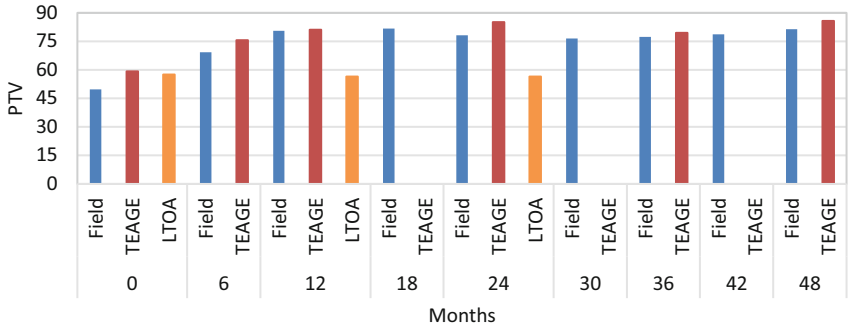


Fig. 4. Pendulum test value

Regarding microtexture evaluated by PTV, negligible changes were observed in the case of LTOA ageing method. However, samples aged under real conditions and the TEAGE method displayed substantial increases in PTV during the initial 12 months (62% and 37%, respectively). Beyond this period, the results demonstrated a trend toward a table PTV. After 18 months, samples exposed to real environmental conditions exhibited a slight reduction in PTV, possibly related with the removal of the aged bitumen film covering the aggregates due to the rainfall action. The sequential Pendulum tests could contribute to this film removal.

4 Conclusions

Road surface characteristics have direct impacts in overall road safety. Both macrotexture and skid resistance are the factors that most influence the road-tire contact mechanism. The bitumen ageing is one of the factors that affects the bituminous mixture surface characteristics during its lifespan. It was possible to verify an evident visual effect with coloration changes from a black tone to a more greyish/whitish tone along the evaluated period. Some variations in terms of macrotexture were observed due to the washing effect of rainfall in the case of real ageing conditions (field).

For the LTOA ageing methodology it was only considered the representativity of the results in first 24 months, as did not exist a consensus of the real ageing that this laboratory method represents.

The Pendulum Test Value increased in the first 24 months for real and TEAGE ageing methodologies. After a slight decrease in real ageing conditions, was observed that it can be associated to the removal of the aged film of bitumen that covers the aggregates by the action of the rainfall and the repeated pendulum tests. The TEAGE method showed to be a promising method to simulate the real ageing conditions in laboratory.

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Improving Real Time Rail Monitoring with EMAT Sensors and Superlets Analysis

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Abstract. The development of online and in filed ultrasonic testing tools for rail defects detection requires advanced signal processing analysis methodologies. The objective is to properly identify the Time of Flight (ToF) of the wave in high noise measurements. We propose an estimator of this physical parameter with the use of a novel time-frequency analysis technique, adapted from the Continuous Wavelet Transform (CWT), called the Superlet Transform (SLT). It provides higher accuracy even at low Signal to Noise Ratio (SNR). We apply this estimator on a simulated example to quantify the reached performances, in terms of errors and variances.

Keywords: ultrasonic testing · EMAT · signal processing · wavelet analysis · superlets

1 Online Non-contact Analysis of Rail with EMATs

Development of efficient maintenance plans requires early detection of damages. For rail inspection, observation of evolution of cracks allows a predictive establishment of defect propagation inside the steel. In this perspective, an online inspection process of rail is mandatory. We present in this article the results of an investigation to perform non-contact analysis of the rail surface with an ultrasonic testing technique, called Electro-Magnetic Acoustic Transducers (EMAT) [1] in high noise conditions, or low Signal to Noise Ratio (SNR).

Surface Rayleigh waves are generated to interact with surface defects, such as squats and head-checks, detected with the Time of Flight (ToF) of the wave. The non-contact advantage allows a fast moving of the sensors on the rail. A mechanical trolley has been designed within the European project IN2TRACK3, to specifically use EMAT sensors, reaching speeds up to 20 km/h, see Fig. 1.

However, numerous exogenous disturbances appear during the measuring processes, that complicates the detection of defects and their characterization. The non-contact aspect of EMAT requires a strict control of the distance between the sensors and the rail (called the lift-off). For this purpose, the presented new

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Fig. 1. EMAT trolley for online rail inspection.

methodology analyzes noisy ultrasonic signals with high levels on noise, thanks to a recent tool called the Superlets [2], based on the wavelet transform, a linear operator for time-frequency representation of signals.

2 Estimation of the Time of Flight

In ultrasonic testing, detection of defects is performed with analysis of the ToF $u^\star$ of the wave pulse from the measurement signal $x(t)$. The Rayleigh wave perturbation propagates inside the rail with a specific shape. On the oscilloscope, the signal is similar to a Gabor pulse, which is a multiplication between a cosine and a Gaussian function, whose mean is the ToF. The Gaussian function is assimilated to the envelope of the signal. A Gabor wavelet $g_\theta(t)$ is entirely described by the parameter vector $\theta = \left[\alpha, f, u^\star, \sigma^2, \phi\right]^t$ with α the amplitude, f the central frequency, $u^\star$ the ToF, σ^2 the spread and ϕ the phase. It is expressed as:

$$g_\theta(t) = \alpha \exp\left(-\frac{(t-u^\star)^2}{\sigma^2}\right) \cos\left(2\pi f t + \phi\right) \tag{1}$$

From the above description of a Gabor wavelet, the ToF corresponds to the time of the maximum of the envelope. Therefore, an extraction of this envelope from any empirical signal could give enough information to recover the ToF. However, signals coming from sensors contain an important level of noise. Quality of the envelope estimation is diminished.

The most simple way to find the ToF on a clean (noiseless) signal is to compute the envelope $A(t)$ from its analytical representation $x_a(t)$, calculated with the Hilbert transform (HT) H of $x(t)$. The trivial estimation $\hat{u}$ of the ToF $u^\star$ is taken as the time which maximizes the envelope:

$$\hat{u} = \arg\max A(t) = \arg\max |x_a(t)| = \arg\max |x(t) + H\left[x\right](t)| \tag{2}$$

However, this simple estimate is very sensitive to noise, and is therefore inappropriate for real measurements. The state-of-the-art analysis methodologies used in this article are:

- Empirical Mode Decomposition (EMD) based method [3]: the EMD is an algorithm to decompose a signal in several components, each one corresponding to one mode of the signal. Decomposition is based on a heuristic procedure, lacking strong mathematical foundations. In the context of pulse waves, the objective is to identify the main mode related to the pulse. The other modes are assumed to contain information about the noise and the random perturbations. The HT is then applied on the main mode;
- Continuous Wavelet Transform (CWT) based method [4]: the pulse is extracted from the scalogram (time-frequency representation of the signal based on the conovultion with a mother wavelet), the envelope is calculated, and the ToF is extracted, the same way as with the HT;
- Quasi Maximum Likelihood (QML) method [5]: an approximate statistical model is fitted to the envelope (with the HT) of the signal based on the analytical representation.

In the following, we present the Superlet Transform (SLT), which is an improvement of the CWT. They naturally share the properties of the CWT. Consequently, both CWT and SLT are usable in real-time and offline procedures, depending on the required quality of the ToF estimation.

3 Continuous Wavelet Transform

A description of the wavelet analysis formalism is now necessary to understand properly the improvements brought by the SLT. The CWT of a signal x at time u and scale $s \in \mathbb{R}^{+,*}$, using the mother wavelet Ψ is defined as:

$$\mathcal{W}_x(u,s) = \int_{-\infty}^{+\infty} x(t) \frac{1}{\sqrt{s}} \Psi^* \left(\frac{t-u}{s} \right) dt \tag{3}$$

where Ψ^* denotes the conjugate function of Ψ.

It has been demonstrated that the CWT provides an unbiased estimation of the ToF if the Morlet wavelet is used as mother wavelet. However, it is no longer possible for the central frequency of the Gabor pulse, the estimation is indeed biased (see [6]), and the bias depends on the central frequency of the pulse.

Very often, a conversion is made from a specific scale s to the related frequency ω to clarify the notation. The conversion is easily made with knowledge of central frequency of the mother wavelet used (see [4] for further details). In the following, we no longer use the scale notation, but the frequency notation ω.

4 Superlets and the Superlet Transform

The Superlet Transform (SLT) has been introduced to bypass the limitations of the time-frequency resolution of the CWT, directly related to the Heisenberg-Gabor principle. It uses the concept of Superlet which is defined as a set of

wavelets with same central frequencies, but different number of cycles (and therefore frequency bandwidths). The SLT reaches higher time-frequency resolutions by taking the geometric mean of the multiples CWT of the signal from the Superlet set. The SLT of signal x of order o is defined as:

$$\mathrm{SLT}_{x,o}(u,\omega) = \sqrt[o]{\prod_{i=1}^{o} \mathcal{W}_{x,c_i}(u,\omega)} \tag{4}$$

With c_i the number of cycles in the mother wavelet of level i. Multiples methodologies exist to define the set of cycles $\{c_i\}_{i=1}^{o}$. The simplest one is the additive way: we define a minimum number c_1 and define $c_i = c_1 + i - 1$. A slightly more complex process is used in this article: the multiplicative way, with $c_i = c_1 \cdot i$. The SLT combines therefore multiple scalograms and achieves a super-resolution on the signal. Qualitatively, the representation is sharper and less redundant than the CWT representation. However, one easily sees that the CWT is a SLT of order 1. The proposed estimator, $\hat{u}_{\mathrm{SLT}}$, using the SLT instead of the envelope of the signal is then:

$$\hat{u}_{\mathrm{SLT}} = \arg\max |\mathrm{SLT}_{x,o}(u,\omega)| \tag{5}$$

It uses a search of the maximum in the absolute scalogram representation, across all analyzed frequencies. The main interest of this estimator is the possibility to fusion information from many wavelet representations, and therefore eliminate noisy contents, which spread across the spectrum. More robustness is expected from this estimator, in comparison with the CWT. See [2] for other advantages of this technique.

5 Quantitative Experiment

A quantitative comparison has been made with a simulation process. The objective was to study a representative example, and evaluate the performances of the proposed estimator $\hat{u}_{\mathrm{SLT}}$. A Gabor wavelet with known parameters is created, and different intensities of noises are added (to reach specific levels of SNR). The parameter vector for the Gabor wavelet is set to $\theta = [\alpha, f, u^\star, \sigma^2, \phi] = [10, 50\,\mathrm{Hz}, 0.5\,\mathrm{s}, 2.5e^{-3}\,\mathrm{s}^2, 0\,\mathrm{rad}]$. Duration of signal is 1 s, with sampling frequency $f_e = 1000\,\mathrm{Hz}$ (1000 samples). The five methodologies are applied, and comparison with real ToF is performed (the score used here is the Mean Absolute Error or MAE), see Fig. 2. For the CWT and SLT, analyzed frequency start are all integer frequencies from 1 Hz to 100 Hz (for a total of 100 frequencies analyzed). The Superlet created uses the multiplicative configuration, starting with a minimum number of cycles of $c_1 = 3$, with order $o = 5$. The Morlet wavelet is taken as the mother wavelet. Experiment is repeated 100 times to obtain Monte Carlo estimates of the MAE and the variance of absolute errors. The HT has obviously the worst errors. Performances of CWT and SLT are clearly the better, in term of both errors and variances. The computational cost of Superlets is justified only at low SNR, from the quantitative point of view. Interestingly, the

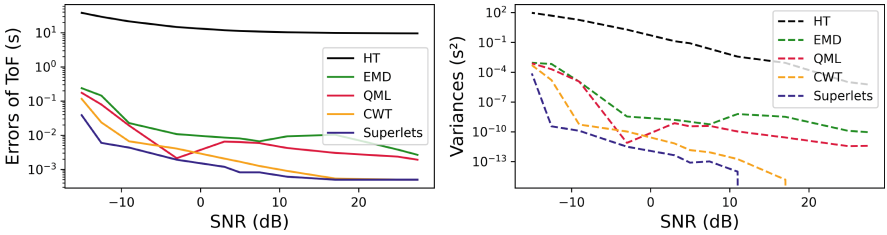


Fig. 2. Monte Carlo simulations for Time of Flight estimations with Gabor wavelet signal corrupted with noise.

wavelet-based methodologies outperform the optimization process (the QML) and the heuristic method (the EMD) and provides a more accessible calculation and estimation of the ToF, with a constant computational cost.

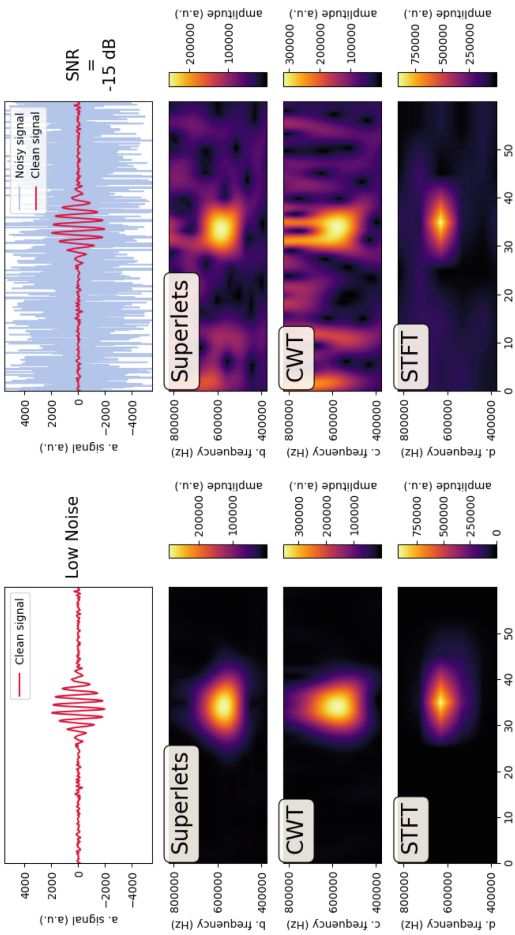
6 Discussions for Practical Implementation

In addition to quantitative estimations, the visual analysis of signals is sometimes also useful: for an operator in-field, a quick view on a time-frequency representation gives important information. The shape of the pulse indicates whether it changes from the expected representation. A base signal is taken from a nearly noiseless EMAT recording on a rail with the trolley system from Fig. 1, with a 2 mm lift-off in Figs. 3aand 3b. This base signal is then polluted with a strong noise, with a SNR reaching -15 dB. A visual comparison of ST, CWT and STFT shows that the ST gives the cleaner shape and allows a better differentiation of the Gabor pulse from the noisy background, in the frequency range of interest.

Besides the numerous advantages of Superlets, the computational burden must be considered for an efficient online analysis tool. The time complexity of the SLT is directly proportional to order selected. For each scalogram, the complexity is linear in the number of scales analyzed. To reduce calculations, the order of the Superlet Transform must be carefully selected, to match the required precision.

7 Conclusion

The ToF estimator described in this article, based on the Superlet Transform, has shown to perform better than the usual estimators on a simulated example. The experiment was designed to approach a realistic configuration, using EMAT sensors which generate Rayleigh waves. The Gabor representation of these ultrasonic waves is a major hypothesis, which hold precisely in this situation, and must not be directly transposed on other ultrasonic signals. However, in this situation, the estimator based on SLT reached higher accuracy than all other estimators, in term of absolute errors, and variances. The gain from the classical wavelet analysis tool, the CWT, has been shown. Furthermore, it removes the need for a



(a) In-field signal. (b) Signal with added noise.

Fig. 3. Time-frequency representations of a real signal with added noise.

precise selection of the mother wavelet, since results from multiple wavelets with different numbers of cycles are merged. The next investigation step will be the in field experiment, to assess the validity of the methodology with real defects on rail, such as squats or head-check.

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Rail Milling: Evolving from A Linear to Circular Infrastructure Asset Management Approach

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Abstract. The Iarnród Éireann/Irish Rail (IÉ) network currently extends to approximately 2400 km of operational track. This includes main line, Dublin suburban and commuter passenger routes, together with freight-only routes. A cross-border connection, located between Dundalk and Newry, connects to the railway system in Northern Ireland.

This paper describes a circular asset management approach to the management of our track asset. An overview of the IÉ rail milling process is discussed and how at its inception, it was devised to address defects observed during our in-house, bi-annual non-destructive rail testing programmes. Rail milling is a low heat generating process which removes a thin layer of metal from the head of the rail, restoring the rail head profile. Through our innovative rail milling pro-gramme, which is underpinned by our bi-annual ultrasonics and eddy current rail testing campaigns. We will demonstrate how we are balancing costs, opportunities and risk against desired performance. Consequently, as a result of optimising the life cycle of our rail assets, we will show how we are reducing whole-life costs, along with both the economic and environmental impact associated with maintaining these strategic railway assets of national importance.

Lastly, we will demonstrate how since the introduction of the programme, we have observed a decrease in rail defect across the Irish Rail network. We will outline how this is giving rise to a new focus, one which is not centred on milling for defect removal but towards a predominantly preventative maintenance rail milling regime.

Keywords: Rail · milling · asset management · circular economy

1 Introduction

Continuous degradation to the rail head by the ongoing operation of suburban, commuter passenger routes and freight routes, is an established stress to the rail, the ballast construction as well as the rolling stock itself [1]. Over time, minor defects will grow and linearise and, thereafter, due to the kinetic energy involved, most rail anomalies tend to grow at a faster rate, the longer they exist and remain untreated [1].

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Evidence of wear to the rail head along with roll contact fatigue are created by straining through wheel and rail contact [1]. These signs of wear include, waves or rippling, as well as head checks, spalling, squat type defects and/or belgrospi. Additional signs of wear such as, white etching layers or swerving spots can also occur. These occurrences are not limited to the plain line track but are also observed in components such as, switches, crossings or road crossings.

The defects have a negative effect on the lifespan of rails, driving comfort and safety if not treated appropriately and therefore increase the life-cycle costs of rails, components and the entire railway. As a result, the focus of mature rail asset owners is not just to concentrate on rectifying and removing existing defects but moreover, towards early intervention and proactive maintenance approach to managing their infrastructure stock. One that ensures best value is realised from our existing assets along with ensuring best service is provided to their customers.

2 Background to Rail Milling

2.1 Rail Milling

Irish Rail recognised a requirement for the removal of rolling contact fatigue (RCF) from the rail head throughout the network in the mid 2010's. These rail defects are generally less than 5 mm in depth and normally result from the effects created by wheel/rail interaction or RCF. The most common categories of surface rail defects identified on the network are gauge corner cracking, corrugations, shelling, squats, wheel burns, wheel indentations and side worn rails [2, 3]. In this respect, milling is utilised to remove rail defects on the top surface of the rail head.

Rail milling as a technology has been in operation on the Irish Rail network for al-most eight years. Initially, milling of main line routes with a 1:40 inclination was undertaken and once the technology was understood in greater detail and successful outcomes were realised This process was rolled out to more challenging areas of transition rails and points and crossings, which have an inclination of zero. Illustrated in Fig. 1, this shows how both 1:40 and zero inclination cutter heads are used to achieve the re-quired milled railway profiles. Illustrated in Fig. 2 is a typical view of a before and after section of rail that has been processed through the rail milling process. As a technology, it is now viewed as a leading technology that controls the occurrence and remediation of defects on the Irish Rail network.

3 Lifecycle Cost Benefits of Rail Milling

The Product Category Rules (PCR) for Railways, stipulates that a lifespan of 60 years shall be used as a basis of calculating the environmental impact of rail infrastructure [4, 5]. For the purpose of this analysis, it is concentrated on this specific part of the infrastructure in detail [6]. Based on the data available for the Irish Rail network the in-service life estimate for this component is taken as a minimum of 50 years.

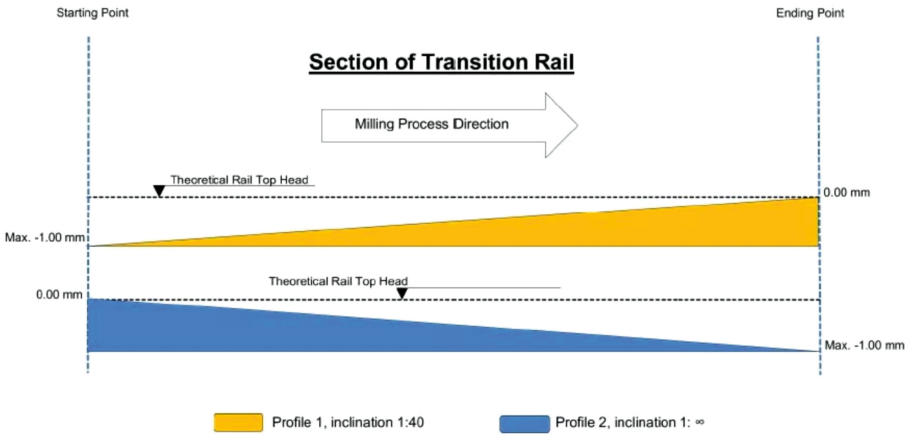


Fig. 1. Section showing cutting head rail milling profiles.



Fig. 2. View of section of rail before and after the rail milling process.

3.1 CO2 Footprint Reduction Caused by Ways of Rail Milling

As a baseline for this analysis, the approach developed by Schmied and Mottschall has been adopted [6]. This methodology proposes that the total CO2 load on the superstructure results from the sum of all its components (e.g. earth works, ballast, sleepers, fastenings). Their study demonstrated that the production and maintenance of the rail element of the railway infrastructure contained approximately the same emissions as the construction and maintenance of the ballast bed, rail fasteners and sleepers.

Shown in Table 1 are calculated CO2 emissions per kilometre of route through the manufacture and maintenance of the track superstructure for both single- and double-line track. Thereafter, this data is presented for different types of rail, of which S54 is similar to the common rail type used on the Irish Rail network.

Table 1. CO_2 emissions per kilometre or route (manufacture and maintenance) [6].

Rail type	Single Track (t/km/p.a.)	Double Track (t/km/p.a.)
S49	6.3	12.6
S54	7.0	13.9
Rail UIC 60	7.7	15.4
Concrete Sleepers & Fastenings	6.1	12.2
Wooden Sleepers & Fastenings	6.9	13.9
Steel Sleepers & Fastenings	10.4	20.9
Non-Ballasted Track & Fastenings	9.4	18.9

Table 1 presents CO_2 emissions per kilometre of route for the rails and on the other emissions for the sum of the ballast bed or slab track, fastening of the rails and sleepers. The data demonstrates that the production and maintenance of the rails lead to approximately the same emissions as the construction and maintenance of the ballast bed, rail fasteners and sleepers.

Within the context of the Irish Rail network, as noted previously, the relevant rail profile is the S54 type. This is demonstrating that it's CO_2 emissions are 7,0 t/km/p.a. (based on 30 years) [6]. This value is calculated by summing up all the CO_2 of the rail from producing it, transporting it on site, installing it, including the expected routine maintenance activities over its service life. Considering the relationship between CO2, design service life and noting that the data is provided per-kilometre of track, it is demonstrated that for every year of extension of the lifetime of the rail above those considered in Table 1, will have a proportional impact to the CO2 emission per t/km/p.a. The values presented for the rail are for 30 years service life and whilst a crude measure, the values (whilst not exactly linear) would be expected to improve with respect to the Irish network, where the in-service life of the rail is known to be at least 50 years. Taking this in service life of 50 years and by back calculating, it is proposed that the CO_2 emissions of the current network is approximately 4,2 t/km/p.a.

Thereafter, the CO_2 benefits are dependent on the type of milling machine employed. Whilst LINSINGER do have a state-of-the-art emission free, Hydrogen based high performance milling machine in their fleet, a diesel combustion engine machine has been utilised for the Irish Rail network. The calculate total emission of the diesel engine for a single milling work shift (also including auxiliary consumption for supporting vehicles etc.) is calculated at 0.78 T CO_2 per kilometre. However, for the purpose of this paper, these values are omitted from our calculations.

Offsetting these CO_2 emissions that are embedded into the process, is where the milling process produces a byproduct in the form of metal shavings or swarf, collectively known as 'scrap' [7]. This by-product is a high quality, recyclable, steel material, free of impurities and of a high strength grade. Taking the S54 profile on the Irish Rail network, it is estimated that up to 1.152 kg/km is returned, at a removal rate of 1 mm per milling operation pass.

The production of steel remains a CO_2 and energy-intensive activity. Considering that scrap accounts for approximately 30% of the total metallic input to steel production globally, the CO_2 benefits of this process are substantial [8]. Where scrap plays a key role in supressing industry emissions, resource consumption of natural materials and where every tonne of scrap used in steel production avoids the emission of 1.5 tonnes of CO_2, the consumption of 1.4 tonnes of iron ore, 740 kg of coal and 120 kg of lime-stone, the environmental benefits of integrating rail milling into the Irish maintenance programme and its circular economy credentials are clear to measure [9].

Data presented in Table 2 shows that between 2016 and 2021, 965 kilometres of rail has been milled on the Irish Rail network and the potential benefits that may have been gained from it by-product scrap. The process has generated approximately 1096 tonnes of scrap of which 100% of this scrap has been recycled by an ISO 14001 certified Irish recycling partner. The data shows that should this scrap has been 100% returned to the steelmaking process, reducing 1843 tonnes of CO_2 production and reduced 1365 tonnes of iron ore, 722 tonnes of coal and 117 tonnes of natural limestone.

Table 2. CO_2 emissions and raw materials savings per kilometre of track, generated from the Irish Rail milling programme from 2016 to 2021 [9].

Year	Milled Length of Track (km)	Estimated Scrap generated (Tonnes)	Benefits of scrap in steelmaking process via savings in CO_2 production and virgin materials usage			
			CO_2	Iron Ore (Tonnes)	Coal (Tonnes)	Limestone (Tonnes)
2016	30	57	45	42	22	4
2017	170	321	255	238	126	20
2018	160	302	240	224	118	19
2019	210	397	315	294	155	25
2020	220	416	330	308	163	26
2021	185	350	278	259	137	22
Total	**975**	**1843**	**1463**	**1365**	**722**	**117**

4 Conclusions

Overall, the measure of success of the rail milling programme is the continued reduction in defects identification on the Irish Rail, railway network. The reduction in the need for capital expenditure (CAPEX) spend to maintain the network in a safe condition, is

reflected by a modest fraction of the saved CAPEX been required to meet the ongoing rail milling maintenance programme. Thereafter, these and other key technical benefits to Irish Rail in implementing the rail milling programme, to date, include:

- Milling the rail head is known to extend the life of the rail for between 5–7 years. At this point the milling process can be repeated therefore, extending the life of the rail for a further 5 to 7 years and up to 14 years in total.
- By introducing a milling programme as part of the annual maintenance regime, surface rail defects have reduced on the network, thus minimising the potential for track faults.
- Rail milling is reducing degradation of the track structure. The elimination of corrugations and the correction of worn rail profiles by the introduction of a milling programme is reducing impact loads from rolling stock on the ballasted track substructure and hence prolong its life.
- Rail Milling improves the running behaviour between the wheels of the train and rail which in turn is improving the ride quality and passenger comfort.
- Rail milling is a low emission process and can be performed even in crowded and urban areas during night-time without any disturbance of the peace by night or risk of contamination of property by dust or other impacts.
- The removed layer of metal from the rail head is entirely collected within the milling machine and is 100% quality controlled recycled.

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Transport Infrastructure Ireland's Approach to Climate Adaptation

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Abstract. Ireland's changing climate is causing extreme weather events to become more intense and frequent, resulting in adverse impacts to national transport infrastructure. It is necessary for transport asset owners, managers and developers to appropriately consider these evolving risks, both when designing new infrastructure and managing existing networks. This paper outlines Transport Infrastructure Ireland's (TII) approach, and progress to date, to better understand and address its climate change risks, through the development of an overarching strategy, technical standards and guidance, and climate change risk assessments. The paper focuses on TII's two-stage approach to climate risk assessment covering both TII's physical assets (national roads, light rail, land and some greenways and cycleways), along with their staff and buildings. The first stage of the assessment has provided a high-level screening of all climate hazards and assets, to identify priorities for the more detailed climate risk assessments. The paper concludes by setting out TII's next steps and priorities in relation to climate adaptation.

Keywords: Climate Change · Climate Adaptation · Sustainable Transport · Climate Hazards · Resilience · Asset Management

1 Introduction

Transport Infrastructure Ireland (TII) is the state agency responsible for the future development and operation of the national road network throughout Ireland and the 'Luas' light rail infrastructure in Dublin County. It is also responsible for delivering the national and regional greenway programme in partnership with local authorities. Its purpose is to provide sustainable transport infrastructure and services, deliver a better quality of life, support economic growth and respect the environment.

TII's infrastructure assets and networks have been impacted by severe weather events in recent decades. Such weather events are anticipated to become more extreme or occur more frequently (e.g. surface water flooding), while others are expected to emerge (e.g. extreme heat). With the total annual costs from extreme weather events to road

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infrastructure in Europe estimated to be 1.8 billion Euros, which could increase by 20% by 2050 [1], along with adverse safety, reputational and environmental impacts, it is essential that TII understands and addresses its climate risks. This paper outlines TII's response and actions to date on climate adaptation. Section 2 summarises TII's progress and approach on climate adaptation. Section 3 concludes with TII's future priorities and next steps to continue prioritising climate adaptation.

2 TII's Progress and Approach on Climate Adaptation

In December 2022, TII published its updated *Climate Adaptation Strategy* [2], which was a response to Action 297 of the Irish Government's *Climate Action Plan 2021* [3].

The updated strategy sets out how the organisation will embed climate adaptation into its activities and decision-making. TII has also published *'Climate Assessment of Proposed National Roads – Standard'* [4] and '*Climate Guidance for National Roads, Light Rail and Rural Cycleways (offline and greenways) – overarching technical document*' [5]. These documents provide guidance and a methodology to conduct a project-level climate impact assessment, that is mandated for new proposed national road schemes through the standard [4]. This guidance ensures consistency of climate assessments across projects and aligns with the European Commission's *Technical guidance on the climate proofing of infrastructure in the period 2021–2027* [6]. The climate standard for national roads [4] ensures all new projects will have adequate climate resilience and mitigation considerations built into their design.

TII has taken a 'six-stage' approach to climate adaptation, which is aligned with the national *Sectoral Planning Guidelines for Climate Change Adaptation* [7] and the *Transport Climate Change Sectoral Adaptation Plan* [8]. The cyclical six-stage approach consists of the following:

- **Stage 1 'Preparing the ground'** – this included the development and publication of the 2022 *Climate Adaptation Strategy* [2] and associated actions. It also sets the responsibilities and governance for climate adaptation in TII.
- **Stage 2 'Climate impact screening'** – this stage comprised a high-level assessment of how a range of climate hazards could or may affect the full range of TII's assets.
- **Stage 3 'Prioritisation'** - this stage involves identifying which climate hazard and asset pairings from the climate impact screening assessments (Stage 2) are significantly vulnerable such that they require further investigation.
- **Stage 4 'Priority impact assessment'** - this stage aims to deep-dive into the priority hazard-asset pairs to better understand the risk, including how the risk may vary spatially based on variable climatic conditions, or based on asset age.
- **Stage 5 'Develop a plan'** – Climate adaptation plans will be produced which will outline the adaptation actions and measures being taken to address the risks outlined in Stages 2–4.
- **Stage 6 'Implement, evaluate and review'** – TII will implement adaptation action and measures outlined in the Climate Adaptation Implementation Plans (Stage 5). TII will monitor the plans' progress, and consider how effective the measures are by setting up a process to evaluate and review performance.

2.1 Climate Risk Assessment

While the TII climate standard [4] and guidance [5] address climate adaptation (and mitigation) in new projects, TII also need to consider potential climate impacts to its existing assets and networks that span wide geographic areas and are therefore exposed to different climate hazards. To address this, TII with support from Arup is undertaking a two-stage climate risk assessment (see Fig. 1), that covers both TII's existing physical assets (national roads, light rail and some greenways and cycleways, land and buildings), along with their staff.

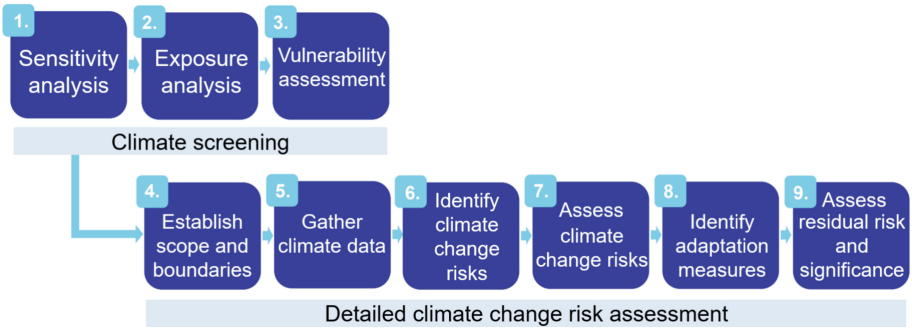


Fig. 1. TII's two-stage climate risk assessment (Source: [5])

At the time of writing, climate impact screening assessments (Stage 2 of TII's six-stage approach to climate adaptation, Steps 1–3 in Fig. 1) and a prioritisation exercise (Stage 3 of TII's six-stage approach to climate adaptation) have been undertaken in line with TII's climate guidance methodology [5]. An Excel™ tool was developed to standardise the climate impact screening assessment which was undertaken for each of TII's six main asset groups (national roads, light rail, rural cycleway and national and regional greenways, land, buildings and people) [9]. Each asset group was broken down into high level asset types (e.g. drainage, earthworks, rolling stock for light rail).

Ratings of sensitivity and exposure for each asset category was assessed against a set of climate hazards (sourced from [5]), with ratings defined using definitions in the TII climate guidance [5]. The climate impact screening was informed by workshops with TII asset managers and specialists alongside a wider literature review to understand how climate is and how it might impact TII's assets and networks in the future. This first assessment takes a geography-agnostic approach to assessing climate risks, and instead aims to qualitatively consider the links between a wider range of assets and climate hazards. This resulted in a 'low', 'medium' or 'high' vulnerability rating for each asset-hazard pairing (see Fig. 2 for scoring descriptions and worked example). Where 'high' vulnerabilities were identified, these have been prioritised for a more detailed climate change risk assessment. Some 'medium' vulnerabilities were taken forward for prioritisation where they were deemed to have a significant impact. The other 'medium' vulnerabilities (typically where hazard or asset data was uncertain/unavailable), along with all 'low' vulnerabilities, were put on a 'watching brief', to be reviewed again in future – for example in the next strategy update, or if new evidence becomes available.

(a)

Vulnerability				
Sensitivity	High	1 * 3 = 3	2 * 3 = 6	3 * 3 = 9
	Medium	1 * 2 = 2	2 * 2 = 4	2 * 3 = 6
	Low	1* 1 = 1	1 * 2 = 2	1 * 3 = 3
		Low	Medium	High
		Exposure (highest score from current and future climate)		

Vulnerability Key (and score)
Low (1-2)
Medium (3-4)
High (6-9)

Sensitivity rating (and score)	Rating definition
Low (1)	It is possible the climate hazard will have a low or negligible impact on the asset category (i.e. periphery or little damage to the asset.
Medium (2)	It is possible or likely that the climate hazard will have a moderate impact on the asset category (i.e. moderate damage to most of the asset).
High (3)	The climate hazard will or is likely to have a major impact on the asset category (i.e. asset destroyed or subjected to large-scale damage requiring major engineering works).

Exposure rating (and score)	Rating definition
Low (1)	It is unlikely or rare this climate hazard will occur (i.e. might arise a number of times in a generation or a lifetime).
Medium (2)	It is possible this climate hazard will occur (i.e. might arise a number of times in a decade).
High (3)	It is almost certain or likely this climate hazard will occur (i.e. might arise once to several times per year).

(b)

Asset categories	Flooding (coastal) - including sea level rise and storm surge	Flooding (fluvial / river)	Flooding (pluvial / surface water)	Extreme heat	Extreme cold
Drainage	3	9	9	3	2
Earthworks	3	9	9	3	2
Embedded track	1	3	3	6	6
Ballasted track	3	9	9	9	6
Direct fixed track (fixed to concrete)	1	3	3	6	6
Rolling stock	1	3	3	3	2

Fig. 2. (a) Vulnerability matrix and sensitivity/exposure definitions used in the climate impact screening assessments (Source: adapted from [5]); (b) Extract of light rail vulnerability results

To assess the climate risks to TII's people, a bespoke approach was developed, considering how climate hazards affect both TII's staff and key external stakeholders and organisations. This considers working environment, such as working from home, in an office, on site or travelling, as a key influencing factor in how at-risk people are to climate change impacts; for brevity, this approach has not been included in this paper.

2.2 Future Priorities and Next Steps

Going forward, TII will progress implementation of its climate adaptation strategy and six-stage approach to climate adaptation. Next steps include undertaking detailed climate change risk assessments (CCRAs) for each of TII's asset groups, based on prioritised vulnerabilities identified in the climate impact screening assessments. These detailed CCRAs will assess climate risks and consequences to TII's assets and services, identify 'hotspots' across the country. They will make use of geospatial TII asset data and climate projections, including the standardised climate projection data, recently produced by the TRANSLATE [10] project supported by Met Éireann, the Irish National Meteorological

Service. The TRANSLATE climate projection data can be used across the Irish transport sector, with future scenario data available for different levels of warming (e.g. 1.5 °C, 2 °C), making it easier to communicate findings to wider audiences. TII has supported the TRANSLATE project by co-creating a fully quantitative assessment of heavy rainfall event impacts to the national road network's drainage systems [11]. This case study, along with other existing detailed assessments (e.g. TII's Flood Risk to Roads [12]), will inform the upcoming CCRAs.

The output of the detailed climate change risk assessments will inform the development of climate adaptation plans for each of TII's six asset groups. These plans will identify appropriate adaptation measures to address the risks identified. These may comprise physical interventions, further development of policies, standards and operational practices. TII will work collaboratively with its wider stakeholders to address the adaptation actions outlined in the climate adaptation plans in line with the five-year cycle and evaluate and review adaptation measures to improve the efficiency and value of future measures. There is also work being undertaken to understand the financial cost of 'do nothing' and 'adaptation-led' approaches.

TII is engaging with Climate Ireland who provide scientific research, policy making and adaptation practice for the purposes of enhancing adaptation decision-making. Climate Ireland are developing climate resilience indicators. The indicators are grouped into four categories, to measure: (i) climate hazards, (ii) impacts to transport infrastructure, (iii) implementation of adaptation actions, and (iv) outcomes of adaptation actions. These indicators aim to measure and quantify climate adaptation progress, and could be applied across the transport sector in Ireland.

3 Conclusion

This paper has provided an overview of TII's key climate adaptation actions, which have accelerated over the past two years. Together these actions aim to help to prepare Ireland's transport systems for climate-related impacts and provide increasingly resilient transport infrastructure. This paper also summarises an approach to asset portfolio scale climate risk assessments, aligning with the European Commission's *Technical guidance on the climate proofing of infrastructure in the period 2021–2027* [6]. It demonstrates the need for collaboration between asset specialists, climate risk practitioners and data experts to best understand how climate hazards can translate to tangible impacts on critical transport infrastructure and take coordinated adaptation action.

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Designing Pavements with Waste and Recycled Materials

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Abstract. Recycled and waste materials from four different sources were investigated as alternatives for crushed rock aggregates in pavement constructions. Two of the materials were coarse fractions of the bottom ash from two incineration plants. The other two materials were crushed concrete from demolished constructions and reclaimed asphalt from road scalpings. Full-scale accelerated tests were conducted on test road-sections constructed with these materials, employing a heavy vehicle simulator (HVS). The materials were also tested in the laboratory e.g., by means of repeated load triaxial (RLT) tests. In both cases, results indicated that the crushed concrete performed the best, followed by the two bottom ash materials and then the reclaimed asphalt. The results from the RLT tests were used to evaluate the model parameters required for simulating the performances of the test-road sections in HVS tests, adopting a mechanistic-empirical pavement analysis tool ERAPave. With this method, good agreements between the measurements and simulations were obtained. Hence, this approach forms the basis for designing pavement sections using these alternative materials for different traffic loading and climatic conditions. With further testing and modelling, it will be possible to create guidelines and design tables for pavement constructions with alternative materials.

Keywords: Waste material · pavement · modelling · HVS test · triaxial test

1 Introduction

With increased urbanization and industrialization, the generated amount of construction and industrial waste is increasing in most European countries [1]. These waste materials are usually dumped as landfill, much of which are estimated to remain in the environment for hundreds, perhaps thousands of years. On the other hand, increased construction activities are posing greater demand on materials obtained from natural resources. However, this has a significant climate impact, and it is also becoming increasingly harder to obtain these materials close to the cities where the needs are the highest. Therefore,

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using the waste products in road constructions is a promising and potentially desirable alternative to reduce the disposal volume of wastes and to cut down the use of natural resources [2, 3]. This in turn will be beneficial for obtaining climate neutrality and circular economy [2–8]. Nevertheless, there is a lack of documentation, building instructions and relevant regulations regarding their usage compared to conventional materials. Hence, prior to employing them in pavement constructions, it is necessary to investigate their mechanical properties and thus create guidelines for their usage.

Most of today's pavement design methods are based on empirical approaches that rely on past performance of specific pavement materials under certain climatic and traffic conditions. The major drawback of this approach is that pavements with new and alternative materials under different climatic and traffic conditions cannot be efficiently designed. Therefore, a new mechanistic-empirical (ME) pavement design method for flexible pavement structures has been developed in Sweden [9, 10]. The main purpose is adequate prediction of the pavement response and long-term performance for any material combinations in varied climatic and loading scenarios. However, this poses new demands on testing pavement materials in the laboratory and on validation through full-scale testing [11–13].

The work presented here is a part of a larger study [14]. In this part, the mechanical performances of four different waste materials as replacements for crushed rock aggregates in pavement subbase layers were examined. Also, a methodology for ME design of pavements using these materials was demonstrated.

2 Methodology

This study was based on full scale accelerated testing of four identical pavement test sections with different subbase layers composed of the four different waste materials under investigation. The waste materials were also tested in the laboratory. The results of the laboratory tests were used to predict the long-term behaviour of the pavement test sections using an ME design tool. The material parameters were calibrated during the ME design process to match the observed behaviour in the full-scale testing.

2.1 The Tested Materials

Four waste materials were included in the study. Two of the materials were bottom ashes from household and operational waste from incineration process. After the incineration, these materials were sieved and went through metal and organics separation. One of the materials, designated as Umeå 0/15, had a grain size distribution in the range 0–15 mm and the other one, referred to as Sysav 0/45, had a grain size distribution in the range 0–45 mm. The third material was crushed concrete obtained from demolished residential buildings. The material had a grain size distribution in the range 0–64 mm. The fourth material was milled asphalt obtained as a surplus material from maintenance work on aged streets, referred to here as reclaimed asphalt. The material had a grain size distribution in the range 0–16 mm. Although milled asphalt is normally used in new asphalt productions, in this case, it was necessary to investigate other potential uses due to the large stored volume.

2.2 Full-Scale Accelerated Testing

The performances of the materials were evaluated in accelerated pavement testing (APT) condition using a heavy vehicle simulator (HVS). The HVS simulates degradation of pavements from heavy traffic. The tests can be performed relatively quickly where many years of traffic can be simulated in a few weeks. The HVS employed in this study is a movable unit which remains stationary over a test structure when performing the test. It has a running wheel (single or dual configuration) in the middle part of the equipment that applies the traffic loading on the structure. The wheel can run at a speed of up to 12 km/h. The wheel load is adjustable from 30 kN up to a maximum of 110 kN. The position of the wheel can also be shifted laterally to simulate the effect of lateral wander of traffic.

For this study, the test structures were built inside a concrete pit measuring 15 m in length, 5 m in width and 3 m in depth (about 1.8 m sand filling was used) [15]. All the structures were identical with respect to materials and layer thicknesses. The only difference was the selection of the subbase material. These structures were instrumented to measure the stresses and strains of the various layers as shown in Fig. 1. In this project, concrete paving stones (typical in urban design) were chosen to compare the results with some previous projects and thus to make use of the data. Normally, asphalt concrete is used as the surface layer in constructions where waste material is used, to minimize any potential risk of leaching.

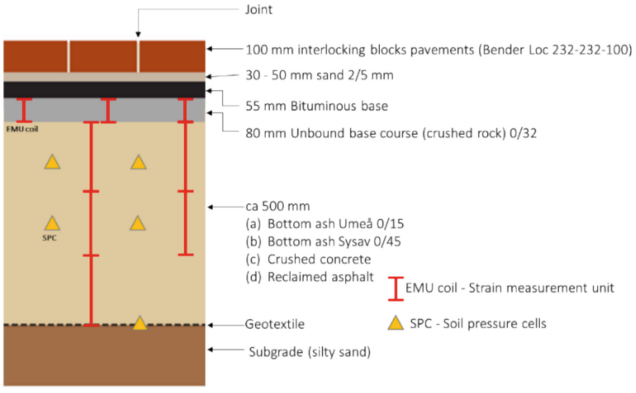


Fig. 1. Cross section of the tested structures with the instrumentation.

During each run of the HVS, two structures were built and tested simultaneously in the test pit. The loading gradually increased from 30 to 60 kN due to uncertainties about how well the construction would withstand heavy traffic. For the major part of the test, the load was kept at 60 kN, which corresponds to the axle load of 12 tons from a heavy truck. The temperature was maintained at 10 °C. The resulting rut depth was measured along five profiles on each surface and a mean rut depth was calculated. During the tests, the ground water table was raised from the bottom in the subgrade up to 30 cm below the subbase.

2.3 Laboratory Testing

The waste materials were tested in the laboratory to get information about their optimum moisture content and maximum dry densities using the Proctor method according to the European standard EN 13286–2 [16]. Multistage (MS) repeated load triaxial tests (with 'low stress level') were conducted following the European standard EN-13286-7 [17] to obtain the resilient stiffness and permanent deformation (PD) properties of the materials, required for the ME design process. These tests were conducted with a few different moisture contents to replicate the field moisture variation as in the HVS tests. The material constants a and b of the following PD model [18] were evaluated:

$$\hat{\varepsilon}_p(N) = aN^{b\varepsilon_r}\varepsilon_r \tag{1}$$

where $\hat{\varepsilon}_p(N)$ is the accumulated permanent strain after N number of load cycles and ε_r is the resilient strain during the *N-th* load cycle.

2.4 The ME Design Tool

For the ME design of the pavement structures, the pavement analysis tool ERAPave, developed by the Swedish National Road and Transport Research Institute [9, 10], was used. ERAPave is a multi-layer elastic theory-based program that, among other things, can predict the stresses, strains, and deformations of the different layers of a pavement structure due to traffic loading. In this study, the tested structures and the loading were modelled in ERAPave using the layer thicknesses and material properties obtained from the laboratory tests and existing database. The objective was to predict the performances of the structure and compare the results with the measurements from the HVS tests. Since laboratory conditions and field conditions are not identical, calibrations of the input parameters were necessary so that the predictions matched the measurements. The assumption was that the calibrated parameters would be applicable for field conditions which may be further used for designing pavements with similar materials under varying traffic and climatic conditions. With this approach, it will be possible to create a database of material parameters for further use in developing design tables and guidelines for various types of pavements with alternative and recycled materials.

3 Results

The accumulated permanent deformations of the four waste materials in the MS RLT tests are shown in Fig. 2. The solid lines represent the fitted PD model, the parameters of which were used in ERAPave. It is seen that the crushed concrete has the best resistance against PD, followed by Umeå 0/15, Sysav 0/45 and reclaimed asphalt. The same ranking of the performances of these materials were observed in the HVS tests, as shown in Fig. 3. The wheel loading of the HVS tests were converted to equivalent standard axle loads (ESALs) of 100 kN. The effect of raising the ground water table is manifested by the increased permanent deformation after 400,000 ESALs. Fig. 3 also shows the calculated total surface rutting of the structures in ERAPave. To account for the uncertainties during the initial post compaction, the first 59,000 cycles of loading were discarded during

the calibration process with ERAPave. The calibrated input parameters in ERAPave are presented in Table 1. With this approach, it was possible to obtain reasonable predictions of the permanent deformations of the structures.

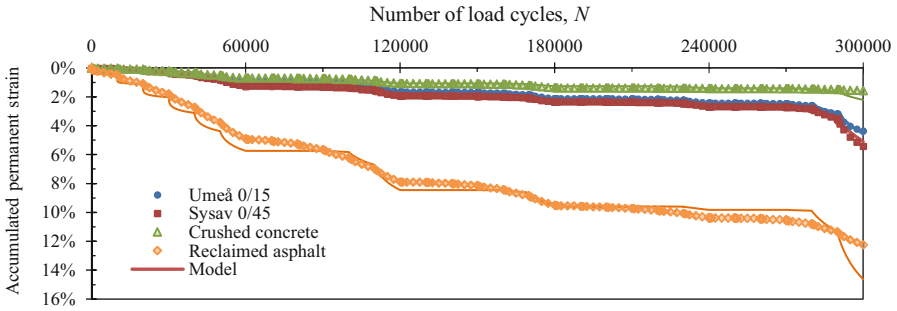


Fig. 2. Accumulated permanent strain of the waste materials in the MS RSL tests.

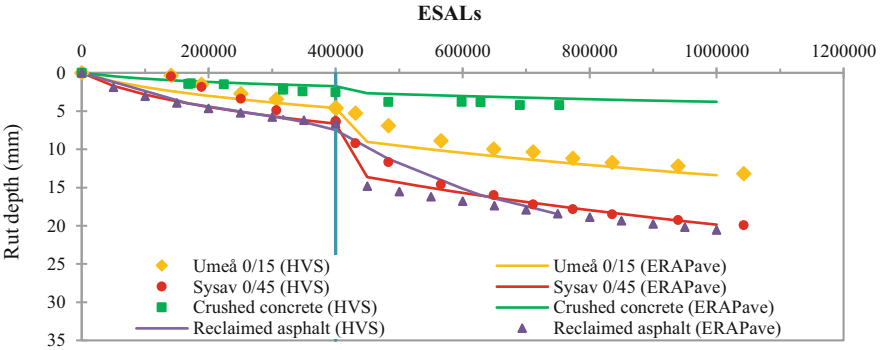


Fig. 3. Total surface rutting of the structures: HVS test vs ERAPave calculations.

Table 1. Calibrated input parameters used in ERAPave.

Layer	Thickness	Umeå 0/15			Sysav 0/45			Crushed concrete			Reclaimed asphalt		
		Modulus	a	b	Modulus	a	b	Modulus	a	b	Modulus	a	b
Block and sand bedding	13	300	0.18	250	300	0.18	250	375	0.2	250	375	0.2	250
Asphalt layer	5.5	3000	0.1	80	3000	0.1	80	3000	0.1	80	3000	0.1	80
Unbound base	8	250	1	250	250	1	250	250	1	250	250	1	250
Subbase	50	130 (100)	3 (6)	250	150 (120)	15 (20)	250	200 (170)	2.8 (6)	250	180 (150)	51 (55)	250
Subgrade	1,000,000	100 (60)	20 (25)	250	100 (60)	20 (25)	250	100 (60)	20 (25)	250	100 (60)	20 (25)	250

Note: Different values in moist conditions (after raising the ground water table) are shown in parenthesis.

4 Conclusions

The use of waste and recycled materials in pavement constructions has the potential to benefit the environment and promote a circular economy. In this study, four waste materials were investigated with this objective. The performances of these materials as pavement subbase layers were evaluated by means of full-scale accelerated tests. MS RLT tests were also conducted to evaluate the material parameters. In both test conditions, the crushed concrete showed the best performance followed by the two bottom ashes and then the reclaimed asphalt. The ME design approach demonstrated here can serve as a basis for designing pavements with alternative materials. The data presented here is still preliminary which should be refined by more extensive testing to compensate for experimental errors and differences between laboratory testing, full scale HVS construction and actual construction of a road. With further testing of various materials, a database of material parameters may be created which can be used to develop design tables and guidelines for pavements with alternative materials under various traffic and climatic conditions.

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Utilizing GPR and FWD for Pavement Structural Assessment and Moisture Detection

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Abstract. Asphalt pavement performance is profoundly impacted by the presence of water and moisture in the road, resulting in substantial costs to society. Research showed that significant portion of the road sections need early maintenance measures regardless of traffic volume due to moisture-related damages. Monitoring moisture conditions, preferably using a non-destructive continuous method, is thus vital to the decision-making and selecting appropriate maintenance intervention. Furthermore, understanding moisture conditions is critical for accurately interpreting automatic road condition measurements, especially during the spring (thawing) when the roads exhibit the lowest load bearing capacity due to increased levels of moisture.

This study employed a multi-receiver Ground penetrating radar (GPR) and a Falling weight deflectometer (FWD) measurements to assess moisture levels and structural condition of an indoor full-scale test road. The groundwater level of the test road was varied by introducing water to the system.

The results revealed a good correlation between the FWD and the average GPR velocity measurements. The GPR measurements provided a relative water content of the test roads. Further exploration of other GPR parameters, such as frequency, magnitude, and amplitude of the GPR signal is recommended, as these may offer an even better correlation to moisture content.

Keywords: GPR · FWD · Moisture content · Moisture damage

1 Introduction

The performance and durability of asphalt pavements are adversely impacted by the presence water and moisture in the road, ultimately incurring substantial cost to the society. Previous research has revealed that, 10% of roads necessitate paving measures within 5 years after construction regardless of traffic volume [3]. Such early maintenance needs are often attributed to damage due to repeated traffic loading coupled with potential shortcomings in the execution of paving work. The presence of moisture and water in the roads also play a pivotal role in affecting the performance of asphalt mixtures. Thus, obtaining information regarding the moisture condition is key for the pavement design processes.

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Previous investigations of road structures at the Swedish Road and Transport Research Institute (VTI) full-scale test facility and field sections, conducted using the falling weight deflectometer test (FWD) clearly indicated the adverse effects of water in the road structure. FWD deflections on the pavement surface increased significantly in the presence of water and have a significant impact on service life [5]. Thus, knowledge of moisture and water conditions during deflection measurements using FWD/TSD (Traffic speed deflectometer) is vital for the analysis/interpretation of the measurement data as well as for selecting appropriate maintenance measures.

The water/moisture content of road materials can be measured using different methods. The methods can be either stationary (or point measurement) or continuous. The stationary moisture measurement methods include laboratory tests of drilled specimens, capacitance-based methods, resistivity-based methods, and Time domain reflectometry (TDR). The continuous moisture monitoring techniques collect continuous moisture data along the length of the road. These methods include thermal camera method and Ground penetrating radar (GPR). GPR-based methods are the most commonly used for continuous road moisture survey. The GPR antenna can be either air coupled, or ground coupled, depending on the way the antennas are mounted with respect to the ground surface. The air coupled GPR permits surveying at a higher traffic speed. Furthermore, depending on the number of receivers in the GPR unit, different analysis methods are adopted, i.e., the surface reflection method (one receiver only) or coreless GPR (multi-receiver). The measurements from the surface reflection method are limited to thicknesses of roughly 25–40 mm depending on the antenna's frequency [1]. In coreless GPR, the travel time shift recorded at each receiver of the electromagnetic wave reflected from a specific boundary is determined. This time shift leads to calculation of the layer thicknesses and the average wave velocity (average dielectric value). Relatively accurate values of layer thickness and average dielectric constants can be found using the coreless GPR [7]. However, a high resolution GPR unit is required to achieve the accuracy and a skilled GPR operator is needed to process the data [1]. The present study evaluated the coreless GPR method (utilizing two receivers) to detect the moisture level of test road constructed within an indoor test facility.

2 Method

2.1 Test Facility

An indoor full-scale test facility at the Swedish Road and Transport Research Institute, VTI, was employed for this work. The test pit is 3 m deep, 5 m wide and 15 m long [6]. The sides and the bottom of the test pit are made of concrete. The groundwater level in the test pit can be varied by adding water to the pavement structure through an installation at the bottom of the pavement structure. The pavement structure was instrumented with asphalt strain gauges (ASG) at the bottom of the asphalt layers. The structural condition of the pavement was evaluated using FWD. In the FWD tests, impact loads of 30, 50 or 65 kN were applied, and the resulting pavement surface deflections at 7 sensor locations were measured. The GPR measurements were conducted to detect the moisture levels in the pavement structure. The GPR and FWD measurements were simultaneously carried out at different ground water levels. The strain responses of the strain gauges under the

FWD loading were also recorded. The indoor full-scale test facility and the cross-section of the test pavement are shown in Fig. 1. The FWD/GPR tests were conducted under the following conditions:

- Dry state - when no water was present in the structure.
- Low moist state - when the groundwater level is 20 cm below the top surface of the subgrade (wet-1).
- High moisture state - when the groundwater level is 20 cm above the subgrade, or in the middle of the subbase layer (wet-2).
- Drained state – the water stored in the pavement was allowed to completely drain.



Fig. 1. Indoor full-scale test facility at VTI (left). Cross-section of the pavement structure (right), the numbers in the layers indicate the thickness mm.

2.2 GPR

GPR is a non-destructive test method used to survey subsurface materials/conditions. GPR involves sending a small electromagnetic pulse via a transmitting antenna and registering the reflected signal via a receiving antenna. The travel time of the pulse from the transmitter to the receiver and the properties of the received signal are used to determine the type and/or the composition of the material. The propagation velocity of electromagnetic waves in soils is strongly influenced by water content ([2, 4]). This is because the dielectric constant increases as the water content in the soil increases. The GPR multi-channel WARR (Wide Angle Reflection) method takes advantage of this property for detecting the relative water content. In this project, multi-channel GPR (having 500 MHz antennas) measurements were conducted to measure GPR velocity. In this setup, the travel times of an electromagnetic pulse from a transmitter (Tx) to the receivers (Rx) are registered in all receivers. Two different antenna configurations were tested to investigate the appropriate distance between transmitter Tx and receiver Rx. A calibration measurement was also made to record the different travel times for the "direct wave" between transmitter and receiver.

3 Results

3.1 FWD and ASG Measurements

Figure 2 presents the FWD deflection basins and the measured strains for dry, wet, and drained conditions. The deflection at 1200 mm reflects the influence of the groundwater within the subgrade or lower pavement layers, i.e., the deflection D_{1200} increases as the groundwater level rises. The deflection reverted to its initial dry state value once the structure was nearly fully drained. Note that, the center deflection D_0 decreased for drained condition. This was due to the temperature drop during the drained test, i.e., the temperature dropped from 12 °C to 3 °C. The effect of temperature on the measured asphalt strain was removed using the FWD back-calculated asphalt moduli. The asphalt modulus-temperature relationship was employed to adjust the strains to 10 °C. The strain increased as the groundwater level rose. The strain for the drained condition is marginally higher than for the dry condition. This difference could be attributed to residual moisture in the base or subgrade layers or potential errors arising from temperature corrections.

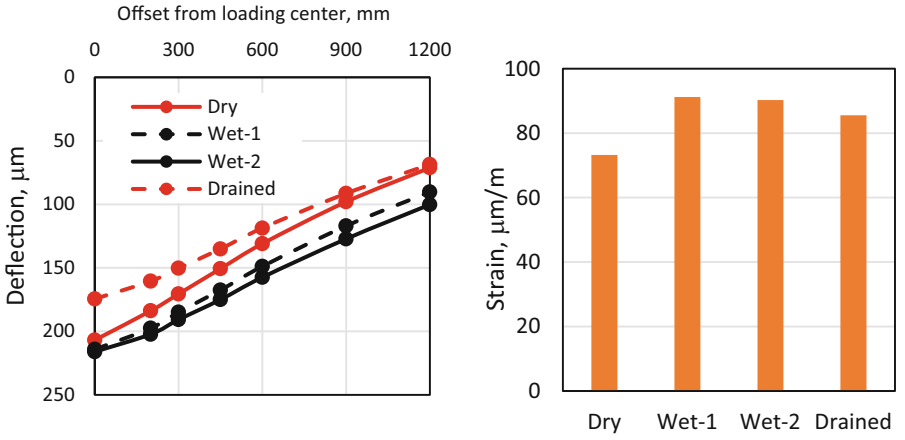


Fig. 2. FWD deflection basin for dry, drained and two levels of raised groundwater levels (left). Measured ASG strain adjusted to 10 °C (right).

3.2 GPR Velocity Measurements

The GPR WARR velocity measurements were determined for depths of 0 to 0.7 m (over the subgrade) and for depth of 0 to 2.7 m (over the whole structure including the subgrade). This approach was employed to explore the most effective means of distinguishing between varying groundwater levels. Figure 3 (left) shows the velocity variation over the depth of 0 to 0.7 m. In this case, the velocity for dry, wet-1 and drained cases produce very similar values of the GPR velocity. This is because the moisture has not reached or migrated to the depth of 0 to 0.7 m, and consequently, it does not impact the velocity. However, for the wet-2 condition, where the groundwater level was in the middle of the subbase layer, the velocity was significantly lower since the moisture reached the depth 0 to 0.7 m. On the other hand, as shown in Fig. 3 (right), both wet-1

and wet-2 conditions produced lower average velocity for the depth 0 to 2.7 m compared to the dry and the drained conditions. In this case, the velocity for the wet-2 conditions was relatively lower than the velocity at the wet-1 condition where the groundwater level was below the top of the subgrade. The dry and drained condition produced very similar values as indicated in the figures. These results aligned with the ranking derived from FWD deflection measurements. However, when examining the average velocity for a depth of 0 to 0.7 m, the wet-1 condition did not correspond to the FWD results.

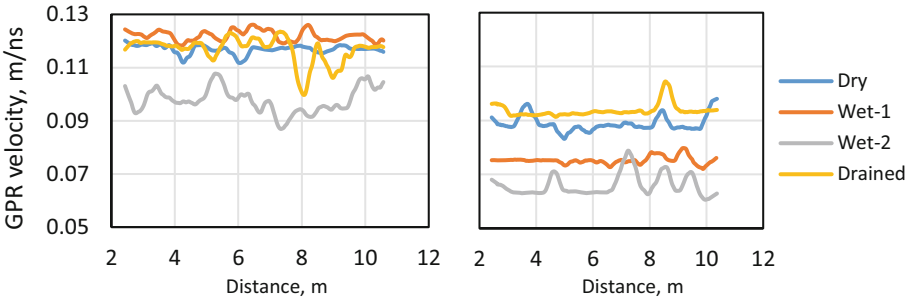


Fig. 3. GPR Velocity variation for depth 0 to 0.7 m (left) and for depth 0 to 2.7 m (right).

In addition to velocity measurements an average frequency spectrum has been performed, Fig. 4. The GPR data samples where truncated so that the remaining data only contained 52 samples, which approximately describes the depth of 0.25 m to 0.70 m.

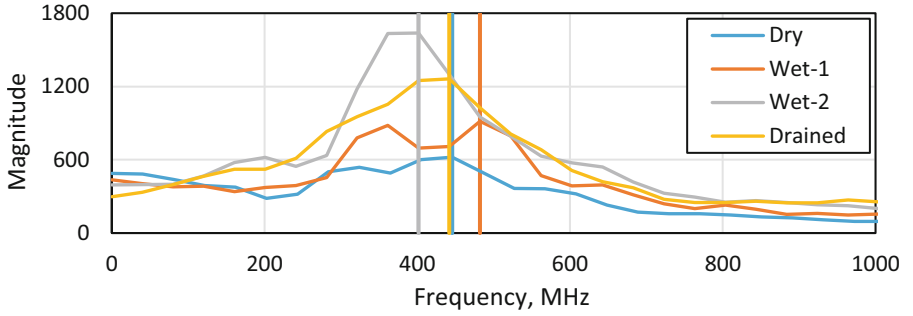


Fig. 4. Average frequency spectrum.

As expected, the result shows that the peak frequency tends to decrease when the material contains more moisture and at the same time the magnitude tends to increase. The peak frequency for dry and drained conditions shows very similar values. The magnitude differs that could indicate that there is still some impact. Important to add is that the groundwater level in wet-1 is still below 0.7 m and it is assumed that there is no impact on the material.

4 Conclusions

GPR and FWD measurements were conducted on indoor pavement structure under both dry and wet conditions. The ground water level was varied by introducing water into the pavement system. A GPR configuration having two receivers, each with 500 MHz antennas, was employed for collecting the GPR data.

The results demonstrated a good agreement between the measured FWD deflections and GPR velocity measurements concerning moisture levels. Elevated groundwater levels led to increased FWD deflections, reduced GPR velocity, reduced GPR frequency, and higher asphalt strain, affirming findings from previous research that this method effectively discriminates road sections with varying moisture conditions. However, it's important to note that the method produced relative water content based on GPR velocity variations rather than providing precise volumetric or gravimetric moisture content data. This distinction was evident in the indoor full-scale facility measurements.

A 500 MHz antenna was chosen for this project to penetrate deeper into the pavement structure. Combining FWD or other automatic road monitoring techniques with GPR having high and low frequency antennas could offer valuable insight into layer thickness and moisture conditions, enhancing the quality of road performance data collection.

While the GPR WARR velocity measurements is proved to be a useful indicator of moisture presence in the subsurface materials, further investigation into other GPR parameters such as frequency, magnitude, or the amplitude of the GPR signal is recommended. These parameters are easier to obtain and may add valuable information when analyzing moisture content.

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Investigation on Ageing Behaviour of Bio-Extended Bituminous Binders and Asphalt Mixtures for Sustainable Road Infrastructure

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Abstract. This paper investigates the use of a plant-based bio-oil in bituminous binders as a partial replacement of petroleum-based bitumen for asphalt mixtures. Its effects on the ageing behaviour of bituminous binders and asphalt mixtures are studied. A total of six bituminous binders and their asphalt mixtures were prepared and analysed in laboratory, including three different binder formulations with varying percentages of bio-oil and their respective reference binders. Both the bituminous binders and asphalt mixtures were subjected to ageing protocols in laboratory. Softening point test, rheological and dynamic mechanical analyses were conducted to evaluate the changes in properties of the materials before and after ageing. The results indicate that the mechanical properties of aged binders and mixtures show very similar relationships as between the fresh materials, but the relationships after ageing are at changed levels due to the laboratory conditioning. This supports further studies to verify their functional performance in asphalt pavements.

Keywords: Asphalt Pavement · Bio-Bitumen · Bio-Asphalt · Ageing · Pavement Material · Road Infrastructure

1 Introduction

The road network is an essential and integrated part of the transport infrastructure. Nowadays, most roads are paved with asphalt mixtures. The petroleum-based bitumen is used as a binder to hold the asphalt mixture together. As a petroleum-derived product, bitumen has a relatively high environmental impact and carbon footprint. For a green transition, the use of bio-based materials in asphalt mixtures from renewable resources, such as plant-based biomass, has been investigated as a potential next-generation solution [1]. Despite some promising results so far, knowledge gaps still exist in understanding the fundamental material behaviours and properties of the new bituminous binders and asphalt mixtures containing bio-based components. This is mainly because the bio-based components have different chemical compositions compared to bitumen and they may affect the binder behaviour and mixture performance in a different way, particularly the long-term performance.

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This paper investigates a specific type of bio-based material, a plant-based bio-oil, for its use in bituminous binders and asphalt mixtures as a partial replacement (extender) of petroleum-based bitumen. The study focuses on a specific and significant knowledge gap, namely understanding how the presence of bio-oil affects the ageing behaviour of bituminous binders and asphalt mixtures. Ageing is an important aspect to consider when evaluating the long-term performance of asphalt materials, which undergo ageing due to various factors, including exposure to sunlight, air, temperature fluctuations, etc. This ageing process can significantly affect the mechanical properties of pavement materials and thus the durability of roads. This paper presents an experimental investigation into the ageing behaviour of bio-extended bituminous binders and asphalt mixtures, aiming to enhance our understanding of their long-term performance and durability.

2 Experimental Plan

2.1 Materials

In this study, a total of six bituminous binders were analysed. These binders are classified into three different grades based on their conformity to EN 12591:2009 and EN 14023:2010 standards. Specifically, the study included two penetration grade 70/100 binders, two penetration grade 160/220 binders, and two polymer-modified bitumen (PMB) grade 40/100-75 binders. Within each grade, there were two types of binders: one bio-extended binder formulated with the investigated plant-based bio-oil predominantly composed of high-boiling esters and free acids (partial replacement of bitumen up to 21% – the bio-160/220 binder contains more bio-oil than the bio-70/100 binder), and the other binder sourced commercially, serving as a reference for comparative evaluation. All the six binders were used to prepare dense graded asphalt mixtures: Swedish ABT16 mixtures with the 70/100 and PMB binders, and AG16 mixtures with the 160/220 binders. For each binder grade, the mix design procedure was the same and the basic characteristics such as volumetric parameters of mixtures were kept as close as possible between the bio-extended variant and reference counterpart.

2.2 Test Methods

The binder samples were subjected to laboratory ageing protocols, including the Rolling Thin Film Oven Test (RTFOT) according to EN 12607-1:2014 and the Pressure Ageing Vessel (PAV) test according to EN 14769:2023, to simulate the short-term and long-term ageing, respectively. For assessing the changes in binder properties due to ageing, the Ring and Ball softening point of binder was tested according to EN 1427:2015 and rheological testing was conducted using a Dynamic Shear Rheometer (DSR) according to EN 14770:2023. In addition, the compacted asphalt mixture specimens were aged in laboratory according to CEN/TS 12697-52:2017 (Procedure B.1 at 65 °C for 15 days) and subsequently tested using dynamic mechanical analyses according to EN 12697-26:2018+A1:2022 (Annex F cyclic indirect tensile test) to evaluate the changes in their mechanical properties due to ageing.

3 Results and Discussion

3.1 Softening Point of Bituminous Binders

The softening point results of the investigated binders are listed in Table 1. The bio-extended binders without polymer exhibit smaller increases in their softening points after ageing than the reference binders. This means that these bio-extended binders harden less due to ageing than their reference binders. As for PMB binders, not only the hardening of the binder but also the eventual degradation of the polymer modifier may affect the softening point after ageing. Table 1 shows that the softening point of the bio-PMB decreases after ageing while that of the reference PMB increases significantly after short-term ageing by RTFOT and then decreases slightly after long-term ageing by PAV. Assuming the same ageing effect due to polymer degradation for both PMB binders, the test results suggest that the bio-PMB hardens significantly less due to ageing than the reference PMB.

Table 1. Softening point results (°C) according to EN 1427:2015.

Ageing status	Bio 70/100	Ref 70/100	Bio 160/220	Ref 160/220	Bio PMB 40/100-75	Ref PMB 40/100-75
Original	47.2	46.8	40.4	38.8	86.5	81.5
After RTFOT	51.2	52.8	43.6	45.0	85.5	88.5
After RTFOT+PAV	57.8	62.4	50.4	53.8	81.5	86.0

3.2 Rheological Properties of Bituminous Binders

The DSR temperature sweep results at 1.59 Hz (10 rad/s) of the investigated binders are presented in Fig. 1-3, including the dynamic shear modulus |G*| and phase angle δ. The results indicate that the bio-extended binders have higher phase angle than their reference binders. After ageing, for binders without polymer, the phase angle decreases and the bio-extended binders without polymer still exhibit higher phase angle than their reference binders after long-term ageing by PAV. As for the PMB binders, the phase angle reaches a plateau in the high-temperature range. The bio-PMB shows very similar ageing effect as the reference PMB but with higher δ values.

For each binder grade, the |G*| curves of the two RTFOT-aged binders are almost identical, although there are some slight differences between the original binders. After long-term ageing by PAV, the |G*| increases, which means that the binder becomes stiffer. However, the bio-extended binders exhibit smaller increases in |G*| after long-term ageing than their reference binders, especially in the high-temperature range. This agrees with the conclusion drawn in the previous sub-section based on the softening point results. Meanwhile, the bio-extended binders without polymer appear to show

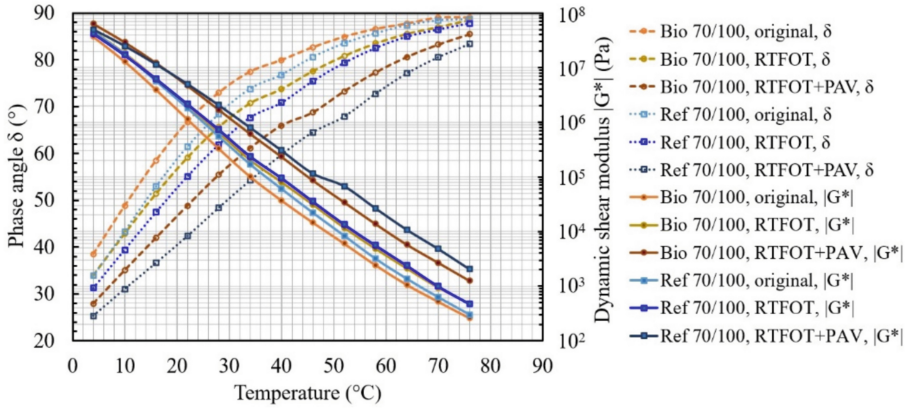


Fig. 1. DSR temperature sweep results at 1.59 Hz (10 rad/s) of 70/100 binders.

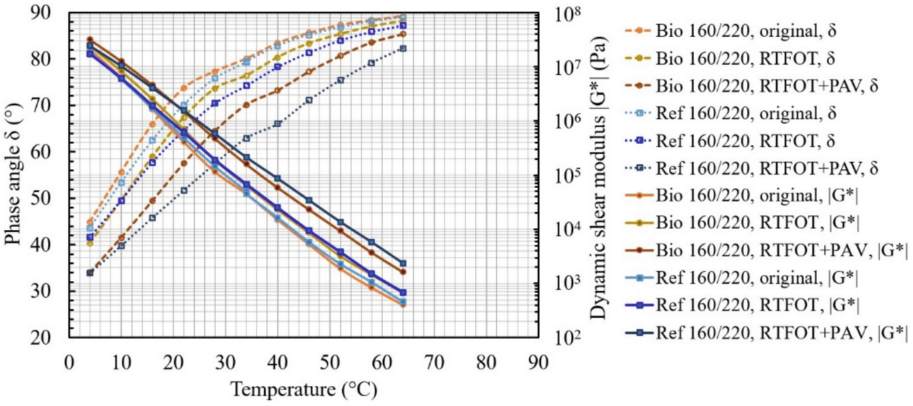


Fig. 2. DSR temperature sweep results at 1.59 Hz (10 rad/s) of 160/220 binders.

slightly higher |G*| values after long-term ageing than their reference binders at the low-temperature end, which suggests that their |G*| is slightly more sensitive to temperature changes after experiencing the PAV ageing.

3.3 Dynamic Mechanical Properties of Asphalt Mixtures

The master curves for dynamic modulus |E*| and phase angle φ of the investigated asphalt mixtures are presented in Figs. 4-6. The |E*| and φ values were measured at different temperatures and frequencies by a cyclic indirect tension test on cylindrical specimens and the master curves were constructed at reference temperature 10 °C.

In the low-frequency (corresponding to high-temperature) range, the asphalt mixtures with bio-extended binders have higher φ values than their reference mixtures. At very high frequencies (corresponding to very low temperatures), however, the bio-extended binders lead to lower φ values of asphalt mixtures than the reference binders, especially

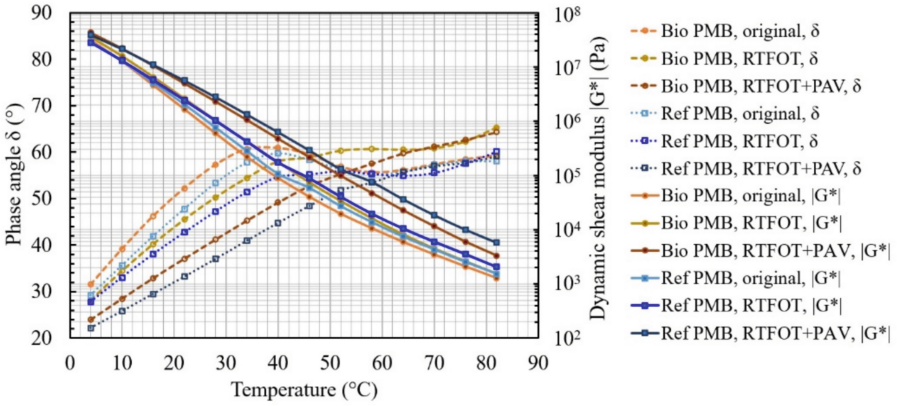


Fig. 3. DSR temperature sweep results at 1.59 Hz (10 rad/s) of 40/100-75 PMB binders.

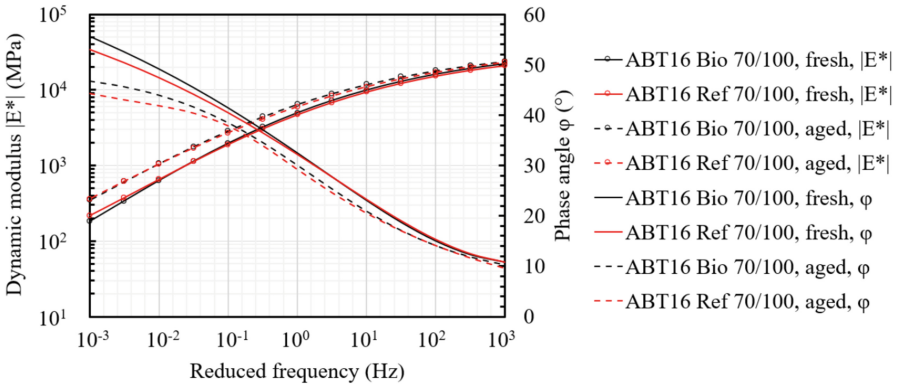


Fig. 4. Dynamic modulus |E*| and phase angle φ master curves at reference temperature 10 °C of ABT16 asphalt mixtures with 70/100 binders.

when the bio-oil content is high (e.g., the AG16 mixtures with 160/220 binders). After ageing, the φ of asphalt mixtures decreases and its peak value (the maximum [2]) moves towards to the low-frequency end. The aged mixtures show very similar relationship of φ as the fresh mixtures but at a reduced level.

The asphalt mixtures with bio-extended binders have lower |E*| than their reference mixtures in the low-frequency range. However, as the frequency increases, the |E*| values of bio-asphalt mixtures surpass that of the references. This effect is the most significant in the case of high bio-oil content such as the AG16 mixtures with 160/220 binders. After ageing, the |E*| of asphalt mixtures increases. The aged mixtures show very similar relationship of |E*| as the fresh mixtures but at an increased level.

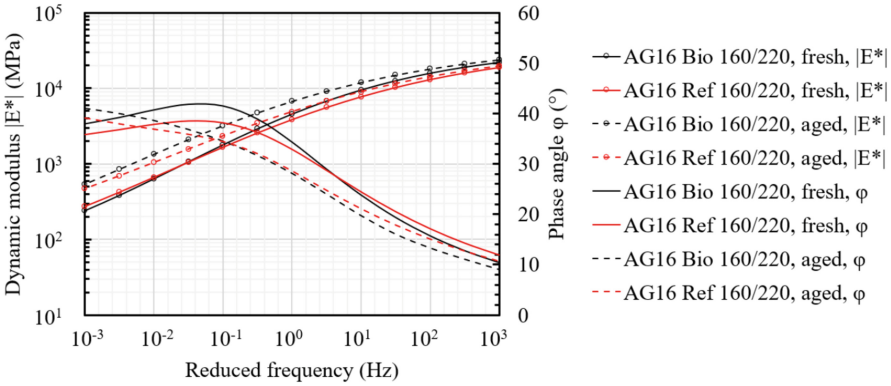


Fig. 5. Dynamic modulus |E*| and phase angle φ master curves at reference temperature 10 °C of AG16 asphalt mixtures with 160/220 binders.

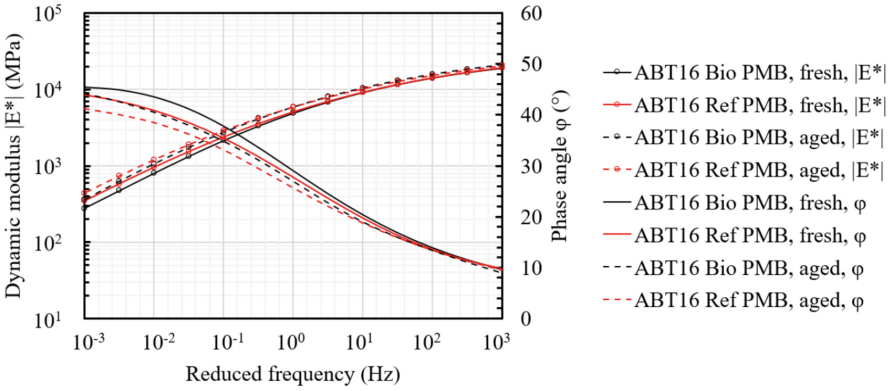


Fig. 6. Dynamic modulus |E*| and phase angle φ master curves at reference temperature 10 °C of ABT16 asphalt mixtures with PMB binders.

4 Conclusions

Using the investigated bio-oil as a bitumen extender results in increased phase angle and decreased modulus of the binders and asphalt mixtures at high temperatures and low frequencies. However, at very low temperatures and high frequencies, the bio-extended binders lead to decreased phase angle and increased modulus of the asphalt mixtures. The effects are more significant at a higher bio-oil content. Ageing hardens the materials. The mechanical properties of aged binders and mixtures show very similar relationships as between the fresh materials but at changed levels due to the ageing. This supports further studies to verify their functional performance.

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Calibrating ERAPave PP with Field Performance Data

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Abstract. The conventional pavement design approach considers various parameters for the optimization of pavements for the prevailing traffic and environmental conditions. Demands related to technological developments, climate adaptation and infrastructure resilience are expected to influence the way pavements are designed and constructed. For this, better and improved flexible pavement design tools are required. ERAPave performance prediction (PP) which is a mechanistic-empirical (M-E) pavement design tool is currently under development with the goal of addressing the several challenges facing the pavement industry. This paper calibrates the permanent deformation prediction approach in ERAPave PP using pavement performance data from actual field pavements. As traffic volume is observed to have a significant influence on predicted results, separate calibration was performed for medium-to-high-volume and low-volume traffic categories. A global calibration factor is used for this purpose, significantly improving the accuracy of the prediction for both categories. Prediction accuracy can be improved further through the consideration of observed rut depth variability.

Keywords: ERAPave PP · asphalt · rut depth · calibration · variability · resilience

1 Introduction

Pavements, as an integral part of the transportation mobility network, play an important role in the well-being of society. The conventional pavement design approach considers various parameters and factors for the optimization of pavements for the prevailing traffic and environmental conditions [1, 2]. The rapid electrification and digitalization of the road network along with climate change are expected to significantly influence the way pavements are designed and constructed [3]. In addition, pavement management systems (PMS) are expected to account for the road network resilience to unforeseen natural and man-made hazards. This requires the development of new pavement analysis and design methods that are appropriate for existing and future challenges.

ERAPave PP, which is a mechanistic-empirical (M-E) pavement performance prediction tool for asphalt pavements, is currently under development with the goal of addressing the numerous challenges that are affecting the pavement industry. The tool is

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currently under consideration by the Swedish and Norwegian Transport Administrations as a possible successor to existing methods. ERAPave PP optimizes flexible pavements for distresses such as fatigue cracking and permanent deformation. It can also be used to evaluate distresses that are typical of cold climate such as frost heave and studded tire wear [4]. The prediction of these distresses is achieved using material models and pavement response, and performance relationships that are developed with the consideration of underlying pavement degradation mechanisms.

The empirical relationships that define distress accumulation and performance evaluation in M-E pavement design tools require comprehensive calibration and validation to guarantee that predicted values capture actual field performances [5]. A preliminary calibration using performance data from laboratory mixtures and heavy vehicle simulated (HVS) accelerated pavement testing (APT) structures can allow the incorporated models to capture the influence of various factors on predicted results [6]. A follow-up comprehensive calibration using performance data from actual field pavements would further improve the accuracy of the models by minimizing the systematic deviation that exist between predicted and observed performances [7].

This paper aims to calibrate the permanent deformation models in ERAPave PP. Furthermore, the study investigates the variability of observed rut depth. For this, several field pavement sections from the Swedish Long-Term Pavement Performance (LTPP) database were used. The calibration was achieved by carefully examining the correlation between observed and predicted values. For this, a global calibration factor that is optimized for annual average daily traffic (AADT) was utilized.

2 Methodology

2.1 ERAPave PP

ERAPave PP employs better and enhanced approaches for inputs characterization, pavement response modelling and pavement performance computation. It uses a heat transfer model to predict the temperature profile in the asphalt concrete (AC) layer while offering axle load spectra (ALS) for truck traffic characterization. Material properties such as layer modulus are characterized in the tool considering factors such as temperature, loading frequency, and moisture content, among others [8]. Rut or permanent deformation development is quantified in terms of total surface deformation, unlike existing methods, where the user is provided only with a damage parameter.

The layer strain approach is used in ERAPave PP to estimates the initiation and accumulation of permanent deformation in flexible pavements. In this approach, each layer contribution is computed separately, and afterwards aggregated to determine the total surface rutting [9]. Therefore, for each layer, unique predictive models or model coefficients were developed and incorporated into ERAPave PP. For the AC layer, the model that was originally developed for Pavement ME was adopted while for the unbound layers and subgrade, a strain-based model that considers the stress-history dependent behaviour of the material was implemented [5, 10].

Both models produced satisfactory results when evaluated using laboratory tests and APT sections [8, 10]. However, as semi-empirical models, further calibration and validation is required before implementation. Therefore, a preliminary calibration of

the models was performed using APT sections that are representative of Swedish in-service conditions. The preliminary calibrated models delivered results that are in good agreement with measured values [4].

2.2 Pavement Structures

The calibration of the rutting prediction approach in ERAPave PP was achieved using 20 field pavement sections, five for low volume and 15 for medium-to-high volume categories. The sections were extracted from the Swedish LTPP database and represent various in-service Swedish conditions. Another criterion for selecting these sections was the availability of high quality input and field performance data. The sections comprise motorways, state and rural roads, allowing the calibration to capture a wide range of traffic, material, structure and climate conditions. The thickness, traffic, as well as location information of the studied sections is provided in Table 1.

Table 1. Layer thickness, traffic volume and location of the studied pavements

Category	Section ID	Thickness (mm)			AADT	Location
		AC	Base	Subbase		
Low volume	C-292-1	85	160	800	787	Uppsala
	C-292-4	35	50	160	787	Uppsala
	U-580-1	80	110	520	400	Västmanland
	U-580-5	80	110	520	400	Västmanland
	W-RV71	50	125	500	559	Dalarna
Medium-to-high volume	E-RV34	95	120	550	1776	Östergötland
	F-E4	150	70	440	5626	Jönköping
	F-RV31	50	115	500	2575	Jönköping
	G-126-1	40	160	300	1461	Kronoberg
	G-126-7	40	160	500	1461	Kronoberg
	H-RV34	75	125	400	2605	Kalmar
	N-E62	180	120	600	6026	Halland
	U-RV56–2	70	150	450	4695	Västmanland
	U-RV56–9	70	75	–	4695	Västmanland
	W-266	70	130	500	1897	Dalarna
	W-RV80	50	120	500	1403	Dalarna
	X-RV561	50	125	400	1053	Gävleborg
	X-RV567	50	125	500	1053	Gävleborg
	Y-RV90	80	100	900	1748	Västernorrland
	Z-E453	130	80	420	2552	Jämtland

2.3 Calibration Approach

The lack of reliable data from field sections on the individual layer contribution to the total observed surface rutting has made it difficult to perform a layer-by-layer model calibration. Furthermore, the measured rut depth of field sections includes, in addition to permanent deformation, studded-tire wear from passenger cars. In a similar fashion, rut depth is predicted in ERAPave PP by summing together permanent deformation and studded tire wear. A calibration approach where a global calibration factor (k) is utilized to minimize the systematic deviation between observed (RD_{obs}) and predicted (RD_{pre}) rut depths is suggested. Equation 1 presents the mathematical expression for the suggested approach:

$$k = RD_{obs}/RD_{pre} \tag{1}$$

As traffic volume was observed to have a significant impact on predicted performance, the annual average daily traffic (AADT) parameter was selected for formulating the calibration relationship. Model calibration was achieved by dividing the studied pavement sections into two categories: low volume and medium-to-high volume. Sections with 1000 or less *AADT* were categorized into low volume while sections with a higher AADT were grouped into medium-to-high volume. Equation 2 presents the relationship of the calibration equation:

$$k = a_1 * (AADT)^{a_2} \tag{2}$$

where a_1 and a_2 are model parameters.

For each pavement, the bias in the prediction was established by relating the original predicted rut depth with the corresponding observed value. The bias was calculated on yearly basis and as such captures the permanent deformation evolution of each pavement. These yearly values were averaged to determine representative unique parameter for each pavement. The calibration equation was formulated by relating these unique parameters through linear regression with the corresponding *AADT*.

3 Results and Discussion

3.1 Model Calibration

The global calibration equation for the low volume category was developed using the five sections listed in Table 1. The derived relationship is presented in Fig. 1a. A good relationship was observed with a coefficient of determination R^2 of 0.90. The comparison between the rut depths before and after calibration is presented in Fig. 1b. A R^2 of 0.83 was obtained for the calibrated prediction, which is significantly higher than the original value.

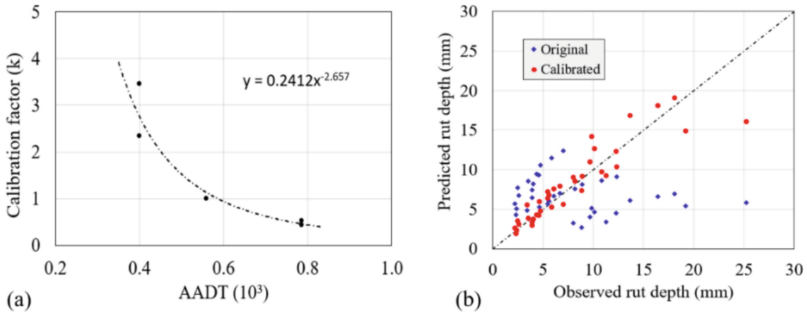


Fig. 1. For low volume traffic category**,** calibration equation (a) and comparison between original and calibrated rut depths (b)

Figure 2a, presents the derived equation for the medium-to-high volume traffic category. This was achieved using the 15 sections listed in Table 1. As the case with the low volume category, a good relationship with a R^2 of 0.9 was observed. Figure 2b, presents the comparison between the rut depths before and after calibration. The calibration delivers a R^2 of 0.82, which is significantly higher than the original value.

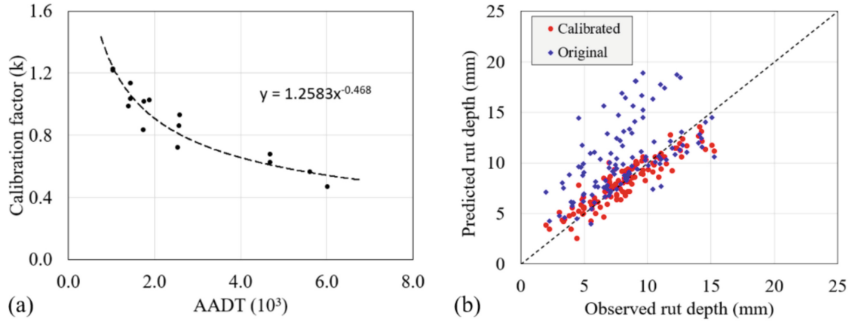


Fig. 2. For medium-to-high volume traffic category, calibration equation (a) and comparison between original and calibrated rut depths (b)

3.2 Observed Performance Variability

For the same pavement structure, the Swedish LTPP reports rut depth by dividing the section into several subsections. It is observed that these rut depths exhibit significant variability. Prediction, on the other hand, is performed assuming a uniform structure. A close study of measured rut depth variability shows significant difference among the studied pavements. A wide coefficient of variation (CV) range of 6% - 31% was obtained. The variability results of the two traffic categories are almost identical, CV of 15% and 17% for low volume and medium-to-high volume, respectively. Figure 3a and Fig. 3b, present the rut depth variability for sections F-RV31 and Y-RV90, respectively. Information on the variability of observed performance will be crucial for incorporating reliability into ERAPave PP and for developing resilience pavement management systems (PMS).

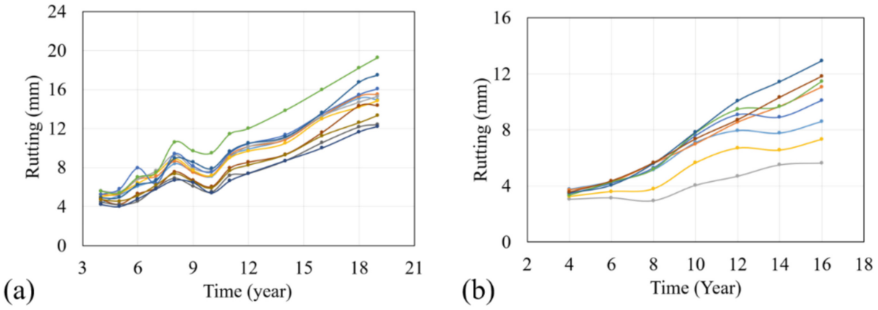


Fig. 3. Variability of observed rut depth for sections F-RV31 (a) and Y-RV90 (b).

4 Conclusions

This study calibrates the permanent deformation prediction approach in ERAPave PP using several field pavement sections. The calibration process has shown the difficulty of performing a layer-by-layer calibration as information regarding each layer contribution to the total observed surface rutting is missing. In addition, the inability to distinguish the studded-tire-wear component from the total rutting has further complicated the calibration. This resulted in the introduction of a global calibration factor that effectively minimizes the systematic deviation between observed and predicted rut depths.

AADT was selected for defining the global calibration factor as traffic volume is observed to have a significant influence on predictions. Original predictions show a marked bias with respect to traffic volume, underpredictions for low volume traffic category. The derived calibration equations for low volume and medium-to-high volume traffic categories are observed to deliver results that are in good agreement with observed performances. The statistical characterization of observed performances has shown a wide range in variability which affects the accuracy of the calibrated model.

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Resilience Assessment and Adaptation for Critical Infrastructure – Modelling Resilient Infrastructure Systems

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Abstract. Creating resilient infrastructure is of crucial importance to society, particularly in the face of escalating climate risks. As such, investments to increase resilience should be spent wisely to yield maximum benefits to transport users and society. However, decision-making regarding infrastructure dependencies is often based solely on qualitative information, which is inadequate for understanding the effectiveness of adaptation measures and the interconnectedness of infrastructure systems. This paper describes the Resilience Assessment and Adaptation for Critical infrastructurE (RA2CE) modeling framework. RA2CE aids infrastructure stakeholders in performing resilience assessments and to identify suitable adaptation options by generating comprehensive resilience maps for climate-induced events and ultimately pinpointing viable adaptation options. The need for systems-scale modeling, including interdependency analysis, demands fast, versatile, and generic models. We illustrate RA2CE's ability to quantify damages, indirect losses, and cascading impacts, supporting long-term adaptation planning on regional and national scales. This approach ensures that investments in resilient transport planning are allocated wisely, maximizing benefits for transport users and society.

Keywords: resilient infrastructure · climate change adaptation · adaptation planning · network criticality · model development

1 Introduction

Creating resilient infrastructure is of crucial importance to society, particularly in the face of increasing risks associated with climate change and climate-induced hazards. As such, investments to increase resilience should be spent wisely to yield maximum benefits to transport users and society. However, decision-making regarding infrastructure dependencies is often based solely on qualitative information, which is inadequate for understanding of the effectiveness of adaptation measures or potentially the interconnectedness of infrastructure systems.

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1.1 Decision-Frameworks for Climate Change Risks, Impacts and Adaptation for Transport Infrastructure

To increase resilience and develop climate adaptation strategies for transportation infrastructure, various decision-frameworks have been developed. These frameworks primarily rely on risk or resilience assessments, which have become standard practice for understanding the effects on infrastructure and transportation networks caused by extreme events. In general assessments adhere to the UNISDR, 2016 [1] definition of risk, involving hazard identification, assessment of infrastructure exposure to these hazards, quantification of vulnerabilities, and an evaluation of the consequences for transportation due to these extreme events (Fig. 1). In this paper, we use the term "resilience" instead of "risk", to include not only the damage to the road, but also the losses for the road users and impact on society during the disruption. We also use the term 'resilience' to underline our focus on enhancing service provision before, during, and in the recovery phase of a network disruption.



Fig. 1. The general steps in decision-frameworks for climate risks, impacts and adaptation for transport infrastructure.

Among the widely applied frameworks for road infrastructure is "Roads for today adapted for tomorrow" (ROADAPT [2]). This framework provides guidelines for road network administrations to prepare adaptation strategies by executing a qualitative quick scan methodology. A recent addition is the international standard [3], which addresses climate change adaptation and includes guidelines for vulnerability, impact, and risk assessments. ISO 14091 introduces the concepts of resilience thinking in climate adaptation. Resilience assessments include the system's ability to prepare for, recover from and adapt to external events, going beyond the scope of risk assessments [4]. Other international frameworks include the CCRI: Physical Climate Risk Assessment Methodology ([5]) and the PIARC International Climate Change Adaptation Framework for Road Infra-structure ([6]). These guidelines generally follow the steps illustrated in Fig. 1 starting with hazard assessment and proceeding to impact assessment, which is in line with the concept of risk outlined by the [1]. However, they differ in their inclusion of resilience, their level of detail in analyses (quantitative vs qualitative approaches), the scope of the assessment (e.g., asset-level, entire infrastructure networks, or multiple infrastructure networks systems), and the intended audience and operational focus (e.g., policy makers or infrastructure operators). ([7, 8]).

1.2 Rationale for RA2CE Modeling Framework

Although in recent years, several guidelines and frameworks have been developed to tackle the issue of infrastructure resilience, these resources often remain conceptual or

rely heavily on specific case studies with specific data requirements. As the complexity of questions regarding infrastructure resilience has increased, there is an increasing demand for versatile tools to quantify both the damages to infrastructure as well as the losses for the users of the infrastructure. Furthermore, there is a growing need to assess the effectiveness of adaptation measures to identify those that offer a cost-beneficial advantage. Furthermore, the importance of system-wide modeling has grown, including the modeling of interdependencies among critical infrastructure networks, including multi-modal assessments, underscore the necessity for models that are fast, versatile, and applicable across various scenarios with different data requirements. For this reason, we introduce the open-source Resilience Assessment and Adaptation for Critical Infrastructure (RA2CE) modeling framework (publicly available at [9]).

2 RA2CE Modeling Framework

Figure 2 illustrates the modules in RA2CE, aligned with the general steps outlined in the existing international standards ([9], Fig. 1). Every resilience assessment in RA2CE starts with the creation of a network (Fig. 2, Table 1). This process is independent of the infrastructure type, although the applications thus far have been on road transportation. The network can be generated for any place in the world through an integrated OpenStreetMap connector or through user-provided networks. The modelling framework is designed to activate the different modules based on the required analyses or available input data. Table 1 describes the various analyses and necessary input data.

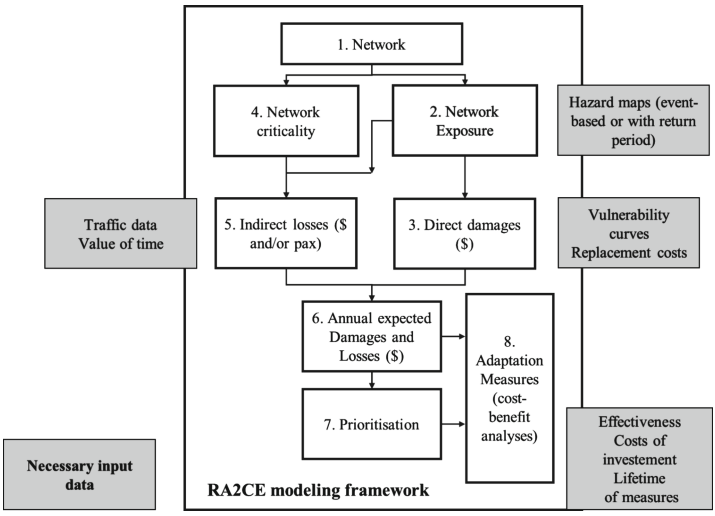


Fig. 2. Overview of the different building blocks in the RA2CE modeling framework applied for a transport network.

Table 1. Description of the RA2CE elements

Module	Short description	Necessary input data
1. Network	Creates the (graph-based) network (graph-based) necessary for any analysis.	Different input data are possible: 1. Area of interest (.geojson) 2. User-provided (.shp or .pbf)
2. Exposure	Creates an overlay of the network with the hazard map(s).	Hazard map (.tiff format). Either event-based or with return period.
3. Direct damages	Calculates the direct damages per hazard map (event-based or with return period).	Vulnerability curves (with % damage per hazard intensity). Replacement costs of the different types of infrastructure.
4. Network criticality	Multiple analyses are available: - Single link redundancy: Determines extra travel time and/or distance when one link is disrupted. - Multi-link disruption: Assesses extra travel time and/or distance when multiple connections are disrupted. - Origin-Destination analyses: Computes the shortest or quickest route between user-specified origins and (nearest) destinations.	Requirements vary: - Single-link redundancy: no data needed. - Multi-link disruption: hazard data (event-based or with return period) - Origin-destination: Needs additionally, origin and destination locations.
5. Losses calculation	Depending on the required analysis and input data calculates the costs and/or number of people affected per hazard event or scenario.	Depending on analysis: - Usage data (e.g., traffic data) - Value of time per user group (e.g., business, leisure etc.) - Number of people at origins
6. Damage and Losses calculation	Calculates the annual expected damages and losses based on the damages and losses per return period.	This can only be done when hazard data with return period has been used in 2. Exposure.
7. Prioritisation	Based on damages and losses a prioritisation of hotspots based on a risk matrix.	Requires validation by the end user (e.g., operator/policy maker).
8. Adaptation measures	Economic valuation per adaptation measure which results in a cost-benefit analysis per segment and/or network.	Requires per measure: Effectiveness, investment costs, and expected lifetime.

The hazard maps provided by the user can be event-based, exploring the impacts of a single scenario, or they can consist of multiple hazard maps with return periods for a full risk assessment including long-term consequences. These hazard maps are overlayed with the network and subsequently enter the damage and/or losses modules. The damages to the infrastructure can be assessed based on built-in damage functions from the OSdaMage model, which have been developed and used for the quantification of flood risk of the European road network [10].

Indirect losses are assessed using a criticality assessment (Fig. 2, Table 1). In resilience assessments, "criticality" is used to show the importance of the road in serving societal needs. RA2CE uses single-link redundancy to quantify criticality and indirect losses, by calculating additional travel time or distance when a link is disrupted. This extra time is then combined with road usage data and users value of time to determine indirect economic losses from disruptions. The criticality module also includes multi-link redundancy for scenarios with simultaneously multi-link disruptions (e.g., floods) and origin-destination (OD) analyses, which allow rapid assessments of whether locations remain accessible during or after an event. These OD analyses have proven valuable in emergency response [11] or cascading impacts [12].

With hazard data, including return periods, and calculated damages and losses for each return period, it is possible to estimate annually expected damages and losses from extreme events. Subsequently, these can be evaluated in collaboration with infrastructure stakeholders to identify hotspots for adaptation.

Finally, when adaptation options are identified as well as user-provided data on effectiveness and costs of the measures are available, RA2CE can perform an economic valuation of these measures. To incorporate uncertainties RA2CE facilitates the option of multiple calculations. Climate change effects can be integrated in both the hazard module, through updated maps, or in the adaptation module, using a climate.

3 Application to the Main Road Network in the Netherlands

The Dutch National Road Authority, 'Rijkswaterstaat', has set the goal to establish a resilient road network by 2050. To achieve this, they have undertaken a comprehensive evaluation known as 'stress test', which results in the impacts of future climate conditions and extreme weather events on road infrastructure. Here, the RA2CE modeling framework has been applied to quantify and monetize these climate-related risks [9]. The stress test covered a total of 13 different hazards, resulting in exposure, damages, and socio-economic losses along specific road segments of 100 m. The analysis was performed for both conservative and worst-case scenarios to account for uncertainties in the stress test and in future developments, including climate change and socio-economic developments. The results were presented and discussed in a risk dialogue with stakeholders, where different adaptation options were identified. Subsequently, a quantitative cost benefit assessment was conducted by using RA2CE, resulting in an overview of effective measures for every 100 m road segment for the entire road network. The assessment accounted for the expected change of likelihood of events due to climate change, the frequency and cost of application of the measures, and applied a discount rate. As a result, maps and tables were constructed, highlighting whether and where adaptation options provide an economic benefit [13].

4 Conclusion and Recommendations

Making infrastructure resilient is essential in the face of increasing climate risks. As the complexity of questions regarding infrastructure resilience has increased, there is an increasing demand for versatile tools to quantify the tangible damages to infrastructure, the losses for the users of the infrastructure and for the development of adaptation plans. The Resilience Assessment and Adaptation for Critical Infrastructure (RA2CE) modeling framework is introduced, offers comprehensive approach to resilience assessments. This approach provides a fast and flexible way to assess risk beyond direct damages to infrastructure and, insight into the robustness of proposed interventions, enabling communities to holistically assess risks and possible solutions. Further developments include the extension of the framework to consider socio-economic vulnerability in adaptation planning, multi-modal ("systems") modelling and the inclusion of network capacity in the route-finding algorithms.

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Indirect Monitoring of Frequencies of a Multiple Span Bridge Using Acceleration Responses Collected From a Passenger Train

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Abstract. In this paper, a field study is carried out to monitor the natural frequencies of Malahide viaduct bridge which is located in the north of Dublin. An indirect bridge monitoring approach is employed is this paper, in which the acceleration responses from an instrumented train are used to estimate the natural frequencies of each span of the viaduct. An Ensemble Empirical Mode Decomposition (EEMD)-based Hilbert Huang Transform (HHT) technique is employed to identify the natural frequency of each span from the signals indirectly measured on the train. This is carried out by calculating the average of the Instantaneous Frequencies (IFs) using 41 runs of the instrumented train. To assess the feasibility of the indirect approach, direct monitoring approaches were also implemented using accelerometers attached to the spans of the viaduct. The measurements were carried out in twelve stages. In each stage, a different span was instrumented and monitored using five accelerometers placed on that span. The free and forced vibrations from each span are used to estimate the first natural frequencies. The frequencies obtained from drive-by measurements are compared to those from direct measurements which confirms the effectiveness of indirect approaches and shows the locations of the two replaced spans with higher stiffness that have higher natural frequencies compared to other spans. This full-scale approach expands the potential for applications of bridge–vehicle dynamic interaction responses, along with their ability to be demonstrators of successful implementations of decisions on public infrastructure.

Keywords: Indirect monitoring · Direct monitoring · Multi span bridge

1 Introduction

Bridges are important structures in transportation infrastructure. They require monitoring to detect local and global damage caused by several reasons such as bridge strike, fatigue, loading and scour [1]. Historically, the collapse of bridges has led to disruptions in

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traffic flow and posed significant challenges to public services. Notable examples include the Caprigliola bridge collapse (2020) [2], and the Malahide estuary viaduct failure (2009) [3]. Due to their critical role in transportation infrastructure, researchers have been seeking efficient and reliable ways to identify bridge damages before they become catastrophic [4]. Traditionally, a bridge is monitored directly by installing sensors to obtain responses to certain excitations [5]. This conventional approach relies on the analysis of on-bridge responses to deduce the mechanical and dynamic properties of the structure and compare them with healthy baseline values to identify any damages present [5]. While this type of monitoring has been seen to be effective, it requires a distribution of sensors along the length of the bridge, that consumes a lot of cost and labour. For longer multiple span bridges in particular, traditional methods of monitoring can become difficult and costly, since they require more sensors. In response to this problem, research efforts have focused on various approaches to facilitate largescale monitoring of the condition of bridges on the transport network. The concept of using sensors installed on train/vehicles, using a drive-by approach to monitor the condition of bridges, has become the focus of much attention in recent years [6]. Studies on extracting bridge frequencies from drive-by measurements have employed several signal processing techniques such as: Hilbert Transform (HT) [7], moving average filtration [4] and wavelet analysis [8].

In this paper, an improved Hilbert Huang Transformation (HHT) is applied to the acceleration measurements from an instrumented train to estimate the natural frequencies of the Malahide Railway Viaduct in Ireland, which consists of 12 simply supported spans. To validate the drive-by technique, a direct test was also carried out to find the natural frequency of each span. The bridge experienced a collapse of two of the spans and one pier foundation in 2009 due to scour. These spans were replaced with stiffer elements [9] which has resulted in a change of their natural frequencies. To find the natural frequency of the spans, the train drive-by data is decomposed using Ensemble Empirical Mode Decomposition (EEMD) [10] to measure the Intrinsic Mode Functions (IMFs), and HHT is applied to obtain the Instantaneous Frequencies (IFs) from each measured IMF. The IFs associated with the natural frequencies of the bridge are computed and then compared with the natural frequencies obtained through direct measurements taken from both the free and forced vibrations of each span.

2 Malahide Viaduct UBB30 Ireland

The Malahide Viaduct is a bridge comprising 12 spans, built in 1844 and spanning the Broadmeadow Estuary in Dublin, Ireland. It accommodates a dual railway track, serving both the Dublin – Belfast railway route and freight trains. In 2009, two of its spans (Spans 4 and 5) and Pier 4 collapsed due to scour caused by a flash flooding event [9]. Following the incident, efforts were made to restore and oversee the Malahide Viaduct to prevent soil erosion and structural damage resulting from the increased loads exerted by passing trains [3]. The collapsed spans and pier were replaced with stiffer spans and new foundations for the pier were established [3].

2.1 Direct Measurements

To establish a reference for comparing with the drive-by measurements, the natural frequencies of each span within the viaduct were directly assessed by installing accelerometers on the bridge structure. Five triaxial wireless MEMS accelerometers (LORD MicroStrain G-Link 200) were installed at span to record the deck free and forced vibrations (Fig. 1). Free vibrations were recorded in response to the passage of trains, and typically, data collection continued for three seconds following the passage of each train. The direct measurements were carried out in twelve stages. In each stage, a different span was instrumented and monitored using five accelerometers placed at the points where the West side handrail uprights are connected to the concrete beam. The first natural frequency for each span of the Viaduct was determined by applying Fast Fourier Transformation (FFT) to the data obtained from both free and forced vibrations. Specifically, for each span, the forced and free vibrations after three passing trains were used to estimate the first natural frequency.

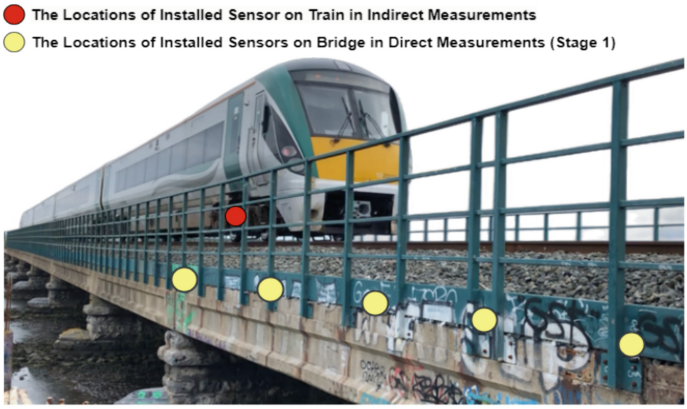


Fig. 1. Layout of sensor installation in indirect and direct monitoring of bridge

2.2 Indirect Measurements

A five-carriage train is instrumented using multiple accelerometers and a Global Positioning System installed at the first bogie of the leading carriage to obtain drive-by accelerations of an in-service train [9] (Fig. 1). A data acquisition system was placed securely in a 'coupler box', and the system was powered directly by the train's supply. Vertical bogie accelerations were recorded over a 5-week period in 2016 as the train traversed the viaduct 41 times. More details of the instrumentation and the test are presented in [9].

3 Results and Discussion

In this paper, EEMD-based HHT is used to identify the IFs from indirect acceleration measurements. IMF-6 was chosen to be used for estimating the pattern of changing frequencies in a multiple span bridge. Since the frequencies must be consistent for each

span, an average of IFs for each individual span is considered. In this study, the train bogie accelerations from 41 train runs are used to verify the efficacy of the proposed approach. Fig. 2 displays the average IFs calculated using IMF-6 measurements for each span, which were derived from the indirect measurements. For comparison, the first natural frequencies obtained directly from both free and forced vibration measurements are also depicted (indicated by dotted and dashed lines, respectively). For the indirect measurements, as the results are collected from multiple runs, error bars are plotted using a mean and (+/−) two standard deviations, representing a confidence interval of more than 95% of the total results.

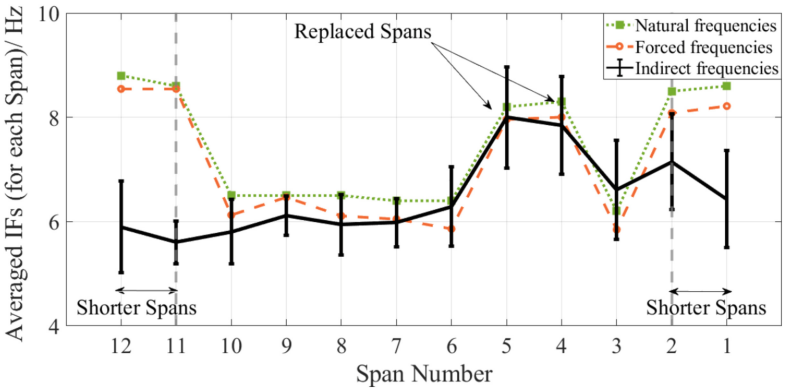


Fig. 2. Comparison of natural frequencies obtained from direct and indirect methods

As depicted in Fig. 2, the average IFs for each span exhibit a similar trend to that of the directly measured first natural frequencies, especially where the replaced spans are located (Spans 4 and 5). Furthermore, the natural frequencies estimated from the indirect measurements closely align with the frequencies derived from forced vibrations. This is an important finding, indicating a shift in the estimated frequencies due to the presence of the passing train. This shift in frequencies is due to the fact that the added mass effect of the train is present in both cases of drive-by and forced vibration, which resulted in a frequency change compared to the free vibration scenario. In addition, for spans of equal length, the consistency in frequencies around the unreplaced spans is well detected by the drive-by approach and follows the same pattern as the direct measurements. However, the results for shorter spans appear less accurate, potentially due to factors such as mode mixing or the presence of edge effects in the HHT process. To assess the impact of mode mixing, the averaged IFs are re-calculated using IMF-5 and are compared to the direct frequencies, as illustrated in Fig. 3.

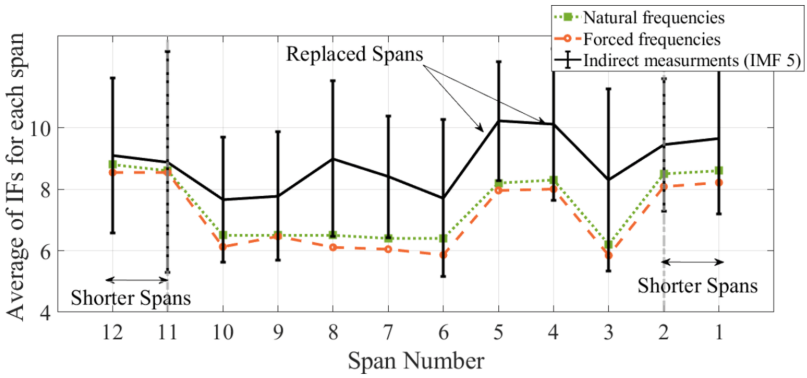


Fig. 3. Average IFs for each span (derived from IMF-5) in indirect measurements (in comparison to direct measurements)

This figure shows that the frequencies estimated using IMF-5 are highly spread around the mean value for all the spans, unlike the more consistent results seen in Fig. 2. This dispersion implies that the results derived from IMF-6 are more reliable compared to those from IMF-5. However, the IFs from IMF-5 estimates the fundamental frequencies of spans 11 and 12 with reasonable accuracy, while the results for spans 1 and 2 are still not acceptable. In summary, it can be inferred that a single IMF calculated from the proposed approach in this study can be used for estimating the fundamental frequencies of the spans with similar length when the spans with different stiffness values can be clearly detected. However, when span lengths differ significantly, the task becomes more complex, and in some instances, a different IMF may be needed to accurately capture the fundamental frequencies of such spans. Additionally, it is worth noting that certain IFs estimated through the HHT include edge effects at the beginning and end of the signals, which could introduce inaccuracies into the frequency estimation process, as observed in in Fig. 2 and Fig. 3.

4 Conclusion

This study conducts a field investigation into bridge health monitoring methods, comparing direct and indirect (drive-by) approaches for a multi-span viaduct. In 2009, two spans of the viaduct were replaced with more rigid beams following their collapse due to foundation scour. The research utilizes acceleration data collected from an instrumented train to estimate the first natural frequencies of each span in the viaduct and identify changes in stiffness within two of the twelve spans. To validate the results, direct measurements from sensors installed on the bridge are also employed. The estimation of frequencies in the indirect measurements is achieved through the EEMD-based HHT technique, which extracts natural frequencies by utilizing IFs obtained from calculated IMFs. Results show that the natural frequencies derived from indirect measurements closely align with the results obtained through direct measurements. Additionally, both sets of measurements exhibit a consistent pattern of frequency changes within spans of equal length. Furthermore, the results from forced vibrations (compared to free vibrations) are closer to the ones obtained from drive-by approach. This similarity can be attributed to the influence of the additional mass introduced by passing trains.

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A Vehicle-Based Sensing Approach for Network-Level Bridge Condition Monitoring

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Abstract. Transport networks rely on well-maintained physical infrastructure to allow them to operate efficiently. Bridges are particularly important, and the failure of a bridge can cause major disruption to the network. Current practices for inspection and monitoring of bridges are slow and expensive, meaning that it is not feasible to constantly monitor the vast quantities of bridges on a transport network. This paper proposes an approach which leverages data measured from in-vehicle sensors to monitor the condition of bridges, without requiring any sensors to be installed on the bridges. The proposed approach uses a machine learning algorithm to account for the influence of varying vehicle speed, and experimental tests show that changes in the structural behavior of a bridge can be detected from measurements taken on the passing vehicle. This approach represents a scalable solution for network-level bridge condition monitoring, which could be extended to account for the effects of various environmental or operational factors which may influence the measured vibrations in a full-scale scenario.

Keywords: Bridge Monitoring · Structural Health Monitoring · Drive-By · Machine Learning · Artificial Neural Network

1 Introduction

Transport networks play a critical role in the day-to-day movement of people and goods. Economic success is often closely linked to efficient, high-quality transport infrastructure [1]. In order for transportation networks to operate effectively and efficiently, the underlying infrastructure must be well-maintained and not subject to any significant deterioration or degradation which could impact the serviceability of the network. Bridges represent critical elements on transportation networks. As demonstrated by a number of recent bridge collapses [2], the failure of a bridge can have catastrophic consequences, and the transportation network is often left to operate at a significantly reduced capacity for the duration of the repair works.

For this reason, bridge inspection and monitoring represent a critical activity for transport operators [3]. Traditionally, there has been a strong dependence on visual-based inspection methods [4], however, these inspections are infrequent and can only

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identify defects which can be seen by the naked eye. In certain cases, where there is particular concern about a structure, sensors can be installed on the bridge to monitor its structural behavior, but these systems are expensive and require maintenance. Both visual inspections and direct structural health monitoring, despite having their benefits, are not suitable for ongoing condition monitoring of the overall bridge stock [5].

As such, there is a need for a cheap and scalable solution which can provide regular updates about the health of bridges across the network. 'Drive-by' bridge monitoring represents a potential solution to this challenge. Drive-by monitoring utilizes vehicle-based sensors to infer the condition of a bridge, based on measurements taken as the vehicle passes over it. Recent review papers provide a detailed overview of the latest developments in the field of drive-by bridge monitoring and the reader is referred to these references for more information [6, 7]. The developments have primarily focused on methods for detecting the dynamic properties of bridges, including natural frequencies [8], mode shapes [9, 10], and damping ratios [11]. Given that such properties are sensitive to damage, the ability to indirectly monitor these properties means that damage-related changes can be quickly identified allowing infrastructure owners to carry out further investigations.

Although there are clear benefits of using passing vehicles to infer the condition of bridges, there are still a number of technical challenges which must be overcome before this technology can feasibly be implemented at a large scale. One of the primary difficulties relates to the fact that the detected properties are often sensitive to environmental and operational factors, so observed changes may not always be related to damage. For example, it has been shown that the speed of the vehicle will cause a slight shift in the observed frequency [12]. Other factors, such as temperature, or the presence of additional vehicles on the bridge can also alter the measured frequency and could result in false indications of damage if their effects are not properly considered. This paper adopts a machine-learning approach to allow the influence of vehicle speed to be considered as part of the damage-detection process and the methodology is tested using laboratory experiments.

2 Machine Learning Approach for Drive-By Bridge Monitoring

The proposed algorithm leverages an Artificial Neural Network (ANN) to facilitate damage detection. The ANN includes an input layer with 2 input neurons, 2 hidden layers (each with 20 neurons), and an output layer with a single output. The two inputs are the vehicle speed and the x-intervals of frequency content of the axle response, and the output of the ANN is the predicted magnitude of each of the frequencies in the Fast Fourier Transform (FFT) spectrum of the acceleration response.

2.1 Detecting Bridge Damage

The ANN is trained using measured vibration data recorded during a number of passages of a vehicle across the bridge, while it is in an undamaged condition. The vehicle speed, along with the FFT of the measured vibrations, for each crossing, are used to train the ANN. Once the ANN has been trained, it can then be used to estimate the FFT spectrum

of the vehicle vibrations for a vehicle crossing at any given speed. The actual FFT spectrum can then be compared to that predicted by the ANN, and a damage indicator can be inferred from the prediction error.

The prediction error, pe_j, for each vehicle passage, j, is evaluated using Eq. (1), where $pred_i$ & y_i represent the predicted and actual frequency content for each frequency, i, in the FFT spectrum of the axle response, considering a total of n frequency samples in the portion of the spectrum being considered.

$$pe_j = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(pred_i - y_i\right)^2} \tag{1}$$

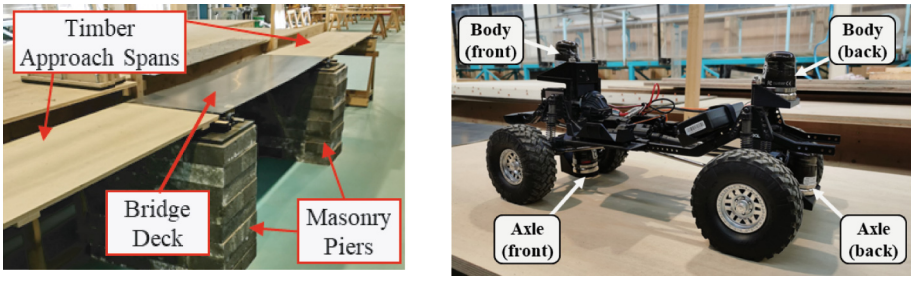
The prediction error is then converted into a Damage Indicator (DI) using Eq. (2) where μ_{tr} and σ_{tr} are the mean and standard deviations of the training errors, respectively. Standardizing the prediction errors in this way reduces the variation for the case when the bridge is in a healthy condition and means that the DI will be close to zero while the bridge is undamaged.

$$DI_j = \frac{pe_j - \mu_{tr}}{\sigma_{tr}} \tag{2}$$

3 Experimental Testing

3.1 Laboratory-Scale Vehicle-Bridge Interaction Model

A scaled vehicle-bridge interaction model was used to test the approach. The bridge model, shown in Fig. 1(a), consists of a 5 mm deep, 600 mm wide steel plate representing the bridge deck, with 6 no. steel angle beams (20 x 20 x 3 mm) bolted to the underside of the deck. The bridge deck spans 2 m between the supports, which were designed to allow simply-supported rotational behavior at each end. The vehicle was modelled using a commercially available remote-controlled Axial SCX10™ III Jeep, with accelerometers installed on both axles and on the body of the vehicle, as shown in Fig. 1(b). Corbally & Malekjafarian (2023) provide further detail on the design of the laboratory model.



(a) (b)

Fig. 1. Laboratory-scale model: (a) general overview of bridge and (b) vehicle model.

3.2 Simulating Bridge Damage

In order to simulate the effects of damage, masses were clamped either side of the bridge deck at midspan, as depicted in Fig. 2. This has the effect of reducing the natural frequency of the bridge, in a similar way to how cracking, or a loss of stiffness in the deck would reduce the natural frequency. The first damage case considered included 1 kg clamped either side of the deck at midspan (i.e. a total of 2 kg) and the second damage case included 2 kg clamped either side of the deck (i.e. a total of 4 kg). Given the total mass of the bridge, at 63 kg, these damage cases represented increases of 3% & 6% to the overall mass. The natural frequency of the bridge, prior to the addition of any mass, was recorded as 8.8 Hz, and the frequency for the damaged conditions were 8.6 Hz and 8.1 Hz, for the case of 2 kg and 4 kg added mass, respectively.



(a) (b)

Fig. 2. Clamping masses either side of the deck at midspan to change the dynamic behavior of the bridge: (a) general view and (b) view of mass clamped to deck.

4 Results

The vehicle was driven across the bridge, at varying speeds, a number of times in each damage condition. Initially, the vehicle was driven across the undamaged bridge 50 times and the FFT of the measured acceleration signal, recorded on the front axle, was evaluated for each vehicle passage and used to train the ANN to model the portion of the FFT spectrum between 7.5–9 Hz. This portion of the FFT spectrum was chosen as it was seen to contain a peak associated with the bridge fundamental frequency. Figure 3 shows the FFT spectra for two separate vehicle passages at different speeds, showing how the FFT can vary with speed, but also showing how the ANN, following training, can accurately estimate the FFT spectrum at each of these speeds.

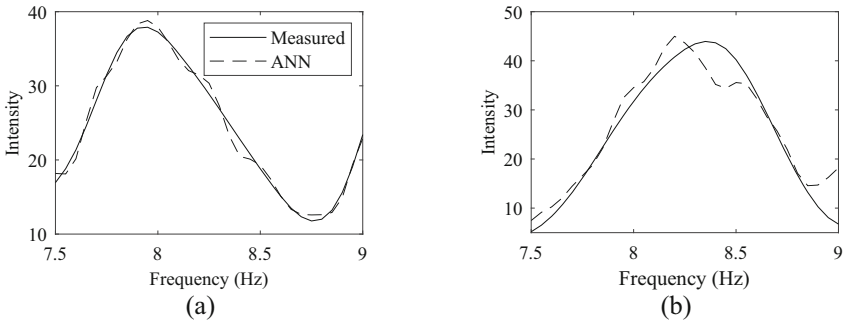


Fig. 3. Comparison of FFT spectrum from measured acceleration and that predicted by the ANN following training for vehicle passage at (a) 0.67 m/s and (b) 0.75 m/s.

Once the ANN had been trained, the vehicle was driven across the bridge an additional 45 times, 15 times in the undamaged condition, and 15 times in each of the two damaged conditions. A *DI* was evaluated, as per Eq. 2, for each vehicle passage based on the difference between the FFT from the measurements, and the FFT predicted by the ANN. Fig. 4 shows the results, with Fig. 4(a) showing the *DI* s for each vehicle passage, and Fig. 4(b) showing a box plot of the *DI* values for each of the 3 bridge conditions. The shaded boxes represent the interquartile range and the horizontal line within the box represents the median value. The whiskers extend to the most extreme values in the data, which are not considered to be outliers. It can be seen from Fig. 4 that the *DI* s are generally close to zero when the bridge is undamaged, but when the masses are clamped to the deck, there is an increase in the median values of the *DI* s. The case of 4 kgs clamped to the bridge has the largest *DI* values, as in this case the actual FFT spectrum deviates most significantly from the original condition from which the ANN has been trained. This demonstrates that the changes in structural response due to added mass can be captured using this method, when combining data from multiple vehicle passages at different speeds.

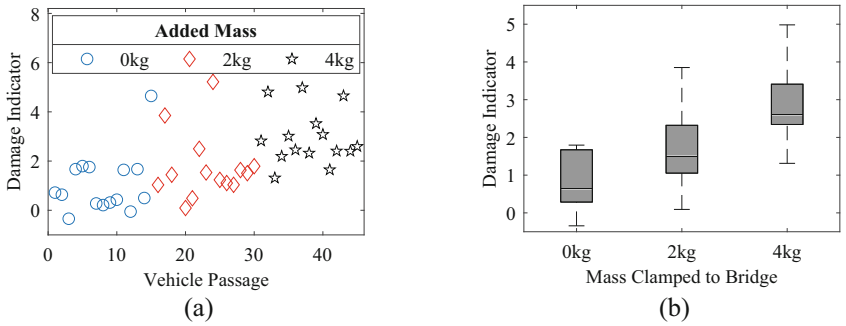


Fig. 4. Detecting masses clamped to the bridge (a) individual damage indicators and (b) box plots of damage indicators for each bridge condition.

5 Conclusions

This paper demonstrates an approach for monitoring changes in bridge condition using vibration measurements from a passing vehicle. The proposed algorithm leverages an Artificial Neural Network (ANN) to account for the influence of vehicle speed allowing damage-related changes to be identified from vehicle crossings at different speeds. An experimental verification of the approach demonstrates that the method can detect changes in the behavior of the bridge caused by additional mass being clamped to the deck. This machine-learning approach for drive-by bridge condition monitoring could be further expanded to consider the effect of various other operational and environmental factors which would influence the measurements in real life conditions and represents a potential solution for network-scale monitoring of bridges.

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Biobased Pavement: Lab Assessment of a Recycling Technique Without Petroleum Bitumen Addition in Irish Context

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Abstract. In the present paper, a lab technical study is proposed aiming at defining the recycling potential of Irish pavement materials using only a bio-material as added binder. The bio-binder used here is mainly made of a kraft paper industry residue, tall oil pitch by-products. It has been designed to replace totally conventional petroleum bitumen. In order to assess the applicability of this alternative solution, objectives are to understand: i) the rejuvenating effect of the bio-binder on the old bitumen, ii) the ageing behaviour of this particular blend, iii) the mechanical behavior of mixes made of reclaim asphalt and the bio-binder. This study shows, at lab scale, a very good ageing resistance of the bio-binder blended with old bitumen and good performances of the corresponding mixes. Hence, it is possible to recycle pavement materials without adding petroleum bitumen. The bio-binder used here could be used in the context of Irish pavement construction expecting a materials durability at least as good as conventional materials and a reduced carbon footprint.

Keywords: Bio-binder · recycling · Reclaimed Asphalt · rheology · pavement · sustainability

1 Introduction

There is growing pressure on the road industry to reduce its environmental impact. Utilization of materials from renewable biomass in asphalt production while increasing pavement recycling rate could present radical opportunities to reduce its negative impact on the environment. In this context, using a bio-binder as an alternative to petroleum bitumen could reduce the carbon footprint by storing renewable carbon for a long time.

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Meanwhile, increasing the use of reclaimed asphalt pavement (RAP) is a practical way to reduce fresh bitumen addition by taking advantage of the old remaining bitumen. It has already been proved, using a full scale accelerated tested, that it is possible to use a bio-binder in recycling technic [1]. The environmental benefit has also been assessed helped by a Life Cycle Analysis [2].

The general objective of the present study is to confirm that it is possible, in Irish context, to recycle old bituminous pavement materials using a bio-bitumen as added binder. More precisely this paper is dedicated to rheological properties of reclaimed bitumen (from Irish road materials) blended with a bio-binder produced by Eiffage company, named "Biophalt" and also assessment of the corresponding mixes (Fig. 1).



Fig. 1. Kraft paper industry residue, the tall oil pitch.

A first study has been carried out at the binder scale. Reclaimed bitumen has been extracted from RAP and blended, following several blending rates, with the bio-binder but also with a conventional bitumen for comparison. Blend properties has been assessed through rheological measurements. A second study has been carried out at mix scale. Mix design has been performed following Irish technical guidelines, by using the bio-binder and Irish materials: a fresh 40/60 petroleum bitumen, RAP and fresh aggregates. Three mixes have been designed. One with conventional bitumen and 30% of RAP, and two others with only the bio-binder incorporating respectively 30% and 40% of RAP.

2 Materials and Methods

2.1 Material

RAP 0/10, aggregates 10/20, 10/14, 6/10, 4/6, sand 0/4 and limestone filler were kindly provided by Breedon Group from the Rossmore-Lagan quarry, Binders used in this study and their properties are listed in Table 1. RA extraction procedure consist in the solubilization of bitumen from RAP in tetrachloroethylene followed by a distillation process in order to separate the old bitumen from the solvent.

2.2 Binder Blending and Ageing Procedure

The mass proportions of the bituminous blends are chosen according to mixture designs (see Sect. 2.4). Three binder blends are carried out accordingly (see Table 2). There are named: RAP32/REF68, RAP32/BIO68 and RAP47/BIO53. Blends are produced

Table 1. Naming and properties of studied binders

Sample number (réf. UGE)	Reference for the present paper	Material description	Penetration grade (1/10 mm) NF-EN-1426	Ring & Ball softening point (°C) NF-EN-1427
22026	RA	Reclaimed asphalt (4.97% of the RAP)	14	68.8
22048	BIO	Bio-binder Biophalt	158	73.2
22049	REF	Irish bitumen – 40/60 grade	55	52.6

by stirring at 130 °C for 15 min. Short (RTFOT) and long term (PAV) aging in lab is performed on blends according respectively to the standard NF EN 12607-1 and NF EN 14769.

Table 2. Blend proportion and ageing

Blend proportions	No ageing	RTFOT	RTFOT + PAV
RAP(47,5%)/BIO(52,5%)	RAP47/BIO53	/	/
RAP(31,8%)/BIO(68,1%)	RAP32/BIO68	RAP32/BIO68 - RTFOT	RAP32/BIO68 – RTFOT + PAV
RAP(31,1%)/REF(68,9%)	RAP32/REF68	RAP32/REF68 - RTFOT	RAP32/REF68 – RTFOT + PAV

2.3 Binder Rheological Measurement

Metravib device was used to characterize binder linear viscoelastic properties at seven frequencies, ranging from 1 to 80 Hz, at nine temperatures, varying from − 15 to 60 °C, in displacement control mode. The complex modulus test was conducted in tension-compression mode (E*) at low temperatures, from − 15 to 20 °C, and annular shear mode (G*) from 20 to 60 °C. The conversion from |G*| to |E*| is made assuming a Poisson's ratio of 0.5.

2.4 Mix Design

AC 20 dense bin 40/60 were targeted following Irish specifications [3]. Two recycling rates are considered: 30 and 40%. The composition of each mix is detailed in Table 4 (Table 3).

Table 3. Mix composition; En023-008 corresponds to aged EN022-295

	ENo22-166	ENo22-216	ENo22-295	ENo23-008 (Rilem)
Gravel 10/20 - Rossmore	22,2%	22,2%	22,0%	22,0%
Gravel 10/14 - Rossmore	10,0%	10,0%	10,0%	10,0%
Gravel 6/10 - Rossmore	10,0%	10,0%	10,0%	10,0%
Sand 0/4 - Rossmore	23,5%	23,5%	14,8%	14,8%
Limestone Filler - Rossmore	1,0%	1,0%	1,0%	1,0%
RAP 0/14 - Rossmore	30,0%	30,0%	40,0%	40,0%
REF	3,3%	0,0%	0,0%	0,0%
BIO	0,0%	3,3%	2,2%	2,2%
Total binder content	4,8%	4,8%	4,2%	4,2%

Mix made of 40% RAP and Biophalt as added binder has been subject to lab ageing following the RILEM protocol (4h at 135 °C and 5 days at 85 °C) [4]. These 4 mixes were evaluated according to the following tests: Compactibility (EN 12697-31) at 180 °C for the mix with bitumen 40/60 and 140 °C in case of mixes with the bio-binder; Water sensitivity (EN 12697–12 - Method A); Rutting test (EN 12697-22, – Large-size device) and Complex modulus tests (EN 12697–26, Annex C).

3 Results

3.1 Binder Properties

Figure 2 shows isochrones of complex modulus and phase angle for the RAP, REF, and BIO binders, for a loading frequency of 1Hz I. The bitumen recovered from reclaimed asphalt pavement shows the highest stiffness. Biophalt is less rigid in comparison to the others. The stiffness of the REF is somewhere between both binders. It means that a blend of Biophalt and RAP with appropriate proportions, could reach Irish bitumen stiffness level. Isochrones of complex modulus and phase angle, for binder blends before and after aging are shown on Fig. 3 and 4. Before ageing, RAP32/REF68 is largely stiffer than RAP32/BIO68 and RAP47/BIO53 (almost one decade above 40 °C). But it has to be noticed that there is tendency inversion regarding rheological properties of both type of blend, depending on the temperature. Indeed, above −5 °C, RAP32/REF68 is more elastic (higher phase angle) than RAP32/BIO68 and RAP47/BIO53 (as it can be seen on the Fig. 9) whereas the opposite behaviour is found below −5 °C. Some chemical species of the Biophalt appear to vitrify at relatively high temperature in comparison to conventional bitumen. Finally, phase angle curves show the effect of a polymeric network.

Indeed, above 25 °C phases angles stop to increase and remains around 70°. Even after ageing, blends with Biophalt remains softer than RAP32/REF68. But the main observation from these results is the outstanding stability of the blend incorporating Biophalt in comparison to the one with the reference bitumen, especially at high temperature. For both blends, stiffness increases and phase angle decreases with ageing (what is generally expected). But, for the blend incorporating Biophalt, there is an inversion of tendency above 25 °C. In this particular case, phase angle increases with ageing. This could be a consequence of the SBS polymer ageing (polymer networking effect decreases in this special case).

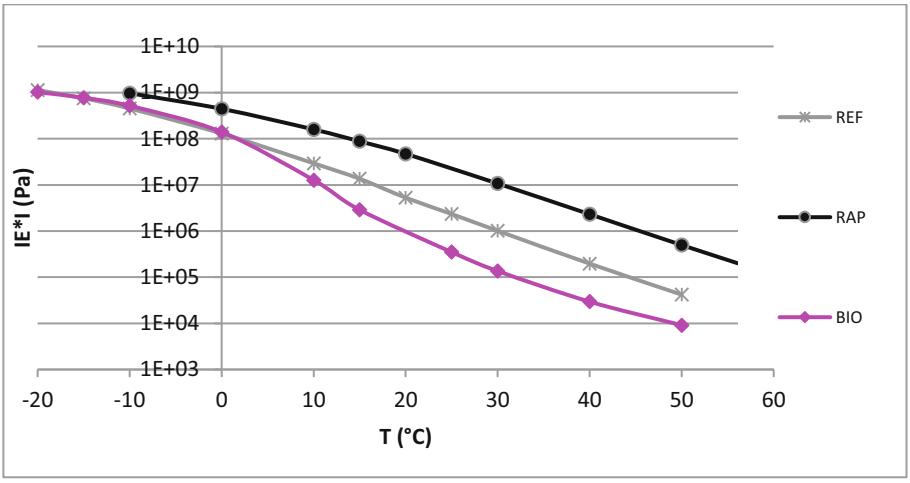


Fig. 2. Isochrones of complex modulus for binders

3.2 Mix Properties

Table 4 shows that ENo22–166, the reference mix with 30% RAP and 40/60 bitumen, meets the Irish specifications. EN022–216, the Biophalt equivalent mix is too soft and does not have the required mechanical properties. A solution, consisted in increasing the RAP content (and thus decreasing the quantity of Biophalt added) and adjusting slightly the grading curve, is successfully proposed: ENo22-295. ENo23-008 corresponds to EN022-295 aged according to the RILEM protocol (which have been designed to create RAP at lab scale). A stiffening effect is observed. This stiffening can be explained by an oxidized state of the binder. This mix behaves mechanically very well and suggests a further good recyclability. This last mix perform very well in comparison to the conventional mix. This result confirms what has been found at binder scale.

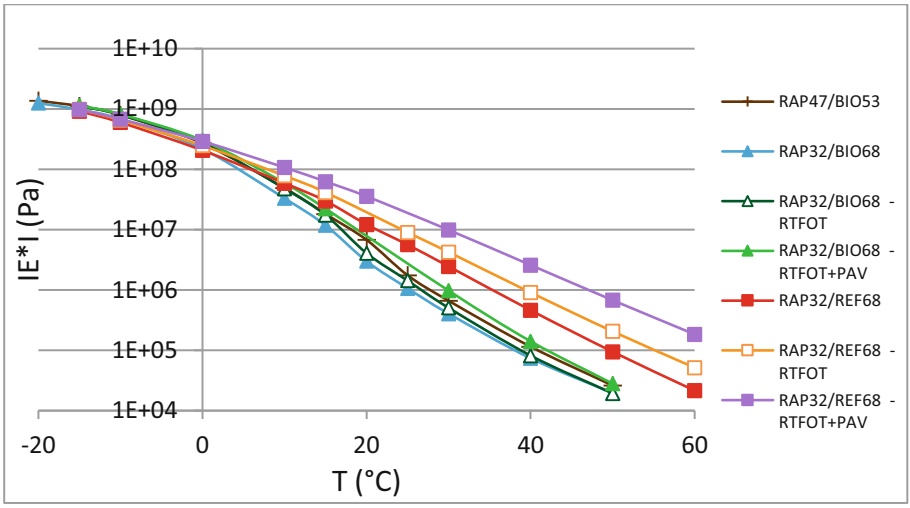


Fig. 3. Isochrones of complex modulus for binders

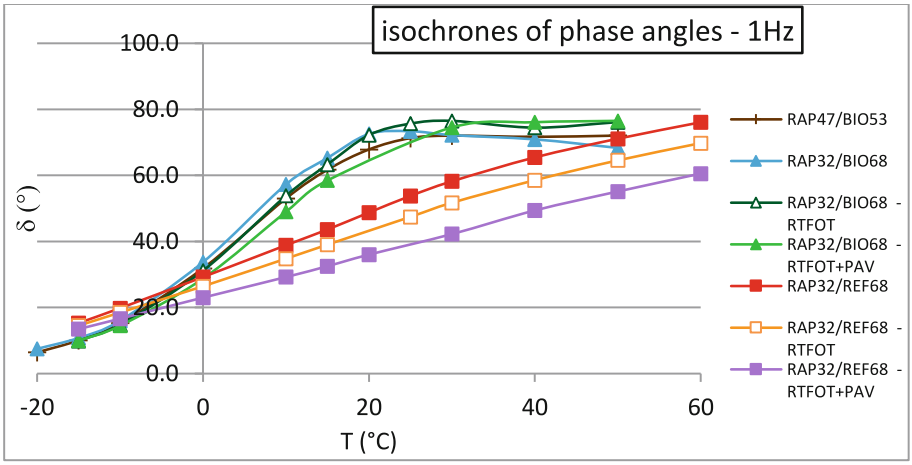


Fig. 4. Isochrones of phase angles for binders

Table 4. Mix properties

	AC 20 dense bin 40/60 spec	ENo22-166	ENo22-216	ENo22-295	ENo23-008 (Rilem)
MVRe (Mg/m3)		2.508	2.519	2.535	2.535

(*continued*)

Table 4. (*continued*)

	AC 20 dense bin 40/60 spec	ENo22-166	ENo22-216	ENo22-295	ENo23-008 (Rilem)
GPC V40g (%)	Vmin4,0 - Vmax7,0	4.7	4.2	5.3	6.9
Resistance to permanent deformation	WTSAir1,0 PRDAir9,0	WTSAir 0.08 PRDAir 3.3	Not measured	WTSAir 0.08 PRDAir 4.5	Not measured
	PLD 30 000 (%)	6.5	>>15	3.7	2.6
Water sensitivity	ITSd (kPa)	3 375	1 945	2 393	3 126
	ITSR70	91	89	85	81
Stiffness	E* - IT/CY 20 °C/124 ms (MPa)	6 500	Not measured	8 400	16 900

4 Conclusion

The possibility to recycle an old bituminous mix from Ireland using only a bio-binder as virgin bitumen has been assessed here. Linear viscoelastic properties of all binders show the high ageing state of the recovered binder and the particular rheological behaviour of the BIOPHALT which contains a strong polymer network.

Short (RTFOT) and long term (PAV) ageing has been applied on blends composed of: firstly, the recovered binder and the reference bitumen, secondly the recovered bitumen and the BIOPHALT. Blending proportions have been chosen according to the mix design. At high temperature measurements, above -5 °C, blend with BIOPHALT shows a very good resistance to ageing in comparison with the conventional blend. Below -5 °C, the opposite evolution is found regarding stiffness while phase angle of blend with BIOPHALT remains constant after ageing. Concerning mix performances, the present study show that it is necessary to add at less 40% of RAP in order to balance the softening effect of the bio-binder used here (BIOPHALT). Mix made of 40% of RAP and including only the BIOPHALT as added binder, performed very well considering the European specification framework.

Next step will be to build a test section with the materials assessed at lab scale and finally to monitor the evolution under traffic.

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Irish Rail Coastal Resilience and Their Response to a Changing Climate and Increased Coastal Erosion

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Abstract. The impacts of coastal erosion from Dublin to Wicklow are increasingly evident with beaches and cliffs being lost on an annual basis, threatening parts of the east coast railway line. This rate of coastal loss is projected to increase in line with sea level rise with the railway becoming more vulnerable to coastal hazards.

In 2017, Iarnród Éireann began to assess the locations along this railway line that are vulnerable to the effects of climate change and the anticipated increase in maintenance required. The outputs framed the current East Coast Railway Infrastructure Protection Projects (ECRIPP), which was established to deliver enhanced coastal protection to the existing railway infrastructure.

Iarnród Éireann and their multi-disciplinary consultant Jacobs, were tasked with creating resilience for these critical sections of rail line. A series of engineering measures to provide climate change resilience were identified. These measures were then reviewed by away of a bespoke multi-criteria analysis to identify those that were most effective to achieve resilience to the railway up to 2100. This paper outlines the process being led by Iarnród Éireann to protect this key sustainable public transport corridor from the effects of climate change in order to support future Greenhouse Gas Emissions reduction.

Keywords: Public Transport · Climate Resilience · Coastal Erosion

1 The Current Context

1.1 Introduction

Iarnród Éireann's Dublin to Wicklow rail line is a critical part of the rail network in Ireland, helping build a sustainable and connected city region, supporting the transition to a low carbon and climate resilient society; with southside DART, Gorey commuter and Rosslare Europort Intercity services operating along this scenic route (Fig. 1). In recent years Iarnród Éireann has seen an increase in the frequency of storm events as result of climate change. This necessitates more and more maintenance works to be carried out to respond to the effects of coastal erosion, wave overtopping and coastal flooding on the rail line and supporting infrastructure. These works result in increasing disruption to existing services and may render the line unviable in this area in the future.

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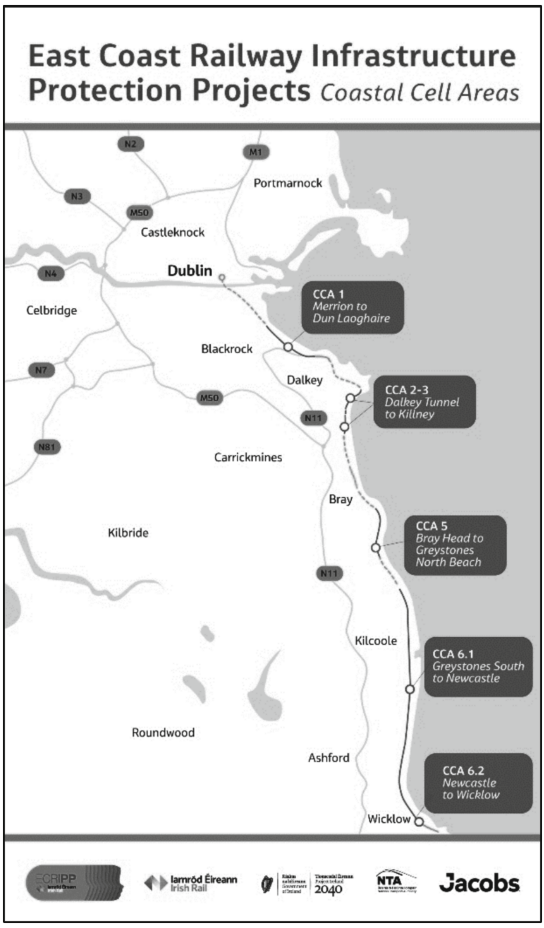


Fig. 1. Study area, showing the high vulnerability coastal cell areas under consideration

In 2017 Iarnród Éireann undertook a feasibility study to assess the anticipated increase in maintenance requirements for this area resulting from climate change. This study identified several key areas between Dublin and Wicklow where strategic intervention at this time would enable existing rail services to continue to operate with minimal disruption. The East Coast Railway Infrastructure Protection Projects (ECRIPP) was established to deliver the necessary enhanced coastal protection to the existing railway infrastructure in several key locations on this rail network.

The primary focus of this project is to address and implement protection of the existing railway and coastal infrastructure against the further effects of coastal erosion due to climate change in five key areas on the railway line between Dublin and Wicklow. These works will complement the delivery of the DART+ Coastal South Project, commuter rail services to Wicklow and the Rosslare Europort expansion.

This paper discusses how Iarnród Éireann has identified intervention sites, the impact of climate change on maintenance needs, data collection requirements for option development, and the creation of a bespoke multi-criteria analysis method. This method draws from the Common Appraisal Framework (CAP) and recent Transport Appraisal Framework (TAF) to support the selection of the emerging preferred options, recognising of the engineering, economic and environmental constraints and opportunities.

1.2 Existing Vulnerability

The East Coast railway opened from Dublin to Dun Laoghaire in 1837 and had extended to Bray and Wicklow by 1855. The selected route closely followed the coastline for ease of construction, but problems with coastal erosion and cliff instability were soon encountered, leading to rerouting of the railway inland at several locations between Ballybrack, Bray and Wicklow in the early twentieth Century.

Today, much of the railway continues to be protected by nineteenth Century coastal defences, and while safe to operate, there are periodic interruptions to services associated with wave overtopping in storms and cliff instability. Iarnród Éireann recognise that climate change will make these interruptions more frequent, and that coastal erosion may eventually threaten the railway, if allowed to proceed unchecked. Beach loss and coastal erosion are long-standing problems at several location on the east coast, largely due to net drift of beach sediment towards the north, with an absence of a replenishing supply from the south due to headland barriers. A proactive approach is therefore being taken to ensure long-term climate resilience of the railway.

Since the railway closely follows the coastline, it provides coastal protection to many communities that developed following the opening of the railway line. The railway also protects extensive lowland coastal habitats, many of which have national and international ecological designations. This not only means that building climate resilience has benefits to wider communities, but also that the selected engineering options must maintain or improve existing protected habitats.

The design horizon for the project is to the year 2100. This means that the coastal defences need to be designed to provide the required Standard of Protection (SoP) to 2100, incorporating an allowance for projected climate change over that period.

1.3 Coastal Cell Areas

The study area between Merrion and Wicklow has been split into six coastal cell areas (CCAs) that form discrete stretches of coastal railway. These sites have been identified by the Irish Coastal Protection Strategy Study (ICPSS) as being at particular risk from coastal erosion (OPW 2010) (Table 1, Fig. 1).

At Merrion (CCA1), the railway runs along a low nineteenth Century embankment that is constructed on intertidal deposits and occasional bedrock outcrops. The embankment is capped by a seawall that is periodically overtopped by storm waves. The base of the embankment is at risk of undercutting and the structure is vulnerable to sea-level rise.

South of Dalkey Tunnel at Killiney (CCA2/3), the railway runs on a bedrock bench with ravines that are crossed by masonry structures. A masonry retaining wall is present

Table 1. Characteristics of Coastal Cell Areas

Coastal Cell Area	Description
CCA 1 Merrion	Railway runs on low embankment forming shoreline of Dublin Bay
CCA 2/3 Dalkey Tunnel to Killiney Station	Cuttings and embankments, with spanning structures over rocky ravines
CCA 5 Bray Head to Greystones North Beach	Complex series of rock and soft sediment cuttings, tunnels, embankments and spanning structures that traverse the base of Bray Head
CCA 6.1 Greystones to Newcastle	Low embankment on barrier beach that fronts lowland marshes and tidal lagoons
CCA 6.2 Newcastle to Wicklow	Low embankment on barrier beach that fronts lowland marshes and tidal lagoons

on the landward side of the railway. Towards Killiney station, the railway runs on an embankment protected by a masonry seawall. These structures are all vulnerable to climate change. At Bray Head (CCA 5), the railway follows a heavily engineered route with rock cuttings, embankments, masonry spans and tunnels. Most of the rock cuttings are protected by netting and catch fences are present where rockfalls are most likely, but embankments and masonry structures below the line are all vulnerable to sea-level rise. At Greystones North Beach the railway runs through a tunnel, but recession of the cliffs, particularly where streams dissect the cliffs, may eventually threaten sections of the line.

From Greystones to Wicklow (CCA6.1 and 6.2), the railway runs on a low embankment at the back of the beach. This embankment was probably constructed on a natural gravel barrier that originally fronted lowland marshes and intertidal lagoons. However, land reclamation since construction of the railway has formed a series of freshwater lakes and marshes that support notified habitats. Beaches along this stretch of coast are locally depleted, requiring defences to be constructed to protect the railway. Given the low elevation of the railway and depleted beaches, this stretch of line is particularly vulnerable to coastal erosion and wave overtopping.

1.4 Climate Change Projections and Coastal Hazards

Climate resilience will be achieved by defining the coastal hazards anticipated up to the 2100 design timescale, and then designing environmentally-acceptable engineering measures to mitigate the hazards. In order to define the level of future coastal hazard, projected climate change needs to be understood. At open coast locations that dominate the study area the principal hazards will comprise sea-level rise and storminess.

The OPW has defined four future sea-level rise scenarios for the next 100 years, which are underpinned by the IPCC central projection for global sea-level rise of around 1 m in 100 years. Data indicates the impact of glacial isostatic land-level change on the Dublin to Wicklow coast is less than 0.5 mm/yr. (Bradley et al. 2011; Shoari Nejad et al.

2022), which means the sea-level rise projections are applicable over the assessment period and land-level change will not affect projections of seal level rise.

The project adopts the 1 m rise in sea-level future scenario to underpin climate change assessments to the year 2100. This scenario is similar to UK Environment Agency guidance for long-term planning at the coast.

In the absence of specific OPW guidance, projected increased storminess follows UK Environment Agency guidance by increasing the offshore wind speed and extreme wave height by 10% (Environment Agency 2022). Guidance from Met Éireann indicates that climate change will lead to changes in the seasonality of rainfall, with wetter autumn and winter periods and dryer springs and summers. Met Éireann predicts an increase in seasonal precipitation events of c. 20% during autumn and winter.

1.5 New Data

In the absence of national coastal monitoring data that records long-term changes in beach levels and erosion rates, the projects have commissioned a series of baseline surveys. Iarnród Éireann undertake comprehensive monitoring of the condition of their asset, but additional datasets are required to characterise the current resilience of the railway and to provide outline designs for engineering measures necessary to ensure future resilience. New data collected to support the study include:

- environmental surveys to document the ecology of the coastal frontage;
- an unpiloted aerial survey to capture high resolution images and a digital elevation model of the coastline and railway;
- a ground investigation, comprising intrusive boreholes and non-intrusive geophysical techniques;
- beach sediment samples to calibrate numerical models studies that support engineering options that include beach recharge; and,
- A bathymetric survey with sub-bottom profiler to provide information on seabed elevation.

In addition to collection of these primary data sets, the project has commissioned a series of studies to characterise current coastal processes and projected hazards that may threaten the railway by the year 2100. These have included a numerical modelling study describing present and future wave conditions, sediment transport potential and projected erosion or beaches; and an assessment of historical Ordnance Survey Ireland maps and aerial photographs to document the pattern and rate of cliff erosion over the past c. 150 years.

2 Engineering Options

In order for the railway between Merrion and Wicklow to be resilient to the effects climate change, the following processes that have potential to adversely affect safe operation need to be managed:

- Dilapidation of existing coastal structures eventually causing their failure. This may be caused by outflanking, toe scour or residual life being exceeded;

- Reduced standard of protection of existing defences due to sea-level rise. This will cause wave overtopping causing temporary flooding of the line;
- Coastal erosion and beach loss causing permanent loss or flooding of the line; and
- Cliff recession causing permanent loss of the line.

Coastal engineering measures that are suitable for ECRIPP include semi-natural or engineered options or combinations of both. All approaches have advantages and disadvantages that need to be reconciled against the need for a long-term standard of protection, limited maintenance and enhancement of habitats (Table 3).

3 Environmental Sensitivity

The five coastal cell areas (CCAs) are characterized by being highly environmentally sensitive with a range of constraints that need to be considered in the development of costal defence measures. (Table 2).

Table 2. Environmental Sensitivities

Coastal Cell Area	Environmental Sensitivities
CCA 1 Merrion	Dublin Bay Biosphere, European protected sites (SPAs and SACs), Nationally protected sites (pNHAs), Amenity and recreational sites, Protected views, Protected archaeological and architectural heritage sites
CCA 2/3 Dalkey Tunnel to Killiney Station	Nationally protected sites (pNHAs), European protected sites (in the vicinity), protected views, Amenity and recreational sites, Protected archaeological and architectural heritage sites
CCA 5 Bray Head to Greystones North Beach	European protected sites (SPAs and SACs), Nationally protected sites (pNHAs)
CCA 6.1 Greystones to Newcastle	European protected sites (SPAs and SACs), Nationally protected sites (pNHAs)
CCA 6.2 Newcastle to Wicklow	European protected sites (SPAs and SACs), Nationally protected sites (pNHAs)

In order to ensure environmental constraints are considered and that impacts on the receiving environment are minimized as far as possible, a number of steps were undertaken in order to inform the development of the Emerging Preferred Options (EPO) leading to the preferred option and these are as follows in line with best practice;

- A detailed assessment of environmental constraints for each CCA was undertaken;
- Environmental criteria were included in the MCA analysis;

- Consultation was undertaken with key stakeholders including; Wicklow Co. Co., Dun Laoghaire Rathdown Co. Co., Dublin City Co. and the National Parks and Wildlife Service (NPWS).

As identified in Table 3, the proposed measures for the coastal cells are within or close to European Protected Sites and as a result a key environmental consideration in the development of the EPOs is to avoid or minimize impacts on the qualifying interests of these sites. Environmental input was central to the early development of the options and this was driven by the key project objectives and the need for the project to move through the consenting process in an efficient manner. This is critical to ensure the delivery of the project on time to provide the requisite coastal protection.

Table 3. Advantages and disadvantages of engineering options

Coastal engineering option	Advantage	Disadvantage
Beach nourishment	Creates additional beach habitat Naturally adapts to sea-level rise and storms Low carbon	Performance predicted by imperfect numerical models. Large volumes of aggregate are needed involving dredging of seabed resources
Beach control measures, timber or rock groynes	Adaptable to revised sea-level projections Rock solutes require very limited maintenance	Timber designs require maintenance Rock designs require large volumes of suitable material
Concrete or rock revetment	Rock revetment is adaptable to revised sea-level projections. Requires limited maintenance Well-established, reliable option	High carbon implications of concrete, or need for large volumes of suitable rock Careful design to avoid toe scour Potential loss of shoreline habitat
Offshore breakwaters	Adaptable to revised sea-level projections No loss of shoreline habitats May provide offshore habitat	Expensive to construct Beach users may object

4 Option Development and Multi-criterion Analysis

A long list of coastal defence measures was developed, covering a full range of structural, non-structural options and nature-based coastal hazard solutions (Table 3). The long list of measures was then reduced to include only those measures that were technically feasible for the hazards present and that allowed the project to meet the project objectives of addressing and implementing protection of the existing railway and coastal infrastructure against the further effects of coastal erosion due to climate change to the year 2100.

The short list of technically feasible measures for each CCA were identified by combining sub-cell measures (long list measures on a sub-cell level) to form overall CCA Options. This process recognised that because of the complex range of hazards present along the railway and variation in coastal geomorphology between and within CCAs, no single option could be universally applied. These options were passed through the detailed MCA under Economy, Safety, Accessibility & Social Inclusion, Integration, Environment, Engineering/Technical and Planning Risk criteria. The leading three emerging preferred options (EPOs) from the MCA were then developed to concept level design before further analysis informed by consultation with the public key stakeholders to identify the preferred option for each coastal cell area. The assessment process leading to the preferred coastal protection measures for each CCA in summarized in Fig. 2.

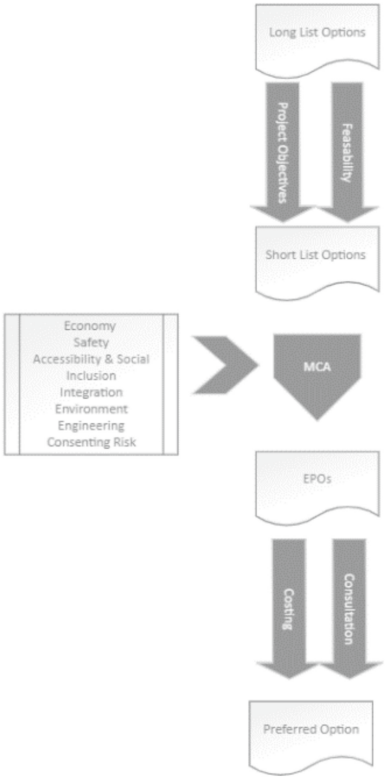


Fig. 2. Process to Preferred Option

As a Department of Transport funded project, ECRIPP's Multi-Criterion Analysis (MCA) methodology was aligned first with the CAF in accordance with the Public Spending Code (PSC). It was subsequently appraised against the recently introduced TAF, which replaced the CAF in 2023. The challenged faced by the project was that ECRIPP is a complex coastal protection study rather than a typical transport project and therefore a bespoke and combined transport/coastal appraisal methodology was needed

to support decision making whilst ensuring the outputs fit the needs of the new TAF requirements. The project team collaborated closely with stakeholders, together with specialists in coastal engineering, environmental issues and economics to develop the MCA methodology. The approach developed supports robust appraisal that is suitable to underpin the consenting regime in the future while recognizing economic, engineering and most evident environmental constraints.

5 Conclusions

The ECRIPP faced significant challenges in following government spending code guidance because it addresses climate resilience of infrastructure rather than new transport schemes. This necessitated development of a bespoke, combined transport/coastal appraisal methodology to support decision making whilst ensuring the outputs fit the needs of the new TAF requirements. The lesson-learnt was collaboration between a diverse project team, with environmental specialists embedded with coastal engineers, and close liaison with stakeholders and other specialists to create the MCA methodology.

This process has identified various risks early in the design process that can be mitigated through further design, engagement with stakeholders and collaboration with landowners.

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Quantitative and Qualitative Assessment of European Research and Innovation Initiatives in Transport Resilience

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Abstract. Transport resilience is fundamental for the functioning of society, as all human activities, such as commuting, recreation, and supply chains, depend on efficient transport systems. The COVID crisis has further emphasised the essential role of transport during global emergencies for the provision of necessary goods and emergency services. The European Union has recognised the importance of transport resilience and has outlined its significance in the Sustainable and Smart Mobility Strategy (European Commission, 2021). This strategy acknowledges the potential disruptions caused by climate change and extreme weather events and highlights the need for cybersecurity in the face of increasing automation and connectivity. Policy measures proposed in the strategy include the upgrading of physical and digital transport infrastructure to ensure continuity, multimodality, and interoperability between different modes. These measures aim to achieve the completion of the Trans-European Transport Network (TEN-T) and the establishment of a Single European Transport Area. In order to achieve these objectives, research and innovation play a crucial role.

The aim of this study is to provide a qualitative and quantitative assessment of relevant EU research and innovation initiatives, identifying key trends, challenges, and achievements. The study utilises data from the publicly available Transport Research and Innovation Monitoring and Information System (TRIMIS) database (https://trimis.ec.europa.eu), which contains information on over 8500 research projects, including approximately 2700 projects funded within the Horizon 2020 Framework Programme. A total of 50 EU-funded projects, including 37 funded within Horizon 2020, were selected for analysis. These projects offer a representative snapshot of recent and ongoing research in the field of transport resilience.

Keywords: transport resilience · cybersecurity · critical infrastructure · disruption · research and innovation

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1 Introduction

1.1 Overall Context

Transport is a cornerstone of all human activity, whether it be supply chains, commuting, or recreation. As recent crises have highlighted, the EU needs to be prepared and able to absorb disruptions of any kind in order to avoid long-lasting consequences for the economy and quality of life of its people.

The EU transport system will face challenges from climate events of increased intensity and other possible natural or human-made disruptions. Strengthening transport resilience is therefore one of the key pillars of the EU Sustainable and Smart Mobility Strategy.

Resilience for a transport system [1] refers to its ability to absorb disturbances, maintain its basic structure and function, and recover to a required level of service within an acceptable time and cost after being affected by disruptions.

EU research and innovation (R&I) plays a crucial role in studying the risks and proposing solutions through durable infrastructure and smart maintenance, schedule replanning, interoperability and flow redistribution between transport modes, and strategies for emergencies.

1.2 Policy Overview

The Sustainable and Smart Mobility Strategy [2] anticipates disruptions caused by climate change and extreme weather events. Furthermore, the need for cybersecurity is highlighted due to increasing automation and connectivity. To safeguard transport continuity, policy measures include upgrading physical and digital transport infrastructure to ensure multimodality and interoperability between different modes, as well as the completion of the Single European Transport Area, with an emphasis on the TEN-T network.

The European Commission Contingency Plan for Transport strengthens the resilience of EU transport in times of crisis. The plan proposes actions to guide the EU and its Member States. Some of these actions require technological developments and R&I, such as ensuring connectivity and passenger protection, efficient border management for freight, sharing transport information, building resilience to cyberattacks, and conducting resilience testing.

The European Climate Law (Regulation (EU) 2021/1119) includes stronger provisions on adaptation to climate change. Transport infrastructure must be adapted to climate change and made resilient to disasters, and the Commission is addressing this through both the TEN-T review and the Climate Adaptation Strategy, including dedicated guidance on climate proofing.

The Climate Adaptation Strategy highlights the need for smarter adaptation by improving knowledge and managing uncertainty, as well as converting available climate information into customised, user-friendly tools. Infrastructure investments must be climate resilient, to minimise the risk of disasters. Finally, climate-proofing standards are needed in the energy, transport, and construction sectors.

The European Union Agency for Cybersecurity (ENISA) Directives on Security of Network and Information Systems constitute a common baseline to enhance cyber-resilience in all activity domains, including transport.

Further strategic and policy documents detail how to achieve resilience objectives for each transport mode. All of the mentioned policy priorities require research and innovation for the development of transport resilience technologies, frameworks, certification, and monitoring.

1.3 Method

TRIMIS [3] has scanned its database of EU transport research and innovation projects to identify the challenges, opportunities, and main achievements in transport resilience. CINEA, the European Climate, Infrastructure, and Environment Executive Agency, manages most of these projects and contributes to EU research and innovation goals through the implementation of relevant EU funding programmes.

This paper provides an overview of recent and ongoing research and innovation activities and discusses what should be the next steps in EU resilience research and innovation, based on the Science for Policy report [4]. The dataset of selected projects is available in [5].

2 Findings

2.1 Role of Research and Innovation

In research and innovation (R&I), the European Framework Programmes address resilience both in a **transversal approach related to global risks** such as terrorism and cyberattacks, as well as the impacts of climate change, and as a **transport specific challenge**. In the latter, the focus is on climate-proof physical infrastructure, advancements in vehicle technologies, and digital infrastructure for increased automation. They also focus on promoting multi-modality across different modes of transportation and inter-modality across different operators. Lastly, they address resilience in aircrafts.

2.2 Research Efforts and Trends

For the analysis of R&I in Transport Resilience, 50 EU-funded projects were selected. These projects were categorised into seven thematic clusters. The majority of the projects were funded through the H2020 programme, but some projects from the FP7 programme were also included if deemed relevant. The 35 H2020 projects that were reviewed (Fig. 1), accounted for EUR 136 million of EU funding, out of a total budget of approximately EUR 145 million. Additionally, 15 FP7 projects were included in the analysis, accounting for EUR 41 million of funding. Overall, the total EU contribution in all analysed projects is EUR 186 million, with a total budget of EUR 215 million.

The majority of projects were funded under Research and Innovation Actions (RIA), with 21 projects falling under this category. RIA actions typically involve low technology readiness level (TRL) research, focusing on new topics and opportunities. A few

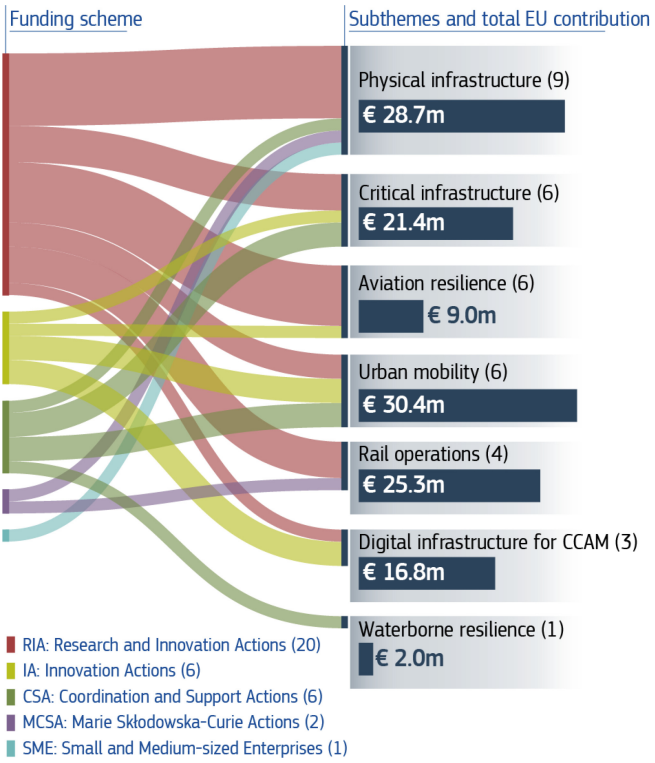


Fig. 1. H2020 transport resilience R&I effort repartition

projects funded under the Marie Skłodowska-Curie Actions (MSCA) were also examined, which correspond to basic research. Additionally, there were 6 projects funded under Coordination and Support Actions (CSA), which promote collaboration and knowledge management within the sector.

Lastly, there were projects funded under Innovation Actions (IA), which focus on solutions that are demonstrated in pilot deployments during the project. These projects mainly address the resilience of urban mobility and urban nodes, as well as the digital infrastructure for connected, cooperative, and automated mobility. These solutions are expected to be deployed in the coming years.

Overall, the most investigated area of resilience in the analysed projects is infrastructure resilience, particularly in the surface network, critical infrastructures, and digital infrastructure. There are 18 projects in this area, with an EU funding of EUR 69 million.

2.3 Research Trends

EU R&I projects address transport resilience at various levels and functions of transport systems. These levels and functions are interconnected and apply to multiple clusters presented in Fig. 1.

Operational resilience at the vehicle level, for aviation and waterborne transport, focuses on ensuring safe operations and mission achievement despite disruptions such as weather, malfunction, and traffic. In this sense resilience is very much related to safety, and is investigated through advanced cockpit and bridge design, pilot and crew navigation aids, and early warning and information systems. Knowledge and practices from aviation are also being transferred to waterborne transport to enhance resilience navigation and management and response to extreme weather events.

Planning and traffic management resilience, **at the node and network level**, is particularly important for aviation and rail transport. Disruptions at one node can lead to delays and cancellations propagating throughout the network. R&I projects are employing Artificial Intelligence (AI) to anticipate, identify, and predict disruptions and their impacts. Real-time planning and information systems that minimise impact and enable faster recovery are also being developed. For automated road transport, integrated traffic management is a significant focus area.

Surface physical infrastructure resilience is crucial for rail, waterborne, and road transport, considering the effects of aging, intensified use, and environmental damage. EU-funded projects are implementing advanced sensor and monitoring systems to assess the health of infrastructure. The aim is to achieve cost and time-efficient maintenance, warning systems, and flow redistribution. Efforts are also being made to enhance the operational resilience of inland waterborne transport in low-water level conditions.

Digital infrastructure resilience is essential in all transport domains due to the increasing automation and reliance on sensor and ICT operations. Robust communication, cloud computing, and human-machine interfaces are necessary for automated road and rail transport. Therefore, research and innovation efforts are directed towards developing robust telecommunications systems for integrated traffic management.

Rolling stock and fleet resilience is another key aspect, similar to infrastructure. Innovative solutions are being proposed to detect damage and monitor the health of vehicles. Predictive maintenance is expected to improve transport efficiency, safety, and resilience.

To address human-made threats, both physical and cyber, **to transport critical infrastructure and ICT infrastructure**, R&I actions focus on developing risk assessment and management frameworks, detection techniques, robust ICT systems, and reaction strategies. This ensures that transport systems can effectively respond to threats.

At the urban scale, resilience encompasses all modes of transport involved in urban mobility. Projects in this area focus on knowledge management, collaboration, and the development of resilience management frameworks. Monitoring the entire urban mobility transport system and flows is a critical aspect of resilience management.

3 Conclusions

Resilience is a major challenge for the EU transport system, considering the rise in complexity and interconnection in transport to address demand, efficiency, and sustainability objectives, as well as the potential increase in frequency and intensity of disruptions.

R&I projects are addressing different aspects of transport resilience. The solutions being examined range from technical to strategic, and there are common patterns across

all modes of transport. These common patterns include, for technical solutions, the use of detection and monitoring techniques, as well as the utilisation of ICT and AI as enablers for resilience management and timely reaction to disruptions. For strategic and tactical solutions, projects are developing resilience management and decision-making frameworks.

3.1 Way Forward

When it comes to transport resilience, R&I (Research and Innovation) can benefit from replicating practices from safety R&I. These practices include safe design, data-driven safety, virtual testing, and safety policy, such as using KPIs to measure progress and virtual certification.

Resilient design and certification should be a requirement for all modes of transport, vehicles, and infrastructure. This includes ensuring structural resilience, such as using materials that can withstand heat, and operational resilience with an increased envelope, such as designing vessels to operate during low water levels or batteries that can function during heatwaves. Additionally, passenger health and adequate thermal comfort should be considered in the design of passenger spaces to promote health preservation and prevent the spread of diseases. This is particularly important for achieving a modal shift towards mass transit following the COVID crisis.

Resilience virtual testing is crucial at the network and traffic system level, as conducting experimental studies on transport resilience is impractical. Simulation and virtual testing can be used to better prepare for disruptive events. By evaluating scenarios of disruptions and predicting system responses, resilience management measures can be developed to preserve and restore operation.

Data-driven resilience is another important aspect of transport resilience. Transport resilience can be quantified, and using key performance indicators (KPIs) to measure factors such as transport flows can help benchmark the extent of a disruption and the efficiency of the response. This can be a valuable tool for monitoring the implementation of resilience policies. Quantification and data acquisition contribute to a better understanding and operationalisation of resilience.

Cross-sector awareness and collaboration are essential to ensure coherence and overall resilience. Transport providers, policy makers, research institutions, and industry stakeholders should work together to incorporate resilience as a core requirement throughout the transport system, similar to the approach taken with safety.

Certain important aspects of transport resilience R&I should be further considered and incorporated into future work programmes. These include:

1. **EU strategic autonomy:** Research and policy aimed at increasing EU technology, industrial, material, and energy autonomy inherently improve transport resilience.
2. **System complexity:** While ICT can increase transport resilience by monitoring systems, detecting disruptions, and facilitating adaptation and response, the increasing interconnection of the transport system and dependence on automation and ICT technology also create vulnerabilities. It is therefore important for research and innovation to address resilience trade-offs.

3. **Modal shift:** Encouraging a modal shift towards active modes of transport and mass transit has a positive impact on transport resilience. It reduces material and energy demand, as well as road traffic and network complexity. However, achieving a robust and resilient public transport system will be challenging due to the increase in traffic.
4. **Workforce availability:** There is a decline in the availability of qualified transport personnel. R&I efforts in automation can partially address this challenge. Adequate training and human-machine interface design are necessary to safeguard transport resilience against overreliance and misuse of automation.

Overall, by considering these factors and incorporating them into future work programmes, transport resilience can be further strengthened and improved.

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A Programmatic Approach for the Delivery of Public Transport Policy in Ireland

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Abstract. Moving from plan to action seems a trivial affair. However, when vast resources are mobilised to deliver the transformation to sustainable mobility this is not so trivial. The Government of the Republic of Ireland is currently investing around €165 billion for infrastructure development over the next 10 years, with more than 20 percent allocated to the transport sector. Key policies provide the ambition and direction for such mobilisation: the National Sustainable Mobility policy (NSMP) and the National Investment Framework for Transport in Ireland (NIFTI). In addition the Infrastructure Guidelines (IG) provides the rules of approvals in the public sector to ensure value for money. From all this, a number of programmes and projects to deliver such policies emerged, such as BusConnects, Metrolink, DART+, and Active Travel programme to name a few. This paper delves into the literature of project management and institutional economics, and presents the case study of the National Transport Authority in Ireland to assess determinants affecting the degree of effectiveness in its delivery. Using an adapted PESTEL analysis, we conducted interviews to selected experts to determine the likelihood of such determinants. Lessons learned offer insights to policy makers and managers of public transport programmes elsewhere.

Keywords: Transport Policy · Programmatic Approach · Transformation · Sustainable Mobility · Institutional Economics

1 Introduction

At the end of 2015, Ireland signed the Paris Agreement signaling its commitment towards the climate agenda. Subsequently, a recalibration of its policies took place. In 2021 the Government of Ireland launched its revised National Development Plan becoming its greenest and most ambitious plan to date. The investment amounts €165 billion for infrastructure development over the next 10 years, with more than 20 percent allocated to the transport sector. This investment - at 5 percent of its national income- is well above the recent EU average of 3 percent. With these resources it is important to delve into the determinants of the speed of transformation to sustainable mobility.

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This paper explores the likelihood of determinants affecting the transformation to sustainable mobility with emphasis on institutions and a programmatic approach to investment. An adapted Political, Economic, Social, Technological, Environmental, and Legal (PESTEL) analysis is used to systematically gather expert opinions with a survey.

Section two delves into the literatures of project management and institutional economics. Section three presents the case of the Irish transport policy and its institutional setting. Section four reports the results of the survey and discusses policy implications. Conclusions are presented in the end.

2 Literature Review

2.1 Project Management

There is a rich literature in project management. However, exploration in detail of the technical aspects of managing public capital projects and programmes in Ireland has been more limited. While broad overviews of capital expenditure and potential outcomes are important, evaluation of the effectiveness of governance and technical management capability are critical to ensuring value for money on the public purse.

There is also growing interest on appraisal and investment management guidance for Irish public capital projects to address environmental impacts and increase the delivery rate of public investments. The Infrastructure Guidelines (IG), formerly known as Public Spending Code (PSC) introduced in 2013, as a decision making system based on project management principles, provides a set of rules and procedures to ensure that the right solution is chosen. A 2023 OECD report [1] examining Irish appraisal guidance in the updated version of the PSC in 2019 noted the opportunity to strengthen project appraisal guidance and improve the rate of delivery of public capital investments, through the use of investment programmes. In addition, Connolly and Newman [2] examined the potential additional appraisal and management guidance that would need to be put in place to ensure effective use of public finances under a programmatic approach. One of the recommendations is including the provision of a basic definition of a programme and proportionate levels of appraisal. However, a number of challenges regarding the use of programmes was also noted, including the potential approval process across a development lifecycle with multiple challenge and approval points.

2.2 New Institutional Economics

The New Institutional Economics helps to understand how the "rules of the game" affect the transformation required to sustainable mobility. Following Peterson St Laurent et al. [3] a spectrum can be considered to depict the Public Transport (PT) resistance-resilience transformation spectrum from active resistance to accelerated transformation. Many barriers slowdown this transformation. The New Institutional Economic school of thought is useful to articulate these challenges, see Fig. 1.

Williamson identifies four levels, where change happens at different paces. Level 1 is the slowest, termed 'embeddedness' where traditional practices, cultural norms, language and behaviour is shaped by a set of unique historic factors. The second level, the

	Theory		Timeline (Years)	Core Focus	Significance in context of accelerating transformation to sustainable mobility
Level 1: Embeddedness	**Social Theory**	Slow Change ↓ Continuous Change	100 to 1,000	Informal Institutions such as customs, traditions and norms	Looking back at how a society travelled is important, in terms of how far people travelled, the freedom and constraints they faced, and what modes were taken. Recognition that there is resistance to institutional change, even informal institutions.
Level 2: Institutional Environment	**Economics of Property Rights and Political Theory**		10-100	Spatial planning and what is permissible at a local level. E.g. National Planning Framework	Project management and PT delivery within planning framework (Rights and Responsibilities) and governance framework, such as the Public Spending Code.
Level 3: Institutional Arrangement	**Contract Theory**		1-10	Governance of contracts which implies certainty or 'lock in' of process for the duration of a business contract	There can be tension between demands placed on delivering PT through accelerated transformative processes and due process through legally binding contracts. Requires the governance of contracts for maximum efficiency, particularly given that PT networks take longer than 10 years to plan and deliver.
Level 4: Resource Allocation	**Economic 'market' theory and invisible hand for efficiencies and resource allocation**		Continuous	Use of big data, real time information, and digital products to overcome transport inefficiencies	Global financial and capital market processes are instantaneous, having an impact on resource availability, prices, innovation and technology in PT systems. Intersection of markets and the 'real economy' which includes the physicality of transport networks.

Fig. 1. Differing timeframes in Economics of Institutions. Source: Adapted from Williamson [4]

'institutional environment' relates to the set of formal rules and legislation in operation at any particular time. The third level relates to the institutional arrangement or the shorter-term contracts that firms and entities enter. The fourth level is the fastest paced level of resource allocation, or what happens within 'the market'. Adam Smith's invisible hand and Schumpeter's creative destruction processes are increasingly relevant for the provisioning of PT. The pace of technological change and digitalisation is transforming so many aspects of how the economy and society operates. PT providers are technology takers at this level, and need to keep apace of innovation that impact services.

There are processes operating at all of the four levels with differing durations. Programmes offer the opportunity to overcome the tyranny of time, and the shorter timescales associated with contract theory. Programmes offer longevity, but not the instantaneous of transactions in markets, which is where accelerated transformation could conceivably happen.

3 The Case of the Irish Transport Policy Delivery

3.1 The National Transport Authority Capital Programme

The National Transport Authority (NTA) in Ireland is the public body responsible for developing and implementing public transport strategies around the country. With an annual budget of nearly €1 billion, some of the NTA flagship programmes are **BusConnects** which is an overhaul of the Public Bus Systems in the major cities; the expansion of the electric rail system known as Dublin Area Rapid Transit (**DART+**); **Metrolink**, which is the first metro line in the country; the **Active Travel** Programme with an ambitious plan to build walking and cycling infrastructure throughout the country, and **Connecting Ireland** Programme focusing on rural areas.

3.2 The National Policy and Institutional Framework

Whereas the National Sustainable Mobility Policy (NSMP) and the National Investment Framework for Transport in Ireland (NIFTI) are the key policies that provide the ambition for the transformation to sustainable mobility, the IG facilitates the appraisal, monitoring, management and delivery of public investment to ensure effectiveness and value for money. The IG has seen improvements from lessons learned in major projects, such as the PWC report [5] on the National Children's Hospital which highlighted deficiencies in the 2013 edition of the PSC including upfront appraisal of costs and the challenge function within the approval process. Nowadays, it takes about one year for a typical project to go throughout the IG process to reach final approval. This is coming down from 1.5 years duration that the IG process used to take prior to recent reforms. Despite these improvements, some limitations remain. For instance, the lack of guidance on programmatic approach to optimize processing times.

Another Important element to bear in mind is the structure of the planning system in the country. Although the national government has control over National Plans and Strategies, such as the National Planning Framework and Metropolitan Area Transport Strategies, it has little control over the efficiency of instances where plans can be overthrown. For instance, An Bord Pleanála as the independent, statutory, quasi-judicial body that decides on appeals from planning decisions made by local authorities have been embroiled in recent scandals undermining its credibility. This creates delays in their resolutions with knock on effects to the delivery of infrastructure, including public transport. In addition, there is a surge of judicial reviews against An Bord Pleanála's resolutions adding extra time in the overall approval process [6]. These deficiencies in the planning system are compounded to the increasing occurrence of NIMBYism (Not-In-My-Back-Yard), which is the behaviour of someone who does not want something to be built or done near where they live.

All this institutional setting operates under the context of two major crises. First a housing crisis where the commuting patterns are distorted and with ramifications on transport demand, congestions, and implications on the design of public transport infrastructure, and network transport effects. And second, a construction sector decimated in the aftermath of the 2008 economic crisis unable to meet the infrastructure demand.

Finally, it is important to consider the private sector participation in the public transport provision. There is a variety of Public Transport operators either State-owned, State-Tendered, or Privately-owned. It is the State-owned Transport Operators who dominate in the area of mass transportation.

4 Results and Policy Implications

An adapted PESTEL analysis enabled a survey[1] to gather the opinion of experts on the likelihood of determinants affecting the transformation to sustainable mobility in Ireland. PESTEL factors were identified and categorized in terms of the aspects of change in Economics of institutions. Given the narrow scope of this research, a dozen

[1] At the time of the survey application in October 2023, the Public Spending Code was the current referent. The Infrastructure Guidelines were published in December 2023.

of experts were targeted given their first-hand knowledge on the topic. The collection of responses was anonymized to increase the response rate and to give freedom of opinion. The results are shown in Table 1.

Table 1. Determinants' likelihood affecting transformation to sustainable mobility.

Aspect for change	Factor	Very Unlikely	Unlikely	Neither likely nor unlikely	Likely	Very likely	No Answer
Level 1: Embeddedness	NIMBYism (Social)				30%	70%	
	Housing Crisis (Social)				30%	70%	
Level 2: Institutional Environment	Anti-climate political party (Political)	30%	20%	10%	40%		
	Long PSC approval times (Technological)		10%	20%	30%	30%	10%
	Planning system (Legal)		10%	10%	20%	60%	
Level 3: Institutional arrangement	Budget reduction (Political)	10%	30%		40%	10%	10%
	More PPPs (Economic)		20%	50%		10%	20%
	Construction sector low capacity (Economic)	10%			40%	40%	10%
Level 4: Resource Allocation	Greater Private sector participation (Economic)	30%	10%	20%	10%	20%	10%
	Public Transport Operators stay technology takers and not innovators (Technological)	60%	10%	20%			10%

(*continued*)

Table 1. (*continued*)

Aspect for change	Factor	Very Unlikely	Unlikely	Neither likely nor unlikely	Likely	Very likely	No Answer
	Current rate of progress - Not meeting Climate Targets (Environmental)				10%	90%	

The collective judgement identifies NIMBYism and the current Housing Crisis as significant threats to the transformation to sustainable mobility. Other two determinants worth to observe are the planning system and the technological capabilities of the PT operators. In the view of most respondents An Bord Pleanála's underperformance and the increase of judicial reviews pose a significant risk to the transformation to sustainable mobility. The implication of PT operators being technology takers without innovative capacity is that it undermines the ambition of Ireland to become a global leader in public transport provision and sustainable mobility. For the rest of determinants under investigation the results are inconclusive as no consensus was detected.

In terms of the programmatic approach, the majority of respondents (60%) stated that a programme level would facilitate a swiftly IG approval process rather than at a project level. However, there are nuances to this consideration. The 'right' level needs to be considered for the various projects in question and a decision made as to where their value is in aggregating them into a programme. As a respondent stated: "*Some projects may be able to proceed perfectly well at a project level. However, focusing on project level misses the big picture (transport strategies need to be combinations of numerous projects and incentives. Some of these may not have a good BCR* [Benefit Cost Ratio] *at a project level, however it is the programme/ strategy level that is important). If individual projects are rejected for poor economic performance then this puts the entire strategy at risk*." Another respondent was more audacious and hinted to the need of a transport programme for climate change in order to achieve transformation at national level rather than with incremental projects. The collective opinion is that at the current rate of progress, it is unlikely that climate targets will be met. Therefore, more and better needs to be done.

5 Conclusions

This paper contributes to the literature of transport economics by using a PESTEL analysis adapted to the differing timeframes in the economics of institutions to assess the likelihood of determinants affecting the speed of transformation to sustainable mobility.

The results point to a high degree of experts' agreement on the likelihood of clear threats to the transformation to sustainable mobility in Ireland: NIMBYism, Housing

Crisis, the planning legal system underperformance, and the poor technological capabilities of PT operators. There recently published Infrastructure Guidelines seem an improvement of the programmatic approach in the right direction. Overall, the literature on the technical management and appraisal aspects of Irish public capital investments and projects remains limited. Noting this, there are widespread opportunities to explore potential improvements.

Future research avenues emerge. Without diminishing the validity of the results presented in this paper, there is an opportunity to apply the survey to a wider range of stakeholders, such as politicians, private sector, PT operators, and civil society. There is also the possibility to delve into cultural norms and how long these take to change. Cultural norms around driving, speed limits, driving in rural areas, cycling, status of car ownership, perceptions of use of public transport. There are a lot of cultural norms that need to be unpicked for the transformational change.

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How do Geopolitical Risks Affect Ship Investment Decisions?

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Abstract. Keeping in mind the severe effect of the recent Russo-Ukrainian war on the global economy, our study aims to address the following research questions: What is the impact of geopolitical risk (GPR) on new ship investments in bulk markets? Are ship-owners more anxious about threats or acts related to geopolitical risk? Does the impact of GPR on newbuilding orders depend on the state of the freight market? For this purpose, we use a GPR index and apply quantitative analysis. We divide our examined time series into distinctive periods based on the behavior of the Baltic Dry Index (BDI), with the breaking point being the financial crisis. We then examine the nature of causality between new orders of bulkers and the GPR index.

Our findings are valuable for the scientific community and practitioners, as they highlight the importance of GPR for the maritime industry and contribute to more holistic and informed decision-making. Overall, our findings can contribute to more resilient strategies in the maritime sector.

Keywords: Geopolitical risks · Granger causality · Ship investments

1 Introduction

Geopolitical risk (GPR) is defined as "the risk associated with wars, terrorist acts, and tensions between states affecting the normal and peaceful course of international relations" (Caldara and Iacoviello, 2018). The international nature of maritime transport makes this sector susceptible to such risks. While geopolitical events are difficult to predict and do not occur frequently, though they may cause serious disruption to certain trades.

Geopolitical risk (GPR) is a factor of instability for the international economy. Its impact on seaborne trade and the maritime supply chain is considered severe, and it is difficult to be predicted and handled from policymakers. Freight rates, port traffic, and connectivity among ports are documented to be vulnerable to spikes of geopolitical risk (Khan et al., 2021; Georgoulas et al., 2022). For some sectors of maritime shipping, only the threats associated with terrorism are enough to cause long-term or even permanent changes. For others, GPR acts are not able to stop their upward march.

The impact of GPR on maritime freight rates is well documented in the literature (Drobetz et al., 2013), but there is scarce research on how GPR affects ship investment decisions. This study aspires to make a first step towards filling this gap in the literature.

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2 Literature Review

The maritime literature includes direct and indirect discussions of several aspects of the impact of GPR on ship investment decisions. A group of studies provided evidence that geopolitical risks are implicated with the ability of shipping companies to raise external capital. Homan (2006) indicated that terrorist attacks and security risks heighten the shipping firms' cost of raising capital for shipping firms. This translates into lower liquidity for ship investments. In this regard, it is noteworthy that ship-owning companies are heavily reliant on debt financing, having a higher debt-to-asset ratio than companies in other industries (Syriopoulos and Tsatsaronis 2011; Drobetz et al. 2013). Syriopoulos and Bakos (2019) also pointed out that political and geopolitical events have a significant influence on strategic financing decisions. In addition, several studies show that when GPR rises, dry bulk and containership companies tend to increase their cash reserves, reducing their investment activity Kotcharina and Maneenopb (2020a,b).

The effect of the GPR may also be reflected in the reduction of company value. This is particularly evident in companies involved in transportation, as they are exposed to disruption in supply chain networks (Hendricks and Singhal, 2005). This reduction in company value creates difficulties in raising capital and making new investments.

Another aspect of the impact of GPR pertains to the operating costs. Higher geopolitical risks in commercial areas often lead to rising oil prices while they also cause disruption to established trades. All in all, it emerges that GPR is associated with financial management decisions, as it may affect the costs of shipping companies Kotcharina and Maneenopb (2020b). Therefore, it may also be taken into consideration in ship investment decisions.

3 Data set

Geopolitical risk index was the basic variable that we utilized in our analysis. It captures the global geopolitical risk which is transmitted through newspapers. Its construction method is textual analysis. There are also two subcategories that contribute to the GPR index: The GPR Acts (GA) which refers only to acts related to geopolitical risk and GPR Threats (GT) which is eliminated in portraying threats regarding military and nuclear sectors. The data were downloaded from www.policyuncertainty.com and covered the period from January 1999 until September 2020 on monthly basis.

The orders of bulk ships which were the main variable of our research covered the same period. The data were downloaded from Clarksons' database. For this study, this variable is represented as ORD.

4 Methodology

For examining how the geopolitical risk affects the willingness for ship construction, we divided our examined times series into two groups based on the state of the freight bulk market. We selected as a breaking point the end of the collapse phase of the market, namely December 2008. Therefore, the first period presents high peaks and intense volatility and referred to January 1999 until December 2008. The second period is

characterized by smoother changes in the level of seaborne trade and regards the interval January 2009–September 2020. Our two selected time periods are in line with the work of previous researchers who demonstrated that the level of Baltic Dry Index (BDI) is distributed differently (Tsioumas et al., 2021). The variables that are referred to the first period are symbolized with 1 in the end, and the ones referred to the second one with 2.

The two groups of variables were studied separately. For the identification of causality among the examined variables, we started our analysis by conducting stationary test (Kwiatkowski et al., 1992). In the continuation, we applied Johansen test for the investigation of existence of long-term relations (Engle and Granger, 1987). The results of the aforementioned tests provided us with the necessary information to conduct Toda-Yamamoto causality tests (Toda and Yamamoto, 1995). Fundamental prerequisite of the test is to formulate a Vector Autoregressive model (VAR). We based our decision for the selection of lag for the VAR model on the Akaike information criterion (AIC), Final prediction error (FPE), Bayesian Information Criterion (BIC), and Hannan-Quinn (HQC) criteria. All the models were also examined for heteroscedasticity and autocorrelation in residuals using Breuch Pagan and Durbin-Watson tests respectively.

For the visualization of how GPR, GA and GT impact on ship orders, we used the Impulse response function (IRF).

5 Results

5.1 Statistical Analysis

In both periods all the time series are non-normally distributed according to the Jarque-Bera test. It is observed that the geopolitical risk is more intense in the first period with higher average values, while in the second period more orders of bulk ships were taken place on average.

The KPSS stationarity tests show that all risk variables of the first period are stationary in their original form, while Ship Orders of the first period are I(3). All the time series of the second period are stationary in first difference.

In the second period the existence of cointegration was indicated by the Johansen test for all the pairs. The time series of the first period were not examined for long-term relations due to ORD1 being I(3).

5.2 Causality Test

The existence of variables which were stationary in third difference, was a decisive factor for the causality method that we applied. The Wald test examines the causality of all pairs independently of their stationarity (Table 1).

GA and GPR are able to affect the level of shipping orders only in the second period according to the Toda-Yamamoto test. The direction of the causality is unidirectional. Surprisingly, the average impact of GPR is on average lower in the second period than in the first.

The models for the application of Wald test were free of serial correlation in residuals. However, the majority of the models suffered from heteroscedasticity in residuals.

Table 1. Causality test

PAIR	ORD1-GPR1	ORD1-GT1	ORD1-G1	ORD2-GPR2	ORD2-GT2	ORD2-GR2
P-Values	0.97/ 0.71	0.91/ 0.45	0.89/ 0.87	0.10***/ 0.35	0.49/ 0.13	0.04**/0.57
Selected lag	2 + 3	2 + 3	2 + 3	3 + 1	3 + 1	3 + 1
Residual Heter.	0.00/ 0.99	0.00/ 0.16	0.00/ 0.99	0.00/ 0.00	0.00/ 0.00	0.00/ 0.00
Residual Serial Cor.	1.98/ 1.99	1.97/ 1.97	1.98/ 1.99	2.03/ 2.02	2.02/ 2.00	2.04/ 2.02
R Squared	0.99 /0.60	0.99/ 0.63	0.99/ 0.60	0.99/ 0.24	0.99/ 0.24	0.99/ 0.44

Notes: *,**,*** Indicates rejection of null hypothesis at 1%, 5%,10% significance level respectively.H_0: Absence of Causality between examined variables. Breuch Pagan H_0: Existence of Homoscedasticity in the residuals. The first P value is referred to possibility of risk causing orders and the second to reversed causality.

5.3 Impulse Response Function (IRF)

In order to depict the nature of geopolitical risk impact on ship orders, we utilized the IRF. The results were the anticipated ones. Both GPR2 and GA2 have a negative effect on the orders. Their impact is noticeable after the second month. Its permanent nature resembles the effect of GT on the world total goods discharged and loaded (Georgoulas et al., 2022). The reaction of ORD2 is depicted in the following graphs (Figs. 1 and 2).

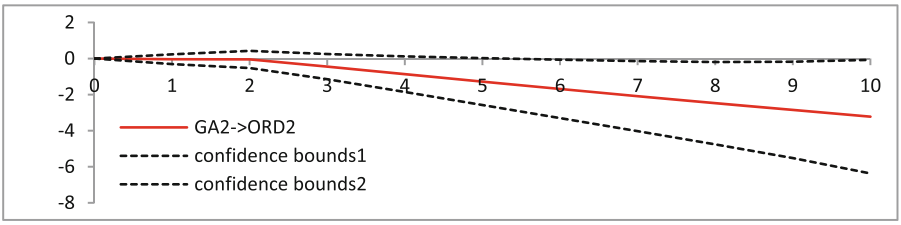


Fig. 1. Impulse response function due to GA2

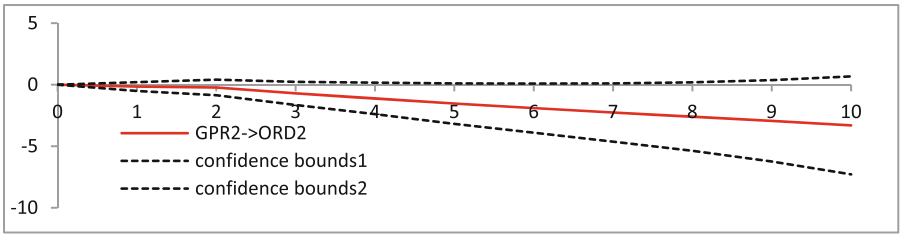


Fig. 2. Impulse response function due to GPR2

6 Conclusions

In this study, we attempt to scrutinize the relation between new orders of bulk ships and geopolitical risk. More specifically, we focused on how and under what circumstances geopolitical risk may affect ship building decisions.

Utilizing Wald tests and IRF we were able to conclude that newbuilding orders are sensitive to GPR Acts. A shock in GPR and especially in GA can induce a decline in the level of ships being built. Therefore, we provide new insights into the impact of GPR on the economy.

The state of the market plays a vital role in the effect of GPR. When the bulk market is dominated by high volatility, GPR has no influence on the decision to order a new ship. The smoother the freight market, the more sensitive to the geopolitical risks.

Considering that ship orders reflect positive expectations of ship-owner about the future state of the freight-rate market (Papapostolou et al., 2014), our findings provide some clues about the impact of GPR on market sentiment.

Besides the academic contribution, our study may support ship investment and ship financing decisions, suggesting that GPR should be taken into consideration. The incorporation of GPR factors into the decision-making process financial losses and enhance the industry's long-term sustainability.

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Stakeholders' Insights for Development of a Decision Support System (DSS) to Foster Resiliency of Greek Ports Against Climate Change

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Abstract. Maritime ports are critical infrastructure that play a vital role in global trade and commerce. However, they are also vulnerable to the impacts of climate change, including sea level rise and increased extreme weather events intensity and frequency. Ensuring the resilience of maritime ports is essential to maintaining their ability to operate in the face of these challenges. ResPorts is an innovative research project studying the Greek maritime ports' weaknesses and vulnerabilities vis-à-vis climate change aiming at developing the necessary tools such as a Decision Support System (DSS) to ensure their resilience.

Keywords: maritime ports · climate change · resilience

1 Introduction

1.1 The Importance of Resiliency in Ports

Climate change introduces numerous hazards that affect both the natural environment and human societies. Rising temperatures, extreme weather events, sea-level rise and alternations in precipitation levels/patterns are among the most important threats that climate change poses to human societies. Transport infrastructure may be affected by climate change both directly and indirectly. Direct effects include among others flooding, erosion, increased maintenance costs, weather-induced disruptions in operations and physical damage as well as the need for future changes in infrastructure investments planning. On the other hand, indirect effects include shifts in transportation patterns and changes in transport demand. As transport usually facilitates induced demand, alternations due to climate change in economic activities that create transport demand (such as agriculture, industry, tourism etc.) lead to the latter.

Ports may be considered as "Critical Infrastructure" [8]. According to the European Commission "*Critical infrastructure is an asset or system which is essential for the*

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maintenance of vital societal functions" [9]. Any type of damage or disruption on critical infrastructure made by natural disasters or other causes can pose a substantial adverse impact on the security of the EU and the welfare of its citizens. Thus, resiliency of the European ports and transport infrastructure against climate hazards is of essential importance.

There are several examples of maritime ports globally which have been affected by extreme weather conditions due to climate change. Between 1960 and 2010, 32% of the world's seaports, saw a tropical storm passed within a 50 km distance [9]. According to climate scientists, climate change increases frequency, intensity, and spatial distribution of extreme weather events. The aforementioned highlight that there is a need for fostering maritime ports resiliency against climate hazards that are introduced by climate change. This constitutes the primary objective of the "Resports" project, funded by the "Green Fund" (Greek: Πράσινο Ταμείο, www.prasinotameio.gr). Resports seeks to bring innovation and empowerment to port operators, management authorities, and the scientific community in addressing the effects of climate change on port infrastructure.

1.2 Extreme Weather Events and Their Impact on Greek Ports

There are several cases of extreme climate events that affected Greek ports during the last years. On 5–6/9/2023 the cyclone "Daniel" (Fig. 1) struck the region of Thessaly. According to the World Meteorological Organization (WMO), Mount Pelion received 700 mm of rain during 24 h, the equivalent of 18 months of average rainfall [10], resulting to severe floods in the city of Volos. Consequently, the port of Volos had to cease all operations for several days. To mitigate the impact, all passenger ferry routes to Sporades were redirected to the port of Agios Konstantinos which is in a distance of 160 km from Volos.



Fig. 1. Severe Floods in the Port of Volos, Greece, after the Cyclone "Daniel". Sources of images: [11].

On 9/9/2023 severe winds (force > 8bf) in the port of Rafina (see Fig. 2) resulted in the entanglement of the anchors of three ferries, leading to a collision incident. One of the ferries, which incurred no damage, continued its scheduled itinerary, while the other two had to undergo either minor or major repairs. The anchors and anchor chains from the affected ferries had to be carefully extracted from the seabed before the port could resume operations. This process necessitated the closure of the port for a period of 5 days. All services were re-directed to the port of Lavrion during this period.



Fig. 2. Ship Collision in the Port of Rafina due to extreme winds. Towage of one of the involved ferries after the incident (left) and the anchor chains after being removed from the seabed (right). Source: Own Pictures.

Moreover, extreme weather events impact not only port operations but also the logistical aspects of crisis management. For example, after cyclone "Daniel", the Hellenic Electricity Distribution Network Operator (HEDNO/Greek: ΔΕΔΗΕ) commissioned a ship to transport electricity generators and construction materials to the South Pelion Region due to the damage made on the local electricity distribution network.

2 The Greek Port System—A Review

Greece is a country with ca. 250 inhabited islands, of which less than 50 have permanent population > 1000 people. Greece has a network comprised of ca. 155 ports [12], with most of them being multipurpose ports facilitating various types of cargo and passenger traffic such as passenger, cruise, ro-ro, bulk, containerized cargo etc. Seasonal variation of traffic is often very high, especially in island ports, as also noted in [12] (Fig. 3).



Fig. 3. Greek Ferry Network: Source: Own Elaboration.

3 Decision Support Systems (DSS) in the Port Industry

There are at the moment several DSSs utilized by port authorities for multiple purposes, which also contribute in the ports' resiliency as well through functionalities such as emergency response planning and predictive analytics. A review of those DSS may be found in Table 1:

Table 1. DSS currently existing in the Port Industry. Source: Own Desk Research.

Name of DSS	Applied by	Level of Decision	Features
Port Forward	Port of Rotterdam	Operational	Vessel Tracking, Cargo movement and other
PILS	Port of Antwerp	Operational	Vessel Traffic & Port Activities
Port Roadmap 2025	Port of Hamburg	Strategic	GIS, Improving Port's Competitiveness
ITMS	Port of Valencia	Operational	Vessel Tracking, Cargo movement and other

Additionally, there is plenty of academic literature regarding ports' DSS, but the majority concerns other than the climate change topics. From a methodological perspective the main methodologies recognized in the literature are probabilistic/fuzzy methods [2–4], digital twinning [1] and GIS tools [5–7].

4 Methodology

The interviews took place in September and October 2023 and had an average duration of 1 h each. Additionally, a focus group was performed with several stakeholders from the port industry, aiming at supporting the design of the DSS. The methodology of this study consists of 4 steps indicated in Fig. 4.



Fig. 4. Methodology.

5 Results

5.1 Discussion with Stakeholders

Stakeholders acknowledge climate change as an undeniable reality. They emphasize the critical significance of enhancing the resilience of their ports and terminals, noting that the recovery period for extreme events, including floods and storms, is diminishing due to the impact of climate change.

The majority of stakeholders highlighted that their ports are vulnerable to wind and sea waves, posing a risk of potential damage to port infrastructures and superstructures as well as the halt of port operations. Consequently, they have implemented measures to alleviate the potential impact of weather-related events on terminals. For instance, they have installed additional ship mooring equipment in response to requests from ship masters. It's worth noting that all stakeholders unanimously stated that climate change is not currently considered in the planning and design of new infrastructure.

Stakeholders identify primary challenges hindering resilience, including insufficient financial and technological resources essential for adapting to climate change. Additionally, a shortage of weather data in time-series format poses a significant challenge. While almost all stakeholders gather various data related to their ports (such as weather, water quality, wind, and wave propagation data), none of the port authorities collect a comprehensive combination of all the data mentioned.

Port authorities were questioned about their efforts to reduce their climate impact in alignment with SDG13 targets. The majority responded affirmatively, citing the adoption of photovoltaic panels for electricity and the provision of cold ironing for ships as prevalent measures. Nevertheless, they emphasized the challenge of expanding these initiatives in the future, attributing the difficulty to land ownership issues prevalent in various ports. This complication arises from the fact that port authorities do not possess full ownership (100%) of the land or buildings they utilize.

Finally, all the stakeholders recognized that commercial scale of a port highly affects its capability to become resilient and "green".

5.2 Physical Limitations in Port Operations

The stakeholders were asked which physical limitations exist for port operations. Their responses reveal that wind force is a limiting factor for 6 out of 7 ports surveyed so far, while meteorological tide poses no constraint for any port. Moreover, depth represents an operational limitation for most of the ports. Changes in wind force or direction, as well as alterations in the depth of the ports due to the deposition of transported materials (both may arise during a single storm event), have the potential to cause significant disruptions in the operations of the surveyed ports (Fig. 5).

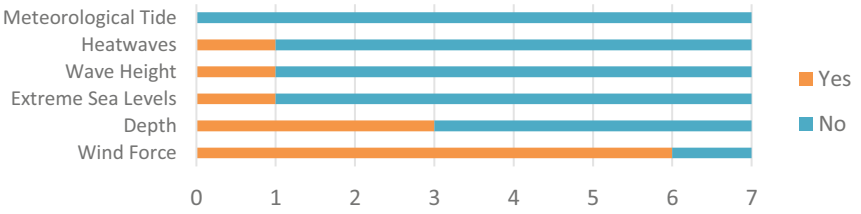


Fig. 5. Physical Limitations in Port Operations for the Greek Ports

In a second stage the stakeholders were asked to specify which negative effects/disruptions may arise to their port infrastructure from extreme wind events, and how important they are, using a Likert scale from "No Impact" to "Very Important". Results are indicated in Fig. 6. As seen, the negative impact of extreme winds tends to be more important for safety of passengers/workers in the port area and potential damages to infrastructure/mechanical equipment ("property damages") and less important for port functionality and supply chain disruptions, because although the sea activities of ports may face disruptions due to extreme winds, multiple land activities (often related to supply chain) continue to operate as usual.

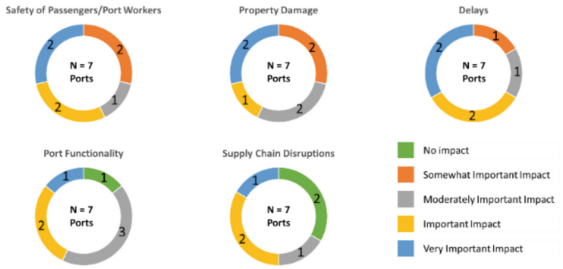


Fig. 6. Negative Effects of Extreme Winds to Port Operations and their Impact

5.3 Designing Resilient Infrastructure: Perceived Feasibility by Stakeholders

Most respondents mentioned that enhancing the resilience of their ports is considered "feasible" to "very feasible." An important point highlighted by the focus group participants is the interconnectedness of port resilience with that of the surrounding city areas, given the close proximity of many Greek ports to urbanized areas. A specific example mentioned by the experts was the reliance of the port's rainwater drainage system on that of the city, as a continuity of the latter. Consequently, a potential flood in the city could result in floods and disruptions to port operations.

According to the respondents, offshore structures such as breakwaters are often easier to be constructed than land infrastructure, primarily due to the high land density around numerous Greek port areas. Consequently, they might be favored over other structures with equivalent potential outcomes.

5.4 Port Activities Supported by a DSS for Climate Resiliency

The focus group participants were asked to mention the anticipated benefits their organization could gain from a Decision Support System (DSS). In a subsequent phase, following the determination of the potential benefits, participants were requested to prioritize their (and the other participants') answers. The outcomes are presented in Fig. 7. A significant observation is that stakeholders assigned greater priority to long-term planning activities (such as planning of technical interventions and financial activities), while assigning lower priority to tasks associated with day-to-day operations (such as berth allocation).

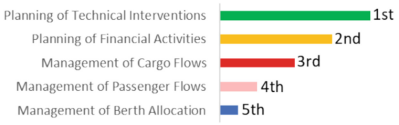


Fig. 7. Anticipated benefits by the stakeholders relative to the DSS

6 Conclusions

Based on the above-mentioned, climate change is already happening, and its impacts can be observed around the world and also in the Greek Ports. Ports are critical infrastructure especially for insular countries such as Greece. To take action, design and implement innovative solutions and measures in order to ensure their resilience is a necessity, and thus development of a Decision-Support System for this purpose is very important. ResPorts aims to promote through its activities sustainable development of the Greek ports in relation to the effects of climate changes, ensuring their contribution to Greece's economy, prosperity, and security.

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Sustainable Approaches to Enhancing Performance and Resilience of Historic Railway Bridges

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Abstract. This paper discusses the ways and means by which Irish Rail has been dealing over the years with aging bridge structures, aiming to improve their performance and resilience in a sustainable manner. The paper outlines the methods for refining the assessments of the structural capacity of historic bridges by the application of site-specific loading and modern computational dynamic analysis to evaluate the performance existing railway bridges. The important phenomena, such us dynamic amplification, serviceability-critical bridge and train accelerations, as well as bridge-train interaction and resonance are outlined. Irish Rail's methods of improving the performance of these bridges are discussed, with the particular focus on the sustainable methods of strengthening and improving the resilience of historic railway bridges.

Keywords: Historic railway bridges · Dynamic analysis · Sustainable strengthening · Resilient bridges

1 Introduction

The first railway line in Ireland was completed in 1834 between Dublin and Kingstown (Dún Laoghaire), [1]. In the years that followed, the railway infrastructure expanded radially from Dublin, with the connection to the main cities such as Cork, Belfast and Galway, but also to smaller local centres, [1]. The main development occurred in the 1850's, hence, a significant part of the railway infrastructure in Ireland dates back to that period. This is particularly noticeable in the bridge stock, where many of the major railway crossings, but also many of smaller bridges, still retain their historic character. Such a heritage provides unique challenges, when faced with the modern requirements for the safety and performance, coupled with the ever-increasing demand for running faster and more frequent passenger services or heavier freight trains on a reliable timetable. These challenges were particularly well visible at the end of the 1990s, at the time of the fast-paced economic development in Ireland, when the rail services could not cope with the increasing demand. The railway infrastructure was in a serious need of investment and upgrading, [2], particularly after the previous decades of underinvestment and closing down of services and complete railway lines. Against this background, Irish Rail's

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Railway Safety Programme came alive in 1999. It was planned as a rolling programme of investments in railway safety improvements, mainly by means of renewals of the railway infrastructure (replacement or renewal of bridges, closures or upgrading of level crossings, embankment stabilisation, coastal defence works, station upgrades), with a specific safeguarded budget for the planned works. A significant limitation on the rail network was imposed by the bridges, which often had permanent speed restrictions imposed, due to their own structural condition or the condition of the track running over. A number of historic open-deck bridges still maintained their original track arrangement with so-call waybeams, i.e., longitudinal timber sleepers directly supporting the rails. This type of railway track on bridges, despite being well proven over the years, suffered from durability problems with the timber. This resulted in a rapid deterioration of the track quality and runability, requiring more stringent inspection and maintenance regimes, which also had significant safety and cost implications. After taking all of these circumstances into account, a programme was put in place in the early 2000's to investigate all the waybeam bridges within the Irish Rail network. This was to be carried out by the structural and traffic safety assessment and, where required, by the provision of modern decks on those bridges with either ballasted or balastless tracks, in an effort to remove or to ease the legacy permanent speed restriction.

In this process, a number of non-conventional approaches and solutions were utilised in order to provide the required upgrades to the infrastructure, but also to achieve the best value for money, all of that within the constraints of a live operational railway and minimising disruptions to revenue-generating rail services. This paper discusses some of these approaches, concentrating on enhanced dynamic analysis of historic bridges subjected to moving trains. Cumulatively, despite not being developed strictly with that purpose in mind, these approaches can now be viewed as a sustainable way of upgrading historic railway bridges, in order to cope with the increasing loads and speeds of the railway traffic and also as means of future-proofing these structures and improving their resilience. In the next sections, some of these approaches and case studies are presented and discussed in the light of their sustainability and enhancements to structural resilience.

2 Dynamic Bridge-Train Analysis for Structural and Traffic Safety Assessments

As a part of Irish Rail's efforts to deepen the expertise on dealing with waybeam bridges, studies on the dynamics of railway bridges subjected to moving loads were carried out in partnership with academic partners. It was partly driven by the realisation that serviceability and runability requirements for new bridges covered in the design codes, such as [3, 4], were sometimes insufficiently addressed for existing bridges. These design codes were found to be very conservative when used for the assessment of existing structures and historic bridges in particular. This can be attributed to the fact that the design codes are developed in a very general manner to encompass a wide range of structures, load cases and other conditions. However, the application of the load models defined in the design codes, such as [4], and the associated dynamic factors can be optimised with a better knowledge of local conditions, e.g., type of rolling stock using the bridge, type and condition of the railway track on the bridge, etc. This is also specifically

allowed within the bounds of the current Eurocode 1 [4], by the provision of the "Real Train" models. It is worth emphasising that the refinement of the assessment, through a bridge and train-specific dynamic analysis, can be achieved without compromising the safety levels of the structure. It only provides refined dynamic factors, acceleration levels and deformations, based on better defined network-specific bridge and train information.

In the research supported by Irish Rail, modern computational dynamic analysis methods were employed to the assessment of the dynamic performance of historic railway bridges. The phenomena, such us dynamic amplification, serviceability-critical bridge and train accelerations, as well as bridge-train interaction and resonance were considered in these targeted efforts to provide sustainable means of strengthening existing bridges. A bridge and train-specific dynamic analysis allows for fine-tuning of the strengthening efforts, assessing safe operational speeds, based on the serviceability and traffic safety criteria, as well as demonstrating the post-strengthening suitability of historic structures to carry modern rolling stock at higher speeds. The main outcomes of the study are covered in [5, 6].

The approach described above was used for the serviceability and traffic safety assessment of the River Nore Viaduct in Thomastown, Ireland. This single-track bridge, shown in Fig. 1, was completed in 1877 and consists of 2 no. masonry arches on each approach and the main 61.0 m span, being a wrought-iron bowstring arch. The original bridge was constructed with the waybeam track fixed directly to the metallic open deck of the bridge. The bridge was modelled within a purpose-developed dynamic analysis software (DBTI) as a three-dimensional bow-string arch with its individual members discretised with three-dimensional beam-type finite elements. The dynamic analysis of the River Nore Viaduct initiated with the modal analysis, which provided the fundamental bending frequency $f_0 = 4.86$ Hz. The transient analysis of the bridge was then carried out for a train at the time operating the line that was identified as causing particularly pronounced dynamic effects. This train was formed by 2 no. of 67 t Irish Rail Locomotives Type 141, followed by 20 no. of 31 t bulk cement wagons. The axles of the wagons are closely and almost evenly spaced with repetitive distances between the axles of $d_1 = 3.40$ m and $d_2 = 3.70$ m. As discussed in [PAGEREF _ENREF_14 \h 6], the resonance and the largest dynamic amplification may occur when the fundamental frequency of the bridge is excited by the moving train, i.e. when the speed of train reaches:

$$V_{crit_i} = \frac{f_0\, d}{i} \tag{1}$$

where d is the regular, multi-times repeated spacing of groups of train's axles. Therefore, in accordance with Eq. (1), the largest dynamic amplification for this specific type of freight train may occur at the critical speeds between 16.5 m/s and 18.0 m/s (Fig. 2).

This theoretical prediction corresponds well with the results of the numerical analysis, obtained using the DBTI software and presented in Fig. 3. The figure shows the displacement-based dynamic amplification factor DAF_U, which describes the increase in the dynamic displacements of the bridge in comparison with the corresponding static displacements. The DAF_U reaches its sharp peak at the speed of 17.50 m/s (63 kph), Fig. 3, indicating an amplified dynamic response. The value of DAF_U at 1.095 is very close to the dynamic factor $1 + \varphi$ for real trains prescribed in [4], which takes the value



Fig. 1. The River Nore Viaduct (UBW 87) in Thomastown: Elevation and view on the new composite deck with embedded track (source: Irish Rail).



Fig. 2. Irish Rail rolling stock considered in the dynamic analysis of the River Nore Viaduct: Locomotive Type 141 and Bulk Cement Wagon 31 t, (source: Irish Rail and [8]).

of 1.099. The time-histories of the bridge displacements in Fig. 3 show high-amplitude vibrations at the speed of 17.50 m/s, whereas the traces for two other speeds of 1.00 m/s (quasi-static load) and 44.45 m/s are very alike. The high-amplitude vibrations increase with the number of axles travelling over the mid-span of the bridge and starts decreasing slowly due to the structural damping, when the train leaves the bridge. The described phenomenon has serious practical implications, particularly when the critical speeds are lower than the operational speed on the bridge. The railway administrations commonly limit the dynamic response and loading on historic bridges by imposing speed restrictions, however, some additional checks should also be considered to establish whether or not the imposed restrictions match with the critical speeds. The assessment of the dynamic performance of the original open-deck structure indicated its susceptibility to an excitation by a specific type of freight wagons, as was historically observed on the bridge during passages of freight trains. The bridge was strengthened in 2004 in a heritage-sensitive manner, which significantly reduced its susceptibility to the dynamic loading. The method used for strengthening is discussed in the next section.

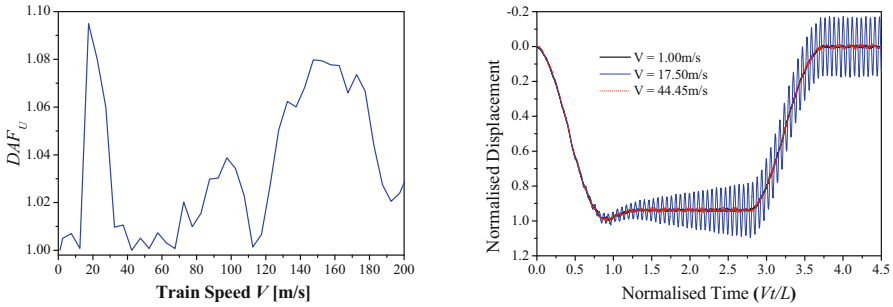


Fig. 3. Results of the dynamic analysis of the River Nore Viaduct: DAF_U versus speed, and normalised displacement versus normalised time

3 Sustainable and Heritage-Sensitive Strengthening for Improved Resilience

One of the main principles when designing the strengthening works of historic Irish Rail bridges was to retain as much as possible of the original fabric of these structures and improve their performance and resilience in a sustainable manner. The strengthening methods were selected individually to suite each of the structures. However, the technique that was the most commonly used was the provision of a new concrete deck acting compositely with the metallic fabric of the main structure. The deck supported the directly laid balastless track with rails embedded in concrete throughs formed in the deck with the use of cork-elastic material. These specially shaped troughs also served as a derailment measure in a manner similar to guardrails. The composite action between the metallic (commonly wrought iron) fabric of the original bridge and the new concrete deck was achieved with the shear connectors provided by HSFG bolts. In order to demonstrate the ductility of such a type of connection, experimental laboratory work was carried out, as described in [9].

This technique was used for the strengthening of the River Nore Viaduct in Thomastown discussed in the previous section. The method has proven itself in practice, as demonstrated by years of a satisfactory service of the strengthened bridge. It was also found to be a sustainable method that allowed to retain bulk of the existing structure but also to satisfy the loading and runnability requirements of the current rolling stock. In comparison with the grillage of the original metallic deck, concrete deck also enhances the dynamic performance and provides an inherently better protection against derailment, which can lead to catastrophic outcomes when wheels of a derailed train damage the supporting cross-beams of an open deck. In this manner, the overall resilience of the former waybeam bridges was also significantly improved. Similar methods of strengthening were also applied to other historic bridges within Irish Rail network, including the Slatty Viaduct (UBC 421), shown below in Fig. 4. More detailed discussion of the strengthening techniques and selected case studies from the Irish Rail's past experience are provided in [9].




Fig. 4. The Slatty Viaduct (UBC 421): view of the superstructure before and after strengthening with the composite deck (source: Irish Rail)

4 Conclusions

Dealing with historic railway bridge infrastructure often requires non-conventional approaches. As proven by Irish Rail's own past experience, satisfactory structural performance and traffic safety can be achieved with targeted advanced analysis and novel strengthening techniques, with the added benefits of developing sustainable and resilient but also cost-effective bridge infrastructure.

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Railway Train Main Power Converter: Model Predictive Current Control of a Modular Multilevel Converter

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Abstract. In electric railway trains two main power systems can be distinguished: The system of the power propulsion and the system of the auxiliary power services. Consequently, since the train is supplied from the catenary in AC, the use of an AC to DC power converter is indispensable. This paper proposes the application of a modular multilevel converter (MMC) as main power converter (i.e., interfacing the AC catenary and the DC link inside the train). The operation of the MMC is ensured by a model predictive current controller, which controls its input AC current according to specific power requirements. The MMC and the model predictive current control are validated recurring to computer simulations. Based on the developed simulation models, the presented results permit to verify the advantages associated with the modularity of the converter and with the performance of the model predictive current control.

Keywords: Railway Power Systems · Auxiliary Power · Power Converters · Modular Multilevel Converter · Model Predictive Current Control

1 Introduction

Power electronics systems have always been extremely important in a modern society, but the fact is that they have increasingly become indispensable for a very wide range of applications [1, 2]. Consequently, more and more, new technologies for power electronics are emerging for several purposes, which is easily verifiable from electrical energy production systems, transport and distribution systems, and also in railway systems [3, 4]. In fact, power electronics is pivotal in any kind of modern railway system, allowing several tasks, including the interface of the catenary and the motor drivers, managing key electrical variables like voltages and currents [5, 6]. Obviously, despite power electronics systems starting from the same principle of converting voltage and current levels into other voltage and current levels, it is easy to see that the power electronics converters that perform the various operations are not all based on same topology [7]. The main power converter of a railway train is a critical component in modern railway systems [8], since it is responsible for connecting the catenary to the electrical system inside the railway [9]. This paper proposes the application of a modular multilevel converter (MMC) as main power converter for interfacing the AC catenary and the DC-link inside the train.

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The operation of the MMC is ensured by a model predictive current control, operating, in real-time, to guarantee that its input AC current in accordance to the specific power requirements of the diverse appliances inside the train.

The MMC under study in the scope of this paper is based on submodules with half-bridge structure, which one permitting the operation with two distinct voltage levels [10, 11]. As main contributions, it can be identified the following points: (i) MMC utilization for interfacing the AC catenary and the internal power system of the train; (ii) application of the model predictive current control for the MMC in railway systems; (iii) computer simulation, both with stable and unstable input AC voltages to fully validate the MMC and the control technique. Figure 1 contextualizes the application of power electronics in a railway system, specifically highlighting the framework of the main converter (in this case, where is applied the MMC).

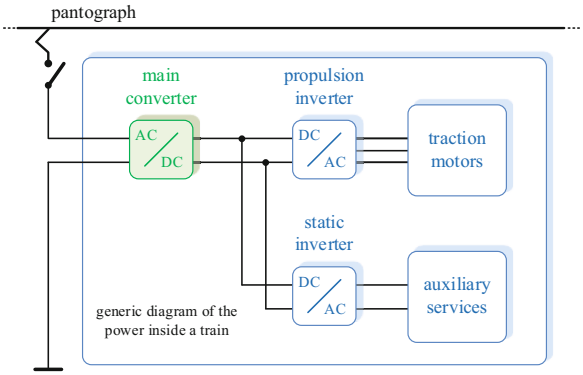


Fig. 1. Contextualization about the application of power electronics in an electric railway system.

2 Modular Multilevel Converter: Application and Topology

The MMC has appeared as a radical topology in power electronics since it is very versatile for several applications, and it a prominent actor in high-voltage and high-power applications such as railway systems [4]. The MMC stands out from usual power converters since it has a modular and scalable design, containing various sub-modules. With the objective of creating a multilevel structure, multiple sub-modules are connected in series, providing a wide range of voltage levels [6]. With a precise control by selectively switching the state of each submodule, it is possible to synthesize an output voltage with high-quality waveform, making it ideal for various applications, such as railway applications. The structure of the MMC under the scope of this paper is presented in Fig. 2. A shown, inductive filter are considered in the interface with the catenary, ensuring the possibility of controlling the waveform of the current. By increasing the number of sub-modules, it is possible to increase the operating voltage levels and the value of the DC-link voltage and reducing the voltage rating of the power semiconductors (cheaper and better in terms of reduced switching losses) and lower stress. Although the application requires the control in unidirectional mode, if properly controlled, the MMC permits the bidirectional power operation.

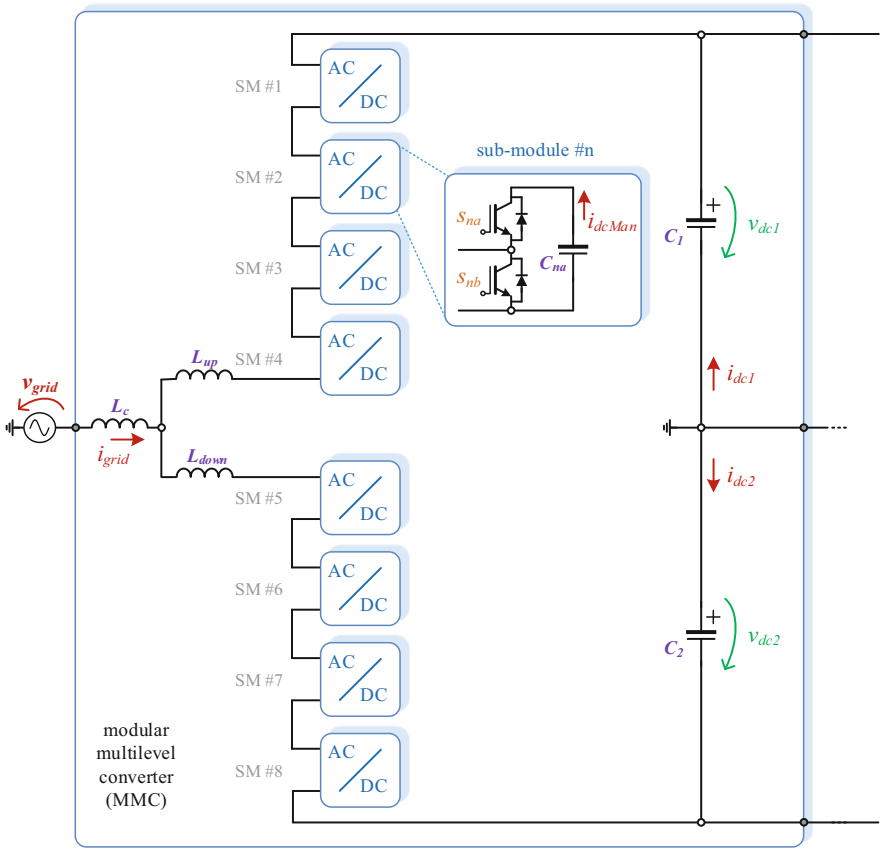


Fig. 2. Structure of the MMC used as main power converter of the electric railway train.

3 Modular Multilevel Converter: Control and Operation

The key point of the MMC control lies on the control of the individual sub-modules, which is critical for synthesizing the desired output voltage. Regarding the voltage balancing across the sub-modules, several voltage balancing algorithms can be implemented, but such analysis is out of the scope of this paper. Typically, each sub-module is controlled using pulse-width modulation (PWM), where control techniques based on phase-shifted PWM strategies are used. The establishment of a precise control of the phase shift for each sub-module is crucial for ensuring that the MMC produce the multiple voltage levels. In the AC side, it synthesizes a nearly sinusoidal waveform with minimal harmonic distortion. In terms of control, several strategies can be considered to regulate the power flow between the MMC and the power grid. In railway power systems, the MMC must be synchronize with the frequency of the power grid voltage, enabling to match its output voltage with the power grid voltage, preventing the operation with undesired reactive power. Due to its fast-switching capability, the MMC exhibits excellent dynamic response, establishing a quick response to changes in the operating

conditions, making it suitable for applications where prompt modifications are required. The block diagram of the control is presented in Fig. 3.

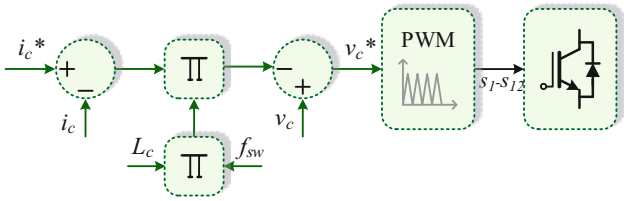


Fig. 3. Principle of the predictive current control applied to the MMC.

4 Modular Multilevel Converter: Computer Validation

This section exhibits the main results that permit verifying the applicability of the predictive current control to the MMC converter and in railway applications. The results that allow to evaluate the current waveform obtained on the catenary side, as well as the respective voltage, are shown in Fig. 4. It is noted that the current assumes a waveform that corresponds to the voltage waveform, i.e., without harmonic content. The operation only happens with active power (i.e., voltage and current in phase).

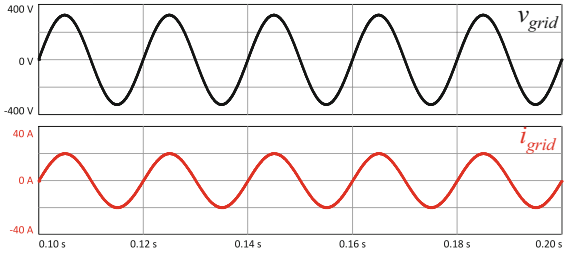


Fig. 4. Validation of the MMC: Voltage (v_{grid}) and current (i_{grid}) on the power grid side.

Figure 5 shows the currents in the main DC-link and on the DC-link of two of the sub-modules (the behavior being the same for the remaining). Each of the currents in the main DC link presents a sinusoidal waveform, and they are in phase opposition due to the positioning of the current sensor. Each current in the DC-link presents a waveform due to the high switching frequency (10 kHz) of the power semiconductors.

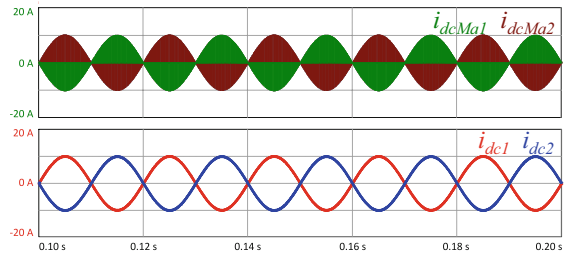


Fig. 5. Validation of the MMC: Currents in the DC-link of the two exemplificative sub-modules (i_{dcMa1} and i_{dcMa2}) and currents in the main DC-link (i_{dc1} and i_{dc2}).

After the previous validations, Fig. 6 shows, again, the voltage and current signals in the catenary, however, verifying a more realistic situation from the point of view of voltage operation. Thus, the voltage has harmonic content, but the current remains as before. This situation is only feasible due to the use of a PLL algorithm, in which the output signal is used as input for the algorithm that allows taking the reference signal. Furthermore, it can also be seen that the current is correctly controlled even under these voltage controlling conditions, which proves the correct application of predictive control in this converter. In this situation, it was reflected a power quality problem that affects the RMS value of the voltage. However, the current stays to be properly controlled, always presenting the same amplitude and the same waveform, not being interfered by voltage fluctuations. It is important to note that the objective was just to control the current and not adjust the operating power.

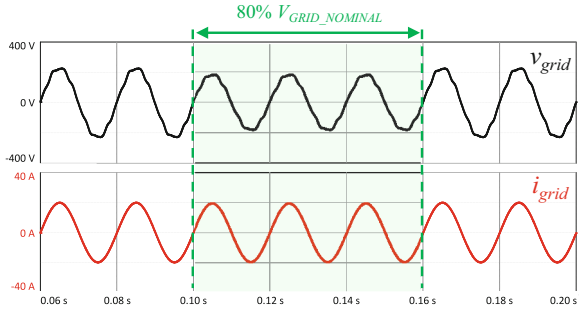


Fig. 6. Validation of the MMC under operation with a voltage sag on the power grid side: Voltage (v_{grid}) and current (i_{grid}) on the power grid side.

Figure 7 presents a result that validates the behavior of a variation in operating power, due to the increase in current. Specifically, this result was obtained for a condition in which the current changes abruptly by double, i.e., resulting in an increase in operating power by double. Once again, the correct application of this control to this converter and this specific application is verified.

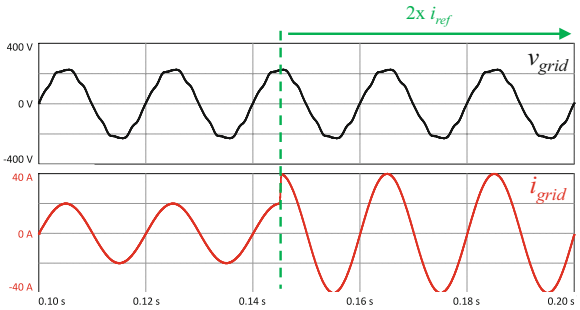


Fig. 7. Validation of the MMC under operation with a sudden variation of the current on the power grid side: Voltage (v_{grid}) and current (i_{grid}) on the power grid side.

5 Conclusions

In the context of electric railway trains, it can be distinguished two main power systems, namely for the power propulsion and for the auxiliary power services. This paper proposes the application of a modular multilevel converter (MMC) for the railway train main power converter, where the application of model predictive current control is a key distinguished feature. The application of the model predictive current control for the MMC in railway systems is presented, highlighting the main principle of operation and functionalities. The validation was carried out with simulations, both with stable and unstable input AC voltages, and with sudden variations of operating power.

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MetProgRé: a Decision Support System to assess Weather Risk for Planning of Railway Renewal Works

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Abstract. As the French railway infrastructure manager, SNCF Réseau is in charge of the maintenance and periodic renewal of the national rail network. To achieve the latter goal with due regard to economic and technical performance as well as the security of daily freight and passenger trains, industrial methods can be used that consist of high-output track and catenary renewal trains (factory trains, known as "suites rapides" in French). To be efficiently used, these expensive machines require planning that takes local weather conditions into account. To this end, a Decision Support Tool called MetProgRé (Météo Programmation Régénération) has been developed in order to assess and minimize disruption due to extreme weather conditions affecting track, catenary or working conditions for the operatives involved. This paper presents MetProgRé giving details regarding the statistical data used and the model implementation. It also provides some insight into use cases and lessons learned during works between 2021 and 2023 when compared to previsions from the model.

Keywords: railway renewal works planning · factory trains · decision support tool · weather conditions

1 Introduction

In France, around 800 km of railway lines are renewed yearly using mechanized methods. The renewal of a railway section can address either the track components (track ballast, rail and sleepers) or the catenary components. On high-capacity railway lines, "factory trains"(also called Suites Rapides) are used to minimize traffic hindrance costs. These renewal works last from two to four months and need to be planned up to five years in advance. They are covered

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by multi-annual contracts with private companies which are managed by SNCF Réseau (around 1.2 Billion euros per year).

Weather can have a significant impact on the productivity of the works. SNCF Réseau, as manager of the French railway network infrastructure, required a statistical approach for extreme weather risk estimation in order to adapt planning of yearly works, adapt schedules or switch to a more favourable location. This paper presents a Decision Support Tool, MetProgRé, that gathers and generates statistics for quantities derived from weather data collected on the French mainland over four decades.

The selected quantities are wind, apparent temperature (both wind chill factor and humidex) and snow. For each of these quantities, specific thresholds have been defined with the help of experts to assess different risk levels. The developed tool has two modes. The first one gives an overview of the risk for the whole French mainland, the second mode gives a more accurate risk evaluation: for given coordinates and a specific time-period, it displays statistical distributions with different time resolutions of up to an hour.

With this intuitive tool, engineers at SNCF Réseau have a new approach which contributes to effective management of works planning. Some insight into tangible use cases is provided in this paper. Beyond the assessment of the aforementioned risks, which will increase due to climate change, the appropriate estimation methodology for the additional time required to guarantee successful and completed renewal operations is also a key component in order to manage and challenge the performance of yearly works planning. "MetProgRé 2.0." is presented at the end of the paper.

2 Background

2.1 Industrial Railway Renewal Works: Challenges and Planning in France

The French railway network consists of 28.000 km of track which requires a large renewal effort to match the political, social and environmental ambitions to develop railway traffic. SNCF Réseau, as the infrastructure manager, uses different methods. One of them is to use mechanized methods, the most emblematic of which are high-output track and catenary renewal trains. These renewal trains, when used in optimal conditions, may renew infrastructure components up to 10 times faster than "manual" methods. In 2023, four different trains are simultaneously renewing the tracks for high-speed and other major lines of the network and two others are used to renew overhead catenary lines. The multi-annual contracts which cover these industrial works specify a minimum number of kilometers/units to be renewed and/or a minimum number of programming days each year. All these are major works that are the first to be planned in order to maximize the use of these expensive means (high fixed costs) and to best prepare their implementation. These works are mainly led with daily limited capacity to preserve traffic as much as possible.

Several parameters or rules have to be considered to prepare consistent yearly works planning, such as the absence or presence of alternative routes or local/national events (Festival d'Avignon ...) which may result in exclusion periods, work massification if possible and as far as appropriate, geographical consistency to limit long-distance displacements throughout the year, availability of local human resources, etc. As a consequence, the planning results in compromises between performance and robustness under contractual management. Historically, weather conditions have also been considered but in a very empirical way: the planner avoided to plan works in the South of France in Summer (especially during daytime) or in the mountainous regions during the Winter (especially when the works are at night). That is why many regions were considered as "grey or neutral areas" from a weather point of view.

2.2 Weather Implications for Works

High-output track renewal works consist of a moving work site where multiple factory trains work one after the other on each renewal section, with about 500 workers involved. Every day, the machines are transported from and back to the operations base, which is the logistical centre of the works, where maintenance and material supply are carried out. Since complete renewal cannot be done at the same track location, ballast tamping and dynamic stabilization are carried out after each renewal period to allow safe traffic until the next works period. For track renewal works, the main steps of a complete renewal are the following: replacement of rail and sleepers; excavation and screening of the ballast layer; ballasting and tamping to bring the track to its final height; de-stressing the continuously welded rail.



Fig. 1. Renewal works: track renewal (left) and catenary renewal (right).

For catenary renewal, two special factory trains are used depending on the voltage of the line. On 25 kV lines, only the catenary bracing is replaced, while on 1.5 kV both the catenary bracing and the catenary pole are replaced. Each train is a sequence of mobile workstations which operate simultaneously and in sequence for each catenary support to complete its renewal.

Weather can have a significant impact on each of the works described above due to the effect on infrastructure components, machinery components as well as the operative working conditions. Below are examples of weather hazard effects:

Extreme temperatures lead to thermal expansion or contraction of infrastructure components such as the rails and catenary lines, resulting in failure in some cases. Maintenance works are governed by SNCF standards which define a range of temperatures to carry out each of the renewal operations [8]. For instance, extreme temperatures can result in lateral instability during ballast excavation works due to rail deformations. Continuously welded rail destressing must be performed at a rail temperatures between -5 and +32°C [9]. Ballast tamping performed before or after rail de-stressing is also temperature dependant. During the works, snow, frost, and ice can also result in locked switches. Furthermore, frozen ballast and frozen machinery components render the ballasting operation impossible.

Heavy precipitation can lead to flooding and water accumulation on track. Such conditions are inappropriate for ballast excavation and renewal as water would infiltrate the subgrade and deteriorate its properties, hindering thereby the sustainability of the renewal. Heavy rain can also damage electronic equipment and increase the risk of accidents due to slippery surfaces.

Strong wind can cause windblown debris to obstruct the railway, potentially leading to accidents. Catenary renewal works are the most affected by wind, as the latter leads to significant swaying of the catenary, and high safety risks for workers operating at height.

Secondary hazards can also result from extreme weather conditions such as wildfires, drought, landslides, flooding ...

The weather hazards described above can lead to security risks, loss of productivity and considerable daily delays. With climate change, the frequency of extreme weather conditions is expected to increase. Thus, SNCF Réseau decided in 2020, with the help of Eurobios Mews Labs, to define and commission the development of a specific Support Decision Tool to better take into consideration weather conditions for yearly industrial renewal works planning.

3 MetProgRé

3.1 The ERA5 Dataset

ERA5 [2] is a reanalysis dataset from the European Centre for Medium-Range Weather Forecasts (ECMWF). A reanalysis dataset combines model data with observations into a globally complete and consistent dataset [3]. We focused on the "ERA5 hourly data on single levels from 1940 to present" dataset, which cover the globe with a resolution of 0,25 degrees (about 20 km at Western Europe latitudes). Within the dataset, we focused on the quantities listed in Table 1, which were retrieved for a grid covering the French mainland for the period 1980–2022.

Table 1. Quantities retrieved from the ERA5 dataset.

Quantity (unit)	Description
10 m wind gust since previous post-processing (ms^{-1})	Maximum three-second wind at 10 meters height
2 m temperature (K)	Temperature of air at 2 meters above the land surface
2 m dewpoint temperature (K)	Temperature to which the air, at 2 meters above the land surface, would have to be cooled for saturation to occur
Snow depth (m)	Amount of snow from the snow-covered area of a grid box; water depth if the snow melted and was spread evenly over the whole grid box

3.2 Computing Quantities of Interest

Wind Speed Correction. As aforementioned, we need the wind speed at a height of 5 m, which is the operating height of the work platform for catenary maintenance. To this end, we use a logarithmic wind profile [1,7]. Surface roughness is determined by combining values from [6] and Corine Land Cover data from the Copernicus program.

Apparent temperature. Air temperature does not reflect well real conditions for workers. Several models have been developed to assess this issue, and among them we selected the wind chill factor [5], which is an estimation of the lowering of body temperature due to the passing flow of lower-temperature air, and the humidity index [4], which describes how hot the weather feels to the average person, by combining the effect of heat and humidity. We define apparent temperature as the wind chill factor if the air temperature is below 10∘C and the humidex above.

Snow height. As the value given by the ERA5 dataset is a height equivalent of liquid water, we have to multiply it by the density of snow to get an estimation of the effective snow depth. Yet, the density of snow can range from 0.02 to 0.9 if we consider cold, fresh or highly compacted snow. We then arbitrarily choose an average density of 0.1 and will handle our results with caution.

3.3 Statistical Processing and Tool Overview

First Tab: Global Map. For each computed quantity, one (two for temperatures) threshold(s) has(ve) been chosen with the help of experts (e.g. 45 kmh^{-1} for wind speed). For every calendar month, we count the average number of times the threshold has been crossed and display it on a map as shown on Fig. 2. This enables the user to have a global overview of the risk in order to compare different regions. The user can also choose to counting only for day (6–18) or night (18–6) hours if some of the scheduled work is already constrained.

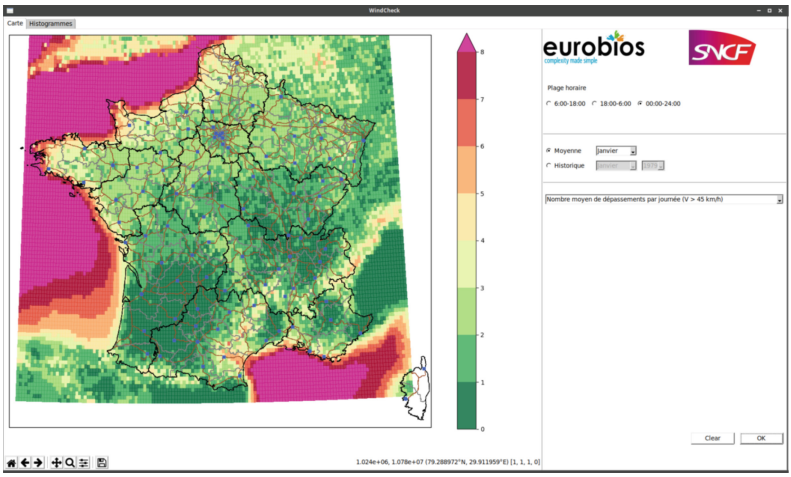


Fig. 2. First tab: global overview, with strong winds in January currently selected.

Second Tab: Focus Map. The second tab lets the user select a point on the rail network and work dates (see Fig. 3). According to this selection, two histograms are computed, both with the bins defined. The first one shows the targeted quantity distribution between selected dates with a resolution of six hours, and the second is the"average day" of the period. The histogram for the year and a threshold table which sums-up what was displayed on the first tab for the selected location are also given. In this case, it allows the user to compare a few sites or adjust the time-period. Resolution up to an hour is critical for the wind, as an example, in the Mediterranean region, where strong gusts that affect catenary works often occur in the late afternoon.

4 Case Studies and Lessons Learned

Since its implementation mid-2020 MetProgRé has been used in different contexts, within different timeframes and by several users involved in the preparation of works.

MetProgRé's extractions have been systematically included in the preliminary studies of track works five years ahead. This early consideration is helpful to recommend additional time if any significant risk is identified. Generally speaking, the planner who has to elaborate draft planning of works can get a global overview of the risk on robustness of the schedules of each operation and if possible, suggest adapted schedules with additional programming days. This newly-gained insight was introduced to draft the 2024 planning of track and catenary works.

At shorter notice, extractions have been useful to secure annual contractual meetings which take place yearly in September to notify the companies of the

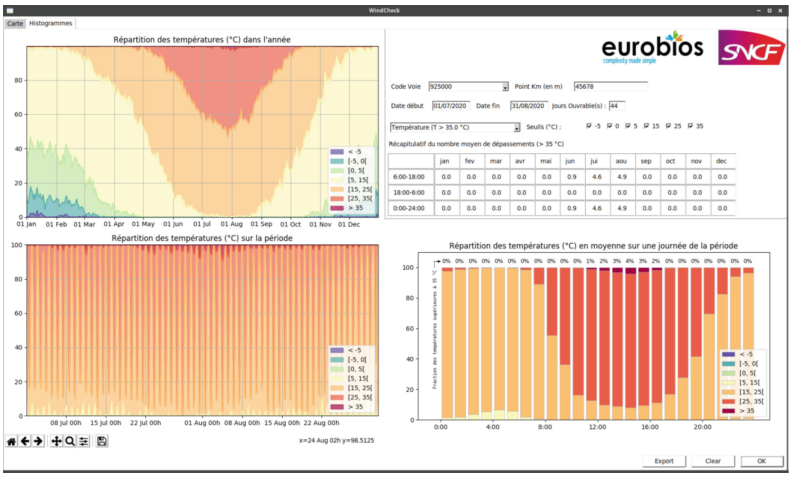


Fig. 3. Second tab: three histograms and a recap table. Test-case is a location in South-East France between July 1st and August 31st, and the targeted quantity is temperature. Top-right: boxes to select coordinates, dates and targeted quantity, plus threshold table summary. Top-left: distribution of targeted quantity (temperature) on all year (reminder). Bottom-left: targeted quantity (temperature) distribution between selected dates (with a 6-hours resolution). Bottom-right: distribution of targeted quantity (temperature) on an "average day" between selected dates.

detailed content of the works to be led the following year. A new item has been added regarding weather conditions.

Finally, on demand, additional extractions or specific contributions have been made to support some project teams when negotiating possessions for works with railway undertakings operating freight and/or passenger traffic on the railway sections to be renewed.

5 Conclusion and Perspectives

More than three years after its implementation, MetProgRé has played a key role in managing the conception and planning of industrial renewal works. Thanks to its ergonomic design, this tool has allowed SNCF Réseau's project teams and planners to introduce a formal method based on weather condition statistics to planning activities. By delivering an insight into possible disturbances due to weather conditions, the most critical works are detected and the risk is streamlined with the companies in charge of the works. From a practical and contractual point of view, this can include adjustment of schedules with some additional programming days, request for more predictive maintenance for the renewal trains, specific precautions for workers and negotiation of additional capacity (day/night).

In terms of user experience, MetProgRé is a very intuitive tool which provides consistent and concise information: extractions are available in a few seconds.

PDF documents can be edited and the level of risk for each quantity can be detected at a glance (second mode). With the same level of information available for every part of the rail network, weather conditions can be properly considered in works planning everywhere.

A new version (MetProgRé 2.0) is currently under development with Eurobios Mews Labs to go a step further in the assessment of the risk level and have a more proactive and accurate role in planning. The new features include: (1) better structure data collection from all kinds of renewal works to help future feedback according to quantitative standards and methods, (2) improve the ergonomic design of the second tab, (3) based on lessons learned in the field, add or adjust some quantities according to thresholds given by operational workers (example: frozen ballast) or (4) define an aggregated index of risk operation to challenge the overall performance while guaranteeing completed works.

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Assessment of Cascading Impacts Across Europe: An Innovative Approach for a Resilient Infrastructure and Society

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Abstract. Despite recent advances in understanding, modelling and forecasting natural hazards and their impact on communities, infrastructure and livelihoods, such events may still cause high economic, environmental and human losses. In recent years, there have been many natural disasters in the world that have caused damage to society and infrastructure. In addition, climate change is expected to lead to more extreme weather phenomena, such as longer and more intense heat waves, more torrential rains, and stronger winds triggering several fires and probably causing many deaths in excess due to extreme temperatures. In this light, the aim of this work is to assess cascading impact by considering the multiple natural hazards involved through a resilient, service-oriented and people-centred approach. This includes identifying possible interdependencies on sectoral goods and infrastructure in particular transport, energy and water as well as on supply chains and networks. Innovative methodology will be developed within a comprehensive European project named "Multi-risk and risk-informed system for better local and regional disaster risk management (MEDiate)" which aims to develop a decision support system (DSS) for disaster risk management. Thanks to its scalability and replicability it will be applied in different contexts taking into account different hazard for different asset.

Keywords: natural hazard · cascading impact · resilience · critical infrastructure · climate change · machine learning

1 Introduction

This paper is part of a broader work under development in the MEDiate European Research and Innovation project. The MEDiate project aims to develop a decision support system for disaster risk management by considering multiple interacting natural hazards and cascading impacts using a novel resilience-informed, service-oriented and people-centred approach that accounts for forecasted modifications in the hazard (e.g., climate change), vulnerability/resilience (e.g., aging structures and populations) and exposure (e.g., population decrease/increase), building on the consortium's existing strengths in this domain.

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The impact of climate change is anticipated to heighten the vulnerability to multiple risks, influencing the scale, frequency, and geographic distribution of hazardous and disastrous events [5]. In this context, the necessity of embracing a multi-risk approach for evaluating the impacts of climate change is stressed by international organizations across different spatial levels, including the European scale.

One of the most concerning consequences of climate change involves the amplification of cascading impacts, where alterations in a specific aspect of climate or the environment trigger a series of reactions that propagate in multiple directions, intensifying overall impacts.

The intensification of cascading impacts in the context of climate change is due to intricate interdependencies, heightened vulnerability and exposure, disruption of ecosystems, social and economic inequalities, and interwoven infrastructure dependencies [5].

This report delivers identification and assessment of the primary types of cascading impacts in European areas as part of the MEDiate project.

2 Key Definitions

This section provides a concise overview of key concepts and definitions related to cascading impacts and critical infrastructure to ensure a clear understanding of the paper's content. The term critical infrastructure (CI) at its broadest level involves elements vital to societal operation [1]. CI consists of complex, geographically dispersed, nonlinear networks interacting with human owners, operators, and users [2]. They exhibit a high degree of interconnectedness and mutual interdependence. For instance, water and telecommunication systems rely on a continuous supply of electricity to maintain their routine operations, while electric power systems necessitate access to water and diverse telecommunication services for effective power generation and distribution [2]. A useful definition to analyse cascading impacts on CI is the distinction between Direct Impacts, Cascading Impacts, and Synergistic Impacts [11]:

- Direct impacts arise from disruptions of critical elements, causing immediate effects on society.
- Cascading impacts propagate through interdependent infrastructures, amplifying disruptions across sectors.
- Synergistic impacts result from simultaneous failures of multiple elements, magnifying their collective repercussions on society.

Pescaroli and Alexander [9] argue that "cascades" are characterized by unforeseen and nonlinear progressions of subsidiary events, spreading towards societal vulnerabilities and disrupting CI. The cascading impact is a focal point in disaster risk reduction, where the direct impact of hazard events generates a sequence of events in human sub-systems, resulting in physical, social, or economic disruption [10].

In the literature several definitions of "dependency" and "interdependency" are present; however, the work of authors Rinaldi et al. [12] is pivotal in evaluating the links between elements. Rinaldi defines (see Fig. 1):

- Dependency: A linkage or connection between two infrastructures, through which the state of one infrastructure influences or is correlated to the state of the other;
- Interdependency: A bidirectional relationship between two infrastructures through which the state of each infrastructure influences or is correlated to the state of the other. More generally, two infrastructures are interdependent when each is dependent on the other.

Rinaldi [12] demonstrated the interdependency of critical infrastructure elements and defined four types of links:

1. Physical: the type of interdependency when each of two infrastructures are dependent on the material output(s) of the other;
2. Cyber: the type of interdependency when an infrastructure is dependent on the information transmitted through the information infrastructure;
3. Geographical: the type of (inter)dependency when local environmental events can create state changes in all infrastructures; it occurs when elements of multiple infrastructures are in close spatial proximity;
4. Logical: the type of (inter)dependency when the state of each of two infrastructures depends on the state of the other via control, regulatory or through a mechanism not a physical, cyber or geographic connection.

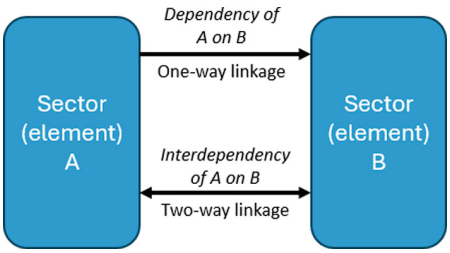


Fig. 1. Types of linkages in a critical infrastructure system (adapted from Rehak, 2016)

3 Methodological Review

This section reviews the studies in the field and broadly groups the existing modelling and simulation approaches into six types [7]:

1. Empirical approaches: these methods analyse historical incident data and expert experiences to identify failure patterns and vulnerabilities;
2. Agent-Based approaches: agent-based models consider infrastructure as complex adaptive systems, incorporating dynamic feedback loops;
3. System Dynamics-Based approaches: they use causal-loop diagrams and stock-and-flow diagrams to study feedback loops within CI systems;
4. Economic Theory-Based approaches: these focus on economic interdependencies within CI systems, including input-output methods and general equilibrium theories;
5. Network-Based approaches: CI systems are represented as networks, either topologically or by analysing dynamic flow processes;

6. Other approaches: various statistical and dynamical modelling approaches exist, incorporating techniques from machine learning or systems theory.

Existing studies offer well-established methods to determine exposure to floods and direct flood impacts [14]. Even though indirect and cascade impacts are widely assumed to be more significant due to the interconnected nature of networks [3, 8], few works are available which address indirect impacts and cascade effects in time and space. Among these works, indirect impacts and cascade effects are mostly addressed with complex conceptual frameworks that, for their application, would require a significant number of models and data [4], simplified risk indexes [13], and/or very limited application to real-world case studies [3, 8]. Storm surges related cascading impacts share similarities with those related to floods, as both involve the rise of water levels. However, the specific impacts may vary depending on the unique characteristics and dynamics of storm surges compared to river floods. Both can cause coastal erosion, flooding of low-lying areas, and damage to critical infrastructure, but storm surges are specifically associated with coastal areas and may entail additional risks such as sea level rise and storm surge waves.

The main cascading impacts related to earthquakes and affecting infrastructures include structural damage to buildings and bridges, disruptions to transportation networks, such as roads and railways, potential liquefaction of soil leading to further instability, and the risk of secondary events like tsunamis or landslides. These impacts can result in a domino effect, affecting critical infrastructure and causing widespread consequences for communities and economies.

4 Methodology to the Cascading Impacts Assessment

The methodology developed for assessing cascading impacts is grounded in machine learning (ML) algorithms capable of discerning patterns in data and leveraging them to predict outcomes for new data.

The initial phase involves defining the inputs required for the analysis, which are informed by the findings of previous literature reviews. It was focused on:

- Definitions of key concepts regarding dependencies between critical infrastructures;
- Selection of sectors for analysis, hazards, and disaster databases;
- Methods to assess cascading impacts;
- Machine learning algorithm selection and validation for cascading impacts assessment.

The publicly available harmonized global spatial dataset of CI [6], was used as input to assess cascading impacts. This global dataset is considered a valuable starting point to gain exposure information for cascading impact assessments. The study led by Nirandjan also proposed a Critical Infrastructure Spatial Index (CISI) at the global scale, at a resolution of 0.10×0.10 and $0.25 \times 0.25°$.

ML requires a constantly evolving database of past events for model training and testing. Starting from the comparison between the existing loss databases, DesInventar (http://www.DesInventar.net/methodology.html) has been selected for the development of the machine learning for the following reasons:

- The events are geolocated: this is a crucial aspect to enable the analysis to be carried out;

- provides the damage of a large set of sectors;
- The collection of historical disaster losses data is provided in a systematic way.

Figure 2 shows the schematic overview of the main components of the proposed methodology.

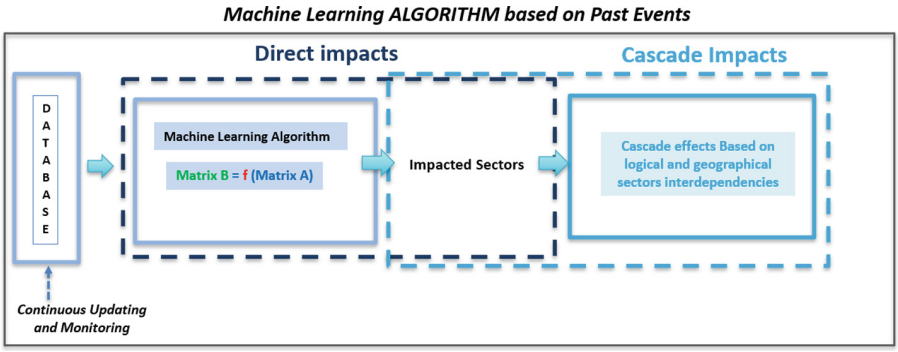


Fig. 2 Main workflow of the methodology

The direct impact phase of the methodology consists in the identification of the direct impacted sectors starting from the knowledge of the scenario and its context with the ML approach. From this first phase the direct impacted sectors are obtained considering a geographical dependency [12]. Then, starting from the directly impacted sectors, is possible to foresee the subsequent cascading impacts over the other remained sectors considering a geographical and logical dependencies.

5 Conclusions

Through the implementation of a methodology grounded in ML approaches the study has gained comprehensive insights into the spatial and temporal evolution of these cascading impacts.

The method should be applicable for describing cascading impacts among a broad variety of societal sectors and critical infrastructures. The approach presented within this framework, seeks to develop a flexible and innovative instrument that offers an overview of infrastructures condition in terms of risks, possible losses and resilience assessment for different kind of hazards. The steps outlined in this framework represent the core of the approach, but each individual phase can be refined or substituted with more detailed analysis or methods. This possibility assumes realistic appearance if input (about hazard, infrastructure system and asset) and specific resources are available. Some of the simplified approaches described here are deemed to be appropriate to a

large portfolio of infrastructure's assets. Further investigations are needed in order to define additional functions from additional literature resources.

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Health Condition Monitoring Techniques for Traction Transformers Immersed in Oil-A Comprehensive Study

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Abstract. The transformer is an indispensable asset in railway network infrastructure. Condition monitoring and asset management is therefore a key concern in all electrical railway utility providers especially for railway infrastructure manager. This paper is a result of an industrial project in collaboration with SNCF Réseau dedicated to the determination of traction transformer faults based on the dielectric fluid analysis, and analysis of the active parts. These methods are the most prevalent techniques for detecting progressing faults in transformers immersed in oil.

Different methods have been employed for analysis of dissolved gas in oil. With these methods, typical faults that manifest in in-service transformers have been identified. Furthermore, in this paper, a statistical study has been done to find the methods between the group which have the same fault code. This study has been applied for different categories of transformers for fixed railway traction electrical substations of SNCF Réseau. The results show the ability oof Duval triangle and CIGRE SC-15 methods to generate more fault code compared to other methods. Also, a validation on several case studies shows the robustness of the method of Duval triangle.

Keywords: Fault detection · fault diagnosis · traction transformer · DGA · condition monitoring

1 Introduction

It has been established that the service reliability of power transformers largely depends on the condition of the oil–paper insulation. In today's economic climate, it is important to test the condition of the oil-impregnated paper mainly used as primary insulation in transformer [1, 2]. Oil not only acts as a coolant but also is itself also an insulating material [3]. Recent studies suggest that many transformers do not live up to their expected lifetime of between 25–35 years [1, 4]. The failure of a single transformer disrupts economic activities for both the consumers and utility company [5].

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To ensure power system reliability, power transformers are monitored, since several operating problems may result in different types of failures. Such stresses may influence the performance of insulating materials of the power transformer, resulting in various failure modes. Thus, the detection and diagnosis of the root fault is very important to prevent sudden power loss and transformer failures [6]. Different diagnostic methods, which are based on dissolved gas analysis (DGA) are widely used for fault diagnosis and monitoring of dielectric liquid filled transformers. Based on the guidelines from IEC 60599 and IEEE C57.104 [7] for the interpretation of DGA technique, several methods are proposed to detect faults. These methods are key gas method, gas ratio method and percentage gas method. With respect to the key gas method, the selection for predominant gas and secondary important gas is difficult due to the existence of other gas traces [8]. Gas ratio methods [7, 9], such as Doernenburg ratio, Roger's ratio, and IEC ratio, have some undiagnosed zones under undefined ranges [8, 9]. The percentage gas method was proposed by Duval, and it is considered the first graphical method, well known as Duval triangle. Duval uses the percentage of three gas concentrations with respect to their sum [10]. Each fault case can be identified by only one point inside the triangle under the crossing of the three percentages. The location of the final point identifies the fault type according to the identified fault zones. The classical Duval triangle has a decision for each case, it is a well-established and widely used method. In case of partial discharge (PD), low thermal (T1) and medium thermal (T2) faults in mineral oil, Duval triangle 4 and 5 were proposed to potentiate the outcome from the Duval triangle 1. Still, the new versions of triangles are based on the classical Duval triangle 1, which is based only on the percentage of the three gases [11, 12]. Duval pentagon shape was proposed by considering all the five formed hydrocarbon gases [13]. Also, Duval proposed Pentagon 1 and 2 to distinguish between lesser concern thermal faults.

In this paper, different methods have been employed for analysis of dissolved gas in oil that some of which are: IEEE gas ratio; CIGRE SC-15; Roger's ratio; Dornenburg ratio; Duval triangle; Duval pentagon; Graphical diagnosis; etc. Furthermore, in this paper, a statistical study has been done to find the methods between the group which have the same fault code. This study has been applied for different categories of transformers for fixed railway traction electrical substations of SNCF Réseau. The results show the ability of the methods of Duval triangle and CIGRE SC-15 to generate more fault code compared to other methods. Also, a validation on several case studies shows the robustness of the method of Duval triangle.

2 Diagnostic Methods—A Statistical Study

A diagram of the different transformer condition diagnosis methods based of DGA analysis, and the necessary data used in this paper is presented in Fig. 1. Several methods from the different standards (IEEE, IEC, CIGRE) have been developed using 10 years data collected from SNCF-R. There are two groups of state detection methods such as:

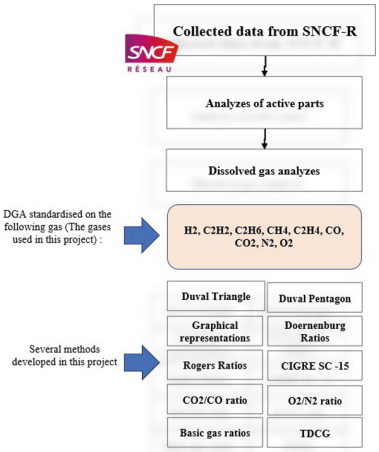


Fig. 1. DGA data requirements and the realized methods

Group 1: Methods that provide a fault code (PD, T1, T2, T3, D1, D2, DT, OHC etc.) such as Duval triangle, Duval pentagon, Roger's ratio, Graphical representations, CIGRE SC -15, and Doernenburg where D1, D2, DT, and OHC are fault in discharges of low energy, discharges of high energy, mix of temperature and electrical discharge, and overheating of cellulose respectively. Table 1 show the results of these methods on a case-study substation of SNCF Réseau for twelve recorded reports between the years 2012 to 2021. Results show the ability of each method to identify the type of fault. ND (not defined) means the method is not able to detect or identifying the type of fault. Many methods seem to be not enough robust to have a successful detection while the method Duval triangle shown the most fault identification. These results have been confirmed from the expert of maintenance center of SNCF Réseau and as this transformer was longtime in the faulty state of D2, eventually it was shut down. A graphical examples of Duval triangle are proposed in Fig. 2 for the sample dates of 14/09/2014 and 14/09/2021 respectively with code defects T2, D1 and D2.

Additionally, for generalizing this approach and to find the most robust method of the group 1, an in-depth statistical study has been done on 6717 SNCF Réseau reports of tested transformers in different categories of transformers as follows:

– For all 60 MVA transformers,
– For all traction transformers with a secondary voltage of 25 KV,
– For all traction transformers with a secondary voltage of 1500 V DC.
– All traction transformers.

The results are presented in Figs. 3a–e. The results prove the robustness of the Duval triangle method. Figures 3a–d show a comparison of the different methods in group 1 for all 60 MVA transformers, all traction transformers with a secondary voltage of 25 KV, all traction transformers with a secondary voltage of 1500 V DC, and all traction transformers with different power and secondary voltage respectively. Figure 3e shows identical faults between Duval triangle and other methods for all transformers.

Table 1. Group's 1 different diagnosis methods for a case-study substation of SNCF-R.

Sampling Date	Duval triangle 1	Duval Pentagon 1	Roger's ratio	Gaz Ratio	Graphical Diagnostic	CIGRE SC -15	Doernenburg	Diagnostic CO2/CO	Diagnostic O2/N2
11/09/2014	T2	S	No Fault	ND	ND	ND	ND	OK	*
24/07/2015	DT	S	ND	PD	ND	PD	PD	OK	OK
18/08/2015	D1	D1	ND	D1	D1	T	D	OK	*
18/08/2015	D1	D1	ND	ND	ND	T	ND	OK	*
23/09/2015	D1	D1	ND	D1	D1	T	D	OK	*
25/04/2016	D2	S	ND	ND	ND	ND	ND	OK	*
24/01/2017	D2	D1	ND	ND	ND	T	ND	OK	*
04/12/2017	D2	S	ND	ND	ND	T	ND	OK	*
28/07/2021	D2	D1	D2	D2	D2	T	D	OK	*
28/07/2021	D2	D1	ND	ND	ND	OHC	ND	**	OK
02/09/2021	D2	D1	ND	D2	D2	T	ND	OK	OK
14/09/2021	D2	D1	ND	D2	D2	DCE	ND	**	OK

*oil oxidation or paper ageing
** Probable paper involvement in a fault in very High value of CO2/CO OK: normal deterioration of paper

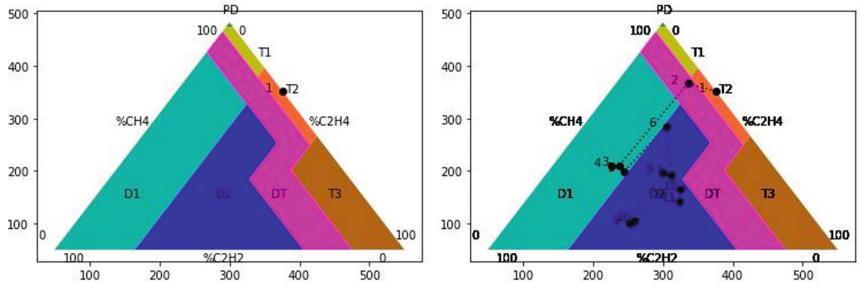


Fig. 2. Duval triangle examples for the sample dates of 14/09/2014 and 14/09/2021

Group 2: Methods that provide explanations of the defect such as CO2/CO, O2/N2. According to this analysis, Duval triangle method shows the most robustness in transformer state detection and after that CIGRE SC-15 method is the more robust and reliable.

3 Conclusion

This manuscript endorses an in-deep statistical study based on different DGA interpretation algorithms. The datasets were used to build and evaluate the performance of the different diagnosis methods of group 1. The results show the effectiveness of Duval triangle 1 and CIGRE SC-15 that have been tested through several actual tests from SNCF Réseau.

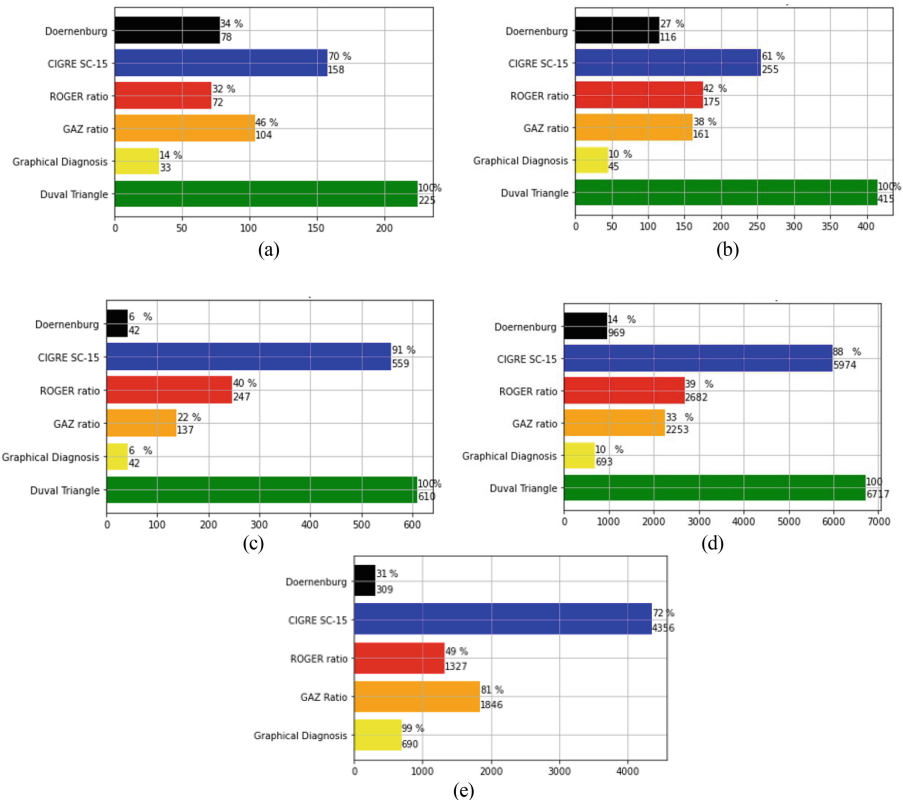


Fig. 3. A comparison of the different Group 1 methods for (a) all 60 MVA transformers, (b) all traction transformers with a secondary voltage of 25 KV, (c) all traction transformers with a secondary voltage of 1500 V DC, (d) all traction transformers with different power and secondary voltage, (e) Identical faults between Duval triangle and other methods for all transformers

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Evaluating the Pollutant Removal Efficiency of a New Retrofittable Sustainable Drainage Material

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Abstract. Urban transport runoff is a significant contributor to water pollution. It contains a mixture of pollutants which originate from sources including fuel combustion, fuel losses and oil leakages from hydraulic systems. This research sought to evaluate a new sustainable drainage material, known as BlueLay, for its pollutant removal efficiency. Initially, the hydraulic performance of the BlueLay was tested in terms of infiltration volume, absorption capacity and runoff compared with asphalt slabs of the same area. Building on these findings, a laboratory-scale pollutant test rig was constructed to evaluate the pollutant removal efficiency of BlueLay. The material was subjected to typical concentrations of Total Suspended Solids (TSS) (i.e., 75–774 mg/L) and a subset of heavy metals – Cadmium (Cd), Copper (Cu), Zinc (Zn) and Lead (Pb) found in road runoff under scenarios that replicated first flush and saturated overland flow events. The findings revealed that the range of TSS removal by BlueLay was >94% for all scenarios, and > 97% removal was achieved for saturated BlueLay. BlueLay in its dry state treated Pb (<145 µg/L), Cu (<110 µg/L), Zn (<315 µg/L) and Cd (<5 µg/L) to values well within the legislative (S.I. 272/2009) limits. For the highest applied concentrations of Cu (170 µg/L), Zn (600 µg/L) and Cd (10 µg/L), dry BlueLay exceeded the legislative limits by 1.4 µg/L, 9.2 µg/L and 0.4 µg/L respectively. In comparision, the exceedance from asphalt for the same metal concentrations, was approximately 100x, 50x and 20x larger. Future work includes testing pollutant removal efficiencies for a subset of Polyaromatic hydrocarbons.

Keywords: Water Quality · Road Runoff · Sustainable Drainage

1 Introduction

An increase in urban development globally has resulted in decreased infiltration and increased surface runoff [1, 2]. This is a major cause of water pollution in rapidly growing cities [3] as pollutants present on impervious urban surfaces get washed into waterways along with the excess water [4]. In the UK, urban transport runoff contributes to nearly 13% of all water pollution [5]. Conventional stormwater drains are designed to mitigate flood risk, but do not treat pollutants present in surface runoff before conveying it into waterways [3].

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Fuel combustion, oil spills, road construction materials [6], and vehicle component wear [7, 8] are some sources that can introduce pollutants onto road surfaces [9]. The composition of pollutants depends on factors such as Average Annual Daily Traffic (AADT) [10], land use, wind, storm events and dry periods [11]. Pollutants in road runoff include Poly Aromatic Hydrocarbons (PAHs) [12], vehicle oils [13], Volatile Organic Carbons (VOCs), heavy metals and Total Suspended Solids (TSS) among others. These can be water-soluble, or sediment bound. TSS and heavy metals [14, 15] are highly prevalent in road runoff [16] and designated as priority/specific pollutants [17, 18] and pose a major ecological risk [19, 20] to freshwater ecosystems. Road deposited sediment (RDS) accumulated in dry weather is mobilized during rainfall events and can act as a carrier [21, 22] for pollutants and as a source of TSS in surface runoff [23]. Pollutants are regulated to comply with various legislative standards globally. Standards followed in Ireland are set by the European Union Water Framework Directive (WFD) [17] and the S.I. 272/2009 [18].

High intensity stormflow conditions in Ireland are predicted to increase by up to 20% [24] in the autumn and winter months, on account of climate change. With an extensive road network of 5306 km comprising dual carriageways, motorways, and single lane roads [25], an increase in high intensity stormflow conditions could further exacerbate the volumes of road runoff and contaminants entering waterways.

Sustainable drainage systems (SuDS), Green Infrastructure (GI) and Low Impact Development (LID) are among available approaches to managing stormwater runoff in a way that minimises environmental impact. SuDS technologies such as constructed wetlands, permeable pavements and filter drains are designed to manage both quality and quantity of urban surface runoff [26]. While installation of these technologies in new developments is feasible and required in Ireland [27], retrofitting them into existing infrastructure can be challenging and resource intensive. A new material called BlueLay was evaluated as a potential retrofit SuDS material. It is a highly porous medium made of compressed rockwool and held between sheets of glass fibre.

In this paper, findings are presented from tests where BlueLay is dosed with TSS and a subset of heavy metals (Cu, Zn, Pb, Cd). Initially, the hydraulic performance of the BlueLay was tested in terms of infiltration volume, absorption capacity and runoff attenuation compared with asphalt (Stone Mastic Asphalt - SMA 10) slabs of the same area. Results of hydraulic tests on BlueLay indicated that attenuation of water was higher (20–27%) in short duration storms (5 min). High intensity (172 mm/h) short duration (5 min) storm conditions were therefore adopted for this study to evaluate the water quality performance of BlueLay, compared to asphalt. The following research questions were investigated:

1. How does dry BlueLay compare with asphalt roads in terms of:
   (a) Total Suspended solids removal?
   (b) Heavy Metals removal?
2. Does pollutant removal efficiency (BlueLay) vary when saturated with water?
3. Does pollutant removal efficiency (BlueLay) vary when saturated with pollutants?

2 Materials and Methods

2.1 Pollutant Test Rig—Rainfall Simulator

Rainfall simulators (Fig. 1) were developed in-house to generate short duration high intensity rainfall (179 mm/h or 0.2 L/min). Each rainfall simulator consisted of an acrylic tube 0.5 m in length with a diameter of 100 mm fitted with 3-D printed nozzles and base plate. An inflow and overflow pipe ensure that a constant head was maintained for each rainfall event. All plumbing fixtures were made from plastic/acrylic to remove any possible metal contamination. Each simulator was supplied with deionised (DI) water from a header tank with an on-off valve arrangement. DI water was used to ensure consistency and repeatability of experiments.

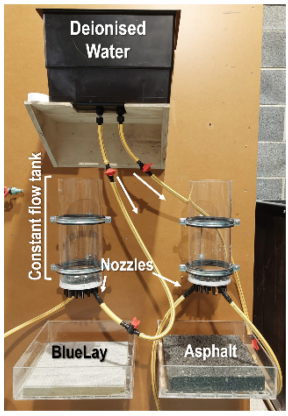


Fig. 1. Constant head rainfall simulators testing BlueLay (left) and Asphalt (right) slabs (305 mm × 305 mm).

Each test slab (BlueLay/Asphalt) was placed below the rainfall simulators in an acrylic tray with drain holes for effluent collection. Slabs were elevated to a slope (0.5%) to emulate the minimum slope of a road surface in Ireland [28]. Pollutants were dosed on the surface of test slabs. To ensure there were no complex interactions between the different pollutant classes, TSS and metals were dosed separately. BlueLay and asphalt were tested under three different scenarios to simulate real life rainfall conditions (Fig. 2). Runoff and infiltration effluents were then analysed (Sect. 2.3) for TSS and metals to assess pollutant removal efficiency of each slab.

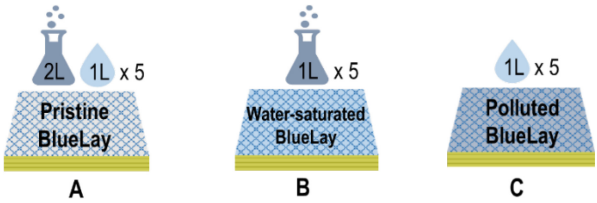


Fig. 2. Test scenarios for BlueLay (Asphalt tested only for scenario A). (A) Pristine material subjected to 2 L pollutant (flush) followed by 5 rain events. (B) Material after high rainfall period subjected to 5 pollutant (flush) events. (C) Material after high rainfall and dry periods subjected to 5 rain events

2.2 Synthetic Runoff—TSS and Heavy Metals

DI water was used while making synthetic runoff (pollutant) solutions for both TSS and metals solutions to ensure repeatability and consistency. The ranges of TSS and dissolved metals typically found in road runoff are provided in Table 1.

Table 1. Ranges of heavy metals and TSS found in road runoff based on literature

Pollutant	Units	Runoff range [16, 26]	Legislative requirements (S.I. 272/2009)
Cd	µg/L	<4.8	<0.8
Cu	µg/L	<136	<5
Pb	µg/L	<179	<20
Zn	µg/L	34–497	<30
TSS	mg/L	75–774	<30*

*Guideline recommends TSS <25 mg/L for freshwater bodies, <30 mg/L for coastal and transitional waters.

Kaolin ($Al_2Si_2O_5(OH)_4$), a naturally occurring hydrous aluminium silicate mineral, was used to create synthetic runoff for TSS tests. Kaolin has a particle size of <5 µm. BlueLay was tested under all three scenarios for TSS removal efficiency. Asphalt was not tested for scenarios B and C as saturation was not possible.

A trace metal solution was prepared with metal standards of Zn, Cu, Cd, and Pb. Stock solutions for each heavy metal were prepared separately using 1000 mg ampoules (Merck) of dissolved metal solutions. Pollutant mixes were made with equal volumes of each metal type with concentrations based on literature review (Table 1). Tests were carried out in triplicate to ensure repeatability and reproducibility. Pollutant mixes for TSS and heavy metals were made in 3 concentrations: C1, C2, and C3 (Table 2). C3 was the highest concentration factoring in 20% increase for climate change [24].

Table 2. Concentrations of synthetic pollutant mixes for testing

Heavy metals (µg/L)	C1	C2	C3
Cd	1	5	10
Cu	50	110	170
Pb	50	100	145
Zn	30	315	600
TSS — Kaolin (mg/L)	75	350	800

2.3 Analytical Methods

TSS was measured using EPA method 160.2, a gravimetric method for TSS analysis (LOD = 0.1 mg/L). Samples were filtered through 0.05 µm Millipore filter paper. Since the presence of TSS in a sample affects its light scattering properties, the amount of light scatter is proportional to the concentration of suspended solids in the sample. Therefore, turbidity of samples was also measured in addition to TSS.

To calibrate a UV-Vis spectrophotometer (Hach DR 2800) for metals analyses, a preliminary analysis was done by ICP-MS (Thermo Scientific iCAP-Q ICP-MS) at the National Centre for Isotope Geochemistry in a high collusion matrix (cell collision mode). The analytical methods and limits of detection (LOD) for Hach DR 2800 are provided in Table 3. Effluent samples from each test were filtered (0.45 µm cellulose filter) and acidified prior to analysis (2.5 M Nitric acid).

Table 3. Analysis methods and LODs for metals using UV — Vis spectrophotometer

Metal	Analysis methods	Limits of detection (LOD)
Cd	Dithizone method (8017)	0.7–80.0 µg/L
Cu	Porphyrin method (8143)	1–210.0 µg/L
Pb	LeadTrak method (8317)	5–150 µg/L
Zn	Zincon method (8009)	0.02–3.0 mg/L

3 Results and Key Findings

3.1 TSS Removal

Scenario A: Pristine dry material (Fig. 3a, b). Dry pristine BlueLay (Fig. 3a) achieved 89% removal for the highest concentration (800 mg/L) of applied TSS after one rain event and an overall of 85% TSS removal after five rain events. For the same concentration, asphalt (Fig. 3b) removed 15% TSS after the first rain event and an overall of 7%

after the fifth rain event. For the lowest concentration (≤75 mg/L), BlueLay removed 84% and 71% TSS after the first and fifth rain events respectively. This shows that BlueLay attenuated low concentrations (≤75 mg/L) of TSS to within WFD guidelines (<30 mg/L). For medium (350 mg/L) and high (800 mg/L) concentrations, dry BlueLay exceeded guidelines by ~26 mg/L and ~ 60 mg/L (first rain event). In comparision, dry asphalt slabs exceeded guidelines by ~268 mg/L and ~648 mg/L.

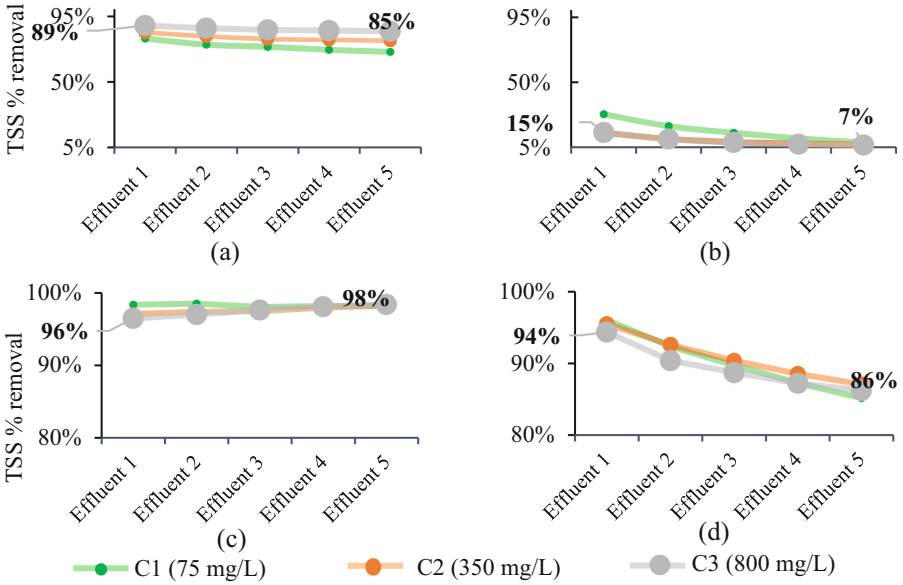


Fig. 3. TSS % removal by (**a**) dry pristine BlueLay, (**b**) dry asphalt, (**c**) water-saturated BlueLay and (**d**) pollutant-saturated BlueLay when subjected to three different TSS concentrations followed by five high intensity short duration rain events. Results are shown for all rain events.

Scenario B: Water-saturated BlueLay (Fig. 3c). Water-saturated BlueLay achieved 97 ± 1% removal after first flush and an overall of 98% removal after the fifth flush event for all applied concentrations. BlueLay attenuated TSS concentrations (≤ 800 mg/L) to <30 mg/L even after five flush events.

Scenario C: Polluted BlueLay (Fig. 3d). Polluted BlueLay attenuated TSS for medium and low concentrations to within WFD guidelines (<30 mg/L). For high concentrations, BlueLay removed 94% TSS after the first rainfall event an overall of 86% TSS after the fifth rainfall event, but the TSS in the effluent exceeded WFD guidelines by ~15 mg/L.

3.2 Heavy Metals Removal

BlueLay in its dry state attenuated all four metals (Cu, Zn, Cd, Pb) to values well within the legislative [20] limits (Table 1) for medium (C2: 520 µg/L) and low range (C1: 132 µg/L) metals concentrations (Table 2).

When high concentration (C3: 925 µg/L) metals solution was applied to BlueLay, after the first rain event effluents (Fig. 4a) showed Cu, Zn and Cd concentration exceeding legislative requirements by 1.4 µg/L (Cu), 9.2 µg/L (Zn) and 0.4 µg/L (Cd). Pb was removed to well within legislative limits (<20 µg/L).

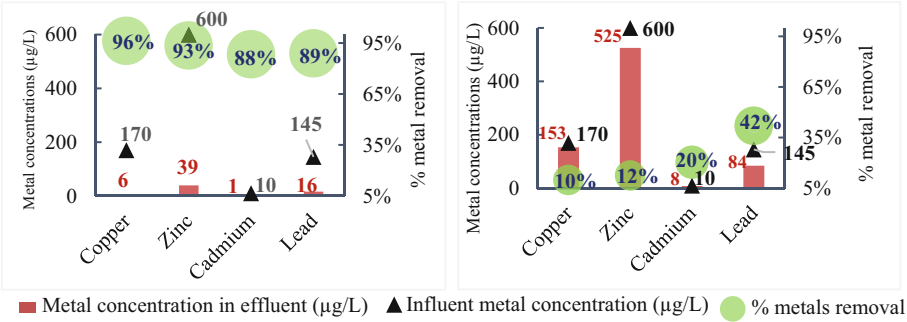


Fig. 4. Attenuation of high concentration metals (925 µg/L) by **(a)** dry BlueLay and **(b)** dry Asphalt after first rain event.

However, these values are considerably lower than the values obtained from the runoff from asphalt slabs of the same size, which exceeded the required limits by ~148.2 µg/L (Cu), ~495 µg/L (Zn), 7.17 µg/L (Cd) and 64 µg/L (Pb). Results shown in Fig. 4 are for a subset of Scenario A where metals concentrations in the effluents from BlueLay (Fig. 4a) and Asphalt (Fig. 4b) exceeded legislative limits.

4 Conclusions and Future Research

This study investigated the pollutant (TSS and heavy metals) removal performance of a porous medium, BlueLay to evaluate its potential as a sustainable drainage material. Attenuation values obtained in this study are for a slab of surface area 0.09 m^2 subjected to high intensity short duration rainfall (179 mm/h, 5 min).

Dry BlueLay attenuated influent TSS ≤ 75 mg/L to <30 mg/L (WFD guidelines). For medium (350 mg/L) and high (800 mg/L) concentrations, both dry BlueLay and asphalt exceeded guidelines. Exceedances from asphalt were ~ 10× and ~ 11× those from BlueLay. Partially or fully water saturated BlueLay attenuated TSS to <30 mg/L for influent concentrations ≤800 mg/L. When saturated with pollutant, effluent TSS concentrations exceeded guidelines by ~15 mg/L. Dry BlueLay effectively removed up to 98% of metal ions when subjected to metal concentrations ≤520 µg/L. For higher concentrations (C3: 925 µg/L), metal concentrations in effluents from BlueLay and asphalt exceeded legislative limits. Exceedances from asphalt were ~ 100× (Cu), 50×(Zn) and 20×(Cd) larger than those from BlueLay.

To meet regulatory requirements for higher concentrations of pollutants, the performance of BlueLay needs be complemented. From this perspective and for its potential application as a retrofit SuDS material, BlueLay is currently being tested for its performance when interfaced with other porous media such as soil, vegetation and gravel that

may be present next to road surfaces. Soil is known to attenuate pollutants like metals by adsorption [29]. Gravel and vegetation can promote sedimentation of TSS by reducing water velocity [30]. It remains to be seen whether these properties could improve the performance of BlueLay.

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Additive Manufacturing for SNCF Réseau: An Opportunity for Generative Design and Laser Powder Bed Fusion

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Abstract. SNCF Reseau investigates metal Additive Manufacturing (AM) with the ambition to leverage its potential in the rail network sector to benefit from a supply chain perspective as well as from an asset manager point of view. Laser powder bed fusion (LBPF) opportunities are quite uncommon in the rail network industry, particularly due to its current high cost. The design freedom of LBPF can nevertheless be very effective for specific consolidation or performance needs. This potential opportunity was identified during the development of a new product designed for the motorization of signal levers. Work has therefore been done with the startup Pint Innovative on the redesign of the part to maximize its performance and minimize its manufacturing cost. The generative design method was used for this purpose. We provide in this article an overview of this project focused on the design work.

Keywords: Railway · Laser powder bed fusion · Generative design

1 Introduction

As network manager of the French rail infrastructure, SNCF Reseau is responsible for the maintenance, modernization, and safety of the network. Our technical scope covers more than 50 000 different parts including several kinds of turnouts which are common devices on the network. In some case, railway switches can be performed by mechanical levers acting through wire connection (Fig 1). Despite a proper maintenance of the installation, the amount of friction can be very important, and levers can be hard to use. Even if the technology is old, there is still almost one third of the signaling post using this kind of mechanical based solution. Although some of these posts will evolve over the coming decades into cutting-edge computing technologies, the investment needed is so enormous that most of them will last at least 50 more years. Given this lifespan, it was decided to improve the technology by developing a motorization for some of these levers. The motorization is based on the addition of a circular gear rack on the lever, of a motor fixed on the frame of the lever and of a gear train between them to transmit the torque (Fig. 2a). The motorization implies several elements, the main device being the support element holding the motor and some of the gear mechanism (Fig. 2b).

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Fig. 1. Overview of the Rail Yard of Rennes (a) Mechanical levers within the signaling post (b) wire transmission (c)

This support element has originally been designed for conventional manufacturing, implying the machining and assembly of 8 parts, with extra time to carry out the assembly operations with the required precision (Fig. 2c). As an industrial player SNCF Reseau is always in search for solution to improve asset management (obsolescence, development of more efficient parts) as well as to relieve the supply chain when possible (delivery time, stock management…). In this search for performance, Additive manufacturing has long been identified as a promising technology to enable new and performant designs as well as to help solve supply chain issues [1]. In the scope of its work on AM and given the analysis of the Support element SNCF decided to produce a consolidated version using additive manufacturing. The aim of this study is to provide an overview of this AM project focused on the design work.

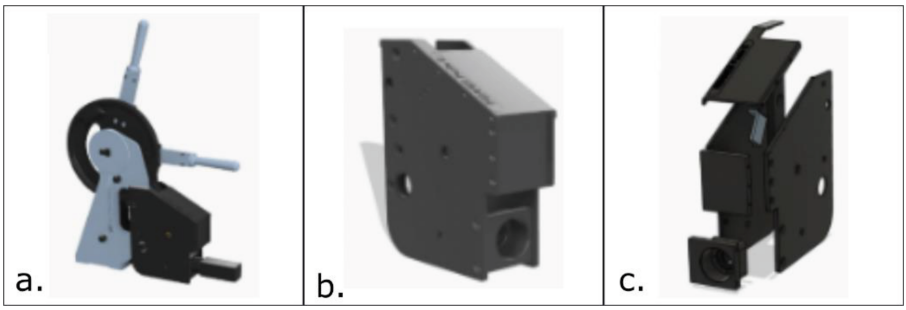


Fig. 2. Motorized lever assembly (a), gear support (b), gear support exploded view (c)

2 Methodology

Design For Additive Manufacturing (DfAM) is a specific area of design [2]. Complex approaches and software can be used to get the better of AM while considering key process-dependent limitations (wall thickness, supports…). The prior choices of process and material are mandatory to build a relevant design. Integration of the final 3D printing

machine from the beginning is optional but can also be valuable to optimize the build plate and hence lower the final cost. In this specific case, we decided to work with LPBF technology and 316L material. Given the fatigue solicitation of the device we also set a target maximal stress of 100 MPa to aim at an acceptable lifetime even in "as built" condition. Indeed, if specific post process treatment (thermal or mechanical) can dramatically improve the mechanical performance, the cost of these post process should be kept as low as possible to be competitive with the conventional solution.

We worked on the design with Pint Innovative on this base, trying to build the most relevant design through Topology Optimization (TO) and Generative Design (GD). Indeed, GD and TO are two interesting and usual tools relevant for exploring the design freedom allowed by additive manufacturing processes [3, 4]. In both cases, the ability to drastically reduce the amount of material while maximizing strength and performance helps build AM solution that can be economically more efficient than conventional design. Both approaches have in our case a quite similar workflow initiated with a native geometry and concluded by a final manual editing and an associated design analysis (Fig. 3). Nevertheless, these tools rely on fundamentally different approaches and give very different results [5].

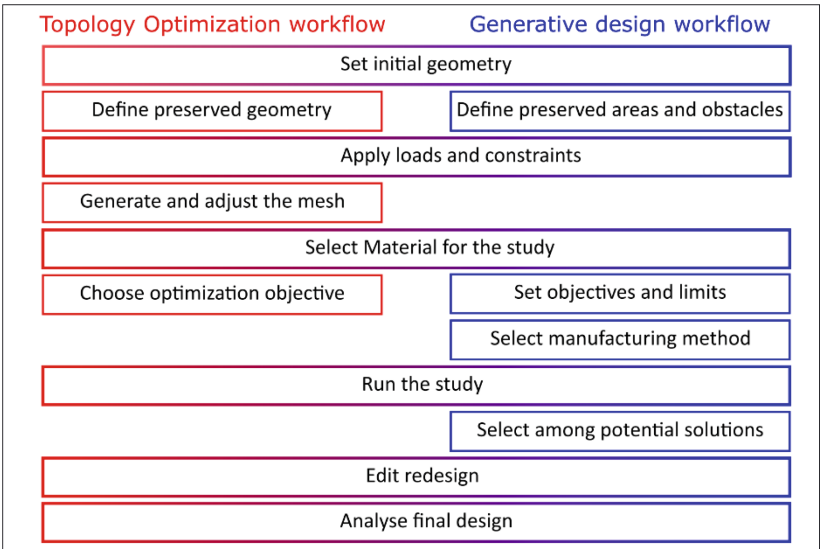


Fig. 3. Comparative workflow for Topology Optimization (red) and Generative Design (blue). Inspired from Vlah et al. [5]

TO is a method derived from numerical simulation. The initial geometry is a design space considered as full of material and the aim of the process is to rearrange material given the loads constraints. It uses the result of a mechanical numerical calculation of a component in order to retain material only where necessary. In our case, the frame parts are isolated from the system and merged to form a single part which is the initial design (Fig. 4a). We used a Single Objective Optimization (SOA) and set our target

regarding weight reduction to 10 to 30% of the initial weight. The software used by Pint Innovative was Autodesk Fusion 360 which is based on the solid isotropic material with penalization (SIMP) algorithm [6, 7].

GD uses a different approach. The method starts with geometries to be preserved and obstacle geometries defined by the user. The design space in mainly empty and the aim of the process is to find efficient way to fill it with the minimal amount of material needed to withstand the loads. This process considers manufacturing methods: additive (with manufacturing orientation and limit angle) or machining (2, 3, or 5 axes), materials (with the possibility of analyzing several materials in the same operation) and generates the material at the locations required to meet all the input criteria. For the GD model, features from the initial parts are isolated and defined as areas to be preserved (Fig. 3b). The gear elements are defined as obstacles to avoid a solution that could not allow the assembly. As well as for TO, the software used by Pint Innovative was Autodesk Fusion 360 which is based for GD on level set method (LSM) [8].

GD usually gives a lot of different solutions among which a selection must be made. Even if stochastic algorithm can be used, in our case TO relies on deterministic algorithm and hence defines one single optimum for a given set of constraints. The variation of this set is the only way to obtain different designs. In TO, it is also mandatory to edit the final design whereas in GD, the consideration for the manufacturing method makes it optional.

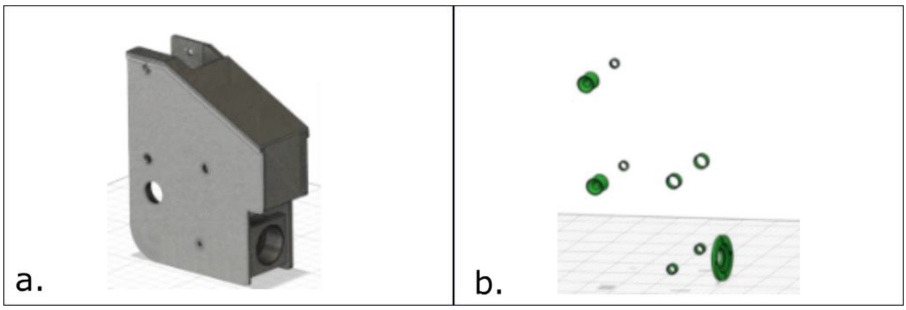


Fig. 4. Simplified meshed component for Topology Optimization (a), areas to be preserved defined from the original geometry for Generative Design (b)

3 Results

3.1 First Results

Several results have been obtained with the two methods, thanks to the different mass reduction aims for TO (between 70% and 90%) and to the inherent variability offered by the GD approach. Our first evaluation of these designs was mainly based on volume, mass and production time of each part. The most relevant designs after this first screening are presented in Fig. 5(a–c).

In this specific case, GD solutions appeared as more efficient than topology Optimization result. This is not surprising as TO was certainly too constrained by the design space limited to the conventional part whereas GD had more freedom to build alternative solutions as the sole limitations was induced by forbidden space. Despite the ability of GD to consider process limitations through the boundary evolution method, the final design needed some manual redesign to improve its manufacturability and performance. The result of this redesign phase is presented below (Fig. 5d). The mass of the final part is 2.7 kg which represents a mass reduction of 78% compared to its conventional alternative.

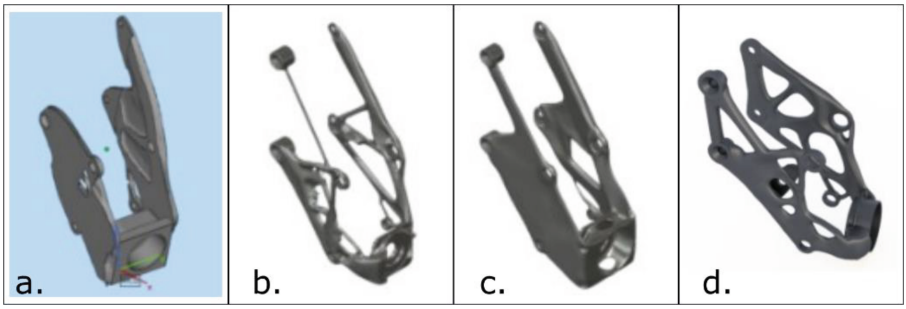


Fig. 5. First results of Topology Optimization (a) and Generative Design (b, c) and redesigned component (d)

3.2 FEA Analysis of the Final Design

The redesigned component was then submitted to a mechanical analysis for both directions of motor rotation (Fig. 6). The need was to verify the compliance of the redesigned part to our initial specifications regarding a maximum stress of 100 MPa. For this part, the maximum stresses are 81MPa and 66MPa in one direction and the other respectively.

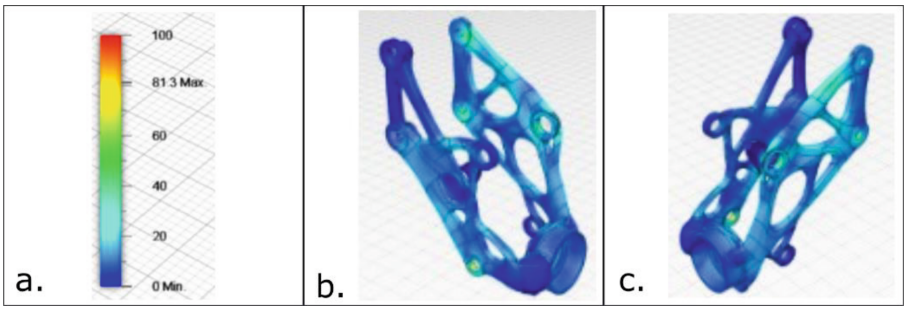


Fig. 6. Stress repartition in the designed part for the clockwise motor rotation (a–c).

3.3 Prototyping and Assembly

Prototypes were manufactured in accordance with our initial specifications in stainless steel 316L on a SLM 280 L-PBF machine equipped with two 400W lasers. A standard parameter set is used with a 50 µm layer thickness. Four parts are built together on the build plate (Fig. 7a–b). Post treatment is limited to a stress relief heat treatment of 700 °C for 1h and sand blasting.



Fig. 7. Part placement on the build plate (a) built parts (b) and final assembly (c)

4 Conclusion and Future Works

The prototype is functional (Fig. 7c), validating the technical part of the project as a success. The economic part is still a work in progress. Some design evolution could indeed be interesting to study, in particular to optimize the build plate of what would be the final LBPF machine (with potential effects on the orientations and the supports to be evaluated).

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Additive Manufacturing for SNCF Réseau: Investigation on Material and Process Opportunities for Industrial Purpose

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Abstract. SNCF Reseau investigates Additive Manufacturing (AM) with the ambition to leverage its potential in the rail network sector to benefit from a supply chain perspective as well as from an asset manager point of view. A wide range of AM materials and processes are available, but we limited our work initially to Multi Jet Fusion (MJF) for polymers and to Selective Laser Melting (SLM) and 3D Sand Printing (3DSP) for metals. We provide in this article an overview of our current work, illustrated with some of our latest achievements.

Keywords: additive manufacturing · supply chain · industrialization · rail

1 Overview and Motivation

As network manager of the French rail infrastructure, SNCF Reseau is responsible for maintenance, modernization, and safety of the network. Our technical scope covers more than 50,000 different parts in different fields: railway signaling, tracks, power supply, bridges and tunnels, telecom… As an industrial player SNCF Reseau is always in search for solution to improve asset management (obsolescence, development of more efficient parts) as well as to relieve the supply chain when possible (delivery time, stock management…). This industrial need for performance of our supply chain is what triggered our investigation on AM back in 2019 with a first identification of potential use case parts based on a whole cost analysis, including stock, shortage, and non-quality cost impacts.

Additive manufacturing is the process of creating an object by building it one layer at a time, thus offering new design spaces as well as a short delivery time. It has long been identified in industry as a promising technology to enable new and performant designs as well as to help solve supply chain issues [1]. The technology is already known in the railway sector, mainly for rolling stock maintenance [2].

There are more than 100 AM processes currently available. The selection of the most promising processes for our use has been made through 2 key expectations: the technical capability with respect to our identified potential use cases (available material, maximal part size, surface condition…) and the economical relevance (cost of the part, industrial maturity, number of suppliers with both machines and know how…). After a

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first step of global assessment, we decided to begin our investigation with 2 among the most mature AM processes available on the market: Multi Jet Fusion (MJF) for polymer and Selective Laser Melting (SLM) for metals. We also choose to investigate Binder Jetting through 3D Sand Printing (3DSP) which seemed a promisingly straightforward process to help with castings.

2 Methodology and First Results Regarding Polymer AM

2.1 Typical Polymer Use Case and Associated Methodology

Our typical needs for polymer parts are parts with low mechanical requirements including gears and covers as well as parts concerned with electrical resistivity (Fig. 1). The technical area of relevance is mainly railway signaling where a lot of legacy parts are Injection Molded (IM) parts with no more molds and sometimes outdated materials. We also have some use cases with casting parts that could be efficiently switched to polymer. Criticality of these parts are variable but most of them are components of security devices and as such we must validate the characteristics and capability of the process.

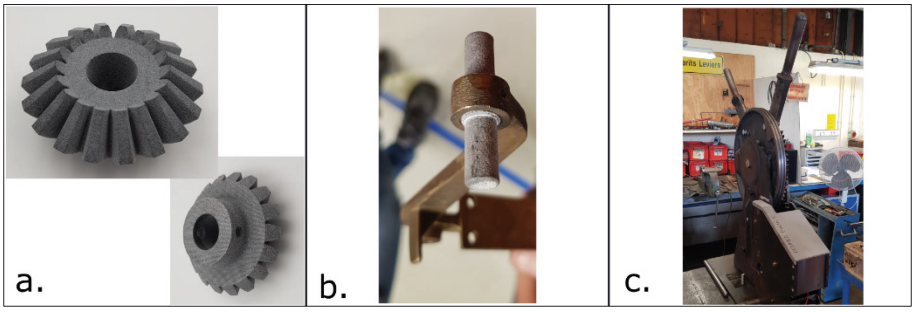


Fig. 1. Some typical use cases for PA12 on the rail network: **a**) gear for railway signaling device **b**) axis with isolation need **c**) specific cover

This validation is based on four successive steps. The first need is to assess the material compliance with our railway standard (NF EN 50125-3). If the part's function relies on specific material abilities, we then must qualify the part with the associated specific complementary tests (solvent behavior, electrical test…) before making field tests with the final part. The last step is related to industrialization with the need to express technical specification for our internal use or for our suppliers as well, which includes our need for verification and control of the final parts.

2.2 Insight into our Investigation on Polymer Processes

MJF materials have been partially studied [3, 4] and many data were missing for assessing the material compliance with our rail norm. Therefore, we had to design a specific experiment for assessing the technology relevance (Fig. 2a). The mechanical results of

PA12 were satisfactory with almost no effect of the first aging and an acceptable drop in PA12 characteristics after the whole aging process (Fig. 2b). Therefore, the process and material have been validated for further consideration.

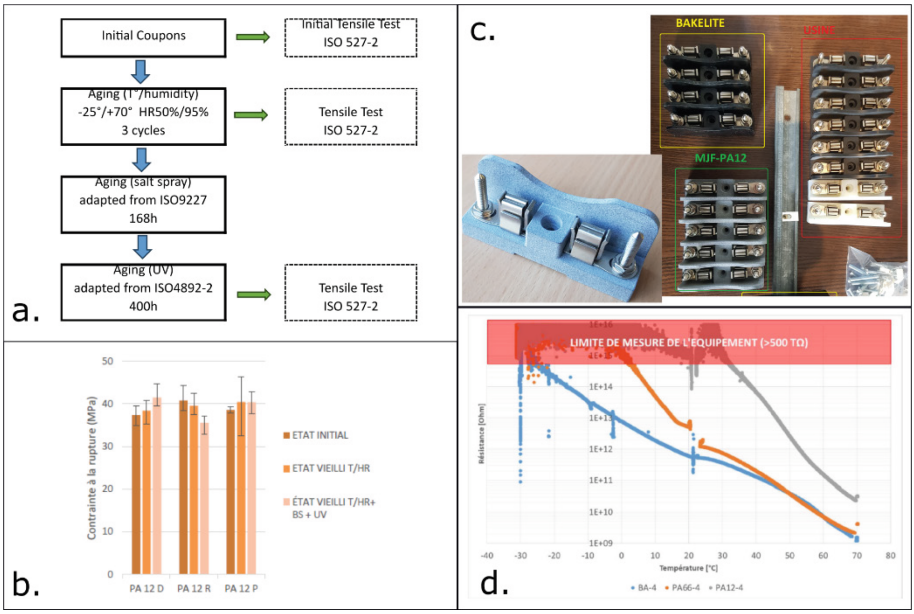


Fig. 2. MJF PA 12 insights: (**a**) general experiment design (**b**) ultimate tensile test results after whole ageing corresponding to experiment (**a**) (D – dyed, R- raw, P – painted, the strong color corresponds to the initial test, the light color to the final test and the medium color to the intermediate test) (**c**) our typical use case for electrical resistivity (**d**) comparative resistivity of PA12, PA66GF30 and Bakelite at different temperature (the red area represents the measurement inaccuracy for too high resistivity)(Colour Figure Online)

Since the use case of electrical insulators seemed promising, we further investigated the electrical behavior of the material, comparing PA12 (MJF printed), PA66GF30 (current intended material for IM) and Bakelite (historic material for IM) for a specific end use part (Fig. 2c). As we can see (Fig. 2d) the test showed a promising behavior of the PA12 parts with a resistivity at least ten times higher than that of Bakelite whatever the temperature and humidity. Field testing on this part remains to be done and may be a bit challenging as field exposure linked to the surface condition can lead to specific issue like organic film which could impact the surface resistivity.

We have also made some assessment regarding the industrialization of the process and the ability of the suppliers to produce consistently our parts. The way we can manage production and ensure repeatability as well as control the end part quality is not established yet. One of the main points of our current work is the management of porosity issues through the understanding of the effect of key process parameters. We also

work on the integration in our technical specification of build qualification through relevant destructive (tensile coupons) or nondestructive tests (density measurement, powder characterization…).

2.3 Next Steps

The currently investigated technology is promising but has not yet reached the degree of industrialization needed for the regular production of end use parts for the rail network. Beyond this work in progress, it is worth noting that SNCF Reseau continues its investigation with new materials like PA11. We also need more rigid materials to expand the scope of relevance of AM to parts with more mechanical requirements. Some investigations are currently led or will soon be led with Selective Laser Sintering (SLS) and specific materials as well as Fused Deposition Modeling (FDM) with continuous composite fibers.

3 Methodology and First Results Regarding Metal AM

3.1 Typical Metal Use Case and Associated Methodology

The scope for metal parts is quite broad as we have on the network a lot of mechanical parts concerned with mid to high mechanical requirements. The technical area of relevance is quite broad with numerous legacy castings having no available molds and a very small annual need. In a first step we have focused on standard parts, avoiding components with very specific mechanical requirements (mostly rolled or forged steel) like tracks or turnouts. However, many might think that the field of track components and its extreme mechanical requirements (technical security) is not a relevant domain for 3DSP, but in fact, the field of turnouts, for example, includes many various molded parts. Of course, the economic relevance must be validated in each case. Like for polymers, criticality of the parts is variable but should be considered as usually high and a technical validation of the process is needed before any field deployment. This validation is here again based on four successive steps: assessment of the material mechanical characteristics, complementary tests when needed (metallography, magnetic test, electrical and thermal tests…), field tests with the final part and lastly industrialization step (technical specification). An economic validation is also carried out in parallel.

3.2 Insight into our Investigation on 3DSP Processes

3DSP relies on the fabrication of the sand mold through AM (Fig. 3a) before a conventional cast (Fig. 3b). As the only difference with casting is on the mold manufacturing technology, 3DSP is sometimes seen as a low hanging fruit of AM. The technology is nevertheless sensitive to a lot of parameters and must be properly managed to obtain acceptable results [5]. We firstly assessed the technology, meaning a specific combination of machine (associated with its sand and binder) on one side and a specific alloy on the other. The first test we made concerned cast iron EN GJS 500-7 on an Exone S-max. These tests were conclusive as they were in line with expectations from a conventional

casting regarding mechanical test, metallography (Fig. 3c) and hardness tests (Fig. 3d). This first experience allowed us to consider 3DSP as a potential solution when we faced a supply chain situation in early February 2022 for the supply of castings at the beginning of April 2022 with no available molds.

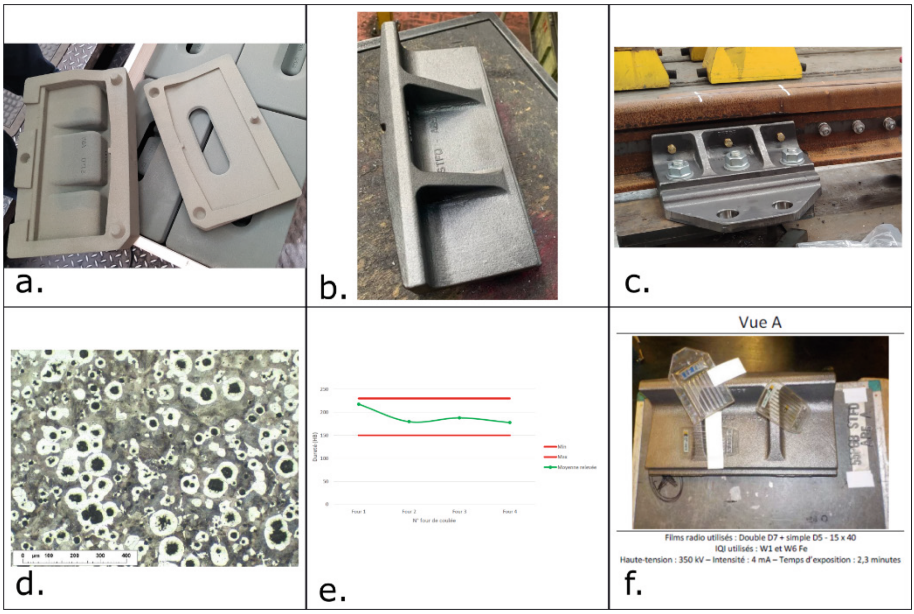


Fig. 3. 3DSP use case: (**a**) sand mold (**b**) casting from the sand mold (**c**) part mounted on the rail (**d**) metallography of the 3DSP part in line with EN GJS Expectation (**e**) hardness results (**f**) part ready for radiography (X ray shooting plan)

We delivered the parts (Fig. 3c) in time successfully passing every step from mold design and validation to part production and verification. Regarding the validation step we chose to activate our existing casting technical specification to its full extent (as for the most critical parts) and even add specific control of the supplier. Every test showed properties in the expected range and the works were able to take place on time.

3.3 Insight into our Investigation on SLM: First Results

SLM is one of the most mature AM processes [6] as it allows efficient redesign. Nevertheless, its high cost limits its relevance for the network, where weight reduction is usually not interesting. The design freedom of SLM AM can however be effective for specific consolidation or performance needs. This potential opportunity was identified during the development of a new product designed for the motorization of signal levers (Fig. 4a). A lot of work has therefore been done on the redesign of the part to maximize its performance and minimize its manufacturing cost (Fig. 4b). The prototype is functional (Fig. 4c), validating the technical part of the project as a success. The economic

part is still a work in progress. Some design evolution could indeed be interesting to study, to optimize the build plate of what would be the final SLM machine.

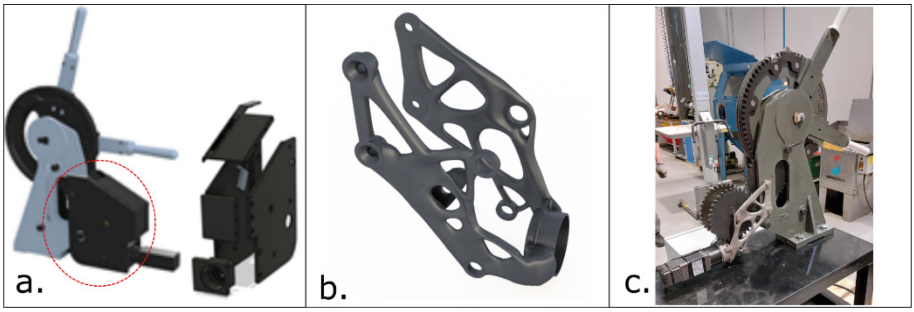


Fig. 4. An SLM use cases (**a**) conventional part made of 8 components (**b**) consolidated part redesigned with generative design (**c**) SLM Part mounted on the lever

3.4 Next Steps

Regarding 3DSP our main need is to expand the use to other alloys like aluminum copper. SLM can be relevant for railway purposes provided we approach the qualification and post-processing stage in an economical way. This is one of our ongoing works with some industrial partners. Other technologies are promising for our use and are being evaluated such as metal binder jetting with a lot of work related to fabrication simulation as well as partial sintering or infiltration.

4 Conclusion and Future Works

At this stage of our investigation, the proof is made that AM has a potential for the rail network. An industrialization framework is underway for MJF, IC and SLM. Improving our ability to identify promising parts, continuing to explore technologies with an industrial spirit (capacity, repeatability, etc.) and improving our economic model are the key areas of future work to move forward on the industrialization of AM.

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Ballasted Track Renewal for High-Speed Mobility

How Recent Technical Innovations Will Allow SNCF to Build a New Model of Track Renewal for Tomorrow

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Abstract. The roadmap for the renewal of French high-speed lines charts the first massive track and ballast renewal operations on the Paris-Lyon High-Speed Line by 2028–2034. SNCF Réseau is initiating a strategic reflection to tackle the major challenges posed by the highest-usage axis in Europe. Framed by the aging laws, the studies in progress will determine the operational maintenance of the main components (rail, ballast, and concrete sleepers), in order to plan -in space and time- the regeneration of nearly 540 km of high-speed lines.

After several years of trying, feedback obtained during the deployment of innovative materials confirms SNCF's choice of designing a "new model of ballast track" with better sustainability and better compatibility with environmental issues. As our recent studies and trackworks have shown, Under Sleeper Pad, ballast gluing, new sleepers and other parts of our Concept Track model reduce maintenance efforts and extend ballast life.

As a matter of fact, innovations in the renewal process provide a global industrial and environmental solution through the reduction of capacity impact (ballast and sleepers renewal at 120 km/h then 160 km/h) to lower impact on commercial traffic and limit resource usage. New methodologies for recycling used ballast allow to greatly cut down on the use of new ballast, thus reducing the environmental footprint and associated costs.

Keywords: track renewal · ballasted track · high speed line · innovative track

1 The Study's Genesis: When Should the Sleepers of the Paris-Lyon High Speed Line (HSL) Be Regenerated?

After more than 40 years of use of the Paris-Lyon High Speed Line, SNCF Réseau (SNCF-R) needs to know the remaining lifespan of the concrete sleepers to plan its financial and industrial strategy for the next decade.

This is why SNCF-R decided to study the various components' lifespan to determine aging laws, based on the following data:

- Track renewal history,

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- Railway assets status,
- Maintenance effort history (Tamping) and future effort estimate.

The theoretical lifetime of the sleepers is estimated at 55 years, which corresponds to an end of life by 2036. 541 km of track are affected by the Vax U41 concrete sleepers' regeneration.

2 Components' Lifespan and Aging Laws

2.1 About Ballast Renewal

In France, the decision to renew the ballast of a part of the HSL is today conditioned by several main factors:

- Arrival of the ballast at mid-life of the estimated lifespan of the sleeper (55 years), i.e., approximately 27 years for a heavily trafficked HSL like the Paris-Lyon (historical criterion),
- Passing through a 25 mm sieve greater than 30%, a criterion from [1, 2] which requires taking numerous samples along the way to determine the remaining life of the ballast,
- The number of tampings. From 28 tampings in the zone (value from [3, 4]) the ballast needs renewal,
- The durability of this tamping and the maintenance of a good quality of track geometry regarding the maintenance effort to be implemented by SNCF.

These criteria complement each other, add up and sometimes come into conflict, which significantly complicates the task of the maintainer in his or her search for performance at the lowest cost.

It therefore became necessary to revisit the subject of ballast aging on HSL to establish new determining criteria. Several studies, still in progress, have been launched for this purpose since 2022 based on this blocking situation and the following findings:

- The ballast does not wear evenly. As shown by [2], the ballast only really wears out in the tamping zones and under the lower level of the sleeper, where the cone of distribution of traffic pressure on the track fragments the ballast that is subjected to compression. A large part of the ballast is therefore not subject to any stress and hardly ages on the track.
- The latest ballast renewals on HSL showed that 70% of the ballast screened by the stripper could be put back directly on the track, a rate which rises to 90% if we consider the ballast reprocessed at the rear base (since 2021, cf. [5]). The "old" ballast is therefore a product which remains of excellent quality, which meets all the standards of new ballast (or even improves them by being already eroded in the protruding places which will inevitably wear out quickly).
- The criterion of 28 tampings used since 2012 is almost always exceeded without excessive problems, and areas with 40+ tampings are frequent.
- The qualities of the platform have been constantly increasing since the first phase of the Paris-Lyon HSL, leading to the rise of fine particles from the platform becoming increasingly rare following the commissioning dates and especially limiting the pollution of the ballast.

All these elements lead us to lean towards a profound reorientation of ballast renewal on HSL, transforming it into an optimized "ballast cleaning" where very little new material is brought in.

2.2 Questioning the End-of-Life Date of the Sleepers

The lifespan estimate of 55 years for HSL concrete sleepers, derived from conventional line concrete sleepers, is now in question for two reasons:

- The first is organizational: if the renewal of sleepers is indeed necessary starting in 2030s, it is appropriate to take charge of its organization in the very next few years.
- The second is of a technical nature: the concrete sleepers deposited since 2020 seem to be, on average, in good general condition. Apart from the faulty fastening system, the rest of the sleeper (the concrete of the blocks of the bi-block sleepers, the spacer) is functional and seems perfectly capable of withstanding a few more years, or even dozens of years, on the track.

Several studies have therefore been launched to question the relevance of these 55 years of lifespan initially estimated.

The first study is a statistical study, launched at the beginning of the 2010s and updated in 2022. By exploiting the heritage bases of the SNCF, we determine the number of sleepers remaining on the track from the number initially installed, focusing attention on the Vax U41 used throughout the whole French Network. Using this vast database makes it possible to better calibrate the aging law.

This makes it possible to estimate a replacement rate, which is then distributed according to a Weibull law with the distribution function:

$$F(t) = 1 - \mathrm{e}^{-\left(\frac{t}{\lambda}\right)^{\beta}} \text{ for } \mathrm{t} \geq 0$$

and a failure probability:

$$h(t) = \frac{\beta}{\lambda}.\left(\frac{t}{\lambda}\right)^{\beta-1}.$$

Although several weaknesses have been identified, this methodology makes it possible to estimate a median time of almost 82 years before sleeper failure with parameter values $\beta = 3.05$ and $\lambda = 91.66$ for heavily trafficked lines.

The second study was the subject of a project at SNCF-R [6] around the concept of accumulation of damage to reinforced concrete structures (Miner's law). Two spectra were used to properly carry out the analysis method: the fatigue loads to which the sleepers are subjected (cumulative tonnage, traffic speed, maintenance effort by heavy tamping) and the properties of its materials (nature of the concrete and its aging, type of soles, type of rail). Indeed, during their lifespan and depending on the impact loads (which are constantly increasing), the materials experience progressive degradation until the structure fails.

In our case, this failure takes place at the level of the reinforcements which are below the support table and is controlled by the positive bending moment in this section. By

integrating all these elements, supplemented by several models, the result for the Vax U41 of the Paris-Lyon HSL of the section considered is a minimum lifespan of 50 years and an average lifespan of 63 years.

However, this preliminary study needs to be completed on several points: experimental tests would be necessary to validate the model and several limitations have been identified on this first phase (in particular, a high sensitivity of the model to the axle load), which justify extending this study to 2024 to refine the results. As such, several samples were taken from the Paris-Lyon HSL in the first half of 2023, which will aim to validate whether the visual trend of a good general condition of the sleepers remaining on the track is confirmed.

At this stage, it therefore seems that the Vax U41 sleepers remaining on the track on the Paris-Lyon HSL have an average lifespan significantly greater than 55 years, depending on the models used. These results will be completed in the coming years, making it possible to reposition the renewal of the sleepers as well as possible in the decades to come.

3 Which Assets for the Future Ballasted Track?

3.1 Concept Track

In the early 2000s, SNCF-R compared the advantages and disadvantages of the ballasted track to the slab track for its HSL. To have a satisfactory basis for comparison, the idea was to study the performance of a new design of HSL track. This new ballasted track was upgraded with the latest component technologies for the track and the platform.

In the beginning of 2021, SNCF-R regenerated 16 km of track, first with a ballast and sleepers' renewal with the components from the "Concept Track" (heavy single-piece M450 sleepers equipped with Under Sleeper Pad), then Rail Renewal using an industrialized method. This renewal project also provided the opportunity to test the ballast gluing (to a depth of approximately 20 cm) and analyzed the improved quality of the track geometry on four different parts of track: renewed track with ballast gluing, renewed track without ballast gluing, unrenewed track with ballast gluing, and unrenewed track.

Three years after the renewal, the results obtained (graph above) show us:

- Track regeneration is a real success with a very significant improvement in track geometry (red and green graph).
- The regenerated track reaches such a level of quality (red graph) that it is difficult to improve more with ballast gluing (green graph)
- Ballast gluing greatly reduces the maintenance effort on the non-regenerated track (yellow graph compared to blue graph). The glue delays the track geometry degradation (Fig. 1).

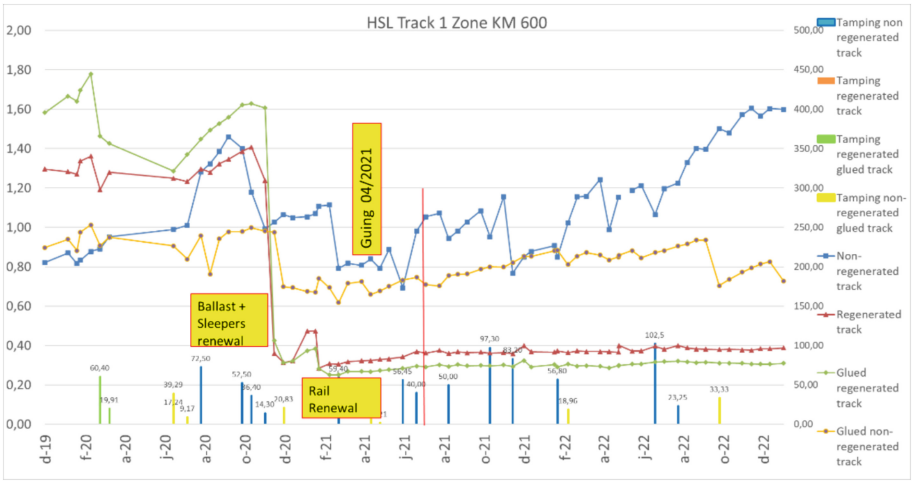


Fig. 1 Paris-Lyon HSL: Quality track evolution and maintenance effort

3.2 Speed Limit After Renewal—Work Processes Improvement

From the end of the 2000s, SNCF-R was challenged to significantly improve speed limit after ballast renewal, specifically to limit the consequences on the commercial traffic, on the Paris-Lyon HSL.

On HSL, the works process in France has always been conditioned by the objective to have traffic impact as low as possible: no interception of long-term traffic, commercial traffic every day (excluding renewal of switches and crossings) [7].

From 1996, at the beginning of the first ballast renewal, the speed limit of 60 km/h appeared too restrictive and not adapted to the capacity requirements of HSL. Studies and new work processes have made it possible to improve this speed limit on HSL to 100 km/h, then, soon after (1998), to 120 km/h.

In 2013, several digital models and track tests have resulted in a speed limit for the first commercial train after ballast renewal of 160 km/h. The consequences of the highest of these speed limits is a more complex and more expensive work process.

When the sleeper renewal was planned in 2020, the same objective to improve the speed limit after work was decided, first at 120 km/h after a long technical analysis and several test on sites. Then, this work process quickly evolved to switch in 2023 to a speed limit of 160 km/h, on the work process model of the ballast renewal, which had been refined and perfected in the meantime.

Currently, this speed limit of 160 km/h is considered satisfactory by railway companies. Although work methodology adjustments are possible to make the worksite more efficient, this commercial traffic speed limit is already very high and has no equivalent in the world for ballasted tracks. It does not seem destined to evolve quickly.

4 Conclusions

The sleeper renewal project on the first French HSL has challenged SNCF-R to invent the ballast track model for the future. This project induces several reflections, both around a study of the aging laws of the components, the choice of the components of tomorrow and the type of track, but also the industrial model to regenerate the track (work methodology, restriction speed, type works, industrial tool to be developed).

The new track assets performance confirms SNCF-R's need to design a new ballast track model. The Concept Track is more efficient and more economical in terms of maintenance effort and therefore CO_2 production.

The new work methodologies with ever higher speeds completely meets the needs of railway companies to reduce the capacity impact to run even more trains.

All these developments and innovations contribute to create the new model of ballast track for tomorrow.

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Mitigation of Large Overloads on Road Bridges

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Abstract. Road remains the main mode for freight transport with increasing commercial vehicle loads along the time. Ageing bridges are used beyond the initially designed lifetime. Therefore, highly overloaded trucks may cause severe damages and bridge collapses. Bridges on secondary roads are the most exposed because of less maintenance.

A bridge collapse rarely occurs under the first high overload. Truck drivers use bridges above their load limit, either by ignorance, or to shorten their route. While nothing wrong happens, they cross them again and again with higher loads, despite of the displayed signs on posted bridges.

The strategy proposed to mitigate large overloading consists installing weigh-in-motion (WIM) systems to detect potential offenders and to deliver admonition by the relevant authority. Such preventive measures, where criminal offenses may be invoked, could be easily implemented and quite effective. A relevant publicity, may dissuade the truck operators and save several bridges and lives.

Keywords: Bridges · Overloading · Collapse mitigation · Weigh-in-motion · Heavy Vehicle

1 Context and Problem Statement

1.1 Road Freight and Overloads

Road represents more than 75% of the freight in the EU, and this share still slowly increases despite of the incentives for mode transfer. Four million heavy good vehicles (HGV) operate in the EU. The Council Directive 96/53/EC [1] lays down, for road vehicles circulating, the maximum authorized dimensions in national and international traffic and the maximum authorized weights in international traffic. It was revised by the Directive EU2015/719 [2]. The new article 10d requires, by 27 May 2021, that the Member States (MS) shall take specific measures to identify vehicles that are likely to have exceeded the maximum authorised weight, in order to comply with the requirements. It is recommended using automatic weighing systems (WIM), either set up on the road infrastructure, or installed on-board in vehicles. The MS are required to lay down rules on penalties applicable to infringements, notify those rules the Commission, and take all measures necessary to ensure that they are implemented. Finally, the MS shall report periodically to the Commission the measures taken and their output.

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Over the last 70 years, the maximum authorized weights steadily raised in the EU, up to +80% (Fig. 1). In some MS, high capacity vehicles (HCV) are authorized for National transport, up to 60 or 74 tons. These HCV can only circulate on dedicated itineraries, main highways and motorways. However, they use parts of the common road network to reach their final destination. In addition, the flow of HGVs doubles approximately every 40 years.

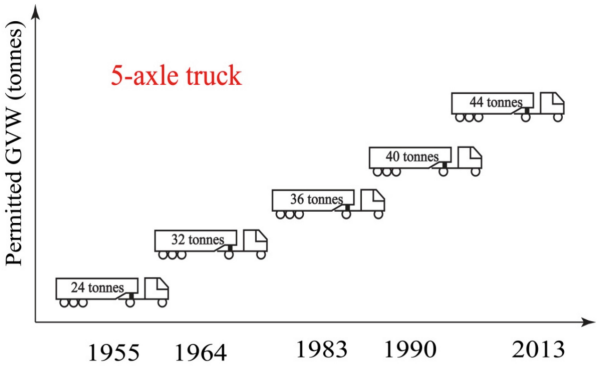


Fig. 1. Maximum authorized gross vehicle weight in the EU over time.

Despite of the overload detection for preselection and rarely for direct enforcement, some HGVs are circulating overloaded. The overload rates vary from 5 to 30% depending on the location, type of road, time (day and hours), categories of HGVs and obviously on the frequency of checks and penalties applied [3]. Most of the overweight does not exceed 10%, however a few percents are much higher. Lower the controls, higher the overloads, therefore, the secondary roads are exposed to more overloads despite of a lower traffic volume. The use of navigation systems also drives heavy vehicles on secondary roads and weak bridges.

Overloads induce bridge wears, fatigue of steel, composite and cable bridges under low overloads, while large overloads may lead to brittle failures and collapses, i.e. severe accidents with fatalities and road closure over long periods. Thus, it is a major challenge to mitigate these large overloads, above all on the most sensitive bridges.

1.2 Road Bridges

Road bridges are designed by codes and load models to withstand traffic loads, in accordance with the regulations in force. In the 90s, the National bridge loading codes were replaced in the EU by the Eurocode 1991–2 "Traffic loads on road bridges" [4]. However, a significant proportion of bridges were built a long time ago with much lower design loads. The design and current service lives of bridges are much longer than the lifetime of any design code and vehicle regulation. The stock of aged bridges increases along time and their lifetimes are steadily extended for economic and environmental reasons [5], increasing the number of bridges exposed to severe failure or collapses under overloading.

While cases of bridge collapse attributable to overloading are rare but not exceptional (Fig. 2), overloading reduces the life and safety of structures, increase the cost of maintenance. Bridges affected by wear such as corrosion, fatigue, creep, shrinkage, cracking, have reduced load capacity. These bridges are mostly posted, but not all the HGVs comply with the displayed limitation. The design and safety factors only cover load exceedance up to 30 to 40%. In all cases shown in Fig. 2, the vehicle weight, which induced the bridge collapse, was much above this threshold, (a) 80 t (crane truck), (b) 32 t instead of 6 t in a National Park, (c) 118 t instead of 44 t, and 51 t instead of 19 t.



Fig. 2. Bridge collapses under overloads: (a) Tittle bridge, Nova Scotia, Canada, 2020, (b) Dale Bend Bridge, Arkansas, USA, 2019, (c) Annone, Italy, 2016, (d) Mirepoix, France, 2019

In France, a Senate Report issued in 2019 warned that 25,000 bridges (10% of the stock, mainly on secondary roads) were in poor structural conditions, because of a lack of resources for inspection and maintenance. It recommended to double the funds allocated to maintenance and repair (from 60 to 120 million €/yr), to create a 1.3 billion € assistance fund helping local authorities to carry an extensive survey and assessment of their bridges and to repair the most damaged ones, and to implement an asset management. In June 2022, a follow-up report noted an increase in funding for state road bridges, but considered "that the resources deployed are not equal to the challenges of stopping the spiral of deterioration of bridges managed by local authorities". The investments on local bridges missed 350 million €. The number of bridges in poor structural condition was re-evaluated to 30,000 and 35,000. It recommended setting up of a national geographic information system geo-referencing bridges and routing HGVs.

2 Identified Issues and Problem Solving

2.1 Identified Issue of Severe Overloads on Sensitive Bridges

Only high or very high overloads, 50% or more above the posted load limit, may cause serious damage or collapse to bridges. Most bridges have a rather good resilience to overloads, by design and redundancies. However, in 2019 the collapse of the steel suspended Mirepoix bridge (1935) on the Tarn river, posted to 19 t, occurred in France under a 51 t truck (Fig. 1d), with 2 fatalities. In 2022, two more collapses were narrowly avoided by good fortune; the steel suspended bridge of Touzac (1930) posted to 16 t, under a 40 t truck was affected by severe damages (>two million €), and the concrete arch bridge of Ravi/Super-Bagnères, posted at 19 t, under two 50 and 90 t crane trucks was slightly damaged but not destroyed.

Mostly, large overloads occur repeatedly and increasingly, and bridge failure never happens after the first crossing of an overloaded vehicle. Near Toulouse, the bridge of Gagnac on the Garonne river (Fig. 3a), a multi-span pre-stressed girder structure, forbidden to abnormal loads is monitored by the city, as a sensitive bridge. A WIM system (Fig. 3b) was installed in December 2021 outside of the bridge on the access road, to monitor the axle and vehicle loads crossing the bridge. Table 1 reports the WIM measurements after one year. The highest overloads reached more than 80 t. However, thank to this WIM system, and before applying any penalties, the overload rate drooped down.

(a)  (b) 

Fig. 3. (a) Bridge of Gagnac near Toulouse. (b) A WIM system installed nearby the bridge is monitoring the (over)loads since 12/2021.

In most cases, carriers and drivers are taking habits crossing bridges above the posted or legal load limits, with the common meaning: “nothing wrong happens, no worry, no reason to self-limit the use of posted bridges”, or “a bridge is designed and built to carry the current loads, whatever they are”. Mainly carriers, without enforcement, pay less and less attention to the signs, and the overloads increase, until a fatal accident.

2.2 Problem Solving: The Wrong Solutions

A strategy to prevent large overloads crossing a bridge, applied to a few cases long span aged bridges, consists of identifying and stopping widely overloaded HGVs prior to the bridge, e.g. with moveable barriers. That is relevant on toll bridges, supervised by on-site staff. However, for common bridges, this approach encounters several issues:

Table 1. WIM data collected on Gagnac bridge from 8/12/2021 until 7/12/2022.

Entity	Number	Percentage
HGVs (one direction)	261,000	100%
Overloads (GVW)	6,607	2.53%
Overloads (GVW > 45 t)	827	12.5%
Overloads (GVW > 50 t)	191	2. 9%
Overloads (axles >14 t)	677	–

- all the bridge accesses should be equipped, inducing high costs,
- the barriers should be efficient to stop the heaviest HGVs in safe conditions,
- the HGVs shall be able to exit or to safely turn around to avoid the bridge,
- miss or non-detection or miss-signalling shall be avoided, otherwise the bridge operator may be (partly) liable if an accident happens.

Therefore, this approach is inappropriate for common bridges.

Another idea could be to deploy a direct enforcement system of overloads by WIM, fining overloaded vehicles crossing the bridge. However:

- the legislation shall allow the use of WIM systems for direct enforcement,
- the WIM system shall be certified and periodically verified,
- the fines for overloads are neither dissuasive, nor balancing the potential bridge losses.

2.3 Problem Solving: The Proposed Solutions, Admonition

The main principles leading to a more appropriate solution are:

- affordable solution, easy to implement with low or no human resources by local authorities, with low or no maintenance,
- to avoid complex and long procedures for common infringements or violations, and to target the large overloads, which may cause significant damages to bridges,
- to better prevent and dissuade than penalize the users,
- to apply severe enough penalties in case of repeated and risky offences.

The fines for axle or vehicle overloads are mostly between a few hundred and a few thousands euros, i.e. not fully dissuasive and quite difficult to recover if not included in a completely automated enforcement system. Immobilisation and downloading of overloaded vehicles is more dissuasive, but requires police staff, storage space and facilities, and loading devices, not available on most secondary roads.

Reversely, the French penal code provides relevant provisions, such as:

- *attempt to destroy a public asset*, or *destruction of a public asset*, with penalties up to 75,000 € and 5 years in jail in case of recidivism or in some circumstances,
- *endangering the life of others, by breaching a specific obligation or failing to comply with safety regulations*, is punished up to 15,000 € and 1 year in jail,
- *involuntary manslaughter by recklessness, inattention, negligence or breach of a duty of care or safety*, is punished up to 75,000 € and 5 years in jail.

Crossing a posted bridge with a very high overload, and above all in case of recidivism, may be punished as described above by a court. Section 3 describes a proposed detailed process, which started to be implemented in France, with 3 steps.

3 Proposed Measures, Test and Implementation

3.1 Step 1: Identification, Assessment and Instrumentation of Sensitive Bridges

The first step, entrusted to the Cerema in France, consists to inventory the most exposed bridges, according to their design and state. The bridge current load capacity is assessed by inspection or calculation, and a relevant posted limitation may be decided taking into account political, economic and operational considerations.

In addition, a WIM system may be installed to monitor the vehicle loads crossing these bridges, using one of the following technologies to identify the overloaded vehicles above a given threshold:

- road sensors WIM system in one or more traffic lanes, and a video-WIM station, as done for the bridge of Gagnac (Sect. 2.1),
- a bridge-WIM system (B-WIM), using sensors installed behind the bridge decks and/or on the girders, coupled with cameras.

Such WIM systems do neither need type approval nor certification, because they do not deliver legal data, but only estimates of the GVW and axle loads if needed, with a certain level of confidence. A tolerance of 30 to 50%, far below the accuracy of marketed WIM systems, is sufficient to identify large overloads with a high level of confidence. Violators exceeding 30 to 50% the posted or legal limit may be identified by AVI (automatic vehicle identification, e.g. using the plate number and a photo of the vehicle). This information, protected and accessible only to authorized officers, complying with the GDPR, is stored for a limited time period.

3.2 Step 2: Identification, Warning and Admonition of Suspected Offenders

The step 2 is not yet fully implemented but there is no lock and the legal frame is already in place. With the agreement of the Commission for Personal Data Management (CNIL in France), photos and license plate numbers of suspected offenders may be collected by video-WIM systems, providing also the measured parameters of the vehicle: date and time of passage, direction and lane, speed, vehicle type (silhouette), GVW and if needed axle loads and spacings. With this information, the representative of the local authority may send, in a first stage, a warning letter (admonition) to the vehicle owner/operator, to explain the potential infringement and incurred penalties. Without damage, loss or accident, such a preventive action without penalty may be sufficient, and does neither require legal action, nor legal frame or approval. It would also not require important human resources, because the high overloads are quite rare, and should quickly decrease, above all if some publicity is made on the preventive measures, locally in newspapers and broadcasting.

3.3 Step 3: Filing a Complaint and Possible Penal/Criminal Proceedings

In case of a significant damage to the bridge, or repeated offense, the local authority can file a complaint to the court through the public prosecutor. The gathered information (WIM data, photos, etc.) are provided to support the complaint, even if in itself, the non-certified WIM measurement is not an evidence. However, the public prosecutor may investigate in the company, and with enough evidences, the case may be prosecuted to the court. In addition to the penalties listed in the Sect. 2.3, a loss of reputation of the company may be decided. The aim is to publicise such an approach and the first cases brought in court, in order to inform the carriers and vehicle operators and to dissuade them to cross bridges with large overloads. The cost of such a procedure could be affordable and require limited human resources. Temporary WIM measurements may allow preventing future large overloads.

4 Conclusions and Perspectives

It is now proposed to experiment such a procedure on a sample of bridges, with voluntary local authorities, and to evaluate after a given period, the effectiveness, efficiency and feasibility of it.

The originality of the proposed procedure consists of using preventive measures more than punitive measures. The idea is to develop a more comprehensive self-control in the companies and to better empowered the decision makers, company managers and drivers. The aim is to allow implementing this process with a limited amount of means and skills, and using the existing and marketed technologies (of WIM).

The stock of bridges to protect is huge and even if a few bridge collapses may be avoided, the benefit would be great for all the stakeholders.

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Resilient Networks and Operations

Enhancing Ambidextrous and Learning Capacities for the Resilience of Public Infrastructure Administrators

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Abstract. In many European countries, the management of transport infrastructure networks faces major challenges due to such issues as climate change, ageing infrastructure facilities, new mobility technologies, and the energy transition. To deal with these challenges, public infrastructure administrators need to develop responsive and innovative solutions while at the same time sustaining and optimising current performance of the present infrastructure networks. This ability to balance innovation and optimisation is called ambidextrous capacity. In addition, developing and implementing new or improved solutions requires the capacity of an organisation to learn. This is especially challenging in project-oriented organisations, where innovations are explored in pilot projects, separated from production-oriented day-to-day processes.

This paper aims to analyse what public infrastructure administrators can do to enhance ambidextrous and learning capacities to develop sustainable solutions and thereby enhance resilience. To this end, we studied the Dutch public infrastructure administrator Rijkswaterstaat. Based on the findings from our study, we propose three recommendations to public infrastructure administrators: (1) formulate and clearly communicate an overall strategy, and translate this strategy to the tactical and operational level, (2) use integrative tactics to overcome the drawbacks of the structural ambidexterity of projects, and (3) strengthen organisational learning by implementing supportive arrangements.

Keywords: Ambidexterity · Learning · Organisational Resilience · Project-oriented Organisation · Public Infrastructure Administrator

1 Introduction

In many European countries, the management of transport infrastructure networks faces major challenges due to such issues as climate change, ageing infrastructure facilities, new mobility technologies, and the energy transition (Arts et al. 2021). Enabling

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sustained and improved performance of transport infrastructure networks in such contexts, requires a resilient organisation to manage these networks (Brown et al. 2017). Although the concept of organisational resilience still lacks a clear definition, a recent literature review by Hillman and Guenther (2020) showed that organisational resilience generally means surviving and thriving amidst adversity. Whereas surviving uncertain environments on the short term involves anticipation and coping capabilities, thriving and fostering future success require adaptation capabilities (Duchek 2020). As such, organisational resilience involves balancing short- and long-term interests.

The growing need for sustainable solutions in infrastructure planning requires public infrastructure administrators to adapt by exploring, developing and implementing new products and processes – i.e., innovation. At the same time, a huge renovation task necessitates public infrastructure administrators in many countries to standardise products, procure faster and more efficiently, and to optimise production processes – i.e., optimisation. Both innovation (exploration, for the long term) and optimisation (exploitation, for the short term) are essential to build organisational resilience; however, they compete for scarce resources. Hence, combining innovation and optimisation requires ambidextrous capacity of public infrastructure administrators – i.e., the capacity to balance exploration and exploitation (Gieske 2019; March 1991). Furthermore, the innovation and optimisation processes that are necessary for organisational resilience, require organisational learning – i.e., integrating and institutionalising at organisational level of what was developed and learned at (project-)team level (Crossan, et al. 1999; Evenseth et al. 2022). Therefore, the aim of this paper is to analyse what public infrastructure administrators can do to enhance ambidextrous and learning capacities to develop sustainable solutions and thereby become more resilient.

2 Theoretical Framework

The relationship between organisational resilience and ambidexterity is clearly indicated by March (1991, p.71) who argued that "maintaining an appropriate balance between exploration and exploitation is a primary factor in system survival and prosperity". More recently, a.o. O'Reilly and Tushman (2013) and Gieske (2019) concluded that organisational ambidexterity has a positive effect on the performance of private and public organisations. There is, however, no 'one-size-fits-all' solution in achieving ambidexterity (Brix 2019). Ambidexterity involves structural and temporal (or sequential) organisational designs, in which exploration and exploitation activities are separated in respectively place and time, as well as contextual designs that allow for simultaneous exploration and exploitation (Kassotaki 2022; O'Reilly and Tushman 2013).

Organisational learning can integrate exploration and exploitation. New concepts, knowledge, technologies, policy goals, et cetera, need to be interpreted, implemented and institutionalised at the organisational level. Current activities, processes, technologies have to be optimised to enhance efficiency and renewed to be able to adapt to new challenges. This is quite a challenge for public infrastructure administrators as they often use a project-oriented approach to efficiently realise and renew infrastructure facilities (Arts et al. 2021). Projects can be seen as temporary constructs with a short-term delivery focus for optimising infrastructure networks. However, the short-term logics of projects

are often at odds with long-term policy goals of the organisation as a whole. To safeguard optimisation (the focus of project teams) and at the same time ensure exploration of innovative solutions, innovation is often organised in temporary arrangements, such as pilots and programmes, or in separate departments of the organisation. This separation of exploration and exploitation across different units of the organisation can be considered as structural ambidexterity.

The upscaling of innovations into the broader organisation and in organisational routines involves learning processes in which professionals collectively interpret the relevance and impact of innovations on their work, and institutionalisation of what is learned in organisational norms, routines, procedures, et cetera (Crossan, et al. 1999; De Groot et al. 2023). Innovation processes typically follow a temporal design, in which an innovation is piloted in one project and context, before upscaling it for implementation in other projects and contexts, and institutionalising it at the organisational level. Despite the benefits of structural ambidexterity, a downside is that what was learned may remain limited to the single project in which it was realised. The larger the institutional distance between projects and their parent organisation, the more learning processes are impeded (Liu et al. 2021; De Groot et al. 2022).

In sum, the literature shows that ambidextrous and learning capacities are important for organisations to balance exploration and exploitation, and thereby enhance resilience. However, it remains challenging for public infrastructure administrators to actually balance innovation and optimisation in practice.

3 Methods

For the aim of this paper, we studied the public infrastructure administrator Rijkswaterstaat. As the executive agency of the Ministry of Infrastructure and Water Management in the Netherlands, Rijkswaterstaat is responsible for the planning, design, construction, and maintenance of the main road network, waterway network and water systems. This case is particularly interesting, because the ministry set explicit ambitions for climate neutrality and circularity for the year 2030.

We analysed a Rijkswaterstaat programme for climate-proof and circular infrastructure (Cannaerts et al. 2022) to identify organisational aspects that should be strengthened to be able to realise the ambitions. We used the 'Erasmus Model for Innovative Capacity' (Gieske et al. 2019) to analyse the connective, ambidextrous, and learning capacity of the programme and the Rijkswaterstaat organisation. The extent of innovation and optimisation in products, processes and instruments for sustainability, and the perceived performance on sustainability goals were measured through a questionnaire (n = 678). Through regression analysis, we determined the contribution of the different capacities to innovation and optimisation. Subsequently, the results and potential action perspectives were discussed in 6 focus groups.

To get more insight in learning capacity, we also analysed the contribution of communities of practice (CoPs) to developing sustainable solutions and upscaling innovations. We conducted a questionnaire among 58 participants of 4 CoPs on project, contract, risk, and quality management, complemented with interviews with 4 CoP leaders and a focus group with 5 Rijkswaterstaat professionals to discuss our findings.

4 Results

The extent in which Rijkswaterstaat optimised products, technology, processes, regulations and routines to achieve sustainable goals was rated 6.2 on a 10-points scale, whereas for innovation this was 5.5. Organisational learning was rated at 5.6. Statistical analysis showed that organisational learning is strongly correlated to both innovating and optimising ($\beta = 0.36$, $p = 0.001$), as are ambidextrous activities by managers (rated 6.2, $\beta = 0.35$, $p = 0.001$) and ambidextrous activities by employees (rated 6.3, $\beta = 0.15$, $p = 0.05$). Reason for the relatively low scores, according to the focus groups, is the difficulty of translating abstract (strategic) goals to actionable (operational) goals. Regarding this, it was considered helpful that, e.g.: concrete paragraphs on sustainability were included in formal project documents; instruments were developed to rate the sustainability of bids by contractors; and specific roles related to sustainability were assigned to support project teams. It was considered helpful that upper management stated and translated the leading (strategic) principle 'we work sustainable, or we don't work'.

The focus group discussions also revealed significant tensions between running projects (focussing on scope, budget, and time), and time for learning within a project and especially for organisational learning. Tensions were also mentioned between current protocols and regulations (mostly based on good practices in the past) and the implementation of new solutions. As a possibility to overcome this, the role of boundary spanners was mentioned. The study of 4 communities of practice (CoPs) corroborated the aforementioned tensions and provided additional insight in their role in organisational learning related to innovation and sustainability.

The results show that the CoPs predominantly contribute to optimisation of work in projects and the organisation by discussing issues from practice and striving for uniformity by developing procedures and templates. However, the extent that CoPs pay attention to innovation – i.e., 'developing innovations' and 'experimenting' – ranged from 8% for contract management to 24% for quality management according to respondents, so was relatively low. In general, respondents argued that participation in CoPs was supported, and even encouraged, by senior management. However, "*CoPs are important, but less urgent than work in projects*" as an interviewee argued. Another interviewee stated "*if it is not really important to senior management and linked to an overall strategy, then motivation to put effort in such developments decreases and it does not work*". This corresponds to the finding that it is difficult to translate strategic goals to the tactical or operational level.

5 Discussion

Public infrastructure administrators face the challenge of providing adequate infrastructure facilities today and at the same time enabling the provision of adequate infrastructure in the future. It is a balance between short-term optimisation and innovation for long-term uncertain benefits. However, since public infrastructure administrators in general are prone to public scrutiny, they focus on delivering concrete results to demonstrate that they are using societal resources efficiently. As such, they are vulnerable to the 'optimisation trap', where continued optimisation no longer contributes to performance (Gieske

et al. 2019). In order to become more resilient, organisations need to explore and innovate next to optimisation. Both literature and our study indicate that the project-oriented character of public infrastructure administrators safeguards optimisation, but also facilitates (local) innovation in separate projects and programmes because projects may act as innovation niches. However, structural ambidexterity challenges the integration of innovations into the broader organisation.

Our study confirms the contribution of learning to (the building of) ambidextrous capacities, but that a multitude of connective and learning tactics have to be applied to make this contribution effective. Institutionalising new solutions and procedures in the current regime and practice remains challenging. Our study also shows that CoPs enable learning relationships across projects and their parent organisation. As such, they decrease the institutional and perceived 'distance' between projects and their parent organisation that impedes organisational learning (De Groot et al. 2022; Liu et al. 2021). Moreover, CoPs may contribute to institutionalisation of new solutions through the development of guidelines and procedures (Crossan et al. 1999). In contrast to programmes, CoPs are (usually) not intentionally designed by the organisation (De Groot et al. 2023). Although this fits with the informal character of CoPs as defined by Wenger-Trayner and Wenger-Trayner (2015), the results indicate that the involvement of management may enhance the contribution of CoPs in the upscaling of innovations as well as in optimisation activities.

CoPs and programmes are in itself insufficient for overall organisational ambidexterity. Innovation and optimisation can exist parallel in different places in the organisation without real choices have to be made or without connecting them or explicitly balancing the one against the other. Our study underlines that a deliberate strategy to connect these processes is necessary to enhance the ambidextrous capacity of project-oriented organisations. Such a strategy may include to combine both processes within the same organisational unit (e.g., a project or a programme) where exploration and exploitation occur sequentially of simultaneously (Brix 2019; Kassotaki 2022). Learning within the unit and from the unit to the broader organisation (through CoPs) may further enhance the building of ambidextrous capacity as operationalisation of the afore mentioned strategy.

In sum, our study provides directions to enhance ambidextrous and learning capacities of public infrastructure administrators in practice:

1. Develop, communicate and operationalise an overall strategy that balances innovation and optimisation to achieve both long- and short-term goals. Pay deliberate attention to the translation of (abstract, strategic) organisational goals and ambitions into (concrete, operational, actionable) working processes;
2. Instead of using structural ambidexterity as a 'one-size-fits- all' solution, add sequential and contextual ambidexterity, and apply integrating tactics in addition to differentiating tactics, for example by incorporating sustainability early and explicitly in the scope of projects;
3. Strengthen organisational learning by stimulating and facilitating different types of hubs (CoPs, programmes, et cetera) where knowledge and lessons learned can be shared and given joint meaning.

6 Conclusion

Although the results corroborate that balancing innovation and optimisation is indeed challenging for public infrastructure administrators, this study also gives practical directions as to how to enhance innovation and optimisation in combination. This study especially shows that the absence of a clear common approach and overarching strategy for innovation and optimisation limits the ambidextrous and learning capacities of a project-oriented organisation. Since projects remain prominent vehicles for sustaining and improving the performance of transport infrastructure networks, developing a balanced and implementable strategy that incorporates different types of ambidexterity and approaches to organisational learning appears necessary to enhance ambidextrous and learning capacities for the resilience of public infrastructure administrators.

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An Adaptive Supply Chain Stress Testing Framework with Deep Learning

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Abstract. Since the COVID-19 pandemic, supply chain disruptions have become the biggest risk to the continuity and stability of the global economy. Therefore, assessing the vulnerability of supply chains and developing the best mitigation plans for high-impact disruptions to enhance supply chain resilience is crucial to the survival of public and private organizations. In this paper, we propose a conceptual framework for diagnosing the vulnerability of suppliers, logistic providers, and commodities for any size of multi-tier supply chain networks for private and public bodies. The framework is based on a supply chain digital twin that will be formed with the industrial Internet of Things technology for accessing field data, machine learning models for disruption prediction, simulation methods for disruption scenario analysis, and optimization methods for developing mitigation plans to minimize the impact of anticipated disruptions. The framework also exploits a deep learning-based surrogate model of the digital supply chain twin.

Keywords: Supply chain resilience · Digital twin · Machine learning · Simulation · Optimization · Deep learning

1 Introduction

Supply chain disruptions have become the dominant factor affecting the global economy since the start of COVID-19. Returning to a "new normal" still looks far away due to ongoing social, political, economic, and environmental problems, as seen from the Global Supply Chain Pressure Index at the Federal Reserve Bank of New York [8]. Therefore, closely monitoring supply chain stakeholders, measuring and predicting risks on each of them, and developing fast and accurate mitigation plans are crucial for ensuring supply chain resiliency.

Since the beginning of the 1990s, global supply chains have been structured to prioritize the low cost in a considerably disruption-free global economy. Consolidating suppliers, applying lean principles, and reducing inventory levels have been the main objectives for strengthening companies competitiveness. However, COVID-19 and the last decade's historical disruptions such as the 2011 Japan

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Tsunami, the 2019 deadly Typhoon Mangkhut, the 2022 Ever Given container ship blockage at the Suez Canal, and the ongoing war in Ukraine showed the vulnerability of the global supply chain. Recently, the World Economic Forum [1] listed the "collapse of a systematically important supply chain" as one of the most important risks in the global economy for the next decade [1]. Hence, a paradigm shift from "cost first" to "resiliency first" is being observed in supply chain practitioners [5].

Monitoring national supply chain resiliency and guiding public and private organisations toward strengthening their supply chain are also becoming important priorities of governing bodies as well ([2–4, 10]). Strengthening global supply chain resiliency is also one of the thematic areas of UN Sustainable Development Goals as depicted in targets 9.1, 9.a and 9.b [7].

Therefore, there is an emerging need for public and business organizations tools for (1) monitoring and evaluating the vulnerability of their supply chains (2) re-design and improving supply chain networks to minimize the impact of disruptions, recommending alternative mitigation plans to make them more resilient to unexpected shocks, (3) without sacrificing sustainability particularly in "energy resiliency" which aims to increase the share of renewable energy sources when designing supply chain networks and minimize resource/energy usage ([6]).

In this paper, we will present an adaptive supply chain testing framework that aims to support public and commercial organisations to enhance their supply chain resilience. In Sect. 2 findings based on interviews conducted with experts from various countries and industries for requirement analysis and justifying the need for a novel approach are summarized. The proposed framework is discussed in Sect. 3. Finally, the paper concludes in Sect. 4 with the significance of the proposed framework and its expected business and societal impact.

2 Industry Perspective

To understand current practices, organisation maturity, and needs, we conducted 16 interviews from various countries and industries. While the majority of the interviewees are from Ireland (8), this number is followed by the US (3), Sweden (2) Germany, India, and Turkey, one from each. A significant number of interviewees were from the manufacturing industry (7), followed by consultancy (5) and retail, software, aviation, and higher education, one from each of them. Interviewees are representing organizations from 5 to half a million of size from varying positions; supply chain manager, analytics team lead, analyst, project manager, professor, and CEO.

All interviewees agreed that the global economy is now living in a permanent disruption era. From SME to multi-national scale, stakeholders noted the difficulty of monitoring their tier-2 and further upstream suppliers. Therefore, supply chain visibility and integration are the primary focus areas for resilience enhancement. The majority of stakeholders noted the lead time and perfect order rate as metrics they use for monitoring supplier performance and did not

point to any resiliency-related performance measure. The resilience of a supplier is understood as their trustworthiness but the impact of their disruption on the overall supply chain, the ripple effect, is not considered comprehensively. Because of that, resiliency mitigation actions noted are mostly reactive rather than proactive. Nevertheless, there is a consensus on several actions; allocating buffer stocks and dual-sourcing and re-shoring but methods to identify the right decisions on these rely on expert opinion. Although Environmental, Social and Governance (ESG) concerns are taken into account during operations management as noted by two stakeholders, none of them pointed their integration into resiliency enforcement efforts.

Interviews and relevant academic literature identified that for end-to-end supply chain resilience, there is a need for (1) a mechanism to anticipate the likelihood of disruption scenarios (2) evaluating the impact of each scenario on the whole value chain (3) ranking the severity of each scenario and node in the supply chain for all tiers (4) preparing and validating mitigation plans on dual sourcing, buffer allocation, re-allocating capacities and transportation of entities (5) yet being robust enough for anticipated disruption scenarios while respecting economic, sustainability and societal concerns (6) and develop the best course of action in a computationally fast way to reduce disruption response time.

It is noted during the interviews that industry representatives can describe only a few aspects of the broader challenge, supply chain resiliency, and testing supplier vulnerabilities. The majority of the interviewees were unable to distinguish the disruptions originated from the customer side (downstream, bullwhip effect) and the supplier side (ripple effect). However, there is an overlapping emphasis from all participants on "lead time variability", "delivery on time full" and "demand fluctuations" as the main disruption scenarios as well as "buffer inventory" and "dual sourcing" as pre-disruption preparation methods. One participant from the pharmaceutical industry declared that they become aware of supplier problems only when they inform them and it is already too late to find the best mitigation actions. Another interviewee who is a consultant and has experience in many public and commercial organisations pointed out the importance of ripple effect for critical industries like chemical manufacturing which could cause a compound effect at downstream of the chain. Another interviewee from a global manufacturing company noted that they have a dedicated team to monitor and mitigate supplier-side disruption, however, their team is capable of tracking only tier-1 suppliers. Furthermore, tracking is handled through a shared digital portal where up-to-date performance indicators are provided by suppliers manually which helps his team to see the trends but in case of an unexpected disruption, communication and mitigation planning are handled through e-mails and phone calls. Indeed, this feedback overlaps with another stakeholder that they want to progress from unknown-unknown to unknown-known capability which means being able to be prepared (i.e. know possible impacts and what to do) for disruptions that are not known the timing.

2.1 State-of-the-Art Industrial Solutions

Industry leader solutions for supply chain resilience analytics mentioned by practitioners during our interviews such as Everstream Analytics, Sphera, and Prewave are promoting their tools with alert notification and monitoring capabilities. While alert notifications rely on web scrapping from social media and news from the locations of suppliers, monitoring capability exploits the information sharing with suppliers. Risk analysis provided to users in these solutions uses qualitative data obtained from regular surveys of suppliers and conventional key performance indicators (KPI) like lead time, on-time delivery, and defect rate. However, node and flow complexity, density, and node criticality of the network are ignored. Besides, none of them quantifies the ripple effect caused by the disruption of each supplier along with environmental and societal impact. Furthermore, the mentioned solutions provide a rigid framework that is not possible to customize or integrate with advanced analytic methods as depicted in the previous section. Currently, only AnyLogistix software offers a digital solution that integrates the decision and simulation modeling capabilities for supply chain risk analytics. However, AnyLogistix also has limitations of relying on commercial decision analytics tools, the shallow learning curve, and lack of customization for different business rules, situational awareness, and modularity of technology used.

The framework proposed in this paper differentiates from state of art tools by (1) being modular for the technology used (2) relying on open source tools (2) integrating risk prediction, stress testing, mitigation planning, and validating (3) minimizing the complexity of the analytics methods for practitioners (4) including network and sustainability based KPIs for a holistic view on the supply chain resiliency.

3 Adaptive Supply Chain Stress Testing Framework

The adaptive supply chain stress testing framework presented in Fig. 1 consists of several components sequentially interacting with each other. The solution provides a mechanism for converting supply chain geospatial data and bill of material (BOM) into a graph model. While each node represents a component/subassembly/product/service in BOM and its relevant facility, edges represent the eligible material flow between facilities and between nodes in BOM. Next, for each facility node, the most likely disruption duration and probability of occurrence is computed through stakeholder historical records and publicly available data via web scraping. Disruption scenarios arefed into a decision model to find the best resource allocation (i.e., mitigation) plan that minimizes the economic, environmental, and societal impact of those scenarios that is adapted from [9]. Next, a high-fidelity discrete event simulation model is used to validate the mitigation plans considering compound disruption scenarios, complex interactions between nodes, and the behavior of the supply chain under uncertainty over time. Diagnosed discrepancies in the mitigation plan from the decision model and their realization in the simulation model are resolved with a

feedback loop between the two models that increases the robustness of the plan. The developed combined decision and simulation model mechanism is used for training a metamodel (artificial neural network, ANN) which enables stakeholders to use the stress testing framework without needing decision and simulation modeling tools.

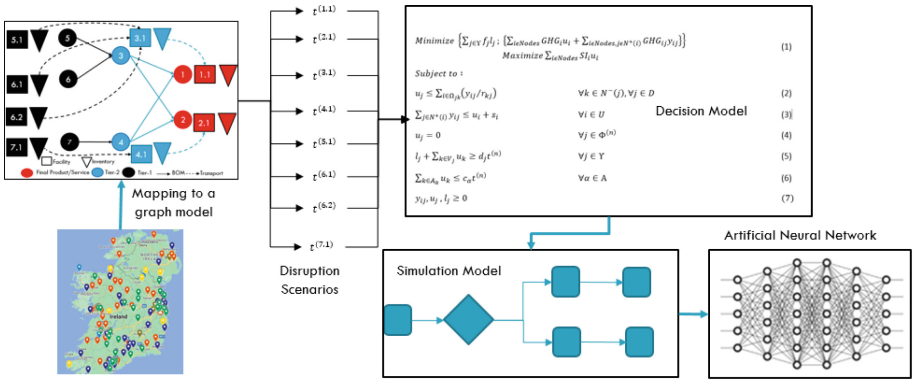


Fig. 1. Adaptive Supply Chain Stress Testing Framework.

4 Conclusion and the Future Research

Recent global disruptions showed that using only delivery performance like lead time, on-time delivery, defect rate or financial health of suppliers is not sufficient as indicated during industry interviews. Also, it is pointed out that, supply chains, particularly ones spread globally require more holistic indicators to test the strength of the supply chain. There is a strong need for anticipating and quantifying the impact of disruptive events. The proposed solution has the potential to address these points by incorporating supply chain network-related KPIs and considering compound disruption scenarios while developing mitigation plans taking into account financial, environmental, and social concerns. Uncertainties in lead times, operation durations, and availability of capacities are putting significant stress on supply chains as noted during the interviews. The proposed solution is incorporating anticipated uncertainties with the high-fidelity dynamic discrete event simulation. The COVID-19 pandemic also showed the need for fast reconfiguration of existing manufacturing facilities for producing urgent health products like ventilators. This unexpected global disruption requires reconfiguring the whole supply chain in a short period as well. The proposed tool has the potential to support governmental agencies, healthcare, and industry in their manufacturing re-purposing efforts during crisis times.

The sequential structure of the proposed framework allows the development of the solution through the waterfall principle. However, individual components

will be developed with continuous feedback from engaged industry stakeholders to make sure they are in line with the challenges identified. Several supply chain networks from academic literature will be used to generate test instances. Disruption scenarios will be generated based on these instances as well as a decision model to develop mitigation plans and validate via a discrete event simulation model. State of art industrial solutions mentioned in Sect. 2 will be used for benchmarking the developed solution.

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INFRACOMS Appraisal Toolkit for NRAs to Assess Emerging Technologies in Bridge and Pavement Management

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Abstract. National Road Authorities (NRAs) draw on a wide range of technologies and tools to support robust decisions on asset maintenance. However, in recent years there has been significant progress in the development of sensing technologies for data collection and advanced techniques for data processing. These technologies present an opportunity to improve asset management decisions, but also present a challenge for NRAs, as they seek to realise the benefits. This contribution presents the appraisal methodology for emerging technologies proposed by the INFRACOMS project commissioned by the Conference of European Directors of Roads (CEDR). The methodology provides objective appraisals since technologies are scrutinised against proposed subsequent criteria. Cost factors, potential benefit categories and limitations are identified. Technologies are ranked by key imperatives and scored. Technologies with a good score are evaluated more thoroughly, which may need specialist input and discussions with the technology supplier. It results in a technical score, a benefit/cost assessment and identified steps in a roadmap toward implementation. The NRAs can share their individual appraisals in a database. The second part of the project develops an action plan to guide NRAs in adapting and implementing promising emerging technologies and training sessions on the use of the developed appraisal toolkit.

Keywords: Monitoring Data · Digitalisation · Sustainability · Asset Maintenance Management · Asset Condition Data · New Technologies

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1 Context at European NRAs and the INFRACOMS Project

The application of consistent, reliable information is a key component of highway asset management. The information and the tools to help interpret and apply data have continuously evolved. However, NRAs are not yet fully exploiting their potential in the highway environment. By bringing these components of sensing and measurement together, NRAs could better understand highway assets and improve both reactive and proactive asset management decisions.

The project "Innovative & Future-proof Road Asset Condition Monitoring Systems" (INFRACOMS) is a CEDR Transnational Road Research Programme Call 2021 project (July 2022 – June 2024), see also at web pages: [1, 2]. It aims to empower NRAs to effectively leverage technological advancements in data/monitoring.

The first action in the project consisted in identifying the information needs, gaps, and priorities of NRAs in terms of their approach to data collection and monitoring, and a list of current and emerging measurement technologies. This was reported in [3].

Commonly used appraisal methodologies that can be used to evaluate the effectiveness, suitability, and potential impact of new technologies for an organisation include Technology Readiness Levels (TRLs), Cost Benefit Analysis (CBA), Life Cycle Cost Analysis (LCCA), Risk Assessment, and Multi-Criteria Decision Analysis (MCDA). Elements of these commonly used methodologies are included in the INFRACOMS appraisal methodology.

The INFRACOMS appraisal methodology described here is designed around the technology use case, that is, a particular application of a technology by an NRA. It also includes processes for NRAs to define their strategic and technical priorities so that the appraisal process can be tailored to addressing their individual requirements, as identified in the first action of the project. Some technologies may have more than one technology use case within an NRA. Each technology use case should be subject to a separate appraisal, as their costs and benefits, risks and limitations will be different. The methodology was designed and fine-tuned by applying it to several examples of emerging technologies. INFRACOMS will ultimately deliver a Technology Database and a Technology Appraisal Toolkit to CEDR. The database will comprise appraisals and will be the subject of a future publication.

2 Core Processes of the INFRACOMS Appraisal Methodology

The proposed INFRACOMS appraisal methodology is presented in Fig. 1. The processes shown in orange boxes represent the core components of an INFRACOMS appraisal. The blue boxes are filtering and prioritisation processes, representing the ways in which the methodology can be tailored to individual NRAs.

An INFRACOMS appraisal has three (3) core processes, with increasing levels of detail and complexity: a Pre-Evaluation, an Evaluation, and a Case Study. These core processes apply at the level of where the technology can be applied: a specific "use case". Although the appraisal focusses on a specific technology use case, the Pre-Evaluation and Evaluation stages are still considered generic, and would be useful to any NRA considering applying that technology in a broadly similar use case. Case Studies are

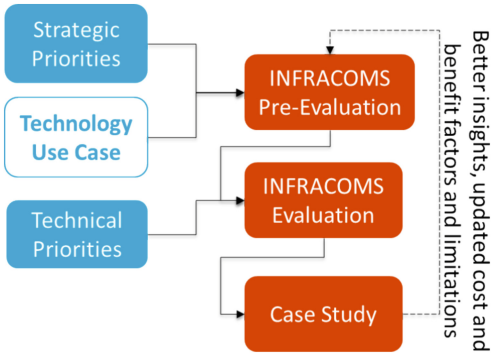


Fig. 1. The Technology Use Case oriented INFRACOMS appraisal methodology.

normally conducted with an individual NRA and more focused, and with use of CBA, LCCA and Risk Assessment criteria for that specific NRA. Shared completed Case Studies will provide valuable insights for other NRAs interested in evaluating that (or similar) technology.

Both the pre-evaluation and evaluation processes also consider the strategic and technical priorities of the NRA. Strategic Priorities must be established by the NRA with respect to the key imperatives that the NRA wishes to address using emerging technology. Four key imperatives were established in the first action of the project [3, 4]: safety, environment, socio-economic, and availability. Technical Priorities must be established by the NRA to define its technical priorities with respect to the capabilities for use and integration of technology. Four key components that that were identified [3, 4] for use in a technical evaluation are: the need for associated data analysis, ease of data visualisation, potential for improvement in decision-making, and ease of data integration. The ranking between these priorities may differ for different NRAs. A technology may be less relevant for an NRA when it does not address any of the priorities.

3 Pre-evaluation

The pre-evaluation process is a high-level analysis of the anticipated benefits, limitations and costs, and an assessment of the readiness level of the technology for a particular use case, based on readily available information about the technology such as supplier's (promotional) material. It also scores the technology for the particular use case against the key imperatives of the NRA. Pre-evaluation should be accomplished quite quickly). It would require general knowledge of technologies and their applications, and an understanding of the potential applications by the NRA.

3.1 Pre-evaluation Appraisal

An overview of the technology is made which includes descriptive text of the overall system from collection to delivery, supported with diagrams, a description of the underlying technologies, and the potential use case in a roads agency. A high-level assessment

is to be made of anticipated cost factors, benefits and limitations for the technology when applied in the proposed technology use case.

3.2 Pre-evaluation Readiness Level

Pre-evaluation includes an assessment of the readiness level of the technology for the proposed technology case from the supplier's perspective, using the generic TRL scale adopted by the European Commission and introduced in EU funded projects in 2020 as the point of reference for determining the development or maturity of a research and its readiness for market uptake and potential investment.

3.3 Pre-evaluation Score

The pre-evaluation also provides a scoring of the technology use case against the key imperatives of the NRA. This is a simple ranking to identify which of the strategic priorities is addressed by the technology (rank of 1 for main priority, to 4 for lowest priority addressed by the technology).

4 Evaluation

The evaluation process is a more detailed breakdown of the benefits, limitations, and cost factors of the technology within the proposed use case, including a more in-depth technical evaluation and an assessment of the steps needed that would be required to implement it in an NRA. It provides an assessment of the readiness level of the technology from the NRA's perspective. Evaluation will certainly take longer to accomplish than the pre-evaluation. It would require input from a specialist or expert in the field, and discussion with the supplier of the technology, to gain a full understanding of the technology and its potential application for a NRA.

4.1 Appraisal of the Technology

The evaluation builds on the expectation that the proposed technology use case is associated with an existing decision-making process in the NRA, and this new technology is being evaluated as a potential replacement for (or improvement to) the technology or data that supports this decision-making process.

The INFRACOMS methodology provides a canvas for the appraisal. It must describe where/how the technology could contribute to improved operation of the network. It must describe the new data collection method and any opportunities for enhancement of the existing process. It must provide a more detailed analysis of the cost factors, benefit categories and limitations of the technology use case than in the pre-evaluation step.

4.2 Scoring of the Technology

In addition to the in-depth evaluation of the technology use case, INFRACOMS includes a simple scoring mechanism to allow comparison of technologies. Four components are given a score from 1 (poor) to 5 (excellent): data analysis associated to the technology, data visualisation, its potential for practical decision-making, and ease of data integration. Before scoring, a description of the technology must be made according to a predefined format. The scoring is guided by predefined matrices with standard questions, where the answers to the questions should be available in the description of the technology. This process is detailed and illustrated on examples in [5], available on the website of the INFRACOMS project ([2]).

A radar diagram where each 'spoke' represents the technical score for a component provides a concise interpretation of the strengths and weaknesses of the technology in each of the technical evaluation areas.

4.3 Roadmap

Evaluation also includes an assessment of the steps needed that would be required to implement the technology (for the identified technology use case) in an NRA. These can include significant amount of detail depending on the technology being evaluated, the maturity level of the technology, and the technology use case.

4.4 Summary Evaluation: INFRACOMS Readiness Levels

Finally, a summary evaluation is made of the readiness level of the technology from an NRA perspective (as opposed to the supplier perspective in the pre-evaluation) for the proposed technology use case. The INFRACOMS Readiness Level have been based on the Readiness Levels defined by Transport Infrastructure Ireland (TII) [6]. The INFRACOMS Readiness Levels (see Table 1) emphasize the use and deployment for an infrastructure authority and for the use case under consideration.

Table 1. INFRACOMS Readiness Levels for a particular use and deployment of a technology.

IRL	Description
9	Proven Solution Deployment
8	System Level Production Verification
7	Pre-Production Controlled demonstration
6	System Based Representative Testing
5	Isolated Representative Testing
4	Laboratory Testing
3	Research and Validation
2	Applied Research
1	Concept Exploration / Fundamental Research

5 Case Study

A Case Study involves a comprehensive analysis of a fully implemented technology within a specific NRA context. The specific inputs required for the study will vary depending on the technology and use case under assessment, potentially taking several weeks to gather all necessary information. It encompasses details about the employed technology, project structure, implementation location, and the NRA's experiences regarding benefits, challenges, and costs. Collaboration and discussions between the technology provider and the NRA are crucial to obtaining the information and gaining insights in the full implementation of the technology. The INFRACOMS pre-evaluation and evaluation stages already identify cost factors for inclusion in CBA and LCCA. The case study findings, such as additional cost factors or benefit categories, will be used to update the pre-evaluation and evaluation stages.

6 Conclusion

In conclusion, the INFRACOMS project commissioned by CEDR aims to equip NRAs with the capability to leverage emerging technologies in data monitoring. The project has developed an appraisal methodology that includes pre-evaluation, evaluation, and case study processes. These processes allow NRAs to assess the effectiveness, suitability, and potential impact of new technologies based on their specific needs. By utilizing the INFRACOMS methodology, NRAs can make informed decisions on adopting emerging technologies, leading to improved asset management and better decision-making processes. The project will provide a Technology Database and Appraisal Toolkit to guide NRAs in implementing promising technologies and offer training sessions for their use.

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Increasing the Capacity of Shunting Yards Within the Current Infrastructure: A Computational Perspective

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Abstract. With a dense infrastructure and limited space, the opportunities for increasing the capacity of the railway network in the Netherlands are limited. One of the bottlenecks is optimally using the available space around stations and in shunting yards. Many details must be considered, increasing the complexity of the problem. Human planners can benefit from computational support to ensure efficient use of the infrastructure. We introduce a framework for positioning previous research in terms of abstractions and highlight a promising future direction: the development of a new approach that combines different methods and uses the relations between the abstractions to create more efficient solutions.

Keywords: railway hub · train shunting · train servicing · abstractions · hybrid model · human-AI collaboration · neuro-symbolic AI

1 Introduction

The dense infrastructure of the Dutch railway system serves almost one million people daily but is restricted in handling more passengers due to a lack of space and limited personnel. To address this, intelligent solutions are being sought, like automating trains to reduce the demand for personnel and decrease the distance between trains. In this paper, we look at a different opportunity for improvement, namely in creating more efficient plans for railway hubs.

To reach a higher capacity, the demand for more train carriages increases and the need for efficient servicing arises. The parking and servicing of trains take place in shunting yards located within major cities in the Netherlands, hence they have limited expansion opportunities. Shunting yard operations include the parking and routing of trains to ensure they leave the yard at their scheduled time to return to their route in the timetable. If a train leaves the yard later than expected, this results in other delays across the timetable. Moreover, to depart correctly, train compositions might require splitting and recombining. Finally,

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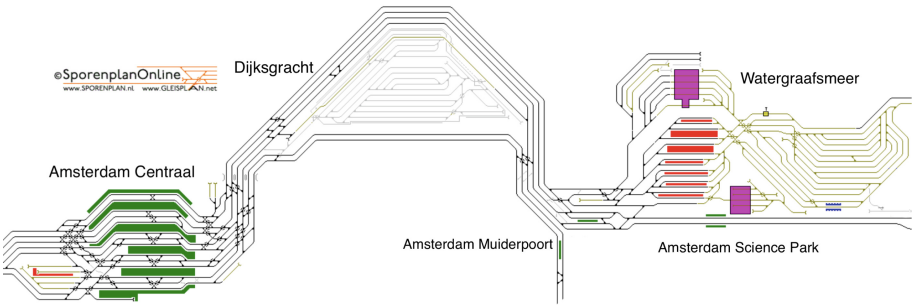


Fig. 1. Schematic layout of the railway hub at Amsterdam Central station.

service actions must be scheduled to clean and maintain trains. All these operations are included in the Train Unit Shunting Problem with Service Scheduling [5]. As the free space on tracks is reduced due to an expansion of the rolling stock, reallocation must often be used to route trains from their initial parking track to another one. Since this is a costly operation, the goal is often to minimize these reallocation moves. Although solution methods to this problem can already solve some real-world scenarios, the problem becomes increasingly more difficult with more added details, and due to complex operations like reallocation.

Shunting yards are part of railway hubs: regions in the railway network operated as one unit and often located around a major station. Figure 1 shows an example of the Amsterdam Central station hub with two yards (*Dijksgracht* and *Watergraafsmeer*) and two smaller stations (*Amsterdam Science Park* and *Amsterdam Muiderpoort*). In practice, most operations in a railway hub are focused on trains outside their scheduled route in the timetable, when they must be parked and serviced. However, the scheduled routes of other trains through a station must also be considered, as these can conflict with trains being shunted.

In this paper, we highlight the importance of finding a good plan for the railway hub operations, including the parking and servicing of trains within shunting yards as well as the movements between stations and shunting yards. Previous studies use many models with various levels of abstraction, in other words, they each consider a different subset of problem components. Including all the details leads to very long computation times, so an abstraction is often used to get meaningful results within a certain amount of time. We introduce a framework to differentiate between these abstractions, illustrate the relations between them, and position previous work within this framework. Finally, we propose a new direction of research towards solving the complete problem.

2 Abstraction Framework

When planning train shunting operations in practice, many relevant details must be considered, from the splitting and combining of trains into different configurations, to the scheduling of personnel to operate them. However, it is often imprac-

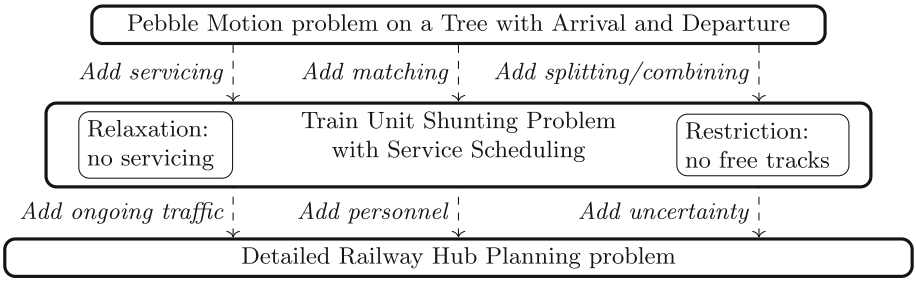


Fig. 2. Examples of different abstractions.

tical or even impossible to include all these details, as this would lead to long and unrealistic computation times. Moreover, having up-to-date and real-time information on all problem components is a challenging task, and human planners would not be able to oversee the details effectively. Therefore, researchers often use an abstracted model, though there are many variations of abstractions to consider.

We propose a framework that shows the relations between different models with varying levels of abstraction, by identifying when one model A is a *relaxation* of another, usually more detailed, model B. This is the case if every solution to model B can be translated to a solution in model A, and we say B is a *restriction* of A. Consequently, proof that no solution in model A exists also proves that no solution for B exists. Often, a more abstract (relaxed) problem is easier to solve, and we can use such relations to combine different models into an approach to find a plan for shunting operations. Besides, these relations can be used to communicate results to human planners and show why a decision was made. In this paper, we highlight three different models, explain their relations, and show how to relate them to other ones. After introducing our examples, we explain how to use this framework to address the complexity of creating a shunting plan.

The first work we discuss is a high-level representation of the practical problem called the Pebble Motion problem on a Tree with Arrival and Departure, which was introduced by Hanou et al. (2023) [9]. The second model, called the Train Unit Shunting Problem with Service Scheduling, was created by Van den Broek et al. (2021) [5], which includes more practical details. As we will show, a lot of previous research is related to this problem, while we point out the need for a more detailed model, which will be our third example. This low-level structure does not have a name yet in the literature, and we refer to it as the Detailed Railway Hub Planning Problem. In the next subsections, we highlight several restrictions and relaxations that are often used, and show the underlying relations between the three examples in Fig. 2.

2.1 Pebble Motion Problem on a Tree with Arrival and Departure

At the highest level, we consider the most abstract representation based on a well-studied problem in graph theory called pebble motion. In the current

variant [9], we consider the shunting yard as a graph, with vertices to define the locations where a train can be parked and an additional track for the arrival and departure of trains. By using an original graph representation, we can also apply graph theoretical results to the railway scenario. These theoretical results can provide new insights to solve the problem and use the results in a more detailed model. The problem is focused mainly on the parking configuration, which is still shown to be a difficult challenge [9]. This abstract representation is a relaxation of the practical scenario, so if there is no solution here, there is no solution in practice. Thus, we can spare unnecessary computation time by quickly determining infeasibility in some scenarios. For example, when there is less space in a shunting yard than minimally required [9][e.g., Fig. 3, p. 5] or when the angles between tracks in the infrastructure are too sharp for a train to make a turn [1]. However, solutions to this model do not always translate to solutions in practice due to missing details, which we consider in the next subsection.

2.2 Train Unit Shunting Problem with Service Scheduling

The second model is probably the most complete representation of a railway hub in the literature. The Train Unit Shunting Problem with Service Scheduling [5] includes the allocation of parking tracks to incoming train units, the routing from the point of arrival in the shunting yard to their allocated tracks, the splitting and combining of train compositions, the matching of train units between arriving and departing compositions, and the scheduling of the service actions to be performed. This problem description is already a lot more detailed than the previous one, and the translation may not always be straightforward.

Many other models can be related to this problem, and we give a few examples of such relaxations. Like, a study focusing on rolling stock scheduling relaxed the problem such that no service actions needed to be scheduled [8]. A different work on human decision support systems initially restricted their approach to handle only last-in-first-out tracks, though they also added a generalization to include free tracks [7]. An overview of several studies related to our second model was previously written [12], though the review does not give the relaxation and restrictions as we described here.

A final direction of relevant abstractions considers studies that have simplified their model to regard either the train station or the shunting yard as a single point. Then, their research focuses on the other component and minimizes the collaboration between the different parts. For example, many studies on shunting yards assume there is a certain point where trains arrive and depart for shunting, which is a simplified version of the track between the station and the yard. This is also the case in the Train Unit Shunting Problem with Service Scheduling. Such a relaxation results in the disregard of the ongoing traffic on the tracks that cross the path between the station and the yard. In railway networks that are not as dense as the Dutch network, the tracks between the station and the shunting yard may be less busy, so the ongoing traffic is unlikely to be a limiting factor.

2.3 Detailed Railway Hub Planning Problem

Finally, our newly suggested model includes the most practical details. We consider the complete hub of a railway station, which should be detailed in the same way as in practice, including track sections, switches, etc. The model considers all the components from the previous problem (parking, matching, routing, splitting, matching, and servicing) and adds three others that have so far only been studied individually.

First, we should consider the movements between the station and shunting yards, as the routing problem must now ensure no conflicts occur between the ongoing trains passing through the general network and the trains that are shunted [10]. The second component regards the scheduling of rolling stock and personnel, their details (e.g., train length or job type), and the constraints posed by them [4]. The latter could include the personal preferences of conductors or the fact that there is often only one driver to operate trains in a shunting yard. Finally, the most important characteristic of this model is the notion of uncertainty since in practice we deal with many uncertainties, like the delayed arrival of a train or a prolonged time to clean a train. These should be included in the model to create solutions robust to small delays [3].

3 Discussion

Artificial Intelligence (AI) can provide promising new approaches to solving practical problems by finding abstractions or combining different models and their outcomes. For example, consider neural networks, which could be used to help the search procedure find good solutions. Neural networks are often bad at satisfying all the problem constraints, while they are very good at generalizing from a lot of data. So, they could very well be used to help the search, though not necessarily taking over. This combination of learning and more traditional methods is called neuro-symbolic AI and is also a very interesting direction of research in general, providing many benefits [11].

Quite some research has already been done considering a more abstract model. Nonetheless, these solutions are not applicable to the practical problem straightaway. Therefore, we suggest a focus on the relations between different abstractions. With the help of simulators, solutions can be tested and propagated through our framework. However, the more advanced railway hub simulators only exist as proprietary software to railway companies [6]. And since most scientific simulators focus on disruption management instead [2], there is still a need for a scientific simulator for railway hub operations.

Combining approaches from different models could also be an exciting focus. Machine learning methods can provide new insights and aid the decision of which approach to use, which is another form of neuro-symbolic AI. Joining several solutions could be more beneficial than striving for more advanced models, as the inclusion of extra details tends to make them more challenging. So, we suggest a model that uses these insights.

Moreover, we highlight the importance of creating methods that work together with human operators. Human-AI collaboration is important to ensure that research is useful and applicable in practice. Then, even in scenarios where AI methods fail, they can provide insights to human operators to solve the last details. Therefore, we propose hybrid methods that not only combine solutions but also have a human-in-the-loop perspective, to assure planners of the benefits.

With this overview, we have provided a framework to position previous research. We have given three examples of different models, shown the relations between them, and positioned them in our framework. Finally, we have pointed out the most promising directions for future research. Given the limited space within a heavily used infrastructure in the Netherlands, we believe that solutions that work for Dutch scenarios will also be useful in other countries, especially when dealing with capacity issues.

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Boosting Holistic Railway Infrastructure Monitoring and Health Prediction by Integrated Data Sets and Analysis

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Abstract. The digitalization and automatization of railway infrastructure health diagnostics using various kinds of embedded wayside and onboard sensors in combination with common monitoring and inspection motivates a more and more integrated health analysis for all the relevant asset components such as rails, ballast, switches and crossings, point machines, and others. In this context, the present contribution discusses how an integrated research data set – as currently being collected by partners within the Europe's Rail project IAM4Rail – is going to stimulate new research and developments as well as innovative solutions with regard to several use cases from the field of railway infrastructure maintenance. This includes the application of modern data fusion techniques based on artificial intelligence as well as physical and hybrid modelling approaches.

Keywords: Holistic PHM · Data Fusion · Data Analytics · Digital Twin

1 Introduction

The railway infrastructure is a complex combination of various components such as rails, ballast, switches and crossings (S&C), point machines (PMs), catenary, interlocking etc., all having their own fault options and therefore often being maintained separately in practice. However, components often do not operate independently, and also their health condition and degradation may depend on each other. Holistic railway infrastructure monitoring thus aims at explicitly taking such dependencies into account for the purpose of enhanced diagnostics and health prediction including considering

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the connections to train operations. As for advancing digitalization and AI (= Artificial Intelligence) research, this requires systematic and synchronized data covering all relevant components including manual and automatic inspection data and maintenance reports as well as structured data from embedded sensors together with information about environmental conditions.

Partners from the Europe's Rail research project IAM4Rail has been collecting such a comprehensive data set for a 22 km long main line with mixed traffic on four parallel tracks and about 40 switches between Amsterdam and Utrecht in the Netherlands. A short overview of the data and measurement technologies used is given in Sect. 2. Based on that, Sect. 3 discusses several use cases and examples that has been or will be addressed in more detail using these data. The paper concludes with a short summary in Sect. 4.

2 Data and Technologies

Intending to foster the development of enhanced tools for integrated health monitoring and fault diagnostics via (simulation-oriented) physical models and/or modern data-driven approaches, various kinds of train-borne data are collected via the so-called LEONARDO platform (cf. Sect. 2.1). All this is accompanied by current curve (incl. control circuit) and sometimes also power supply measurements for the PMs together with environmental data such as temperature (cf. Sect. 2.2). For a dedicated switch, also sleeper displacements (per axle) and blade positions via inductive sensing are going to be measured. In addition to that, by using different modelling techniques and simulation frameworks, synthetic data sets will be generated by means of virtual sensors to complement the data obtained by means of real sensors in field test campaigns. Synchronized maintenance and manual inspection reports will help to validate and interpret the automatically generated measurements as well as the results that are going to be derived from them algorithmically.

2.1 The LEONARDO Platform in a Nutshell

The LEONARDO platform [1] uses a retrofitted tamping machine which has been transformed into an advanced rail measurement train for gathering comprehensive and accurate data on both the rail condition and the environment (cf. Fig. 1). Its "Trackscan" laser measurement system is employed to measure the railway tracks while a LIDAR (= Light Imaging, Detection And Ranging) sensor is utilized to map the surrounding environment alongside the tracks. Both the railway tracks and the surroundings are captured through an optical camera system which gathers detailed visual information. The LEONARDO also incorporates 3-dimensional ground penetrating radar (GPR) to measure ballast and ground layers, providing valuable data regarding the stability and consistency of the rail infrastructure. Additionally, axle-mounted acceleration and displacement sensors are integrated to record vibration patterns and measure the elongation of primary suspensions, aiding in the assessment of overall rail performance and safety including estimating relevant track geometry parameters.

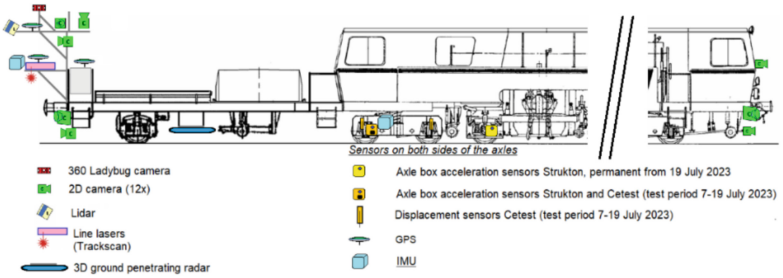


Fig. 1. Overview of the sensors mounted on the LEONARDO platform.

2.2 The POSS® System in a Nutshell

POSS® [2] is a condition monitoring system for assets in the railway and power industry. It consists of local dataloggers and sensors that collect measurements and send the data to a central server where it is visualized in a User Interface. The main focus of POSS® is the monitoring of PMs which includes measuring the consumed current during a throw, as well as the state of some related relays and the ambient temperature. When anomalies are found in these measurements (e.g., through the exceedance of predefined thresholds), the system triggers a warning or alarm, indicating to a team of maintenance experts that the behavior of the switch deviates from the expected patterns. The maintenance experts then go on to further analyze the data to see if any maintenance or repair activities are required.

3 Use Cases and Examples

3.1 Enhanced Monitoring of Plain Line Tracks Via Data Fusion

The automated detection and diagnosis of rail surface defects (e.g., rail corrugation, squats) and track geometry defects is important for the efficient maintenance of plain line tracks. While anomalies can already be detected quite well using suitable algorithms for analyzing the information from vehicle-borne sensors (cf. [3]), a comprehensive defect diagnosis, i.e., the automatic identification of the type of defect and the understanding of its underlying cause, is still a big challenge. Here, the algorithmic combination of camera data and measurements of the dynamic vehicle-track interaction from axle-mounted accelerometers in terms of data fusion based on multi-sensor systems (multi-purpose-vehicles) is expected to increase the accuracy of automated defect classification. Furthermore, combining established methods for monitoring the track geometry (e.g., longitudinal profile) using vehicle-borne accelerometers with insights into the ballast and ground layer derived from GPR data will provide unprecedented information on the underlying cause of geometry defects.

3.2 Enhanced Fault Diagnostics for Point Machines

Recent fault diagnostics for (electro-mechanical) PMs often relies on current curve measurements (cf. Sect. 2.2) which are then interpreted by maintenance practitioners for

triggering suitable maintenance actions. Modern approaches for automatically detecting anomalous current curves and identifying the underlying primary faults based on AI and ML (= Machine Learning) can help to make this process more effective while reducing the manual effort (cf. [4]).

In this context, the integration with onboard and wayside sensor data correlated to ballast quality and track geometry, for instance, is expected to allow for even better results when accelerated degradation or misalignment of movement-related switch components such as rods or rollers are just a secondary effect of bad track geometry or ballast conditions. Therefore, GPR and train-borne acceleration data (cf. Sect. 2.1) together with wayside measurements of displacements and/or blade position can be used for better parameterizing existing diagnostic models (cf. Fig. 2) which are mainly based on current curve analysis so far. Note that this might also include or require optimizing the models' structure in view of causal inference (cf. [5]).

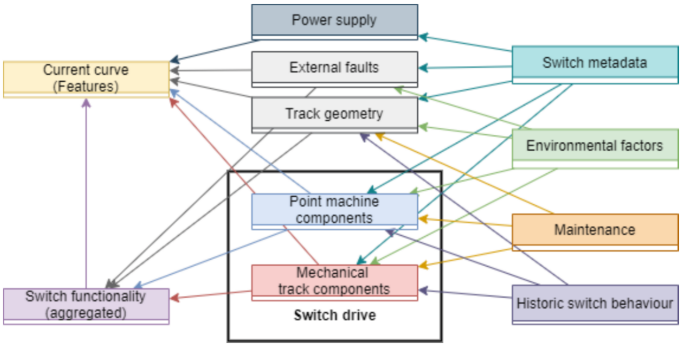


Fig. 2. Simplified Bayesian network model for holistic PM diagnostics [6]. Note that track geometry and switch drive components, for instance, are conditionally dependent here given the current curve as evidence. Thus, knowing track geometry is expected to immediately affect the inferred fault probabilities of the switch drive components.

3.3 Enhanced Modelling of Crossing Degradation

Digital twin frameworks can be very helpful for analyzing the health condition of crossings [7] and for optimizing the design of related sensor systems. For this purpose, MBS (= Multi Body Simulation) and FEM (= Finite Element Method) models are going to be used for simulating the vehicle-track interaction at different running conditions. On the one hand, MBS simulations allow for calculating the contact patches between wheels and the turnout. On the other hand, FEM models are necessary to study medium and high-frequency domain accelerations. Processing these synthetic accelerations then reveals the most relevant KPIs (= Key Performance Indicators) for defining the degradation level of the assessed turnout within a degradation trend. Moreover, knowing the set of most relevant KPIs also helps to reduce the number of required sensors and to choose suitable ranges and sampling rates for real world applications.

Figure 3 shows a flowchart of the approach using both MBS and FEM models. From simulations at different degradation levels and running conditions, a degradation

database (DDBB) is going to be generated to eventually define the health conditions with real measurements, such as those described in Sect. 2 by means of sensors installed in the S&C. Although previous field tests are required to validate the models, the leverage of this methodology is the simulation of faulty conditions and degraded scenarios [8].

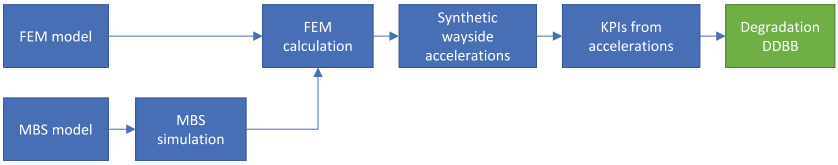


Fig. 3. Flowchart to obtain degradation databases for a specific turnout.

3.4 Optimized Sensor Selection and Positioning

Parallel measurements for the same infrastructure asset or the same track element using various wayside and/or onboard sensors (cf. Sect. 2) are likely to contain redundant information about the respective health conditions. While data fusion (cf. Sect. 3.1) can help then to increase the reliability of the estimated health states, the data at the same time allow for analyzing which sensors or combinations of sensors (together with their positioning) are the most informative ones or, on the contrary, could be dropped from the overall sensor layout without too much loss of information. Even more, transferring knowledge as obtained from a few highly equipped and comprehensively monitored infrastructure assets could reduce the sensor needs for the large rest of similar assets in the rail network. As a result, sensors can be selected and positioned in a more optimal way considering both statistical power of the data and cost efficiency.

3.5 Train Operations and Asset Criticality Analysis

Train operations are not only important as influencing factor for the physical degradation of infrastructure assets (cf. Sect. 3.3), but also determine or affect the criticality of relevant assets (e.g., S&C) in the network because of a possibly limited availability of bypass options in the case of failure (cf. [9]). Combining such a criticality perspective with information about the respective assets' current or predicted health conditions (as obtained by methods like mentioned in previous sections) can help to optimize maintenance decisions not only on the asset level, but also on the network level while systematically reducing the total amount of delay and disturbances in train operations from a holistic perspective.

4 Conclusion

Comprehensive and systematic real-world data sets based on various kinds of sensors in parallel for a dedicated track section or pool of fixed assets as described in Sect. 2 are still rarely available in practice, but have the large potential of pushing research and development forward with regard to many use cases of infrastructure monitoring and

maintenance (cf. Sect. 3). The proposed holistic approach is expected to provide further insights into the relations between the different infrastructure or track components by means of data analytics and modelling. By that, it promotes a more integrated view on the health management of railway infrastructures, possibly even including analyzing asset criticality from the perspective of train operations.

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Automated Adaptive Traffic Network: Adapting the M50 in Real-Time by Optimizing Speed Limits Using a Proposed Intelligent Agent

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Abstract. Traffic congestion has been one of the most important issues in urban areas, which results in pollution, fuel cost, loss of time (work hours), stress and anxiety. It is possible to increase the traffic network efficiency through solutions such as Intelligent Transport Systems (ITS) by adapting the existing network to ongoing operational conditions, especially in bottle neck conditions. In this study to minimize travel time losses, speed limits are optimized to adapt the traffic network to its operational conditions in real-time. To do so, an intelligent agent is developed to estimate the traffic in part of the M50 motorway in Dublin and is given the capability to learn and change the operational scenarios of the motorway that allow it to perform online management of its speeds.

Results, tested in SUMO, indicate that the intelligent agent can reduce the travel time at peak congestion by a maximum of 60% in average travel times for a period of 10 min, and it has an overall significant benefit to alleviate congestion in the M50 section of interest during peak morning and afternoon times.

Keywords: Machine learning · Traffic system · Optimization algorithms · Transport services and sustainable cities · Artificial neural network · Simulation

1 Introduction

Since the last century, traffic congestion has been one of the most important issues in metro cities, which results in pollution, fuel cost, wasting people's time (work hours), and the stress and anxiety caused by congested traffics [1]. Hence, the necessity of congestion controlling is undeniable. Two main solutions have been tested to solve this problem: a) expanding the traffic infrastructure, which is significantly costly and hard to implement, and b) reducing the number of vehicles by encouraging people to use shared transportation (providing cheap and convenient shared transport alternatives) and discouraging the usage of private vehicles (such as tolls and fines) which is crucial due to growth in demand and people's expectation.

However, it is possible to increase the traffic network efficiency by adapting the existing network to the ongoing condition especially the bottle neck conditions. To do so, it is needed to define congestion in the first step. Congestion is the travel time that is

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more than what it is supposed to be under a free-flow condition [2]. There are multiple actions that can be taken to decrease the congestion such as changing the speed limits of the roads, switching lanes direction in favor of the congested traffic's direction, changing the traffic lights' timings to name a few. Although each one of these actions has been used in some of the main roads in developed countries they are not being used in the optimum way. It is either based on the history of the traffic flow in that road, which can be wrong due to unusual circumstances or human judgment which is not the optimum option. Therefore, the traffic network is not being optimized in real-time.

In this study an intelligent agent is developed using Artificial Neural Network (ANN) to predict the travel time and an optimization algorithm to optimize a part of M50 motorway in Dublin by changing the speed limit of each lane individually. However, it should be taken into consideration that the performance of an ANN depends on its structure (the number of hidden layer and the number of nodes in each hidden layer). Thus, another optimization algorithm is used to optimize the ANN's structure.

2 Methodology

In order to optimize the speed limits in the motorway we need to run an optimization algorithm using a simulation as its cost function, which may call the simulation hundreds of times that results in a significantly high computational cost. Therefore, in this study an ANN was trained to predict the simulation outputs (i.e., travel time). Moreover, an optimization algorithm called Salp Swarm Algorithm (SSA) [3] was used to optimize the ANN's structure in order to minimize its error. Interested reader are referred to [4] for further explanation of this method. As it can be seen in Fig. 1 the intelligent agent consists of two parts: a) estimator and b) decision-maker. The hybridized ANN that was explained before is the estimator while the decision maker is another SSA that searches for the optimum combination of speed limits for each lane and calls the ANN (estimator) in each iteration to predict the travel time for each speed limit combination.

In this study Simulation of Urban Mobility (SUMO) that is a multi-modal microscopic agent-based traffic simulator was used to prepare the dataset to train the intelligent agent and to validate its performance.

3 Results

In the current study, a day is divided into 10-min time steps which means the agent is activated every 10 min at the start of the time steps to predict the travel time for the time step and optimize the speed limit combinations if necessary. Here is the performance of each part of the agent individually.

3.1 Estimator's Implementation

The optimum ANN (estimator) has 12 neurons in its input layer for 12 inputs, two hidden layers with six and five neurons in the first and second hidden layer, respectively, and one neuron in its output layer for its only output. The R-value of 0.98 and the mean absolute percentage error (MAPE) of 3.3% represent the high accuracy of the estimator (see Table 1). Moreover, Fig. 2 shows the estimator's cross validation.

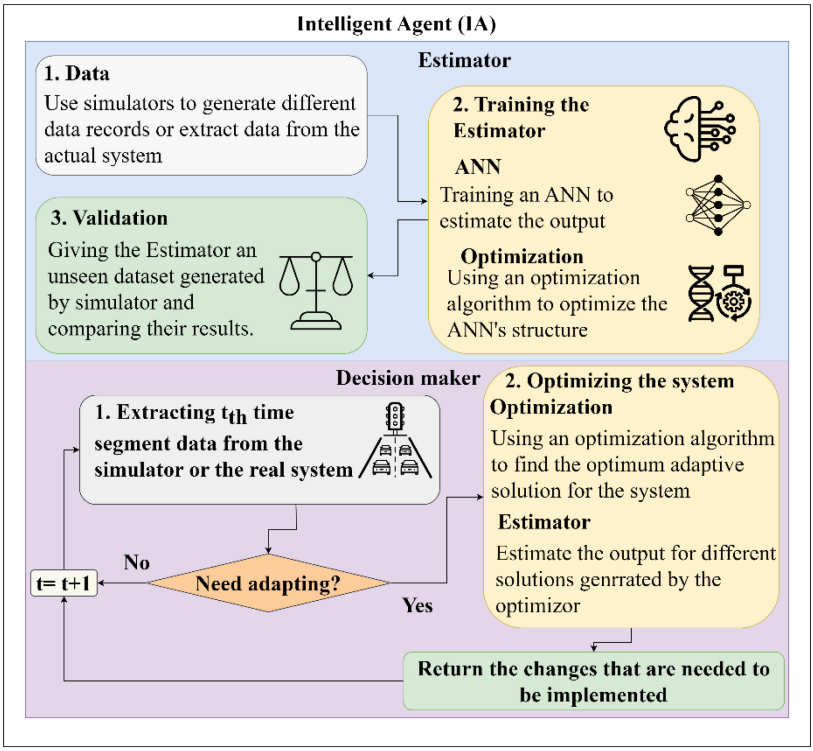


Fig. 1. Proposed agent's flowchart.

Table 1. Table captions should be placed above the tables.

Structure	RMSE (s)	MAPE (%)	R-value
12-6-5-1	34.6	3.3	0.98

3.2 Decision-Maker's Implementation

The intelligent agent was applied to a 24-h simulation of a part of the M50 motorway in Dublin. In a 24-h time-period there are two peaks in the traffic, first one approximately between 7 am and 11 am, and the second one approximately between 4 pm and 8 pm. Figure 3 compares travel time of each vehicle individually (a) and of each time step as the mean value in normal and optimized traffic network (b). Results showed that the travel time decreased significantly when the speed limits were optimized. The biggest reduction in mean travel time is 55% and the same value for a vehicle is 69%. Table 2 presents the reductions in travel time.

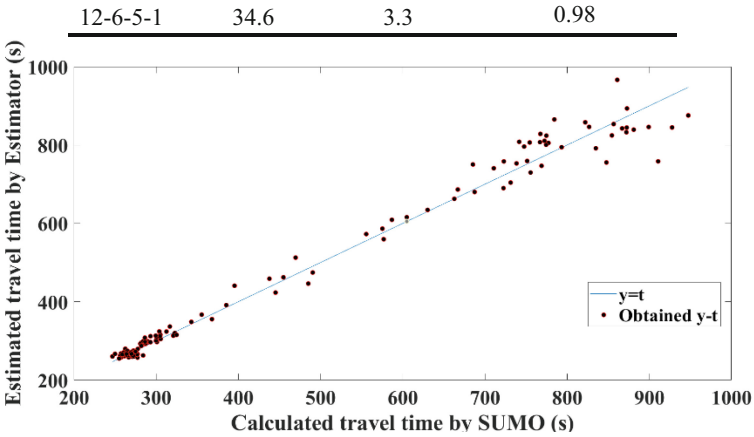


Fig. 2. Estimator's cross-validation (Predicted travel time by the Estimator vs. calculated travel time by the simulator).

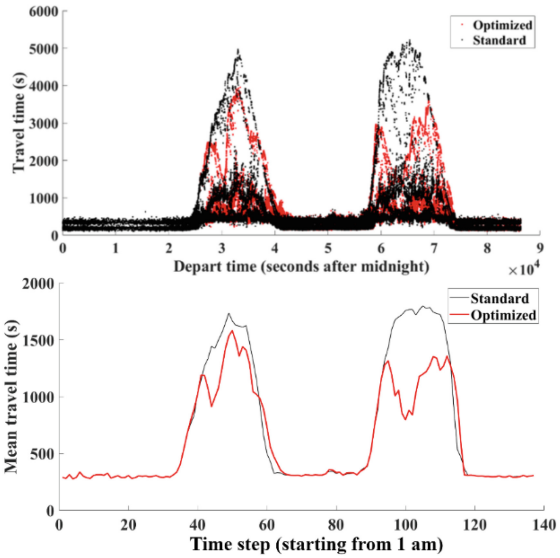


Fig. 3. Decision-maker's performance: a) individual vehicle's travel time and b) time steps' mean travel time.

However, travel time may not be a proper representative of congestion in traffic, since it does not reflect the extra time that vehicles spend in traffic because of the congestion, and it only states how long it takes the vehicles to reach their destination. Thus, another indicator named waiting time is introduced in this study which indicates the accumulative time that a vehicle spends in the traffic network while moving slower than 0.1 m/s. Figure 4 compares vehicles' waiting time individually in the standard and

Table 2. Reductions in travel time caused by the intelligent agent.

	Highest reduction in mean travel time of a time step (%)	Highest reduction in travel time of a vehicle (%)
First peak	37	60
Second Peak	55	69

optimized traffic network (a), and different time steps' mean waiting times in the standard and optimized traffic networks (b). As can be seen in Fig. 4, waiting time also drops significantly after optimizing the traffic network. The biggest reduction in a vehicle's waiting time is 91% while the biggest reduction in a time step's mean waiting time is 97% (see Table 3).

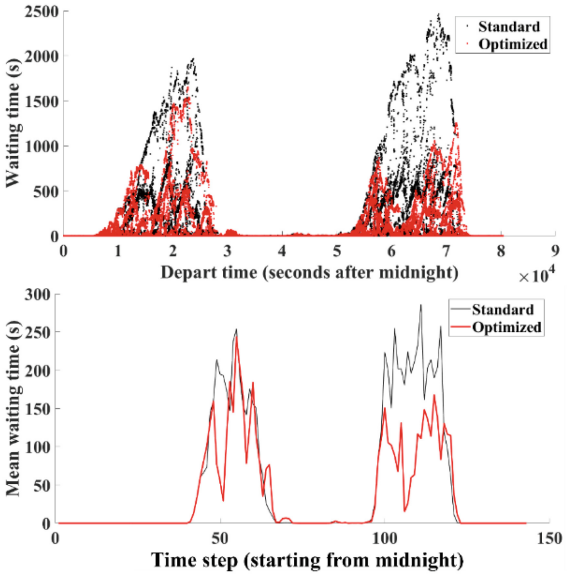


Fig. 4. Decision-maker's performance: a) individual vehicle's waiting time and b) time steps' mean waiting time.

Table 3. Reductions in waiting time caused by the intelligent agent.

	Highest reduction in mean waiting time of a time step (%)	Highest reduction in waiting time of a vehicle (%)
First peak	97	91
Second Peak	91	93

4 Conclusion

To reduce the traffic congestion and have a more consistent traffic flow a novel methodology called intelligent agent including two different parts (i.e., estimator and decision-maker) is developed in this study. The drawn findings of this study are as follows:

- The hybridization of an ANN and SSA as the estimator can predict mean-travel time in 10-min time steps with almost 97% accuracy.
- Since the estimator's outputs match the simulation's outputs with a high accuracy, it can be concluded that the estimator is a good representer of the real traffic network.
- There are two peak times in a 24-h simulation of the case study.
- Waiting time is introduced beside travel time since it is a better indicator of congestion.
- The proposed intelligent agent can reduce the target vehicles' travel time and waiting time.
- The significant reduction in waiting times reflects a meaningful reduction in traffic congestion and it shows that the optimized traffic network has a more consistent and free flow compared to the standard network.

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Flight Centric ATC: Reflecting Three Years of Research on an Efficient and Eco-friendly Air Traffic

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Abstract. This paper presents the Flight Centric ATC (FCA) concept, which has been investigated as part of the Single European Sky Air Traffic Management Research (SESAR) 2020 Programme over the last three years, combining the increase of airspace efficiency with the aspect of environmental sustainability. The FCA concept distance itself from the classical airspace structure consisting of sectors in which in Europe typically one controller team is responsible for all aircraft. Instead, the FCA airspace is seen as a uniform area in which several controllers are each responsible for a certain amount of aircraft. In combination with other conceptual approaches such as the Free Route Airspace and the use of controller support tools such as the Conflict Detection & Resolution, flight trajectories in FCA can be optimized and conflict situations between two or more aircraft can be solved with the least possible trajectory deviations. The concept also enables a better distribution of the overall workload among all controllers, avoiding the overloading of individual controllers and making more effective use of their capacities. With those effects, FCA enables a reduction in the total fuel required and at the same time decreases the emission of environmentally harmful CO_2.

Keywords: Air Traffic Management · Flight Centric ATC · Fuel Efficiency · SESAR 2020

1 Introduction

The demand for air travel continues to grow steadily. With the removal of the Covid-19 restrictions in the European travel sector, Europe is once again experiencing a significant increase in air traffic. Forecasts predict a return to pre-crisis levels by 2025 at the latest [1]. This means that the aviation industry is once again facing the well-known airspace bottlenecks and a corresponding increase in airspace efficiency is essential [2]. At the same time, environmental sustainability is becoming increasingly important in the transport sector. Within the Single European Sky ATM Research (SESAR) Programme, this aspect represents one of the main pillars [3]. Complementing innovative concepts for improved approach and departure procedures, new types of controller support tools or airport procedures aiming to minimize the impact of air traffic on the environment,

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the Flight Centric Air Traffic Control (FCA) concept introduces the idea of fundamentally restructuring the established sector-based air traffic control in the upper European airspace to adapt to today's needs. The concept not only closes the gap between environmentally friendly ground, approach and departure procedures, but also profitably integrates air traffic controller support tools designed for the upper airspace. Through this, the concept enables a reduction in the total fuel required per flight and consequently decreases the emission of environmentally harmful CO_2 [4].

2 Flight Centric ATC Concept

The FCA concept offers the possibility to use the en-route airspace more efficiently, to distribute the controller workload more evenly, and at the same time to increase the airspace capacity. In doing so, it moves away from the traditional, fairly rigid structures of sectorized airspace, where the responsibility for the air traffic within a sector is usually allocated to a team of air traffic controllers consisting of an executive and a planning controller. Instead, the new FCA concept combines several en-route sectors and creates a uniform, large airspace without internal boundaries. In this FCA airspace, a singular team of one planning and one executive controller is no longer responsible for all air traffic. Instead, several single controllers or controller teams share this task. Thus, different conceptual approaches are possible in FCA, which are more or less suitable depending on the airspace under consideration. According to [5], a distinction is made between the following controller compositions:

- One Flight Centric ATC Planning Controller (FCA PC) is responsible for the traffic entering, exiting and passing through the Flight Centric ATC airspace.
- More than one FCA PC is responsible for the traffic, and they are associated each to several Flight Centric ATC Executive Controllers (FCA EC) or to specific flows (e.g. arrivals, departures, overflights).
- More than one FCA PC is responsible for the traffic, and they are associated each to a specific FCA EC, that means the FCA EC and FCA PC share the same situational awareness.
- No FCA PCs. In this case all ATC tasks will be performed by the FCA ECs. This configuration is also referred to as Single Person Operator (SPO).

These SPOs or controller teams are assisted by support tools which enable controllers to maintain an overview of the relatively large FCA airspace while carrying out necessary changes to an aircraft's trajectory as efficiently as possible. The tools used for this purpose are Tactical Controller Tool (TCT)/Planning Controller Tool (PCT), Less Impacted Flight Algorithm (LIFA), allocation system incl. workload prediction function and filtering; all described in detail in [6, 7].

3 Analysis of the Environmental Impact

Within the framework of the SESAR 2020 project PJ.10-W2-73 FCA, two real-time simulations (RTS) were conducted to validate the FCA concept under different aspects. In the first RTS conducted by DLR, Frequentis and HungaroControl, the Hungarian

airspace above Flight Level (FL) 325 was declared as Flight Centric ATC airspace. In this airspace, air traffic controllers worked in single person operations supported by conflict detection and resolution tools. An allocation center was used to allocate aircraft to the individual FCA ECs, with the workload distributed evenly among the available controllers [6, 8]. The second RTS, conducted by ENAIRE and INDRA, investigated the FCA concept on the example of the Madrid Area Control Center (ACC) for the upper airspace (from FL365 to FL660) excluding the Terminal Maneuvering Area (TMA) Madrid. The composition of the controller team complied with the conventional team composition of an executive and a planning controller. A semi-automatic allocation was applied using a combination of an allocator and an allocation centre [9]. Within the framework of both RTS, a large number of use cases were analysed and validated to demonstrate the feasibility of the concept. These included the validation of traffic allocation, conflict detection and resolution, ground-ground coordination and frequency management. Furthermore, communication failures, emergencies and adverse meteorological conditions were examined as so-called abnormal conditions. The link between the FCA concept and Dynamic Airspace Configuration (DAC) as well as the switch between sectored ATC and FCA operations were also analyzed [5]. The assessment of both simulations has proven that the concept is in general operationally feasible. This applies to both normal conditions as well as abnormal conditions, such as large thunderstorm areas or an in-flight emergency declared by an aircraft, e.g. due to decompression in the aircraft cabin. The operational feasibility of the system under degraded-mode conditions, e.g. the failure of individual system components, was also demonstrated [8]. In terms of expected benefits, it has been shown that a more even distribution of aircraft, based on individual workloads, could reduce the total number of controllers required. The expected fuel savings, due to long-term conflict resolutions with minor trajectory deviations, and the resulting CO_2 savings, could also be demonstrated in the validation runs. Depending on the density of air traffic, savings between 7.12 kg and 19.00 kg fuel per flight could be achieved in the relatively small Hungarian airspace, while in the high-density airspace of Madrid ACC 12.45 kg fuel per flight could be saved [4]. However, it became apparent that the confidence of the controllers in the new support tools is still very low. Controllers tend to rely more on their own conflict resolution instead of following the system's suggestions. Specific training on the tools' mode of operation can further strengthen the controllers' confidence in the tools, so that further savings in fuel and CO_2 can be expected [8]. In addition, a fast-time simulation (FTS) was carried out by EUROCONTROL and AgentFly to support the Cost-Benefit Analysis (CBA) considering a Europe-wide implementation of the FCA concept. In this simulation, the European airspace was divided into eight Flight Centric ATC areas, fictitious so-called Virtual Airspace Blocks (VABs), which were created according to the complexity of the traffic and the existing ACC boundaries. Using a fast-time simulator, various implementation scenarios were analysed in order to compare the economic benefits of the FCA concept with the expected costs of implementation and operational execution. Table 1 shows the different scenarios for an implementation of the Flight Centric ATC concept that were examined. A distinction was made between the tools used (basic vs. advanced), the type of environment (fragmented vs. consolidated) and the type of implementation (static vs. dynamic) [8].

Table 1. Implementation Scenarios [10]

	Static Implementation		Dynamic Implementation	
	Fragmented Environment	Consolidated Environment	Fragmented Environment	Consolidated Environment
Basic Tool Support	Scenario 1	Scenario 3	Scenario 5	Scenario 7
Advanced Tool Support	Scenario 2	Scenario 4	Scenario 6	Scenario 8

While "basic tool support", with the exception of a rudimentary allocation center, refers to tools already used in today's sector-based air traffic control, the term "advanced support tools" relates to the use of new support tools such as a conflict resolution tool. The distinction between a static and dynamic implementation describes whether the Flight Centric ATC airspace exists 24/7 with a fixed lower airspace boundary (static) or whether the lower boundary of the airspace can be dynamically adjusted depending on the time of day and thus on the traffic load in order to keep the complexity of the traffic in the FCA airspace stable (dynamic). A fragmented environment refers to the implementation of the FCA concept at ACC level, whereas in a consolidated environment the implementation is based on the eight VABs mentioned above. The fuel savings shown by the two RTS and the FTS were extrapolated to a European Civil Aviation Conference (ECAC)-wide airspace, using the SESAR Common Assumptions [11] as a reference. According to these, 15.60% of all ACCs in ECAC are classified as very high-complexity, 26.55% as high-complexity, 39.10% as medium-complexity and 18.75% as low-complexity airspace. Due to characteristics of each VAB, such as traffic volume of individual flight levels and fluctuations of traffic volume throughout the day, a fully static implementation of FCA in all VABs is not realistic. Considering these factors, an expert judgement (Table 2) was used to determine the percentage of the respective VAB airspaces in which the FCA concept can be applied using static implementation. Based on this expert judgement, the potential fuel savings for the individual VABs were calculated [4].

Table 2. Expected applicability of static FCA per VAB [4]

VAB 1	VAB 2	VAB 3	VAB 4	VAB 5	VAB 6	VAB 7	VAB 8
10%	10%	15%	50%	40%	80%	60%	80%

For the calculation of a dynamic implementation, the calculation of the fuel savings was done by using the performed FTS, supported by the results of the RTS of a dynamic implementation in scenario 5. It became apparent that the highest possible fuel savings in the different VABs cannot necessarily be achieved with the same of the eight scenarios mentioned above, as the influencing factors, such as traffic volume and traffic complexity, are quite different. Table 3 shows the maximum fuel savings per VAB [4].

Table 3. Maximum fuel saving per VAB in kg/flight [4]

VAB 1	VAB 2	VAB 3	VAB 4	VAB 5	VAB 6	VAB 7	VAB 8
−30.88	−120.52	−145.29	−2.65	−21.46	−1.50	−26.38	−3.06

The analysis of the scenarios presented in Table 1 showed that, from a macroeconomic perspective, scenario 1 offers the highest benefits (2 834.4 M€) compared to the expected costs, followed by scenario 8 (1 825.5 M€) [10]. An initially surprising result, as scenario 8 would be expected to deliver the overall best results due to better support tools and larger airspaces. However, the outcome can be explained as follows: In scenario 1, the costs of introducing the concept are much lower. This is due to the low costs of developing and implementing new tools, as in this scenario the existing controller support tools are used to the maximum extent possible. Furthermore, although the same time horizon (2023–2042) was used to calculate the net present value for all scenarios in the cost-benefit analysis, the Initial Operating Capability (IOC) and the Final Operating Capability (FOC) differ from scenario to scenario. For scenarios 1 and 5, the IOC is at 2027 and the FOC at 2032, while for all other scenarios the IOC is 2032 and the FOC is 2042 [10]. Accordingly, scenarios 1 and 8 are only comparable to a limited extent. Furthermore, it must be taken into account that an introduction of the FCA concept based on the parameters of scenario 1 is only possible in low complexity airspaces, whereas in scenario 8 more complex airspaces can also be controlled using the FCA concept.

4 Conclusion and Next Steps

The real-time and fast-time simulations conducted within the framework of the SESAR 2020 project PJ.10-W2-73 FCA have shown that the FCA concept is operationally feasible. However, especially in airspaces with higher traffic density, controller support tools are indispensable to guide air traffic safely and at the same time as efficiently as possible, thus keeping deviations from the optimal flight trajectory as minor as possible. It is therefore essential to build trust in the highly automated support tools through comprehensive training and the development of a strong understanding of the system by the controllers [12]. First analyses of abnormal and degraded-mode conditions also revealed that controllers could achieve better results in terms of trajectory deviation in FCA than in sector-based airspace [8]. This can be explained in particular by a more even distribution of the workload among all controllers, as capacity exceedances leading to large re-routing, e.g. in the case of large thunderstorm cells, could be avoided. The project reached the maturity level V3-ongoing within the SESAR 2020 programme. This means that the concept is not yet ready for industrial use and further investigations are necessary, including real-time simulations. These investigations are currently being carried out as part of a follow-up project under the umbrella of the SESAR 3 programme. In 2026, these investigations are expected to be completed and the FCA concept should then have reached a corresponding level of industrial maturity (V3). In addition, further research is needed on the application of the FCA concept in very high-density airspaces

and in cross-border FCA airspaces. Moreover, challenges regarding legal issues, Human-Machine Interface (HMI) design, communication as well as standards and regulations must be addressed, as [13] has summarized in a corresponding roadmap. Further studies on possible allocation strategies of aircraft to controllers and the general restructuring of the air navigation service providers in Europe are also key areas to be investigated in a correspondingly large, cross-country FCA airspace [13]. First approaches of possible allocation strategies have already been analyzed in [7].

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Impact of the COVID-19 and Russian-Ukrainian War on Rail Freight Transportation – Analysis of Turkiye

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Abstract. Over the last two decades, global supply chain management has introduced many innovations to minimize costs and to create lean supply chains with faster, more reliable, and more flexible transportation services. However, though leaner supply chains are cost-effective, they are more vulnerable to external risks. Unexpected events such as economic crises, natural disasters, political and cyber security events, and epidemics endanger the functioning of transportation modes and increase the risk in the journey of goods in the supply chain from the first supplier to the final customer. Therefore, the relationship and balance between economic efficiency and resilience are vital in supply chain performance.This article aims to analyse the impact of the COVID-19 pandemic and the Russia-Ukraine War on Turkiye and the Middle Corridor by putting forth the steps the rail industry must take to serve better in future crises and to increase rail competitiveness and resilience.

Keywords: Rail freight transport · COVID-19 · Russia-Ukraine War · Turkiye · Middle Corridor · resilience

1 Introduction

While cyclical economic crises led to a slowdown in growth, a decrease in demand, and freight traffic volumes, the COVID-19 outbreak caused difficulties in the delivery of products. In addition, the war that started with the Russian invasion of Ukraine in 2022 disrupted global supply chains. As a result of these crises, the shrinkage of freight traffic volumes, the deterioration of supply chains, and the change in the geography and market structure of transportation brought the importance of alternative transportation routes, especially railway corridors, to the agenda again.

In light of the upcoming global economic recession forecast, the picture is expected to be more fragile and have consequences for both developed and developing economies. This article analyzes the impact of the COVID-19 pandemic and the Russia-Ukraine war, in particular in the Middle Corridor and Turkiye. This study was conducted using grey literature. Grey literature is information produced outside traditional publishing

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and distribution channels and is not rigorously peer-reviewed. Some examples of grey literature are reports, policy literature, working papers, newsletters, government documents, speeches, white papers, theses, conference proceedings, discussion boards, and blogs [1].

2 Impact of COVID-19 and the Russia-Ukraine War on Eurasian Freight Transport

The sustainability of freight transport has been a long-debated issue. However, the pandemic has made the issue of sustainability and resilience even more crucial to recover from the worldwide crisis more quickly [2]. The widely accepted United Nations (UN) definition for the term resilience of supply chains, which is one of the issues raised by the COVID-19 pandemic in 2020, is as follows; "The ability to resist, absorb, adapt to, and recover from the effects of a hazard in a timely and efficient manner, including the preservation and restoration of the essential structures and functions of a system, community or society exposed to hazards" [3]. The resilience of a railway transport system is the ability of the railway system to resist, absorb, adapt, and recover quickly from disruptions or disasters and provide efficient services under normal conditions [4].

Like most transport systems, rail freight demand is subject to systematic and random changes. Moderate random fluctuations can be accommodated by the spare capacity in the system. Sometimes, however, bigger contingencies lead to demand shocks that cannot be fully absorbed by standard planning processes but require resilience planning [5].

2.1 Impact of COVID-19

The COVID-19 pandemic has exposed the limitations of contemporary supply chains. Established practices of freight consolidation, lean stock, and just-in-time delivery have limited the resilience of international supply chains and created imbalances in freight delivery, leading to shortages of some critical goods [6]. Unlike other modes of transport, Eurasian rail freight transport has experienced a period of growth. In particular, rail freight transportation, which started to play a significant role in the trade between Europe and Asia with the revival of the Historical Silk Road, experienced a boom during the pandemic and has become the priority mode of global logistics companies. Rail transport has also quickly adapted to the shipment of different types of goods, which is not typically the basis for rail transport. In this way, rail freight transportation has proven to be a resilient and reliable alternative mode of transportation in risky environments [7].

Container freight train transportation between China and Europe has developed to connect 108 cities in China, 208 cities in 25 countries, and 6.04 million containers have been transported in the last decade [8]. It is expected that China-Europe train freight transport is explode in 2023, as China relaxes its policies regarding Covid-19 as of January 8, 2023, after nearly three years of strict measures, and it is the 10th Anniversary of the Belt and Road Initiative (BRI) [9].

Although the pandemic highlights regionalization, Central Asian countries are expected to maintain their place in production and consumption and increase their share in global imports and exports. Therefore, China and other Asian countries will be the prime transportation destinations [10].

2.2 Impact of the Russia-Ukraine War

The Russian invasion of Ukraine in February 2022 dealt a major geopolitical blow to the Eurasian transport network.

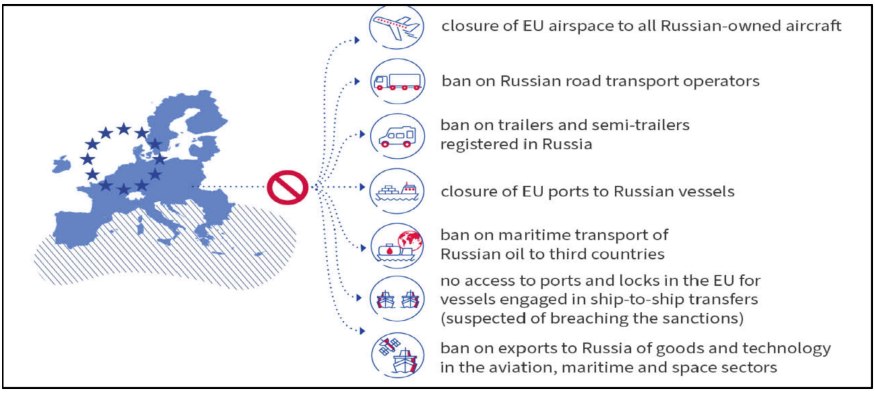


Fig. 1. EU sanctions against Russia in the field of transportation [11].

In particular, the sanctions and restrictions that the European Union started to impose on Russia in 2022 in transportation (Fig. 1) affected air and sea transportation, but the railway was less affected by the sanctions. Turkiye was the only NATO country that did not participate in these sanctions.

The rail route potentially impacted by the Russia-Ukraine war occupies only 2% of the westbound rail traffic from China to Europe compared to the results of 2021 [12]. Cargoes transiting through Ukraine were diverted north to Poland or south to the Middle Corridor after the war [13].

3 Middle Corridor and Turkiye

The most used Eurasian route for containerized rail freight transport is the Northern Corridor [14] due to its various competitive advantages, the second best option by land is the Middle Corridor (Fig. 2). Middle Corridor, also called the Trans-Caspian International Transport Route (TITR), aims to offer an alternative route to the Trans-Siberian Railway by creating a natural synergy with the Belt and Road Initiative(BRI). Middle Corridor is an approximately 6,500 km multimodal route from China via Kazakhstan, the Caspian Sea, Azerbaijan, Georgia, and Turkiye to Europe. The Corridor is at least 2,000 km shorter than the Northern Corridor through Russia [15]. It also attracts the attention of the landlocked countries of the region.

The strategic geographic location of Turkiye connecting Asia and Europe has made it an increasingly attractive partner of the Middle Corridor in the context of global supply chain reconfiguration. The shipping volume via the Middle Corridor in the first quarter of 2022 reached 19,500 TEUs [17]. The pandemic caused Turkish exports to fall in the first half of 2020, but the recovery started in the third quarter of the year and continued



Fig. 2. Middle Corridor Route [16].

in 2021. In 2022, despite the Russian-Ukrainian war, foreign trade increased compared to the previous year [18]. During the pandemic, the interest in the railway increased due to long border waiting times and bureaucratic highway transit documents, however, the share of the railway in export shipments could not exceed 1.0%.

The pandemic has accelerated Turkiye's demand for East Asian intermediate goods, especially in the machinery and electronic equipment sectors demonstrating Turkiye's dependence, to some extent, on East Asian second and third-tier suppliers [18].

4 Conclusions

Though COVID-19 and the Russia-Ukraine war have set the Middle Corridor in motion, high costs and slower transit times make it practically uneconomical and endanger its commercial use [19]. Moreover, the slowdown in economic growth and international trade may be the main challenge for rail freight flows through the Middle Corridor. Considerable actions are needed to create an attractive alternative to other Eurasian transport routes to realize the full potential of the Middle Corridor. Such actions may include improving interoperability between rail systems, digitalizing and harmonizing customs and transport documents, building container hubs- logistical centers and intermodal terminals, and upgrading transport infrastructure across participating countries. For seamless Middle Corridor, effective co-operation among all the countries along the route is critical. The analysis of Turkiye's position revealed that carriers generally use the Poti (Georgia)-Constanta (Romania) line to Europe and mainly serve the Turkish domestic market in Istanbul [20].

Despite many challenges, the results of this study point out that the opportunities are immense, and the will from all the Middle Corridor countries and private actors is clear. As the various components come together, the Middle Corridor will reshape trade and connectivity across the continents, strengthen regional cooperation and integration, introduce new investment opportunities, and stimulate economic growth. It will also lessen dependence on congested maritime routes and offer an alternative for moving

goods, mitigating disruptions caused by geopolitical tensions, international sanctions, natural disasters, and epidemics. Further research on operational user perceptions related to COVID-19 and the Russian-Ukrainian War on rail freight transportation is needed.

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Empowering Urban Authorities: Data-Driven Solutions for Effective Public Transport Management

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Abstract. Cities have an imperative role in achieving climate neutrality goals by 2050 through sustainable mobility. Transforming Public Transport (PT) into the cornerstone of the urban mobility stands as a promising opportunity, yet it also poses significant technical, political, cultural and financial challenges to the cities. Focused on PT, the UPPER project introduces U-TWIN and U-NEED, two data-driven tools aimed at supporting cities facing these challenges by enhancing real-time PT monitoring and long-term planning. These solutions empower urban authorities, PT operators, and authorities to optimize PT efficiency and accessibility, fostering increased usage and user satisfaction. This paper highlights the significance of U-TWIN's transformative real-time visualizations and U-NEED's comprehensive data analysis for efficient PT management. Emphasizing the anticipated benefits, the tools enable proactive issue detection, identification of corrective actions required, and understanding of passenger flows, contributing to resilient and responsive urban PT systems. Anticipating future use cases to demonstrate the effectiveness of the tools, these solutions are envisaged to be catalysts for sustainable development in all European cities, in line with the overall goal of greener and more efficient urban mobility.

Keywords: Digital Twin · PT optimization · Origin-Destination

1 Need and Context

Cities play a crucial role in reaching the objective of climate neutrality by 2050, which is a key goal of the European Green Deal [1]. As the mitigation of climate change relies significantly on actions taken in urban environments, it is essential to provide assistance to cities in expediting their transition towards environmentally friendly practices and digital advancements. European cities, in particular, have the potential to make substantial contributions to the Green Deal's target of reducing emissions by 55% by 2030.

In this context, Public Transport (PT) plays a vital role in fostering sustainable mobility, offering cities a significant avenue to pursue their goals. UPPER [2] - Unleashing the Potential of Public Transport in Europe – is a Horizon Europe project that takes the lead in spearheading a revolution in PT, elevating its position as a symbol of sustainability and innovation in urban mobility. By driving the transition towards zero-emission

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mobility, it sets the cornerstone of achieving climate neutrality in the field of European urban transport, empowering cities to embrace a greener future.

Bringing together 10 major European cities and regions and 31 partners with vast expertise in transport planning and operations, the UPPER project is born to unleash the potential of PT, transforming it into the central pillar of mobility systems across European cities. To realize this ambitious vision, UPPER aims to conceive, enact, and showcase 80 measures designed to both discourage private vehicle usage through access and parking restrictions, charging schemes, regulations, etc., and stimulate PT adoption by enhancing its offer, multimodality, efficiency, safety, comfort, and introducing economic incentives, among others.

Collectively, the 80 measures will work in conjunction to push people out of cars and pull them towards PT and shared mobility services, improving urban mobility in the 10 cities and regions of the project: Valencia, Rome, Oslo, Île de France, Mannheim, Leuven, Thessaloniki, Budapest, Hannover Region and Lisbon. In view of the potential challenges arising from the implementation of these measures within cities and regions, the UPPER project steps in to bridge the gap with research and innovation. Central to this initiative is the creation of a pivotal 'Measures Implementation Support Toolkit'. This toolkit, integrating seven cutting-edge technology solutions (U-TWIN, U-NEED, U-SIM, U-SUMP, U-GOV, U-KNOW, U-TRANSFER), is crafted to empower the cities and regions by assisting them in every phase of the process, from design and simulation to monitoring, evaluation, scaling-up, and ultimately, maximizing the efficacy of their 'push and pull' measures.

This paper focuses on two of the core components of the UPPER Toolkit, U-TWIN and U-NEED, two data-driven solutions for effective PT management.

U-NEED emerges in response to the cities' need to enhance the PT service reliability and to optimize the travel structure. Existing tools often struggle to integrate and analyse multimodal travel data, predict service inefficiencies accurately, and construct origin-destination matrices when data is incomplete, limiting the support in the decision-making process. U-NEED aims to overcome these limitations, enabling proactive, data-driven decision-making in the dynamic urban transportation landscape.

U-TWIN builds on the Urban Digital Twin (UDT) concept. A Digital Twin can be defined as "a virtual representation of a physical system that is updated through the exchange of information between the physical and virtual systems", while the expansion of UDT is attributed to the knowledge gained from the development of smart cities [3]. UDTs have gained traction in optimizing urban management, improving urban planning, and creating sustainable smart cities. However, the lack of standards and low levels of maturity of existing UDTs triggers the need to develop U-TWIN. U-TWIN aims to advance the state of the art by offering the digital twin of the public transportation and mobility assets of the city in an open and interoperable way, so as to become a building block for city/urban digital twins.

2 Data-Driven Solutions for Effective Public Transport Management

U-TWIN and U-NEED are designed to assist local authorities, Public Transport Operators (PTO), and Public Transport Authorities (PTA) in enhancing the efficiency, resilience, and accessibility of PT at different timescales. In the short term, U-TWIN enables real-time monitoring of PT operations, enabling swift responses to service disruptions or inefficiencies and the activation of corrective actions. In the long term, U-NEED facilitates the evaluation of overall multimodal transport flows and the detection of offer-related inefficiencies, helping to define optimal capacity and PT offer, and supporting decisions on necessary changes to ensure accessible and efficient PT services for all citizens.

Together, these tools contribute to building a dependable and adaptable PT system, capable of withstanding emergencies, incidents, and crises. This paper presents how these two IT tools, combining social and technological innovation, will support the ten UPPER living labs and twinning sites in the implementation of their measures, with the overall target of increasing the use of PT by $>30\%$ and the user satisfaction by $>25\%$, leaving nobody behind in the process.

2.1 U-TWIN: Overview and Functionalities

U-TWIN operates as a transformative solution rooted in the UDT concept, delivering vital support to cities. It achieves that by offering an integrated and modular real-time representation of urban mobility assets and their operational status. This advanced platform equips both the city and mobility authorities with a comprehensive toolset that simplifies the intricate connections between PT operations, traffic dynamics, user demands, events, and various urban elements. Notably, U-TWIN's impact extends beyond real-time visualization and monitoring of PT activities; it possesses the capability to identify anomalies, encompassing excessive occupancy, schedule deviations, and compromised air quality. Moreover, it provides projections of key insights such as travel times, estimated arrival times, occupancy rates, and air quality projections, facilitating prompt corrective actions when required.

The distinct functionalities of U-TWIN are crucial to its effectiveness. In particular, U-TWIN provides an adaptable and unified real-time representation of urban mobility assets and PT operations, fostering a comprehensive view of the urban transportation ecosystem. Static components like background maps, PT stop locations, and PT routes are harmoniously integrated and displayed within the U-TWIN framework. U-TWIN seamlessly integrates and displays standardized real-time data, encompassing traffic status, precise PT vehicle positioning, occupancy levels of PT vehicles, demand at PT stops, ongoing events, and ongoing roadworks. Leveraging data analytics, U-TWIN identifies abnormal situations, presenting a series of alerts that highlight issues such as vehicle delays, overcrowding, accidents, vehicle malfunctions, and suboptimal in-vehicle air quality. Through the application of deep learning models that analyse historical data, U-TWIN delivers predictive insights regarding the upcoming arrival time of PT vehicles at designated stops. U-TWIN builds upon an architecture with enough flexibility to be

integrated into current systems and is prepared by design to be interoperable and scalable for potential extensions.

U-TWIN's primary beneficiaries are city authorities, PTOs, and PTAs, who rely on its real-time monitoring capabilities and its ability to identify irregular situations in order to activate mitigation strategies, via simulation of potential corrective measures facilitated by U-SIM.live. However, U-TWIN's role as a data integrator and standardizer extends its utility beyond these primary users, enabling it to serve as a valuable data repository for supplementary systems like simulators (U-SIM.live) and other applications seeking real-time insights, such as Mobility-as-a-Service platforms. In brief, U-TWIN is emerging as a transformative tool, weaving complex urban mobility data to anticipate potential challenges and drive proactive measures within the changing urban transport landscape.

2.2 U-NEED: Overview and Functionalities

While U-TWIN is primarily focused on short-term optimization, U-NEED complements this by addressing the long-term aspects of PT optimization and planning, concentrating on the analysis of user needs and passenger flows. U-NEED emerges as a comprehensive data analytics and big data visualization tool, designed to provide city authorities, PTOs, and PTAs with insights into multimodal transport demand and the dynamics of urban mobility. It aids in understanding how people move around the city using different modes of transport, thus facilitating adjustments to the PT services in response. At its core, U-NEED integrates origin-destination (OD) information sourced from various transport modes and provides a layered, geographically oriented 3D representation of passenger flows. This visualization technique assists in identifying pivotal inefficiencies within the PT services, such as geographical areas with inadequate coverage, extended travel durations, and insufficient capacity.

In practice, U-NEED achieves its objectives through a set of cohesive functionalities. The tool seamlessly integrates origin-destination (OD) matrices sourced from different transportation modes, facilitating a holistic view of passenger movement patterns, and uses novel algorithms to construct origin-destination matrices when data is incomplete. It provides a sophisticated 3D geographic representation of passenger transport flows from various modes in overlapping layers, rendering a comprehensive visual representation of the same. Moreover, the tool allows for the creation of versatile filters based on variables such as day, month, time, weather, and more, aiding in the identification and visualization of pertinent information. Based on geoprocesses delimited on the public transports zones, the tool allows juxtaposing the PT offer against the broader passenger flows to identify inefficiencies and shortcomings in the system. This process highlights areas with inadequate coverage and inefficiencies in PT travel times. The presentation of summarized reports serves as a concise overview, detailing the identified inefficiencies and showcasing the filters applied to the OD matrices.

Harnessing the capabilities of deep learning, U-NEED also deals with predictive analytics, foreseeing PT demand and traffic congestion under specific circumstances like weather and events. This predictive aspect empowers stakeholders to identify in advance abnormal situations and implement corrective actions in a timely manner, ranging from route adjustments to frequency modifications, introduction of new regulation points and more. U-NEED's synergy with U-SIM.plan offers the ability to simulate potential

mitigation measures for the abnormal situations, thus aiding stakeholders in selecting the most fitting strategies.

U-NEED's main beneficiaries are PTOs, city authorities, and PTAs, collectively utilizing the tool to develop a richer comprehension of urban movement patterns, identify and rectify inefficiencies within the PT offer, and define corrective strategies to enhance and optimize the PT network across medium and long-term horizons, rendering urban PT systems more responsive and aligned with the evolving user needs.

3 Future Use Cases

The ten cities and regions participating in the UPPER project will have the chance to utilize the tools introduced in this paper—namely, U-TWIN and U-NEED. Depending on their specific measures' nature and goals, as well as the existing tools within their urban contexts and data availability, each site will strategically select the appropriate tools from the UPPER toolkit to facilitate the execution of their respective 'push and pull' measures. Although the detailing of use cases occurs in later project stages, a few examples can shed light on sites that will leverage the presented tools to develop and implement their measures.

Valencia serves as a prime example of a city that will benefit from employing U-TWIN. Valencia aims to establish a real-time information service for PT, delivering timely updates regarding performance-affecting elements and travel durations (such as traffic, road maintenance, events, accidents, etc.). U-TWIN will serve as the means to convey this information to transport operators, empowering them to oversee service management and implement corrective measures as needed. Additionally, U-TWIN will be utilized to ensure citizens receive transparent and easily accessible information before and during their trips. The real-time data collected by U-TWIN on traffic conditions, road maintenance, accidents, and other relevant factors influencing PT performance will be presented to users via screens and apps before and during their journeys. This approach aims to enhance transparency, instil trust in the service, and reinforce its credibility.

Lisbon is also one of the UPPER sites benefiting from the use of U-NEED. The city of Lisbon will use U-NEED to enhance the PT and micromobility network around certain schools. The overarching goal of Lisbon is to reduce the use of private vehicles for transporting children to school. To achieve this, U-NEED will identify inefficiencies based on Origin-Destination (OD) data derived from student movement patterns, collected through the transportation pass. By analysing this data, U-NEED will enable Lisbon to identify service inefficiencies and adjust PT to cater to the schools' requirements, including the creation of new routes and schedules. Similarly, U-NEED will assist Lisbon in defining school perimeters where traffic will be restricted, while also displaying various walking routes from different stops around the schools. This way, users will be able to determine if routes within the designated school perimeter lack nearby stops, allowing them to decide whether to establish new stops or bring existing ones closer for improved accessibility.

4 Conclusions and Future Work

UPPER project addresses the pivotal role of cities in achieving climate neutrality, with a strong focus on PT transformation. The introduction of U-TWIN and U-NEED tools, focusing on real-time monitoring and long-term planning respectively, will be crucial for achieving an efficient and effective PT management. U-TWIN's dynamic visualizations enable prompt anomaly detection, while U-NEED's comprehensive analysis enhances long-term planning, both contributing to increased PT utilization and passenger satisfaction. These tools will empower urban authorities for effective PT management. Anticipated benefits include resilient PT systems, proactive issue resolution, and adaptive planning. The tools' effectiveness will be underscored through future use cases, demonstrating their impact on diverse urban environments.

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Railway Assets Resilience to Climate Change Application of the Smarter and Faster Adaptation EU Strategy

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Abstract. Despite the global will to limit the rise in temperature to 1.5 °C [1], the devastating effects of climate change are obvious. Climate change is a fact and last IPCC assessment report [2] confirms that global warming will continue to increase over the coming decades. It will bring with it all kinds of risks: more frequent extreme weather events such as heatwaves, droughts, or floods, to coastal erosion due to rising sea levels. The impacts will affect every human activity. Railway is one of them, and as it is one of the best solutions to dramatically reduce GHG emitted by transportation [3], making it resilient is crucial.

The work presented is a part of the European research project for a sustainable rail system, Europe's Rail flagship project #4 named Rail4EARTH. The four-year project started in December 2022. This paper presents the research undertaken as part of WP2 (Work Package 2) Adaptation to Climate Change (ACC), which aims to increase the resilience of the European railway system to the current and future climate conditions.

The method is to implement the EU adaptation strategy [4] to the railway sector, structured at this stage around its two first objectives 'Smarter adaptation' and 'Faster adaptation'.

Railway operators, infrastructures managers, train manufacturers will bring their expertise and experiences to the project: SNCF (France - Leader), ADIF (Spain), ALSTOM (France), PKP (Poland), Trafikverket (Sweden).

Regarding 'Smarter adaptation', the objective is to develop knowledge on climate change adaptation related to the railway assets design in order to make them resilient to the predicted climate scenarios for the coming decades, as their life duration ranges from 40 years (trains) to 100 years (infrastructure).

Concerning 'Faster adaptation', some geographical areas in the World are certainly currently facing the future climate conditions of Europe: the technical solutions already implemented for railway activities will be benchmarked.

Keywords: Climate change · Resilience · Adaptation · Railway · Assets

1 Framework and Scope of the Study

When considering the activities needed to minimise the impacts of climate change by increasing resilience, mitigation and adaptation are often confused, even though they are in fact different issues requiring very different modes of action. Although the study

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focuses solely on adaptation to climate change, given the scale of the subject and the fact that it is the very first step, it was necessary to limit the scope of the study. Thus, in phase 1 of the European project, only railway assets are considered (rolling stock, infrastructure, and station). The adaptation of maintenance and operation, linked to organisation and resources (equipment and personnel), should be addressed at a later stage.

The first two objectives of the EU's adaptation strategy for the rail sector - "Smarter adaptation" and "Faster adaptation" - must feed off each other. It was therefore crucial to draw up an overview of the study, clarifying its framework. This took the form of a flowchart shown in Fig. 1.

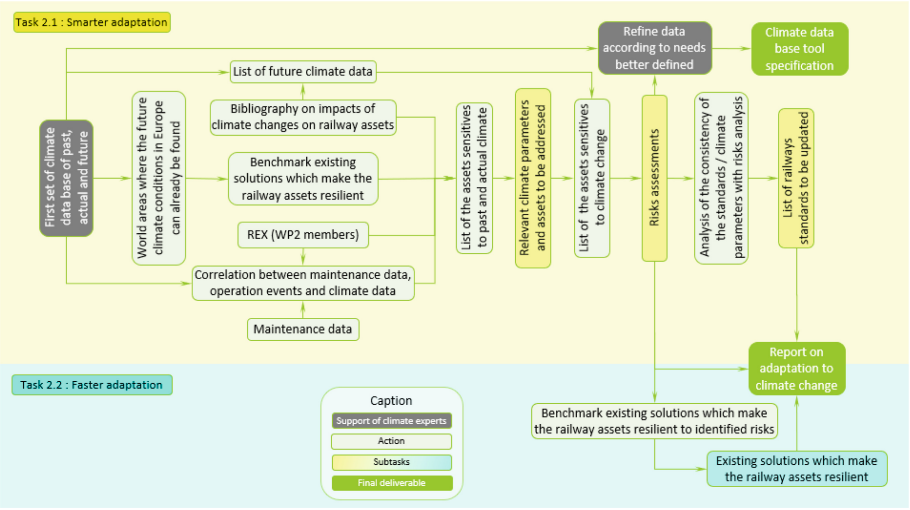


Fig. 1. Flowchart agreed within FP4-Rail4EARTH WP2 – Adaptation to climate change

2 Smarter Adaptation

The objective is to develop knowledge on climate change adaptation related to the railway assets design in order to make them resilient to the predicted climate scenarios for the coming decades, as their life duration ranges from 40 years (trains) to 100 years (infrastructure).

The main expected results are to provide European rail sector with standards and tools to help them define their resilience strategy.

To achieve the main intermediate result of this objective, i.e. the "List of the assets sensitive to climate change", several subtasks illustrated in Fig. 1 were launched in parallel including: **state-of-the-art** gathering the tasks "REX (Return of Experience) of WP2 members", "Bibliography on the impacts of climate change on railway assets" and "**correlation between maintenance data, operation events and climate data**".

Figure 1 shows that the **assistance of climate experts** is also required.

2.1 State-of-the-Art

The state-of-the-art offers partners the opportunity to share knowledge, to open up reflections and to gather data to create references of technical solutions implemented, resilience assessment methodologies used, standards involved and weather-related failures that railway assets have already faced. It will be compiled based on feedbacks from group members and open access information.

The news on websites - like the specialised rail media - is full of extreme weather events that have caused sometimes devastating damages to rail systems. This shows, if proof were still needed, that climate change is already having a significant impact on railway assets. And sometimes these events can turn tragic, like the derailment of a passenger train in Carmont (UK) in 2020 [5], due to debris on the track, washed out from a drainage trench after a heavy rain. It cost three people their lives.

Works in academic literature is mostly related to the infrastructure and meteorological conditions [6–10].

However, data on technical solutions are scarce.

- **Rolling stock**: Mitigating the effects of heat waves on trains is a key concern for rail operators. On the one hand, this involves keeping the trains functional and on the other hand ensure a level of passengers' thermal comfort deemed acceptable (with controlled energy costs). For the first point, the vulnerability of the (electronic) control and traction systems are particularly studied to avoid malfunctions due to overheating. For the second point, technical solutions are implemented in trains, such as tinted films on windows to limit heating of the passenger compartment by solar radiation [11].
- **Infrastructure**: Landslides caused by torrential rains are particularly dreaded by infrastructure managers. This type of earthworks failure is particularly common in the case of incidents on railway networks caused by climatic hazards. The direct cause of the derailment at Carmont in 2020 was a landslide. Enhanced preventive maintenance of water drain is often cited as the preferred mode of action.

  Regarding the scale of the task of adapting networks to climate change from a technical point of view, the tendency is rather to instrument and monitor those sections recognised as sensitive to climatic conditions to promptly apply safety measures such as limiting train speed.

2.2 Correlation Between Maintenance Data, Operation Events and Climate Data

The effects of climatic conditions on assets can be divided into three categories:

- Effects that have already (by now) caused major asset failures, climate change will only make things worse.
- Effects which are already appearing sporadically and have caused minor asset failures - often resolved by curative maintenance and not identified as a consequence of climate hazards - but which will become major with climate change.
- Effects that are not yet apparent but will become apparent with climate change.

Correlation between different databases aims to trap the second category.

As part of its corporate policy, the SNCF Group organised a Datathon (a Hackathon-type event dedicated to data processing) held in October 2023. A use case (UC) on Adaptation to Climate Change was included in this two-day event aimed at finding correlations between weather events and rail operating incidents/maintenance data by designing a data tool to allow these correlations to be fed by various data sources.

Data sources collected are shown in the Fig. 2.

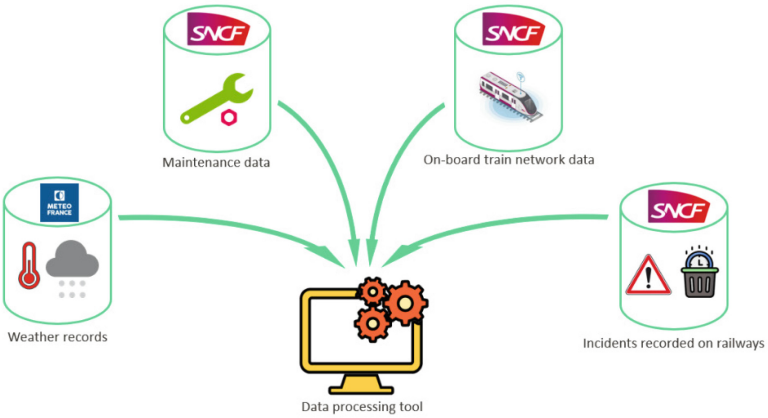


Fig. 2. SNCF Datathon 2023 – UC ACC: Data sources used for the data processing

As shown in Fig. 3, a good correlation was found between the outside temperature and the occurrence of operational incidents. There is even a trigger temperature threshold of around 32 °C. This is just one example of the very promising results obtained.



Fig. 3. Correlation between air temperature and hot weather incidents in operations

Even over such a short period, the event proved that this type of data reconciliation will also be relevant and decisive in assessing the vulnerability of rolling stock. Less than 6% of the data from the on-board network of SNCF trains was made available for the Datathon. SNCF-Voyageurs therefore has huge potential data to exploit in order to characterize the vulnerability of its rolling stock in a robust way.

2.3 Climate Experts' Assistance

The first exchanges of information within the group of European railway experts have revealed that the railway sector, like many other industrial sectors, deplores the lack of sufficiently relevant climatic data to guide their technical choices in terms of adaptation of their assets.

Past, present, and future climate data are available, often in open-access, but they are too global to be used to design assets and/or define their specifications and functionalities.

For instance, knowing the number of days over the next few decades when the temperature will reach over 45 °C in large areas of Europe is useless to consciously decide on the specifications and degraded modes of an air-conditioning system appropriate to future climate change.

The number of days with a temperature between 35 °C and 40 °C, between 40 °C and 45 °C and between 45 °C and 50 °C and so on, according to various IPCC scenarios, in geographical areas corresponding to distinct mission profiles in terms of railway applications would be much more insightful.

Exploiting raw climate data is a task that needs expertise in climatology.

In order to be used by industrial sector, these data must be processed by climate experts. Such an expert profile is nowadays absent from the staff of railway companies. Finding competent climate experts, capable of providing accurate and relevant statistics on the identified climate parameters, is also a task to be accomplished as part of this study.

3 Faster Adaptation

Current geographical areas in the World are certainly currently facing the future climate conditions of Europe: the technical solutions already implemented for railway activities will be benchmarked.

The aim is to define geographical zones corresponding to distinct mission profiles in terms of railway applications, to determine future climatic conditions in these zones and to identify the regions of the globe where it is possible to encounter such climatic conditions today. For all these aspects, the help of climatology experts is needed.

4 Results Expected in 2024

Finalising the state of the art by bringing together information from the literature and experiences shared by each member of the Work Package. This task of developing knowledge should make it possible to obtain a clear status on the following points:

- standards and regulations;
- prediction tools.
- weather conditions impacting railway assets and operations.
- sensitive assets.
- risks on assets.
- technical existing solutions.

Follow up the Datathon by structuring and launching an internal SNCF project to industrialise the promising approach developed during the event.

Panel of climate experts available on the market: it is expected to map the possible offers and their level of adequacy with the needs of the rail sector.

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Increase Resiliency Against Extreme Weather Events

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Abstract. Extreme weather events, for example heavy rainfall, storms and heatwaves, have effects on maritime logistics and hinterland transport. In case of extreme weather disrupts a mode of transport, each logistics company tries to shift their load to other means of transport. Because of a lack of cross-company coordination, goods of all priorities are then shifted to the remaining modes of transport. Not distinguishing between high-priority and low-priority cargo can cause delays for urgent shipments.

In order to improve the resilience against extreme weather events, a cooperative measure was designed. In this approach, an inland hub should coordinate the transports to strengthen the resilience and sustainability of transport chains. Inland hubs are important for more efficient freight distribution and are developed to promote a shift from road transport to rail or barge transport. This paper describes a simulation of an inland hub, which coordinates all transports between a port and the hinterland. This intermodal hub will also favour more environmentally friendly transport and should therefore increase sustainability.

Keywords: Resilient networks · sustainability · simulation · extreme weather events · adaption measure · inland hub

1 Introduction

Extreme weather events such as heavy rain, storms and heat waves directly affect the supply chain [1]. To address these challenges and achieve a resilient supply chain, stakeholders across various transportation modes must collaborate [2]. Attaining an ideal level of supply chain collaboration in practice is challenging due to numerous reasons, such as competitive nature of stakeholders who may seek a solution independently [3].

Moreover, barges and trains are usually only available to a limited extent. In order to strengthen these transport modes and to improve resilience to climate change effects, the inland hub concept was identified as a cooperative adaptation measure. Inland hubs are important for more efficient freight distribution and are developed to create a modal shift from road transport to rail or barge transport and to prevent the overcrowding of seaport areas [4]. The term “inland hub” is often linked to other terms as dry ports, inland terminals, etc. [5, 6].

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The major advantages of such hubs are lower logistics and distribution costs, reduced congestion, energy consumptions and improved capacity [5]. It helps to connect cargo handling from the port with other types of cargo in one common transport centre and can help the development of hinterland areas [7]. Based on existing inland hubs, it can be seen that the capacity problems of a seaport can be reduced. The inland hub should be a central point to absorb disruptions caused by extreme weather events.

For this study, a simulation of an inland hub was implemented to assess the increase in resilience and sustainability. Proposed climate adaptation measures are a suitable treat against heavy rain, storms and heat waves. Cooperative adaptation measures are a special case, as here several actors act together to increase resilience to disturbances.

2 Simulation

2.1 Simulation Model

Within the framework of a simulation, a model of an inland hub was used to test whether sustainability and resilience can be improved in the event of a transport mode breakdown because of an extreme weather event.

Specifically, in Bremen/Bremerhaven (Germany), an inland hub would be connected upstream and downstream of the seaport of Bremerhaven. For the simulation, Bremen was chosen as most of container traffic to Bremerhaven flows through Bremen. The seaport and inland hub cooperate closely and containers to/from Bremerhaven are primarily transported via the inland hub. Efficiency in handling at the terminals can be increased, e.g. by having all trains call at only one terminal at a time (terminal-only loading) and by using inland vessels with higher capacity.

For the simulation model, it was determined that direct containers between the inland hub and the seaport in Bremerhaven are primarily transported by rail or inland waterway transport. This would reduce truck transports between Bremen and Bremerhaven. Trucks may only be used during a breakdown of a transport mode and only if container are otherwise delayed. In this way, pollutant emissions are reduced, which improves overall sustainability.

In order to be able to handle these additional volumes with alternative modes of transport, both rail and barge capacities must be increased. Therefore, both more trains and feeder vessels were used in the model for the additional transport demand by rail and water respectively.

2.2 Data

The Institute of Shipping Economics and Logistics (ISL) in Germany examines traffic flows annually, including container traffic. From the data set of the ISL ship database for 2021, container volumes for inland vessels and rail lines were taken and processed as direct transports between the ports.

Besides the seaport of Bremerhaven, the simulation model considers the inland ports of Bremen, Minden, Hanover, Braunschweig, Fallersleben and Haldensleben and Magdeburg (all in Germany).

In order to move the determined container volumes between the inland ports and Bremerhaven, four inland vessels with capacities between 48 and 72 Twenty-Foot Equivalent Units (TEU) are currently used. In addition, a shuttle ship with a transport capacity of around 384 TEU sails between Bremen and Bremerhaven. Only two direct barge transports in the region were identified. One is between Minden and Bremerhaven (82 TEU daily) and the other is between Braunschweig and Bremerhaven (82 TEU weekly).

For the simulated situation with Bremen as an inland hub, the following assumptions were made based on the data used:

- 75,000 TEU from 2021 between Bremen and Bremerhaven will be transported by inland waterway transport.
- 1 million TEU of current direct truck traffic between Bremen and Bremerhaven will be transferred to inland waterway transport and rail.
- An additional 700,000 TEU of direct truck traffic from the hinterland south of Bremen will also be transported via the inland hub between Bremen and Bremerhaven.
- Instead of 75,000 TEU, around 1.775 million TEU will be moved between Bremen and Bremerhaven by ship or rail in the simulation model. This means 24 times the quantity in the region under consideration.

The concept considers that the capacity by rail can only be increased slightly, as the port in Bremerhaven has almost reached its capacity limits regarding rail handling. However, a planned increase in capacity of around one third is envisaged. In order to transport more goods to/from Bremerhaven, the capacity of inland waterway vessels must increase significantly. Simulation helped determine the number of feeder ships and their transport capacity for additional containers in the simulation model. According to the experiments, 6 feeder ships with a capacity of 1,500 TEU are needed to run a shuttle service between the inland hub in Bremen and the seaport in Bremerhaven.

The simulation processes various data, including time specifications (planned arrival time at destination) and priorities of containers (classification of the logistics service provider, e.g. according to value, sensitivity, urgency of the cargo), locks and shunting times and the handling speed in the ports. Different procedures for empty and full containers (empty containers are flexible in handling whereas full containers are subject to a time restrictions) are considered. In addition, information on inland waterway traffic, port and lock restrictions and container transport between the seaport of Bremerhaven and the Bremerhaven catchment area in 2021 were considered.

2.3 Experiments

To validate the simulation model, an as-is scenario was defined that corresponds to the current situation without an inland hub. The results from the simulation could be successfully validated with the data from reality. The scenario was then expanded to include the inland hub, and it was determined how many additional trains and feeder vessels would be needed to transport the required quantities that were previously transported by trucks. To account for seasonal changes, traffic patterns were analysed for a full year. To examine the impact on resilience, an average of four extreme weather events was simulated for the simulated year, leading to a rail breakdown with an average duration of 48 h. Here, the containers to be transported must be transferred on a barge to compensate

for the bottleneck. During this process, it may happen that not all containers can meet their time restrictions. Only in this exceptional case may trucks be used for transport.

2.4 Results

The following key figures were defined, against which an evaluation of the results and an assessment of the experiments were carried out:

- Container reliability in %: Percentage of containers that reach their destination on time.
- Container reliability after rescheduling due to rail breakdown in %: Proportion of containers affected by a rail breakdown which still reach their destination on time.
- Capacity utilisation of the preferred modes of rail transport and inland waterway: Average and maximum capacity utilisation of the transport mode.
- Amount of trucks used: Number of trucks used in the case of a breakdown.

In the simulation of the as-is situation during a breakdown, the pre-planned containers of the railway can be rescheduled to a barge or a truck in case of time or capacity problems. However, the loaded containers remain on the railway. The reliability of the rescheduled containers is still relatively high. The reliability of the high-priority containers, at 94%, is still below the overall reliability of 95.5% because the containers are not rescheduled according to priority.

In the simulation of the situation with the inland hub, the truck can also be used between Bremerhaven and Bremen during a breakdown of a transport mode and in case of capacity problems in order to bring a container to the destination on time. However, since more rail lines are used in this simulation and consequently more containers can be affected by a rail breakdown, the reliability decreases slightly compared to the as-is situation. However, if the affected containers have a high-priority, their reliability increases significantly from around 92% to around 98% compared to the overall reliability. This increase in overall reliability results from the permissible use of trucks between hub and seaport during a rail breakdown.

3 Discussion

3.1 Discussion of the Simulation Results

The simulation only represents a section of reality, but already shows that the establishment of an inland hub offers advantages in sustainability and efficiency. Rail and inland waterways are strengthened by the establishment of an inland hub. Container transports become more sustainable by reducing pollutant emissions through the increased usage of environmentally friendly transport modes. Efficiency is increased because with the use of large feeder ships, the handling of large container volumes is significantly simplified in contrast to the handling of small means of transport.

In the event of an extreme weather, the inland hub fulfils its contribution to resilience by minimising the disruption of logistics chains and resulting impacts. In the event of a rail breakdown, the planned rail containers can be redistributed according to

the time specifications, so that especially high-priority containers can meet their time specifications.

A breakdown of the inland waterway connection between Bremen and Bremerhaven was not examined, as a breakdown of the expanded inland waterway connections between Bremen and Bremerhaven with feeder ships cannot be compensated for.

Irrespective of the simulation, various effects are achieved with an inland hub regarding the efficiency of the logistics chains. For example, full-length terminal-only loading trains (block trains) are assembled at the inland hub, so that additional shunting trips in the port are avoided. The transshipment process at the seaport terminal can be optimised, as transshipment between a feeder ship and, for example, an ocean-going vessel can take place with no costly, longer-term interim storage. In addition, the provision of data between the seaport and the inland hub makes it possible to improve planning and react better to changes at short notice.

3.2 Limitations

The creation of the simulation model is based on some assumptions. For example, before installing an inland hub, a suitable location for the inland hub in Bremen (possibly expandable) would have to be determined. This would have to have sufficient road, rail and waterway connections with transshipment facilities and infrastructure capacity and sufficient space for temporary storage of containers. It would have to be clarified whether the port in Bremerhaven has sufficient berths and container cranes for handling the additional feeder ships. It should also be examined whether the containers (on the sea side) can be temporarily stored and whether an increase in rail handling of the required magnitude is possible. Finally, it should be noted that the economic viability of the approach would have to be checked by a cost/benefit analysis.

4 Conclusion

The results of the simulations show that an inland hub can help to make container transports more sustainable, reducing truck transports in favour of rail and inland waterways. The resilience of supply chains can be increased during disruptions. In detail, containers can be intelligently distributed to available modes of transport. In addition, the efficiency of the seaport is increased, as containers are already consolidated and wisely reassembled at the inland hub. With rail, shunting trips can be avoided at the port and longer-term interim storage minimised. If data exchange is set up between the seaport and the inland hub, changes in transport planning, for example, can be identified earlier and therefore better responded to.

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Water Management As a New Saving Opportunity for Bus Managers: Evidence from the LIFEH2OBUS Project

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Abstract. LIFEH2OBUS, a project within the European Commission's LIFE program, aims to evaluate water usage in the bus sector during vehicle cleaning. This research is pioneering because water conservation in this field remains largely unexplored, lacking specific standards to prevent unnecessary water consumption. A single bus cleaning session requires around 300 litres of water, occurring four times a week per bus, totalling 43 million cubic meters annually for the European bus fleet. Furthermore, bus washing is energy-intensive, and most garages lack wastewater treatment facilities. LIFEH2OBUS and this paper assess the implementation of three innovative water-saving technologies in bus garages across Europe: water reclamation, water reclamation and harvesting, and waxing. A cost-benefit analysis reveals an impressive 84% reduction in water consumption after one year, saving 37 million litres for the test fleet of 680 buses. Scaling up to 50% of the European transit fleet over five years could save 18 billion litres/year, equivalent to 42% of the transport sector's water use, reduce energy consumption by 1,159 GWh, and cut 504 ktCO_2eq greenhouse gas emissions, saving 151 million Euros. This paper introduces this technological process and demonstrates its substantial water and energy-saving potential in the transport sector, advancing scientific knowledge in this field.

Keywords: Water · Bus · LIFEH2OBus · Water Saving

1 Introduction

The European bus fleet industry has been driven by a strong commitment to environmental sustainability, primarily focusing on reducing pollution and resource consumption. Over the past few decades, considerable Research and Development (R&D) efforts have been dedicated to shaping the vision of the "European bus of the future." Financial support from the European Union (EU) has been instrumental in facilitating successful research projects since the early 2000s. Notably, energy management has emerged as a key area of innovation, encompassing electrification, cleaner engine technologies, and alternative fuels [1, 2]. Several factors have propelled these R&D endeavours, including uncertainties in energy supply [3], increasingly stringent European environmental regulations, and the growing consensus on green economy strategies [4]. A particular

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focal point is the development of vehicle components and systems aimed at reducing emissions and energy consumption. Numerous studies have underscored the advantages of such innovations, including heightened productivity, improved reliability, optimized resource utilization, cost savings, and environmentally conscious performance [5, 6]. Consequently, transport operators are often driven to innovate to achieve cost savings and comply with stricter environmental standards. Strikingly, water management and consumption have remained a relatively neglected area, not only among transport operators but also among policymakers and researchers. The scarcity of data, recommendations, guidelines, or organized information at the EU level regarding water usage in the public transport sector indicates this oversight. Moreover, the existing transportation literature offers limited insights into this domain, with a conspicuous absence of comprehensive contributions beyond informal sources. To address this gap, the EU-funded project LIFEH2OBUS, focused on promoting best practices for water management and savings in the bus industry, seeks to evaluate water-saving technologies at three European bus garages. This paper thoroughly examines the processes and outcomes achieved at one of these garages, highlighting the substantial potential for water-related savings. These findings could catalyze additional case studies and further advancements in scientific understanding.

2 Understanding the Problem

Globally, water scarcity has become a pressing issue, with reported stress situations worldwide. According to the European Environmental Agency, about 100 million Europeans face water stress, exacerbated by declining renewable water availability, partly due to climate change. Agriculture accounts for 40% of annual water use, followed by energy production at 28%, with households requiring 12% [7]. Remarkably, washing a single bus consumes approximately 300 litres of freshwater three times a week [8], resulting in an annual water requirement of approximately 46,800 litres per vehicle. When scaled up to encompass the entire European bus fleet, consisting of 684,285 vehicles [9], this equates to a staggering total of around 32 million cubic meters of freshwater needed for washing operations. While commercial literature is abundant online regarding various bus washing and wastewater systems, scientific literature analyses water consumption within the broader context of car washing operations, with few studies explicitly focusing on the bus sector [10, 11]. In contrast, there is more substantial interest in water treatment practices and technologies, although not always directly related to transit operations. The environmental [12, 13] and economic [14] implications of wastewater treatments are discussed without focusing on the transit sector. These observations underscore the pressing need for specialized knowledge regarding sustainable water management practices for bus operators, especially in light of policies aimed at achieving more sustainable transportation, such as the European Green Deal's goal of reducing greenhouse gas emissions in the transportation sector by 90% by 2050. The COVID-19 pandemic has also brought cleanliness in travel choices into focus [15]. However, much of the analysis has centered on personal protection equipment and physical distancing [16], with bus washing remaining largely unexplored. This aspect is particularly pertinent as increased fresh air intakes on buses might offset previous energy-saving efforts [1, 16], emphasizing the

continued significance of water for sanitization. Moreover, transit cleaning standards often depend on local tender agreements, leading to inconsistent practices and inadequate wastewater treatment, often directly discharging highly polluting wastewater into the sewage systems. The energy required for these processes is also substantial, with data indicating that 6.60 kWh are needed to pump 1 m^3 of water [8]. This results in an annual energy requirement of around 211.36 GWh for washing the European bus fleet. Regarding CO_2eq emissions, approximately 0.005 t CO_2eq [17] is generated for each cubic meter of water pumped, resulting in roughly 160,122.69 t CO_2eq emitted annually by the bus sector solely for washing operations. Budget constraints and financial considerations inherent in bus operations make energy savings crucial. Water, as demonstrated, can no longer be considered a minor cost item, especially as water costs in Europe have escalated over the past decade, and the price of sewerage and wastewater services has followed suit [18].

3 Understanding the Problem

All of the above also highlights a significant gap between policy development and current knowledge and practices, which the LIFEH2OBUS project aims to fill by providing bus operators with practical insights into the benefits of recycling wastewater during bus washing and/or adopting waterless methods. To assess potential savings in energy, operations, and environmental impact, a do-something scenario lasting 30 months was developed, simulating the introduction of three distinct technologies across three European garages (in the Mediterranean, Western, and Central Europe regions, to cope with specific weather conditions, i.e.). These are:

- Basic reclamation involves a wastewater system comprising a 1,000-liter oil separator, a coalescent filter, and a 5,500-liter post-sedimentation tank. A water pump facilitates the removal of oils and suspended solids. Further filtration and disinfection occur in a recirculation section with a sand filter. The cleaned water is stored in a 2,000-liter tank, ready for subsequent washing operations.
- Reclamation and harvesting, combining wastewater treatment and recycling with a rainwater harvesting system.
- Waxing without the use of water, as for aircraft.

All were selected to address the research question of reducing water consumption during washing operations while maintaining cost-effectiveness and scalability.

The scenario fleet consists of 680 buses operated by Arriva (the LIFEH2OBUS coordinator) and corresponds to the fleets that are really in use at each garage. The do-something scenario was created without modifying the service operations, thus maintaining the washing schedule as four times a week for each vehicle (300 litres of water per operation). Cost calculations for the three technologies are based on market conditions and regional prices. Expenses encompass the construction of all the infrastructure, equipment, and electrical and control software units. These costs range from 250,000 to 290,000 euros. Basic reclamation equipment costs approximately 110,000 euros, with the water re-rotation system and scissor bus lift being the pricier components (53,000 euros). Site preparation and design, including hydraulics and groundwork, range from

50,000 to 70,000 euros. For the waterless waxing procedure, each operation costs 250 euros. The scenario envisions ten operations per year per bus, resulting in an annual cost of 187,000 euros for the 75 vehicles across the three garages. Lastly, training the maintenance team to operate the new equipment is anticipated to require an average expenditure of around 10,000 euros.

4 The Saving Potential

According to the conditions above reported, the performance comparison between the do-something scenario vs. the reference practice shows, at the three test sites, that it is possible to reduce water consumption, and most specifically, the weekly freshwater intake passes from 1200 litres to 480 litres (basic reclamation), 96 litres (reclamation and harvesting), and finally to 24 litres (when waxing). Contrarily, the majority of the water is supplied by processed wastewater and rainwater. The cumulative impact of having two technologies in a single garage generates a potential saving of almost 37 million litres of freshwater in the three test sites. This means an average of 84% due to the deployment of the three technologies (Table 1), with reclamation and harvesting delivering a 92% reduction of freshwater intake, basic reclamation only enabling 60 and waxing being the most water-saving approach (−98%).

Table 1. The combined effect of technologies on water-saving.

Technology	Scenario	Performance	Test areas		
			Mediterranean	Western Europe	Central Europe
Reclamation and harvesting	Reference	Consumed freshwater by garage fleet (l/y)	12480000	21840000	
	Do-something	Consumed freshwater by test fleet (l/y)	873600	1622400	
Basic reclamation	Reference	Consumed freshwater by garage fleet (l/y)			8112000
	Do-something	Consumed freshwater by test fleet (l/y)			2620800
Waxing	Do-something	Consumed freshwater by test fleet (l/y)	31200	31200	31200

(*continued*)

Table 1. (*continued*)

Technology	Scenario	Performance	Test areas		
			Mediterranean	Western Europe	Central Europe
Total water consumed (l/y)			904800	1653600	2652000
Water consumption reduction (l/y)			−11575200	−20186400	−5460000
Water consumption reduction (%)			93	92	67

Table 2. Monetary savings and pollution reduction (30-month do something scenario).

Performance	Test areas			
	Mediterranean	Western Europe	Central Europe	Total
Water consumption reduction (l/y)	−11575200	−20186400	−5460000	−37221600
Energy consumption reduction (kWh)	−743128	−1295967	−350532	−2389627
Pollution reduction - GHG (tCO_2eq)*	−338123	−582665	−159492	−1087280
Savings (Euro)	−321	−561	−152	−1034

*assumed rate: 0.02777 kWh/m^3 [18]

The monetary conversion of these results is computed on assumptions derived from real-world situations. Local expenses for water and energy may vary, but Arriva's analysis of its depots indicates that, on average, the cost of water usage is 0.13 Euros per cubic meter. When considering the EU's average energy price during the first half of 2021, which was 0.1283 Euro per kWh [19], each cubic meter of water pumped for bus washing incurs a cost of 8.24 Euros. Pumping one cubic meter of water demands 64.2 kWh. Consequently, the total cost of water for the entire washing process averages 8.37 Euros per cubic meter. Utilizing the EPA model [17], Table 2 calculates that the 84% reduction in water wastage at the three test locations translates to savings exceeding 300,000 euros and an emission reduction of over 1000 tCO_2eq.

5 Concluding Remarks

Figures in Tables 1 and 2 may seem modest at first glance, but their implications become evident when applied to Europe on a larger scale, even with a conservative upscaling scenario. The 43 million cubic meters of freshwater needed to wash the European 684,285 buses result in an annual energy consumption of 2.77 TeraWh and the emission of 1.2 $MtCO_2eq$ of greenhouse gases, assuming consistent maintenance standards for the entire European bus fleet. Scaling up the savings potential calculated for the three test areas

and projecting a 50% adoption rate in the European bus transport sector within five years (equivalent to 342,143 buses), 18 billion litres of water annually can be saved, a substantial −42% reduction in total water usage in the transportation sector. This also leads to a 1,151 GWh reduction in energy consumption and a significant −496 $ktCO_2eq$ decrease in greenhouse gas emissions, resulting in a total cost reduction of 150 million Euros. To put this into context, this cost reduction could finance the purchase of more than 230 modern 12-m electric buses, priced at around 650,000 euros each, or potentially double that number for standard EURO-IV models. These insights serve as a sustainability benchmark, and results prove to meet environmental requirements and resource-saving objectives; consequently, bus operators may find transitioning from conventional washing systems to innovative washing technologies a viable and less expensive alternative to fleet renewal.

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Review of Transport Network Criticality from a Capabilities Approach Perspective

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Abstract. This review explores the application of the capabilities approach in the domain of criticality assessment of transportation networks. While typically used to gauge the development and wellbeing of communities, the capabilities approach is gaining prominence and has garnered growing interest within the field of transport studies. The review looks at the problem of accessibility of various facilities essential for wellbeing and the associated studies that focus on road criticality as a problem of accessibility. It delineates each capability based on Nussbaum's list of capabilities and its relevance to transportation access. This highlights a substantial overlap between studies on road criticality assessment as a framework for prioritization of crucial links and routes within a network, and the capabilities approach aimed at community wellbeing. While most studies in the domain of criticality assessment do not explicitly follow a capabilities-based approach, the review underscores commonalities and highlights the potential of the approach in wellbeing focused transportation planning.

Keywords: Transportation Criticality Assessment · Capabilities Approach · Community Wellbeing · Transportation planning

1 Introduction

Wellbeing is a multifaceted concept that has gained increasing prominence in the development and implementation of effective public policies in recent years [1–3]. Wellbeing evidence and research can be used to determine what matters to people, can appraise the success of government policies, can inform costs and benefits of a particular scheme, and develop indicators which can be used to measure the outcomes of the policy initiatives [2]. In this context. the Capabilities Approach towards promoting wellbeing [4, 5], evaluates social arrangements based on the extent of freedom people have, to achieve functionings they value. It focuses on assessing individuals' opportunities and wellbeing by considering personal features, aspirations, and choices, rather than solely how resources are distributed [4, 6]. Thus, in the domain of transportation, operationalizing the Capabilities Approach involves shifting the focus from solely assessing the functionality of transport infrastructure to evaluating how these systems contribute to the

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wellbeing of its users. Such an approach pursues a more comprehensive understanding of accessibility and mobility, which, in turn, can inform the development of transportation policies and projects that better serve diverse communities and promote social inclusion and equity [7].

The objective of criticality analysis in transportation networks is to assess and prioritize transport infrastructure components according to their impact on the overall performance of the network [8]. Criticality analysis aids in prioritizing interventions, enhance resilience, allocate resources effectively, manage risks, and ensure equitable access to essential services [9–12] especially during disruptions and disasters. However, measuring criticality purely from a technical perspective, as is often the norm, risks excluding the needs and choices of the users of the system. Using a straightforward example, what holds significant importance to an employed adult might not carry the same level of significance for a retired elderly individual. Thus, a capability-based approach towards criticality assessment has the potential to address these disparities by taking into consideration the variability with respect to the changing needs of different populations before during and after a disruptive event, and thus aiding in planning a resilient and inclusive transportation system.

The primary objective of this review is to assess the feasibility of application of a capabilities-based approach in criticality assessment for transportation networks. Concomitant to this objective, it highlights past studies in the domain of criticality evaluation frameworks with elements of capabilities approach. The review is structured into two sections. The first section provides a general overview of the utilization of the capabilities approach in the context of transportation systems and derives a relationship between access facilitated through transport infrastructure and capabilities. The second section examines existing studies related to criticality assessment, evaluating them through the lens of the capabilities approach. Finally, recommendations regarding application of capabilities approach within the scope of road criticality assessment are made.

2 Capabilities Approach in Transportation Research

Although the capabilities-based approach has received significant attention in welfare economics and strategic public policy research [13], there is a notable scarcity of studies that specifically examine the intersection of transportation and the capabilities approach. This gap in research exists even though transportation infrastructure plays a crucial role in policies designed to enhance public well-being. Some researchers have focused on the aspects of capabilities approach and its influence on resilience and recovery of engineering systems in event of disasters and have concluded that assessing the impact of a disaster using purely on engineering or economic metrics is inadequate in measuring the human impact of the hazard [14]. A related study by Boakye et al. [15] used a capabilities-based approach to assess the resilience of the transport network of a town affected by an earthquake causing the collapse of bridges. The study assessed connectivity-related metrics, considering capabilities such as “Maintaining health” and “Being Sheltered” in the response phase and “Being educated”, “Earning income” and “Being mobile” in the recovery phase. To capture the diverse needs of various age groups within the population, the study incorporated age as a population disaggregation metric. While this study is a

reference example of the application of the capabilities approach in a framework to assess the performance of transportation networks with a resilience rationale. Nonetheless, research gaps remain unaddressed in this topic, and include issues such as, additional capabilities essential for maintaining wellbeing in the short term and long term, as well as the need to address equity and social justice aspects using additional measures of population disaggregation.

Vecchio and Martens [7] reviewed literature which link capabilities approach and accessibility. The authors suggest a two-pronged approach: a top-down approach involving transport planning and developing infrastructure and a bottom-up approach involving the various factors that influence a person's ability to transform accessibility into actual access. A conceptual framework was proposed to incorporate accessibility as a capability into transportation planning. Beyazit [16] reviewed the social justice aspects of transportation using a capabilities-based approach and acknowledged that while there has been increasing awareness of the same, there is still a lack of comprehensive assessment tools, partly due to the dominance of market-oriented evaluation methods.

Building upon the capabilities chosen by Boakye et al. [15] a complete list of relevant capabilities and their associated access is listed in Fig. 1. The list of capabilities and a brief description of associated functionings are per Nussbaum's list of "The Central Human Capabilities" [6]. The functionings associated with each capability have been stated in brief. Evidently, evaluating the access to essential facilities provided by transport infrastructure as outlined in Fig. 1 could provide valuable guiding principles in developing frameworks for transportation network criticality assessment. Considering

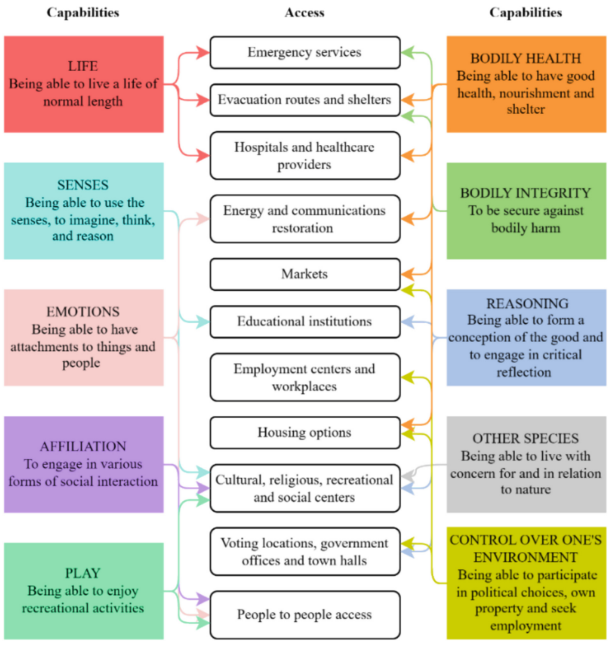


Fig. 1. Capabilities [6] vs. Access to various facilities and infrastructure.

this, the following section reviews prior works in the domain of criticality assessment and investigates the plausibility of applying principles of capabilities approach into it.

3 Capabilities Approach Applied to Road Criticality

While several studies have examined the evaluation of road criticality through different metrics [8], a few investigate applications of the same in context of access provided by the network to the specific necessities of the users of the system. This is important because in the aftermath of a disruption to the network, the prioritization in restoration efforts can vary based on the importance of a link or a route and its functionality within the network. For example, considering the capabilities depicted in Fig. 1 and their corresponding accessibility, during the immediate aftermath of a disaster the most crucial links would pertain to the "Life," "Bodily health," and "Bodily integrity" capabilities. However, in the long run, i.e., the recovery phase, to restore the community's functionality to pre-disaster levels or to formulate policies aimed at enhancing the overall well-being of the community, it becomes relevant to consider the complete set of capabilities. As the importance attributed to each of these capabilities can vary based on the needs and demands of the community, a priority score approach [17], can be adopted to assign an importance indicator to each capability.

As previously discussed, some studies [7, 15, 16, 18] have either adopted the "capabilities approach" or examined the measurements of "wellbeing" [19, 20] when assessing the impacts of transportation on communities. Although studies focused on transportation network criticality do not explicitly reference these concepts, a more in-depth examination of related research reveals significant overlap. Several of these evaluate the access to "critical" or "essential" infrastructure [9, 12, 21] which are directly associated with the capabilities of "Life", "Bodily health" and "Bodily integrity". These evaluations are closely tied to access to emergency services, hospitals, evacuation routes, evacuation shelters, and restoration of energy and communication networks as illustrated in Fig. 1.

Most of the criticality assessment studies fall within the three aforementioned groups. For example, Gangwal et al. [9] introduced a network-based model that incorporates a modified betweenness centrality metric to evaluate the importance of roads in connecting communities to essential services including EMS, hospitals and emergency shelters. Helderop et al. [22] formulated modified grid-based centrality method for identifying critical road segments considering non-road landscape features, providing higher-resolution criticality metrics for individual road segments and offering valuable insights for planning evacuation, and rescue. Zografos et al. [24] explored the accessibility of electric companies to emergency repair issues for electricity supply restoration.

Yet others have focused on other important aspects as economy, access to jobs and equity in access. He et al. [25] investigated the impact of floods on transportation systems in Kinshasa, Democratic Republic of Congo focusing on access to workplaces and highlighted significant socio-spatial heterogeneities in travel time impacts, with lower-income residents disproportionately affected. Jafino [26] operationalized the principles of equity in criticality assessment in the context of transportation planning focusing on an inter-district freight transport network in Bangladesh. Nyberg et al. [27] looked at the accessibility of social services to elderly (cared for at home) in event of road blockages

caused by storm felled trees. However, it is evident that multiple factors which are relevant to access and wellbeing are not considered, individually or in an integrated form. Hence, from a perspective of operationalizing the capabilities approach in transportation, future works should focus on the integration of the different indicators that allow the holistic analysis of the networks and its infrastructure; and also on the systematic characterization of the relevant capabilities tailored to each operational application.

4 Conclusion

The review explores the applicability of the capabilities approach in criticality assessment of transportation networks and highlights the gaps in research. The studies discussed show that research on road criticality usually tend to focus on access to a critical infrastructure in the immediate aftermath of disasters. However, community wellbeing has many more aspects to it which usually get ignored in such an approach. A more comprehensive framework that integrates a broader set of capabilities outlined in here has the potential to facilitate the planning of a more inclusive and sustainable transport infrastructure for both the current and future wellbeing of communities.

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Identifying Infrastructure Demand and Performance Changes Through Agent-Based Modelling Using Fuzzy Logic

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Abstract. Renewing and upgrading infrastructure is crucial for addressing societal, technological, and environmental challenges. Yet, such interventions can temporarily disrupt infrastructure availability, causing ripple effects on interconnected networks. This can alter user and stakeholder behavior, impacting demand and performance. In transportation, unavailable routes can increase costs, prompting alternative choices. Unfortunately, infrastructure agencies often neglect the behavioral aspects and uncertainty of freight forwarders' mode choice. To address this, a fuzzy logic approach is proposed to model mode choice in an agent-based simulation. Fuzzy logic accommodates imprecise data and subjective uncertainties in decision-making. Demonstrated in a Dutch multi-modal freight network case study, this model reveals how interventions affect mode choice and demand shifts. It offers valuable insights for infrastructure managers, aiding demand and performance estimation. Levers can be evaluated for their potential to promote modal shifts, enhancing environmental, functional, and safety aspects of transport networks.

Keywords: Agent-based model · Fuzzy Logic · Infrastructure performance

1 Introduction

Transportation infrastructure plays a vital role in the economic prosperity and social well-being of countries. Meanwhile, countries face societal, technological and environmental challenges that also need to be addressed through their infrastructure. Renewing and renovation of infrastructure is necessary to deal with these challenges. However, interventions to infrastructure are almost inextricably linked with temporary unavailability of infrastructure assets. These temporary capacity restrictions can have cascading effects on not only the targeted network, but also other networks. Thus, when infrastructure agencies consider geographical and functional interdependencies they can leverage synergies in planning, tendering, contracting, design, and construction [1]. Yet, possible ripple effects are often failed to consider as infrastructure agencies operate in isolation.

The interconnectedness of infrastructure and asset interventions is evident in the transport sector. For the duration of an intervention, a network segment's capacity may

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be partially or completely restricted. As a result, travelers are forced to adjust their travel behavior, which can lead to an increase of transport time, distance and costs. A commonly reported reaction is the switch to an alternative transport mode [2–7]. Freight forwarders or logistic managers provide forwarding services to link the goods owner and the carrier together [8]. Their primary objective is to choose an affordable and reliable mode of transport to distribute goods using the transport network. In the process, freight forwarders continuously weigh up alternative transport modes against each other. There is a bidirectional influence between the decisions from the freight forwarder and the infrastructure performance [9]. On the one hand, freight forwarders' mode (and route) choice determines the intensity of network segments. Conversely, the network intensity affects travel time, which in turn influences mode (and route) choice. Capturing the mode choice is challenging because it depends on the attitude, perception and subjective uncertainties of the decision-makers (e.g. freight forwarders). Unfortunately, infrastructure agencies oftentimes neglect to take the behavioural aspects of shippers into account. Disaggregate models are most appropriate to account for behavioural details. To this end, random utility discrete choice models are favoured for their mathematical accuracy, complexity and manageability. In the context of mode choice they may include time- and distance-dependent costs variables. However, modelling human behaviour remains a challenge in transport planning, because acquiring insights into behavioural aspects requires costly surveying.

1.1 Fuzzy Logic

Fuzzy logic is a mathematical framework that accommodates uncertainty and imprecision in decision-making Zadeh. Unlike classical binary logic, fuzzy logic allows for degrees of truth by assigning values between 0 and 1 to propositions. This nuanced approach is particularly useful in complex systems where variables are not easily categorized as simply true or false. By capturing vagueness and ambiguity, it enables machines and systems to make more human-like, context-aware decisions.

2 Research Design

2.1 Case

To explore the potential of fuzzy logic as a mode choice submodel we use the case material from the study by [1]. The case covers the Betuweroute, which is a major freight railway route which connects the Port of Rotterdam terminals to the hinterland. In a period from 2020 to 2065, in monthly time steps, three main and three pop-up terminals and their container handling are simulated. When a (main) terminal goes under maintenance, freight forwarders look for an alternative terminal with the available capacity to receive containers for the duration. Containers can either be shipped via railway, road or waterway. In the original study a simplified mode choice submodel with cost functions is used to compare the three modalities based on travel time and distance.

2.2 Fuzzy Logic Submodel

In order to take ambiguities and uncertainties into account, the simplified mode choice model was substituted by a fuzzy logic mode choice decision making submodel. The implementation of the fuzzy logic mode choice model originates from [10]. The four antecedents (decision variables) are transport costs (€/tonne), transit time (hours), reliability (%), and emission (kgCO2/tonne). The consequent is the preference level (%). We adopt the inference rules established in the study. Since the application of the submodel is on the Port of Rotterdam, where the transit times are lower due to the shorter shipment distance, the membership functions have been scaled accordingly. In addition to the established inference rules, three back-up rules per strategy with a negligible weight have been added to ensure that in all possible cases a preference level can be determined (Fig. 1).

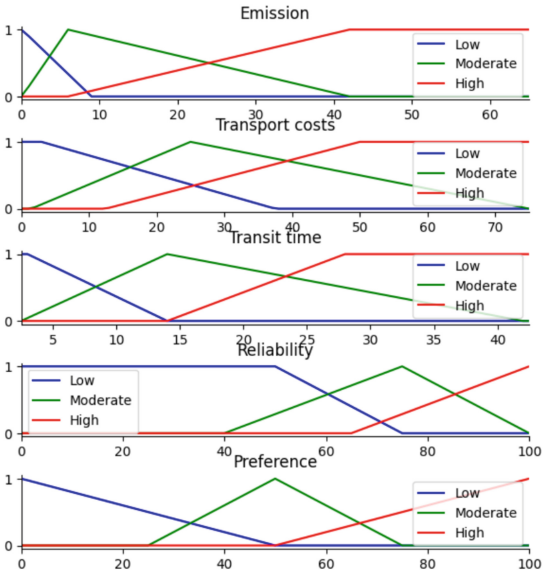


Fig. 1. Membership functions

The fuzzy logic submodel has been developed in Python. The *skfuzzy* package emerged as the ideal tool for this analysis due all of its fuzzy logic functions such as defining the antecedents, the consequent, the inference rules, and for the builtin *matplotlib* visualisations such as 1. The *py* extension in netlogo was used to substitute the python fuzzy logic submodel for the cost functions in netlogo.

3 Results

At the timesteps where transportation to an alternative terminal is required, the fuzzy logic submodel has successfully evaluated the four input values (cost, time, reliability, emission), to determine the preference level for each transport mode. 1 shows the computed preference degrees rounded to the nearest decimal of railway, road, and waterway

respectively. The three different shipment strategies can also be compared side by side. Each row represents an mode choice evaluation. The first column shows the tick numbers at which a terminal went under maintenance.

The letters A and B stand for the two alternative terminals that are available for storing freight for the duration of the maintenance. The submodel identifies the transport mode with the highest preference degree at each tick and assigns the freight via said mode to the respective terminal. The runtime of the script with the fuzzy logic versus the cost function mode choice submodel increase only from 25 to 30 s on average (Table 1).

Table 1. Preference degrees per strategy per mode (%). Modes from left to right: railway, road, waterway.

Ticks	Cost-oriented	Environment-oriented	Time-Oriented
38A	57; 70; 70	46; 56; 72	41; 56; 61
38B	62; 64; 60	54; 48; 48	47; 48; 34
86A	70; 71; 61	70; 63; 62	57; 58; 53
86B	43; 52; 31	47; 26; 47	41; 38; 30
134A	57; 54; 60	46; 35; 48	41; 40; 35
134B	70; 67; 56	62; 51; 48	56; 53; 37
385A	70; 71; 61	70; 63; 63	57; 58; 53
385B	43; 52; 31	47; 26; 47	41; 38; 30

The results show a dynamic preference, both between different transport modes, as well as between shipment strategy orientations. For each row the preference degree changes. Noticeably, at each tick, the three preference degrees to the alternative two terminals seems to be clustered. This is in line with the expectations, as one alternative terminal may be closer than the other. In that case the travel time and costs inputs will be higher for all modes, which results in a lower preference across the three transport modes. This dynamic is most evident at tick 386, where all strategies and all modes have a higher preference for storage at terminal A, rather than terminal B. Similarly, the strategies show a pattern. Shipment between the same two terminals, using the same mode, yield a different preference degree per strategy. For example the waterway preference degrees are lowest in all cases for time oriented. It is in line with expectations that when shipment time is valued, the preference of a mode with high transit times is not preferred.

4 Discussion

The model presented in this paper sets a first step in the direction of capturing the bidirectional dynamics between freight forwarders' mode choice and the infrastructure performance. The submodel allows for differentiation between human preferences by allowing the user to dictate three different strategies, which has a noticeable effect on the outcome in line with expectations.

In this study the implications for the infrastructure performance remains unexplored and plays in turn no role in the subsequent input of the mode choice. In future work the network's capacity should be taken into account to elucidate the interplay between increased transit times (& consequent costs), and mode choice. Fuzzy logic can then be used to inform infrastructure agencies how freight forwarders may react to scheduled interventions. This contributes to the decision making process of where and when to schedule interventions, and how these can potentially be combined.

The functionality and validity of a fuzzy logic model hinges upon the inference rules. Upon accumulation (as part of the inference engine) the area under the curve should be greater than 0. Otherwise, the preference level cannot be determined. Thus, the modalities cannot be compared. The inference rules from [10] were only included upon 100% agreement among experts. The consequence however is that for a set of scenarios at the outer bounds there are no relevant rules. The introduced back-up rules obviate these edge cases. However, in this case study those rules never needed to be activated. Nevertheless, for proper operability, more research is recommended on the preference consensus among freight forwarders.

5 Conclusion

The goal of this study was to explore the potential of fuzzy logic as a mode choice mechanism in an agent-based modelling paradigm. We have demonstrated that fuzzy logic can provide differentiation in mode choice preference on the basis of shipment strategies and four shipment-specific mode characteristics (emission, transport costs, transit time, and reliability). This study provides novel insights for infrastructure managers regarding the effect of planned interventions on mode choice and demand shifts from freight forwarders. The utilisation of this modelling approach offers an enhanced estimation of infrastructure demand and performance. Intervention levers can be assessed through their possible impacts on mode choice, which can stimulate modal shifts to enhance the environmental, functional, and safety performance of transport networks.

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Simulation Based Infrastructure Critical Boundary Identification for Multi-modal Transport Hubs

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Abstract. Providing an integrated transport delivering a door to door service is a mean to lead people to shift to public transports. Nevertheless, it has been demonstrated that a close orchestration of the different modes of transport introduces new potential critical coupling from a safety/security point of view. Assuming the existence of these couplings, the study proposes a collaborative defence strategy. Inspired by Concepts of Airport common decision Making (A-CDM), the proposition is to enrich the set of concepts in order to extend the application to various modes of transports. The contribution of the current paper is to identify by the mean of dedicated simulation tools, the edge-states where a disturbance or an attack can be managed locally. When it is not the case, the collaborative strategy is triggered.

Keywords: Multi modal transport Hub · safety and security. Crisis management

1 Introduction

In order to provide a door to door integrated transport service to passengers, the collaboration of the various available transport modes is proposed. It has been demonstrated that a close orchestration of the different modes of transport introduces new potential critical coupling from a safety/security point of view [8]. Among the couplings introduced, there are particularly critical passenger flows when integrating civil engineering infrastructures [1]. Considering a multi-modal transport hub as a whole for safety and security analysing becomes a mandatory need [7]. In this paper, authors propose to build a common crisis management policy. The main idea is to identify the system status from which common management policy are derived. The global security goals are shared between the various transport modes but their implementations are specific for each transport mode.

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In this context, the current paper presents a simulation-based methodology aiming to identify the numerical values characterizing the upper bound of critical parameters. Under the maximal value, the event can be handled locally and it is better to avoid information sharing with other transport infrastructure managers for efficiency and confidentiality reasons. To provide an illustration, when the delay or the passenger flow density are over a given value, the other transport modes involving connected neighbor infrastructures must be involved by triggering a common mode management, in order to achieve the common strategic safety and security goals. The next section presents a study concerning the use of the **CAST airport** simulation tools **by ARC** in order to characterize the limits, in other words the robustness upper bounds of transport infrastructures. The third section focuses on the simulation framework and the last section provides conclusions and prospects.

2 Safety and Security Context

The most evident coupling existing between public transport infrastructures is the management of passenger flows. This parameter is considered safety critical, as shown in [4] and [5]. As passenger queuing for boarding have been targeted by terrorist attacks, passenger flows are security critical too. As an example, the 22th March 2016 in Brussels, a coordinated terrorist attack occurred: there were two explosions in the departure hall in the check-in area of the Airport of Zaventem, and another explosion in the neighbour metro station of Maelbeek (10 km far from Zaventem) [2]. From a state of the art analysis, it makes sense to propose a collaborative defence strategy to face a coordinated multi-attack [7]. As an example, some procedure involving infrastructures and institution in the neighbourhood can be considered [6]. Focusing on the management of passenger flows, the structural margins of the concerned infrastructure to characterize robustness properties [8]. In the state of the art, there are various definition of robustness:

- Passive robustness: the needed properties are preserved in case of unexpected event without triggering any reaction.
- Active robustness: the needed properties are preserved in case of unexpected event, when some local action preserving the structure of the system are used.

In both cases, it is not worth using a collaborative policy (i.e. changing the structure of the system while enlarging the problem to the neighbour infrastructures management). A scenario-based approach, using some specific key productivity indicators (KPI) linked to the safety and security concepts of a given transports mode is proposed. Depending on the transport infrastructure status, crowd density may or may not allow a rapid evacuation or an efficient rescue services intervention in a given area (see Fig.1).

For efficiency reasons, the proposition uses the airport collaborative decision making (A-CDM) framework, which industrially proved to be efficient for airport management collaborative decisions (see Fig.2). As A-CDM is a well-defined

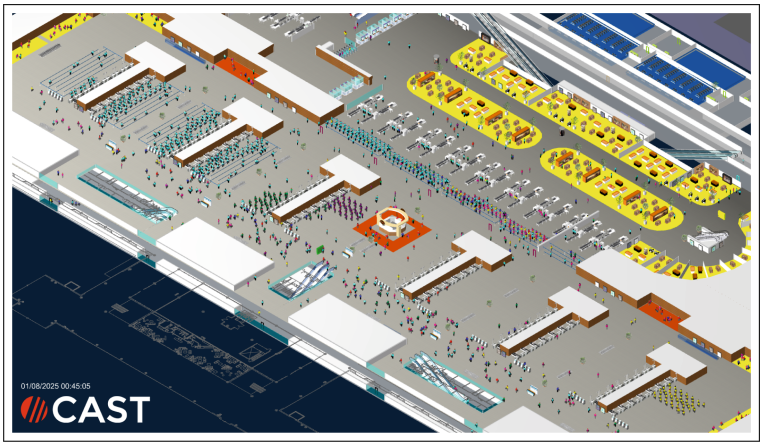


Fig. 1. Airport terminal simulation created using CAST. CAST is a simulation software tool built and owned by ARC (https://arc.de/cast-simulation-software/). Image reproduced with permission.

framework, the proposition is built on the concepts of A-CDM named meta CDM in the state of the art [3].

The next section presents a study concerning the use of ARC simulation tools[1] in order to characterize the limits, in other words the robustness upper bounds of transport infrastructures.

3 Upper Bound Value Definition by the Use of Simulation

The intuitive motivation of the underlying strategy is to reuse an existing knowledge for decision making as in [9]. The main contribution of simulation use is the possibility to build a dedicated knowledge concerning a given infrastructure from a virtual experience. As an example, the infrastructure represents the layout, reaching from the railway station over connecting elements to the airport terminal. It includes all relevant elements with their real dimensions as platforms, rooms and areas, but also connecting elements like aisles, ways, stairs, escalators and lifts as well as all relevant movement areas, which are used by passengers or other persons on their journey through the system. Within this infrastructure, every passenger is a so-called agent with several properties reflecting his individual intentions and capabilities. Considering this profile, he is able to walk or use means of transport while recognizing the environment and interacting with other persons.

As the infrastructure, processes can be designed according to status-quo or scenarios, which are specified according common transport Hub goals. This includes the different treatment or behaviour of different types of travellers as

[1] https://arc.de/cast-simulation-software/.

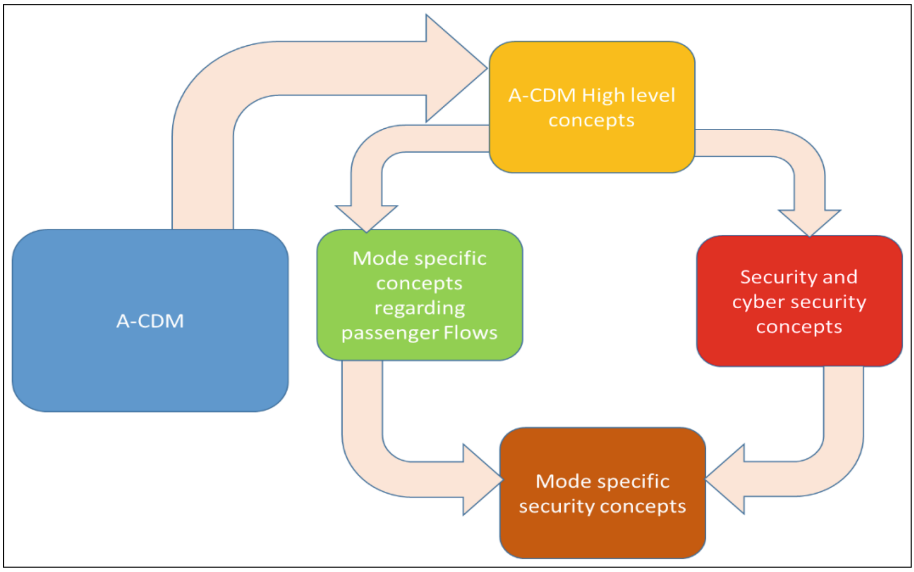


Fig. 2. Conceptual framework

well as the stochastic character of process times which will be set using respective distributions. As a further component control and management elements representing the concepts to be tested or developed are included. These are elements like a general resource allocation but also elements, which can trigger dynamic decisions based on a situation. An example is a dynamic provision of capacity, e.g. by opening counters or a routing depending on the current situation and goals. As an essential part of the processes and control/management elements, new technologies as they are address within this project are considered.

Detailed knowledge of specific process design, allocation strategies, overall concepts and the management of a connected railway-airport hub is available and will be used for the project. As the model set-up design is fully flexible it is possible to build and compare different scenarios and perform a capacity analysis and sensitivity analysis as well as so called "What-If" experiments by testing different configuration and situations. By scaling the knowledge and capabilities of the information management and decision process different strategies as well as different degrees of performance can be tested and rated. Projects usually comprise a system analysis including data collection and (big-)data analysis leading to a comprehensive knowledge and data baseline for the project. Consequently, individual KPI can be defined. In transport hubs, the passenger flow management is critical and some KPIs are linked to:

- crowd density in a given state of the system tacking into account:
  - level of terrorist alert;
  - previsions concerning correlated traffic modes and weather previsions;

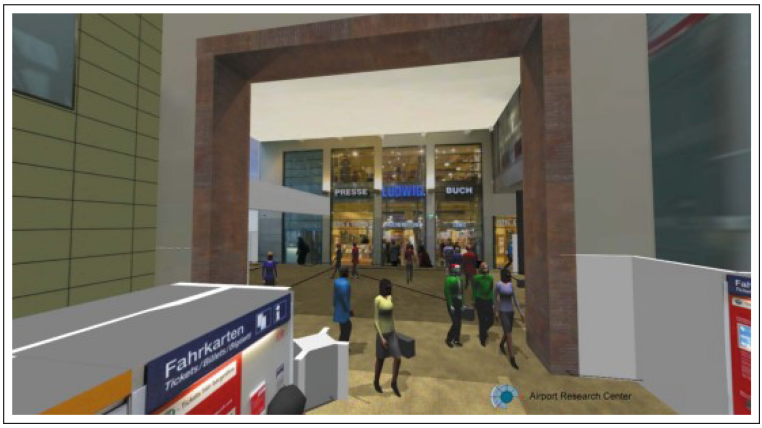


Fig. 3. Model of Cologne Main Station from the VerSiert project [10], created using CAST. CAST is a simulation software tool built and owned by ARC (https://arc.de/cast-simulation-software/). Image reproduced with permission.

- crowd density in a given zone that can be a target for an attack;
- crowd density in a zone that must be used by rescue teams (namely, medical staff, firemen or police) to access a critical area (see Fig.3).

The Fig.3 well illustrates the potential dynamic of a transport hub. There are tickets automatons in a lobby which create queuing phenomenon in the temporal neighbourhood of peak hours. In the background of this lobby, there is a commercial zone. What may happened in case of attack in the commercial zone during the peak hours? What is the dynamic of the queuing effect? Finally, the point where the system states become too dangerous must be identified in order to trigger the adequate collaborative policy. This last example shortly illustrate how the simulation methodology contribute to a global safety/security management of transport hubs by identifying weak states of local transport systems.

4 Conclusion

This paper presented the contribution of a simulation based evaluation of KPI linked to safety and security objectives. Firstly, using the scientific state of the art and previous work, the adequacy of a collaborative defence strategy is developed. In the same time, it is explained using robustness concepts that acting locally as long as possible is a policy which is conceptually formalised. Nevertheless, robustness values can be numerically characterized in order to be able to anticipate emergency situations, allowing to take deterministic decisions in real time. The proposed simulation tool is a well know industrial tool performed using well known industrial processes: as the global provided services are safety critical, stability and reliability are mandatory qualities and the main innovations lay in modelling integrated safety and security KPIs. Considering the confidentiality of data, the next reasonable step would be to validate the realistic design of a

multi modal transport hub with the collaboration of concerned authorities and professional in order to build a proof of concept able to convince safety head of concerned hub. The objective is to be realistic enough to convince professional, but generic and conceptual enough to preserve the confidentiality of identified weak points. In this contest, reinforcement learning may be used to validate efficient strategies.

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On the Capacity of Roadside Communication Networks for Supporting the Delivery of Emerging C-ITS Services

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Abstract. Today, more and more vehicles on the road are being connected via roadside communication networks for a wide range of services, ranging from road safety and navigation applications to in-vehicle entertainment. Cooperative Intelligent Transport Systems (C-ITS) services are aiming to improve road safety, traffic management and environmental performance of road transportation by sharing data between vehicles and road operator's infrastructure via roadside communication networks. This paper investigates the capacity requirements of roadside ITS-G5 and cellular communication networks for supporting the emerging C-ITS applications, based on the C-ITS pilot implemented by Transport Infrastructure Ireland (TII). The results indicate that although the current communication networks are able to support the capacity demand of C-ITS applications at a low penetration rate of C-ITS equipped vehicles during the early uptake of C-ITS, new measures are required to improve the capacity of roadside communication networks when the number of C-ITS applications or the penetration rate of C-ITS equipped vehicles on the road goes high.

Keywords: Cooperative Intelligent Transport Systems (C-ITS) · ITS-G5 · roadside communication network · connected vehicle applications · capacity demand

1 Introduction

Cooperative Intelligent Transport Systems (C-ITS) aim to improve road safety, traffic management and environmental performance of road transportation by sharing data between vehicles, and between vehicles and road operator's infrastructure. Wireless communication technologies play a pivotal part in delivering these emerging C-ITS applications, especially, ITS-G5 (i.e., IEEE 802.11p) and C-V2X for short-range communication [1] and 3G, 4G and 5G for long-range communication. In Europe, more than 2000 ITS-G5 Road-Side Units (RSUs) have been deployed by road operators across 18 member states covering over 20,000 km to support the delivery of C-ITS applications to road users, as part of the C-Roads platform [2].

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The C-Roads platform provides common specifications for implementing more than 30 C-ITS applications (referred to as 'use cases' in C-Roads documents). More and more new C-ITS applications are being developed and tested across the member states. Can all these services be supported by the roadside wireless networks, especially during a worst-case scenario with multiple incidents and vehicles in a particular area? What are the limits of the existing wireless networks?

This paper investigates the requirements of roadside ITS-G5 and long-range cellular communication networks for the C-ITS pilot being implemented by Transport Infrastructure Ireland (TII), as part of the C-Roads platform. The requirements were investigated in terms of the capacity of wireless networks (data rate and number of concurrent connections) for delivering C-ITS applications over ITS-G5 and cellular networks, at different penetration rates of C-ITS equipped vehicles on the road.

2 System Model

Figure 1 (a) depicts TII's C-ITS pilot deployment architecture for implementing C-ITS services on the national roads, via RSUs (ITS-G5) and cellular (IP-based) communications between the vehicles and the road operator's infrastructure. The C-ITS Central Station generates C-ITS messages based on the information received from the Advanced Traffic Management System (ATMS) for traffic incidents and warnings related to traffic management operations. The Central Station disseminates the C-ITS messages to the relevant RSUs, to be broadcasted via ITS-G5, and IP-based connections are established with the vehicle's On-Board Units (OBUs) to disseminate the C-ITS messages via the cellular network.

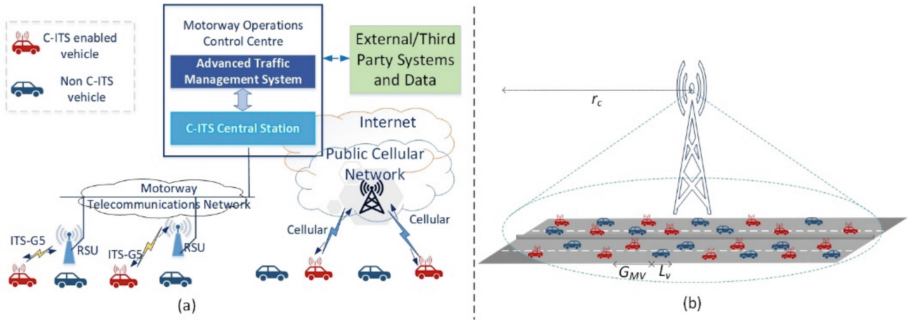


Fig. 1. (a) C-ITS pilot system architecture; (b) C-ITS access network.

2.1 Roadside Access Network Model

To analyse the capacity requirement of roadside communication network, we consider an access network model with a single RSU for ITS-G5 or a cellular Base Station (BS) for IP communication, with the coverage radius of r_c and the C-ITS equipped vehicles

(i.e., vehicles with OBUs) as depicted in Fig. 1 (b). There are mainly three modes of message exchange depending on the application: Infrastructure to Vehicle (I2V); Vehicle to Infrastructure (V2I); and Vehicle to Vehicle (V2V). It is worth noting that the ITS-G5 (short-range) is a broadcast technology, i.e., a C-ITS message transmitted by an RSU via ITS-G5 will be received by all OBUs within its coverage. To ensure the successful delivery of messages via ITS-G5, each message will be repeated by the sender at 1–10 Hz depending on the application. In ITS-G5 communications, the wireless channel is randomly accessed by the C-ITS stations (RSUs and OBUs) using a de-centralised access control mechanism - Distributed Coordination Function (DCF) [1].

Conversely, in cellular communications, C-ITS messages generated by the C-ITS central station are communicated to vehicles via individual IP connections i.e., a message will be communicated over multiple individual IP connections over the cellular network. The IP-based cellular communication is only used for I2V and V2I modes of message exchanges and not for V2V.

2.2 Road and Traffic Model

The key consideration for the Road and Traffic Model is to estimate the average number of OBUs (N) within the coverage area of an RSU or cellular BS. This is mainly influenced by the road topology i.e., the number of lanes n_l, traffic density d_k and penetration ratio ρ_k (≤ 1) of OBUs in lane k. Therefore, N can be expressed as:

$$N = \sum_{k=1}^{n_l} 2 r_c d_k \rho_k \tag{1}$$

For the purpose of this analysis, we consider a bi-directional highway (dual carriageway) environment with three driving lanes in each direction (i.e., $n_l = 6$). We assume that the traffic density and the penetration rate of OBUs are same in all lanes. Also, the average coverage radius is 300 m and 2500 m for an RSU and a cellular BS respectively. The capacity requirement of roadside communication network is investigated for varying traffic density d and penetration ratio ρ.

2.3 C-ITS Application Data Model

In the Irish pilot, selected C-ITS applications were implemented following C-Roads specifications using standard ETSI C-ITS message: In-Vehicle Information, Decentralized Environmental Notification and Co-operative Awareness messages (IVIM, DENM and CAM) [3] as listed in Table 1. A new C-ITS application: Point of Interest (POI) - Electric Charging Stations Information using a custom Electric Vehicle Charging Spot Notification (EVCSN) message was also piloted in Ireland. The key factors that will impact the amount of data generated for an application a are: the probability of the corresponding event (or notification) being active (ϵ_a); the size of the C-ITS message (β_a); and the repetition rate of the message (γ_a).

For a given C-ITS application a, $\epsilon_a$depends on several factors, for example, a Weather Condition Warning being active will depend on the likelihood of severe weather incident (e.g., fog) being identified and notified by the ATMS within the coverage area of an RSU or a cellular BS. The assumed value for ϵ_a for each application is given in Table 1. In

Table 1. Piloted C-ITS applications in the Irish national C-ITS pilot.

Service Category	C-ITS Applications	Message	TX Modes	Assumed ϵ_a
In-Vehicle Information (IVI)	In-Vehicle Dynamic Speed Limit	IVIM	I2V	0.5
	Other Signage Information	IVIM	I2V	0.5
	Embedded VMS 'Free Text'	IVIM	I2V	0.5
Hazardous Location Notification (HLN)	Stationary Vehicle	DENM	I2V	0.02
	Slow Vehicle	DENM	I2V	0.02
	Weather Condition Warning	DENM	I2V	0.02
	Traffic Jam Ahead Warning	DENM	I2V	0.02
	Emergency Electronic Brake Light	DENM	V2I, V2V	0.02
	Emergency Vehicle Approaching	DENM	V2I, V2V	0.02
Road Works Warning (RWW)	Lane Closure Warning	DENM	I2V	0.05
	Road closure Warning	DENM	I2V	0.05
	Mobile Road Works Warning	DENM	I2V	0.05
Point of Interest (POI)	Electric Charging Stations Info	EVCSN	I2V	0.03
Probe Vehicle Data (PVD)	Vehicle Data Collection	CAM	V2I, V2V	1

addition, the repetition rate γ_a for all applications, except PVD, is assumed to be 1 Hz. The CAM messages are not repeated; however, they are generated at 1 Hz to 10 Hz based on the movement of the vehicle [4] - the average CAM generation rate was assumed to be 5 Hz in our analysis. Similarly, our early observations in our pilot indicated that the average size of DENM, IVIM, CAM and EVCSN were 500, 500, 400 and 300 Bytes, respectively.

3 Requirement Analysis

The capacity requirement of roadside communication networks (ITS-G5 and cellular) to support the emerging C-ITS applications was investigated based on the system model described above for a limited set of C-ITS applications piloted in the Irish C-ITS pilot. It is worth noting that our investigation focuses on the capacity demand created by C-ITS applications on the roadside communication networks (i.e., ITS-G5 and cellular), and

not on the capacity offered by the networks, which was analysed in existing literature [5].

Let A_{I2V} and A_{V2X} be the set of all applications that exchange C-ITS messages in the modes I2V and V2X, respectively. Therefore, the average amount of C-ITS data that needs to be broadcast (i.e., the average data rate) over ITS-G5 within the coverage of an RSU is

$$C^R = \sum\nolimits_{\forall a \epsilon A_{I2V}} \epsilon_a \beta_a \gamma_a + \sum_{\forall a \epsilon A_{V2X}} \sum_{n=1}^{N} \epsilon_{a,n} \beta_{a,n} \gamma_{a,n}. \tag{2}$$

On the other hand, the cellular network is not a broadcast network and in general, downlink (DL) and uplink (UL) do not use the same radio resources. Hence, the amount of data exchanged for I2V and V2I need to be estimated separately. Therefore, the amount of C-ITS data that needs to be transmitted in the downlink (i.e., I2V) is

$$C^B_{DL} = \sum_{\forall a \epsilon A_{I2V}} \sum_{n=1}^{N} \epsilon_{a,n} \beta_{a.n} \gamma_{a.n}, \tag{3}$$

and the amount of C-ITS data that needs to be transmitted in the uplink (i.e., V2I) is

$$C^B_{UL} = \sum_{\forall a \epsilon A_{V2X}} \sum_{n=1}^{N} \epsilon_{a.n} \beta_{a.n} \gamma_{a,n}. \tag{4}$$

3.1 Numerical Analysis and Results

The figures below show the capacity requirement of the ITS-G5 (Fig. 2) and cellular networks for supporting piloted C-ITS applications for the assumed system model, where the peak capacity assumes that all applications are active at the same time (i.e., $\in_a = 1 \forall a \in A_{I2V}, A_{V2X}$), and the average values are for assumed values of ϵ_a in Table 1.

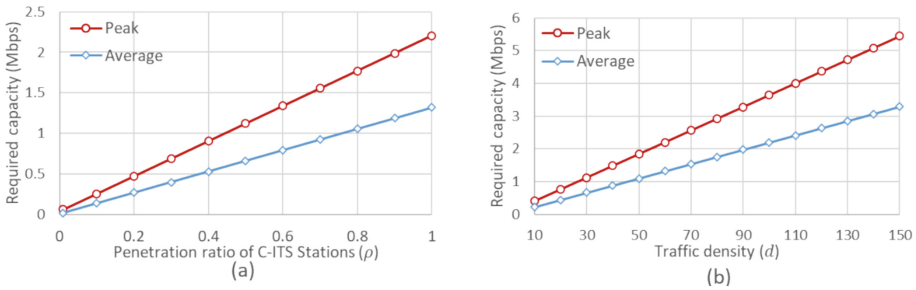


Fig. 2. ITS-G5 capacity requirement: (a) at vehicle density of 30 (i.e., $d = 30$) against varying C-ITS Station penetration ratio (ρ); and (b) at ρ= 0.5 against varying d.

As shown in the above figures, the capacity demand of both networks steadily increases with increased penetration of C-ITS Stations and increased traffic density, as expected (Fig. 3). The peak capacity demand for ITS-G5 is reaching above 5 Mbps for a high-density traffic scenario at 50% penetration of C-ITS Stations (worst-case scenario). However, most of the current ITS-G5 implementations are based on the (default) IEEE 802.11p 6 Mbps transmission rate (10 MHz channel with QPSK and ½ channel coding rate) [6]. It is worth noting that the actual channel capacity offered by ITS-G5 at 6 Mbps rate is much lower due to the nature of the DCF access mechanism, and the over-heads introduced by the lower layer protocols. In addition, our analysis was based on the limited number of selected C-ITS applications, but in the future, more C-ITS applications are expected to be implemented [2]. Therefore, the current implementation of ITS-G5 may not be able to handle the demand of C-ITS applications in the future when the penetration rate of C-ITS equipped vehicles or the number of applications is high. However, the use of advanced modulation and coding schemes and multiple ITS-G5 channels can support the future demand [6].

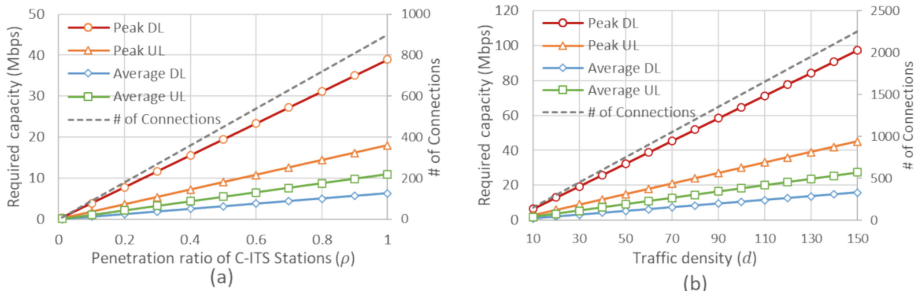


Fig. 3. Cellular capacity requirement: (a) at vehicle density of 30 (i.e., $d = 30$) against varying C-ITS Station penetration ratio (ρ); and (b) at $\rho = 0.5$ against varying d.

On the other hand, we can observe that the peak capacity demand reaches up to 100 Mbps for cellular DL in the worst-case scenario. Although the current cellular networks (4G/5G) can handle such high data demand, we can observe that the number of connections to a single cell reaches up to 2200 in that case, which could increase further with a higher penetration rate of C-ITS Stations.

4 Conclusion and Future Work

In this paper, we analysed the network capacity demand created by emerging C-ITS applications on short-range ITS-G5 and long-range cellular network infrastructure. The results indicated that at low penetration of C-ITS Stations (e.g., at the pilot phase or during early uptake of C-ITS), the existing networks (both ITS-G5 and cellular) can support the delivery of all the applications, even if all are active at the same time. However, the current implementation of ITS-G5 may not be able to handle the demand of C-ITS applications in the future when the penetration rate of C-ITS equipped vehicles or the number of applications is high, while long-range cellular networks may suffer from the

very high number of connected devices. However, employing a hybrid communication approach with advanced modulation and coding schemes and multiple ITS-G5 channels can support future demand. As part of the Irish C-ITS pilot, we will collect a vast amount of real-world data of a hybrid C-ITS network implementation (approximately 60 km of ITS-G5 and cellular) in Ireland. This will allow us to validate our analysis and further enhance the model, and new findings will be published in planned future work.

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A Review of Tools and Guidance for Undertaking Climate Change Risk Assessments for the Transport Sector in Britain

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Abstract. This paper provides a review of resources available for undertaking climate change risk assessments for the transport sector in Britain. The authors undertook research to identify tools and guidance currently available, and used by, all parts of the British transport sector in assessing the risks from climate change to transport infrastructure and operations. Through gathering evidence, expert opinion, and stakeholder engagement a comprehensive list was prepared that covered both physical and transition risks to transport. The review was undertaken in March–July 2023. The authors are aware this is a fast-moving area and anticipate that new tools and guidance may be available at the time of publication.

No one tool or guidance was identified that provided output that could be considered best practice for all transport sectors (rail, highways, aviation and ports). However, this paper lays out which items are potentially useful for British transport organisations at different stages and levels of maturity. The paper also highlights where there are gaps in the understanding, usage or existence of tools and guidance and provides recommendations on how these gaps may be filled.

Keywords: climate risk · hazard · vulnerability · exposure · criticality · adaptation · resilience

1 Introduction

The impacts of climate change are already being experienced across the United Kingdom (UK) and the rest of the world. Central England temperature records indicate that the 21st century so far has been warmer than any 20-year period in the previous three centuries, and sea levels have risen 1.4 ± 0.2 mm/year since 1901 [1]. Additionally, there is growing evidence that extreme events are becoming more frequent and intense, with the UK experiencing unprecedented high temperatures and heavy rainfall in recent years [1].

Extreme weather, likely exacerbated by climate change, has a documented history of disruption to the British transport network. Heatwaves in July and August 2022 cost Transport for London (TfL) £8 million in lost revenue [2]. The 2022 extreme

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temperatures are estimated to have been made 10-times more likely by climate change, based on a rapid-attribution study [3]. Winter storms in 2015–16 caused much disruption, an estimated cost of £121 million to the rail network and £220 million to the road network [4], and some evidence suggests attribution to climate change [5]. Additionally, chronic effects of climate change can act as long-term stressors to the transport sector. For example, changes in weather patterns are likely to accelerate deterioration of many types of transport assets, such as drought causing embankment deterioration [6].

The UK's third Climate Change Risk Assessment (CCRA3) identified thirteen key risk areas relating to infrastructure in the UK, of which seven are directly applicable to transport infrastructure. These are, in brief: cascading failures; river and surface water flooding; coastal flooding and erosion; risks to bridges and pipelines from flooding and erosion; slope and embankment failure; subsidence; and temperature extremes, high winds, and lightning [4]. This study focuses on risks to the physical infrastructure itself; additional considerations include transition risks such as novel physical vulnerabilities introduced by low carbon technologies.

Considering these issues, it is more important than ever for transport practitioners to develop a firm understanding of their network and organisation's risks through climate risk assessment. This consists of both assessment of present-day risks associated with climatic conditions and evaluation of how future climate conditions could alter these risks or introduce new risks. Different transport organisations are at highly variable levels of maturity, with many at the very early stages and seeking further guidance.

2 Methods

The Department for Transport (DfT) is responsible for England's transport network and has some involvement in Scotland and Wales, where devolved powers share responsibility. Transport matters are fully devolved to the Northern Ireland Assembly [7], therefore this paper focuses on Britain rather than the United Kingdom. The stakeholders consulted reflect this focus. However, the findings are useful throughout the UK. Recognising the importance of climate risk assessment in the transport sector, and the difficulties many organisations face in implementing them, DfT set out to identify the tools and guidance that are being used in the British transport sector, identify gaps in the available tools and guidance, and discuss barriers to climate risk assessment. DfT therefore sought to consult with and gather information from representative organisations from across the British transport sector, including representatives of road, rail, aviation, and ports.

Participating organisations for roads included a selection of local authorities and national level organisations. The rail sector was well represented, with organisations responsible for almost all of Britain's public rail infrastructure participating. Participants from the aviation sector represent three of the five largest airports in the UK. The participating port organisations represent a broad range of major British ports including the UKMPG and Associated British Ports. The full list of participating organisations is available in the project report [8].

2.1 Data Collection

Prior to engagement with the representatives of the British transport sector, an initial desktop study was conducted to collate tools and guidance potentially used. This entailed research through trusted public sources including Adaptation Reporting Power (ARP) reports and professional and public bodies (e.g., the Climate Change Committee). The ARP was established by the UK government under the Climate Change Act 2008. It allows the Department for Environment, Food, and Rural Affairs (Defra) to direct organisations to produce regular reports on their current and future climate risk, and proposals for adaptation. The third round of reporting under ARP was published in 2022. The list of organisations and their adaptation reports is published by Defra [9].

The representative group was convened for an interactive online workshop at which a summary of the tools and guidance collated from the primary desktop study was shared with the attendees. This was to enable missing tools, possible connections, and similarities to be easily identified and recorded. A survey was also issued to the participation group. The wider group feedback was recorded and used to evaluate the initial desktop research compilation and classification applied.

2.2 Classification and Evaluation System

A range of frameworks for risk assessment have been developed by different organisations e.g., the Intergovernmental Panel on Climate Change (IPCC) [10]. This study has employed a risk assessment framework modelled on the Supplementary Green Book Guidance on Accounting for the Effects of Climate Change published by Defra [11]. Our framework expands on the Green Book definition through the addition of criticality, an intermediate step between risk and overall impact that is of particular importance to interconnected transport networks. It also adds a definition for cost-benefit assessment.

The BSI [12] and IPCC framework for risk assessment similarly defines risk as a product of hazard, exposure, and vulnerability, with vulnerability a function of sensitivity to harm and adaptive capacity.

It is noted that exposure is primarily assessed through the combination of spatial hazard data and asset inventory data. Asset inventory management tools and guidance are out of scope for this study, therefore, tools and guidance for exposure focus on the provision of spatial hazard data only (Fig. 1). Tools and guidance were classified and evaluated based on four key areas:

- **General**: information concerning the applicable sectors, year of launch, and access (e.g. open or commercial).
- **Climate Data and Uncertainty**: The type of climate data used in each tool, referring to the climate projections/scenarios employed and the maximum assessment date range, if applicable.
- **Applicability**: The stages of the infrastructure lifecycle where a tool or guidance item could be applied (e.g., planning, design, or operations and maintenance), the intended scale of use (e.g., asset or network), whether the output is intended to facilitate decision-making or simply provide supporting data, the specific risks as defined by the CCRA3 (see the Introduction) that it applies to, and whether confirmed usage was identified.

- **Assessment Type:** The aspects of hazard assessment, as defined in, that can be evaluated using a particular tool or guidance.

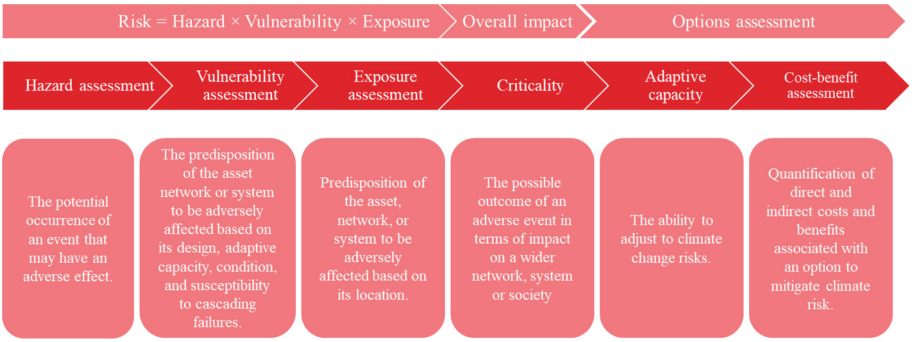


Fig. 1. Risk assessment framework applied in this study

3 Results and Discussion

Fifty-three tools and guidance that could support climate risk assessment in the transport sector were identified. As shown in Fig. 2 (a), most of these tools and guidance are cross-sector and can be applied equally to any infrastructure sector. Ports have the largest number of sector-specific items. While most items are open access, a large proportion of rail items are restricted, primarily consisting of Network Rail in-house tools and guidance.

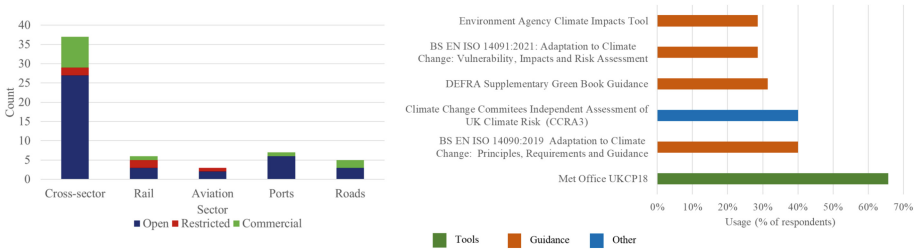


Fig. 2. Left: (a) Counts of tools and guidance by sector. Right: (b) Most widely used tools and guidance based on workshop responses

Of the 53 identified items, 48 were found to have at least nominal usage in the British transport sector. However, most items had only limited reported usage. Of the 40 items presented to the workshop participants, 33 items were used by less than a quarter of respondents, and the average tool was used by 14% of respondents.

The Met Office UKCP18 platform is used by over half of survey respondents. This tool provides access to UK climate projection data and in most cases is the primary

source at the initiation of a climate risk assessment. Despite the high reported usage of the platform, several workshop attendees reported difficulty accessing and applying climate projection data. The other widely used items are high-level, generally applicable resources. They either provide initial guidance and principles for climate risk assessment, as in the case of the ISO standards and Defra guidance, or a first-pass assessment of potential climate impacts across the UK, as with the Environment Agency's Climate Impacts Tool and the CCRA3.

The rail sector has the greatest uptake of existing tools and guidance averaging over double the usage of the other sectors, as shown in Fig. 3. Three of the ten most used tools and guidance are Network Rail's own. This suggests that the rail sector likely has the greatest maturity in the field of climate risk assessment.

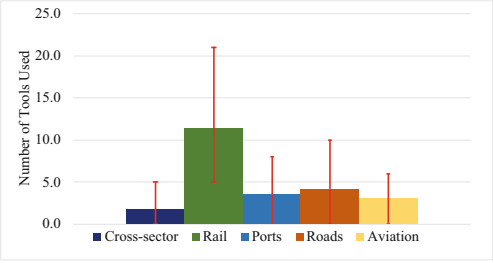


Fig. 3. Average number of tools used by respondents in different sectors. Red bars show minimum to maximum range.

Some workshop participants were unclear on their organisation's climate projection needs, with only 39% having existing knowledge of the projection scenarios most appropriate to them. Of these respondents, all but one aimed to at least consider the most extreme emissions scenario, RCP 8.5. 24% of total respondents also aimed to consider one or more intermediate scenarios, RCP 6.0 or RCP 4.5. Respondents from the roads sector tended to have shorter timescale requirements, up to the 2040s or 2060s, compared with Rail, Aviation, and Ports who typically needed to consider up to the 2080s and 2100+.

The existing tools and guidance available for use in the British transport sector are largely very generalised, providing instructions or support for climate risk assessment at a high level. 70% of items were found to have no clear applicability to a specific lifecycle stage, and 64% were suitable for generic risk assessment rather than being specifically targeted towards any of the CCRA3 key risks. The distribution of tools and guidance in terms of the stages of risk assessment identified in the classification and evaluation stage showed that hazard assessment was the most identified use case for tools and guidance.

It would not be feasible to identify the 'best' available tools and guidance for every situation and organisation's needs, given the complexity and variety of the British transport sector. However, a selection of tools and guidance considered to be useful resources for a range of scenarios has been identified, as shown in Table 1 below.

Table 1. Summary of recommended resources.

Resource	Description
ISO 14090:2019 & ISO 14091:2021	These two standards provide a high-level outline of what organisations should be considering as part of climate risk assessment and in endeavouring to create resilience in general. ISO 14091:2021 walks through the climate change risk assessment process in more detail, through screening for climate impacts, identifying indicators, to managing data [12]. These standards give a comprehensive, though undetailed, view of climate risk assessment suitable for users looking to ensure they are covering the right aspects in their approach.
Physical Climate Risk Assessment Methodology (PCRAM)	Originally intended for use by financial institutions to assess risks to their investments, PCRAM outlines an alternative approach to climate risk assessment and resilience options appraisal [13]. The guidance is also high-level, although it is generally more detailed and specific in its requirements than the ISO standards, but with more limited applicability. This resource is most appropriate for users at the early stages of climate risk assessment seeking to evaluate their data needs and areas of focus.
UKCIP's Adaptation wizard	The Adaptation Wizard provides a comparatively detailed process for a full climate risk assessment, including assessment of present day and future climate risks, appraisal of options, and continued monitoring and review [14]. Arguably the most useful complete guide, the primary disadvantage of this resource is that it is increasingly outdated, with reliance on UKCP09 data. Many resources included in the Adaptation Wizard remain useful however, such as the BACLIAT vulnerability assessment approach. Given the highly organisationally specific nature of climate vulnerability, this approach relies heavily on working with the members of a given organisation. A simple process and template are provided for a workshop-based assessment, or an alternative rapid spreadsheet-based evaluation.

(*continued*)

Table 1. (*continued*)

Resource	Description
The Met Office UKCP18 data platform	The primary source of climate projection data for the UK. Although noted as less user-friendly than other platforms, this is the only source of all UKCP18 data. Some guidance is provided for accessing UKCP18 data [15, 16, 17], although these do not explain the use of the data itself in any detail specifically for the transport sector.
UK Climate Resilience Programme Climate Risk Indicators platform	A useful platform for rapidly producing maps of various climate risk indicators across the UK under a range of climate scenarios [18]. Considered particularly valuable for developing an initial understanding of climate risks and communications or stakeholder engagement. The platform includes a selection of climate variables such as average and extreme temperatures, in addition to estimates of specific indicators such as the number of days per year with a road melt risk. The platform is arguably more user-friendly than the UKCP18 data platform, although the data it provides is more limited in scope.
National Trust Climate Hazards platform	This tool provides readily accessible maps of climate hazard data [19]. The datasets provided are qualitative only, however they offer readily interpreted risk levels for overheating and humidity, storm damage, slope failure, and soil heave under current and future climates. The results should not be relied upon for complete risk assessments as they do not consider site specific factors or different emissions scenarios. However, they might serve as a helpful first-pass screening tool.
Open Climate Impacts modelling framework (OpenCLIM)	At the time of writing, this platform is not available to the public. However, it is due to launch in 2023 and, based on the information currently available, appears likely to be a valuable tool for transport practitioners to assess criticality and impacts. Intended as an integrated impact assessment model of the UK, accounting for various climate scenarios, physical processes, socio-economic scenarios and risk assessment models [20]. Once completed, the model is intended to be integrated with the open access DAFNI platform, where transport practitioners are able to request access [21].

4 Conclusions

Our review of the existing landscape of tools and guidance for climate risk assessment in the British transport sector identified 53 potential resources: a wide selection covering all modes, commercial and open-access, covering all stages of a climate risk assessment from hazard through to cost-benefit assessment. These are useful resources that will support the British transport sector to carry out climate risk assessments. However, several of the resources are highly generalised or do not provide sufficient support for the sector's needs. Gaps remain:

1. There is a need for additional tools to cover the following functionalities: support quantitative climate risk assessments in consistent terms such as incurred costs, disruption times, or harm to individuals; support the assessment of transition risks; provide hazard-specific information to assess climate risks e.g. geotechnical slope stability; and support cost-benefit assessment.
2. There are few levers beyond ARP to incentivise organisations to undertake challenging and potentially costly climate risk assessments, including a lack of design standards that consider climate change.
3. Additional research regarding how climate change is quantitatively impacting transport systems is required. There is little to support the conversion of climate projection data into hazard frequency and severity data, a gap particularly highlighted by the rail sector. Significant academic work exists in this area [22, 23], but little has been done to translate this research for the transport sector. Beyond flooding, there is limited understanding of how climatic factors interact with transport assets.
4. There is a need for increased support and understanding of climate risk assessment across the sector, many practitioners report feeling overwhelmed. This includes support to identify relevant emissions scenarios.
5. Interdependencies and cascading impacts are generally not well understood, partly due to barriers to data-sharing and collaboration.

Based on these findings, the DfT has developed a set of actions to be taken to support the transport sector in developing and implementing climate risk assessment approaches, including development of guidance to clarify the process of how transport bodies should undertake climate risk assessments. For the wider transport sector, the authors recommend that transport bodies in Britain should adopt a framework for a climate risk assessment process, taking the first step towards developing a complete approach and helping them to identify where their individual gaps lie. Forthcoming guidance from DfT will provide a voluntary framework for this process. In addition, where possible transport bodies should engage with cross-industry forums, opening the door for knowledge sharing and improved understanding of interdependencies. These activities, combined, will support the British transport sector to improve climate change risk assessments.

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Using Travel Demand Modelling and Traffic Simulation for Crisis Management

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Abstract. Crisis management can be seen as the process of implementing practices to prevent and manage man-made and natural disasters. It also aims to mitigate their negative consequences that could affect the performance, reputation and normal operation of the affected system and its associated critical infrastructure. Transportation represents one of such infrastructures whose protection and management during normal and crisis situations is essential for the safety of the society. Based on this, an approach is proposed that focuses on the analysis of citizens' behaviour to support crisis management using traffic data. In particular, it allows the selection, monitoring and analysis of arbitrary regions of interest. The simulated scenario, which focuses on a time-based estimation of the number of people affected within specific regions, is illustrated using traffic data from the German city of Darmstadt.

Keywords: Crisis Management · Mobility · Simulation · Urban Critical Infrastructure

1 Introduction

In modern society the word crisis is used in many contexts and sectors related to the life of citizens (e.g. financial, energy, water, mobility, health). The crisis manifests itself as an extraordinary event, characterised by external visibility, which breaks into the life of a community, disrupting its balance and causing malfunctioning. It is a perturbation in which rules and norms of ordinary functioning appear ineffective for dealing with the problem that has emerged. Often crises have strong repercussions, such as to jeopardise the lasting and autonomous existence of a social organisation, thus forcing citizens to act under stringent time constraints, and requiring imminent choices and decisions. For successful crisis management fast and reliable information (e.g. the number of the involved persons, the status of critical infrastructures) is a key factor to evaluate the situation and take the appropriate actions. Moreover, densely populated regions,

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such as urban areas, imply additional challenges as already small scale events can have catastrophic impacts and threaten a large number of people. The mobility in such areas is characterised by high variability of number of persons within the area throughout the day; for example, in industrial zones the majority of workers are only present through daytime. To provide a realistic estimation of the number of affected persons by a crisis such variations needs also to be considered.

From the conducted literature review, it has emerged that some research is devoted to the simulation behaviours of the society on large scale by focusing on traffic and crowds [4], as well as on mass evacuation scenarios to represent mixed and non-normative traffic [1]. In [2], adaptive reinforcement learning were used to derive patterns trajectories of human mobility in a flooding scenario after a hurricane. Whereas, in [5,7] the authors focused on the concept of resilience and related measurements in the mobility context. In particular, in [7], a model for assessing the transportation infrastructure and network resilience were defined; whereas, in [5], a 2-layered framework was presented (i) based on the collection of traffic-related data obtained from Twitter and Waze App, and (ii) by adopting a probabilistic-based approach for assessing the resilience of the mobility system in the metropolitan areas. On the base of our knowledge, additionally to [1] two important contributions ([6,10]) placed particular attention on the evacuation problem. In [10], the evacuation behaviour was analysed by simulating individual day plans on large scale scenarios in case of a hurricane. The analysis used detailed input data for the scenario description and simulation, by making the proposal strictly dependent on the specific crisis scenario, as in [1], which focused on a flooding scenario. Both publications provided detailed insights for possible bottlenecks during large scale evacuations and thus gave valuable information for evacuation planing. However, in both cases the lack of flexibility and responsiveness make a usage for acute crisis management difficult. Whereas, in [6] a software that supports the modelling of evacuation scenarios allows a flexible definition of the affected area and the number of persons. The main drawback lies in the use of a random spatial distribution that does not take into account the mobility of citizens. Such aspect makes it hard to provide reliable information about the number of affected persons for the assessment of the situation during crisis management.

In the current work, we propose a solution, to support the management of crisis situations, based on modelling the travel demand of citizens by analysing traffic in urban areas. It is centred on the analysis of traffic in normal situations, thus supporting the decision-making process in the early phase of a crisis. The proposal is built on top of the TAPAS (Travel and Activity PAtterns Simulation) [3] tool and exemplified through an evacuation scenario centred on data of the city of Darmstadt.

The rest of the paper is structured as follows: in Sect. 2 the methodological process, the used data, the implementation, and the reference scenario are described. Then, simulation-based results including implications of the findings as well as current limitations of the study are highlighted in Sect. 3. Finally, a summary of the contribution, its impact and future perspectives are drawn in Sect. 4.

2 Modelling Approach and Implementation

Our adopted modelling approach of crisis phenomena was inspired by the theory of equilibrium. In particular, starting from a given system $\mathrm{Z}(P_{t_0})$, where P represents the state of the system Z at the initial time t_0, Z is stable if, after having applied a perturbation d to Z, after a certain period t_f when the perturbation is not affecting Z anymore (i.e. $d \xrightarrow{t_f} 0$), the perturbed system $Z^d(P_{t_0})$ reaches a final status $\mathrm{Z}(P_{t_f})$ which is the same or similar to the initial state $\mathrm{Z}(P_{t_0}) \approx \mathrm{Z}(P_{t_f})$. On the basis of that, our system Z represents a region which can be broken down into a set of zones z_k of interest, $Z_{t0}(P) = \{z_1(p_1) \cup z_2(p_3) \cup ... \cup z_k(p_k)\}$. The state P is represented by the total population in the region at the time t_0, and p_1 ,..., p_k represent the part of the population that live in zone z_1,...,z_k, respectively. Starting from that, we formalised our reference model through the following equations:

$$p_l^z(\Delta T) = p_l^z(t_f - t_0) = \sum_{l \in p_k} z_k^l(t_f - t_0) \text{ Number of people } p \text{ leaving the } z \text{ zone within } \Delta\mathrm{T} \quad (1)$$

$$p_a^z(\Delta T) = p_a^z(t_f - t_0) = \sum_{a \in p_k} z_k^a(t_f - t_0) \text{ Number of people } p \text{ entering the } z \text{ zone within } \Delta\mathrm{T} \quad (2)$$

By exploting Eq (1) and (2), the following cases have been defined:

$$p_a^z(\Delta T) - p_l^z(\Delta T) = \begin{cases} \approx 0 \pm threashold & \text{z is stable - normal situation} \\ < 0 - threashold & \text{z is not stable - possible evacuation indicator} \\ > 0 + threashold & \text{z is not stable - possible overcrowding indicator} \end{cases} \quad (3)$$

Such equations represent the core of our analysis model and of the implemented tool. The *threshold* is a parameter that we use to model non-crisis-related changes (e.g. people that are temporary visiting or leaving the city). The most important processing macro phases, which are depicted in Fig. 1, are described in the next subsection. This includes a short description of the travel paths generation step, followed by the zones definition and agents identification step and risk assessment step, along with the used input-output data.

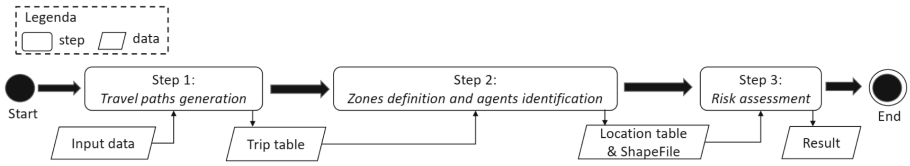


Fig. 1. Process overview of the proposed approach: steps and input-output data.

2.1 Step 1: Travel Paths Generation

The first step focusses on the generation of travel paths of citizens. To deal with that, we utilised the TAPAS tool, developed at the DLR-Institute of Transport Research [3]. It is a microscopic agent-based travel demand model, primarily used for simulating the travel demand of a synthetic population within a region over the course of a day. It is built upon models that depict travel behaviour patterns, including, for instance, trip purposes based on socio-economic characteristics or used modes of transports.

To initiate the travel paths generation through TAPAS, various *Input data* involving a combination of both automated and manual data preparation processes are required. For example, *synthetic population*, *activity locations*, *travel time* and *distance matrices* and *traffic analysis zones* (TAZs). The synthetic population is generated by a Synthesizer [9], whereas, TAZs are basically derived from the borders of the statistical regions provided by the municipality. Furthermore, according to [8], large non-homogeneous TAZs are split for better analytical meaning, whereas, travel time and distance matrices are generated with the UrMoAC[1] tool. A sample of the population is extracted and fitted to match the provided marginal totals, thus creating a complete synthetic population. Additional data sources here are disaggregated population data coming from Microcensus, marginal totals from the statistical department of the federal state of Hesse (Germany) and data about car ownership from the Federal Motor Transport Authority (KBA). Activity locations represent trip destinations, with their geographical coordinates, specific activity type (workplace, education, shopping, leisure and personal matters) and maximum daily capacity being relevant attributes. Data for activity locations come from a commercial data provider, OpenStreetMap and administrative authorities. All such data sources refer to the time period before the COVID 19 pandemic.

At the end of this step, a *trip table*, that means a list of all trips along with associated attributes (e.g. travel time, purpose, mode of transport) is generated for every agent (i.e. user) of the synthetic population.

2.2 Step 2: Zones Definition and Agents Identification

The *trip table* created in the previous step is used to derive the *location* for each agent for every hour of the day. As a rule, if an agent visits multiple locations within 1 h, then the last location for this hour is taken into account, and the location and agent information are stored in a *location table*. To choose the *zones* to be analysed, polygons can be drawn on an interactive map (see Fig. 2) and the related agents information are stored into a *ShapeFile* for further processing.

2.3 Step 3: Risk Assessment

Starting from the previous step, by querying the *location table* the number of agents within the *ShapeFile* are extracted according to the time, and the number

[1] Urban Mobility Accessibility Computer https://github.com/DLR-VF/UrMoAC.

of agents are plotted (see Fig. 3) during the day. This allows one to use the tool in a responsive way so as to obtain a fast overview of the current situation independent from the specific crisis type and to further support the risk analysis evaluation. In the current implementation, we focused on the number of persons who evacuate, that means people moving among different zones as well as the change of the number of persons in the zones throughout the day. This enable to identify whether there are considerable population declines or peaks in particular areas during specific daily time slots.

Whereas, from a performance point of view, the processing time of the whole process after the creation of the trip table takes approximately 3 min. The majority of the time is used by loading the trip table. Whereas, the analysis of selected zones is performed within only 15 s.

3 Reference Scenario and Results Discussion

The two zones on the map[2] in Fig. 2 represent a residential zone (red zone, in the south) and a zone primarily containing educational institutions (blue zone, in the north) in the centre of the city of Darmstadt.

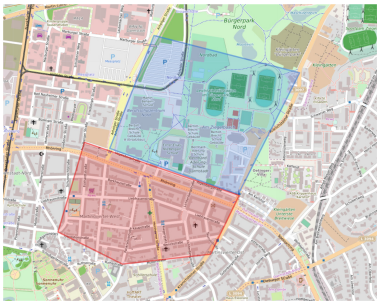


Fig. 2. Selected zones in the city of Darmstadt. (Color figure online)

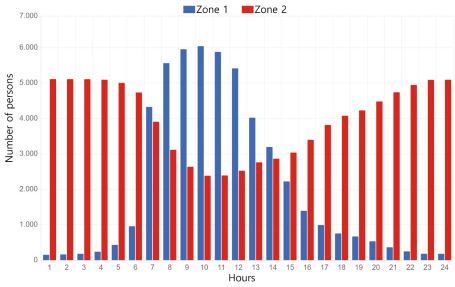


Fig. 3. Change of the people within the selected zones in the course of the day.

The change in the number of people in the selected regions depicted in Fig. 3 show significant differences throughout the day. As one would expect the number of people in the residential areas drops in the morning and slowly increases in the afternoon and the evening. The opposite behaviour can be observed for the educational institutions, with a very sharp rise between 7 and 8 in the morning and a slow but constant decrease after noon. The differences in the change of affected people show the utility of this data for the crisis management.

In particular, from the risk analysis conducted according to the mathematical model proposed in Sect. 2, a first stability indicator of the system that emerged is that the number of inhabitants of the zones of interests (i,e. red and blue) at the beginning and at the end of the period $\Delta T{=}24$ h under observation does

[2] Map data from ©OpenStreetMap.

not reveal excessive changes in terms of population. Moreover, a second stability factor is shown by the smooth and regular trend of the movements between the two zones as well as by the absence of sudden peaks, and therefore of crisis phenomenon in the reference scenario.

4 Conclusion

This paper focused on the use of data related to the travel demand for supporting the management of crisis. A mathematical model was proposed for modelling the phenomenon followed by its implementation based on the TAPAS simulation tool. Whereas, the experimentation was conducted with reference to the German city of Darmstadt and concerned the analysis of the evacuation phenomenon by monitoring the inhabitants' movements between zones of interest. Future works will deal with the modelling and integration of traffic limitations characteristics (i.e. roadblocks) into the travel demand, as well as live traffic data.

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Agile Multi-sensor Platform LEONARDO: Evaluation of New Monitoring Technologies in an Operational Environment

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Abstract. Integrating new rail infrastructure measurement techniques requires a deep understanding of data and monitoring goals. The LEONARDO platform facilitates rapid testing of technologies, providing easy access to operational data for collaboration with industry and research partners. The platform focuses on acquiring data from infrastructure assets from on-track perspective within a ± 5-m radius, aiming to gather valuable information, including the possibility of detecting underground problems. Practical examples showcase that applications are working and are more than a one of test: this is due to the involvement of end-users and their persistence to use the information. The diverse data sources pose also intriguing challenges for in-depth research, making this setup appealing to researchers. Crucial to its success is the unobstructed access to operational infrastructure.

Keywords: railway infrastructure · digitalisation · data-based diagnostics · monitoring platform

1 Introduction

Implementing new rail measurement techniques is complex and time-consuming. Understanding data in line with monitoring goals is crucial. The LEONARDO platform swiftly incorporates and tests emerging technologies, providing the ability to combine the data of all technologies onboard.

Repurposing an old tamping machine and incorporating various measurement systems such as Lidar and ground-penetrating radar can result in a valuable testing platform. Collaborating with end-users involved in maintenance and renewal projects, as well as researchers, fosters a dynamic environment instrumental for exploring novel practical applications and deployment [1].

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Section 2 elaborates on the platform and its current technologies, Sect. 3 delves into recently integrated technologies, discussing their selection criteria and applications in addressing various rail infrastructure challenges. Finally, Sect. 4 outlines initial results and provides a glimpse into future development steps.

2 LEONARDO Platform and Available Technologies

Strukton developed the "LEONARDO" platform, an agile measurement vehicle, to improve rail infrastructure understanding amidst increased competition, stringent maintenance contracts, elevated safety standards, higher train traffic, and a shortage of technical expertise. The platform's focus was on collecting extensive digital track data during a single trip and integrating it with other digital data for comprehensive remote analysis, utilizing a blend of established and emerging technologies.

2.1 Scope of the Platform

The scope covers data acquisition, particularly for assets along the railway line within a range of 360° and approximately 5 m around each asset (cf. Fig. 1). The goal is to gain valuable information, potentially even observing underground issues.

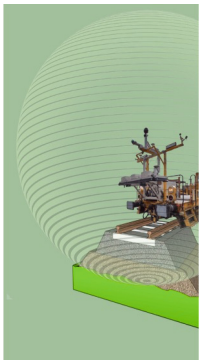


Fig. 1. Scope rail infrastructure monitoring, range of 360°

The platform is equipped with the "TRACKSCAN" laser measurement system to measure railway tracks and a Lidar sensor to map the track surroundings. Additionally, the "GEOCONDA" optical camera system captures detailed visual information of both the railway tracks and their surroundings.

The LEONARDO (cf. Fig. 2) also incorporates 3D ground radar to measure ballast and ground layers, providing valuable data regarding the stability and consistency of the rail infrastructure. Additionally, axle-mounted acceleration sensors are integrated to record vibration patterns, aiding in the assessment of overall rail performance and safety.

With these combined sensor technologies, comprehensive and accurate data on both the rail condition and the environment can be gathered.

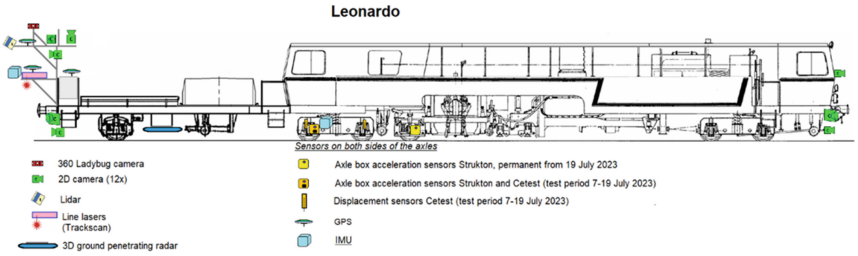


Fig. 2. The LEONARDO platform

Specific objectives have been outlined to facilitate the generation of readily accessible digital data within an organization tasked with daily maintenance and renewal projects, initiating the LEONARDO concept. Three goals have been formulated for this:

(a) Digitally capture as much rail infrastructure data as possible in one trip.
(b) Process this data and enrich it with other available digital (process) data;
(c) So that the user can do his work from behind a computer based on current track information

The platform, to be a valuable tool, had set general requirements. These include operation between trains (90 km/h) on Dutch tracks day and night with a 5 m coverage, accuracy in GPS-based location (+/−20 mm), precise measurements for PVR (<1 mm) and PVS (<10 mm), suitability in typical Dutch weather, operation in a temperature range of −10 to 40 °C, compatibility with standard PC software, seamless data streaming, and proper linkage of the data with location, date, and time.

2.2 Implemented Technologies

The Leonardo platform integrates Geoconda video, Lidar, and Trackscan systems. The Geoconda video system has 360° and flat image cameras capturing images from "Leonardo front" or "Leonardo back" viewpoints based on travel direction. In 2021, Lidar (Velodyne), a 360° camera (Flir Ladybug), and an Applanix POS LV box were integrated into Leonardo.

Velodyne's Lidar generates point clouds, Ladybug captures 360° photos, and Applanix box records GPS positions. The calibrated Lidar system can be easily mounted within 5 min using a sled construction. Trackscan, part of the Strukton Network Scan, assesses overhead wire and track condition. It offers flexible data acquisition suitable for various network scales, excelling in challenging areas like urban tram/metro networks or network hotspots. Installation on different hi-rail vehicles allows section measurements on regular roads, adapting to specific requirements (cf. Fig. 3).

Integrating Trackscan, cameras, and Lidar has advanced significantly. Coordination is improved through synchronized measurement targets on Applanix boxes. Adding more systems to the vehicle is effortless, focusing on accurately recording their orientation in relation to existing targets, making them central components of the setup.



Fig. 3. (L) Measuring equipment on a lorry and (R) the LEONARDO

3 Recently Implemented Technologies

3.1 Ground Penetrating Radar

The original goal for the LEONARDO platform was to comprehensively survey a 5-m radius around the measurement train (cf. Fig. 1). The recent integration of advanced 3D ground-penetrating radar (GPR) technology has significantly enhanced detection accuracy.

Key advancements in GPR technology include higher resolution through increased grid density and step frequency, refined signal processing to reduce noise and improve object detection clarity, expanded depth range for effective detection of underground anomalies and irregularities. Additionally, 3D imaging improves spatial object understanding, and automation coupled with AI expedites detection processes, enhancing overall reliability.

GPR accuracy is affected by ground and environmental factors, making it applicable across various domains, such as inspections, track maintenance support, and renovation tasks. GPR provides detailed data at different depths, offering valuable insights with radar penetration depth varying by soil type. Its applicability at track speed aligns with operational needs. Notable potential applications of Ground Penetrating Radar (GPR) include visualizing ballast pockets for rail maintenance, detecting track alignment issues, identifying ballast layer depths, locating badger setts, and potentially uncovering historical explosives. Figure 4 shows the 3D GPR antenna mounted on the Leonardo and located ballast pockets at a level crossing.

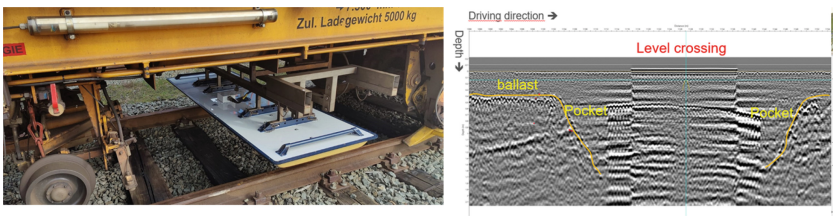


Fig. 4. 3D GPR antenna and (R) ballast pockets found on each site of a level crossing

3.2 Axle Box Accelerometers

Measuring train axle accelerations isn't a new concept, with active research in this area. It's commonly used to replace costlier track geometry measurement systems and monitor rail wheel contact. These measurements, taken close to the rail contact point, can detect factors influencing rail contact response, like rail imperfections or crossings. While data collection is simple and cost-effective, extracting meaningful insights remains complex.

Incorporating this into the measurement platform offers two advantages: 1) The platform's inspection-grade equipment enhances the development of independent ABA applications by enabling simultaneous data collection. 2) Combining measurement results, even from other inspection-grade equipment, can likely improve data analysis, making this integration a valuable step forward.

We have tested two different types of sensors: The DC and AC (500–5000 hz) sensors are mounted on both axle boxes of an unpropelled axle (cf. Fig. 5).

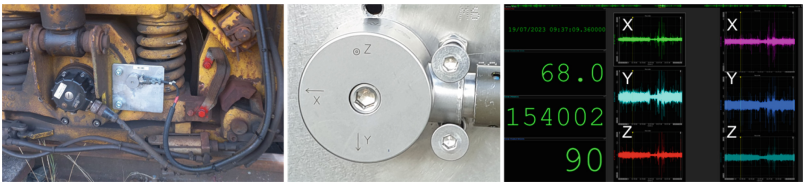


Fig. 5. Acceleration sensor (500–5000 hz) mounted on axle box

4 Initial Results and Future Developments

The use of the LEONARD proofs to be good for several practical applications. In this section we present some of these, such as: finding causes for anomalies in the track and creating track layouts.

4.1 Causes Anomalies in the Track

First analysis shows that it seems possible to use ABA data to detect anomalies in the track. Based on their locations we found possible causes in the video- and the Trackscan data. Figure 6 shows two types of anomalies found in Leonardo track data by using of the ABA data for detection. This can help to quickly find hotspots in the tracks that needs other maintenance than standard used.

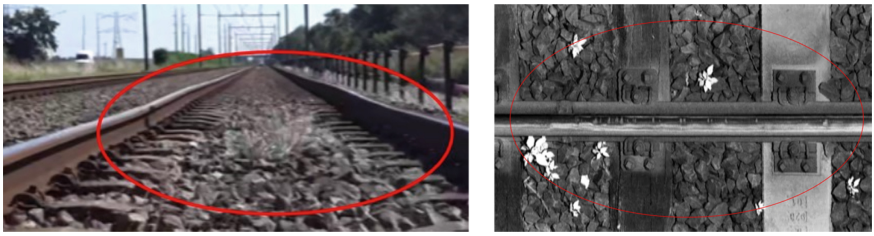


Fig. 6. (L) a negative thermite weld and (R) corrugated rail

4.2 Track Layout Design

Effective track layout designs necessitate precise information about various track components like rail type, welds, joints, sleepers, and fasteners. This involves extensive fieldwork and manual processing of collected data. During field inspections, components are visually identified, and their approximate locations are recorded using a GPS rover set. The results of object detections from track scans are accurately positioned, and a transformation pipeline converts them into CAD drawings. In the example, rail position and profile type, welds, joints, sleeper types, and fasteners are detected and represented accordingly. The use of a commercial ETL (Extract, Transform, Load) tool streamlines the conversion of track scan results into CAD drawings (cf. Fig. 7).



Fig. 7. Trackscan results directly into a CAD drawing

4.3 3D-Modelling Underground Infrastructure: Pipes & Cables

Like the aforementioned practical use (see Sect. 4.2), we recognize the potential of utilising the data to create an image of the underground infrastructure. In the context of implementing systems like ERTMS and positioning balises, an accurate representation of the current infrastructure is crucial. This involves a digital representation of both aboveground and underground reality (cf. Fig. 8). This up-to-date digital representation is then linked to current data regarding rail objects, as accessible in underlying databases.

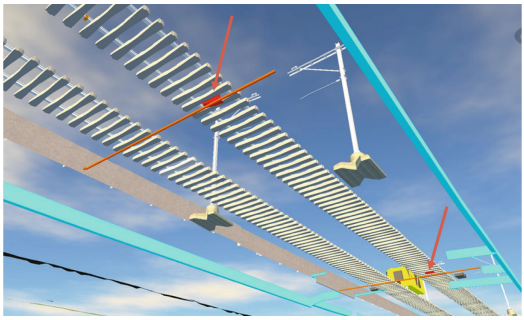


Fig. 8. Example of visualisation of the underground infrastructure

5 Conclusion

Our experience shows that easy access to real-world operations is very important. This access helps in two main ways: it lets us quickly use practical monitoring data in different ways and provides essential data for research. The LEONARDO platform takes the needs of both people who work with the system and researchers seriously, treating them as important users. Being able to access the real-world operational setup is incredibly useful for these users. It helps in situations like fixing errors, calibrating equipment, or testing new tools. Also, it allows for useful comparisons with other tools to improve their performance and reliability, such as comparing different ABA technologies to use in active train services, for instance.

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Transport Network Planning and Analysis Decision-Support Tool for South Asia

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Abstract. A versatile tool is being developed to support climate resilience investment planning in the transport sector for South Asian countries. The tool utilizes readily available datasets, incorporates rapid hazard mapping, integrates multiple infrastructure modelling perspectives, combines methods of varying sophistication, and facilitates large-scale assessment of socio-economic indicators. It has been designed to offer a tailored decision-making experience, accommodating different strategic risk management priorities, decision styles, and risk appetites. Applicable to diverse geographical regions and hazard environments, it aids in identifying vulnerability hotspots within a transport network, enabling prioritized interventions. It also assists in estimating climate adaptation funds, analyzing post-disaster network performance, and planning for redundancies. Ultimately, it supports users in planning network-level upgrades for climate resilience, while minimizing the expected losses and ensuring cost-efficiency in the decision-making process.

Keywords: Climate resilience · Decision-support systems · Network performance · Investment optimization

1 Objectives, Scope, and Approach

In an era where global infrastructure investments are reaching unprecedented levels, transport systems face increasing exposure to natural hazards, compounded by the impacts of climate change. This presents a dual challenge in a socio-technical context: (a) Knowledge of the extent to which critical transport infrastructure is exposed to natural hazards is limited, especially in Emerging Markets and Developing Economies, and (b) The link between infrastructure damages and affected population is not straightforward, especially in environments that are characterized by social inequalities and poverty.

South Asia is particularly vulnerable to the adverse effects of climate change, including rising sea levels and more frequent and intense extreme weather events such as floods and heatwaves. These climate impacts pose significant economic risks across various sectors, including transport, energy, and water infrastructure. Given the region's poor

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environmental and socio-economic conditions, poverty, and limited capacity for adaptation, it is imperative for South Asian governments to invest in the climate-proofing of critical infrastructure. Decision-makers urgently require a tool that prioritizes investments in adaptation measures, optimizing climate resilience, and maximizing the benefits of interventions. The multidimensional nature of such an endeavor calls for a "system-thinking" approach to risk and resilience assessment.

To address this challenge, we introduce a globally scalable decision-support tool tailored to facilitate strategic planning of climate resilience investments in the transport sector. The tool supports two distinct decision-making streams: *resilience planning* for long-term strategies and *business continuity* for short-term interventions. Resilience planning employs probabilistic risk assessment to estimate expected losses from all possible events over a specific period. On the other hand, business continuity focuses on reducing disruptions and losses from frequently occurring climate events. Low-risk investment options for such events are particularly suitable for resource-constrained environments.

Following its development, the tool is being deployed to evaluate a range of climate adaptation strategies for the national road network of Pakistan. By collaborating with local stakeholders, we aim to produce results that will guide more informed climate resilience investment decisions in the region.

2 Methodology & Results

2.1 Overview of the Tool Structure

The tool is developed in Python and consists of eight computational modules, as shown in Fig. 1. Leveraging global, open-source datasets (such as OpenStreetMap data, Digital Elevation Models, Population and GDP data, and Land Use/Land Cover maps), it operates efficiently with minimum input requirements from the user. Nevertheless, it offers the flexibility to accept user-defined input (provided in designated format) at every calculation stage to enhance the accuracy of the results. Its primary functions are briefly explained in the ensuing.



Fig. 1. Summary of the tool modules.

2.1.1 Travel Demand Estimation and Network Criticality Assessment

Module 1 automatically retrieves road network data from OSM, estimates the total number of trips produced and attracted by each zone in the modeled region using census and

economic data (Origin-Destination matrix generation), and allocates trips on the network using the well-established 4-step approach [1] (Figs. 2a–c). Module 2 utilizes this data to assess the significance/criticality of individual links within the network (bridges, roadways, or tunnels), aiming to depict the importance of each link in supporting a region's socio-economic activities (Fig. 2d).

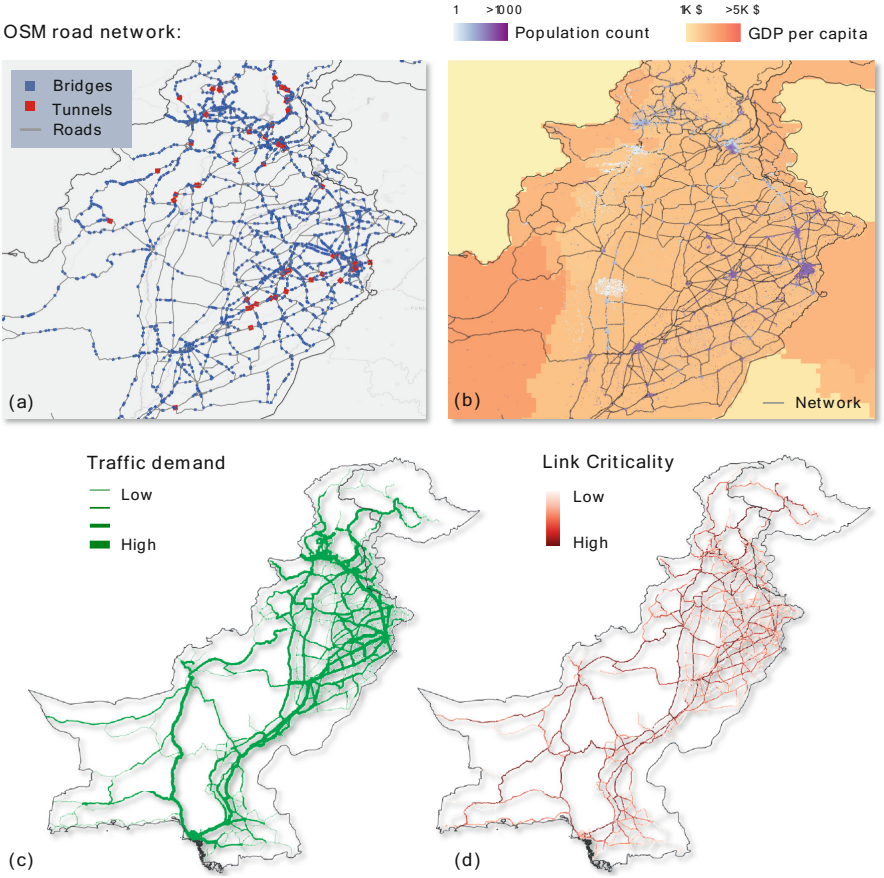


Fig. 2. Example input/output of Modules 1 & 2 for the country of Pakistan: (a) Automatically retrieved OSM road network data (zoom-in to the northern part of the country); (b) Employed population and GDP data for OD matrix generation; (c) Estimation of traffic demand based on the constructed OD matrices; (d) Calculation of criticality for network elements [displayed metric: betweenness centrality].

2.1.2 Hazard Mapping & Vulnerability Analysis

The tool performs hazard mapping and exposure assessment to visualize the extent and intensity of climate hazards potentially affecting the network (Modules 3,4). Particular emphasis is placed on the assessment of flood hazard (fluvial, pluvial and coastal),

incorporating a refined methodology that predicts flood-related impacts on transport infrastructure considering both inundation and flow velocity effects – the latter being determined as a function of land cover and ground slope using appropriate Digital Elevation Models (Fig. 3). For the Pakistan pilot, flood hazard maps are provided by JBA, while the required Digital Elevation Model and Land Use/Land Cover maps were sourced from NASA-USGS [2]. Of course, the physical damage induced by natural disasters is not only dependent on the type and intensity of the disaster itself, but also on the technical characteristics of the infrastructure. To this end, the tool incorporates asset-specific damage functions, along with suitable post-disaster recovery models to reflect the physical vulnerability of network elements to floods (Module 5).

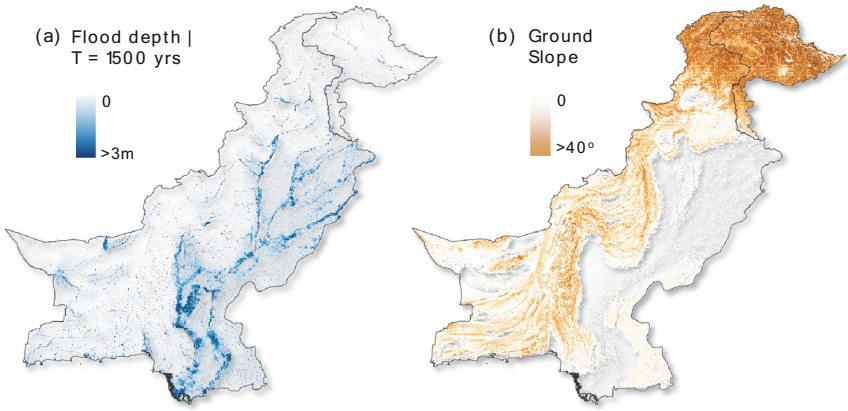


Fig. 3. Flood-induced stressors on Pakistan's road infrastructure: (a) Inundation, characterized by flood depth; (b) Hydrodynamic impact, characterized by flow velocity (low/high) and calculated as a function of ground slope and land cover.

2.1.3 Direct and Indirect Loss Assessment

Module 6 evaluates the financial implications of hazard impacts on the network by aggregating: a) *Direct losses* that reflect the costs associated with the repair of damaged infrastructure, and b) *Indirect losses* that reflect the additional strain placed on network users (both passenger and cargo) by the reduction of network functionality (Fig. 4a).

Ultimately, the tool presents findings in terms of total *Expected Annual Loss* (EAL) for the examined region, applicable on either a national or regional scale (Fig. 4b). This is achieved by aggregating losses from (i) all possible events across different return periods [resilience planning], or (ii) frequent events with return periods up to a user-specified duration [business continuity planning].

2.1.4 Cost-Benefit Analysis and Investment Prioritization

Building upon the loss and criticality assessments, Module 7 aids users in pinpointing network 'disaster hotspots', prioritizing adaptation actions, and evaluating the effectiveness of various climate adaptation investments against a set of climate scenarios (current

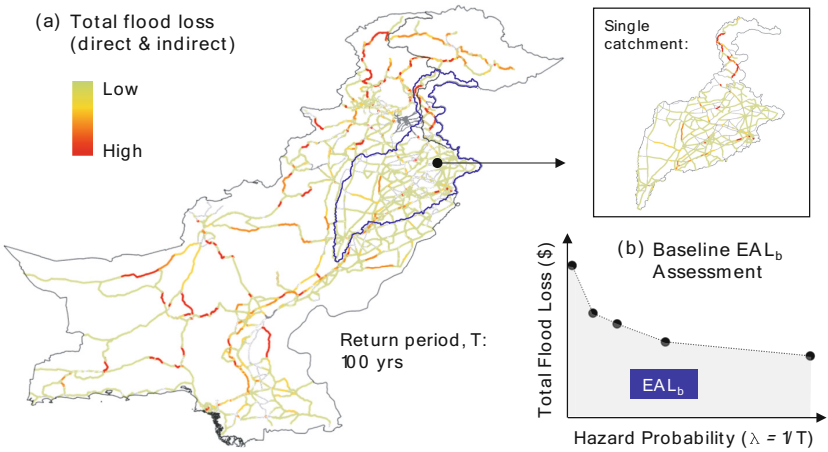


Fig. 4. Example loss assessment output for the country of Pakistan: (a) Total flood loss across the country for a T = 100 yrs. flood event; and (b) Estimation of Expected Annual Loss (EAL) caused by flooding of the road network within a single flood catchment.

and future) using Cost-Benefit Analysis (Fig. 5). Users may perform evaluations over different investment timelines, catering to diverse risk management decisions. These can range from immediate, cost-effective solutions like enhancing roadway drainage systems to substantial long-term investments like erecting flood defenses against rising sea levels for coastal network sections.

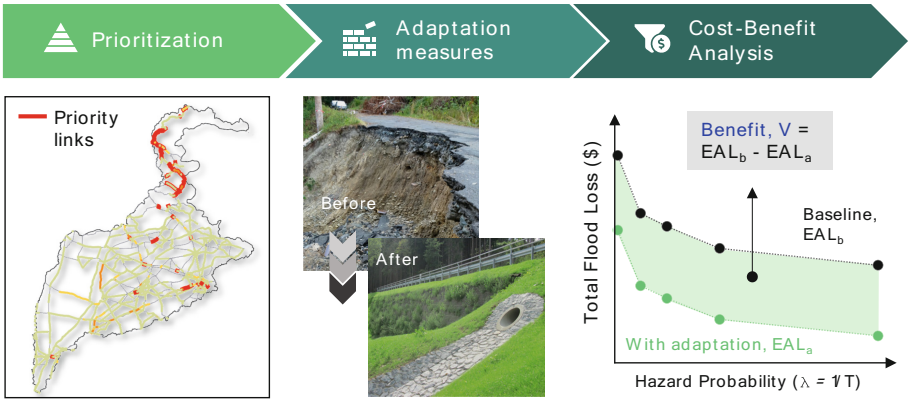


Fig. 5. (a) Network 'disaster hotspots' highlighted as priority links for adaptation; (b) Asset-specific adaptation measures incorporated in the tool in the form of new damage functions that decrease the assets' vulnerability at a certain cost; (c) Net benefit of an adaptation strategy, defined by subtracting the EAL_a after adaptation from the EAL_b before adaptation.

Of course, the economic viability of any investment decision is influenced by several variables, which often come with a degree of uncertainty. To address this, the tool

integrates a stress-testing feature to the Cost-Benefit Analysis results. This allows users to gauge how sensitive an investment decision is to particular parameters, such as the unit cost of adaptation, the return period of extreme weather events, or the travel demand within the network. Economic metrics (such as the Benefit-to-Cost Ratio, the Net Present Value, or the Return on Investment) pertaining to each adaptation strategy are recalculated based on potential variations (within established confidence intervals) in these parameters.

By leveraging this stress-testing capability, users can: (a) *Track how economic metrics shift with evolving climate conditions,* pinpointing investments that offer resilience across multiple climate scenarios; (b) *Detect cases in which adaptation investments may become ineffective or suboptimal* (e.g., the value of an investment may be questionable in case small fluctuations in economic parameters result in a Benefit-to-Cost Ratio < 1); (c) *Identify 'switching' climate conditions below which the economic value of the solution is not justified,* which is especially pertinent for high-cost adaptations that could see their BCR drop with a decrease in climate stressing.

2.2 Stakeholder Engagement

Engaging stakeholders is essential to tailor the tool's scope for each pilot study and deliver actionable intervention insights beneficial to local authorities. A streamlined data collection process orchestrated by the World Bank in cooperation with country officials is of immeasurable value for ensuring accuracy of results and wider tool applicability. In the case of Pakistan, consultations with local stakeholders enabled us to:

(a) *Define the strategic road network* for analysis, taking into consideration the country's development priorities.
(b) *Validate the traffic assignment procedure performed within the tool against measured traffic counts,* ensuring reasonable traffic pattern representation.
(c) *Calibrate the built-in asset damage functions and recovery models* to resonate with the local setting by evaluating post-disaster data from past flood occurrences in the country.
(d) *Apply realistic capital expenditure (CAPEX) and maintenance costs per adaptation strategy, alongside direct and indirect unit costs in line with the local economic landscape,* thus reducing potential discrepancies in the economic appraisal calculations.

3 Conclusions and Outlook

The presented decision-support tool offers a framework for evaluating climate-resilient transport network investments in South Asia, exemplified through its inaugural pilot application in the transport network of Pakistan. Application in two more South Asian countries, each with unique climate strategic priorities, are underway. Thanks to its flexible and scalable design, the tool can be conveniently tailored for use in data-rich or data-poor environments (though with corresponding accuracy implications), while it can be adjusted to different regional settings, hazards, transport modes (e.g., passenger or freight transport) and network dimensions.

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Value Based Decision Making for Rail: A System of Systems Approach.

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Abstract. Modern railways face a formidable challenge of transitioning from conventional technologies and established practices to becoming a vital component of a transport infrastructure of the future which places the railway as the backbone an environmentally sustainable multimodal transport ecosystem. This transformation necessitates a fundamental shift in the operational paradigm of railways, a shift that is already well underway. However, many railway organisations continue to make decisions based on traditional views of asset disciplines such as track and rolling stock, as well as specific work types like maintenance and renewals. A system-of-systems approach is proposed that devolves decisions as far as possible while providing the necessary degree of integration to optimise the performance of the whole railway system.

Keywords: Whole-System · Value · Decision Making · Rail · Asset Management · Sustainability · WiSDoM

1 Introduction

Over the coming years and decades, railways will face a range of opportunities and challenges that are on a par with the biggest they have experienced in their 200-year history. The UIC's Vision for Rail [1] sees a leading role for railways in achieving global net zero and in becoming an integral part of a physically and digitally enabled 'door to door' transport system that will transform cities and connect communities.

Realising these opportunities will only be possible if the railway infrastructure delivers sustained high levels of performance and if the cost base is reduced so that rail travel becomes more affordable. This will require a change in the way that decisions are taken on operating, maintaining, renewal and upgrading rail networks. The current tendency

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of taking decisions in business silos needs to change to one that is based on a whole system approach, with a primary focus on the value delivered to passengers and freight customers and to the wider economy.

This paper argues that a System of Systems approach based on a clear definition of value is the most credible foundation for enabling integrated and optimised decisions for the whole railway approach.

2 A System of Systems Approach for Railways

Railway managers are faced with two competing drivers when taking major decisions. On the one hand there is pressure to take decisions quickly with clear accountability, which requires a degree of autonomy. On the other hand, it is necessary to understand both the impact of these decisions on other decisions that are being taken, and the wider impact of decisions on the whole system. This is inevitably slower process requiring consultation and consensus.

The risk of adopting an autonomous-based approach is that the railway system does not respond as anticipated, the benefits fail to materialise, and new weaknesses are introduced. Examples include the introduction of new technologies where the degree of business change has been underestimated or where improvements in availability (shorter possessions) leave insufficient time to deliver work efficiently. A consensus-based approach mitigates the risk of acting without sufficient consideration of the wider impact but can introduce delays leading to increased costs and the erosion of benefits from competing initiatives.

A System of Systems (SoS) based approach has the potential to overcome these difficulties. Since its introduction in the defence sector [2] the approach has spread to sectors as diverse as energy, transport, healthcare, media and banking [3]. Effective SoS designs are based on the principle of subsidiarity, in which decisions are taken as far as possible within the component systems. Decisions are mediated at the whole system level only where the impact of a decision taken in one of the component systems has a material impact on the performance of another. An appropriately designed system enables faster decisions with clear accountabilities while providing a focus for maximising value and minimising system risk.

In the UK, the Infrastructure Transitions Research Consortium (ITRC) has developed a SoS approach [4] to support the development of the national infrastructure strategy by considering the interdependencies between key infrastructure networks: transport, energy, water and communications. Within the rail sector, the System Pillar of Europe's Rail research programme has adopted a SoS approach to coordinate activities with an initial emphasis on the command, control and signalling system (CCS).

Despite frequent references to SoS in railways, the underpinning architecture has only been partially developed, with limited applicability to the whole system. A hierarchical approach for transport infrastructure has been proposed [5] comprising three layers: a physical layer, a services layer, and an interventions and operations layer. These three layers transfer relatively seamlessly into the structure and decision-making processes of the railway requiring only minor changes to provide context and to define them more precisely.

- The physical layer is represented by Rail Corridors. These are individual routes, or collections of routes, that are characterised by the passenger and freight markets they serve.
- The service layer can be described using a Value Framework. The Value Framework defines the service outcomes that the railway provides to passengers and freight customers, and to the wider economy and society.
- The interventions and operations layer are where major decisions are taken and implemented. Within the SoS, integrated rail corridors become the focus for decisions that are taken consistently with a common Value Framework

The following three sections provide more detail on each of these layers and on the way in which they combine to improve the efficacy of decision making.

3 Physical Layers: Rail Corridor

While there is no formal definition of a rail corridor, it is a widely used term for describing a defined pathway for the movement of passenger and freight trains between principal nodes on the rail network. As such, rail corridors provide a natural focus for linking decisions on interventions and operations to the outcomes that are experienced by passengers and freight customers.

Given the weblike nature of rail networks, rail corridors cannot be treated as independent entities. They interface with other railway corridors and often cross organisational boundaries. Within a rail corridor the composition is not homogeneous with variations, for example, in the train service pattern and different geographical boundaries for the infrastructure sub-systems e.g., signalling, electrification, telecoms.

In order to enable decisions to be taken at the appropriate level of the network, it is necessary to position the rail corridors within a hierarchy that represents organisational, operational and infrastructure geographies as well as the granularity used to specify and monitor value outcomes.

This is illustrated in Fig. 1 which shows a typical hierarchy for a railway infrastructure. The branch in the hierarchy makes the distinction between how resources are organised in maintenance areas (or delivery units) and how rail services are delivered along lines of route. Figure 1 also provides an example of such a railway corridor on the GB network serving markets from the English midlands to the England/Scotland border. It comprises six route sections crossing two regions and five maintenance delivery units.

Construction of the hierarchy is the first step in defining the information architecture for decision making. Data sources, such as revenue, capacity, capability, train performance, safety, asset condition, work activities, and costs, can be mapped to each of the segments at the lowest level of the hierarchy. The hierarchy allows the aggregation of data at all levels up to the entire network. It allows rail corridors to be placed at the centre of decision making - maintaining the connections with the wider network, without losing the underlying variability in train services and the composition of the infrastructure. The segments in Fig. 1 form the building blocks of the SoS framework.

When analysing options for the future management of the railway infrastructure, it is necessary to have a consistent interpretation and a common reference for outcomes

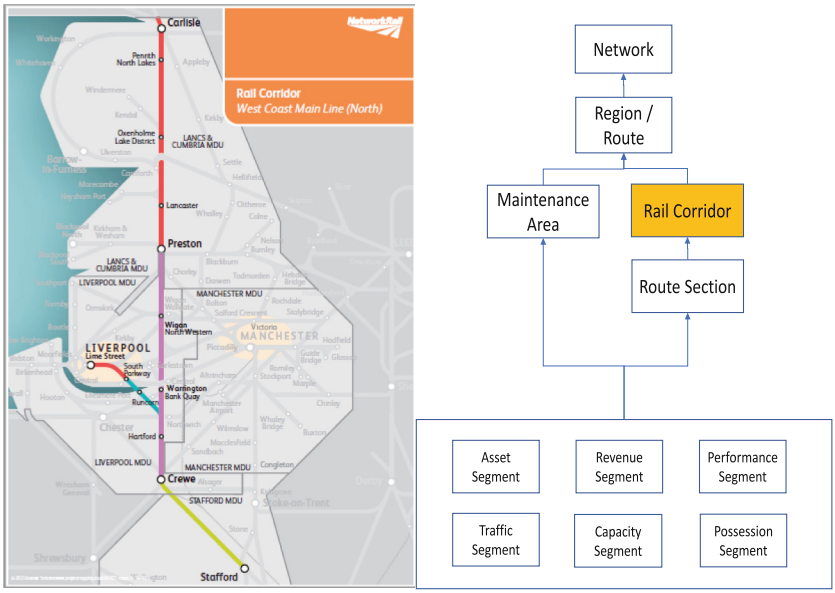


Fig. 1. Segmentation of the rail network and illustration of a rail corridor on the GB network

and costs. This is best provided by the Value Framework which is introduced in the next section.

4 Service Level: Value Framework

Decisions on maintaining and renewing the railway infrastructure have traditionally prioritised three main drivers: minimising safety risk; maximising asset condition and asset reliability; and minimising lifecycle costs. These criteria will always be at the core of decision making but they do not by themselves provide a sufficient representation of the requirements of stakeholders and funders. A broader representation of value is required including, for example, the contribution of rail to decarbonisation, sustainable connectivity, and regional development.

Value based decision making is increasingly being adopted in many industrial and service sectors, including healthcare where Michael Porter's 'Value Agenda' [6] is being implemented on a global scale. The objective of the Value Agenda is to achieve the best outcomes for the lowest cost. Outcomes are directly linked to patients' needs and to wider social benefits. Value is expressed in the form of an equation in which value is defined as the full set of patient outcomes (over the cycle of care) divided by the total cost of resources used to care for the patient's condition over the care cycle.

Similar approaches are being adopted in other asset intensive sectors such as the water and electricity utilities, power generation and telecommunications. Consistency across sectors has been helped by the publication of the Six Capitals Framework [7] which identifies categories of capital which help organisations create value. The six capitals are financial, manufactured, intellectual, human, social, and natural.

Currently, there are fewer implementations of Value Frameworks in railways than, for example, in the utility sector. The UIC, including the authors of this paper, have developed a Value Framework which attempts to integrate existing measures of railway performance with the Six Capitals Frameworks and other sources [8]. The Value Framework is divided into the following two service groups, which are further divided into ten value components (see Fig. 2).

- **Service Offering** – Represents the fundamental purpose of the railway infrastructure i.e., the provision of pathways that enable the movement of passengers and goods between locations, with the desired journey times, frequency, infrastructure capability, and customer amenity.
- **Service Performance** - The components represent how well the service is being provided, based on levels of train performance, safety, availability and customer satisfaction. The components also include the broader impact on the environment and on the wider economy and society.

Figure 2 includes the definitions for each of the value components. Each value component is represented by 3–4 key performance indicators [8]. The KPIs are selected as far as possible from international standards and codes of practice, or from expert groups and international research programmes. KPIs specific to individual organisations are used by exception where there isn't a suitable international metric.

Most railways have mature corporate scorecards, with KPIs designed to monitor the most important aspects of business performance. Most scorecards are based on functionally based KPIs, which promote clear accountabilities, but which may lack a whole system perspective based on value. A Value Framework can be used to complement and challenge corporate scorecards. In the longer term an opportunity exists to integrate scorecards and value frameworks.

5 Interventions and Operations Layer: Optimising Decisions

The physical layer and the service layer establish the foundations for asset management decisions. The central role of rail corridors enables decisions to be focussed on the needs of passengers, freight customers and communities. The value framework provides a consistent reference and a common currency for evaluating and comparing strategies and investment options. The SoS approach identifies the sub-system (or sub-systems) that would be affected when considering specific options and captures the interfaces with other sub-systems so that the impact on whole system costs and outputs can be understood.

The ultimate objective of the SoS approach is to enable better decisions, the final stage in this process. The discipline of decision theory has been researched for over 50 years and has reached a consensus around the principal components of an effective decision-making process. The approach adopted in this work is illustrated in Fig. 3, adapted from [9], which in turn was derived from a large body of work at Stanford University [10].

The process is generic to all types of decision and the main steps are explained in the references provided. Three of the steps have a particular meaning for railways and are summarized below.

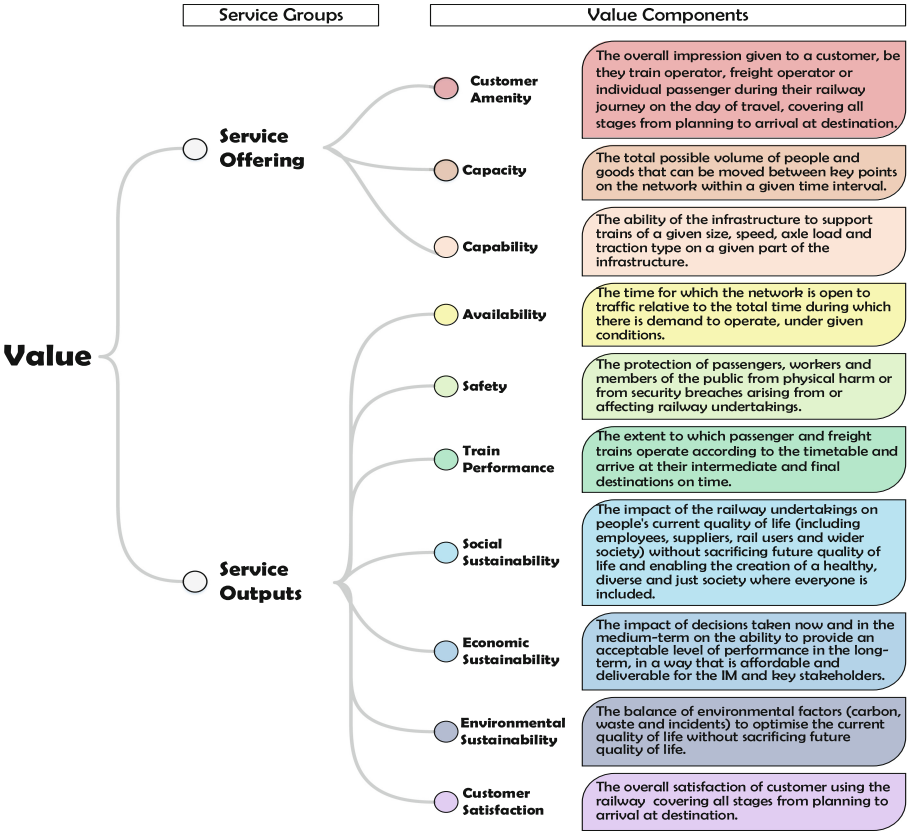


Fig. 2. The UIC Value Framework for Railways

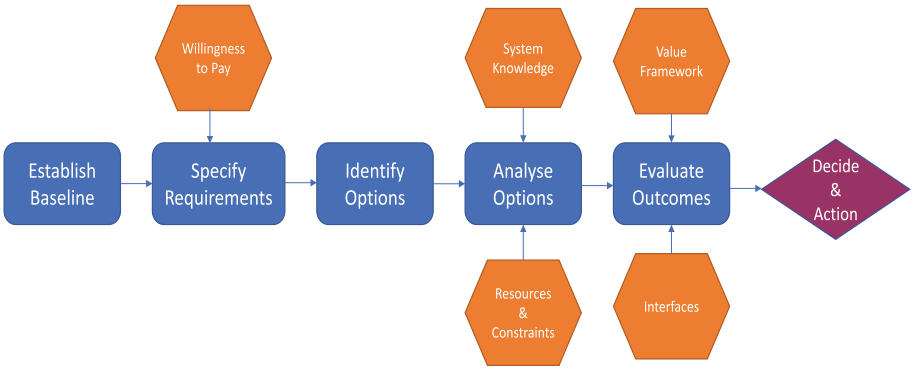


Fig. 3. Decision making process adapted from (Spetzler, 2016)

Establish the Baseline: The baseline describes the historical and current performance of the railway, expressed in terms of key infrastructure outputs such as punctuality,

safety, capacity, capability, asset condition etc. It also includes historical maintenance and renewal volumes and costs. Railways tend to have rich sources of data - the SoS approach enables this data to be integrated and analysed in a way that provides insights into problems and opportunities. Infrastructure improvements and operational changes can be overlaid on the baseline to support business cases, for example, technology improvements, such as remote monitoring, can be added to the baseline to enable a quantification of the incremental benefits and costs based on the net system impact and other potential changes that may be competing for the same benefits.

Specify Requirements: The Value Framework captures the wide range of outcomes that are demanded by customers and funders. Stakeholder consultation plays an important role in the developing a coherent set of requirements as does the process of establishing the 'willingness to pay'. Most railways have formal processes for eliciting and managing stakeholder requirements from up to 100 stakeholder groups. Placing rail corridors at the centre of decision making improves the structure of, and adds consistency to, the consultation process.

Analyse Options: Railways have a range of tools and methods available to support the analysis of options and are particularly strong in the areas of socio-economic modelling, lifecycle cost analysis and quantified risk assessment. Basing the analysis on rail corridors improves the alignment between the various modelling and analytics tools. Safety decision making in the rail industry is well supported by analytical frameworks such as the Common Safety Method [11] and the associated methods and tools are transferrable to other areas where risk-based approaches are beneficial. Methods for dealing with uncertainty [12] are also being introduced to deal with the complexity inherent in many railway decisions.

It may be concluded from the above that railways are in a good position to embrace data driven approaches to decision making. The main challenge to implementation is related to the scale and complexity of rail networks. A whole system approach requires a major commitment, challenging deeply embedded traditions that have developed over many decades.

6 Conclusion

Modern railways face a formidable challenge of transitioning from conventional technologies and established practices to becoming a vital component of a transport infrastructure of the future which places the railway as the backbone an environmentally sustainable multimodal transport ecosystem. At the same time the cost base of managing the railway has to be reduced to make services more affordable to users and taxpayers. This transformation necessitates a fundamental shift in the operational paradigm of railways, a shift that is already well underway.

By combining the use of a robust value framework with a structured whole system decision-making process the outputs of investment can be directly linked to actual outcomes in terms of benefit to value to our customers and stakeholders. This approach enables railway organisations to quantitatively assess the value of various interventions, ensuring investments align with both infrastructure conditions and customer needs.

Embarking on journey will be daunting and will require strong leadership and a change in culture with the highest potential issue being the around tendency of stakeholders to revert and continue to operate within disciplines and silos. The System of Systems approach advocated in this paper provides a pragmatic framework for implementation, maintaining the strengths of traditional approaches while connecting and optimising decisions based on the whole system impact.

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Variable Speed Limit on Motorway: A Feedback Control Implementation

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Abstract. Variable Speed Limits (VSL) is a well-established method of reducing congestion especially on highways and motorways. Often, VSL is used manually though in literature there exists some control mechanisms to implement automatic VSL. This work proposes a method of implementing VSL by measuring the traffic conditions of the road and using a Proportional Integral (PI) controller to produce the optimal VSL based on existing conditions and the desired outcome. The aim of this control system is to reduce the amount of vehicles entering a congested area, allowing the congestion to resolve more quickly. To examine the effectiveness of the strategy, a section of the M50 was simulated using a model to describe traffic flow called the Cell Transmission Model (CTM). The simulation model considered observed traffic conditions from loop detector data supplied by Transport Infrastructure Ireland (TII) with and without the controller incorporated. The results showed a reduction in travel time of up to 27% with the controller applied. Sensitivity analysis was performed to investigate the robustness of the model to certain input parameters associated with both the controller and the implementation of the VSL in the CTM.

Keywords: VSL · Proportional Integral Controller · Congestion Reduction

1 Introduction

The problem of congestion is of ongoing interest to researchers and policymakers. Congestion leads to longer commutes, increased pollution, and decreased quality of life among commuters. Wider economic effects such as decreased productivity and increased transportation costs also occur. Many solutions have been proposed to this issue. Among these is Variable Speed Limits (VSL), a temporary reduction in the posted speed limit of the road, designed to reduce congestion and improve safety.

The literature on variable speed limits is broad. It can be loosely categorized into three areas [1]. The use of simulations to assess and improve control algorithms for VSL, the evaluation of real VSL systems in operation and examining the addition of VSL to ramp metering. This study focused on simulation based studies especially the ones utilizing Cell Transmission Model (CTM). Hegyi et al. [2] demonstrated a method of including this effect by altering the desired speed equation in the traffic simulation

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tool METANET [2] while Carlson's model, defines a speed ratio as the ratio of the VSL to the posted speed limit of the road [3].

There exists several control strategies including machine learning to rule-based controls. In this study, feedback control has been used similar to Carlson et al. [4]. For other studies using similar control strategy can be found in [5].

Congestion on the M50 is a long standing issue and has been the source of many negative impacts on the wider Dublin area for the last number of years. Increased travel time, pollution and decreased quality of life are just a few of the issues associated with it. Recently, VSL were introduced on the M50 in an attempt to tackle this problem. However, the current implementation relies on traffic controllers to set the VSL based on the observed onset of congestion. This is inefficient and may not maximise the benefit of the infrastructure. The aim of this work was to investigate a control strategy that could utilize the VSL to significantly reduce travel time on the road and maximise the potential of the existing facilities.

2 Methodology

The VSL controller implemented in this study is based on Proportional Integral (PI) control. This is a popular closed-loop control and is briefly described in this section. PI controllers use two gains, a proportional and integral gain to drive the error signal to zero. The proportional gain is proportional to the error signal which is the discrepancy between the actual output and desired output. This gain is used to quickly stabilize system to the desired operating state when large deviations occur. However, the proportional gain cannot eliminate this error entirely as the gain is only proportional to the error term. Therefore, an integral gain is employed which sums the error accumulated over time and acts to gradually drive this to zero.

The control system employed in this thesis uses two of the macroscopic traffic variables as inputs, namely the traffic density and flow. The first input is the traffic density measured at the site of congestion. The second input the system utilizes is the traffic flow just downstream of the VSL application area. A simplified diagram of the controller operation area is shown in Fig. 1.

The outer loop takes a measurement of the density at the site of congestion. This value is compared to the critical density and an error signal is generated from the difference between the two. This is minimised as the aim of the controller is to keep the traffic density close to critical to ensure maximum throughput. The transfer function for this loop, in the time domain is given by Eq. 1.

$$\hat{q}(t) = \hat{q}(t-1) + (KP + KI)(k_{set} - k(t)) - KP(k_{set} - k(t-1)) \tag{1}$$

In this equation, $\hat{q}(t)$ represents the desired flow, *KP* and *KI* the proportional and integral gains, respectively, and k_{set} is the setpoint density. This transfer function provides the desired flow just downstream of the VSL application area to ensure optimal flow into the bottleneck to alleviate congestion. The inner loop is used to set the variable speed limit based on the flow measurement taken just downstream of the VSL controlled area (Eq. 2) where b(t) represents the variable speed limit of timestep t.

$$b(t) = b(t-1) + KI\,\hat{q} - q_{VSL}\Big) \tag{2}$$

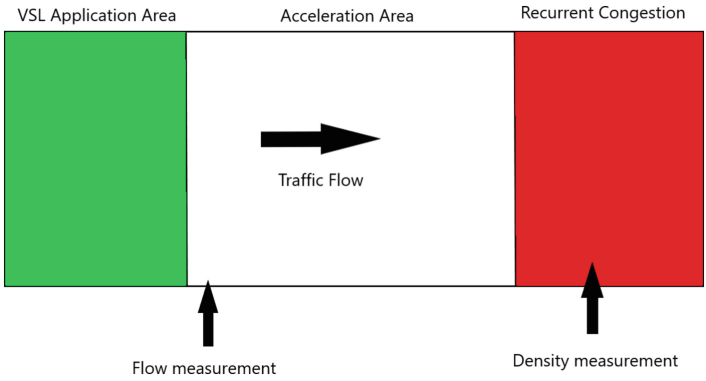
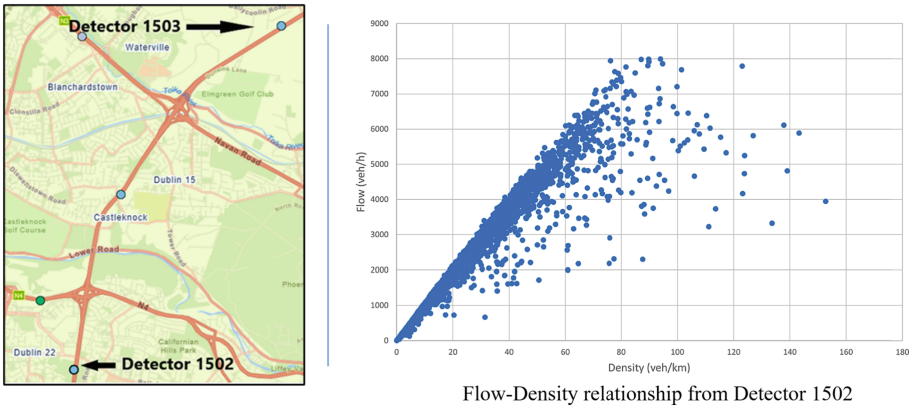


Fig. 1. Simplified diagram of road section with VSL controller applied.

The section of M50 was simulated using Cell Transmission Model (CTM) [6]

3 Study Area

Ireland's busiest motorway is the M50 situated in Dublin is modelled in this study. Spanning 50km from Dublin port to the airport, spanning 8 lanes for the majority of its length, it is Ireland's biggest motorway. Traffic between 6 and 7am increased by 86% from 2014 to 2019, according to Transport Infrastructure Ireland (TII). There are nearly 1400 incidents per year on the road. Variable speed limits were first introduced to the M50 in 2021, between junction 4 and 6, in an attempt to tackle some of the congestion. Further VSL gantries were later introduced all along the motorway in 2022 and 2023 (See, Fig. 2).



Flow-Density relationship from Detector 1502

Fig. 2. M50 road section used for simulation; Map of the road section modelled; Flow-Density relationship from input detector. (Map data © OpenStreetMap contributors, ODbL 1.0)

Figure 2 shows a month worth of data from October 2019. From the data, a maximum flow of 2,000 veh/h/lane was observed. This corresponded with a critical density of 22 veh/km. A linear regression was performed on the uncongested portion of the data to determine a free-flow speed of approximately 84 km/hr. Not enough congestion data was present to determine the jam density, so it was assumed to be 100 veh/km. From the maximum flow and assumed jam density, the speed of the congestion wave was estimated at 25 km/hr. These parameters were used in the CTM simulation of the road.

4 Results & Discussion

The implementation of the VSL system when simulated through a model showed effective congestion control which is shown in the density heat maps shown in Fig. 3.

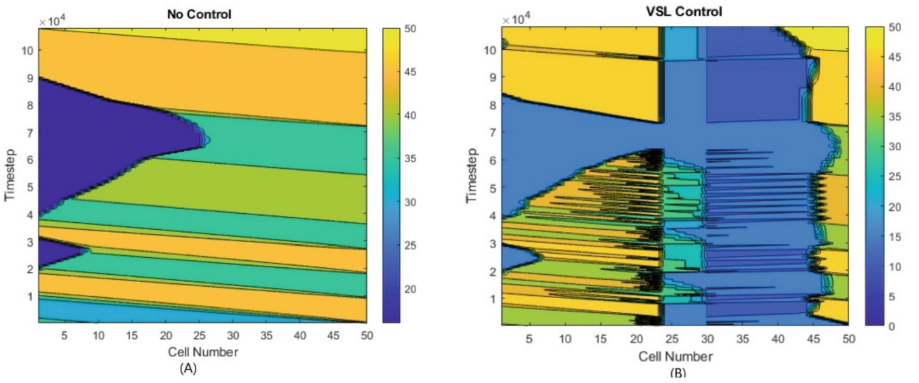


Fig. 3. Density heatmaps M50 road section used for simulation for traffic between 7am-10am; without control and with PI-based VSL control.

The traffic density throughout the day is depicted for each cell with spikes in congestion visible for the morning rush, 7–10 am. The y axis represents the timestep of the simulation in units of 10 to the power of 5. The congestion induced by the VSL application area upstream of the recurrent bottleneck is evident. The induced congestion is followed by areas of lower density corresponding to the acceleration area. The speed harmonization goal of variable speed limits is seen in this area, with a constant density evident. This constant density implies little variation in speed for this section.

The vehicle hours travelled (VHT) is a measure of the total time spent by all vehicles on the road for the entire simulation period. The total VHT for the no control simulation was 843. The VHT travelled for the simulation with the controller implemented was 620, a reduction of 26.45%. This means that the delay introduced by the artificial congestion created by the VSL did not exceed the normal delay caused by the recurrent congestion and in fact improved it. The peaks in the control case still fall below that of the no control scenario with the reduction present for the entire simulation period.

Figure 4 shows the density at the recurrent bottleneck for the no control and control scenario. For the no control scenario, the area is constantly congested fluctuating between

40–50 veh/km with active controller, the density is successfully kept below and around the critical density of 19 km/hr for significant portions of the simulation. This critical density ensures maximum throughput of traffic. However, when there are relatively fast changes in density, the controller's ability to achieve its objective decreases.

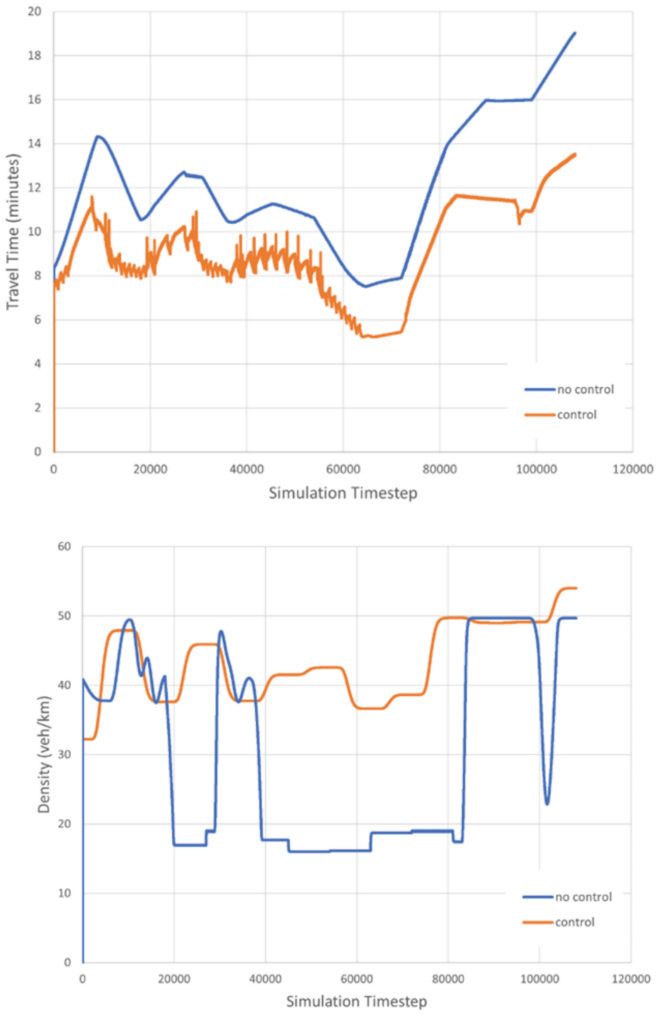


Fig. 4. Travel time and density changes due to VSL control on M50 road section.

4.1 Sensitivity Analysis

The effect of altering the controller gains on the VSL furnished by the secondary controller was studied for sensitivity analysis. The different controller gains produce

markedly different VSL rates throughout the simulation, highlighting the importance of an appropriately tuned controller. The integral gain of the secondary controller was varied from 0.0003–0.05. A minimum VSL value of 20 km/hr was set. Table 1 shows the VHT for the different controller gains. As the integral gain of the controller increases, the improvement in travel time increases.

Table 1. Table captions should be placed above the tables.

Controller Gain	VHT	Change
No Control	843	N/A
0.0003	669	20.6%
0.0005	623	26.09%
0.0007	620	26.45%
0.05	598	29.06%

A limitation to note is that, there was no data available for the effectiveness of the current VSL framework on the M50 for comparison, but it is a safe to assume that the controller is capable of improving the traffic situation based on this analysis.

5 Conclusion

In this study, a PI controller based VSL control has been studied for its effectiveness. The proposed method has been evaluated on the M50 Motorway in Dublin, Ireland utilizing a CTM based simulation model. The controller made use of two real time traffic measurements, the density and flow, to produce a VSL.

The PI controller significantly reduced travel time throughout the simulation period.

The controller demonstrated its competence at keeping the density at the bottleneck close to critical for significant spells throughout the simulation period. It is important to note that, although the gains supplied were described as robust and suitable for most road sections, to achieve the best controller performance possible, the controller ought to be tuned using conventional tuning methods.

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Analysis of Extreme Weather Effects of Travel Time Reliability

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Abstract. Extreme weather condition spose serious impacts on the reliability of the transportation networks greatly, as it causes significant disruptions to traffic flow. Hence, it important to look at the effect of extreme weather conditions on traffic flow characteristics to prepare the system for future circumstances. In this regard, the present study carried out a detailed spatio temporal analysis on traffic data during storm days to understand the impact of weather on traffic. In order to conduct this study, the present study identified two extreme weather in the year 2019 and 2020 based on the warnings issued by National Meteorological organization of Ireland and analyzed the reliability indices of travel time/speed. The present study sourced from eight traffic counter locations across different provinces of the Republic of Ireland with main focus along the coast and extracted traffic data during the warning dates. The present study utilized the collected traffic data to carry out temporal analysis of the speed/travel time reliability indices such as Planning Time Index (PTI), Buffer Index (BI) to understand the changes in the traffic flow behavior and reliability. The results indicated the travel time reliability is impacted greatly during storm days and the impacts of post storm period was found to be significant across different locations. A dashboard has been developed using Jupyter Dash package to monitor the evolution of traffic system during these warning dates.

Keywords: Extreme weather · Travel time Reliability indices · Traffic Counters

1 Introduction

Reliability is a critical factor in analyzing the efficiency and service quality of transportation networks, as it impacts the decisions of stakeholders, including users (travelers), service providers, planners, and managers. Quantification and analysis of travel time reliability is really important to understand the impact of the non-recurring events like extreme weather conditions on the traffic system to improve and manage the system efficiently. Traffic updates are often disseminated in terms of mean speed/travel time however, the commuters experience the deviations from the average values, which reflects the actual reliability of travel time. Hence, it is necessary quantify the reliability to fathom impact of recurring and non-recurring events in the traffic system. Numerous

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studies have been conducted in the field of travel time reliability modelling, and some significant ones are discussed further. Various measures/indices have been proposed in the literature to quantify the travel time reliability [1, 2]. However, Planning Time Index and Buffer Index (described in Table 1) are widely recommended by Federal Highway Administration (FHWA) [1].

Table 1. List of FHWA recommended travel time reliability indices.

Reliability Indices	Authors/Organization	Equation/Description
Buffer Index (BI)	FHWA [1]	$BI = \frac{T_{95th\ Percentile} - T_{mean}}{T_{mean}}$
Planning Time Index (PTI)	FHWA [1]	$PTI = \frac{T_{95th\ Percentile}}{T_{freeflow}}$

Various studies have studied the impact of weather factors on traffic and reported the influence of climate changes on driving behavior increasing risk of traffic accidents [3, 4]. Extreme weathers significantly increase the probability accidents [5] may be due to poor visibility, icy roads, precipitation, windy conditions, etc. While there are warnings being given about these effects of extreme weather, it inherently affects the driving behavior resulting in impacted reliability of traffic system. A few studies experimented the correlation of weather and traffic system [6]. However, it is important to quantify the impacts caused by extreme weather. A few studies [7] quantified the impact by estimating the reduction in flow during storm, and such effect is expected due to prior warning issued. Very limited studies explored the aspects of travel time reliability to quantify the weather impacts under Irish traffic conditions [8]. In this regard, the present study developed a series of analyses framework to quantify the travel time reliability to understand the evolution of the traffic system during and after extreme weather conditions on Irish highways.

2 Irish Weather Characteristics

The Irish weather are known to be temperate with mild, moist, and often dynamic with lot of rains, and winds. Ireland does not suffer from the extreme temperature experienced by many other countries at similar latitude (www.met.ie) due to the dominance influence of Gulf streams, a strong ocean current that brings warm water into the Atlantic Ocean. However, due to North Atlantic Oscillation (NAO) that creates fluctuations in atmospheric pressure at sea level, occurrence of storm events is more pronounced at the Republic Ireland. Figure 1 shows the list of storm events occurred from the year 2016 to 2021, provided by Irish Meteorological Service 'Met Eireann'. It can be observed that the country experiences a greater number of storm events consequently every year served as a motivation to study its impacts on traffic system. The present study considered two storm events: Ciara (2020) and Erik (2019) to analyze the impacts of the same on Irish traffic. The warning of Ciara was given from 7th to 9th February 2020 whereas for Erik, warning was given from 7th to 8th February 2019.

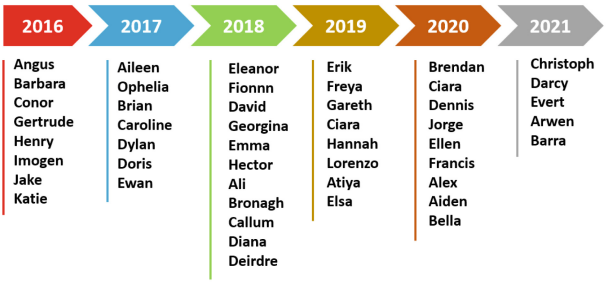


Fig. 1. Storm events of Ireland (2016–2020)

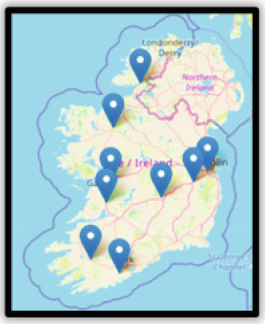


Fig. 2. Map of counter locations.

3 Data Description

The data for this study was sourced from Traffic Infrastructure Ireland (TII) traffic counters installed on the Irish road network. The present study identified eight different locations (as shown in Fig. 2 and Table 2) across the Republic of Ireland to analyze the effects of extreme weather events. Traffic counters provide information on the volume of traffic by time of the day and vehicle class.

Table 2. Details of counter locations chosen for this study.

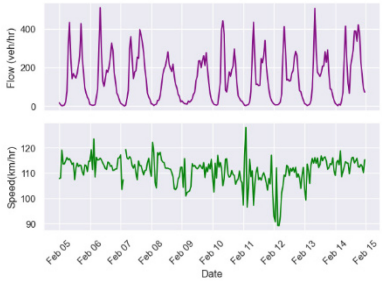
Storms	Road Type	Details
Site 1	Motorway	M50 Jn07 and Jn09 Red Cow, Palmerstown, Co. Dublin
Site 2	National Primary	N17 Between Tobercurry and Charlestown, Co. Sligo
Site 3	National Secondary	N71 Between Halfway and Inishannon, Co. Cork
Site 4	Other Roads	R445 Between Borris-in-Ossory and Mountrath, Co. Laois
Site 5	Motorway	M18 Between Jn13 Tulla Road and Jn14 Barefield, Co Clare
Site 6	National Primary	N22 Between Killarney and N22/R569 Jn, Co. Kerry
Site 7	National Primary	N15 Between Ballyshannon and Donegal Town, Co. Donegal
Site 8	Motorway	M7 Between Jn10 Naas South and Jn11 M7/M9, Co. Kildare

The raw data obtained were vehicle transactions consisting of time of passage, speed, vehicle type, and lane identifiers. For this study, the speed and flow values from the vehicle class 'Passenger cars' were considered from January 2019–March 2020. The sourced data were processed to set up time series of flow and speed with the resolution of one hour. The speed values were obtained by averaging the speeds of all the vehicles that passed over the counter during one-hour period. Missing speed values due to no vehicles during a one hour period were imputed by temporal substitutions. The speed limit observed on the motorways is 120 km/h., national roads are 100 km/h., and other

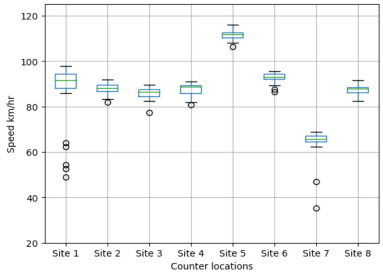
roads are 80 km/h. In this study, the travel time was calculated for 1 km stretch, spanning 500 m from both sides of the detector location using the average speed of all vehicles during the one hour period.

4 Results

In the first stage, the present study describes the impact of extreme weather events by analyzing the fundamental traffic flow variables like hourly flow and speed for the duration of ten days with extreme weather warning dates in between. Figure 3a shows the time series plot of hourly flow and speeds of a sample location during the storm duration. From the figure, it can be observed that the traffic flow during the storm days is lower compared to other days, which is expected due to the prior warning. However, the speed drops are visually evident even after storm warning dates. Figure 3b shows the sample box plot of mean speeds across all the site locations during the storm days. It can be observed that the mean speeds are significantly lowered in all the locations during the storm days when compared to free flow speed. During Storm Erik, the traffic at Site 7 is found to be the most impacted location with mean speeds dropped to 60 km/h. under relatively low flow conditions compared to other locations.



a) Sample plot of speed and flow during Strom Ciara.



b)Sample box plot of mean speeds across the site locations during Storm Erik.

Fig. 3. Traffic characteristics during the storm events.

In the next stage, the present study analyzed travel times to understand the variations in travel time. Figure 4 shows the multi plane bar chart of travel times across the test sites during stormy days. Variations in travel time values are found to be higher ranging from 30 s to 55 s (7 am slot) to traverse one km during Storm Ciara.

In the next stage, the present study analyzed the travel time reliability indices during the storm events to quantify the impact of the same on the traffic. Figure 5 shows the heat map of hourly estimated BI and PTI for the duration of ten days with storm days placed in between to understand the temporal evolution of reliability due to extreme weather events. PTI is observed to be sensitive in quantifying the travel time reliability when compared to BI. PTI values range from 80% to 140% describing one km travel takes 140% more time than the free flow travel time reflecting the magnitude of impact. The

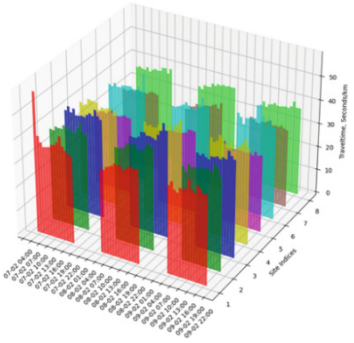
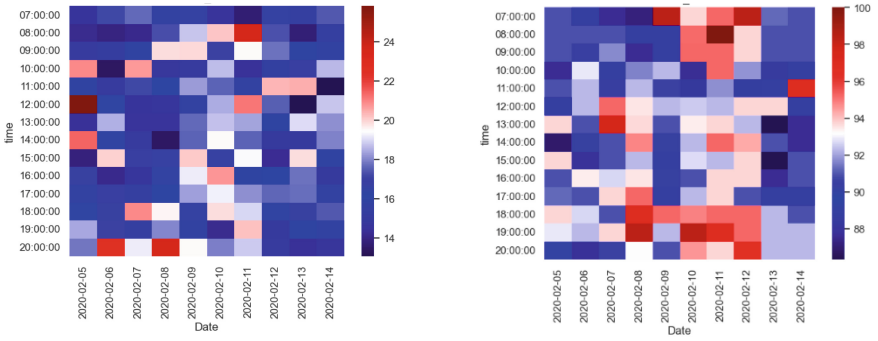


Fig. 4. Variation of travel time during storm Ciara.

magnitude and period of impacted travel times are observed to be increased after the actual storm warning dates. For example, during Storm Ciara PTI values are found to be less than 95% before the warning dates and the reliability slowly deteriorated during storm and it continue to worse with higher PTI values till 12th February showing the post storm effect. People who refrain from travelling/driving during weather warnings, embark on travelling immediately after storm resulting in higher PTI values. Storm induced damages to infrastructures may hinder the travel/driving behavior which in turn reduces the means speeds at the test sites considered in this study.



a) BI during Storm Ciara

b) PTI during Storm Ciara

Fig. 5. Sample heatmap of travel time reliability indices

In the next stage, the present study developed a highway performance monitoring dashboard to automate the aforementioned process of estimating reliability indices and to visually summarize the variation of indices across multiple days. This dashboard was developed using Plotly library of Python language. Figure 6 shows the snapshot of the developed dashboard with its components. The developed dashboard automatically retrieves traffic counter data from TII counter data website and process the information to generate the plots instantly. This dashboard has been developed as a

part of the research project "Transportation Data Analysis Phase II" collaborated with Transportation Infrastructure Ireland.

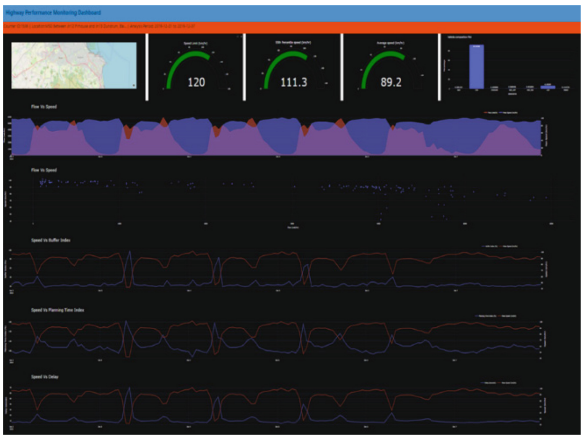


Fig. 6. Snapshot of Python HPMS Dashboard

5 Conclusions

The present study carried out the reliability analysis to understand the impact of extreme weather events on the traffic system and developed a dashboard**, a** disseminating tool to help the travelers to know the impact of any recurring and non-recurring events on a day-to-day basis, if launched publicly.

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A Simulation-Based Assessment of the Effectiveness of Vehicular Ad-hoc Networks in Enhancing Transportation Resilience

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Abstract. A resilient transport network can effectively lessen the negative impact of disruptions such as man-made accidents or natural disasters and rapidly restore normal operation. New evolutions of Intelligent Transportation Systems (ITS) bring new solutions to enhance transportation resilience, but their specific effectiveness remains unclear. Vehicular ad-hoc networks (VANETs) are one of the most popular ITS technologies currently, promoting the inner connection of various entities in transport networks. This paper takes VANETs as an example to explore the positive effects of ITS technologies on the enhancement of transportation resilience through the simulation of Vehicles in Network Simulation (Veins) framework based on the data of Dublin city centre. The results show that, compared with scenario B, the road network equipped with VANET technology in scenario A has a 30.24% reduction in resilience loss after the traffic accident and a 25.94% increase in the speed of restoring its basic performance, thus relatively enhancing the resilience of the entire road network.

Keywords: Intelligent Transportation Systems · VANET · Resilience · Veins · Simulation

1 Introduction

Transport networks are vulnerable to disruptive events, such as man-made accidents or natural disasters [1]. Therefore, transportation resilience was introduced to help better deal with these disruptions [2], whose basic connotation refers to the ability of the transport network to reduce adverse effects and quickly restore normal operation in the face of disruptions [3]. By enhancing transportation resilience, the negative impact of disruptions can be lessened, making operations more reliable and safer.

Nowadays, the continuous application of innovative technologies has promoted the development of ITS. These technological advancements have changed the response behavior of the transport network to different disruptions to some extent and brought new opportunities to improve transportation resilience [4], but the exact effect is unclear. Currently, VANETs are becoming a new key enabler of ITS, which enable real-time

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information sharing in transport networks through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication [5]. This technology can enhance the connection between different transportation entities and improve the efficiency and safety of the existing transport network [6].

Hence, this paper intends to take VANETs as an example to explore how the application of ITS technologies can promote transportation resilience. Specifically, this paper sets up three different scenarios to evaluate the positive impact of VANET technology on transportation resilience based on the urban road network and traffic loads of Dublin city centre. The relevant simulation is implemented by the Veins framework [7], which relies on the Simulation of Urban MObility (SUMO) [8] to simulate road traffic and the Objective Modular Network Testbed in C++ (OMNeT++) [9] to achieve vehicular communication. In addition, this paper selects resilience loss and recovery speed as metrics to measure transportation resilience.

2 Materials and Methods

2.1 Data Description

As shown in Fig. 1, this paper takes the open data of the urban network of Dublin city centre [10] as the simulation basis. The associated traffic loads are typical workday traffic generated from real traffic observations in Dublin [10].



(a) (b)

Fig. 1. Urban network of Dublin city centre from: (a) OpenStreetMap; (b) SUMO.

2.2 Evaluation Scenarios

Three different scenarios are set to evaluate the effect of VANET (see Table 1).

The baseline scenario simulates the normal operation of the urban network in Dublin city centre to compare the system performance of scenarios A and B.

Scenario A sets up a traffic accident in the urban network that equipped VANET, which is caused by the long stop of vehicle 11 on the Father Mathew Bridge (see Fig. 2). Specifically, vehicle 11 begins to decelerate at 70 s and restarts after 1200 s, which leads to

Table 1. Features of three evaluation scenarios.

Evaluation scenarios	Features
Baseline scenario	Urban road network without traffic accidents
Scenario A	There is a traffic accident in the urban network (with VANET)
Scenario B	There is a traffic accident in the urban network (without VANET)

subsequent vehicle queuing and congestion. The urban network equipped with VANET supports V2V and V2I communication. All vehicles can exchange various information, such as driving behavior and road conditions, with surrounding vehicles and the roadside units (RSUs) in real time through Dedicated Short-range Communications (DSRC) technology. This paper assumes that the urban network is equipped with enough RSU devices so that the communication range of vehicles is large enough to guarantee good communication. Therefore, when an accident occurs in the urban network, relevant accident information can be sent to surrounding vehicles in real time through communications (see Fig. 3). Vehicles that have not yet been affected can choose whether to change their route based on information like received accident messages and scheduled routes.

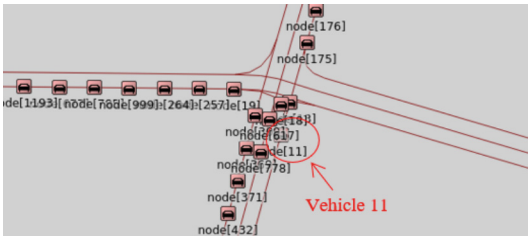


Fig. 2. A traffic accident caused by the long stop of vehicle 11 on the Father Mathew Bridge.

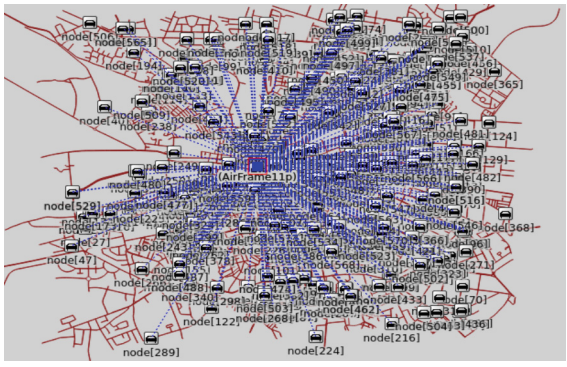


Fig. 3. Communication diagram of scenario A equipped with VANET.

Scenario B sets up the same traffic accident in the urban network, but the difference is that the road network is not equipped with VANET. That is, scenario B simulates the reaction of the urban network when it suffers a traffic accident under existing conditions.

The above three scenarios are simulated in the Veins framework for 3600 s.

2.3 Resilience Metrics

Regarding the measurement of transportation resilience, this paper takes resilience loss and recovery speed as resilience metrics [11] (see Fig. 4, Eq. (1) and (2)).

$$R_{loss} = \int_{t_0}^{t_2} \left[100 - Q(t)\right] d_t \tag{1}$$

$$tan_{\beta} = \frac{Q_0 - Q(t_0)}{t_2 - t_1} \tag{2}$$

where Q_0 refers to the original performance level of the transport network, set to 100%; $Q(t_0)$ is the ratio of system performance before and after the disruption; t_0 refers to the time when the disruption occurs; t_1 and t_2, respectively, refer to the time when the transport network begins to recover and fully restores its basic performance.

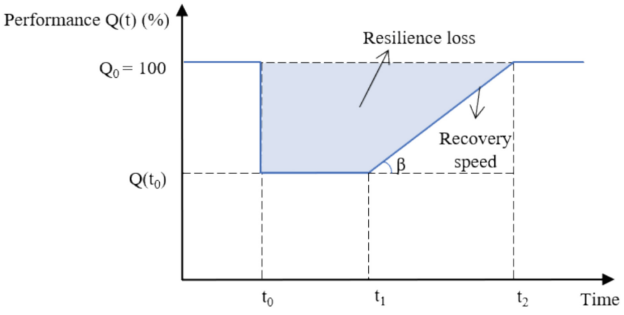


Fig. 4. A schematic diagram of the measurement of transportation resilience [11].

As shown in Eq. (1), resilience loss refers to all performance losses of the transport network from the occurrence of a disruption to the complete recovery of performance, which is mainly calculated by the simplified trapezoidal area [11] (see Fig. 4) in this paper. Specifically, the performance of the transport network is determined by the average travel time of all vehicles during the analysis period [11]. Besides, the recovery speed refers to the speed of the entire process of the transport network from the beginning of recovery to the restoration of its basic performance, which can be expressed as the slope (see Eq. (2)) of the recovery stage in Fig. 4.

3 Results and Discussion

As mentioned in Sect. 2, resilience loss and recovery speed are calculated based on the occurrence time of the accident, the start and completion time of restoring system performance, and the average travel time obtained from simulation observations. Specifically,

the occurrence time of the accident and the start time of recovering performance are the braking time and restarting time of the vehicle 11, respectively. The values of these two attributes are consistent in scenarios A and B, which are 73 s and 1270 s, respectively. The completion time of performance recovery in scenarios A and B is considered to be the time for the last vehicle that braked due to the accident to return to normal driving speed after the accident, which is 1808 s and 2142 s, respectively. In addition, for the convenience of comparison, taking the entire impact period of the accident in scenario B as the analysis period, the average travel time of all vehicles that completed the trip during this period in the baseline scenario, scenario A, and scenario B is 247.69 s, 305.14 s, and 326.90 s, respectively. Based on the obtained average travel time, the performance after the accident in scenario A can be calculated as $247.69/305.14*100\% = 81.17\%$, and the performance in scenario B dropped to $247.69/326.90*100\% = 75.77\%$. From this, the obtained resilience loss diagram is shown in Fig. 5, and the resilience losses in scenario A and scenario B are calculated to be 276.02 and 395.70, respectively, and the recovery speeds are 0.00034997 and 0.00027788, respectively.

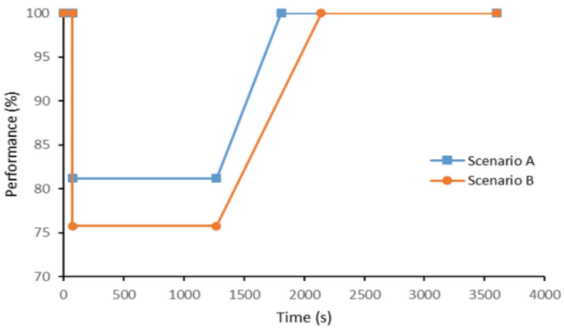


Fig. 5. Results of the resilience assessment for scenarios A and B.

From Fig. 5, compared with scenario B, scenario A reduces the loss of system performance after an accident by 30.24% and improves the recovery speed by 25.94%. This shows that the urban network equipped with VANET can disseminate accident messages in real time after an accident, allowing unaffected vehicles to reduce unnecessary waiting time and thereby mitigating the negative consequences. In addition, as more vehicles are prevented from getting into queues and congestion in time, the accident is relatively easier to recover from. Therefore, VANET technology is conducive to improving transportation resilience to a certain extent. However, it should be noted that since the detour time caused by the route change behavior will also increase the total travel time of the vehicle, it is necessary to comprehensively consider the time costs of detour and continued waiting based on the severity of the accident.

4 Conclusion

This paper takes VANETs technology as an example, sets up three different scenarios based on data from Dublin city centre and uses the Veins framework for simulation to explore the potential positive role of ITS technology on transportation resilience. The

results show that, compared to scenario B, scenario A equipped with VANET reduces the resilience loss of the road network by 30.24% and increases the speed of restoring its basic performance by 25.94%. Therefore, VANETs can potentially enhance transportation resilience.

Regarding future research directions, this paper simplifies the calculation of resilience metrics, and a more accurate resilience assessment of the road network can be further considered. In addition, this paper sets up a common accident to evaluate the effects that VANET may bring, but the severity of the accident itself could be a key influencing factor. Therefore, different severities of accidents can be further designed to study the potential impact of VANETs on transportation resilience.

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Reimagining the Future Ridership of City Bus- A Case of BRTS Bhopal

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Abstract. In India, one-third of the population lives in urban areas. Urbanization has increased from 31.28% to 35.39% since 2010, indicating demand for public transport in urban areas. New mass transit systems and unconventional situations (like COVID-19) pose challenges to existing bus services. Bhopal, a metropolitan and state capital has operated successful BRTS for a decade. The study aims to foresee the role of BRTS Bhopal in coming years as Phase I of the metro will be functional by 2026 expecting a shift in ridership from bus to metro causing a serious threat to the relevance of the bus. Factors affecting ridership can be categorized as travel attributes, user's attributes, service quality and operational attributes as discussed in numerous studies. Statistical methods are used to analyze all four factors. Significant factors helped in comparing study area with other cities having metro. The 3 scenarios are built assuming the shift on overlapping routes. Recommendations on bus route rationalization, route lengths and fleet augmentation are given, priority areas for the routes are identified using PTAL (existing and predicted 2026). This study suggests when and how much fleet and route length of the bus network should be augmented with the example of Bhopal.

Keywords: Public Transport · City Bus · Metro · Ridership

1 Introduction

In India, urbanization is increasing at a very fast rate. The rate of urbanization was around 35.39% in 2021 [1], indicating a growing demand for public transportation in urban areas. As cities urbanize, the need for efficient and sustainable transportation grows. Public transport plays a vital role in meeting this demand. It is influenced by several factors including unconventional situations like COVID-19, the introduction of new mass transit systems etc. Understanding how these impact ridership and predicting their future impact is a key focus of this study. Additionally, the study addresses the lack of fleet standardization in India. The study aims to foresee the role of BRTS Bhopal in the coming years. This is achieved through objectives such as studying the factors that influence choosing a bus as transportation mode through various literatures, analyzing the Bhopal city trends, fleet standardization followed by the impact of the metro on

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BRTS Bhopal, and finally making recommendations for the efficiency of the BRTS in the future. These are accomplished by conducting a comprehensive review of relevant literature and primary sources. The study excludes the financial and engineering aspects of BRTS and focuses on operations within the city municipal boundary.

2 Literature Study

A Bus Rapid Transit (BRT) system comprises dedicated bus lanes and prioritizes buses. By examining numerous studies, it was found that the key factors of all these are trip purpose, travel distance, travel time, travel cost. An empirical analysis found that travel distance is the most influential factor in determining a transportation mode [2]. It has been proven in many studies that user attributes such as age [3], gender [4], income [5], occupation [6], vehicle ownership [7] are key parameters in choosing a transport mode. Service quality can significantly impact the choice of public transport mode such as reliability [8], availability of infrastructure such as bus shelter [9], cleanliness [10], level of comfort [11] and information about the bus [6]. The operational parameters of a bus, such as route design, and fleet size can have a direct impact on its ridership. Various studies have shown that increasing bus revenue vehicle kilometers is a key factor in increasing bus ridership [12].

3 Selection of Study Area

A list of Tier-II cities is created according to their population size and area as Tier-II cities are better representatives of India [13]. Cities are compared based on available formal and unorganized buses, auto rickshaws as IPT, BRTS, Public Bike Sharing (PBS) and metro. Considering these parameters and fact that Bhopal has the largest BRTS network for past decade, it has been chosen. As per census 2011, population of Bhopal was 18, 86,100. According to Bhopal City Link Limited, 360 buses operate on 13 routes of around 290 km in length. Bhopal is growing so fast with increase in trip lengths [14]. According to BDP-2005, planning area was 601.06 sq. km., which has now increased to 1016.9 sq. km. Due to this, metro was introduced in city. First phase of metro i.e., 2 lines will be operational by 2026.

4 Data Collection Strategy

The data is collected through primary sources including users (sampled using Yamens's formula at 80% confidence level), operators and secondary sources. (see Table 1).

Table 1. Data Checklist

Source	Data Required
BCLL	No. of routes, route length, fleet size, and Bhopal bus ridership trend.

(*continued*)

Table 1. (*continued*)

Source	Data Required
MPMRCL	Proposed Bhopal metro details
Other bus operators	Bus details in other cities from KSRTCL, JCTSL, and CHALO
Other metro operators	Metro details in other cities from KMRL, JMRC and NMRCL
Users (208 samples)	User's attributes and travel attributes

5 Analysis and Findings

The SPSS program is utilized for analyzing discrete choice data, with the MNL model results helping to ascertain whether a significant relationship exists between the mode choice (dependent variable) and the set of independent variables (factors chosen from literature study). It (Table 2) was found adequately fit with likelihood test and 0.732 Pseudo R-square value (The result of the users choosing bus as a mode is shown here).

Table 2. Parameter Estimates of Multinomial Logistic (MNL) Regression (MLR)

Variable (Attribute)	B	Significance Value
Private Vehicle Ownership	−2.807	0.003
Trip Purpose (Education)	3.788	0.017
Travel Distance (6–8 Km)	1.482	0.034
Gender (Female)	0.158	0.050
Age (25–45 years)	2.925	0.049
Income (10,000–25,000)	1.593	0.028

The result of service quality attributes suggests that reliability, availability of bus shelter, cleanliness, level of comfort, and information about the bus are found to be important factors (See Fig. 1).

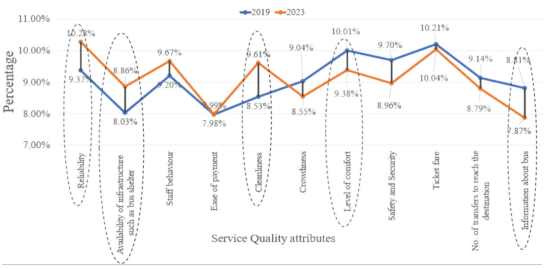


Fig. 1. Percentage Change from 2019 to 2023

By examining correlation matrix, ridership is found to be strongly correlated with fleet size (r = 0.86) and route kilometers (r = 0.64). Hence, to standardize fleet augmentation, these are considered. This analysis is based on data spanning from 2015 to 2023 of Bhopal (See Fig. 2). The findings suggest that fleet should be expanded when either ridership per bus exceeds 550 or route kilometers per bus exceeds 240 km. Also, according to BCLL, the operating hours of the bus are 12 h, and journey speed is 23 Kmph which makes a total of 276 km per bus that can be traveled in a day. This also proves suggested distance of 240 km per bus.



Fig. 2. Fleet size and Total Route Km of Bhopal (Source: BCLL)

5.1 Comparison with Metro, an Unconventional Situation

Buses and metro mass transit share several similarities including fixed routes, schedules and designated stations or stops. The upcoming metro is considered an unconventional situation for buses. Bhopal is compared with Kochi, Nagpur and Jaipur as they have comparable populations and areas with functional metro and buses (See Tables 3, 4 and 5), where B implies Bus and M, Metro.

Table 3. Comparison of Average Daily Ridership and Trip Length

City	Av. Daily ridership -B	Av. Daily ridership -M	Av Trip Length of City (in Km)
Bhopal	1,52,000	35,407 (Expected)	–
Kochi	1,05,360	38,000	7
Nagpur	1,50,000	1,40,000	7
Jaipur	1,15,000	20,000	9.1

Table 4. Comparison of Bus and Metro

City	Base Fare-B (in Rs.)	Max.Fare- B (in Rs.)	Base Fare-M (in Rs.)	Max.Fare-M (in Rs.)	Av. Trip Length -B (in Km.)	Av. Trip Length -M (in Km)
Bhopal	7	60	–	–	–	–
Kochi	10	35	10	60	5.5	5

(*continued*)

Table 4. (*continued*)

City	Base Fare-B (in Rs.)	Max.Fare- B (in Rs.)	Base Fare-M (in Rs.)	Max.Fare-M (in Rs.)	Av. Trip Length -B (in Km.)	Av. Trip Length -M (in Km)
Nagpur	8	62	5	20	9.4	9.4
Jaipur	10	60	6	22	11.4	6.1

Table 5. Comparison between Bhopal and Kochi

City	Mode	Age (yrs.)	Gender	Income (in thousand)	Trip Purpose
Kochi	Metro	21–30 (32%), 31–40 (39%)	F (51%)	20–40 (35%), 6–20 (22%)	Work (77%)
	Bus	31–40 (33%), 41–60 (38%)	F (52%)	0–20 (62%)	Work (84%)
Bhopal	Bus	26–45 (52%)	F (59%)	10–25 (31%)	Edu. (40%), Work (38%)

As a result, metro users in other cities are similar to the users of buses in Bhopal.

When considering service quality attributes, it is observed that 60% of metro users in Kochi prefer using the metro over buses due to factors such as safety/security, cleanliness, comfort, and reliability [15]. It is found that our results are very much comparable to these cities. Thus, it is certain that current bus users will shift to the metro in the coming years.

However, both systems must coexist harmoniously rather than compete.

5.2 Scenario Development

Ridership is projected according to the projected population which is 1,73,092 [14]. 3 distinct scenarios have been developed i.e., 1, 2 and 3 considering percentage shifts from bus to the metro of 50%, 75%, and 100% respectively.

6 Recommendations

6.1 Fleet Augmentation and Route Length

Linear regression analysis is employed to forecast the ridership in 2026. By utilizing regression equations specifically designed for ridership post-2020 both for fleet size and route km. One is mentioned here as an example.

$$\text{Ridership} = -23357.7 + \left(627^{*}\ \text{Fleet Size}\right) \tag{1}$$

Fleet size required according to the above equation for BAU, scenario 1, scenario 2, and scenario 3 is 315, 329, 344, and 360 while the route length required is 524.4, 550.6, 576.8, and 603 Km. The fleet size recommended here aligns with the route length. It also follows the route kilometers per bus and passengers per bus standards discussed in the Sect. 5 of this study.

6.2 Area Identification for the Routes

A comparison is made between the Public Transport Accessibility Level (PTAL) of existing BRTS routes and the projected PTAL (with metro) for the year 2026. The metro phase 1 routes are superimposed on the existing PTAL to assess accessibility in 2026, identifying areas with lower accessibility.

Regions with low PTAL values i.e., ranging from 0 to 15 are identified as areas where bus routes are less active as compared to the actual demand, accordingly, these corridors are recommended on a priority basis for the provision of bus services. Areas are marked in Fig. 3, considering road networks and built-up areas. Additionally, it is recommended to extend the bus routes in alignment with the city's growth.

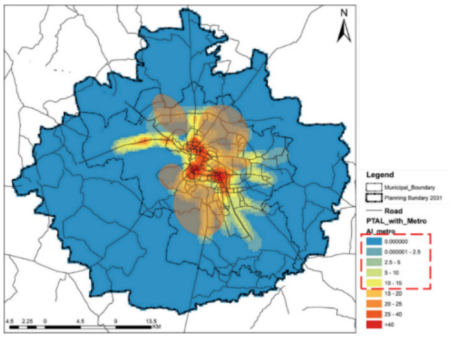


Fig. 3. PTAL for the Year 2026

6.3 Route Rationalization

To enhance connectivity and facilitate seamless transfers between the modes, an effective approach is to design bus routes that intersect perpendicularly with metro routes i.e., staggering of routes, where both will complement each other. By implementing this, passengers can conveniently switch between buses and metros at designated intersection points, optimizing overall connectivity within the public transportation system.

7 Conclusion and Contribution of the Research

The city bus system is a vital public transportation mode in urban areas. To fully realize its potential and ensure its efficiency, it is important to implement measures in unconventional situations. This study focuses on the case of metro system, although the findings can be applied to other scenarios as well. The study recommends several measures to achieve an efficient city bus system, specifically addressing the augmentation of the fleet and route length in Indian cities by illustrating the example of Metro Phase I and BRTS in Bhopal. The study also highlights the importance of factors such as user's attributes, service quality and travel attributes. In addition to these factors, a few factors such as frequency and scheduling, etc. can also be added for the route optimization of the city bus to have a more efficient bus system.

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BIG-Data Handling of Complete and Simultaneously Measured Road Condition Data

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Abstract. Preserving the economic value of the road infrastructure is essential to provide society with an operational, environmental, sustainable, and safe asset for road transport. In order to ensure the road capital is preserved and optimal maintenance strategies are carried out, it is required that the functional, as well as structural conditions of the road infrastructure, are known. Advanced and complete measurements of road conditions support the following of the UN's global goals for a sustainable future:

1. Accessibility and mobility, 2. Safety, 3. Environmental impact, 4. Air quality, 5. Noise, 6. Traffic safety.

An efficient, safe and sustainable road infrastructure can be maintained to meet the mobility needs of the next generation.

Optimizing the condition of the road infrastructure, to ensure it contributes to the fulfilment of the mentioned world goals, is complex. Therefore, it is necessary, in context, to look at how the condition of the road infrastructure, traffic flow and traffic pattern, together with environmental and economic challenges, affect the overall strategic goals.

For road owners, it is important to balance the positive and negative effects from a road network on society, through robust maintenance strategies, strategies which are supported by complete and efficiently (simultaneously) measured road condition data, and which, through intelligent BIG data handling processes, support and optimize operation and maintenance of the road infrastructure, in a cost-effective manner.

This paper shows how road assessment data, when handled and analyzed systematically, can support optimal management of the road infrastructure.

1 What Is Full Spectrum Road Condition Measurements

The unique capability of continuous high accuracy and high-resolution data enables infrastructure managers to more precisely identify areas where the pavement structure may be subject to failure.

By collecting structural and surface condition data simultaneously, at traffic speed, a more comprehensive assessment of infrastructure condition is provided. This enables an effective and intelligent management of road infrastructure assets.

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The Full Spectrum of Road Condition Measurements (Fig. 1) includes simultaneous measurements of:



Fig. 1. Full Spectrum, Road Condition Measurements, by Intelligent Pavement Assessment Vehicle.

- pavement strength
- cracking
- longitudinal and transverse road profile
- pavement macro texture
- road geometry
- geospatial position
- digital imaging
- asset inventory and condition
- ground penetrating radar

2 Value Decisions for Road Administrations

Increased knowledge of the road infrastructure condition improves the possibilities of the right activities being budgeted, planned, procured, and carried out effectively, in a way that is cost-effective in the long term.

The three major groups of models engaged in valuable decisions for road administrations are:

- **Strategy models**, – which identify, from approved standards, when intervention ought to be considered, and what maintenance solutions may be possible options.
- **Performance models,** – which project, how economical and physical parameters will perform into the future, taking deterioration and future intervention into account.
- **Optimization models**, – which from objective criteria, single out the optimum plan of intervention from the list of possible options, that can be carried out within the budget constraints.

The strategy models will set the limits when functional and structural criteria are exceeded, and rehabilitation options may be considered as possible solutions.

The performance models extrapolate present condition of structural and functional pavement parameters according to deterioration models, and describe how parameter values changed, when intervention is carried out.

However, the fundamentals for all the above models, are robust and valid data. Without the access to reliable data, the value-based management by the road administrations will be challenged and have a negative effect on the maintenance strategies.

3 Road Inventory in Big-Data Size

A well-maintained road infrastructure will correctly identify/prioritize intervention strategies to ensure an economically feasible use of resources. This is a vital element in keeping society in motion and, ultimately, make roads safer globally. Technologies for road infrastructure condition surveys continue to advance. Pavement conditions can now be collected continuously, at traffic speed without any disturbances for the traffic in general. The ability to perform Full Spectrum, Road Condition Measurements, brings greater awareness of the true resource needs for securing the values of the infrastructure through optimized maintenance and rehabilitation.

However, for better decisions to be made, more and better information is often required. This can be facilitated by using higher precision sensors to record present pavement conditions relating to both the functional and structural conditions.

Collecting full spectrum pavement condition data using sensors that can detect pavement surface characteristics down to millimeters, and pavement deflection under loading at a precision of μm, will generate data volumes in the range of 4 giga byte per km, for network level surveys.

To handle such amounts of data and turn the data into information that can be used for maintenance planning and forecast maintenance strategies, requires sufficient and robust tools.

4 Processing of BIG-Data

A robust processing software shall be able to provide full data processing, analysis and management capabilities on all imaging, profile, distress, and pavement data collected. It is important the software allows for full control and synchronization for all raw and processed data streams collected and enables analysis down to all incremental levels and up to all aggregative levels, as required (Fig. 2).

The process of handling BIG-data road surveys requires a significant amount of data control and data management, from the time the datafile has been received, until the data has been processed and delivered. Processing quality and clear targets for values to be delivered to support pavement management is an absolute must. These targets must be defined as part of the data processing plan. Standards and protocols are a must in securing correct data delivery and parameter reliability.

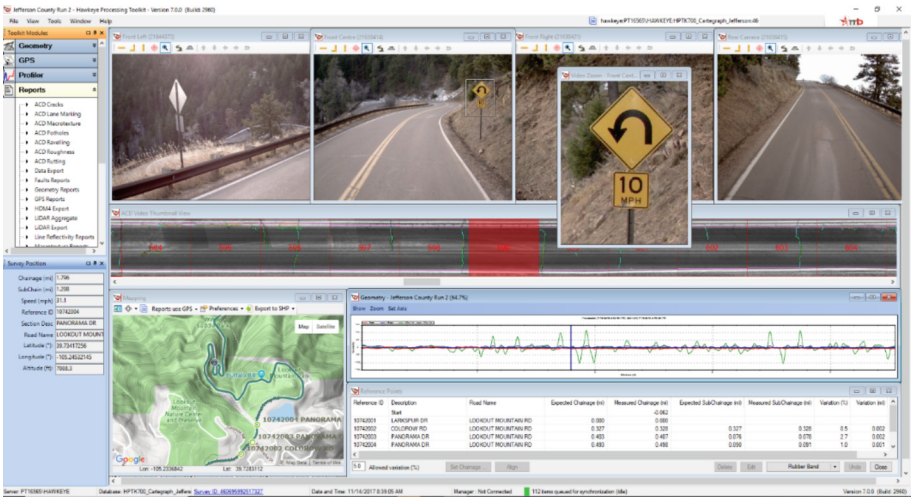


Fig. 2. An example of the data processing platform for handling of BIG-data.

5 Holistic Visualization and Usage of BIG-Data

Following the data processing comes the ability to interpret and use the vast amount of information in an easy and flexible way. The ability to locate road sections where apparent degradation needs to be attended, and the ability to be able to prioritize maintenance needs in a road network correctly, is key to be able to optimize budget spending and thereby save on needed financial resources for maintenance. To have the ability to swiftly compare data from year to year, is vital so degradation trends can be monitored, and long-term maintenance strategies can be established.

Being able to apply the correct filtering of data, in accordance with applicable pavement condition acceptance levels, provides a unique opportunity to locate road sections in need of maintenance. Figure 3 shows an example of how the location of troubled road sections can readily be identified by filtering of the data. In addition, by providing adjustable filtering tools, intervention levels can easily be changed to suit individual road administrations needs and requirement for condition standards.

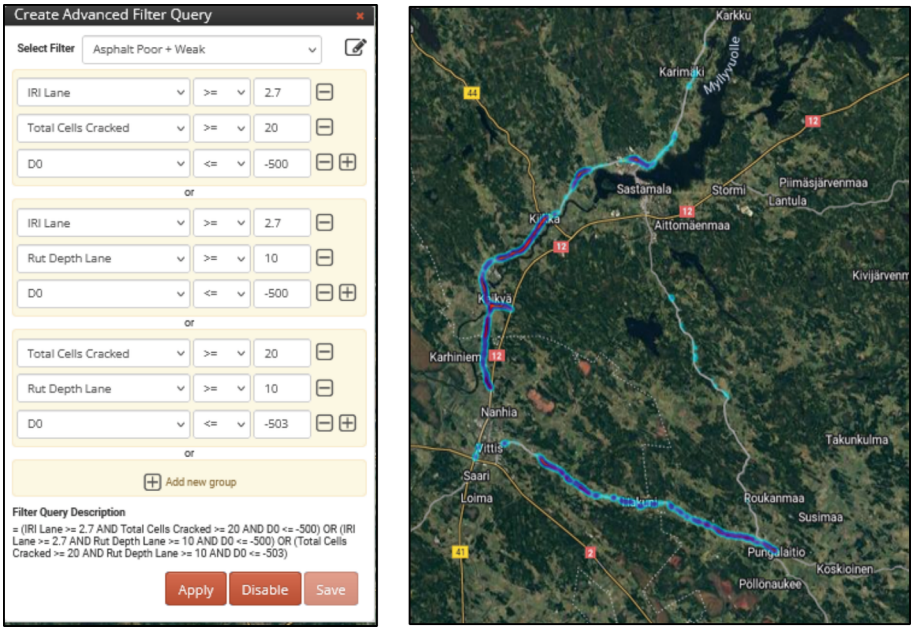


Fig. 3. An example of filtering road network data in BIG-data size to locate road where the pavement surface is poor, and the structure is weak. Image was created using the ARRB Systems Insight data viewer, reproduced with permission.

6 Holistic Visualization of Pavement Degradation Over Time

Being able to monitor pavement changes or degradation with time is often time consuming. The use of a visualization tool that incorporates the surveyed data in a robust and correct manner, will provide for strong analysis and investigations of pavement degradation over time. The ability to display multiple customer-defined data layers and multi-years of data side by side, gives the possibility to investigate and analyze any changes, being functional and structural, to the road infrastructure pavements that might occur over time. More so, a holistic view of road infrastructures condition provides the ability to cross reference the quality of the roads in the network. The cross referencing can be a first step towards prioritization of the maintenance needs and lead to further optimization of the available financial resources (Fig. 4).

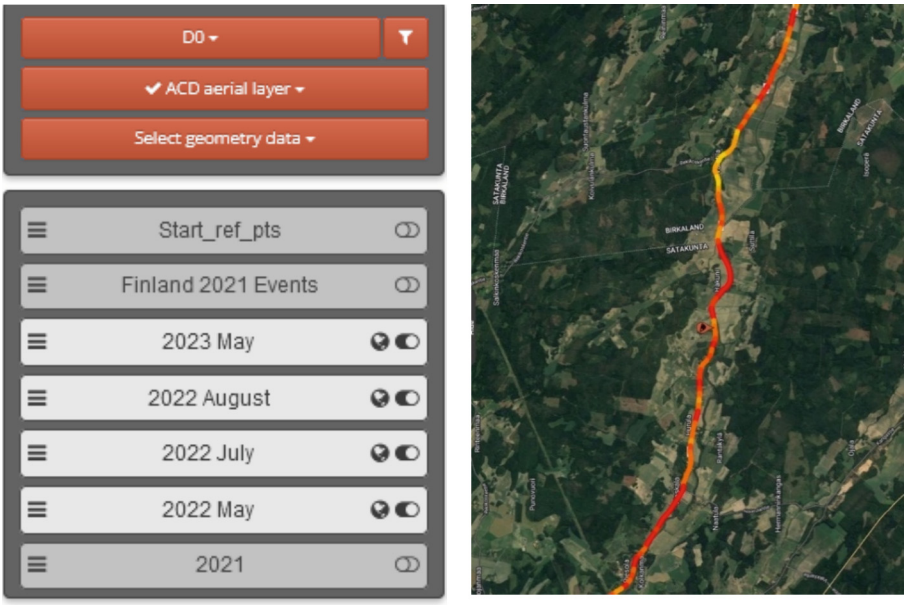


Fig. 4. Providing the ability to directly compare data from different measurements campaigns. Image was created using the ARRB Systems Insight data viewer, reproduced with permission.

Figure 5 shows, as an example, the seasonal effects on a road structural capacity, expressed by the deflection measured by the comprehensive assessment vehicle. The structural capacity, and it's changes due to seasonal impacts, has for many years been a subject of interest. However, a comprehensive way of studying this phenomenon has been challenging. With the introduction of Full Spectrum, Road Condition Measurements and the suit of data processing and viewing tools, it has become a much easier task to handle the vast amount of data in the BIG-Data sizes, which opens new potential ways of analyzing and investigating road condition data.

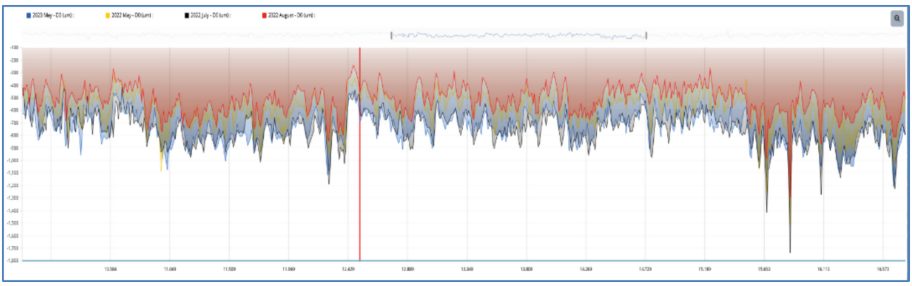


Fig. 5. Comparing one of the collected data sets, road bearing capacity.

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Healthy Sailing: Prevention, Mitigation and Management of Infectious Disease on Cruise Ships and Passenger Ferries

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Abstract. COVID-19 revealed a need to address known, expected and emerging infections on large passenger ships. HEALTHY SAILING (Project Nr: 101069764) provides an integrated, methodological approach to address this need. The three-year project is establishing an evidence-base for mechanisms facilitating infection spread onboard passenger ships and effectiveness of prevention, mitigation and management (PMM) measures. Foundational activities in the first year

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of implementation include systematic reviews, epidemiological studies, surveys and focus groups to identify risk factors, infection frequency, outbreak dynamics, and barriers to compliance with PMM measures. Mathematical models are being developed to predict infection spread onboard and evaluate measures' impact. Computational Fluid Dynamics modelling explores airborne respiratory pathogen dispersion in ventilated spaces of cruise environments. An Integrated Health E-surveillance System is under development to perform real-time syndromic, laboratory and environmental health surveillance onboard, and will feed an AI Intelligence Immune System to produce health threat alerts, characterize threat levels and recommend/monitor health measures. A toolkit monitoring cleaning and disinfection is being prepared to improve effectiveness of current practices onboard, while a toolkit for technology-induced behavior change is underway, to improve hand hygiene practices onboard.

Keywords: Maritime health · infectious disease epidemiology · cruise · ferry · expedition ship · traveler

1 Introduction

Large passenger ships can be characterized as semi-closed, crowded environments with frequent interaction among travelers from different origins. Infectious diseases may rapidly spread if effective detection and control measures are not in place. Cruise ships' health and hygiene programmes traditionally focused on gastroenteritis prevention and control, through implementation of the United States Centers for Disease Control and Prevention (CDC) Vessel Sanitation Program (VSP) [1]. Meanwhile, European guidelines for passenger ships addressed prevention and management of infectious diseases including gastroenteritis, Legionnaires' disease, vaccine-preventable diseases and influenza [2]. Although health and hygiene standards were rigorously implemented, cases and outbreaks still occurred onboard. COVID-19 demonstrated the inability of preparedness and response plans to respond to new emerging diseases effectively. Expected and extraordinary events such as COVID-19 impact the health of travelers, communities and the entire passenger shipping sector, potentially creating severe economic consequences.

The Horizon Research and Innovation Action HEALTHY SAILING (Project Nr: 101069764) provides an integrated approach to address known, expected and new emerging infectious diseases that may occur on large passenger ships [3]. Launched in 2022, the three-year project unites 24 partners from 12 countries comprising universities, governmental institutions, research institutes, a non-governmental organization, ship and engineering companies. Our aim is to describe how HEALTHY SAILING will introduce innovative, evidence-based, cost-effective and tested measures for infectious disease prevention, mitigation and management (PMM) in large passenger ships, while presenting the project's preliminary outcomes after one year of implementation.

2 Methods

HEALTHY SAILING applies a four component multi-method approach differentiated for cruise, large ferry and expedition vessels. Multi-disciplinary expertise is harnessed from experts, policymakers and target groups. Expert groups for epidemiology, artificial intelligence (AI), social sciences, legal aspects, modelling, port operations, hygiene and ship design have been established. These groups contribute to designing the project's foundational activities and will be consulted during all project phases.

The second component consists of evidence accumulation to establish a scientific foundation for future activities. Systematic reviews were designed in accordance with PRISMA 2020, epidemiological studies, surveys and focus groups were conducted to identify: risk factors, infection frequency and outbreak dynamics onboard; infectious disease risks during the entire traveler journey; barriers and facilitators in adherence with PMM measures, and ensure project outputs are compatible with ship operation/design regulations. An analysis of the infection chain differentiated by ship type is being conducted, to identify critical points where PMM measures are essential to interrupt the infection chain for each transmission mode. Mathematical modelling is being conducted to understand drivers of infectious disease spread on ships, and evaluate the impact of existing and novel control measures onboard. Computational Fluid Dynamics (CFD) modelling is being used to explore airborne respiratory pathogen dispersion in mechanically ventilated spaces of cruise environments, and the effectiveness of mitigation methods to reduce infection risk. Cost-benefit analysis will be conducted to assess introduced PMM measures.

PMM measures are being developed using AI and machine learning techniques, and technology-induced behavioral change strategies will also be used for developing PMM measures. Measures will be validated by pilot-testing IT and technological outputs within existing ship systems, and conducting technological demonstrations both onboard ships and at ports. Several intervention studies onboard passenger ships will be conducted to assess the impact of introduced PMM measures.

Finally, project outputs will be integrated into appropriate contexts through the development of evidence-informed guidelines, a blended learning training toolkit for travelers, and measures to ensure ship-port interoperability.

3 Results

3.1 Establishing a Scientific Evidence-Base

The scoping review conducted identified over 600 documents on infectious disease PMM in large passenger ships and at ports, including specificities of medical operations in expedition vessels. The scoping review of scientific literature, guidelines, regulations and policies provided knowledge related to mechanisms facilitating infection spread on board large passenger ships, and helped to better understand effectiveness of PMM measures implemented. Scoping search results were collated into two publicly available searchable inventories, as resources for the maritime health and scientific communities, and to support development of future project deliverables [4].

A systematic review and epidemiological studies are underway to generate evidence about mechanisms facilitating infection spread onboard passenger ships, and to understand effectiveness of measures implemented, considering all infectious diseases and vessel types. A specific systematic review and meta-analysis on preventing and controlling Norovirus on cruise ships has been conducted (manuscript under publication). Moreover, a systematic review to understand capacities and interactions of passenger ships and land-based operations is nearing completion. Two additional systematic reviews were conducted to understand behavioral, social and cultural aspects affecting infectious disease spread among passengers and crew (manuscripts under publication).

Focus group discussions were conducted among specific groups of crew with two cruise ship companies. The aim was to explore the perspectives of crew– from different ranks, positions and backgrounds – on how to improve compliance with PMM measures such as handwashing, symptom reporting and isolation/quarantine. Moreover, focus group discussions provided insight into barriers that crew and passengers face in complying with measures, and preferable strategies to improve compliance.

A report has also been prepared regarding compatibility and interoperability of project outputs within existing maritime operations onboard large passenger ships.

3.2 Computational Modeling of Droplet and Aerosol Dispersion in Ship Environments

An extensive experimental trial was conducted onboard a live cruise voyage. Measures of aerosol and droplet dispersion, as well as CO2 along with thermal comfort parameters were taken under controlled conditions within selected cruise ship locations, using different ventilation scenarios. Experimental data onboard were collected by using aerosol and CO2 sensors in order to: identify aerosol and CO2 levels inside those spaces; find thermal comfort level inside the spaces; and build a set of validation data for improving and tuning computational modelling of infection risk in those spaces.

3.3 Systems to Enhance Early Detection Capability of Public Health Threats and Risk-Based Proportionate Public Health Response

An infectious disease syndromic surveillance system for large passenger ships is being completed, with syndromes for surveillance and syndrome definitions defined. The system is being pilot-tested onboard a cruise ship to ensure interoperability and practicability.

This syndromic surveillance system will provide input to the Integrated Health E-surveillance IT System (E-SS) for infectious diseases. The E-SS is currently under development, and is being designed to perform real-time syndromic, laboratory and environmental health surveillance to support early health threat detection onboard. Heterogeneous data sources have been defined as inputs into E-SS, which will provide analytics related to epidemiological indicators, disease threshold levels and epidemic curves. E-SS will feed the AI Intelligence Immune System (IIS), a prototype currently

under development for health threat alerts. The IIS will support health measures decision-making by producing alerts and describing the threat, providing options for health measures to be implemented in response to a specific threat, and provide follow-up functions for monitoring measures implementation.

3.4 Toolkit for Systematic Monitoring of Surface Cleaning and Disinfection

A toolkit for systematic monitoring of surface cleaning and disinfection is being produced to further improve hygiene standards onboard and the effectiveness of current cleaning and disinfection practices. A detailed intervention mapping has been conducted through observing the application of cleaning and disinfection practices onboard different areas of two cruise ships. Through this mapping, a more in-depth understanding was gained of daily cleaning and disinfection practices as they are applied in a real-world setting, with useful insights into appropriate training approaches for crew. Critical points throughout the cleaning and disinfection process were identified with potential interventions also identified to improve practices and define key performance indicators.

3.5 Technology Induced Behavioral Change in Hand Hygiene Management

A four-arm intervention study is being conducted onboard a cruise ship, to identify effective measures to improve hand hygiene practices onboard and assess differences between ship areas regarding contamination rates and hand hygiene practices. Two of the four study arms have been completed, including the application of innovative surface-disinfection methods onboard. This will be followed by a study arm introducing a hand hygiene monitoring system and an arm including onboard training of crew members.

3.6 Evidence-Based Guidelines for COVID-19 PMM Onboard Large Passenger Vessels

Evidence-informed guidelines for COVID-19 in routine operations of ferries and cruise ships have been prepared; the draft document will be publicly available for consultation with the passenger shipping industry. Guidelines include everyday PMM measures, outbreak response and preparedness for pandemics.

3.7 Harmonization of Public Health Practices

The framework for an International Scientific Committee for Infectious Diseases related to Passenger Ships has been established, to exchange best practices and harmonize practices globally for proportionate public health response measures. The Terms of Reference for the panel were defined outlining the panel's scope, composition, and methodology for decision making. Members of the panel are representative of different vessel types, geographic regions and areas of expertise.

4 Discussion and Conclusions

Significant scientific and societal impacts are expected from the project's foundational activities including systematic reviews, epidemiological studies, focus group discussions and intervention studies. These activities have produced new evidence and insights into how infectious diseases spread onboard different types of passenger ships, including risk factors and transmission dynamics. Furthermore, they help consortium partners gain a deeper understanding of how effective measures are for preventing and controlling infectious diseases in large passenger ship settings. This evidence will be used to inform the development of specific PMM measures.

Evidence collected during the first year of HEALTHY SAILING identified in real-world settings, the facilitators and barriers for implementing PMM measures. These activities helped project partners understand the complex structural and behavioural reasons why compliance with different measures can be difficult to achieve among both passengers and crew. Through intervention mapping, intervention studies and focus group discussions, project partners were better able to identify training needs and areas where risk communication for travellers must be improved. The results of these activities are guiding partners for the next phase of the project, to develop PMM measures, guidelines and training that are evidence-informed and risk-based.

HEALTHY SAILING project outputs are expected to help the shipping industry improve the quality of passenger shipping services brought to society, to facilitate recovery from COVID-19, to prepare for future pandemics, and make the passenger shipping sector safer, more resilient, competitive and efficient.

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Parameters for Assessing Public Transport Accessibility for Indian Cities

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Abstract. Public transport plays a crucial role to meet the growing demand of sustainable and equitable cities. But merely providing the service does not serve the purpose. It should also be equally accessible to all. PTAL is one such tool to assess accessibility of existing PT system which uses 4 primary parameters of POIs, SAPs, walk network and frequency. However, studies suggest that there are other parameters as well which impact accessibility. Therefore, this research focuses on incorporating build cover, building density and land use in the standard tool. Hence, the revised tool is capable of providing accessibility and priority of the area for the service. The study also brings out how PTAL results differ for million plus cities and smaller cities.

Keywords: Public transport · Accessibility · PTAL · GIS

1 Introduction

Public transport is generally considered a feasible travel alternative in developing countries. Unfortunately, it often gets overlooked in favor of private transportation modes. This is often driven by perceived advantages of the latter like improved facilities, last-mile connectivity, privacy, and safety. However, one of the main reasons for choosing private mode is the poor accessibility of PT. Nevertheless, improving accessibility has the potential to influence people's choice of shifting toward PT as the preferred mode of travel. Therefore, it is important to evaluate the accessibility of PT services and ensure that it is equally distributed among the population.

2 Literature Review

With the growing awareness of sustainable development, people have realized the significance of PT. However, studies have proven that merely providing the service and a good road network would not encourage PT usage. People who are deprived of access to PT have fewer opportunities resulting in social exclusion [1]. Therefore, PT also marks a symbol of social equity, and it is important to ensure that PT is equally accessible to all. But, how can we measure accessibility?

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2.1 PTAL (Public Transport Accessibility Levels)

There are several tools available to measure and map the accessibility of existing PT systems. Some of the widely used tools are TTSAT, LUPTAI, and Public Transport Accessibility Levels (PTAL). This research focuses only on the PTAL tool. PTAL "measures the accessibility of reaching the nearest service access point from the origin within a defined maximum travel time." It was developed by the London Borough of Hammersmith and Fulham in 1992 and was adopted as a standard method for evaluating existing PT systems by Transport for London in 2004 [2]. It uses four parameters- POIs (Points of Interest) i.e., the origin of trips; SAPs (Service Access Points) including stops and stations; walk network- from POI to nearest SAP, and frequency of service. It has been adopted by various countries across the globe [3].

2.2 Case Studies

Numerous cities have applied PTAL to assess their current PT system to understand its relevance and test its accuracy. One such study conducted for Montevideo suggested that travel time and fare also have a significant influence on accessibility. The study also indicated that people's preference to choose PT is also influenced by the quality of service provided which includes availability of infrastructure, universal design, level of comfort, safety, cleanliness, etc. [4]. In another study of the Melbourne region, PT was evaluated using PTAL, PTAI (Public Transport Accessibility Index), and SI (Supply Index). It was found that SI provides the most accurate results for areas like Melbourne. The research also highlighted the importance of considering population density when planning for PT systems. It also concluded that accessibility cannot merely be analyzed based on residential land use [5]. It discovered notable differences between the observed and the expected PTAL values as well. Can this gap be reduced by incorporating more parameters into the tool? In the case of India, PTAL analysis has been conducted for only a few million plus cities. No accessibility assessment has been conducted for comparatively smaller developing cities.

Therefore, this research aims to conduct PTAL analysis for smaller cities and also revise the standard tool to minimize the gap between observed and expected.

3 Study Areas

For this research, three sites have been shortlisted based on population (<5 lakhs), area, and availability of structured PT and IPT systems. These are Satna, Rewa, and Singrauli cities of the eastern region of Madhya Pradesh state, India. Satna holds a population of 3.38 lakhs (projected 2022) in a planning area of 110.40 sq.km. It has a structured bus system functional since 2020 operating in 4 routes. The city also has IPT serving the same routes. Rewa is one of the oldest cities of the state with an estimated population (2022) of 3.24 lakhs spread over an area of 146.15 sq.km. It has structured a city bus system since 2018 with 2 operational of 6 proposed routes. However, IPT plays an important role in the city's connectivity by running along all 6 routes. Singrauli, the energy capital of India, has a population of 2.74 lakhs (projected 2022) in an area of 838.18 sq.km. It has a city bus functioning along 2 routes same as IPT.

4 Data Collection and Analysis

Data input like PT/ IPT routes, stops, frequency, etc. has been collected from respective municipal authorities. An observational survey was conducted to register the existing condition of infrastructure facilities and services at the stops and stations. Most of the stops either do not have bus shelters or are encroached on Satna and Rewa. On the other hand, stops in Singrauli are in decent condition. A primary survey was also conducted to record PT/ IPT user's perceptions about the quality of service provided. It has been analyzed that people opt for PT due to its low fare whereas IPT is opted for its easy boarding/ alighting facility.

4.1 Standard PTAL Analysis

PTAL analysis has been conducted for all three sites using the standard method. Whole of the planning area is divided into hexagonal grids of 1 ha and centroid of ach grid is treated as POIs. The data inputs like walking speed, maximum walking distance, and reliability factors are borrowed from case studies of Surat and Delhi.

PTAL has been generated for PT and IPT separately to assess the accessibility of each mode. Later, the accessibility of both modes is summed up to get the overall accessibility of the city.

It is evident from Figs. 1 and 2 that all the selected sites have very poor accessibility of both PT and IPT. Except for the PT of Satna, the rest of the modes have <50% accessibility in the respective cities. The following observations have been drawn from the above analysis:

1. Overlapping routes within and among modes increases accessibility.
2. More is the route coverage, and better is the overall accessibility.
3. Reliability has a greater impact on the accessibility index (AI) than the frequency of services.

On analyzing deeper into the AI of the sites, it has been found that the main reason for overall poor accessibility is the consideration of planning area. Since all the study areas are smaller cities, the majority of the land is covered under vegetation, forest, or mines. When accessibility is assessed for the city as a whole, it even considers such non-trip-generating areas.

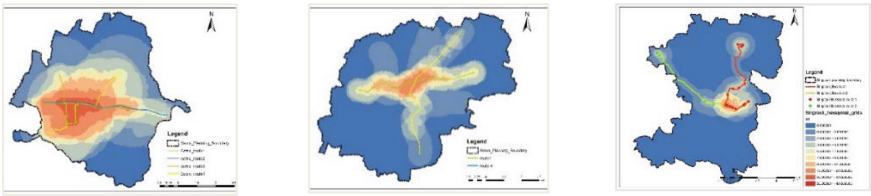


Fig. 1. PTAL of Satna, Rewa and Singrauli.

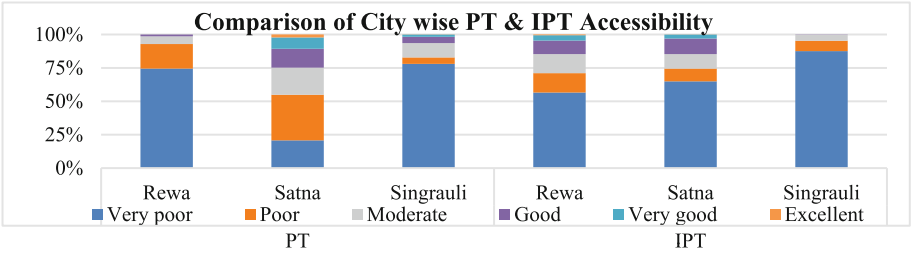


Fig. 2. Comparison of city-wise PT & IPT accessibility.

4.2 Revised PTAL

In smaller cities, where the frequency of PT is unable to cater to the demand, IPT plays an important role in providing accessibility to all. Therefore, IPT stands should also be considered as SAP in the tool.

To avoid any void areas in evaluating the overall accessibility of the city, it is being proposed to only consider build cover. That is AI should only be calculated for areas that consist of settlements. It will not only reduce time and effort but also improve the accuracy of the tool. On incorporating built cover as a parameter, it has been evaluated that poor accessibility is deducted by 20%, 14%, and 18% for Satna, Rewa, and Singrauli respectively.

However, adding just built cover results in weighing all densities equally. It is impossible to provide doorstep service to all the settlements. To cater to a larger population, the said service must cover denser areas of the city. Therefore, another layer of building density is added to the revised tool, with the assumption that population and building density are directly proportional. For implementing this in the study areas, building density has been categorized into low, medium, and high based on normal distribution. And, PTAL is generated for each density independently for all the cities. It has been analyzed that density is directly proportional to accessibility (Fig. 3).

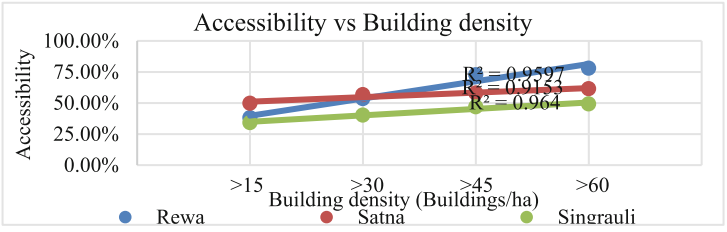


Fig. 3. Comparative analysis of accessibility Vs building density.

As areas with different densities cannot be considered the same, similarly different areas with varied potential of trip generating and attracting capacity cannot be treated equally. Hence, a layer of land use is added in the revised PTAL tool. For doing so, PTAL has been generated for major land uses- residential, commercial, institutional, and industrial (in the case of Singrauli). It has been analyzed that commercial and institutional

areas have slightly better accessibility to the existing service than residential areas in all three cities.

Figure 4 is an example of incorporating further layers into the standard PTAL tool. It is important to note that the values of AI are not being recalculated, but are only counted for certain regions. Figure 5 shows the addition of identified parameters at different steps of the PTAL.

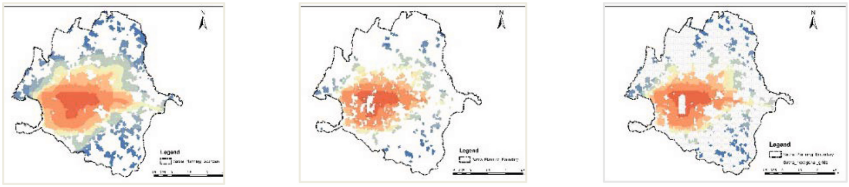


Fig. 4. Adding build cover, medium building density, and major land uses for Satna.

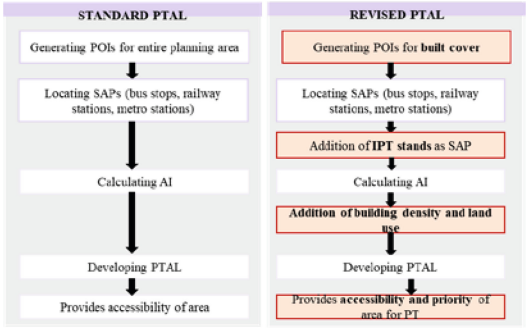


Fig. 5. Comparison of Standard and Revised PTAL tool.

4.3 Utilizing Revised PTAL

By using the revised PTAL tool, it becomes easier to evaluate PTAL for different land uses and densities with reduced efforts. To improve the outcome, these parameters can be clubbed together to identify priority areas for proving the service. Priority areas here is referred to as the areas which are expected to generate high travel demand. These are categorized into 3 classes- Priority I (Highest), II, III (Lowest).

Following are the assumptions made for identifying these priority areas:

On the basis of above assumptions (Table 1), each grid is scored by the following

$$\textit{Grid score} = \Sigma\,(\%\ \textit{area of building density}) * P + \Sigma\,(\%\ \textit{area of land use}) * P \quad (1)$$

Using the above formula, priority areas have been identified for each city. These priority scores when compared with AI makes it easier to analyze if the existing PT/ IPT system is able to cater all high priority areas. Service routes in Satna are well planned to cover

majority of the priority areas whereas if all the routes are operational in Rewa, PT will be able to cater high demand areas. In Singrauli, no priority I areas are identified because industrial area has low building density. However, even the priority II areas are not being covered by the existing PT system (Fig. 6).

Table 1. Assumptions for priority area identification.

	Priority Score (P)	Ranges	Building Density	Land Use
	I	>4	High	Institutional/ Industrial
	II	2.01 - 4.00	Medium	Commercial
	III	0.00 – 2.00	Low	Residential

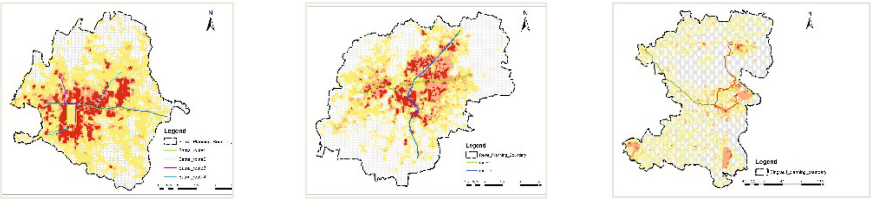


Fig. 6. Priority area identification for Satna, Rewa and Singrauli.

Therefore, such analysis conducted using revised PTAL tool can be beneficial for future planning. It is important that the modifications suggested are utilizable and applicable on ground. For example, new routes or diversion in the existing routes can be proposed to cover all the priority areas of Singrauli. Also, the routes which connect majority of the priority areas can be considered to be serving higher demand and hence, profit-making. In case of limited funding sources, profit and non-profit-making routes can be identified and funds can be allocated accordingly. The identified priority areas can also help in land use planning or TOD. Or city's growth can be planned by planning priority areas in the desired direction.

5 Conclusion

It is important that PT is equally accessible to all. There are several tools to measure accessibility, one being PTAL. It is a well-established tool using 4 primary parameters for assessment. However, this paper suggests to make certain modifications by adding more parameters namely, build cover, building density and land use in the tool to yield more accurate outcomes. Revised tool provides priority along with accessibility. It can be developed as GIS plugin for practical application in the professional field.

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Optimizing Transit Connectivity: A Synchronization Model Applied to Porto Campanhã

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Abstract. In the context of transport networks, synchronization techniques refer to a set of optimization approaches whose output is the timetables of different lines obtained through the minimization of transfer waiting time and vehicle bunching. Accordingly, synchronization techniques can improve the overall quality of transfers in transport systems by making them smoother for passengers. The synchronization of transport lines at strategic locations improves the system's overall connectivity and integration and, ultimately, its attractiveness to passengers. This work aimed to synchronize strategic transport lines connecting Porto to other cities, having Porto as the only focal point. The morning peak hours were selected as the analysis period. A synchronization model already proposed in the literature was adapted and applied to this case study. The results include the comparison between the real and synchronized timetables and the sensitivity analysis of the solutions obtained by changing headway and time window parameters.

Keywords: Public Transport · Timed Transfer System · Timetable Optimization · Synchronization

1 Introduction

In the context of transport networks, synchronization techniques refer to a set of optimization approaches whose output is the timetables of different lines obtained through the minimization of transfer waiting time and vehicle bunching. Accordingly, synchronization techniques can improve the overall quality of transfers in transport systems by making them smoother for passengers. The synchronization of transport lines at strategic locations improves the system's overall connectivity and integration and, ultimately, its attractiveness to passengers.

This work sought to synchronize strategic train lines connecting Porto to nearby cities, having Porto as the central focal point. The study centers around the operations of "Terminal Intermodal de Campanhã (TIC)", a critical hub integrating different transportation means. The morning peak hours were selected as the analysis period.

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This study included collecting and analyzing the timetables currently used by the lines under study. Data was gathered from Comboios de Portugal (CP), considering train routes passing through or terminating at the TIC during the designated time periods.

A synchronization model already proposed in the literature was adapted and applied to this case study. The results include the comparison between the real and synchronized timetables and the sensitivity analysis of the solutions obtained by changing headway and time window parameters.

2 Literature Review

Timed Transfers is a Synchronization Timetabling technique in which vehicles on two (or more) routes meet simultaneously at focal points, at regular intervals, to exchange passengers smoothly. The goal is to reduce transfer waiting time as much as possible by allowing many passengers to transfer simultaneously. The time window in which vehicles simultaneously meet at a focal point is called the contact period.

Several cities have been implementing Timed Transfers, even if empirically, since the early 20^{th} century. Nelson, Brand, and Mandel [4] reported a survey of 39 transport systems using Timed Transfers in the USA. Petersen [5] reviewed the application of Timed Transfers in rural areas of Switzerland. Salzborn [6] proposed one of the earliest published optimization models addressing Timed Transfers, including a deterministic model to synchronize a lineup network and a model to synchronize each focal point with other local routes, following a uni focal setting.

Ceder and Tal [1] proposed a model that maximizes the number of simultaneous arrivals at focal points. Many other synchronization models have been proposed and applied in the literature. The model by Ibarra-Rojas and Rios-Solis [3] maximizes the number of simultaneous run arrivals at focal points and minimizes bunching, whose constraints ensure that the first and last runs of each route depart within the planning period while separating consecutive runs of each route by a minimum and maximum headway, and considering simultaneous run arrivals as feasible if their contact period range complies with previously defined time-windows. Other relevant work include Ibarra-Rojas, L'opez-Irarragorri, and Rios-Solis [2].

3 Synchronization Model

This study applied an adapted version of the synchronization model proposed by [3]. The main difference between the model considered in this work is that we did not include the constraint $T - H_i \leq X_{i,f_i}$. Accordingly, the model used in this study is defined as follows:

$$\max \sum_{i}\sum_{j}\sum_{b}\sum_{p}\sum_{q} Y_{ijbpq} \tag{1}$$

$$\text{s.t.} \tag{2}$$

$$X_{i,1} \leq H_i \tag{3}$$

$$X_{i,f_i} \leq T \tag{4}$$

$$X_{i,p+1} - X_{i,p} \leq H_i \tag{5}$$

$$X_{i,p+1} - X_{i,p} \geq h_i \tag{6}$$

$$(X_{j,q} + t_{j,b}) - (X_{i,p} + t_{i,b}) \geq w_b - M \cdot (1 - Y_{i,j,b,p,q}) \tag{7}$$

$$(X_{j,q} + t_{j,b}) - (X_{i,p} + t_{i,b}) \leq W_b + M \cdot (1 - Y_{i,j,b,p,q}) \tag{8}$$

$$X_{i,p} \in \mathbb{N}^0, \forall i \in I, p = 1, \ldots, f_i \tag{9}$$

$$Y_{i,j,b,p,q} \in 0, 1, \forall i \in I, j \in J(i), b \in B_{ij}, p = 1, \ldots, f_i, q = 1, \ldots, f_j \tag{10}$$

where: $X_{i,p}$ is the departure time of each line i in each run p (decision variable); $Y_{i,j,b,p,q}$ is a binary decision variable returning 1 when run p from line i and run q from line j are synchronized at node b, and 0 otherwise; I represents the set of lines of the transport network; $J(i)$ represents the set of lines that may have synchronization nodes with line i (for each line $i \in I$); B_{ij} represents all the synchronization nodes for lines i and $j \in J(i)$; T is the planning period (in minutes); f_i is the number of trips needed to fulfill the demand of each line $i \in I$; $t_{i,b}$ represents travel time from the terminus of each line i to each synchronization node b; The interval $[w_b; W_b]$ is the waiting time window for each node b; h_i and H_i are the minimum and maximum headway times between runs of line i.

4 Case Study

The "Terminal Intermodal de Campanhã (TIC)" opened to operation in 2022. This is an intermodal terminal built to provide the city of Porto with a platform connecting transport operations of both public and private operators of different transport means, including urban and long-distance trains, metro, buses, and taxis. In addition to regional transportation, the terminal serves as an important connector to integrate train lines covering the entire country and more, from Lisbon to Spain.

Having this terminal as a central focal point, the synchronization of two train networks was studied, as represented in Fig. 1.

Following a lineup layout, the first network considers the connection between Braga, Porto, and Aveiro. Following a star layout, the second network considers the operations between Porto and four nearby cities (Vigo, Braga, Marco de Canaveses e Aveiro). The train lines connecting Porto to each nearby city are also represented in Fig. 1, where the first network includes four lines and the second network eight lines. Each line either starts or ends its operations in Porto.

The daily timetable of a workday can be divided into several planning periods where demand is considerably homogenous and within which the travel behavior is assumed to be similar enough so that the period can be studied as a whole.

This case study considers the analysis of morning peak hours, corresponding to the period of workdays starting at 08h00 and ending at 10h30 (i.e., 150 min).

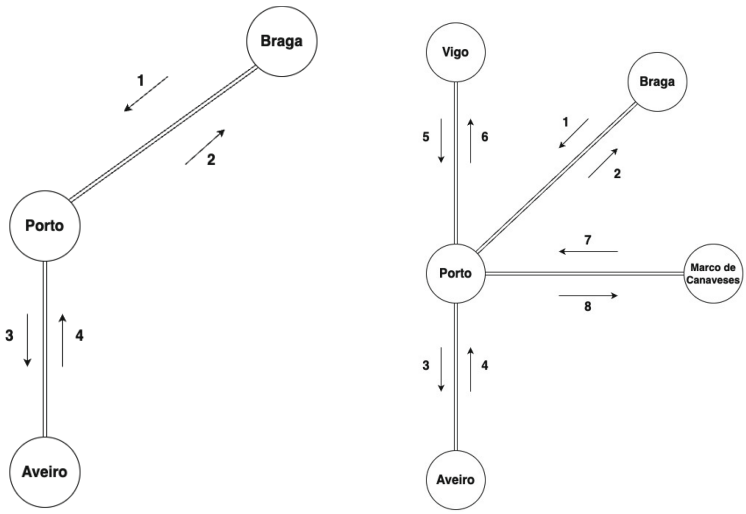


Fig. 1. Representation of the transport networks studied.

5 Results

5.1 Base Scenario Vs. Real Timetables

This section compares the timetables currently used by operators and those obtained with the synchronization model. The parameters for the base scenario were meticulously selected to ensure optimal vehicle synchronization while providing passengers with enough time to transfer between different lines. Accordingly, the base scenario considered the following values: $w_b = 5, W_b = 5$.

Compared with operator timetables, the base scenario could get two synchronized runs for the line-shape network and 14 for the star-shape network. Figure 2 shows the space-time diagram of the real and synchronized timetables for the star-shape network.

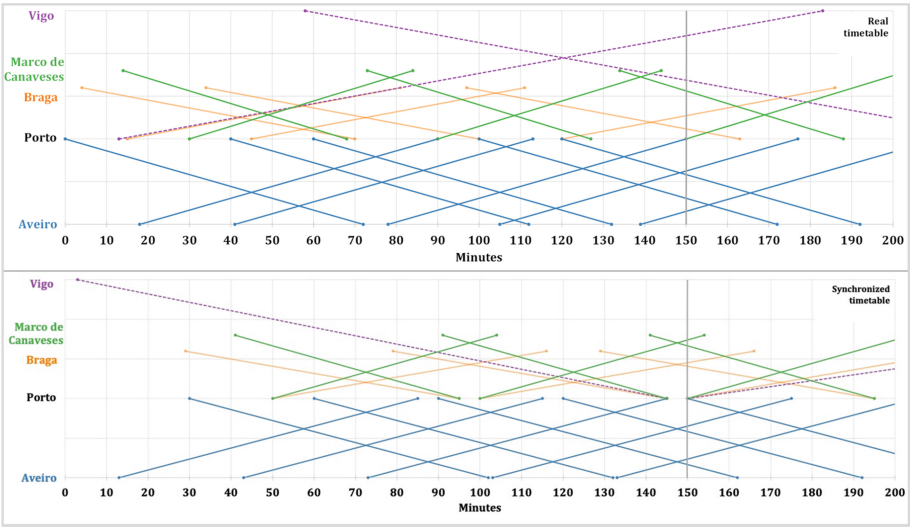


Fig. 2. Space-Time Diagrams of real (top) and synchronized (bottom) timetables for the star-shape network.

5.2 Sensitivity Analysis - Changing Parameters w_b and W_b

This study analyzed five scenarios to understand the sensitivity of the model to parameter W_b considering the following values [12, 15, 18, 20], corresponding to scenarios A to D. The results are summarized in Table 1. Accordingly, extended waiting time windows led to increased synchronized runs due to an expanded solution space. With $W_b = 15$, scenario B returned 4 and 18 synchronized runs for the line and star-shape networks, respectively.

Table 1. List of the scenarios tested and the corresponding changing parameters, alongside the number of synchronized runs obtained in each case.

Scenario	Changed parameters	Line-Shape Network	Star-Shape Network
Base	None	2	14
A	$w_b = 5; W_b = 12;$	2	14
B	$w_b = 5; W_b = 15;$	4	18
C	$w_b = 5; W_b = 18;$	4	18
D	$w_b = 5; W_b = 20;$	4	18
E	$h_i^E = h_i - 5; H_i^E = H_i + 5;$	4	18
F	$h_i^F = h_i - 10; H_i^F = H_i + 10;$	4	20
G	$h_i^G = h_i - 15; H_i^G = H_i + 15;$	5	21

5.3 Sensitivity Analysis - Changing Parameters h_i E H_i

For this sensitivity analysis, the headway limits were systematically modified by 5, 10, and 15-minute increments corresponding to scenarios E to G. The results are detailed in Table 1. The results show that increasing the range for possible headway values for each line in the model increased the number of synchronized runs.

6 Discussion and Conclusions

This study applied a synchronization model to the case study of Porto Campanhã, considering a single focal point. The analysis of results showed that increasing the waiting time windows in the model increased the number of synchronization opportunities, as expected. Moreover, increasing the range for headway values in each line increased the number of synchronization opportunities.

Although we observe several vehicles arriving and leaving simultaneously in the solutions obtained, this does not represent a congestion problem since the different lines operate on independent platforms.

Future research can include the study of additional optimization objectives, such as the total number of synchronized passengers, and enhancing the model's overall ability to address the analyzed system's specificity.

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Digital Transport Infrastructure

Test Vessel Development for Autonomous Maritime Research

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Abstract. Digitalization and climate neutrality are the current global mega trends, in which autonomous transportation can provide solutions. This paper presents the Turku University of Applied Sciences test vessel eM/S Salama and the related remote operations center for autonomous maritime research. We briefly describe the status of autonomy in maritime environments, the related technologies, our test infrastructure and the future research directions. The test vessel sensoring system is also used to collect data, which will be published in annotated open access datasets for machine learning.

Keywords: Autonomous maritime operations · machine learning · sensoring · remote operations · connectivity

1 Introduction

Digitalization and increased levels of autonomy in transport are expected to take leaps forward in the coming years. This development can help create more sustainable, safer, more efficient, and more reliable service chains following the two global megatrends: digitalization and climate neutrality. With constantly growing maritime traffic, safety and security are essential. Autonomous operation of maritime vessels is globally recognized as a potential solution to the safety and security issues. International Maritime Organization (IMO) has defined four levels of autonomy [1], the fourth level being the full autonomy. To enable fully autonomous operation, for example methods to define the ship state, smart path planning and navigation, collision avoidance, remote monitoring and control, wireless communication systems, sensors and machine learning algorithms to provide situational awareness are needed.

Turku UAS is building a test vessel with aluminium catamaran hull, which is 6.8 m long and 3 m wide and uses electric propulsion. In parallel, we have developed a remote operations center, which can be used to control and monitor the test vessel remotely over wireless links with sufficient data rate and latency, such as mobile networks or satellite connection. Even when the vessels are intended to be operated autonomously, they need to be at least remotely observed, and there needs to be a means to take control of the vessel remotely. Therefore, the

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remote operations center is considered an integral component of an autonomous vessel.

Reliable communications link between the vessel and the shore is required to enable remote monitoring and control. As vessels can move in diverse environments, hybrid connectivity systems are considered the best solution. Hybrid connectivity translates into utilizing several different connectivity networks (e.g. 4G, 5G, VDES, Satellite) for data transmission.

In recent years, there have been several studies and trials on autonomous vessels and ferries [2] [3] [4] [5] [6], but further research and trials are still needed to make full autonomy a reality. Our test infrastructure can be used to test new technologies for autonomous operations to see if they are ready for industrial practice and if they can be used in a safe and efficient manner. The infrastructure can be used to trial novel machine learning algorithms for situational awareness and smart navigation, and simultaneously assess the trustworthiness of AI in real-life scenarios. We are also developing digital twins of the test vessel and ROC for different purposes. This allows us to link physical and virtual test environments to cover extensive number of different test scenarios.

This paper is organized as follows: Sect. 2 describes the situational awareness systems needed for autonomous operations, Sect. 3 introduces our test vessel and remote operations center (ROC), while Sect. 4 gives the concluding remarks.

2 Situational Awareness for Autonomous Operations

It is evident that autonomous vessels require precise situational awareness for safe and secure decision-making and collision avoidance. However, the maritime environment presents challenges for object detection using computer vision, such as changing light and weather conditions, view distances, and sea waves. No single sensor can ensure accurate and reliable data in all situations, but combining or fusing data from multiple sensors can significantly enhance the accuracy and reliability. In sensor fusion, data are combined from multiple high-bandwidth perceptual sensors such as visible-light and thermal camera arrays, radars, and Lidars. Features can be extracted and classified from the obtained data by using for example deep neural networks. This semantic information can then be combined with spatial information from positioning sensors such as Inertial Measurement Unit (IMU), Global Navigation Satellite System (GNSS), Automatic Identification System (AIS), and map data. Implementing the required operations for sensor fusion in real time requires significant amount of computing power, and thus the sensor fusion could also benefit from the processing power available in cloud environments. This of course would require availability of sufficient and reliable wireless connectivity to transfer the sensor data. The amount of transmitted data can be reduced by doing pre-processing on-board.

Prior research has focused mainly on sensor fusion for visible light and thermal cameras [7] [8], given their affordability and easier data annotation compared to Lidar [9]. Weather and illumination impact the performance of visible light cameras, which can be enhanced by merging thermal data. Thermal cameras

detect object temperature, distinguishing them better in diffucult weather conditions. However, detecting small objects remains challenging even with advanced fusion methods. Lidar generates 3D point cloud of the surroundings, usable in object detection with neural networks [10]. When fused with other data, Lidar enhances environment understanding. The information from multi-modal sensoring thus allows the autonomous vessel to detect obstacles and avoid collisions.

The high-level description of subsystems for autonomous operations of our test vessel is illustrated in Fig. 1. The detection of the obstacles is performed on fused sensor data using machine learning algorithms. The route of the vessel is defined in the route planner subsystem, where the waypoints are defined, and the situational awareness system together with the collision avoidance system applies changes to the route based on observations from the sensor system.

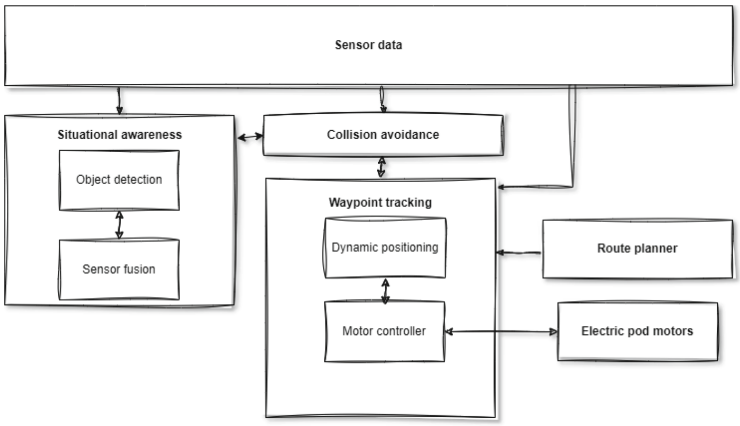


Fig. 1. Autonomous navigation functional architecture.

3 Test Vessel and Remote Operations Center

Turku UAS has designed and built a test vessel for autonomous maritime research. The development process has allowed us to gain a comprehensive understanding of every aspect of the operation of the test vessel. The main goal has been to establish a research platform rather than develop a product for commercial purposes.

The test vessel is equipped with an extensive multimodal sensoring system. The current sensoring setup used to obtain situational awareness includes three industrial daylight cameras (Allied Vision Prosilica GT), three thermal cameras (Teledyne Dalsa Calibir DXM640), Lidar (Velodyne VLP-32C), Radar (Furuno DRS4D-NXT), and IMU (OXTS xNAV650). Selected sensor data will be published as annotated open access machine learning datasets available to all

researchers. We are also developing an onshore data platform where the sensor data will include extensive metadata which allows to search the data for example by the location or time.

The GNSS of the test vessel can use all the major satellite systems available. The vessel has a connectivity solution which can aggregate several networks into one data pipe. Currently we have three 4G modems and one 5G modem, and in the future we plan to add a satellite component. The test vessel ICT subsystem facilitates AI algorithm testing, data processing, storage, and communication.

We have procured the hull, the motors, and the batteries from commercial suppliers. The hull is aluminium catamaran, which is 6.8 m long and 3 m wide and has a cabin. The boat has two 10 kW electric motors installed to the rear of the boat. The total capacity from our 8 Lithium Iron Phosphate batteries is 34 kWh. The vessel has several different electronic devices that require different voltages, so we have built a system with 12/24/48 V DC and 230 V AC electricity. There are several non-trivial safety, interference and grounding issues that had to be solved to make the system work in a safe and efficient manner. We also designed and built a charging system and procured an aggregate as a backup energy option.

The Controller Area Network (CAN) is a critical component for communication between vessel devices. Our devices use NMEA2000, J1939 and CANopen messages. We designed and built the overall CAN architecture from scratch. Extensive simulations were performed for the overall vessel CAN/NMEA2000 system and the vessel resistance, including frictional resistance, wave-making resistance, and air/wind resistance.

A ROC was built to allow remote monitoring and operation of the vessel. The telemetry data from the vessel is transmitted with NMEA2000 messages and the video streams using Real Time Streaming Protocol (RTSP). Surround sound will be added during autumn 2023. The ROC software was procured from a commercial supplier. The ROC is currently in the final testing phase and will be launched during autumn 2023.

The vessel's motors and rudder are operated using an ESP32 microcontroller unit (MCU) -based dynamic control unit (DCU), which communicates with the vessel's NMEA2000 bus. A custom printed circuit board incorporates the MCU with a CAN controller for NMEA2000 and a digital to analog converter (DAC). The DAC provides input for motors and rudder position. The DCU includes several fail-safe functions. A heartbeat signal must be sent by the commanding unit at set intervals to maintain operational mode. The vessel's local operator can also revert to manual operating mode by moving the engine control lever from idle or pressing an emergency button.

Figure 2 shows a high-level illustration of the ROC implementation. The data from vessel interfaces is transmitted to a data processing and communication unit, which transmits the data wirelessly to a ROC-PC through a cloud service. The ROC consists of five 55-inch screens and three 24-inch screens for 180-degree front and back views, telemetry data, and map data. Tablets are used to control the vessel, as this allows an easier way to modify and test different

control systems than having a physical controller or an exact replica of the vessel dashboard. Additional screens can be added for example to show information from other sensors, such as side-view, thermal cameras, and Lidars.

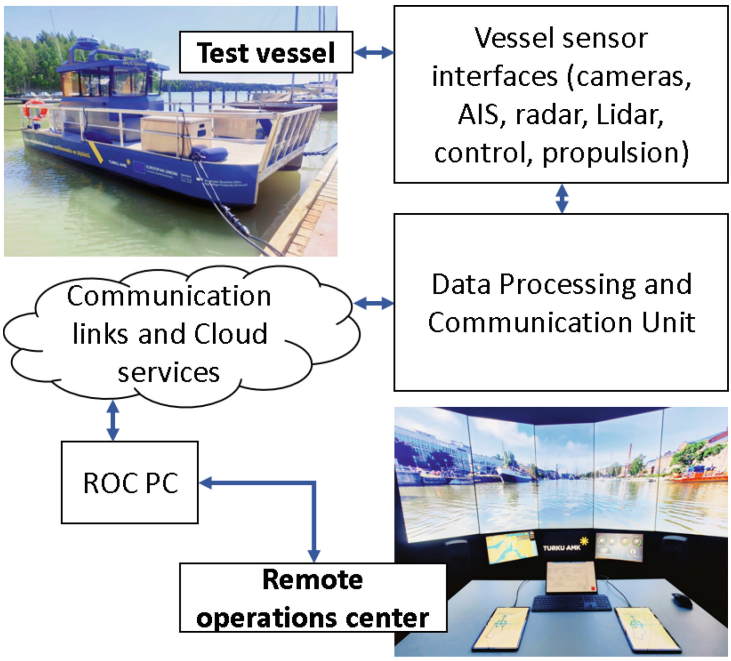


Fig. 2. Remote Operations Center Architecture.

4 Conclusions

This paper introduces a versatile research platform comprising a test vessel and a ROC. The platform facilitates diverse research. The current key research areas in Turku UAS autonomous maritime research are:

- Development of novel autonomous control and navigation systems exploiting situational awareness from sensors and enabling safe and efficient maritime transport in compliance with COLREGs [11].
- Research on the suitability of mobile and satellite networks for remote operation of vessels and for data transfer from vessel sensors.
- Studies on autonomous vessel cybersecurity, including finding and fixing vulnerabilities, risk management, and developing safety protocols.

During summer 2023, the test vessel gathered a maritime dataset with daylight, thermal camera, Lidar, IMU, and GNSS data. An annotated dataset will be created during the winter months.

During the winter when the vessel is not on water, the focus will shift to software development. A software architecture based on the Robotic Operating System 2 (ROS2) is being developed for the autonomous operation of the test vessel. A way-point tracking and dynamic positioning system will be built first, and then the autonomous and smart navigation components exploiting the situational awareness from the multi-modal sensoring system. The first autonomous features trials on the sea are planned for summer 2024. Concurrently, we will study wireless connectivity for remote operations and cybersecurity.

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Accelerating the Deployment of Shared and Digital Mobility Hubs Across Europe

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Abstract. The access to or use of goods and services without owning them is a central promise of the sharing economy, a disruptive concept that supports the global transformation towards entering more climate-resilient, sustainable development pathways. Potentially reducing carbon footprints, alleviating urban traffic congestion and pollution, as well as increasing social mobility, shared and digital mobility solutions are gaining increasing popularity in cities around the globe. Moreover, the implementation of shared mobility schemes may not only result in more efficient and competitive urban transport systems, but also contribute to social equity and positively impact the quality of life in cities. We introduce a distinctive integral approach to improve multimodal accessibility in urban areas. By providing real-life evidence of the introduction and uptake of so-called shared and digital mobility hubs the needed transition of current transport systems towards a sustained and climate-friendly regime may be accelerated. These measures will be explored in a set of cases from the Netherlands and Norway that may pave the way for further implementation, upscaling and replication of mobility hubs across Europe.

Keywords: shared mobility · implementation · upscaling

1 Introduction

The access to, or use of goods and services without owning them is a central promise of the sharing economy, a disruptive concept that supports the global transformation towards entering more climate-resilient, sustainable development pathways. Shared mobility is said to be a key feature of a shared economy, reflecting sustainable travel behaviour as well as sustainable urban infrastructure (Shokouhyar et al., 2021; Wu & Zhi, 2016).

Potentially reducing carbon footprints, alleviating urban traffic congestion and pollution, as well as increasing social mobility, shared and digital mobility solutions are gaining increasing popularity in cities around the globe. Accordingly, the global market

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volume of shared mobility[1] is expected to amount to US$ 1.44 trillion in 2023, of which the shared vehicles market has a major share of US$ 1 trillion (Statista, 2023). Moreover, the implementation of shared mobility schemes may not only result in more efficient and competitive urban transport systems (Machado et al., 2018), but also contribute to social equity and positively impact the quality of life in cities. Assessing potential environmental benefits from transforming passenger transportation into more sustainable modes and considering socio-technological drivers of transportation, including well-being, digitalisation, shared mobility, and electrification (Castellanos et al., 2022; Hu & Creutzig, 2022a).

In this perspective, the literature in the field tackles shared and digital mobility in several ways. For example, Castellanos et al. (2022) propose in their paper a taxonomy for shared mobility by exploring the connection of concepts such as digital technology, transport and shared economy. Geurs et al. (2023), in turn, conduct a literature review in order to unveil definitions and categorisation of shared mobility hubs involving three main dimensions: physical, digital and democratic. Some reviews also aim at providing the big picture of shared mobility, evidencing the several modalities such as car sharing, personal vehicle sharing, bike sharing, ridesharing and on-demand ride services, indicating that shared mobility could contribute to reducing pollution and traffic jams and creating efficiency, increasing sustainability, and guaranteeing a better quality of life for people in large cities (Machado et al., 2018). Others focus on the importance of upscaling and replicability of shared mobility schemes since these could not only enable more widespread adoption, maximise positive externalities and efficiently address several city transportation and sustainability problems but also make transportation as a service more accessible and replicable to different cities (Petzer et al., 2021; Sadu, 2021; van Waes et al., 2018).

In this sense, this paper aims to add value to the ongoing literature on urban mobility by introducing a distinctive integral approach to improve multimodal accessibility in urban areas. By providing real-life evidence of the introduction and uptake of so-called 'shared and digital mobility hubs' – the central aim of the INTERREG-funded EU project which bears the same name – the needed transition of current transport systems towards a sustained and climate-friendly regime may be accelerated (https://www.interregnorthsea.eu/sharedimobihub).

2 Methods

This study builds on some first lessons learned from the EU Interreg Project "Shared and Digital Mobility Hubs", in short: ShareDiMobiHubs (see https://www.interregnorthsea.eu/sharedimobihub). The interdisciplinary project pursues a case study-based approach, with distinctive measures supporting a modal shift and behavioural changes entail, amongst others, providing space for shared mobility, nudging and communication, a digital participatory platform, and improved integration with public transport and with mobility as a Service (MaaS).

Adopting a case studies approach (see Arias-Molinares & Carlos García-Palomares, 2020; Franssens et al., 2021; Ruhrort, 2020; Sadu, 2021) can help to explore specific

[1] The shared mobility market, can be differentiated further into shared rides and shared vehicles.

contexts and gather practical insights into how to address complex urban transportation challenges, i.e. how to further upscale and replicate business models, initiatives and policy making in other regions. In line with this, we explore two distinctive measures supporting a modal shift and behavioural changes: 1) The case of Vestfold and Telemark County, Norway; and 2) The case of Amsterdam, Netherlands. These distinctive measures support a modal shift and behavioural changes towards more sustainable, efficient, and equitable transportation systems in the evolving urban landscape.

The authors had access to secondary data pertaining to the aforementioned project, such as existing data sources, reports, datasets produced by the project partners and other relevant documents. The data analysis, in turn, the authors adopted a qualitative approach (Smythe, 2012) based on data compilation, organisation (Creswell & Poth, 2016; Stake, 1995) and narrative synthesis (see Cruzes et al., 2015; Thornton et al., 2007) of the three case studies of the ShareDiMobiHub project. Tentative results were cross-checked against some of the main papers published in the field. Finally, it is worth considering that these data-collection strategies were possible since the authors of this study are part of the aforementioned project, with full access to data in order to conduct an analysis of the cases.

3 Results and Discussion

Shared mobility, as integral part of modern urban transport systems is increasingly supported by cities to induce changes in transport behaviour among their inhabitants by offering more multimodal alternatives, potentially leading to a decline in private car use (Docherty et al., 2018). However, creating truly sustainable shared mobility offers remains a challenge. From global via EU to local levels, strategies exist that focus on emission reduction, supporting countries in their transformative efforts to become carbon-neutral, i.e. entering a more sustainable development path (Ruhrort, 2020). Particularly the transport sector has to reduce emissions to comply with global commitments as defined in the respective UN climate action plans against which countries will be measured (Filho & Kotter, 2015).

The imperative of transforming the transport sector into one characterised by green, smart, and affordable mobility looms large. This specific European vision is slated for realisation through the twin pillars of environmental sustainability and digital innovation, underpinned by a comprehensive blueprint encompassing 82 strategic initiatives. These initiatives are poised to chart the course of urban development in European cities over the next four years, in line the European Green Deal. By 2030, the European Commission aims at 30 mio. Zero-emission vehicles on European roadways, and simultaneously, a transformative journey towards climate neutrality in 100 European cities, a doubling of high-speed rail traffic crisscrossing the continent, and a commitment to making collective travel for journeys under 500 km carbon-neutral. Furthermore, large-scale deployment of automated mobility solutions is pushed forward, heralding a new era in transportation (European Commission, 2021, 2023).

Shared and digital mobility hubs (Geurs et al., 2023) contribute to sustainability-related objectives of cities. Scholars are increasingly exploring the optimal physical infrastructure and strategic locations for shared and digital mobility hubs by exploring the most effective placement of these hubs within urban environments to maximise

accessibility and convenience (Arnold, Dale, et al., 2023; van der Meer, 2022), 2) the creation of seamless connections between different modes of transportation within the urban environment (Conticelli et al., 2021), the integration of digital technology and data to optimising the functionality and efficiency of mobility hubs (Bibri, 2019), understanding the environmental implications of shared mobility hubs and their potential to reduce emissions (Blad et al., 2022; Santos, 2018), the shared mobility hubs´ design to ensure equitable access and promote social inclusion among diverse urban populations (Cass et al., 2005; Lucas, 2012) and the development and implementation of effective regulatory and policy (Hu & Creutzig, 2022b; Shaheen & Cohen, 2018). Finally, assessing the scalability and replicability of shared mobility hubs across different urban contexts (Campisi et al., 2021; Cassinadri et al., 2019) as well as creating effective communication and engagement strategies capable of nudging stakeholders (policy-makers, civil society and entrepreneurs, etc.) and leading them to take collective action towards sustainable urban shared mobility (Anthony Jnr et al., 2021; Arnold, Frost, et al., 2023) are critical aspects of ongoing efforts since understanding how successful models can be adapted and expanded to different cities and regions is essential for a broader adoption.

3.1 Upscaling Shared Mobility Through Combined Travel Experiences – The Case of Vestfold and Telemark County

The following case can serve as a blueprint for upscaling action through the design of sustainable combined travel offers: Located in Southern Norway, the Vestfold and Telemark county has decided to extend and supplement its public transport by means of eBikes in the district of Grenland, i.e. creating and marketing a combined travel experience for users with attractive pricing. To be launched in late spring 2024, the Vestfold og Telemark fylkeskommune (VTFK), the public transport administration, will offer at first 150 and later increase to 250 eBikes in strategic locations close to junction points and key destinations, confined to the central areas of Grenland (see Fig. 1). This continues throughout the year, also during winter under snowy and icy conditions. In parallel, communications campaigns, positive and restrictive measures and comprehensive monitoring of mobility use support the implementation of the eBike scheme. VTFK is leading the multi-level government cooperations in Grenland ("Bypakke Grenland") and in Tønsberg ("Bypakke Tønsberg"), based on a "Zero-Growth Goal". With the pilot measure, the county aims at increasing the share of biking in the district of Grenland and firmly establishing a new combined travel offer. This directly supports the district's zero growth strategy ("Bypakke Grenland") for passenger car transport. Moreover, the action may serve as a starting point for exploring synergies between eBikes, kickbikes, potentially other shared mobility services and the public transportation system. As practical implementation of the upscaling action is still in its preparation phase, the next years will show the impact of the measures.

3.2 Upscaling Neighbourhood Hubs Through Appropriate Spatial Strategy Design – The Case of Amsterdam

Amsterdam set up a citywide spatial strategy entailing about 2000 neighbourhood hubs and 200 district hubs. Being still in an exploratory phase (2023) and considering needs

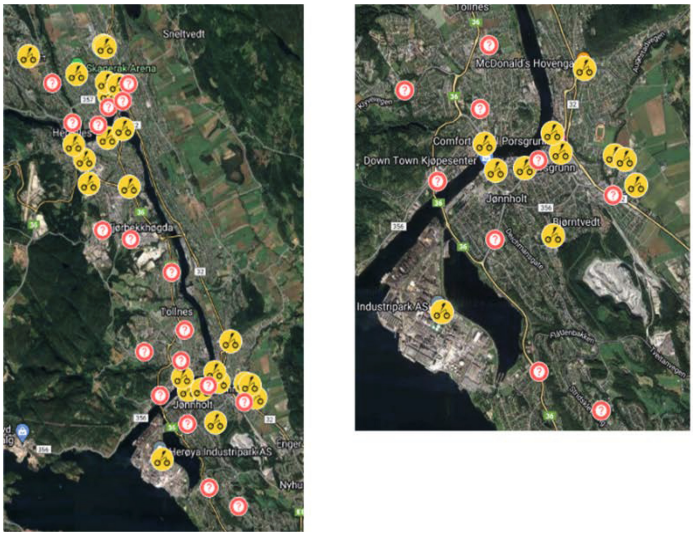


Fig. 1. Example of upscaling activity in Southern Norway. Map of parking zones (yellow) and potential new zones (red). Left: Skien, right: Porsgrunn. Source: ShareDiMobiHub (2023). Used by permission.

and constraints of other organisations involved in urban mobility, the city's strategy supports the upscaling of so-called neighbourhood hubs (see Fig. 2), first and foremost focusing the centre and previously unserved areas, or areas with limited offers, located in the outskirts of Amsterdam. Further ideas to be explored include establishing shared mobility utilising designated car and bike garages.

Currently, Amsterdam's urban mobility sector is characterised by a system of permits and exemptions for various shared mobility providers for a maximum number of shared vehicles. As the maximum was already reached for certain modalities, a separate policy rule has (temporarily) been set up for neighbourhood hubs, limiting additional shared two-wheeles to 800. In July 2023, a 'Shared Transport Memorandum' was adopted by the city council, which, among other things, allows the number of shared scooters and cargo bikes to be further expanded from 2024 onwards, i.e. contributing to further upscaling. However, due to the difference in morphology and administrative contexts, differentiated approaches need to be designed to generate the envisaged impact: Realising hubs outside of Amsterdam is challenging as shared mobility providers are hesitant to start operations beyond the densely populated regions; smaller municipalities are constrained by limited capacities, resulting in a lack of practical implementation action; and finally, upscaling needs to be included as an integral part of overarching strategic urban mobility policy and planning, a time-consuming process and requires combining multiple, sometimes contradictory stakeholder interests.



Fig. 2. Selected examples of neighbourhood hubs in Amsterdam. Source: ShareDiMobiHub 2023. Used by permission.

4 Conclusions

The emergence and rapid growth of the sharing economy, with shared mobility at its forefront, are currently reshaping the urban transportation landscape and hold promise for addressing pressing global challenges. This paper explored the multifaceted implications of shared and digital mobility solutions, drawing on real-life case studies from the EU project ShareDiMobiHub, a real-world example of pan-European action. As such, this paper offers practical insights from two case studies on upscaling of mobility hubs in Norway and The Netherlands. Both case studies show how policy, location selection for hubs, choice of shared vehicles involved and further challenges may be tackled. While infrastructure availability, a seamless integration of travel modes into existing transportation systems by digitalisation and MaaS platforms and policy support is elementary, our examples also show that the involvement of commuters as well as the local community is pivotal for the acceptance of shared mobility hubs.

As a limitation to our findings, the differences in the deployment of shared and digital mobility hubs in The Netherlands and Norway underscores the importance of tailoring solutions to local contexts and needs, as shared mobility is not a one-size-fits-all solution. Complementary project deliverables such as development of a digital participatory platform and the integration of behavioural approaches such as nudging may play further pivotal roles in transforming urban mobility by offering an interaction mechanism for external stakeholders, i.e. fostering knowledge sharing between planning and implementing partners in need of information on best practice examples and hand-on, practical guidance how to steer user behaviour onto a more sustainable path. Finally, as to further research in this particular field of sustainable mobility, we propose to continue exploring innovative ways to enhance shared mobility, including the integration of emerging technologies such as autonomous vehicles and the expansion of electric and sustainable transportation options.

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Assessing the Readiness of European Cities for Distributed Traffic Management: A Smart Infrastructure Readiness Index

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Abstract. The ever-increasing emergence of novel intelligent traffic systems that aim to improve traffic flows and reduce congestion in cities is creating a growing need for assessing the readiness of cities around the world to implement such systems. Yet, no standardized method currently exists for assessing a city's readiness for smart traffic management infrastructure. This research paper aims to develop an index, the Smart Infrastructure Readiness Index (SIRI), to assess the readiness of cities for novel traffic management schemes. For the development of the index, interviews with representatives from over 10 different EU member states were conducted to gather information on the importance of different factors that affect implementing smart traffic solutions. Analytic Hierarchy Process was then utilized to extract the priority of each factor, considering both their relative importance and their interdependencies. Findings provide a hierarchical ranking of 6 EU cities, highlighting their current state of smart infrastructure readiness.

Keywords: Smart Infrastructure · Readiness Index · Smart Cities

1 Introduction

Cities worldwide are currently struggling with the challenges posed by rapid urbanization and technological advancements, particularly when it comes to managing their infrastructure in an efficient manner. Transportation systems and mobility, critical aspects of a city's livability, have now assumed paramount importance. As urban areas become more congested and populations continue to rise, cities need to adopt intelligent transportation systems (ITS) and embrace a distributed paradigm that ensures smooth and sustainable movement of people and goods.

To address this pressing need, within this research, we aim to create an index that measures the readiness of cities to deploy smart infrastructure, the Smart Infrastructure Readiness Index (SIRI). Such an index can serve as an evaluation tool to measure a city's ability to harness the benefits of cutting-edge transportation technologies. SIRI also enables city authorities, policymakers, and stakeholders to assess their progress and identify areas for improvement concerning mobility infrastructure.

The necessity for such a city-scale Smart Infrastructure Readiness Index requires little explanation. The index could serve as a vital tool for city authorities and policymakers

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to assess their level of readiness in adopting and implementing smart infrastructure solutions, identify areas that need attention and investments, compare with other cities for benchmarking purposes, promote innovation, embrace technological advancements, and attract investments and talent. All the above would lead to an increased well-being and quality of life of the citizens.

2 Methodology

The first step of our approach in developing SIRI was an extensive literature review focused on similar indices already established in the field. Utilizing the work of [1–7] we identified Key Performance Indicators (KPIs) that are crucial for assessing the readiness of cities in terms of smart infrastructure and ensured that our approach is built upon established best practices. Taking inspiration from the literature, particularly from [7], we also categorise the KPIs into four main categories to provide a complete assessment of a city's smart infrastructure readiness. These categories are as follows:

1. **Vision, Priorities, and Mindset** - *Does the city demonstrate a good understanding of the potential opportunities around ITS? Does it have a systematic and integrated plan meeting the challenges?*
   - **Strategic planning**: Extent to which the city has an overall vision / plan related to ITS and the degree to which they are integrated.
   - **Funding**: Funding allocated to ITS-related initiatives and programs
   - **Knowledge sharing**: Partnerships with other cities and organisations to share knowledge and best practices related to ITS implementation.
2. **Activation** - *Are the city and its stakeholders well-positioned to carry out forward-looking plans?*
   - **Stakeholders' involvement**: Diversity of stakeholders involved in ITS planning and decision-making, including community groups, academic institutions, private sector, and government agencies.
   - **Collaborations**: Level of collaboration and coordination among different stakeholders involved in ITS planning and implementation, measured through joint initiatives, joint funding, and joint decision-making.
   - **Public support**: Degree of public awareness and support for ITS initiatives
   - **Flexibility of governance**: Degree of flexibility and adaptability in the city's governance structure to accommodate changes in technology and shifting priorities.
3. **Asset Base** - *Does the city have existing assets that will act as enablers to support enacting its vision?*
   - **Workforce - Human capital:** Level of STEM education and training for the future ITS workforce.
   - **Private sector maturity:** Number and diversity of ITS-related businesses in the city - existence of leading global firms.
   - **Quality of digital infrastructure:**

  - Connectivity: This measures the degree of connectivity of the transportation system, including the availability of cellular and Wi-Fi networks.
  - Interoperability: This measures the ability of different ITS components to work together seamlessly, such as communication between vehicles, traffic management systems, and other infrastructure.
  - Data management - Sensoring: This measures the ability of the transportation system to collect data from a wide range of sensors -like data on traffic flow, weather, and road conditions, as well as cameras and other monitoring devices to provide real-time information to users-, store them and analyse them.
  - Cybersecurity: This measures the level of security of the transportation system and the ability to protect against cyber threats.

- **Quality of physical infrastructure:**

  - Multimodality: This measures the integration of multiple modes of transportation, such as public transit, biking, walking, and car-sharing services.
  - Adaptability: This measures the ability of the infrastructure to adapt to changing conditions, including dynamic traffic management, and the integration of new technologies and services.
  - Reliability: This measures the degree in which the infrastructure is designed to be highly reliable, with built-in redundancy and failover mechanisms to minimise disruptions to services.
  - Maintainability: This measures the degree in which the infrastructure is designed for easy maintenance and upgrades, with the ability to remotely diagnose and fix problems.

4. **Trajectory and Development** - *Is the city trending in the right direction?*

- **Innovation:** Trends in the city's innovation capacity and entrepreneurship, measured through the number of patents, startup investments, and new business formations.
- **Investments in R&D:** Level of investment in ITS research and development, measured through the amount of public and private funding for ITS initiatives.
- **Penetration rate of intelligent vehicles**: Number and percentage of vehicles in the city's transportation fleet that are equipped with ITS technologies (e.g., vehicle-to-vehicle communication).
- **Penetration of novel mobility services**: Novel mobility service providers operating in the city, and their market share of the total mobility market.
- **Trends in car ownership**: Number of registered vehicles per capita over time, to assess trends in car ownership and changes in transportation demand.
- **Traffic mix and multimodality**: Degree of integration and coordination between different modes of transportation, measured using integrated ticketing systems, shared mobility platforms, and multimodal trip planning tools.

To prioritise the identified KPIs, we employed the Analytic Hierarchy Process (AHP) [8] methodology in the form of a questionnaire, designed and distributed to experts from 10 European countries and Israel. By utilising AHP, we were able to assess the relative

importance of each KPI, considering the experts' diverse opinions and preferences. This process helped us assign appropriate weights to each KPI, thereby ensuring the robustness of the assessment framework.

Then, we assessed the readiness of 6 European cities, Amsterdam, Utrecht, Bordeaux, Athens, Glyfada, and Barcelona, pilot cities of the EU project "DIT4TraM" (Distributed Intelligence & Technology for Traffic & Mobility Management). To derive the final scores of each city on the Smart Infrastructure Readiness Index, a second questionnaire was deployed. This time, it was specifically addressed to pilot leaders of the DIT4TraM pilot cities and relevant experts within those cities. The questionnaire requested qualitative scores for each KPI, allowing the experts to provide their assessments based on their knowledge and experience within their specific urban contexts. This qualitative scoring approach ensured that the index reflected the unique characteristics and priorities of each pilot city, while still maintaining a standardised assessment framework.

3 Results

The first questionnaire, which aimed to assess the importance of KPI for SIRI, received responses from experts representing 12 different countries. Among the respondents, Greece had the highest frequency with 5 participants, followed by France and Spain with 2 participants each. The remaining countries, namely Germany, Israel, the Netherlands, the UK, Portugal, Switzerland, Hungary, Luxembourg, and Finland, each had 1 respondent. The profile of the respondents was diverse, comprising individuals primarily affiliated with academic institutions. However, it is worth noting that representatives from private companies involved in the field of mobility also participated, ensuring a well-rounded perspective that encompassed both theoretical expertise and practical industry insights. Figure 1 displays the weights of all the KPIs within the SIRI that were calculated by the AHP analysis.

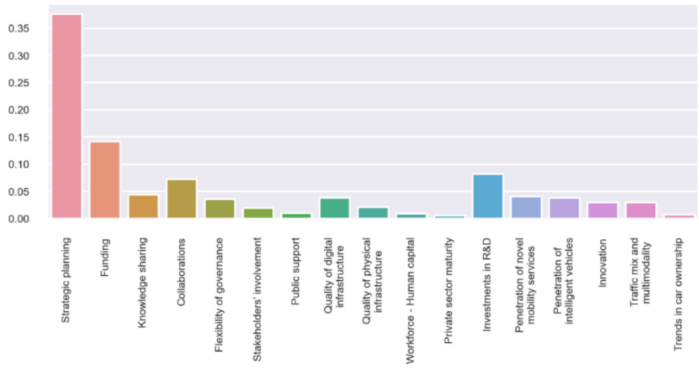


Fig. 1. Global weights of all the Key Performance Indicators (KPIs) SIRI.

The second questionnaire, aimed at extracting the final scores of each city on SIRI, received responses only from experts that were directly involved in the relevant cities (8

in total). The respondents primarily consisted of the pilot leaders, who played a key role in overseeing and implementing the smart infrastructure initiatives within their respective cities. Additionally, in some cases, other local experts with relevant knowledge and expertise also contributed to the questionnaire responses. This composition of respondents ensured that the assessments and qualitative scores provided were grounded in the first-hand experience and insights of those directly involved in the pilot cities' smart infrastructure projects.

The evaluation results are first analyzed to derive the performance scores of each city across the four fundamental categories: "Vision", "Priorities and Mindset", "Activation", "Asset Base" and "Trajectory and Development". These categories serve as key dimensions in evaluating the readiness of cities for smart infrastructure. The radar plot of Fig. 2 showcases the average performances of each city in these categories, providing a visual representation of their strengths and areas for improvement. By analyzing the performance scores within these categories, we can gain valuable insights into the overall readiness and progress of each city towards embracing advanced mobility solutions and distributed intelligence. By combining the KPI weights obtained from the first questionnaire, which assessed the importance of each indicator, with the qualitative evaluations provided by experts for each city's performance on these KPIs, a comprehensive ranking has been established. This ranking provides valuable insights into the current state of smart infrastructure readiness across the evaluated cities, offering a benchmark for comparison and a guide for further improvements. Figure 3 presents the final rankings, showcasing the cities that have demonstrated increased readiness in harnessing the potential of distributed intelligence and technology for effective traffic and mobility management. As observed, the SIRI scores of the 6 cities range from 2.68 to 3.49, with higher scores reflecting higher levels of readiness. Overall, all cities have



Fig. 2. Performance of pilot cities on the 4 basic criteria categories.

relatively good scores, signifying progress in embracing advanced mobility technologies and intelligent transportation systems. Utrecht emerges as the top performer with the highest SIRI score of 3.49, indicating its leadership in smart infrastructure readiness. However, other cities' SIRI scores are relatively close, suggesting comparable efforts across EU in embracing intelligent transportation systems, with slight variations possibly due to implementation progress, funding availability, or other city-specific factors.



Fig. 3. Ranking of the pilot cites according to SIRI index.

4 Conclusions

The results provided a hierarchical ranking of 6 EU cities, highlighting their current state of smart infrastructure readiness. Utrecht emerged as the top performer, indicating its leadership in ITS. However, all cities displayed relatively good scores, suggesting comparable efforts across the EU in adopting advanced mobility technologies. In conclusion, the development and implementation of SIRI holds immense significance in addressing the challenges posed by rapid urbanization and technological advancements in cities worldwide. By considering key elements such as vision, funding, investments in R&D, collaborations, and infrastructure quality, the index empowers cities to plan their investments and identify areas for improvement in mobility infrastructure. Reflecting on the diversity and expertise of our respondent pool, future enhancements of this research will aim for a more balanced representation from various sectors and institutions, enriching our findings and broadening the applicability of the SIRI index.

By prioritizing the readiness for smart infrastructure, cities can adapt to changing demands and stay at the forefront of innovation, ultimately paving the way for smarter, greener, and more livable urban environments.

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Improving Data Exchange in Transport and Logistics Through System Federation: Application Evaluation Results

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Abstract. Establishing better system connectivity by linking disparate legacy systems and information silos across Europe has been at the center of research the past years. Concepts like service federation, interoperable logistics, data spaces and system unification highlight the significance of unifying systems and data by promoting system interoperability and compatibility. Although promising, these are still at conceptual level, while limited practical evidence has been provided at the moment. FENIX Federated Network established the first pan-European federated network of interoperable platforms as an enabler of B2B and B2A data exchange and sharing between transport and logistics platforms in Europe. Using the Operational Evaluation Measurement Framework, this paper measures the impact of FENIX Federated Network, used as enabler for end-to-end supply chain digitalization, to the operational performance of selected logistics operations across Europe. Notable outcomes include higher load factors, increase in modal shift for both road and rail operations, increase in delivery reliability, enhancement of the digitalization processes (digital document exchange, process automation), as well as important decreases in the operational externalities (CO2, NOx emissions) and the related process times (i.e., fulfillment, customs, turnaround, (un)loading, administration, automation, travel).

Keywords: Transport & logistics · operational evaluation · system federation

1 Introduction

Seamless exchange of data between different actors and systems within supply chains and logistics networks is essential for achieving efficient transport and logistics (T&L) operations [1, 2]. However, the lack of interoperability and integration among the various data systems used in the industry can represent significant barriers to achieving this goal [3]. These barriers can result in delays, increased costs, and reduced service quality within the supply chain. Thus, efforts to improve interconnectedness of data sharing systems are critical to achieving greater efficiency in T&L operations.

Collective initiatives, fueled also by the European Commission, aim to tackle this by establishing better system interoperability and connectivity [4] and linking disparate

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legacy systems and information silos across Europe. Concepts such as services federation [5], interoperable logistics [1] and system unification [6] highlight the significance of unifying systems and data by promoting system interoperability and compatibility. Although promising, these models are still at conceptual level, with limited practical evidence, particularly regarding the effects of digitalization on T&L operations performance [7]. Given that supply chains involve complex processes and operations, numerous stakeholders, interconnected workflows, and integrated systems, comprehending the full implications of their digital transformation becomes a highly intricate task.

The FENIX Federated Network (or Federation) established as the first pan-European federated network of interoperable platforms as an enabler of Business-to-Business (B2B) and Business-to-Administration (B2A) data exchange and sharing between T&L platforms in Europe [8]. Through FENIX, 90 T&L operations were tested, and their performance was evaluated. In this paper, the evaluation results are presented. Notable outcomes include higher load factors, increased modal shift in road/rail operations, increased reliability, enhanced digitalization (document exchange, process automation), as well as decreases in operational externalities (CO2, NOx emissions) and process times (i.e., customs, turnaround, (un)loading, administration, automation, etc.).

Section 2 analyses the theoretical background, Sect. 3 describes the methodological approach, Sect. 4 briefly presents the FENIX Federated Network concept, while Sects. 5 and 6 present the study results and draw useful conclusions, respectively.

2 Theoretical Background

The significance of performance measurement in T&L operations has been extensively emphasized in existing supply chain management studies. Performance measurements are necessary to assess the effectiveness of supply chain strategies, benchmarking operations and enhancing overall governance and decision-making [9]. An entirely untapped territory lies in the domain of performance measurement of systems that enable the exchange of information among stakeholders throughout the supply chain [10].

Early research has been centered on economic metrics [11], which continue to hold sway. However, there is a growing recognition of the significance of social and environmental metrics recently [11–16]. Concepts such as sustainability, circular economy, and green logistics have taken center stage in this context (e.g., [12]).

In 2022, Ayfantopoulou et al., [18] developed an operational performance measurement framework (OPMF) as a framework for measuring the impact of digitalization on the operational performance of logistics processes. The OPMF is grounded on theory and developed for industrial application. It consists of 5 analytical levels; starting from general concepts spanning to impacts and specific Key Performance Indicators (KPIs) (e.g., CO2, load factor, document exchange, delivery reliability, shipment visibility, status updates, waiting times, routing efficiency, order fulfilment, customs, transit time, turnaround, (un)loading, accidents, modal shift, automation, administration, etc.).

3 Methodology

The assessment of operational performance, in this study, adheres to the principles outlined in the Operational Performance Measurement Framework (OPMF) [17]. OPMF evaluates digitalization impacts on the operational efficiency of logistics processes, considering sustainability supply chain performance aspects. The 5th analytical level of OPMF is utilized, here, to gauge, quantify and analyse pertinent operational KPIs. KPIs are defined as a set of metrics used to assess the efficiency and/or effectiveness of an operation [18]. They focus on aspects of organizational performance that are crucial for the current and future success of a service [19] that also serve as benchmarks [20].

KPIs for each operation are tracked at predefined time intervals before and after the disruption caused by FENIX. An ex-ante/ex-post analysis is employed to examine and contrast the two situations, emphasizing potential disparities articulated as percentage changes. A comparison of the values is conducted per KPI using the following formula:

$$Comparison = \frac{KPIex\text{--}post\ value\text{--}KPIbaseline\ value}{KPIbaseline\ value}$$

4 The FENIX Federated Network

FENIX (A European FEderated Network of Information eXchange in LogistiX) aimed at developing the first pan-European federated network of interoperable platforms as an enabler of data exchange between T&L platforms, in order to achieve: 10% increase in load factor, >15% reduction in CO2 emissions, 10% improvement on delivery reliability related to SLAs, and 70% reduction in document exchange for all corridors.

The FENIX Federated Network [8] takes on a distributed format, akin to data spaces, connecting various T&L platforms that utilize a FENIX Connector to enable seamless communication. The Connector, fundamental within the Federation, is integrated into each platform, facilitating functions like identity management, service brokering, and data exchange. Organizations involved in the federation can seamlessly use and share services across Europe with minimal adjustments needed in their operational systems-maintaining full control over their data throughout the process. This decentralized approach lowers communication costs and mitigates governance disputes through digital service compatibility and standardized data exchange.

Between 2019–2023, FENIX Federation was implemented and evaluated through 66 real-environment cases across 11 pilot sites in nine European countries (AT, BE, DE, EL, ESP, FR, IT, NL, SK) and all corridors of the TEN-T. It has been carried out under the guidance of the Digital Transport & Logistics Forum (DTLF), testing more than 90 services (99.97% at TRL ≥7) covering operations such as track & trace, customs services, e-documentation, cargo monitoring, dangerous goods management, emissions monitoring, dashboards & catalogues, traffic management, slot management, trip & capacity planning and, gate and parking management [17].

5 Analysis and Discussion

Based on the project requirements, the efforts of data collection and analysis were primarily put on the measurement and quantification of a set of 7 core KPIs of the OPMF, concerning operational outputs (CO2 emissions, NOx emissions, load factor, digital document exchange, delivery reliability, shipment visibility, shipment status) across 4 impact categories (emissions, load factor, document exchange, and shipment visibility). Although the KPIs list could have universal application across the TEN-T corridors, in practice the quantified KPIs selected based on the scope of the trial sites (the geographical scope of the measurements is indicated for each KPI).

Impact 1 Emissions-Externalities consisted of KPI01 CO2 emissions and KPI09 NOx emissions. FENIX disruption recorded higher average reduction of emissions than initially expected, amounting to 16% of the CO2 and 7.32% in NOx emissions, in selected logistics operations across the North Sea-Mediterranean, Mediterranean, Rhine-Alpine, Orient/East Med, and Baltic Adriatic TEN-T corridors.

Impact 3 Load Factor and the respective KPI03 Load Factor was measured across the Rhine-Alpine, Baltic Adriatic, and Mediterranean corridors. FENIX application facilitated a >9% (10% increase requirement) increase of load factor across the selected operations. Nevertheless, a decrease to the total km driven per shipment has been achieved at the same time that could be translated as an increase to load factors and significant decreases in the related CO_2 emissions (i.e., reduction of the total km driven in the LF fraction for the ex-post measurements).

Impact 4 Document exchange quantified through KPI04 Digital document exchange recording a 70% increase to the average number of digital exchanges and a 64% reduction of the number of different documents exchanged per process (some documents become obsolete due to digitalization and the federation). KPI04 was the most applied metric across trial sites, covering operations in all TEN-T corridors in 7 countries.

Impact 5 Delivery/pick-up reliability and visibility was quantified by KPI05 Delivery reliability, KPI08 Product/Shipment visibility and KPI37 Shipment status updates of the OPMF. FENIX Federation facilitated an average increase of 32.71% in delivery reliability, an average 43% increase in product/ shipment visibility and an increase in shipment status updates of 92% (compared to a requirement for 10% improvement in delivery reliability related to service level agreements). The geographical tests for the KPIs covered all TEN-T corridors across 6 countries.

Besides the core set of KPIs, a series of other KPIs, important to trial site operations were measured and quantified during FENIX (Table 1). From this set of KPIs, KPI02, KPI10, KPI14 and KPI15 stand out due to their extensive application across FENIX.

6 Conclusions

This paper measured the impact of supply chain digitalization to the operational performance of selected logistics operations; The FENIX Federated Network has been used as the enabler for seamless data exchange among 90 T&L services across Europe.

Table 1. Average change of (selected) KPI values after the FENIX Federation disruption.

KPI	Metric	Average change	Geographical scope
02 Waiting times	Min	(−) 42.26%	7/9 TEN-T corridors
06 Order fulfillment	Min	(−) 40.24%	1/9 TEN-T corridor
07 Customs procedures	Min	(−) 79.31%	4/9 TEN-T corridors
10 Turnaround time	Min	(−) 22.27%	6/9 TEN-T corridors
11 (Un)Loading time	Min	(−) 10.2%	3/9 TEN-T corridors
12 Modal shift	LF%	(+) 42.28%	All TEN-T corridors
14 Workflow automation	Min	(−) 82.59%	All TEN-T corridors
15 Administration time	Min	(−) 78.02%	6/9 TEN-T corridors
26 Number of accidents	Number	(−) 98.5%	1/9 TEN-T corridor
33 Corridor transit time	Min	(−) 12.5%	2/9 TEN-T corridors
34 Level of traffic service	Km/h	(−) 3.74%	1/9 TEN-T corridor
36 Pick-up travel time	Min	(−) 15.2%	2/9 TEN-T corridors

The outcomes of the evaluation of the services and FENIX infrastructure indicate that digitalization through the Federation concept impacts sufficiently the actual logistics operations across different operational levels. Most importantly: (1) Emissions – reduction beyond the expected for CO2/NOx emissions across the TEN-T corridors; (2) Load Factor – increased by 9%; (3) Digital document exchange – increased the % of digital documents exchanged and decreased the total number of different documents exchanged per process.; (4) Delivery reliability – increased the reliability of shipments significantly; (5) Delivery visibility – increased shipment order tracking. In addition, FENIX impacted significantly (6) Process times by decreasing the times required to perform operations, i.e., waiting times, order fulfillment, custom procedures, turnaround times, loading/unloading times, administration, automation, travel times; (7) Automation by increasing the digitalization of processes and workflow automation across different operations; (8) Service visibility through the increase of corridor services visibility and dashboards to enhance information diffusion across the supply chain.

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Examining the Impact of System Federation on Transport and Logistics: Selected Cases in Greece and Italy

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Abstract. New supply chain governance models transform operations by establishing large-scale, intelligent infrastructures that merge, objects, data and business processes. Considering that supply chains are intricate structures encompassing multifaceted operations, evaluating the consequences of their digital transformation is imperative. System Federation has emerged as an enabler of interoperability and seamless data exchange in transport and logistics. The Federation is a promising concept that is still new and tested only in a few instances, while; its impact has yet to be measured substantially. This paper presents the impact of Federation on the performance of selected logistics operations in Greece and Italy. Using a mixed-methods approach, the assessment performed as part of the FENIX project, focusing on operational performance, cost-effectiveness and gap analysis, and impact assessment. Results showed that the Federation showed promising overall impact. Operational improvements ranged from better shipment visibility, shorter waiting times, faster deliveries, to less CO2 emissions. The most effective services were related to a higher visibility of shipments (Italy) and improved notification and exchange of customs documents (Greece). The gap analysis was successful showing that 100% of all reported gaps in Greece and 71% in Italy could be closed with the use of the Federation.

Keywords: Transport & Logistics Digitalization · System Federation · Impact Assessment

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1 Introduction

The digitization of transport and logistics (T&L) operations has emerged as means to revolutionize supply chains and managing multi-modal transport corridors. Digital transformation, supported by the Industry 4.0 explosion, promises to optimize resource and capability utilization, facilitating seamless communication and improving the efficiency and sustainability of operations [1]. However, transforming supply chains to "intelligent" cannot rely on fragmented applications; it requires coordination. New supply chain management governance models transform operations by establishing large-scale, intelligent infrastructures merging objects, data and business processes [2].

The federation concept has emerged, supported by the Digital Transport & Logistics Forum (DTLF), enabling interoperability and seamless data exchange in T&L. Federation, similarly to data spaces [3], refers to decentralized infrastructures for reliable data exchange between actors, based on common principles. It aims to create collaborative environments of interconnected and interoperable platforms through which T&L actors share and use services [4]. However, as a concept is still new and tested only in a few instances (i.e., FENIX & FEDeRATED projects) with its impact has yet to be substantially measured. End-to-end supply chain digitalization is still at conceptual level, with efforts being scattered and evidence not provided yet; especially when assessing the impact of digitalization and of disruptive technologies on the performance of operations [6]. Considering that supply chains are complex structures encompassing multifaceted operations, a multitude of stakeholders, and interconnected processes, evaluating the consequences of their digital transformation becomes an even more intricate task.

This paper presents the impact of federation on the performance of selected logistics operations in Greece and Italy. The assessment performed as part of the FENIX (FEderated Network of Information eXchange) project (CEF/TRAN/M2016/1364071), focusing on operational performance, cost-effectiveness and gap analysis, and impact assessment, using a mixed-methods approach [8]. Significant operational impact has been achieved from the disruption of the FENIX Federated Network (Federation) encompassing increases in process reliability and digitalization, as well as important decreases in operational externalities (CO2, NOx emissions) and related process times. Overall progress in technology readiness has been recorded, while it was demonstrated that the Federation can overcome the limitations detected in the condition prior to the start of FENIX, by bridging most of the detected gaps. Similarly, the introduced services made it possible to improve the efficiency and effectiveness of interventions from a managerial, logistics, environmental and safety point of view. The increased digitization improved the conditions, not only indicated by the expected metrics (admin & waiting times, etc.) but also by less obvious ones such as CO2 emissions or (un)loading times.

Section 2 presents the state-of-the-art in system interoperability and the Federation. Section 3 outlines the applied impact analysis methodologies, while Sect. 4 cross-analyzes the analysis results, before important conclusions are drawn in Sect. 5.

2 Data Exchange and System Federation

2.1 System Interoperability and Data Exchange in T&L

Recent research and business practice highlight the integration of new technologies for the digitalization of supply chains to facilitate the efficiency and sustainability of freight T&L networks [1]. The concept of Logistics 4.0 [6, 8] signifies and enables the evolution toward supply chain digitalization [9]. The transition of supply chains into 'intelligent' entities necessitates robust coordination extensive intelligent infrastructures that seamlessly integrate information, data, assets and operations [2].

Many researchers argue the importance of developing "a standardized and interoperable collaborative transport network […] to interconnect currently independent networks" [5, 9]). Interoperability refers to the capacity of systems to not only exchange information but also effectively utilize it. To prevent system incompatibility, which could impede collaboration [11], interoperable systems must share specific 'communication' and 'cooperation' parameters in the form of regulations and governance [12], as well as a certain level of operational protocols [5]. Federated structures, such as data spaces, are decentralized structures that ensure reliable exchange of data between actors in the value chain of a specific sector, based on commonly agreed principles, which feed services that create business value for all participants [13]. Key principles of such structures are [14]: Data sovereignty; Data level playing field; Decentralized infrastructure; Public-private governance.

2.2 The Concept of System Federation

The FENIX project aimed to establish the first pan-European, decentralized federated network of platforms for seamless exchange and sharing of data between T&L systems [15]. FENIX developed the Federation and demonstrated its operational feasibility across 11 pilot sites in 9 European countries (AT, BE, DE, EL, ESP, FR, IT, NL, SK), with the participation of 60 T&L organizations (industry, academia, policy, NGOs), testing more than 90 services covering various operations such as track & trace, customs services, e-documentation, cargo monitoring, etc. [13]. The work has been carried out under the guidance of the DTLF and it scales-up through the newly established organization FENIX2.0.

FENIX foresaw to enable sharing of information and services needed to optimize TEN-T corridors from economic, environmental and social perspectives, support total supply chain visibility based on real-time data availability; feedback-driven, flexible collaborative planning including sourcing, manufacturing, delivering, and returning goods; as well as reduced times to complete the T&L procedures from and to large logistics hubs (ports, airports, distribution centers). Once a stakeholder is registered to FENIX, obtains services visibility, requiring a single sign on to securely and safely communicate with others. Each participant platform in the network is equipped with a FENIX Connector, a connectivity engine supporting (1) Identity Manager (IDM): identification, authentication and authorization within the Federation; (2) Broker: service resource catalogue; (3) FENIX Data Exchange: information exchange operations [15].

3 Methodology

The evaluation methodology comprises a 6-step process for assessing the overall impact of technological disruptions on the performance of T&L operations. It was developed and applied in FENIX between 2019–2023 [16]. It entails data gathering (e.g., impact, KPI, baseline quantification, data collections) and analysis (operational evaluation, CEA, gap analysis and impact assessment) processes.

3.1 Operational Performance Evaluation

The operational performance evaluation aligns with the recommendations outlined in the Operational Performance Measurement Framework (OPMF) [16]. OPMF serves as a guide to assess the influence of digitalization on the operational efficiency of logistics while considering the sustainability dimensions of supply chain performance. This study applies the 5th analytical level of OPMF to measure, quantify and analyze relevant operational KPIs. KPIs are metrics that measure the efficiency and effectiveness of an operation concentrating on performance facets [17]. Six KPI properties are considered important [18]: (1) Appropriateness; (2) Objective, accurate and reliable measurability; (3) Considering all dimensions; (4) Realistic in effort, cost and time; (5) Defensible to interpretation; (6) Forecastable using current tools. An ex-ante/ex-post analysis to analyze and compare the two situations and highlight their potential differences is adopted. Once both values collected, the KPI defined by the following formula:

$$Comparison = \frac{KPIex - post\ value - KPIbaseline\ value}{KPIbaseline\ value}$$

3.2 Cost-Effectiveness Analysis

The Cost-Effectiveness Analysis (CEA) is a methodology used to compare alternatives, providing decision-makers with information about the effectiveness of a service. CEA captures information on effectiveness, even when monetary aspects are not quantifiable [19]. To perform it, a widely used index is used: the ratio between the average cost expressed in monetary terms and the benefits per unit of result [20]. This calculation was made for each possible alternative, using its specific cost and measure of effectiveness, by means of the equation below; where i represents the set of possible alternatives, Cost(i) is the cost of the alternative (i) expressed in monetary terms, Ej is the effectiveness of the alternative i expressed in non-monetary terms. By comparing the values resulting from the calculation, it is possible to sort the alternatives from the one that expresses the lowest cost per unit of result, or the lowest value of the distribution.

$$CE^i = \frac{Cost^i}{E^i}$$

The data collection was performed through customized surveys aiming to identify the costs and effectiveness associated with the services. Participants evaluates the effectiveness of the services with reference to the objective expressed in the KPI. Firstly,

an analysis of the service effectiveness considering the relation to different KPIs was performed based on:

$$Cost\ per\ unit\ of\ effectiveness = \frac{Service\ Cost}{Effectiveness\ of\ the\ service\ associated\ with\ the\ single\ KPI}$$

This cost-effectiveness index was useful in identifying the most effective service for each KPI. The second step aimed to understand the effectiveness of each service regardless of the KPIs. This was reached by aggregating the average of the effectiveness values relating to the service. The cost-effectiveness index was the ratio between the service costs and the average effectiveness value resulting from the aggregation of the effectiveness levels associated with the service, based on the formula below.

$$Cost\ per\ average\ unit\ of\ effectiveness = \frac{Service\ Cost}{Average\ Effectiveness\ of\ the\ service}$$

3.3 Gap Analysis

Evaluation has gained increased importance within European (EU) projects with the Commission creating standardized guidelines [21] for certain methodologies: however, for the GAP analysis, a standard methodology does not exist yet. A tailored made methodology was created to perform the analysis: (1) data collection in the pre-FENIX situation through a specific questionnaire; (2) Data processing and elaboration of the pre-FENIX GAP to create a common terminology thus grouping similar GAPs into macro-areas; (3) Data collection in the post-FENIX situation through a specific questionnaire created to identify the GAPs overcome and those still remain [22, 23]. The GAP analysis allowed to better understand the problems related to project implementation and to support policymakers in decision-making in different fields (in line with [24]).

3.4 Impact Assessment

Seven steps were performed to obtain the overall impact assessment using an overall impact indicator for each of the sites: (1) Decision Problem: Each site has a different number of UCs installed to test the implementation of (in most cases) different federated networks. In each, a different number of pre-defined KPIs were used, often with different measurement types; this made it difficult to combine them into a single parameter. (2) Define evaluation criteria: The KPIs for each UC served as evaluation criteria. The KPIs (or better: the measurement of changes of these KPIs) indicated a change in performance of a key feature of the selected UC. (3) Define alternatives: The various UCs in the sites represented the respective site and indicated in which way the site's performance increased after implementation of the FENIX connector. (4) Performance Evaluation: resulted from the change of a KPI measurement within a UC. This evaluation was performed for all KPIs in all UCs and then 'merged' to provide an overall value (impact assessment indicator). (5) Criterion weights: Criterion weights are understood as the relative importance of the KPIs within a UC. An Analytical Hierarchy Process (AHP) approach was used to identify the weights of the different criteria. (6) Decision rules:

were used to transform the KPI measurements (more accurately: the changes of KPI measurements in between 'before' and 'after' implementation of the federated networks) into standardized numbers or a 'scale'. This scale was defined from '0' to '1', where '0' meant no change in the measurements (worst possible performance) and '1' meant the most optimal change (best possible performance), respectively. (7) Aggregation matrix: within the last step of the evaluation, all previously obtained results were brought together to determine the impact assessment indicator. The approach used different matrices (results for KPIs in UCs) which were aggregated using the calculated weights from (5) using AHP.

4 Results and Discussion

4.1 Case Descriptions

Greece - Section of Orient/East-Med in Greece/FENIXGR operated as an open innovation community covering multimodal T&L operations along the Orient/East-Med TEN-T Corridor; emphasizing on the leg connecting the Piraeus port to the cities of Athens and Thessaloniki and the northern national borders (Idomeni). The site focused on improving the corridor competitiveness and footprint through the operational digital transformation and disruptive technologies application. This enabled smart supply chain management through real time information and seamless data exchange.

Italy - The Italian Rhine Alpine Pilot was composed by two separate realities: Milan Malpensa and Genoa-La Spezia. In this article, just the Milan Malpensa side will be considered. The aim of this Pilot was to provide tools to optimize the planning and the real-time operation of the Milan Malpensa Airport which focuses on specific UCs targeting the improvement of the air cargo supply chain by developing or enhancing digital solutions and processes.

4.2 Operational Performance Evaluation

Greece: Data collection focused on three areas (1) the Piraeus Port, (2) the surroundings of the port and (3) the main T&L corridor. The impact of the federation in the reduction of T&L externalities in the port was measured indirectly in the form of not operated truck km. Across 5-months, an average of 9,406 truck visits occurred. Using the Federation for digital exchange unnecessary truck visits in the port reduced, avoiding 30,099.20 km per month. The reduction of port visits also affected the waiting times of trucks significantly. In two scenarios tested in the port the time to check and validate documents at the gate has been reduced by an average of 12.5%, while the waiting time of trucks at the customs gate reduced by 1.7%. Document check and validation at the port gate identified that FENIX federation resulted to 72.4% of the total document flow to be digitally exchanged; an amount 1.94 times higher than the baseline value. Similarly, 5.88 times higher were the digital documents exchanged for customs clearance with the administration work reducing by 95.49%. Across the corridor, important optimizations achieved mainly in shipment visibility (tracked containers and failed deliveries reduction). Almost, 8,000 containers were tracked across 5-months (from a baseline of 0). Also, the success rate

of urban deliveries has increased by 0.68% to reach 99.12% of the total deliveries. Improvements have been recorded to the traffic level in the surrounding areas of the port (urban environment) with 3.74% increase in the average speed of the trucks in the network and 0.75% reduction in traveling times.

Italy: The data collection and analysis concentrated on the Milan Malpensa site of the Italian Rhine Alpine pilot. The federation has been applied to selected operations across different services, focusing on operational times reduction to increase the overall supply chain efficiency. Smart Unload allowed truck companies/freight forwarders to provide a thorough digital description of the goods loaded on trucks that are about to leave the warehouses and reach the Malpensa Cargo City for outward shipment. This information included data about the truck load factor. Smart Move focused on document digitalization of exchange flows otherwise requiring manual data entry or semi-automated processing. Smart Truck aimed to track and trace document acceptance, unload operations and other tasks that truck drivers perform inside the Malpensa Cargo City. Waiting times measured the time difference (in minutes) between document delivery and truck unloading. The percentage of all events which exceed the maximum waiting time as regulated by Malpensa Charter of Services was reduced to 18.86% by FENIX, achieving an average reduction of 0.89% of the required time. The time required for truck unloading has decreased by 10.2%, reduced by an average total of 4.18 min.

4.3 Cost-Effectiveness Analysis

Greece: Two services were found to have the best balance between the cost and the effectiveness (Table 1). The first one was developed for the identification and setup of trigger points from different systems that utilize the HPCS Notifications module to notify all involved parties; the second focused on the implementation of the HPCS Customs Module to improve documentation exchange required for customs clearance. The minimum value of the distribution corresponded to 11.470,59 euro, while the other values are associated with the same distribution, but with higher levels of Cost per average unit of effectiveness. These values are respectively associated with the levels of Cost per average unit of effectiveness ranging from 24.375 to 19.500, from 19.500 to 15.000, and from 15.000 to 12.187.

Italy: In Milan Malpensa, the Smart Clearance service was found to be the one with the best balance between cost and effectiveness (Table 2). This service was introduced with the aim of improving shipment visibility during the logistics operations in airports. The minimum value of the distribution corresponded to 6.769,50 euro, while the other values are associated with the same distribution, but with higher levels of Cost per average unit of effectiveness.

Table 1. Average effectiveness of individual services – Greek Pilot.

Service	Avg effectiveness based on varied KPIs	Cost per avg. unit of effectiveness
Proof of delivery e-preparation	2,83	11.470,59
Customs clearance e-notification	2,83	11.470,59
T&L actors e-notification	2,67	12.187,50
Secure entry to D&C centre	1,67	19.500,00
Cargo monitoring & e-notification	2,17	15.000,00
Cargo bundling	2,00	16.250,00
Cargo notification generation	2,00	16.250,00
Visibility status reposting system	2,33	13.928,57

Table 2. Average effectiveness of individual services – Italian Pilot

Service	Avg effectiveness based on varied KPIs	Cost per avg unit of effectiveness
Smart Unload	2,20	64.019,09
App Smart Move – task management	1,80	59.907,22
Smart Move – management of rolling stock	0,20	553.075,00
Smart Truck	0,60	109.621,67
Smart Corridor	2,67	78.432,75
Smart Clearance	2,00	6.769,50

4.4 Gap Analysis

In relation to gap analysis, the contribution of FENIX in overcoming the gaps is above all raising awareness of the existence of some problems linked to specific areas: some gaps are related to the different regulatory frameworks and legislative systems of the Member States and the European Union and could not be overcome through FENIX.

Greece: Table 3 summarizes the gap analysis in the Greek pilot site showing which services were particularly useful in overcoming a specific gap: 100% of the Gaps declared by the Greek Pilot has been successfully overcome.

Table 3. Services particularly useful in overcoming the gap – Greek Pilot

Service	Services useful in overcoming the Gap
Lack of real-time information	Customs clearance e-notification; T&L actors e-notification; Cargo monitoring & e-notification; Cargo notification generation; Visibility status reposting system
Lack of standardization	T&L actors e-notification; Cargo monitoring & e-notification
Lack of data completeness	Proof of delivery e-preparation; Customs clearance e-notification; T&L actors e-notification; Cargo notification generation; Visibility status reposting system
Low actors' involvement	Cargo bundling; Cargo notification generation
Lack of optimization (resources, infra, planning)	Proof of delivery e-preparation; Customs clearance e-notification; T&L actors e-notification; Secure entry to D&C centre; Cargo monitoring & e-notification; Cargo bundling; Cargo notification generation; Visibility status reposting system
Lack of connectivity/ integration between different systems	Proof of delivery e-preparation; Customs clearance e-notification; T&L actors e-notification; Secure entry to D&C centre; Cargo monitoring & e-notification; Cargo bundling; Cargo notification generation; Visibility status reposting system
Lack of specific systems, services, and technologies (or need for an improvement)	Proof of delivery e-preparation; Customs clearance e-notification; T&L actors e-notification; Secure entry to D&C centre; Cargo monitoring & e-notification; Cargo bundling; Cargo notification generation; Visibility status reposting system
Lack of control of the risks related to cyber-security	Cargo bundling; Cargo notification generation; Visibility status reposting system

Italy: 71% of the Gaps declared by the Milan side of the Italia Rhine Alpine Pilot has been successfully overcome, while the remaining 29% has not been overcome (Table 4). Table 5 shows the reason behind the failure to bridge the gaps.

Table 4. Services particularly useful in overcoming the gap – Italian Pilot

Service	Services useful in overcoming the Gap
Lack of real-time information	Smart Move – task management; Smart Move – management of rolling stock; Smart Corridor
Lack of standardization	Smart Move – task management; Smart Corridor
Lack of data completeness	Smart Unload; Smart Move – management of rolling stock; Smart Truck
Lack of optimization (resources, infra, planning)	Smart Unload; Smart Corridor; Smart Clearance
Lack of a harmonization of legal processes	Smart Corridor; Smart Clearance
Waste of time	Smart Unload; Smart Corridor
Bottlenecks and queues	Smart Unload; Smart Corridor; Smart Clearance
Lack of specific systems, services, and technologies (or need for an improvement)	Smart Unload; Smart Move – task management; Smart Move – management of rolling stock. Smart Truck; Smart Corridor; Smart Clearance
Lack of digitalization	Smart Move – task management; Smart Move – management of rolling stock
Lack of automation	Smart Move – task management; Smart Move – management of rolling stock

Table 5. Reasons behind the failure to bridge certain gaps – Italian Pilot

Gap declared	Reasons behind the failure to bridge the Gap
Lack of appropriate monitoring of emissions	Problems related to the COVID-19 pandemic and consequent time-restriction problems
Lack of strategies for effective emissions reduction	
Lack of connectivity between systems	
Lack of safety	It was not in scope of the FENIX app

4.5 Impact Assessment

The results of the impact assessment for the sites Greece and Italy are displayed in this section. The same settings and weights were used to allow for a fair comparison between the sites. The initial weight preference for KPIs selection via the AHP methodology was set to a shippers' perspective. A variation of this preference will be discussed later in this article. As indicated earlier, different sites and UCs have used different KPIs so that a direct comparison in between sites depends on the ranking of the KPIs. The more KPIs were used in the UCs, the more balanced results could be achieved.

Greece: For Greece, there were 5 UCs and 15 unique KPIs covering various aspects from CO2 emissions over custom procedures and administration work time to shipment status updates. Overall, the result for the site (IAI = 0.631) shows that the implementation of the FENIX connector has a very positive impact on the performance of the site suggesting that the digitalization of the site is a key prerequisite for better performance. In more detail, 3 out of 5 UCs have reached or almost reached the thresholds set for the improved KPI performance, where only 1 UCs did not indicate a significant impact, and one other UC did not report any (valid) data. The Greek site has used the highest number of unique KPIs across the 5 UCs where most of the KPIs were only used once.

Italy: For the first Italian site, the result (IAI = 0.742) shows that the implementation of the FENIX connector has a very positive impact on the performance of the site, especially considering the high number of UCs (although not all UCs were able to provide measurements). The result suggests that the digitalization of the site is a key prerequisite for better performance. In more detail, 7 out of 18 UCs have reached or almost reached the thresholds set for the improved KPI performance, 8 UCs have not reported (valid) data, and only three UCs reported less significant impacts. For the second Italian site (Milan Malpensa), the result (IAI = 0.365) is lower and shows that the implementation of the FENIX connector has some, but not significant impact on the performance of the site, especially considering the high number of UCs. Again, the result suggests that the digitalization of the site is a key prerequisite for any better performance. Three UCs have reported the same data with a not very high performance which results in a relative high weight of this result. Three other UCs have not reported (valid) data, so that it was mostly UCs 6,7, and 8 which contributed to the result.

Comparison: For the Greek site, an Impact Assessment Indicator (IAI) of 0.631 was achieved whereas for the Italian the results range from 0.365 to 0.742, all of which are significant impacts of the implementation of FENIX connectors. In order to achieve comparable results for the different sites, the same settings, specifically for ranking the KPIs (stakeholder perspective), were used for all UCs of all sites. In order to check the variability of the results, this stakeholder perspective was varied using three different perspectives, namely 'Authorities', 'Customers', and 'Terminal Operators'. For the Greek site, the overall result is then hardly varying, showing results from IAI = 0.59 to IAI = 0.633. This confirms that regardless of which stakeholder is looking to the implementation of a federated network, the impact is very positive. For the site Italy 2 (Milan Malpensa), the result range a bit wider, from IAI = 0.331 to IAI = 0.515 where the results tend to be higher than for the initial stakeholders' view.

5 Conclusions

The implementation of the FENIX federated networks into various sites, amongst which the Greek and Italian, has been evaluated according to its technical and operational performance, the cost-effectiveness of specific services, the gap analysis (overcoming certain gaps in the services provided), and an overall impact analysis.

The implementation of the Federation showed a very positive impact across several services and KPIs. Operational improvements ranged from better visibility of shipments,

shorter waiting times, faster truck deliveries, and less emissions. The most effective services were related to a higher visibility of shipments (Italy) and improved notification and exchange of customs documents (Greece). The gap analysis showed that 100% of all reported gaps in Greece and 71% in Italy could be closed, where the remaining 29% were mostly due to pandemic-related issues. Finally, the overall impact assessment compared the success of the FENIX implementation across all sites where the results for Greece and Italy showed excellent overall results using the Federation.

The measurements were all performed around KPIs which were agreed upon at the beginning of the project. Due to practicalities and the way measurements were performed, not all KPIs were measured in the same way and in the same unit. This made a direct comparison sometimes difficult and might have led to (slightly) different results for identical KPIs. These differences, however, have not been significant and had no impact on the overall performance. In addition, the pandemic had some influence on the number of measured data which were performed which has led to some reduction in comparable data sets before and after the implementation of the federated network.

The current study focused on the Greek and Italian sites of FENIX. For a better comparison, the other sites, considering also other aspects of the supply chain (and additional KPIs), should also be considered to obtain a wider picture of the implementation of the FENIX federated network and to confirm results of this study. The FENIX consortium consisted of partners from industry, civil society, public administration, and academia, representing 'ecosystems' around the development and implementation of federated networks in the sites. These ecosystems need to be further developed to allow for more research and tests. The recently started non-profit organisation FENIX 2.0 (https://fenix-network.eu/fenix-2-0) is an example for such an ecosystem which will attract and convince stakeholders (especially from industry) of the value of federation.

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Railway Switches and Crossings: Identifying and Clustering Passages Using GNSS Measurements

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Abstract. This paper proposes a methodology to identify passages of a rail vehicle on switches and crossings using GNSS measurement and the railway infrastructure database of the considered region. Given the imprecision of GNSS measurements, a map matching task is performed. Then, a database containing all identified switch passages is populated, containing construction parameters of the switch as well as passage parameters such as the route taken or the speed of the vehicle. Further, the switch passages are clustered in representative categories. For this, a dimension reduction using the t-SNE algorithm is performed and an agglomerative clustering algorithm is used. The methodology is applied to 2400 km of measured rides of a German regional train, resulting in 2139 turnout passages, classified in 22 clusters.

Keywords: Railway switches · map matching · GNSS · GPS · digital twin · switches and crossings · railway infrastructure

1 Motivation

Today's maintenance of rail vehicles mostly relies on fixed time-based intervals at which components must be inspected or exchanged. This method is easy to apply, yet it does not necessarily consider the actual usage and wear of the assets. This often leads to premature, unnecessary maintenance operations and unavailable vehicles, and, in the end, drives up maintenance costs. This is especially true for the wheelsets of passenger rail vehicles, as they represent up to 50 % of the whole life-cycle costs of a vehicle.

An alternative to time-based preventive maintenance is the digital twin approach: The actual usage and operation of each vehicle are tracked and serve as an input to build a digital model of the asset, allowing to predict wear and tear. Regarding the wheel profile wear, it is necessary to know precisely on which track the vehicle has been operated, and which switch or crossing it has passed. This information can be exported from modern railway infrastructure tools, yet the

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infrastructure manager is not involved in the maintenance process of the vehicles, which are usually operated by an independent railway undertaking having no access to this data.

2 Overview

This contribution proposes and demonstrates a methodology to identify over which switch and crossing elements the vehicle has passed. First, a so-called map matching is performed against the railway infrastructure database. It is presented in Sect. 3.3. Based on this, the passages over switches and crossings are identified as well as the corresponding parameters: curve radius, turnout angle, further construction parameters, vehicle speed, route taken, etc.

The proposed methodology is shown schematically in Fig. 1.

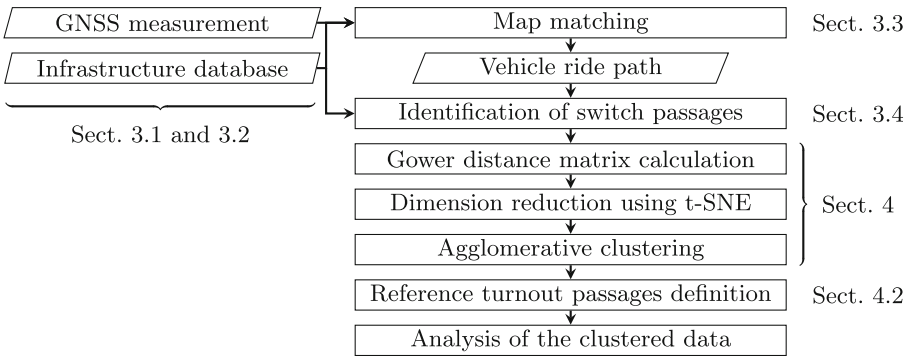


Fig. 1. Workflow of the proposed methodology and corresponding sections in this paper

3 Identifying Switch and Crossing Passages

The study makes use of GNSS (e.g. Global Positioning System, GPS) measurements of a train, which is presented in Sect. 3.1, and of the corresponding infrastructure database, presented in Sect. 3.2.

3.1 GNSS Measurements

DB Regio AG, a subsidiary of Deutsche Bahn AG (DB AG), operates a fleet of regional trains of type FLIRT 3 (BR 429.1) in the so-called SÜWEX network in South-West Germany. One vehicle has been equipped by DB AG with a so-called CTM measurement device. Among others, the measurement device records the GNSS position of the vehicle at a frequency 1 Hz. In total, 2400 km of rides in actual operations in May 2022 are used for this study.

3.2 Infrastructure Database

In order to identify which switches and crossings have been passed by the train, the railway infrastructure database of DB Netz AG, the German state-owned infrastructure manager is used. It is described using nodes and edges. Edges represent the railway track and might be constituted of many intermediate points to describe the track geometry precisely. Edges usually start and end at nodes, which are punctiform objects and represent infrastructure elements such as switches or buffer stops. Nodes are defined by their geospatial position, to which further parameters are appended. For switches and crossings, the parameters of interest in this study are defined in [1]:

- Turnout angle,
- Turnout radius,
- Type of switch element (turnout, crossing, crossing with slips, etc.),
- Nominal rail profile of the switch.

3.3 Map Matching

GNSS measurement usually have a precision of 5–10 m. Identifying which switch element has been passed, and especially with which parameters (e.g. the route: through or diverging, the direction: facing or trailing, etc.) requires to augment the quality of the GNSS measurement. For this, a map matching is performed. Using the infrastructure database described in Sect. 3.2, the measured GNSS points are fitted to the actual track position. The map matching algorithm used is based on a Hidden Markov Model (HMM) using the implementation by Meert [4]. It is very robust as it considers the course of the measured points related to each other instead of each point independently. Figure 2 shows exemplarily the result of the map matching task.

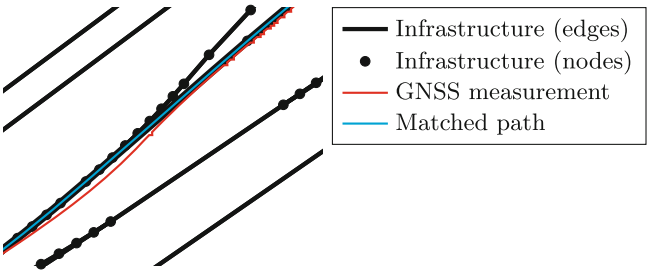


Fig. 2. GNSS measurement errors fitted to the actual infrastructure using a map matching algorithm

3.4 Identifying Switch Passages

The matched path of the vehicle on the infrastructure is used to identify which switch has been passed. An in-house tool developed in Python creates a switch passage database including the information listed in Table 1.

Using the available GNSS measurements, a total of 2139 switch passages have been identified. The distribution between turnouts, crossings and crossings with slip(s) is as follows:

- Turnouts: 90.5%;
- Crossings: 2.6%;
- Crossings with slip(s): 6.9%.

Therefore, only turnout passages are considered for the clustering task presented in Sect. 4.

4 Clustering Switch Passages

The number of 2139 switch passages detected is very high, and would even grow with more measurement data. For further processing such as digital twins using numerical simulation, this corresponds to high calculation time. Also, it is supposed that all switch passages can actually be represented by a limited number of representative switch passages based on similar characteristics of each switch passage. Accordingly, a clustering task is performed to identify these representative switch passages.

The identified turnout passages are classified using the approach described in Sect. 4.1. A reference turnout passage for each cluster is defined in Sect. 4.2.

4.1 Methodology

Clustering is a common application of machine learning algorithms where observations are classified in groups based on their similarity. For this, the observations are described by so-called features, with which the similarity between the samples can be calculated. In this study, the observations are the turnout passages, described by the features listed in Table 1 determined as described in Sect. 3.4.

Table 1. Considered features and their characteristics

Feature	Type of variable	Weight
Velocity	Continuous, numerical	2
Route	Categorical	2
Squared curvature	Numerical, categorical	2
Angle ratio	Numerical, categorical	1
Rail profiles	Categorical	1
Direction	Categorical	0.5

The Gower distance is used as a metric to evaluate the similarity between observations, as it allows to consider both numerical and categorical features [2]. Using the Gower distance matrix, a t-SNE dimension reduction is performed [3]: The observations can now be represented in a two-dimensional plan. This is shown in Fig. 3, where each point represents a turnout passage.

Further, an agglomerative clustering algorithm is used to cluster the observations in 22 clusters. The agglomerative clustering is a common algorithm for this kind of application [6]. The number of clusters has been previously determined by maximizing the silhouette index, a metric to evaluate the quality of a clustering [5]. In Fig. 3, each cluster is surrounded by a gray surface.

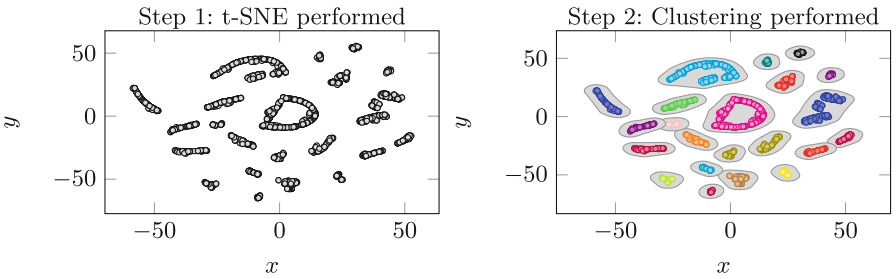


Fig. 3. Dimension reduction (t-SNE) and clustering of the turnout passages in the dimensionless coordinate system x-y

4.2 Definition of a Reference Turnout Passage for Each Cluster

For each of the 22 clusters, a representative turnout passage is defined using the following rules:

- Velocity: Median velocity of the observations;
- Radius and angle ratio: Mean value of the observations;
- Route, Rail profiles and direction: highest number of observations for each feature.

Figure 4 shows exemplarily the distribution of the values of the features for a cluster composed of 218 observations.

5 Outlook

The proposed methodology demonstrates the identification and classification of switch passages using common algorithms and approaches. The applied approach allows the accurate identification and classification switch passages. This methodology can be extended to further measurement data. Especially, considering a higher number of features would allow for a more precise description of

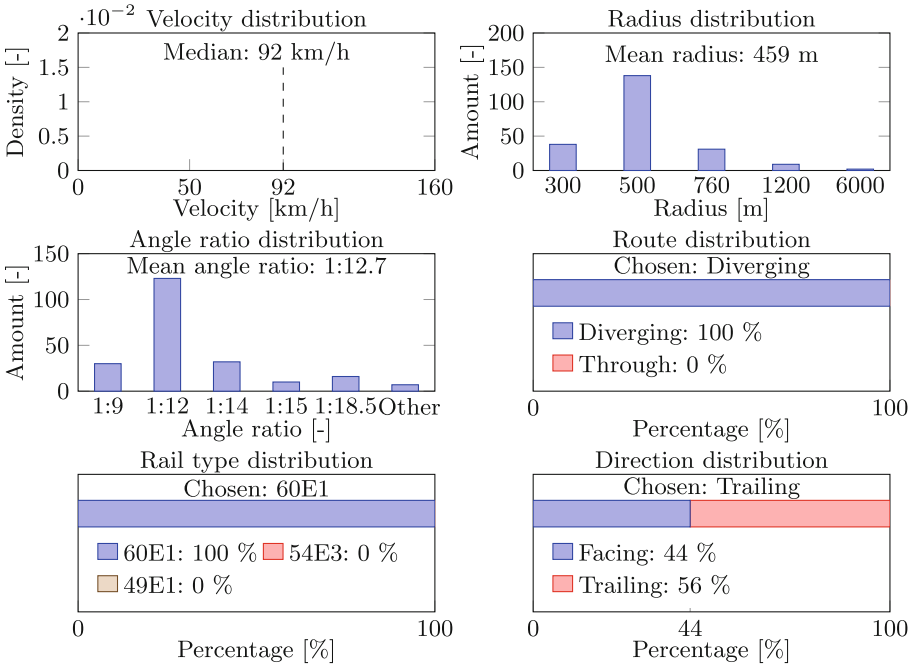


Fig. 4. Exemplary feature distribution of the turnout passages inside a cluster

the switch passages. Also, a fine-tuning of the feature weighting would result in a more relevant and precise classification, fitted for the specific use-case, such as wear calculation or ride comfort evaluation.

The outcome of this study is an accurate description of the switch passage behavior of a rail vehicle. In further processing, the detected switch passages or, more precisely, the representative switch passages of each identified cluster, can be used to evaluate the corresponding wear occuring on the vehicle by using numerical simulation.

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Frugal Connectivity for Railway Applications

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Abstract. Today, new challenges are emerging for the railway industry: the digitalization of the infrastructure and the automation of supervision, maintenance, and even trains. These new requirements and the growing number of applications demand comprehensive connectivity with high reliability, high availability, low latency, and, in some situations, high throughput.

Furthermore, the existing private telecom network dedicated to railway is built on 2G technologies and has to be replaced by 2035. The European FRMCS program relies on the standardization of "5G plus MCx" for railway applications, shifting from a network as an asset vision to a more modern one: the Network as a Service. However, despite the transition from 2G to 5G for the existing infrastructure, a significant portion of the railway network will still lack coverage from the private telecom network.

Given this context, the emergence of new high-performance applications prompts us to explore new telecom solutions, ranging from sharing a public terrestrial network to using satellite communication networks and incorporating millimeter-wave technology. One potential solution could be orchestrating these technologies to provide the train with the best available connection at any point during its journey.

Keywords: SatCom · mmW · 5G · critical communication · orchestration · dedicated network

1 Railway Applications and Related Infrastructure

The railway infrastructure is progressively becoming more digital. Numerous new requirements and emerging applications demand connectivity with high reliability, high availability, low latency, and, in some situations, high throughput.

Historically, the railway industry has relied on private networks to fulfill its communication needs:

- GSM-R for critical applications such as ERTMS (European Rail Traffic Management System) and critical voice communication.
- TETRA for enterprise communication.
- Corded phones on railway tracks for emergency calls.

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These networks offer high availability to meet the security requirements of applications such as ERTMS. However, these criteria necessitate a dedicated infrastructure, incurring significant deployment and maintenance costs. To deploy a private 5G network, the order of magnitude of the cost can reach nearly €100,000 per kilometer with an additional €3,000 per kilometer for annual maintenance.

SNCF manages a railway infrastructure spanning over more than 28,000 km, as shown in Fig. 1. Half of this network is already covered by GSM-R and will be equipped with a private 5G FRMCS network. Nevertheless, due to the high costs associated with deploying and maintaining a private telecom infrastructure, the remaining portion of the network will not undergo digitalization through this mean.

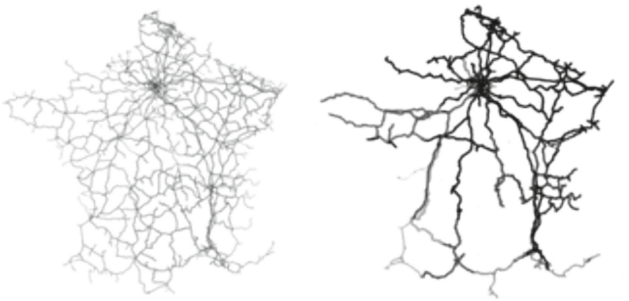


Fig. 1. French railway infrastructure and GSM-R network

2 Future Needs

In a context of reducing the carbon footprint, French Government defined an objective of zero emission by 2050 (in French, the name of the program is ZEN for Zero Emission Net). In 2019, transportation represented 31% of greenhouse gas emission [1] and as we can see in Fig. 2, train is by far the less consuming transportation mode.

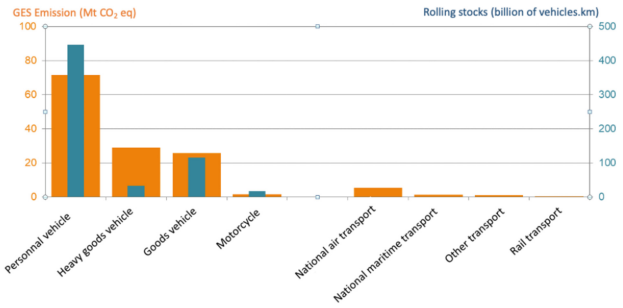


Fig. 2. Repartition of French greenhouse gas in transportation [2]

To reduce the carbon footprint of transportation, SNCF aims to double the fret traffic by 2030 and double the volume of passenger by 2040.

Digitalization and telecommunication are identified vectors which can help this ambition. First, the modernization of the network is a need to simplify the exploitation, bring signaling technology such as ERTMS to reduce the gap between trains or also giving maintenance new tools to reduce incident on the network. Secondly, services are a must have to attract people on train: having internet on board is mandatory, either to use the commuting time to work or to have entertainment.

3 Acceleration of the Digitalization

3.1 FRMCS

In the digitalization process, FRMCS is a key enabler for digitalization, interoperability in Europe and managing new applications with the same general bearer and cybersecurity.

By 2035, FRMCS should replace GSM-R and TETRA network with a private terrestrial 5G network on the 900 MHz and 1.9 Ghz RMR frequency bands; this private 5G will offer 20 Mbit/s per frequency band, and even up to 40 Mbit/s per frequency band if we are considering implementing MIMO. This data rates addresses the needs of all the critical applications and a part of performance ones, as they are described in FRMCS URS specification [8] and summarized in Ericsson study [6]. Nevertheless, private 5G will not answer the whole digitalization of the railway infrastructure:

- very low latency and high-quality, especially for remote driving multiple trains in a restraint area;
- secondary lines will not be covered by this private 5G.

FRMCS use cases define average telecom performance requirements to address the needs of the future railway network; Fig. 3 provides an illustration of these requirements; extract from an Ericsson study [6].

Use Case	Message Type	UL/DL	Data Rate	Latency	Packet Reliability
Voice	Audio	50/50	24 kbps	100 ms	99.9%
ETCS	Position Report	UL	10 kbps	100 ms	99.9999%
	Movement Authority	DL	10 kbps	100 ms	99.9999%
ATO	Journey Profile	DL	10-50 kbps	100 ms	99.9%
	Segment Profile	DL	100 kbps	1 s	99.9%
	Status Report	UL	1 kbps	100 ms	99.9%
Remote Driving	Video & Audio Stream	UL	1 – 7 Mbps	10 ms	99.9%
	Control Data	DL	10-100 kbps	10 ms	99.9999%
Video Surveillance	Video/Audio Stream	UL	1-7 Mbps	100 ms	99.9%

Fig. 3. KPIs for FRMCS defined use cases

If private 5G answers the modernization of the main lines, secondary ones will not be able to support the cost of such an infrastructure. Thus, we need to rethink the possibility to bring high reliability connectivity with secure connection at lower cost. Multiple solutions are under study:

- satellite communication compatible with the specific railway environment combining foliage, catenaries, …;
- deploying millimetre waves technologies;
- hybridizing and orchestrating multiple public and private networks bringing enough security and cybersecurity to guarantee the quality of service for critical applications.

New bearers, such as SatCom, are already considered to be added in the next step of FRMCS specification. This is definitely an opportunity to bring FRMCS connectivity on all the railway lines, even the less used.

3.2 SatCom

In the last decades, SNCF and the railway industry have tested multiple SatCom technologies, giving more and more hope for the possibility of making SatCom an enabler for railway applications.

Thanks to their maturity, GEO satellites used to be the cheapest solution, but MEO and LEO constellations become very attractive in term of pricing. Moreover, it has been proven that GEO Satellite performances do not meet the expectations of railway applications as they are defined today:

- Latency is too high for critical needs as an end-to-end roundtrip involving a GEO Satellite is 700 ms long typically
  - 4 times 125 ms corresponding to the ground-space propagation delay
  - 200 ms of ground infrastructure delay
- Data rates demonstrates less than 1 Mbit/s, which may be sufficient for low-consuming data but not for video needs.
- In term of coverage, GEO constellations face issues with the signal orientation when trains are running through environments such as urban lines, forest or mountain.

LEO and MEO constellations are bringing new hope for railway needs. Technology has evolved significantly in recent decades, with constellations like StarLink offering throughput of up to 200 Mbit/s in the downlink, 25 Mbit/s in the uplink, a latency below 100 ms and costs 10 times lower than previous SatCom operators.

As Starlink is a private American company, this solution is not offering governance, which is highly recommended for critical communication. Fortunately, for European actors, the European Commission has launched an ambitious program to propose SatCom services with a full multi-orbit constellation, named IRIS^2 [4], which is expected to reach full operational capability by 2027.

SNCF is already involved in the IRIS^2 program, leading an innovative project focusing on terrestrial and non-terrestrial 5G interworking, modeling SatCom RF behavior, and exploring SatCom edge computing opportunities. SNCF is also working on LEO

SatCom mobility testing on railway infrastructure, especially through the HSGR project [5].

3.3 Millimeter Waves (mmW)

Another promising technology is millimeter waves. With very high frequencies ranging from 30 GHz to 300 GHz, it offers a very high throughput, enabling, among other things, high-performance Internet on board. Millimeter waves can provide data rates above 1Gbit/s with a 1 ms track to train latency. These performance capabilities meet all rail needs.

One of the key benefits of mmW is to lower the cost of infrastructure, compared to 5G FRMCS or the previous GSM-R network. As we have seen in Sect. 1, civil works is the largest part of the cost of our telecom infrastructure, especially due to the construction of tall pylons and the infrastructure for optical fiber and energy.

These 3 points can be addressed by millimeter waves, especially 802.11ad (WiGig):

- Infrastructure: pylon are smaller and lighter than classic telecom infrastructure and do not require heavy civil works;
- Energy: millimeter waves equipment are low consuming in term of energy and could be supported thanks to an energy autonomous system;
- Optical Fiber: backhaul network can implemented using mmW as a virtual fiber to avoid deploying optical fiber backhaul

Regarding railway use cases, these points are under study from technical and economical perspectives.

3.4 Hybridization

Last but not least, it can be stated that a hybridization of telecom bearers is the philosophy to adopt for our rail infrastructure. Considering our infrastructure spans from mass transit to rural areas, encompassing high-speed lines, it is essential to address the railway needs with a cost-effective and appropriate solution in terms of required Quality of Service (QoS). Figure 4 illustrates this expectation.



Fig. 4. Telecom hybridization through the rail infrastructure

In this hybrid architecture, there are 2 key points to address:

- Using multiple bearers means the telecom system has to be orchestrated at both the Groud and On-Board levels. The FRMCS specification embeds this need through the

TOBA (Telecom On-Board Architecture) Box. Therefore, for future non-FRMCS lines, other solution like ACS [7] or HSGR [5] one could provide with a solution managing seamless connections for rail applications.

- Multiple bearers also imply multiple network access points. This leads to an increase in cybersecurity concerns. Therefore, it is imperative for all projects to include a cybersecurity analysis to disruptions in rail applications. Such disruptions may lead to security or safety issues.

4 Conclusion

New telecom technologies are bringing new solutions to fulfill all rail needs in terms of QoS, cost, and architecture. Given the upcoming work on innovation and specification, a large part of these technologies will be harmonized through 5G or 6G the latest.

Nevertheless, within this multiple bearer system, orchestrators will remain a fundamental component of this future system. For the rail industry, it is important to harmonize these solutions with the future FRMCS TOBA box, which could bring about full convergence for telecom solutions as well as rail applications.

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Improving Cyclist Safety and Infrastructure Planning: A Data-Driven Case Study of Cork City Council Project

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Abstract. This technical paper advocates data-driven urban transportation sustainability, prioritizing cyclist detection via radar and thermal imaging sensors. It offers a model for cities striving to improve cyclist safety and sustainable transit while emphasizing the integration of precise cyclist detection into existing transportation systems. Funded by Ireland's National Transport Authority (NTA) through the Active Travel Grant program, the Cork City Council (CCC) cycle detection project aims to enhance cyclist safety, promote sustainable transportation, and gather data for future infrastructure planning. This aligns with CCC's active travel strategy, highlighting technology's role in supporting sustainable and secure transportation. The paper underscores the critical importance of accurate cyclist detection and provides guidance for urban planners, transportation engineers, and policymakers. Data-driven decisions prioritize safety, sustainability, and a better urban cycling experience. The project evaluates various cyclist detection technologies at 102 Cork city junctions, ultimately selecting radar detectors and thermal imaging. Implementing these technologies ensures precise cyclist detection, counting, and the supply of invaluable data for future planning and cyclist safety. Strategic technology implementation empowers the CCC traffic management system, facilitating accurate cyclist detection and counting, which informs infrastructure investments and safety measures, enhancing the cycling experience and urban efficiency. Continuous data collection and dashboard visualization streamline analysis, fostering improvements in cycling infrastructure for all road users.

Keywords: Active travel · cyclist detection · cyclist priority · adaptive traffic signal control · data-drive decision making

1 Introduction

As global concern over urban vehicular emissions and rush hour traffic grows, more city residents choose sustainable transportation, with cycling at the forefront. Cork County's population surged by 7.6% from 2016 to 2022, reaching 580,000 residents,

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and is projected to hit 800,000 by 2050 [1]. Yet, Ireland falls short of its Greenhouse Gas (GHG) reduction goals for 2030. To tackle these challenges, Cork City Council unveiled an active travel strategy, emphasizing cycling and walking. One crucial project within this strategy is the Cork Cycle Detection Project, addressing safety and convenience at signalized intersections. To boost cycling, the council invests in advanced green signalization and green wave systems for cyclists. This initiative promotes eco-friendly cycling and enhances urban cyclist safety. The Cork Cycle Detection Project employs advanced detection technologies at selected junctions, precisely detecting and counting cyclists. It significantly impacts traffic signal timing, providing secure and efficient routes for cyclists. This paper delves into the methodology, requirement analysis, intersection selection, technology market analysis, and product selection for the Cork Cycle Detection Project. It aims to enhance cyclist safety, promoting eco-friendly urban mobility.

2 Methodology

The methodology employed for the successful execution of the project encompassed various phases, ranging from initial requirements management to the technology and product selection. The following 4-steps methodological framework ensured a structured and efficient approach to achieve project objectives. The following steps were undertaken (Fig. 1):

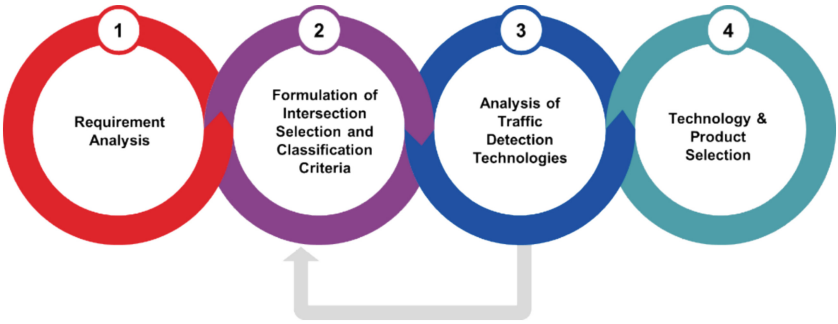


Fig. 1. 4-Steps methodology for technology and product selection process.

1. Requirement Analysis: The specific needs of Cork City for cyclist detections were identified. A comprehensive examination of analogous projects and technical references from Europe and the United States provided valuable insights into best practices and methodologies.
2. Formulation of Intersection Selection and Classification Criteria: An essential step in the process involved the development of a logical foundation for selecting and categorizing intersections based on well-defined criteria.
3. Analysis of Traffic Detection Technologies: Extensive research was conducted to evaluate the market for traffic detection technologies.

4. Technology and Product Selection: Considerations were technology and product selections were defined to identify the suitable technologies and products for the identified Cork City intersections.

Throughout the process, an iterative methodology was applied when necessary. For instance, adjustments were made in response to the outcomes of the traffic detection market analysis, which in turn influenced the development of intersection selection criteria, creating a dynamic and responsive approach to project execution. This iterative nature ensured the project's adaptability and effectiveness.

3 Requirements Analysis

This section synthesizes insights from a literature review and feedback from other city councils with similar projects. These collective insights shape the tailored requirements for the Cork City Cyclist Detection Project.

3.1 Literature Review

The review covered key sources: The literature review encompassed the following key sources:

1. Traffic Detector Handbook: FHWA's handbook offers insights into traffic detection systems, serving as a foundational reference for defining requirements. It provided comprehensive insights into the principles and practices of traffic detection, aiding in understanding the technical aspects and operational considerations essential for our project.
2. Netherlands Bike Sensors: Insights from the Netherlands' advanced bike detection technology inform benchmarking and relevant requirements. This source provided a comparative analysis of different detection methodologies, enabling us to identify innovative approaches and potential solutions applicable to our requirements [6].
3. Cycle Safe Intersections in Dublin: This study evaluates bicycle detectors in Dublin, offering insights directly relevant to the Cork project. This source provided practical recommendations that can inform the design and implementation of our project's bicycle detection infrastructure.

3.2 Feedback from Dublin and Limerick City Councils

Feedback from these councils informs Cork's requirements, providing real-world input from cities facing similar urban challenges. The councils' insights offer valuable perspectives on the practical implementation and performance of traffic detection systems, including bicycle detection, in urban environments.

3.3 Cork Cyclist Detection Project Requirements

Cork Cyclist Detection Project are formulated by synthesizing insights from the literature review and feedback from other city councils with similar projects. These collective

insights shape the tailored requirements for the project, aligning with the real-world input obtained from cities facing similar urban challenges.

The technology and product selection for the Cork Cyclist Detection Project are guided by the following requirements, derived from a combination of literature insights and feedback:

1. Demand-based Green for Cyclists: Addressing a fundamental need, this requirement ensures that nearly all of Cork City's intersections grant green signal phases based on cyclist demand, reducing wait times.
2. Advance Green for Cyclists: This feature enables safe cyclist crossings by providing a green signal ahead of vehicles.
3. Cycle Data Collection and Stats: To inform planning and improvements, detectors must count cyclists and transmit data centrally.
4. Public Dashboard Presentation: Data integration into Cork City Council's public Active Travel Dashboard promotes cycling within the city.
5. Compatibility with Future Implementations: The project must be adaptable to future initiatives, including green wave systems and cyclist prioritization.
6. Performance Requirements: Metrics, particularly accuracy rates for cyclist detection and counting, align with the project's objectives of improving safety and enabling data-driven decisions.

4 Intersection Selection and Classification

Over 200 signalized intersections in Cork underwent analysis for cycle detection suitability and necessity. This assessment considered intersection complexity, available vehicle detectors, presence of cycle facilities (e.g., cycle tracks, dedicated lanes), cyclist waiting bays, and signal phases. Out of these, 109 intersections were identified for cyclist detector installation. To cater to varying requirements and characteristics, intersections were classified into three classes:

Class 1: Basic Functionality for Outlying Junctions

This class for the junctions located furthest from city centre where only detection is requirement without counting function where the mode of traffic control is traffic actuated or semi-traffic actuated.

Class 2: Higher Accuracy for Complex Junctions

This class is considered for the junction where the number of lanes is more than two and or right turns have separate signal phase. This class is considered for where both detection and counting are requirements. This is particularly important for the junctions with cyclist waiting bays in front of vehicles as they should be behaved as same vehicles to be awarded with green time based on the demand, they send to intersection controllers.

Class 3: Highest Accuracy for Critical Locations

This class aims for the highest accuracy for critical locations where high volume of cyclists are anticipated. This class is considered for where both detection and counting are requirements. Another important requirement for these locations is that they have cycle tracks or dedicated cycle lanes and share a space with pedestrians. On the other hand, this class also covers some mixed lanes where highest accuracy of detection is required.

5 Analysis of Cycle Detection Technologies

In this section, we present a comprehensive evaluation of the various cyclist detection technologies considered for this project:

1. Induction Loop Technology
2. Video Technology
3. Active Infra-Red Technology
4. Lidar Technology
5. Mobile App based Detection.
6. Radar Technology
7. Thermography/Thermal Camera

Each technology's strengths and limitations are analyzed to inform the selection process for Cork City's cyclist detection project.

Induction Loop Technology: Induction loop detectors have a long history of providing vehicle detection but are less effective for cyclists. They can struggle with calibration when used in lanes shared by different vehicle types, as sensitivity adjustments to detect bicycles might inadvertently trigger sensors for other vehicles. Additionally, they rely on detecting the metal in bicycles, making them incapable of identifying non-metallic bikes.

Video Detection Technology: Video detection technology uses cameras for detection, but it's susceptible to adverse weather conditions, such as rain, sun, and fog, which can reduce accuracy. This technology may have challenges counting cyclists due to their smaller size.

Active Infrared Detection Technology: Active infrared sensors use low-power infrared energy to detect vehicles and cyclists. While they are commonly used in traffic detection, their applicability to cyclist detection is limited and unproven. They are also vulnerable to weather and lighting conditions.

Radar-based Detection Technology: Radar-based detectors use Continuous-wave (CW) Doppler and Frequency-modulated continuous-wave (FMCW) techniques to detect vehicles and cyclists at junctions. They can classify various road users, including cyclists, with high accuracy. Installation and maintenance typically require minimal road closures.

Thermography/Thermal Camera: Thermal cameras are highly accurate, thanks to their heat-sensing technology, and are impervious to factors like oncoming headlights and environmental elements. They can monitor multiple traffic zones effectively. However, they may have obstructed views and are relatively costly.

Lidar Detection Technology: Lidar is a precise and reliable technology but is often complex and expensive. It's commonly used in environmental mapping and autonomous vehicles rather than traffic detection.

Mobile App-based Detection Technology: This technology relies on smartphones and sensors for cyclist detection. It's cost-effective but depends on user participation and sensor quality. Mobile app-based solutions are often used in conjunction with other detection methods to enhance accuracy.

6 Analysis of Cycle Detection Technologies

6.1 Consideration for Technology Selection

Existing Urban Traffic Control and Management System: Our selection process considers the existing traffic control and management system. Intersections are managed using vehicle actuated signals or SCOOT. Basic solutions were considered for vehicle actuation intersections, while advanced technologies were explored for SCOOT.

Junction Layouts and Signal Plans: Cyclist facilities like cycle tracks and dedicated lanes influence our technology choice.

Characteristics of Cycle Infrastructure: The presence of cycle facilities like cycle tracks and waiting bays is considered.

Intersection Classification: Intersection classifications, as outlined in Sect. 4, are harmonized with the above-mentioned aspects to determine technology choices.

6.2 Selected Technologies and Products

After careful assessment, Radar-based and Thermal Camera Technologies were chosen based on a comprehensive evaluation of detection technology and market product analysis. Upon evaluating available market products, distinct solutions were identified for each class (Table 1):

Table 1. Comparison of selected technologies for different intersection classes.

Product	Yunex Heimdall Radar	Smartmicro UMRR-11 Type 132	Class 3: Flir Thermicam AI
Intersection Class	Class 1	Class 2	Class 3
Stop Line Detection	X	X	X
Approach Detection		X	
Counting		X	X
Classification		X	X
Advance Green		X	X
Green Wave		X	X
Prioritization		X	X
Number of Lanes	1	6	2
Accuracy	Good	Very Good	Excellent

Class 1: Yunex Heimdall Radar: The Yunex Heimdall Radar is a straightforward choice for Class 1 junctions, offering cyclist detection without classification or counting capabilities. Its affordability, direct connectivity to Cork City's intersection controllers, and easy installation on traffic signal poles make it ideal for single-lane junctions far from the city center.

Class 2: Smartmicro UMRR-11 Type 132 – 77Ghz Radar: Smartmicro's UMRR-11 Type 132 radar excels at detecting cyclists, especially in complex intersections. Operating at 77 GHz, it boasts high accuracy (anticipated over 90% for detection and over 85% for

counting). Suitable for advanced features like green wave, cyclist prioritization, and data collection, it can cover up to 6 lanes. An extension pole is recommended for elevated mounting.

Class 3: Flir Thermicam AI Thermal Camera: The Flir Thermicam AI thermal camera offers exceptional accuracy (anticipated detection rate over 95% and counting rate over 90%) for critical intersections with up to two lanes. It supports advanced features like green wave and prioritization but doesn't track cyclists for extended periods. While it's the most expensive option, mounting it on an extension pole ensures unobstructed views. These technologies are chosen to suit different intersection classes and cycling infrastructure scenarios in Cork City's cyclist detection project, providing a comprehensive solution.

7 Conclusion

In conclusion, the Cork Cycle Detection Project, a significant initiative led by the CCC, addresses the challenges posed by urban growth, emissions, and sustainability as Cork County's population approaches 800,000 by 2050. In line with the council's active travel strategy, the project enhances cyclist safety at intersections using advanced detection technology. Following a structured methodology outlined in Sect. 2, Radar-based and Thermal-based detection methods were selected for various intersection classes. This strategic approach improves signal timing, alleviates congestion, and reduces emissions, thereby promoting cycling as a more appealing and healthier transportation option. Furthermore, the project's data supports sustainable urban planning efforts and encourages public involvement through the Active Travel Dashboard. Serving as a model for similar initiatives, it highlights the transformative potential of technology-driven solutions in fostering a sustainable, cyclist-friendly future.

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Operational Obstacles of the Building Information Model in Railway Infrastructures

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Abstract. The development of a BIM (Building Information Model) digital model of a railway infrastructure is based on the various BIM standards. This BIM digital model can also be a part of a digital twin. BIM standardization work (pre-standardization phase) and BIM digital model work (post-standardization phase) must ensure four levels of interoperability: semantic, organizational, technical (or technological tools) and legal. The various actors in the railway sector need to have, in each phase, visibility of the operational obstacles to be dealt with and their articulation. In this context, an empirical study based on the ISO 9001 standard, makes it possible to identify the main findings. It ranges from the implementation to the operation and maintenance of the works in the two phases (pre and post-standardization), and this, on the four levels of interoperability. This empirical study allows to summarize the operational obstacles such as the maintenance of the IFC standard; its implementation by software publishers; adapting the LOIn standard to the railway sector; sharing object libraries in OpenBIM; lack of training, understanding, or application of BIM standards in BIM digital model projects, etc. Finally, this study ends with the identification of priorities in terms of actions and describes their added value, in order to improve the management of the life cycle of standards and digital BIM models.

Keywords: Railway · BIM · Standardization · IFC · IDM · LOIn

1 Introduction

Digital transformation has profoundly reshaped the way we design, build and manage infrastructure, particularly in the transportation sector. In this context, the concepts of digital continuity, interoperability, standardization and building information modeling (BIM) have emerged as fundamental pillars for the efficient, integrated management of complex infrastructure projects. These concepts have been the driving force behind the development of innovative solutions, including the digital twin, to overcome the challenges inherent in infrastructure design, construction, operation, and maintenance.

The notion of digital continuity represents the ideal of a smooth, frictionless transition between the different phases of an infrastructure project. In this context, **interoperability** is described as the ability of different systems to function and exchange information with each other in a coordinated manner. It is characterized by several levels: semantic,

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technical, organizational and legal [1]. Interoperability makes it possible to develop high quality products while reducing costs throughout their life cycle.

Interoperability standards (including those for BIM) play a key role in defining common terminologies, protocols and specifications to facilitate communication and data exchange between the parties involved. However, the development of technical-technological interoperability standards, such as the IFC, is based on knowledge engineering and model-driven engineering (MDE) [2].

BIM is emerging as an integrated approach to the lifecycle of buildings and infrastructure. BIM is a methodology that consists of: putting in place "processes" that define the working methods used by project stakeholders to circulate "information" between them; using a common "standardized terminology" to ensure semantic interoperability; predefining standardized data exchange "formats" to ensure the interoperability of the "technological tools" used [3]. However, the transition to optimal use of BIM is not without its challenges, and it is in this context that the concept of DT is emerging.

The DT concept consists of creating a digital representation of a physical entity (system, product, process, or other) that can be synchronized at a given frequency and with a specified fidelity [4, 5].

In this introduction, we delve into the complex world of railway infrastructures and explore the operational hurdles involved in implementing BIM, from standardization to reality in the field. We look at the specific challenges encountered in the pre- and post-standardization phases, taking into account semantic, organizational, technical and legal levels of interoperability. The aim of this study is to identify the major issues and propose courses of action to improve the lifecycle management of BIM standards and digital models, thereby contributing to the harmonious evolution of the rail sector in the era of digital continuity and the digital twin.

2 Methodology

The ISO 9001 standard [6] can be summarized in four key stages: Plan, Do, Check and Act. Firstly, the "Plan" stage is characterized by the production or updating of processes. In the second phase, the "Do" stage is characterized by the adoption of processes, with awareness-raising and change management support for human resources. Thirdly, the "Check" stage is characterized by verification and analysis through audits, surveys and/or feedback. In the fourth stage, the "Act" phase is characterized by improvement through corrective and predictive actions.

In view of the work carried out in the various projects to develop BIM standards and BIM models. We felt it essential to position this article, which identifies the operational obstacles hindering BIM implementation, in the "Check" stage, analyzing the two previous stages. This will enable us to propose adjustments and/or improvements that decision-makers can include in the "Act" stage of the concerned projects.

The "Check" stage involves an empirical study. 46 interviews are conducted on two types of projects: **standardization & BIM models**. Four levels of **interoperability** were examined: **semantic, technical, organizational, and legal** (Fig. 1).

An interview guide was drawn up, and a selection of the most complete sample enabled us to carry out a series of interviews. These are analyzed in the following section.

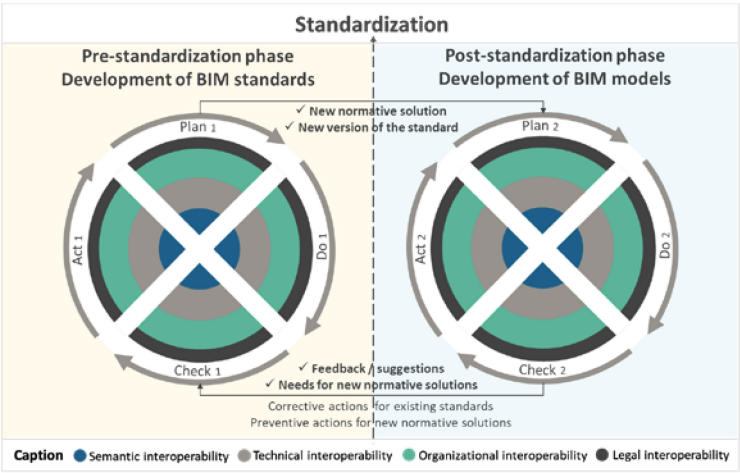


Fig. 1. A quality improvement process in line with ISO 9001 standard, describing two types of projects: "development of BIM standards & BIM models" on four levels of interoperability: semantic, technical, organizational, and legal.

3 Experimental Results

In this section, we present the results of our empirical study. These results first list the various operational obstacles to the implementation of BIM in the railway sector. Secondly, they are categorized in a table identifying, on the one hand, the type of interoperability involved and, on the other, the type of the concerned project (Table 1).

1. Obstacles to legal interoperability arise from the contractual aspect of collaboration. More specifically, in data management. Some of these elements are not taken into consideration: data/model ownership; responsibility for data/model production and evolution; lack of standardization requirements, protocols, and disputes; responsibility of the collaborative work coordinator for data sharing, access rights, data protection (copyright). In the absence of one or more of these elements, the repercussions are as follows: increased organizational workload; loss of workflow automation, with difficulties in searching, extracting, modifying, integrating, exchanging, and sharing data throughout the product lifecycle.
2. Lack of requirements to apply the interoperability framework in contracts for collaborative projects to develop BIM-related standards.
3. Standards provide a basis for harmonizing and aligning practices. However, they cost money and are not always purchased or made available in projects.
4. Open access documentation for the various standards is very poor.
5. Explanations are sometimes missing from certain standards, making them difficult and/or confusing to understand.
6. Lack of awareness of existing standards and repositories, which fall within the scope of the standard or the BIM model to be developed.

7. The effectiveness of standards improvement is reduced, due to the absence of decision history, as well as the processes developed and followed on previous versions.
8. The methodologies used to develop standards (e.g., the IFC standard, since 1997) are not called into question, as they are considered too costly to rework on new bases. This makes modifications and/or extensions equally difficult and costly. In particular, this difficulty is linked to the lack of one of the levels of models based on the Model-Based System Engineering (MBSE) approach, called the Platform Independent Model (PIM).
9. Lack of requirements for interoperability standards in projects.
10. Need for a common and explicit vocabulary, as well as the definition of a paradigm (tools, methods, means) for aligning railway concepts from heterogeneous sources.
11. Lack of continuous improvement in organizations (audit, change strategy, training, follow-up and feedback) for effective change management.
12. A state of the art on common industry resources, know-how from previous projects, and their feedback are sometimes neglected.
13. Each stakeholder (infrastructure manager, rolling stock manufacturer, etc.) has its own frame of reference for these activities, which leads to difficulties in aligning their requirements for producing BIM models and DT.
14. Resistance to change in the current industry culture, requiring change management towards new digital practices. The following challenges have been identified: Lack of acceptance of BIM by management and/or employees; Lack of awareness of the benefits of BIM; Lack of interest from customers, partners, and employees in establishing BIM contractual elements; Lack of BIM experts in the rail sector.
15. Optimal choices of materials, technological tools and associated training are often not profitable for organizations in the short term. This is also the case for change management, including the definition of production and/or business processes.
16. The extension made to the IFC4x3 standard includes railway infrastructure objects, but not all software publishers have implemented it yet. This creates a need for mapping between IFC4 and IFC4x3 to ensure the digital continuity of BIM models.
17. Unavailability of Open-BIM object libraries for the rail sector. They are only developed in Closed-BIM within organizations.
18. In the railway sector, BIM models can be extremely detailed and complex, which can make it difficult to apply numeric simulations in a timely manner. It is therefore essential to find the right balance between model accuracy and BIM model performance requirements. However, on the one hand, BIM models are produced for specific use cases and not for large-scale use. And on the other hand, libraries of railway use cases (UC) and libraries of related information exchange requirements (EIR) do not exist. This wastes the time of project stakeholders, who must redefine these EIRs for each UC themselves.
19. Lack of semantic clarification of the different modeling level expectations for each system/subsystem. The Level of Information Need (LOIN) standard offers a methodology for identifying the levels of detail and information of objects (geometric information, structured data and related documentation). The rail industry believes that LOIn should be used as a basis for specifying detail and information requirements to optimize the performance needs of a BIM model. Object complexity levels can

therefore differ. They are convinced that LOIn can help them, but they fear that they do not have sufficient hindsight on the complexity of the work involved in implementing this solution.

20. The rail industry needs to develop several Model View Definition (MVDs). To date, only one MVD has been developed.
21. Collaborative platforms dedicated to BIM collaboration are not always a systematic choice in railway projects. On the one hand, because of their cost, on the other, because of each partner's choice of platform, and finally, because of the ambition to create one tailored to the needs of the rail industry. The latter is the subject of an analysis of minimum and optional functionalities according to special UCs. It also considers the feedback of the business and the feedback on the levels of interoperability it must ensure. We cite the MINERVE project as an example.
22. DT projects are numerous, but it is important to be vigilant about the standards framework for interoperability right from the start. DT architecture methodologies are diverse and varied, but the experts agreed on two references to frame their work: the ISO 23247 standard and the Digital Twin Consortium. Examples include the TELLi and MINERVE projects.

Table 1. Categorization of results by type of interoperability and type of project concerned.

Type of interoperability	Projet type	
	Standards development	BIM model development
Semantic	2, 3, 4, 5, 10, 13, 22	3, 4, 5, 10, 13, 18, 22
Technical	1, 8, 10, 16, 18, 19, 20	1, 10, 13, 16, 17, 18, 19, 20
Organizational	1, 2, 3, 6, 7, 11, 12, 14, 15, 21, 22	1, 3, 6, 9, 11, 12, 14, 15, 18, 21, 22
Legal	1, 21	1, 21, 22

4 Conclusion

In the railway sector, to ensure optimal digital continuity for all types of digital projects, whether collaborative, competitive, or otherwise, it is crucial to implement appropriate measures from the project's inception. For this purpose, we suggest the following actions:

1. Maturity analysis: Conduct an initial evaluation of the normative interoperability knowledge, BIM, and digital twin (DT) of all stakeholders using an assessment grid.
2. Digital continuity manager: Appoint a digital continuity manager for the project, proficient in the normative framework of interoperability based on open standards. This manager should draft an agreement outlining the four levels of interoperability to ensure effective information exchange (human-human, human-machine, machine-machine).
3. Awareness and training: Provide, if necessary, awareness and/or training sessions on specific interoperability standards.

4. Documentation and communication: Document and share the project results and feedback.

Continuous improvement within each organization is based on the analysis of project output data. Enhancing internal and external interoperability levels will rely on analyzing process quality and implementing necessary adjustments.

This digital revolution continually requires evolution and innovation to effectively respond to the challenges of the rail sector.

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Fiber-Optic Technology for Monitoring Asphalt Roads-Results of a Feasibility Study

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Abstract. Infrastructure operators such as the Autobahn GmbH of the Federal Government in Germany depend on being able to use as much information as possible about the existing infrastructure for planning and maintenance. In addition to the existing non-destructive measurements, monitoring with sensor technology built into the infrastructure can also provide useful information for efficient maintenance planning. As part of a feasibility study, various setups of new developments in fiber-optic sensors were installed in a rehabilitated autobahn section in order to investigate traffic-related information as well as long-term integrity. In addition to temperature monitoring during the road construction, strain and acoustic measurements were recorded and evaluated during defined crossings of traffic. The preliminary results show that traffic relevant information such as the counting of passing vehicles, their velocity, vehicle type and axle load can be derived from the fiber-optic data. Furthermore, the results suggest that relevant parameters about the elastic properties of the roadwork (Young's Modulus and material fatigue) can be extracted. At the present time, considerable efforts are still required for data preparation and data analysis to apply this monitoring technology permanently. This is the objective of the current and future development stages.

Keywords: fiber-optic sensing · temperature measurement · strain measurement · acoustic measurement · asphalt roadwork · integrity monitoring

1 Introduction

1.1 Problem Statement and Motivation

Roads have a certain service life. Depending on the climate conditions and the amount and type of loading, the durability can alter vastly [1]. This is mostly due to the embrittlement of the bitumen compound in the asphalt composite. Due to climate change, the roads heat up more and more which potentially leads to a faster degeneration of the mechanical integrity of the road. By legislation, roads need to be repaired after

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12–15 years (top asphalt layer) and 30 years (down to the top of gravel base layer) to guarantee safety. This is costly, inefficient and has a high potential for optimisation in terms of energy and resource investment. Up to date, the road integrity is assessed with a broad spectrum of non-destructive measures [2]. These measures however only give punctual information of the road structure both in terms of spatial localization and in time. Distributed fiber-optic sensors are robust and allow to passively monitor relevant information such as temperature, deformation and acoustics in real-time at all locations of the cable installation. The aim of this feasibility study is to obtain both traffic-related information and information on the long-term integrity of the road surface. A tailor-made design including numerous fiber-optic sensor cables and layout strategy was developed and implemented in a rehabilitated section of a high-way.

1.2 Introduction to Fiber-Optic Sensing

"Fiber-optic distributed sensing" is a collective term for a variety of optical measuring devices designed to record physical data along an optical fiber. The operation of the measuring devices is shown in simplified form in Fig. 1. A measuring unit pulses light into an optical fiber. At each location along the optical fiber, a small fraction of the light is backscattered by inhomogeneities of the glass. The two-way travel time of the light in the glass can be used to determine the location of the reflection. The evaluation of the backscattered light allows conclusions to be drawn about the physical state or changes in state at this location, e.g. strain or strain rate or temperature.

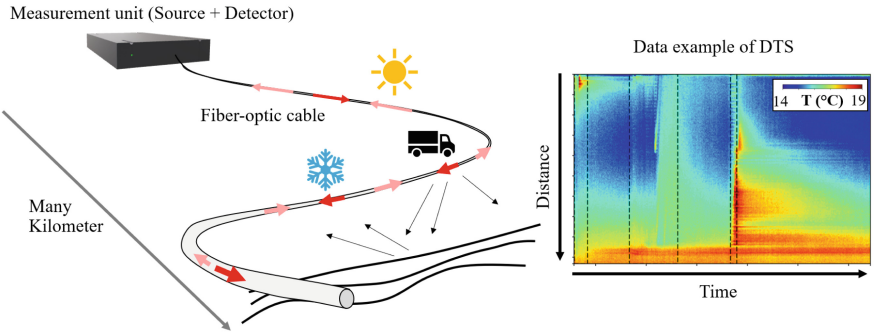


Fig. 1. How distributed fiber-optic sensors work.

The three fiber optic measurement systems listed below were used in the pilot study:

1. "Distributed Temperature Sensing" (DTS) names the technology that uses the optical fiber in a distributed manner, i.e., each location of the optical fiber, as a temperature sensor [3]. DTS is an established technology and routinely used e.g. in geothermal boreholes to measure the spatio-temporal temperature patterns therein [4, 5]. A DTS data example is shown in Fig. 1.
2. "Distributed Acoustic Sensing" (DAS): when an optical fiber is contracted or dilated, the strain rate of the fiber, i.e., the time derivative of the relative length change, can

be measured [6]. DAS technology has found a broad field of applications in science and engineering of the last years. With respect to traffic monitoring, studies have shown the potential to use DAS technology on standard telecommunication glass fibers which run parallel to roads to observe, categorize and count traffic [7–9].

3. "Fiber Bragg Grating" (FBG) measures the strain of the fiber compared to DAS technology at a small number of point sensors. These are realized by optical gratings, which are permanently inscribed at defined points on the fiber.

2 Pilot Study Site

Figure 2 shows a schematic overview of the pilot study site with the locations and depth of the installed fiber-optic cables. Two fiber-optic cables are installed diagonally over the roadway and permanently installed below the surface at different depths. One cable is installed at the interface between the gravel base layer and the base of the asphalt base layer ("Cable A"). The second diagonal cable is installed within the asphalt base layer ("Cable B"). Furthermore, a cable is permanently installed below the main traffic lane (first lane) parallel to the driving direction for several hundreds of meters within the asphalt base layer ("Cable C"). "Cable A" and "Cable B" each contain 10 FBG sensors which are placed in such a way, that 5 sensors are distributed below the 1st lane and 5 sensors are distributed below the 2nd lane. The long "Cable C" contains fibers that allow for DTS and DAS measurements. No additional FBG are present in "Cable C".

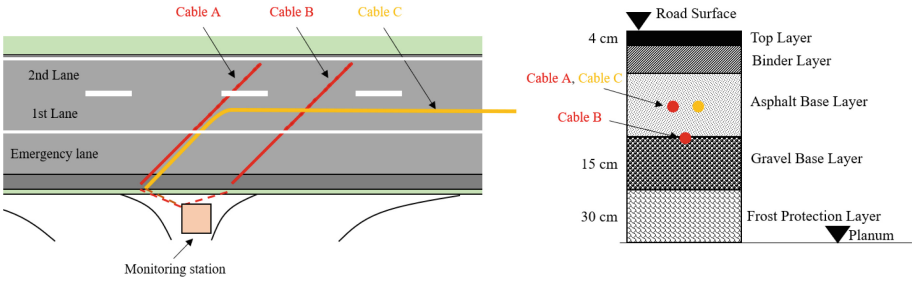


Fig. 2. Schematic overview of the installation locations of the fiber-optic cables (left) and cross section through the highway section with installation depth of the cables (right).

2.1 The Monitoring Campaigns

Two measurement campaigns were conducted in the frame of the feasibility study. First, the construction process of the overlying asphalt layer was monitored and documented with DTS. Second, DAS and FBG measurements recorded the passage of different types of vehicles with defined dimensions, weights, velocities and orientations relative to the sensing fiber-optic cable. In this publication, we focus on the outcomes of the DTS and DAS measurements.

Continuous DTS measurements accompanied the asphalt work of the second part of the asphalt base layer (between Cable A and C and the base of the binder layer) with a measurement repetition rate of 1 min, a spatial resolution of 0.5 m and a measurement accuracy of +/− 0.1 °C. In parallel, temperatures of the asphalt at the pavers is occasionally recorded with a temperature probe.

A 3-h measurement campaign with DAS was performed along cable C after the asphalting process of the top asphalt base layer was concluded. The regular traffic is redirected over the opposite lane of the high-way. Numerous test drives were conducted along the installed cable length on the closed road. The DAS data recorded the strain rate with a sampling rate of 1000 Hz, an optical pulse length of 10 m and a spatial sampling of 1 m.

3 Results

3.1 DTS Monitoring During the Pavement Process and Cable Testing

Figure 3 shows an example of the recorded DTS data during a full day work shift.

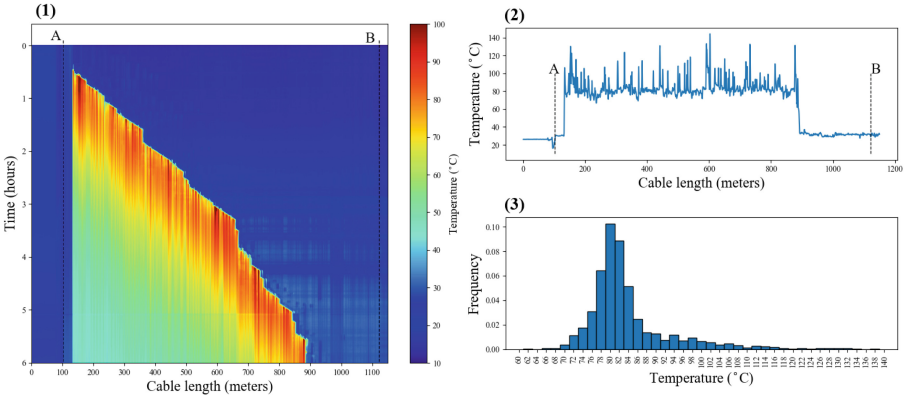


Fig. 3. DTS measurements during the pavement of the second layer of the asphalt base layer.

The first subplot (left) shows a colormap with the length of the cable on the x-axis and the time on the y-axis. The vertical dashed line marked “A” at 100 m shows the feed-in location of the fiber-optic cable from outside into the asphalt area. At the working day prior to the data set, 33 m of road have already been paved (between 100–133 m). Slightly elevated temperatures are still present in this interval prior to the asphalting start of the day. The pavement process of the day starts at 0.5 h at 133 m indicated by the sudden heating of the fiber-optic cable up to 100 °C. After 5.5 h, the last asphalt truck of the day reaches at a distance of 885 m. The vertical line “B” marks the cable exit from the road at the rear end. The step-like appearance of the heated interval along the fiber is related to interruptions in the supply of asphalt material.

The second subplot shows the maximum temperature that is reached for each location during the working day and the third plot a histogram with the temperature distribution

of the pavement process. On average, the maximum temperature reached at the base of the asphalted layer is 84 °C. On the lower side, maximum temperatures go as low as 70 °C, with some isolated exceptions down to 62 °C. Towards the high side, temperatures reach up to 118 °C, with exceptions up to a maximum of 132 °C. The temperature probe recorded temperatures at the top of the asphalt layer in the range of 115 °C to 125 °C.

3.2 DAS Monitoring During Vehicle Crossing Over the Asphalted Road

Figure 4 shows a 60-s excerpt from the DAS measurement campaign. The location along the fiber-optic cable is shown on the horizontal axis. The time is proceeding from top to bottom. The color coding shows relative compression of the fiber in blue color and relative extension in red color. The passing-by of multiple vehicles can be seen as diagonal streaks in the picture. The marker "car" shows a car at constant velocity driving along the cable where the slope of the streak is equal to the car's velocity. At 450 m, the car decelerates due to an accelerating construction side vehicle (parking position at 560 m) heading towards the car. The car accelerates once the other vehicle has passed. A number of other road users are visible in more subtle/faint colors. These events stem from the traffic on the redirection lanes travelling parallel to the fiber in more than 12 m distance.

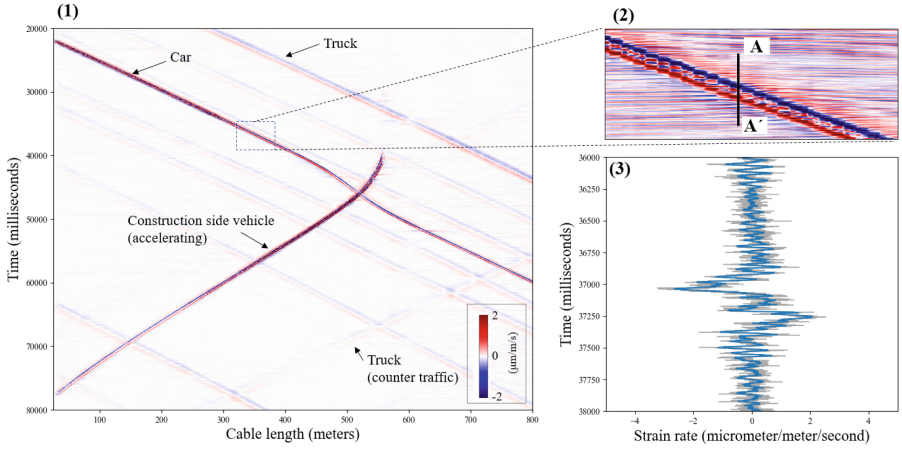


Fig. 4. DAS example data set of a test drive. (1) DAS colorplot of a test drive with additional surrounding traffic (2) close-up of the DAS response of a passing car (3) strain-rate profile along the line marked in panel (2) from A to A′.

The subplot 4(2) shows a close-up of the DAS recording with a profile marked from A to A'. The strain rate response for this profile is shown in the subplot 4(3). The passing-by of a car gives the characteristic response of a phase of relative compression of the sensing fiber followed by a neutral phase and a phase of relative extension of the fiber. The integral over time of the strain rate response (which is the strain) moves back to the initial state after the mechanical excitation from the bypassing vehicle.

4 Discussion and Outlook

In the scope of a feasibility study, the potential of distributed fiber-optic sensing for road and traffic monitoring is assessed. The DTS data clearly delineates the asphalt paving progress, which is indicated by the sudden temperature increase. The data also shows intervals in which the asphalting process was interrupted by the stopping of the temperature front. It is found out that the average temperature at the base of the asphalted layer is significantly lower compared to the temperature measured by the asphalt paver. The DTS data gives valuable information for the road operator about the workflow during the pavement process in terms of efficiency as well as quality of the fresh material. DTS also allows for a better management of construction site opening to traffic. DTS measurements of the pavement process is just the first phase of life cycle monitoring. Over the entire lifetime of the road, the operator is now able to acquire valuable temperature data from the inside of the road passively in real-time.

The results from the DAS data show a clear deformation signal during controlled drives with test vehicles. The velocity of a passing vehicle is simply extracted from the recording by analysing the slope of a passing vehicle in the time-space-domain. The distinction of a vehicle type is also realisable by analysing the strain response over time at a fixed location. The strain curve in Fig. 4(3) shows a typical curve for a passenger car. With increasing weight and number of axes of the vehicle, this pattern will change accordingly. The measurement of the axle load of a vehicle is also possible but still requires further work for an accurate assessment. Currently, much work is being done to set-up an empirical model that links the one-dimensional strain array from DAS with a mechanical deformation model of the loaded substrate. Also, further test drives with calibrated vehicles are going to be conducted. The DAS technology can also be applied in an inverted manner. If the weight of a passing vehicle is known, the model can be used to invert for mechanical parameters of the asphalt compound (e.g. elasticity). In the near future, this technological approach has a great potential to provide in-depth continuous information about the mechanical integrity of critical infrastructure over its entire lifetime. This knowledge can help operators to optimize maintenance intervals and to save money and resources.

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Advancing Automated Freight Transport: Unveiling the Requirements and Readiness of Physical and Digital Road Infrastructure

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Abstract. This study aims to unveil what requirements the introduction of Connected and Automated Vehicles (CAVs) will have for the Physical and Digital Road Infrastructure (PDI) on public roads. The study is based on a literature review of reports from research and innovation projects combined with literature from academic databases. The findings indicate that supporting CAVs with an adapted public PDI will be beneficial for the CAV industry and required for authorities. Most requirements concern the digital infrastructure, emphasising technologies for improved perception, oversight, control, positioning, and navigation. Requirements for the physical infrastructure concern adaptions for avoiding conflicts with other road users. Standardisation of the PDI requirements and the information representing the real world is a critical issue to solve before fully introducing CAVs. The information needed to define and extend CAVs' Operational Design Domain (ODD) will be crucial for continuous driving in an automated mode.

Keywords: automated freight · infrastructure for automated driving

1 Introduction

Connected and Automated Vehicles (CAVs) are gradually being introduced into road infrastructures worldwide, bringing complex challenges to physical and digital infrastructure (PDI). Close collaboration between authorities and industry stakeholders is needed to optimise the planning and design of the infrastructure.

Automated freight operations on highways are expected to develop faster than passenger vehicles operating in an urban environment, as highways are more controlled environments with restricted access and less complex situations. The EU-funded project MODI [1] aims to accelerate the introduction of highly automated freight vehicles through demonstrations and by overcoming barriers to the rollout of automated transport and logistics. The logistics corridor from the Netherlands to Norway was chosen for demonstration activities.

This paper discusses early findings from the MODI project concerning requirements for the PDI.

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2 Methodology

The literature review discussed in this paper establishes a foundation of knowledge from previous and ongoing research and innovation concerning PDI requirements for automated driving.

The literature review followed two parallel tracks. One track searched for relevant literature in project databases to align with EU projects and anchor requirements in previous work for deployment. A second track identified literature in academic databases, providing insights into future possibilities and requirements. The thorough search and compilation identified 133 academic documents and 44 project deliverables or other reports. Due to page limitations, only a selection of the documents can be included as references in this paper. A complete list of literature will be included in a MODI deliverable.

The review gave a comprehensive overview of the state of the art regarding requirements that CAVs will put on the PDI for public roads. We have not found any other recent study consolidating a combination of findings from project deliverables and academic literature on this topic.

A series of semi-structured interviews will follow up on the findings in the literature review. Finally, a workshop with stakeholders will be held to discuss the combined results from the two previous steps.

3 Findings

3.1 General Observations

A general perception in the studied literature is that the support provided by the physical infrastructure to human-operated vehicles is expected to be sufficient for automated vehicles. The industry aims to produce vehicles that can operate on any road rather than being limited to specific roads. However, the digital infrastructure must be developed to support its physical counterpart [2].

Investing in the infrastructure requires caution and is preferred for the digital infrastructure over the physical due to costs, flexibility, and unclear future requirements. Infrastructure tailored to specific vehicle technologies should be avoided due to rapid technology evolution [3,4].

Consistency and continuity within and between road networks are crucial for automated driving. Therefore, standardising the PDI before vehicles are introduced in large numbers is considered an urgent issue where authorities are recommended to take a leading role [2,3,5].

3.2 Physical Infrastructure

Although CAVs are being developed to operate on the existing road network, some preparations may be needed. Automated systems have higher electromagnetic sensitivity and a different field of view than human drivers. For future road design, it is essential to factor in the height of sensors, the dimensions of road features, and the expected reaction time [6].

Research suggests automated drivers may benefit more than humans from standardisation and better visibility of signs and markings [2,7]. Therefore, new standards will be required for design and increased maintenance [2,3,5,7]. More and better edge lines have been suggested to complement High-Definition (HD) Maps with sensor observations [7].

CAVs require safe harbours for minimum-risk manoeuvres without interfering with other road users. Wide shoulders may be used but might clash with their role in traffic efficiency [5,8,9]. Complex intersections pose particular challenges, which is one reason highways are considered the most prepared for CAVs [7,10].

Some studies have suggested dedicated lanes for CAVs to boost safety and efficiency, especially for freight vehicles [11]. Yet, this impacts other road users and is not viable until many vehicles are automated [2,12,13].

Platooning with virtually linked trucks driving closely is a powerful measure to boost efficiency and safety and save fuel. While platooning relies on communication in the digital infrastructure, physical road factors like weight limits, curvature, overtaking space, and pavement rutting are crucial. Pavement rutting can be reduced by varying truck positions but requires wide lanes [14–16].

3.3 Digital Infrastructure

Support from digital infrastructures for expanding the CAVs' Operational Design Domain (ODD) and enabling consistent use of automated mode is crucial for implementing CAVs. Studies have identified critical elements for defining the ODD [5,11,13,17] and found that road authorities and operators are responsible for, and need to improve, information sharing [2,5,7,18].

Infrastructure-based perception using roadside units (RSUs) like cameras and radars can improve CAVs' situational awareness through vehicle-to-interface (V2I) communication. CAV onboard units (OBUs) tend to lack full road awareness, especially concerning occlusion in complex intersections. Therefore, investments in roadside equipment may be required [15,19], and tools have been developed for optimised equipment placement [20]. While most studies have centred on single-sensor systems, there is a shift towards multi-sensor systems. Synchronising these systems is crucial for addressing occlusion issues [21]. However, as OBUs become more affordable and efficient, the need for infrastructure nodes might diminish [21].

Connectivity services ensure seamless, stable, and secure communication between vehicles, roadside equipment, and traffic managers through vehicle-to-everything (V2X) communication. With the number of CAVs on the road expected to grow rapidly, the networks for communication must be scaled for large data traffic. 5G will become increasingly crucial concerning capacity, speed, and coverage [9]. Short-range communication with C-ITS is envisioned as support at complex traffic points, specifically at intersections in dense areas, tunnels, underground parking lots, and other areas without mobile coverage [2,3].

The connectivity services must be available and understood independently of the vehicle manufacturer [11]. Therefore, standardisation is essential, whether the communication is based on the regular cellular network or special C-ITS

networks. Standards and an organisational structure are already in place for the further development of C-ITS [2,22].

It is not expected that road authorities will own or operate cellular networks. Still, as road owners, the authorities should play a role in ensuring coverage of connectivity services along road networks to support automated driving [7].

Positioning technologies are crucial for matching CAVs' positions and observations with accurate HD Maps. The required accuracy depends upon the complexity of the environment and the task at hand but generally exceeds what can be provided by today's Global Navigation Satellite Systems (GNSS) [2].

To enhance accuracy in positioning, governments and commercial entities offer positioning services [9]. These services must be scaled to handle a large volume of vehicles and should have standardised interfaces and content, especially regarding geodetic reference frames [1,9]. Given the importance of positioning for CAVs, it is crucial to protect positioning services from vulnerabilities such as spoofing, interference, and cyberattacks [3].

Vehicles cannot rely on one single positioning technology but must combine complementary approaches [2]. Local positioning can be improved through navigation based on point clouds and accurate positions of landmarks [5,11]. Consequently, point clouds and accurate positions of roadside landmarks have been defined as essential information for CAVs [13].

HD Maps are the basis for the CAVs' route planning and navigation. The maps provide a reference for CAV sensors and enable the automated driving systems to make informed decisions [5]. There is a lack of precise specification of the content and structure of HD Maps. Commercial actors produce vendor-specific maps with little or no standardisation and information exchange. The actors must frequently collect and update data for their products with precise and accurate information through a costly and time-consuming process [18,23]. Dynamic changes such as road works are particularly challenging for automated vehicles and HD Map maintenance. Studies have investigated technologies for more efficient data collection for HD maps [24,25]. Still, it has been argued that HD Maps are not expected to cover the whole road network due to the costs involved [2,3].

Road and mapping authorities may play a significant role in an ecosystem for HD Map production. Road authorities may provide machine-interpretable rules and regulations for navigation, while mapping authorities collect accurate geospatial information such as point clouds and landmarks. It is not expected that the authorities will own or operate HD Maps. Still, their data may give better authoritativeness and coverage and lower the production costs of commercial HD Maps [7,18]. However, the data must be better prepared for the requirements of automated vehicles in terms of content and quality [11,18].

4 Discussion

The findings from the literature review reveal a lack of consistent standards and requirements for the PDI and the attributes for defining CAVs' ODD. Further-

more, the findings indicate that the CAV industry and authorities have different perspectives on what infrastructure support will be required.

Industry actors seek to develop CAVs that can drive on any road in any country with minimum reliance on support from the public PDI. Therefore, they must rely on onboard sensors supported by commercial positioning services and vendor-specific HD Maps. Support from a public PDI will be beneficial but not always required.

On the other hand, authorities must focus on the safety of all road users and ensure that CAVs from any vehicle manufacturer are at least as safe as human-driven vehicles in any situation. Extended support through the digital infrastructure to enhance the CAVs' perception and positioning will be crucial to ensuring safety for all road users. Also, authorities must communicate with and control CAVs differently from human drivers. Therefore, authorities may require solving the challenges before CAVs can be introduced.

Despite the differences in perspectives, developing the PDI to support CAVs will benefit both the industry and the authorities. They must collaborate to standardise PDI requirements so authorities can support CAVs in the best possible way and the industry can know what support to expect.

5 Conclusions

This study has investigated recent research on the required physical and digital road infrastructure (PDI) for connected and automated vehicles (CAVs).

Authorities need to plan for the future of automated drivers but invest cautiously and avoid vehicle-specific technologies. More safe harbours may be required to prevent conflicts between CAVs and other road users. Upgraded maintenance of signs and markings is crucial for the perception of onboard units.

The digital infrastructure will be crucial for authorities to support and control CAVs. Critical elements include roadside equipment for enhanced situational perception; continuous coverage of communication networks; the availability and accuracy of services, point clouds and landmarks for positioning support; and provision of machine-interpretable traffic rules and regulations.

Standardisation of the PDI and requirements is needed before introducing CAVs in large numbers to ensure information exchange and continuity, and authorities are recommended to take a leading role.

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Radar Satellite Observations of Bridge Deformations—A New Method for Monitoring Without Applied Sensors

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Abstract. The evaluation of structures with the help of remote sensing radar satellites offers new possibilities for the permanent monitoring of deformations of entire structures and their surroundings. Instead of equipping structures individually with expensive discrete sensors or surveying them terrestrially with expensive instruments such as laser scans or drones in a labor-intensive manner, deformations can be continuously recorded with the use of radar satellite data. In the future it might be possible to centrally monitor, evaluate and assess various bridge deformations network-wide.

A recently completed research project on Semmering-Autobahn S6 in Austria investigated new approaches to improve deformation detection based on radar-satellite measurements using open data form ESA's Sentinel 1 Mission. The aim was to evaluate how satellite data can best contribute to deformation monitoring of engineering structures and how structural thermal deformation can be compensated. On the S6 Schottwien bridge (main span 250 m) corner reflectors (artificial back scatterer with known coordinates), temperature sensors and inclination sensors with low energy consumption were installed. A new proposed temperature compensation model, which is based on thermodynamic parameter studies, can predict the structure temperature of the bridge only with using central historical weather data. The accuracy of radar satellite measurements can be dramatically improved without any sensors applied at all.

An annual cycle shows that the satellite measurement has an accuracy of 2–3 mm related to an installed long-term levelling reference sensor system and are well suited for monitoring long span bridges.

Keywords: Bridge Monitoring · Nondestructive Testing · Synthetic aperture radar interferometry (InSAR)

1 Methods for Deformation Monitoring of Bridges

Until today, the condition of bridges is mainly recorded periodically by visual inspections, whereby the procedure is following different country specific guidelines (e.g., in Austria manual inspection take place every 6 years according to [1]). Measuring of

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bridge deflections is usually not taken place. This happens for example when an inspection shows anomalies or when heavy bridge loads – such as special transports – are known to be carried out. The most common way for measuring bridge deformations is the tacheometric geodetic survey (theodolite/total station) and levelling measurements.

Periodic measurements can record the changes in structural deformations to constant loads (dead loads) or observe the bridge deflection during events (e.g known heavy loading). Continuous deformation monitoring of bridges is a potentially promising indicator, but not easy to perform. Currently, the most common system for determining vertical displacement differences is still a flexible digital hose scale. Maintenance of these sensors (e.g. fluid change) is required as well as an intact connection between the sensors via tubes and fluids, which limits the range of the observation points.

A new method uses satellite-based Synthetic Aperture Radar Interferometry (InSAR) data, which eliminates the need to install and maintain sensors. InSAR provides time series of displacements and enables continuous regional and local monitoring. The method has already been used successfully for observing glacier or slope movements, for example, for which the accuracies achieved have so far been sufficient to determine deformation trends.

2 InSAR for Bridges

The European Space Agency - ESA uses the Sentinel-1 satellites for research in the field of Earth observation via remote sensing. Sentinel 1 satellites are orbiting the Earth's surface at an altitude of 693 km in two different directions (trajectories). One orbit is from south to north (ascending orbit ASC) and the other one from north to south (descending orbit DSC) and are seen in Fig. 1. The remote sensing measurements are carried out with a radar antenna, which transmits the signals and receives them again from the earth's surface from a time series of persistent scatterer (PS) points. The flight path of one satellite takes place in a sun-synchronous orbit with a repetition cycle of 12 days in the same orbit or every 6 days in the opposite orbit seen in Fig. 1.

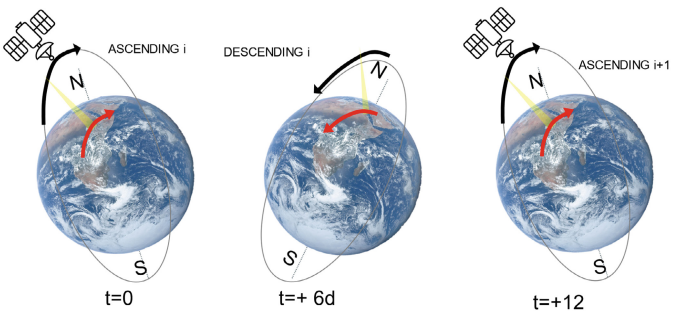


Fig. 1. Flight path of Sentinel 1A Satellites. The points on the Earth's surface are flown over in two orbital directions (trajectories). Points on Earth are passed in every 12 days in Ascending ASC direction (south to north) with a time shift of +6 days in the opposite orbit Descending (DSC (north to south).

In general, the previous approaches [2, 3] used data from both orbit directions ASC and DSC, which must be combined in a coordinated transformation. The oblique distances in Line of Sight (LOS) for different recorded time steps are directly combined to enable the transformation in absolute vertical and horizontal direction. At present, this only allows monitoring of objects with a mainly east-west orientation to be viewed. Another disadvantage is that ASC and DSC were recorded at different times (Δt up to 6 days). This would lead to an inaccurate coordinate transformation that is distorted by the temperature deformation of the bridge at different recording times. For general applications on the earth's surface, in particular slopes and ground surfaces, a horizontal displacement due to thermal change is insignificant. However, if structures such as bridges are examined, a structure-related temperature compensation is necessary, details are presented later in the Sect. 3.2.

In the European Ground Motion Service (EGMS) Database [4] time series measurements of identified PS-points are central web-based stored and are freely available on a graphical interface since 2015. These data are preprocessed including different remote sensing corrections (e.g. atmospheric, orbital, geoid, etc.) and include GPS coordinate information. To establish a correct object reference, the z-coordinate can be used to check whether selected PS-points are on the bridge or in the immediate vicinity (height differences of less than 8–10 m may be difficult to separate; seasonality should be used instead). Data are available for various orbits over the territory of the European Union.

Converting the data from the line of sight (LOS) to the vertical deformation of the bridge is generally not trivial [2]. Relative movements are particularly interesting for structural monitoring. If at least two reference points and their relative object distance are known, it is possible to calculate the temporal deformation variables of two clearly determinable observations in the vertical direction. The thermal deformation effects between the recording times can be included. Based on this, corresponding algorithms were developed, which were also filed as a patent [5]. This has following advantages:

- Denser time series are possible (more measurement points are available when viewed relatively, as no opposing orbits must be intersected).
- More measuring points are located on the bridge (each point used does not necessarily have to be seen by two orbits).
- Increased accuracy (no blurring due to thermal effects between the temporal differences of different re-cording times).
- No restriction of the measurement object orientation (currently only objects with approximate orientation in the viewing direction of the satellite are possible (e.g., Sentinel east-west orientation necessary).

3 Case Study Schottwien Bridge

The bridge object Schottwien viaduct on the S6 Semmering motorway is located near the alps in Lower Austria. It has a total length of 632 m and is one of the largest prestressed concrete beam bridges in Austria. It is up to 130 m high and was built using the free cantilever method, opening in 1989. The bridge consists of three concrete piers (2 double piers and one single pier) with the highest pier being 75 m high. The observed main span is 250 m and is located between the two main pillars (double pillars)

and shows a known long-term deformation. Deflection measurements with a long-term digital tubular reference sensor system is installed on site, including temperature sensors, and are available for the whole year 2020. EGMS-data have been available for the bridge since 2015, but no onsite sensor data for temperature deformation are available for this long period.

3.1 Satellite Data Using Preprocessed EGMS-PS-Point-Data

The bridge is covered by at least 4 different sentinel orbits where the EGMS-database provides data. The orbit DSC022 is providing the best PS-point coverage of the bridge and was taken as basis for further data processing as seen in Fig. 2 right. Most interests were in evaluation of deformation differences between the pier and the midfield. Focusing on this these two chosen reference points, the thermal horizontal terms in the longitudinal direction Δd_{Long} and transversal Δd_{Trans} can be calculated as differential object motion in the angle of the bridge $\alpha_{B,}$ when the temperature changes are known. The relative vertical movements Δd_{up} can be processed as seen in Eq. (1) [5]:

$$\Delta d_{up} = \frac{\Delta d_{LOS} + \left(\Delta d_{Long} * \cos(\alpha_{ALD} - \alpha_B) + \Delta d_{Trans} * \sin(\alpha_{ALD} - \alpha_B)\right) * \sin(\theta_i)}{\cos(\theta_i)} \tag{1}$$

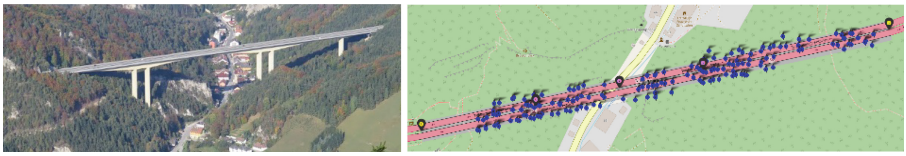


Fig. 2. Left: Schottwien Bridge ©ASFINAG, right identified PS-points on the bridge using EGMS-databases from 2020 for orbit DSC022. @OpenStreetMap.

3.2 Thermal Compensations

Instead of using onsite temperature sensor data, an empirical temperature model developed by AIT [6, 7] was applied. The bridge temperature was calculated using a transient stationery thermodynamic analysis on the basis from historical climate data from meteorological reanalyzes. These data are provided for several years in a grid of different resolution (e.g. 1 km x1 km) by the national meteorological institute GeoSphere Austria with a temporal resolution of 1 h. The model is based on meteorological information of air temperature, solar radiation, position of the sun, precipitation, and wind. From which the associated bridge temperature is calculated for each timestep of satellite overflight.

The main advantage of the non-contact measurement method is the complete elimination of sensor mounting on the bridge. Therefore, also the structure temperature, which is necessary for the temperature compensation, can be process using historical data back to 2015 where EGMS-data already exists. The uniform cross-sectional temperature, which is responsible for the expansion of the bridge in the longitudinal direction

d_{Long}, is mainly evaluated using an empirical temperature model [7, 8] adopted to cross-sections for the Schottwien bridge [6]. It is perfectly suitable for calculating the bridge temperature. Compared with onsite sensors an accuracy of about 1 °C within 1σ was reached. An empirical model was used to calculate the structural temperature.

4 Results and Discussions

Since the structure is longitudinally oriented, Δd_{Trans} could be neglected. Δd_{Long} is calculated by using the known distances L between the observed points with the temperature derived from the empirical model. To evaluate the vertical differential deformation Δd_{up}, Eq. (1) is applied to each overflight as well as a time series of deformations.

The relative deformation in the center of the main field in relation to pier 3/1 for the annual cycle for 2020 is processed for the relative movements and plotted in Fig. 3 for INSAR-data of DSC 022 (yellow line) and compared to the reference sensor (blue line). The clearly measurable jumps result from the fact, that the piers either warm up and expand (positive shift upwards) or cool down/sink (negative shift downwards) due to the temperature change within the 12 days between the satellite recordings. As the bridge is statically indeterminate, the longitudinal expansion of the deck due to temperature causes its rotation around the pier heads. This results in additional up and down movement of the center span.

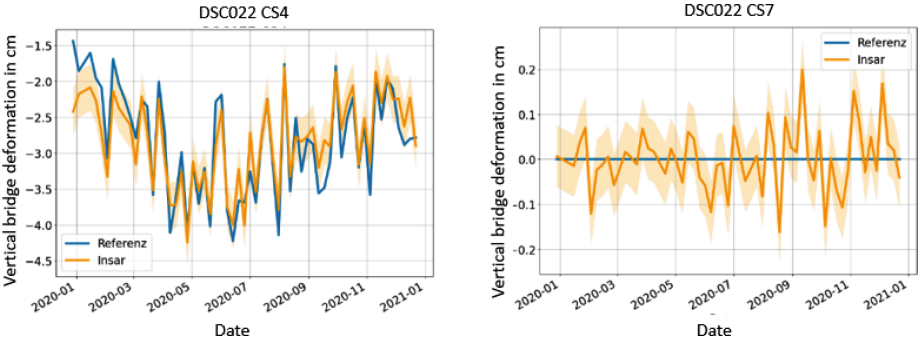


Fig. 3. Left: Relative deflection of the middle span related to bridge Pier 3/1 for the year 2020, right direct comparison of reference sensor and satellite data evaluation, the accuracy is within 2–3 mm range. Below historical evaluation between 2015 and different point of year.

In Fig. 3 it is clearly recognizable, that the annual course for 2020 of the relative deformations of the reference system corresponds very well, both qualitatively and quantitatively to the processed EGMS-satellite data of orbit DSC 022. The direct comparison (Fig. 3 right) of reference sensor (digital hose scales) and satellite measurements demonstrates that the accuracy is within a 2 mm range.

5 Summary

A method for processing relative deformation for structures using free available pre-processed radar satellite data from the EGMS-database has been presented. With this method InSAR data are applicable for assessment of relative deformation in vertical direction of bridges without using any in-situ sensors. The determination of the vertical relative deformation is possible independent of the bridge orientation. The limiting factor is whether enough PS-points are recorded from the satellite overflights and when the database is updated. Up to now, processed EGMS-data are only suited for long-term deformation phenomena and not for instant warnings – e.g. in the event of overloads. The yearly update of EGMS takes place in summer/autumn for the previous year. Compensation of the thermal structural deformations is mandatory for the evaluation, especially in the longitudinal direction of the bridge. Structural temperatures can be calculated with sufficient accuracy using an empirical model and historical recorded weather data. The achieved accuracies on the demonstrated site of S6 Schottwien bridge have a standard deviation of approx. 2.0–3.0 mm in the best case compared to reference sensors (digital hose scales). Satellite InSAR technologies open up completely new possibilities for structural monitoring thanks to the simultaneous large-scale remote sensing of entire sections of transport routes and bridges.

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Benefits of Radio Coverage Planning of Large-Scale Roadside C-ITS (ITS-G5) Communication Networks

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Abstract. Cooperative Intelligent Transport Systems (C-ITS) aim to enhance road safety, traffic efficiency and environmental performance of road transportation by enabling communication between the vehicles and the road infrastructure. Today, vehicle manufacturers and road operators are investing significantly in C-ITS technology and infrastructure implementation to realise its potential benefits. In Europe, the C-Roads platform aims to harmonise the deployment of C-ITS infrastructure and services across Europe. As part of the C-Roads platform, Transport Infrastructure Ireland implemented C-ITS pilot infrastructure to deliver C-ITS services to road users via ITS-G5 and cellular communications. For the deployment of ITS-G5 Roadside Units along a 60 km distance of the pilot routes in Ireland, a radio coverage planning exercise was undertaken to optimise the deployment. Several technical and practical factors were taken into consideration during this exercise. This paper outlines Transport Infrastructure Ireland's C-ITS pilot infrastructure, discusses the key technical and practical factors taken into consideration and summarises the results achieved. As a result of this radio coverage planning exercise, we were able to achieve over 50% cost savings on infrastructure deployment for C-ITS services via ITS-G5 technology on the M50 and M1 motorways.

Keywords: Connected Vehicle (CV) · Cooperative Intelligent Transport Systems (C-ITS) · Radio Coverage Planning · ITS-G5 · Roadside Unit (RSU)

1 Introduction

The emergence of Connected Vehicles (CVs) provides many benefits to road transportation and traffic management. Digital connectivity is a key enabler for efficient and safe operation of automated and autonomous driving functions and can significantly contribute to the maintenance of an efficient, sustainable and resilient transport network. To this end, vehicle manufacturers and transport infrastructure operators are increasingly investing in Cooperative Intelligent Transport Systems (C-ITS) that enable CV services

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between the vehicles and the road infrastructure. In Europe, C-ITS infrastructure is implemented mainly using ITS-G5 communications technology that is based on IEEE 802.11p operating in the 5.9 GHz spectrum. Currently, there are many pilot implementations of C-ITS infrastructure across Europe as part of the C-Roads platform.[1] As part of C-Roads, the Irish C-ITS pilot infrastructure being implemented by Transport Infrastructure Ireland (TII) aims to provide continuous ITS-G5 coverage over approximately 60 km on the M50 and the M1 motorways to deliver C-ITS services to road users around Dublin.

Since C-ITS provides safety-related information, ubiquitous ITS-G5 coverage is required along the road. A previous European C-ITS pilot (InterCor) report [1] revealed that the average communication range of an ITS-G5 Roadside Unit (RSU) is 225 m to achieve an acceptable Packet Delivery Rate (PDR) of 75%. Based on this estimate, RSUs were expected to be installed approximately every 500 m for continuous coverage. For the Irish C-ITS pilot, this resulted in 49 brownfield and 59 greenfield sites to provide continuous ITS-G5 coverage along the pilot routes on the M50 and the M1 motorways. However, this was not an optimal solution, because implementing roadside infrastructure for communication along motorways (i.e., major roads) has other complex considerations, such as the extent and accessibility of existing power and communications infrastructure and site access requirements, which have cost, time and programme implications.

Although some previous works exist on ITS-G5 coverage planning e.g., [2], they mainly focused on the technical and environmental factors related to radio signal propagation in a test bed environment with one or a few RSUs. To the best of our knowledge, there is no coverage planning and optimisation analysis for a large-scale ITS-G5 RSU deployment considering all possible technical and practical factors impacting the coverage. Therefore, a radio coverage planning exercise was undertaken in the Irish C-ITS pilot to optimise RSU deployment over approximately 60 km on the M50 and the M1 motorways.

In this paper, we aim to describe radio coverage planning for large-scale ITS-G5 RSU deployments, based on the results achieved in the Irish C-ITS pilot. Section 2 describes the C-ITS pilot infrastructure implemented in Ireland to deliver C-ITS services to road users using ITS-G5 radio communication. Section 3 provides the radio coverage planning work undertaken considering the key technical and practical factors and the results achieved in the Irish C-ITS pilot. Section 4 concludes the paper.

2 TII's C-ITS Pilot Infrastructure for ITS-G5 Communication

Figure 1 shows TII's C-ITS pilot deployment architecture for delivering C-ITS services on the national roads, via ITS-G5 communication between the vehicles and the road operator's infrastructure. The Central C-ITS Station (C-ITS-S) is implemented in the Motorway Operations Control Centre (MOCC) and integrated with the Advanced Traffic Management System (ATMS), TII's new Network Information and Management System (NIMS), for receiving operational traffic management-related information e.g., dynamic

[1] https://www.c-roads.eu/platform.html.

speed limit, variable message sign, roadworks warning, stationary vehicle notification, etc. The C-ITS-S generates C-ITS messages based on the information received from the ATMS and distributes them to the relevant RSUs delivering corresponding C-ITS services to road users. ITS-G5 RSUs were deployed along the pilot routes on the M50 and the M1 motorways and connected to the C-ITS-S via TII's motorway telecommunications network (on M50) and cellular network (on M1). The RSUs broadcast C-ITS messages via ITS-G5 radio communication to the OBUs within their coverage range. Therefore, to deliver reliable C-ITS services to road users within the pilot routes, it is important to provide continuous ITS-G5 communication coverage from the RSUs. For this, a coverage planning exercise was undertaken for the deployment of RSUs.

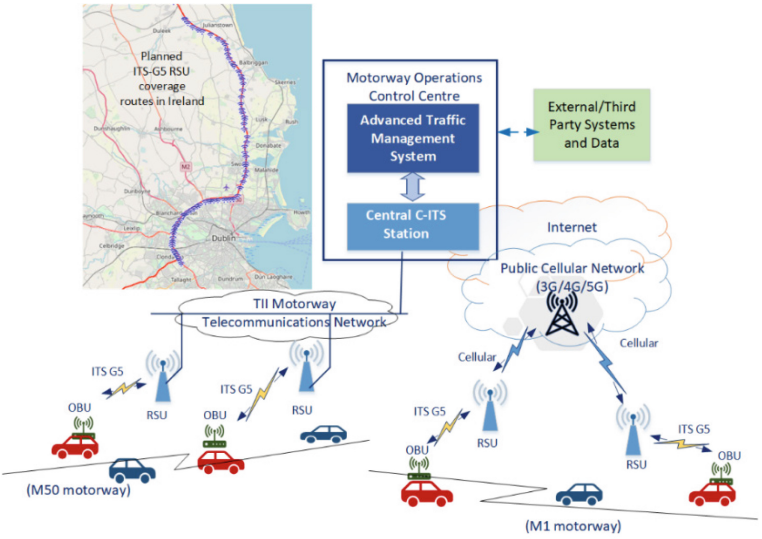


Fig. 1. TII's C-ITS pilot deployment architecture.

3 ITS-G5 Coverage Planning

For the coverage planning, several technical and practical factors related to the deployment of ITS-G5 RSUs along the motorways were taken into consideration. The following subsections describe the key technical and practical factors considered, the methodology used and the results achieved.

3.1 Key Technical Factors

European Standards and Regulations: European standards and regulations were taken into consideration when setting the technical factors related to the operation of ITS-G5 radio equipment. The key technical standards and specifications considered were ETSI EN 302 663 [3] which defines the ITS-G5 access layer requirements, and ETSI EN 302 571 [4] which specifies technical characteristics of radio equipment operating in the

frequency range of 5,855 MHz to 5,925 MHz for ITS applications and ETSI TS 102 792 [5] that specifies requirements to ensure coexistence between ITS-G5 stations and CEN Dedicated Short Range Communication (DSRC) technology based tolling stations, to mitigate interruptions from the ITS-G5 stations to the DSRC tolling operations.

Manufacturer's Specification of the Radio Equipment: The pilot uses RSUs (RIS-9160) supplied by Kapsch TrafficCom. The manufacturer's specification of the key radio parameters of the RSU are summarised in Table 1 below:

Table 1. Radio parameters of the RSU.

Parameter	Value
Frequency range	5.860 GHz–5.920 GHz
Channel bandwidth	10 MHz
Output power (max)	20 dBm
Receiver sensitivity	−92 dBm @ 6 Mbps
Antenna gain (max)	7.5 dBi
HPBW	360°(horizontal), 18° (vertical)

3.1.1 Radio Signal Propagation Model

The ITU-R Rec. P 530 [6] propagation model was chosen for the radio planning part. Since the pilot routes are mostly open environment with vegetation on the sides of the road, multipath was not considered as a significant factor.

3.2 Key Practical Factors

Digital Terrain Model (DTM) of the Motorway: To take into consideration the variation of terrain, a DTM model based on LiDAR survey data with a resolution of 2 m was used. This provided a good model for the cuttings and embankments on the M1 and the M50 motorways for the coverage planning tool.

Radio Signal Propagation Barriers Along the Roads: Although the DTM provided a good terrain model of the M1 and the M50, it did not include man-made objects such as bridges, gantries and large traffic signs which are key physical barriers for ITS-G5 signal propagation. Therefore, those structures were added over the DTM as a custom 'clutter' layer.

Interference Mitigation with Existing DSRC Electronic-Tolling Stations: Without mitigation, ITS-G5 radio communication can interfere with the Dedicated Short-Range Communication (DSRC) tolling stations that operate in the 5795–5815 MHz frequency band. Therefore, during the ITS-G5 coverage planning, the maximum transmit power was adjusted for ITS-G5 RSUs located near the tolling stations, to mitigate harmful interference to the DSRC tolling operations in accordance with ETSI TS 102 792.

Installation Infrastructure: Key installation infrastructure requirements included availability of roadside civils infrastructure e.g., mounting pole/gantry, ducts, and safety barriers, access to power and access to the motorway telecommunications network, cellular coverage was also considered. Sites with existing civils infrastructure (i.e., brownfield sites) were preferred over the sites that required the installation of new civils infrastructure (e.g., mounting poles, safety barriers, etc.) to reduce the cost.

Considering these factors, RSU installation sites were categorised into four main types: Type 1 – Brownfield site with access to power and motorway telecom network; Type 2 - Brownfield site with no access to power and motorway telecom network; Type 3 - Greenfield site with access to power and motorway telecom network; and Type 4 – Greenfield site with no access to power and motorway telecom network. From Type 1 to Type 4 the installation cost increases and the flexibility of RSU location for coverage optimisation improves.

3.3 Methodology

LS telcom's radio coverage planning tool CHIRplus_TC [7] was used for this coverage planning work. All the aforementioned technical and practical factors were incorporated with relevant parameters (i.e., the radio parameters of the equipment, propagation model, DTM, the custom cutter layer, etc). In addition, the RSU's and OBU's antenna heights were set to 8 m and 1.5 m respectively, and the minimum required signal level for C-ITS services was considered as −75 dBm, for the analysis.

Then the coverage planning tool was loaded with the initial 108 combined brown and greenfield site locations (manually chosen based on site survey data). Signal coverage was analysed for overlapping coverage or gaps in the coverage along the pilot routes using colour-coded signal level contours in 5 dB steps.

The RSU locations were updated through an iterative process to find the minimum number of RSUs to provide continuous coverage along the pilot routes while considering the fact that the most preferred RSU site type is Type 1 and the least preferred is Type 4 in terms of cost of installation. Potential interference with the DSRC tolling stations on the pilot routes was avoided by relocating the nearby RSUs and reducing their maximum transmit output power. Also, the target service signal level was relaxed from −75 dBm to −80 dBm in some parts of the routes where the gap with the −80 dBm contour is a very small distance (< 50 m) as shown in Fig. 2 – in such areas the actual signal strength was expected to be more than −80 dBm. Note the grey area shown in the figure is outside the area of interest and was not included in the coverage analysis.

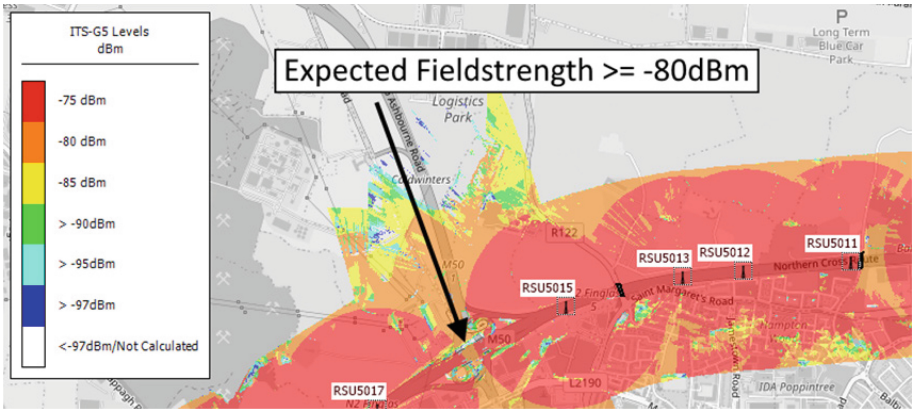


Fig. 2. Example of ITS-G5 RSU signal coverage

3.4 Results

Significant investment would have been required to provide continuous ITS-G5 signal coverage along a 60 km distance at 49 brownfield and 59 greenfield RSU sites that were initially identified on the M50 and the M1 pilot routes. Radio coverage analysis using the software tool and incorporating the key technical and practical factors, reduced the number of RSUs required to provide sufficient coverage along the pilot routes by 30% from 108 (49 brownfield and 59 greenfield RSU sites) to 74 (45 brownfield and 29 greenfield RSU sites). This resulted in significant cost savings for the installation of RSUs, estimated to be over 50%, mainly due to the significant reduction in the number of greenfield sites needed to provide sufficient coverage over the pilot routes.

4 Conclusion and Future Work

ITS-G5 RSUs are being deployed across Europe to provide C-ITS services to road users, as part of the C-Roads platform. This paper presented the C-ITS pilot infrastructure being implemented by TII in Ireland, and the key technical and practical factors that were taken into consideration for ITS-G5 coverage planning on the M50 and the M1 motorways. By undertaking coverage planning analysis using a software tool, significant cost savings were achieved whilst maintaining sufficient ITS-G5 signal coverage along the road network for C-ITS services, as part of a large-scale deployment of ITS-G5 roadside infrastructure. The efficacy of coverage planning will be validated with real-world data after completing the installation of the RSUs at the identified locations and any new findings will be published in planned future work.

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A Framework for Road Authorities to Assess Their Readiness to Support Connected and Automated Driving

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Abstract. Connected and Automated Driving (CAD) will bring disruption to individuals, economies, and society. Most forms of CAD require some level of support from the infrastructure for their safe operation, in particular communications. However, additional infrastructure services to support CAD could improve safety and robustness and bring further benefits such as increased capacity. However, the infrastructure requirements of vehicle Original Equipment Manufacturers (OEMs) are not always clear, and it is therefore difficult for National Road Authorities (NRA) to prepare future levels of support for CAD, given rapidly evolving technology and uncertain projections of future CAD demand. There is a need to articulate those requirements, bringing stakeholders together to formulate a structured approach, and a roadmap that will advance safe and smart roads that support CAD.

This paper presents the DiREC project (consortium partners: TRL, ARUP, TU Delft, VTT, VTI and FEHRL) funded by the CEDR Transnational Road Research Programme Call 2020 with funding provided by CEDR members of Belgium (Flanders), Denmark, Ireland, Israel, Netherlands, Norway, Sweden, Switzerland and the United Kingdom. DiREC is seeking to address the above challenge. The project has established a CAV-Readiness Framework (CRF) based on a level of service approach to understand the needs of CAD, and to define the infrastructure and services that NRAs could provide to support these needs.

Keywords: CAD · Digital Infrastructure · Framework

1 Introduction

Whilst Connected and Automated Driving (CAD) will bring new choices and capability to users of the road network, it is an area of technology which is likely to bring disruption and change to the design and operation of road network infrastructure. Most forms of

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CAD require some level of infrastructure support for their safe operation. Additional infrastructure and services to support CAD would have the potential to improve safety even further, and to bring other benefits such as increased capacity or reduced congestion. However, conventional road infrastructure is already costly, amounting to around 1–2% of GDP for OECD countries, and accommodating the needs of new CAD technologies may increase these costs. But the infrastructure requirements from OEMs are not always clear, and it is difficult for NRAs to predict and plan the future levels of support needed for CAD, given the rapidly evolving technology and uncertain projections of future CAD demand. There is a need for better dialogue between NRAs, OEMs and service providers to articulate those requirements and to define a roadmap and responsibilities for achieving safer and smarter roads through CAD.

DiREC proposes to establish a CAV-Readiness Framework (CRF) to support dialogue between NRAs, OEMs and service providers, based on a Level of Service approach. The CRF would define the needs of CAD in terms of physical and digital infrastructure, services, and operational policies and procedures that NRAs could provide to support them. The CRF would consider a wide range of components that influence the ability of the NRA to become a digital road operator, including machine readability of physical infrastructure, digital services, connectivity, and aspects such as governance of the infrastructure and services, and legal and regulatory requirements.

This paper summarises the results of the DiREC project.

2 Stakeholder Management

DiREC conducted a review of literature and held a series of meetings and workshops with NRAs, OEMs, telecoms and other service providers. The purpose of this review was to determine the attitudes of NRAs towards CAD, and the levels and types of support that they are willing to provide. This review and engagement identified many differences of opinion among NRAs on how and even whether they should support CAD. These differences were the result of many factors, including lack of engagement between NRAs and OEMs and hence lack of understanding of needs, NRAs' lack of visibility on the rate and extent of technological progress in vehicle systems and communications technologies, NRAs' lack of involvement in development of national and regional regulations, and uncertainty regarding the uptake of CAD at all its different levels. In general, many NRAs feel underequipped to understanding current technologies and future direction.

Based on the stakeholder management, the project proceeded to identify the as-is situation, gaps, and future trends in CAV and CAD as well as the types of support and services that NRAs are providing. In addition, the appetite of NRAs to invest in infrastructure and services to support CAD including digital twins were investigated alongside the views of OEMs and service providers as to what support would be useful and what the priority areas are. The subject areas tackled are infrastructure design and operation, infrastructure connectivity, data exchange, digital twins, legal and regulatory, impact of emergent technologies and costs and benefits.

As a result of this review process, DiREC developed a vision to empower NRAs with the tools and techniques to make measurable assessments of their investment decisions that will drive the adoption of CAVs on the road network. The associated mission was to deliver a CAV-Readiness Framework (CRF) for NRAs that supports current and future requirements of the network. The CRF can help NRAs to define the ways in which they wish to support CAD, specifically through assistance to the provision of Cooperative Intelligent Transport Systems (C-ITS) services. C-ITS services and use cases are well-defined at a conceptual level, although their implementation and standardisation are still evolving. NRAs can support the implementation and evolution of C-ITS services through a mix of physical, digital and communications infrastructure, operations, and inputs to standards development. The CRF allows NRAs to articulate the type and extent of support they wish to provide. It helps NRAs to prioritise that support through identification and analysis of costs and benefits. It also helps NRAs to develop roadmaps to enable them to plan for that support.

3 CAV-Readiness Framework (CRF)

3.1 Development of the Framework

DiREC structured the CRF around C-ITS Services and Use Cases as defined under the C-ROADS project. C-ROADS is a joint initiative of European Member States and road operators for testing and implementing C-ITS services, with a desire for cross-border harmonisation and interoperability.

Under C-ROADS, the deployment of C-ITS is seen as evolutionary, starting with less complex use cases ("Day-1 Services" encompassing messages about traffic jams, hazardous locations, road works and slow or stationary vehicles, as well as weather information and speed advice). "Day 2" and "Day 3+" services are being investigated in R&D projects. Hence the C-ITS Service and Use Case definitions [1] provided a firm basis on which to implement the CRF, both now and in the future. The CRF thus becomes a framework which can be used by NRAs to help assess their aspirations and readiness to support CAD, and to implement individual C-ITS services and use cases. It does this by (see Fig. 1):

- Defining the C-ITS services to be provided.
- Breaking those services down into use cases and enablers.
- Scoring the NRAs readiness, aspirations and high-level assessment of costs and impacts of each enabler to help plan and prioritise the NRA support for CAD.

In C-ITS terminology, a service is a clustering of use cases based on a common denominator, for example an objective such as awareness of road works. Services are also known as 'applications'. C-ITS services are identified as shown in Table 1.

In DiREC terms, and for the purposes of the CRF, use cases are described using a set of enablers. The 'enabler' is the lowest building block of the CRF tool. Some examples of enablers are shown in Table 2 along with their category which groups them under one of Physical, Operation, Digital, Connectivity, or Standard.

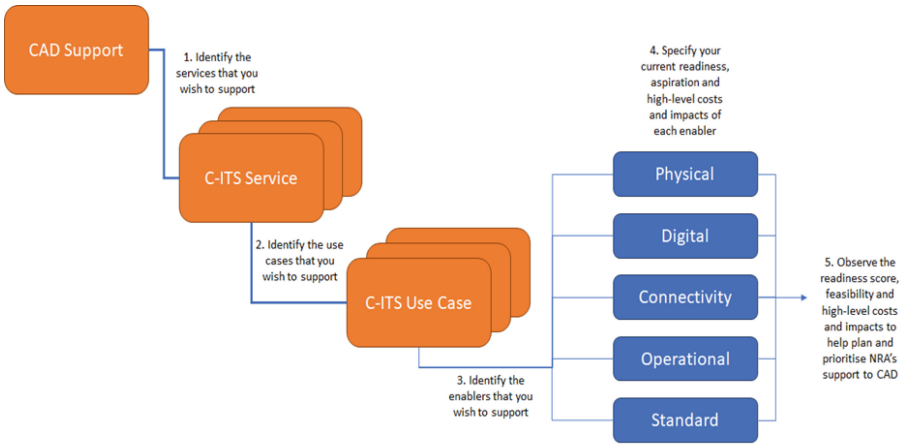


Fig. 1. Overview of the CRF

Table 1. C-ITS Services

C-ITS Services
In-Vehicle Signage (IVS)
Hazardous Location Notification (HLN)
Road Works Warning (RWW)
Signalized Intersections (SI)
Automated Vehicle Guidance (AVG)
Probe Vehicle Data (PVD)
In-Vehicle Signage (IVS)

Table 2. Sample enablers in the CRF tool

Enabler	Enable Category
Roadside Units (RSUs)	Physical
DENM messaging (ETSI EN 302 637–3)	Digital
ETSI EN 302 637–3	Standard
C-ITS Mobile Roadside ITS G5 System Profile	Connectivity
Cameras	Physical
Response plan	Operation

The CRF defines, for each enabler:

- the readiness of the NRA to provide or deploy each enabler individually.
- the aspiration of the NRA to provide or deploy each enabler.
- the feasibility threshold for the service which defines the minimum level of support provided by the NRA to make implementation of this enabler feasible.
- high-level costs and impacts of each enabler.

The scores, costs and impacts of each of the above can be rolled up to the level of the use case, and the service, and indeed the total package of support for CAD, to help plan and prioritise NRA support for each enabler.

3.2 Level of Service Approach

The Level of Service (LoS) is a widely employed metric that quantifies the performance and quality of a provided service, utilizing a predetermined scale. For C-ITS services (i.e., information provision) the aim is to provide information that is, among other things, accurate and timely to CAVs so they can react accordingly to events on the road network. The CRF aims to illustrate the progress of (NRAs) towards becoming a digital authority, meaning that the NRAs should provide information (data provision) to CAVs that are precise, accurate, and timely. As such, three distinct LoS categories can be defined:

- Basic: Minimum acceptable performance/quality.
- Enhanced: Not optimal but sufficient performance/quality.
- Advanced: Ideal or best performance/quality.

Additionally, a fourth level of service can be considered, for services that are already available. In this case, the LoS metric may be utilized by NRAs to assess the performance and quality of existing services.

The CRF LoS is a quality and performance evaluation metric based on a set of enablers with predefined requirements. The goal in the CRF was to develop a generic LoS tool that could be applied to any road environment, to any use case or technology. The definition should therefore be generic, applicable to all cases, and technology agnostic.

3.3 CRF Spreadsheet Tool

DiREC produced a spreadsheet version (CRF tool) of the CRF to demonstrate how the CRF could be applied in practice by an NRA.

The CRF tool is structured into separate tabs:

- Instructions for use of the tool, including colour coding of pages and fields to identify data inputs and outputs.
- Definition of which C-ITS services and use cases are to be analysed.
- Detailed analysis of a particular C-ITS service and use case to calculate the aspiration, readiness and feasibility of NRA support for that service and use case.
- Side-by-side comparison of the analysis of multiple services and use cases.
- Overall assessment of an NRA's readiness to implement an entire service.

This spreadsheet can be found on the DiREC website at: https://direcproject.com.

4 Conclusions and Recommendations

4.1 Using the CRF to Develop a Roadmap for an NRA

The CRF provides a framework to help NRAs understand their current readiness to provide or deploy C-ITS services and to understand potential investment decisions and link them to an overall strategic approach to deployment and delivery of a range of services. In addition to measuring the readiness of the NRA to support individual services and use cases, it also adds the concepts of the aspiration of the NRA to provide or deploy each enabler and helps identify a feasibility threshold for the service which defines the minimum level of support provided by the NRA to make implementation of this use case feasible.

4.2 Implementing and Refining the CRF

C-ITS and CAD are rapidly developing fields and to reflect this the CRF itself should evolve to refine its features and capabilities to help NRAs plan and prioritise their support to CAD. Figure 2 outlines a timeline of sets of potential actions that could help to implement and further develop the capabilities of the CRF. Some of the items proposed under the Actions are described below.

Actions 1: a) to support the effective use of the CRF, NRAs should undertake a number of internal workshops to help articulate their position on the topics raised; b) consolidate at NRAs, the list of enablers and the impacts associated with the various investment decisions.
Actions 2: a) Utilise existing asset management tools and Digital Twins in road operators to help consolidate the various equipment types, utilisation, impacts, and costs and benefits linked to the CRF and the deployment of CAD on the road network; b) develop a database at a National and European level to help inform the various parameters linked to the CRF and the wider Mobility sector.
Actions 3: a) Create a European CRF approach to help consolidate investments linked to the European Directives and local modification to allow for national investment decisions to take place; b) Link ongoing Road Investment decisions to the utilisation of the CRF and help articulate the business cases of the wider road network in this way.



Fig. 2. Action plan for implementation and development of the CRF

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Framework for Rail Level Crossings Digital Twin Development

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Abstract. The digital Twin (DT) is a technology that can be used to create a virtual representation or model of any physical entity. With the help of DT it is therefore possible to optimise the performance of the virtualised physical system and have a direct impact on increasing its competitiveness, efficiency and productivity, as the data flow can also be bidirectional.

The DT of rail level crossings (RLCs) holds great potential for increasing rail safety. With the introduction of digitised components of the railway signalling system, the development of a suitable DT of RLCs is of great importance. Therefore, the aim of this paper is to define the basic requirements for the DT development of RLCs. The paper first analyses the past practises in the development of DTs in railway applications. Furthermore, essential input parameters of RLCs are defined, including the time of closing and opening of RLCs, the warning time, and the operating and blocking times of RLCs. With the aim of reducing the waiting time of road users in the era of train automation and digitalisation, the optimal location of balises and train speed should also be considered. The defined requirements and parameters form the essential elements of the framework for the development of the digital RLC twin.

Keywords: Railway · Level crossing · Digital twin · Digitalisation and automation

1 Introduction

Digital twin technology (DT) is definitely a very popular and promising concept that has been used for digitalisation of various fields the last decade. It is a technology that allows a virtual copy or model of any physical entity to be created. This virtual copy is then connected to the physical environment via real-time data exchange, and allowing analysis, measurement, optimisation and simulation to be performed on the virtual copy as they would in the real environment.

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In recent decades, digitalisation has become a priority in all industries, and the railway sector is no exception. The DT of RLCs holds great potential for increasing rail safety. In 2021, more than half (59%) of fatal rail accidents in the EU were due to people being on the tracks without authorisation and more than a third (34%) occurred at level crossings [1]. With the introduction of digitalised components of the railway signalling system, the development of a suitable DT of RLCs is of great importance. Therefore, the aim of this paper is to establish the basic requirements for the DT development of RLCs. The paper first analyses the past practises in the development of DTs in rail applications. Furthermore, essential input parameters of RLCs are defined, including the time of closing and opening of RLCs, the warning time, and the operating and blocking times of RLCs. With the aim of reducing the waiting time of road users in the era of train automation and digitalisation, the optimal location of balises and train speed should also be considered. Therefore, this study also addresses the parameters of train speed and location of the balises depending on the infrastructural and operational constraints. The defined requirements and parameters form the essential elements of the framework for the development of the digital RLC twin.

2 Digital Twins in Railway Field

In the field of railway transport, the development and application of DT has been recognised for the purposes of railway construction, manufacturing and maintenance. From the conclusions of some previous studies [2]. DT in the railway sector is mainly focused on infrastructure and traffic management. Basically, the results of the literature review show that the developed DTs mainly refer to **static components** such as tracks as well as rails and infrastructure facilities. DTs have also been developed for turnouts, the only studied case of dynamic components [3].

In the field of railway maintenance, DT has been developed for the life cycle management of a railway turnout system [4], for the maintenance of power supply systems for electric railways, for a model to predict the maintenance of switch machines, for monitoring the condition of railway turnouts under different conditions [3]. In [2], a new methodology was presented, which includes the DT as one of four stages for train maintenance. To meet the requirements of DTs collaboration, a conceptual framework using the combination of blockchain, predictive analytics techniques and DTs technologies was proposed in [5].

The application of DT in the railway sector has been considered for the construction of railway infrastructure parts such as stations [4]. In addition, DT has been developed for the production of railway axles, as shown in studies [6].

3 DT Framework of Rail LC

In this section, main components, their functioning and the data exchange between them for the development of a DT system of LCs, as well as the formulation of variables for optimising the LC operation are described. As can be seen in Fig. 1, the physical and virtual parts of the DT system for the operation of LCs are included.

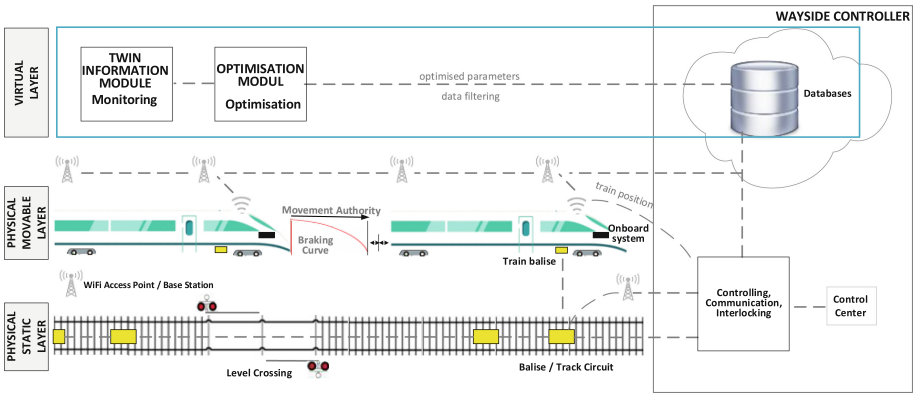


Fig. 1. Framework for DT for LC.

3.1 Physical Layer

The static physical layer includes tracks, detection devices and all components of active LCs as well as wayside controller, while the movable physical layer includes all types of trains (see Fig. 1). The activation and deactivation of LCs is nowadays achieved with devices known as track circuits. Track circuits are fixed on the rails and are connected and controlled by nearby interlockings. In this case, LCs are connected to interlockings or control centres because they are track-dependent, while other LCs are autonomous and not connected to interlockings or control centres [7]. The time of activation and deactivation of LCs is determined by the first axle of the locomotive and the last axle of the last waggon in the composition.

3.1.1 Operation Procedure of Physical Layer

The moment from the activation of the warning devices on the track circuits and the barriers on LC to the closing of the barriers to the last horizontal position and the reopening of barriers is called ***the operating time*** of LC. Then, the train **needs time from the activation of LC to reach** LC. Nowadays, track circuits are used as (de)activation devices, which include an arming loop and a trigger loop and will be replaced by balises in the future. The balise are placed alone **or in a group** (two or more) to ensure a high level of safety. During the operation of the warning device on LC, this time is called the warning time for road users, including **minimum warning time and additional warning time**. From the activation warning, LC is blocked for use by road users. This time is called the blocking time of LC and should be shorter than the sum of the operating time and the total time of the train leaving the arming loop. LC is closed and not opened before the last axle of the train leaves LC and this time is called **traversing time of the train**.

When the train approaches LC, the required transit time until leaving LC and this time is called the **train's clearance time**. This time and the traversing time of the train may be higher or equal to the total time required to activate and open LC, depending on the speed limit or train length. Based on the rules of LC with track circuits, the **waiting**

time of the road users depends on the running time of the trains in addition to the different characteristics of the trains.

3.2 Virtual Layer

The components of the virtual layer of DT (see Fig. 1) are a virtual network and one or more database servers with a special DT database, a monitoring module and a management module. The monitoring module is connected to the interlocking system or another stand-alone system and to the digital optimisation model. The processing unit is connected to each level crossing and to the database server and allows access for monitoring and/or management purposes from the control centre, the interlocking system and/or another stand-alone site connected to the network.

The virtual layer represents the core of the DT system of LC. It interacts with the static and movable physical layers through data exchange. As you can see, the static and movable physical layers provide two types of data, namely static and dynamic, i.e., historical/permanent data and info and timetables. The collected data and information are used by DT to find the optimal solution. A monitoring module is used to monitor and analyse the proper operation of the barriers, signals and horns on the LCs. The management model in the monitoring module is used to add, delete or change values for some parameters in the optimisation model.

3.3 Critical Parameters and Values of DT

To create DT of LC, essential variables should be considered. Values of variables should also be suggested for simulation or optimisation of LC operation in DT. To protect road users from moving trains, LC is activated and the time from the activation of the barriers to their last position is called the closing time of LC [8]. On the active LC, the barriers start to close 5 to 8 s after the flashing starts, and after a maximum of 10 s the barriers reach their final position, while 5 to 7 s are needed to open the barriers [9]. The length of the track circuits varies from 250 and 1000 m. With the introduction of ERTMS, the balises as detection means can be placed closer to LC. The minimum distance of balises for train parking was dealt with in [10]. In the calculation example in [11], it was assumed that the distance between two groups of balises in the LC area is no more than 500 m. Assuming ERTMS Level 1 and at least two balises in one group to avoid malfunctions, the distance of balise 1 (trigger loop in the track circuit) from LC was assumed to be 700 m, while the distance of the second balise from LC (arming loop in track circuit) was assumed to be 50 m. In Europe the permitted speed over LCs is normally 160 km/h [12].

There is no data on the train's transit and clearance time and therefore it can be assumed that the time is counted in which the train has covered half of the distance since the activation of LC, i.e., the barriers have reached the last position. Considering the length of the train, it was assumed that a 400 m long train with a speed of 120 km/h can cross LC within 10 s. Therefore, the clearance time was set at 10 s.

According to [9], the warning time depends on the design of LC and is between 20 and 30 s. The warning time may include additional time depending on other factors.

The waiting time for road users is calculated from the moment the driver stops at LC until the moment the driver has passed the crossing and includes the time needed to reach LC, the time to stop on LC and the time to cross to the other side via LC behind the stop line. This time varied between 1.5 and 10 min [13]. Assuming that the road is not congested, road users do not need additional time to reach LC. It was also assumed that the flow of road users stops in the middle of the warning period and at the beginning of the closure. Therefore, it can be assumed that the waiting time of the first road user is equal to the sum of the closure, opening and half of the warning time, i.e. 40 s.

The blocking time of LC is defined as the total time from the approach to LC and its activation to the last axis crossing detection on the opposite side [14]. This time should not be shorter than the sum of the time from activation to reaching LC and the clearing and passing time of the train. Therefore, 55 s can be chosen as blocking time. The time between the activation of the flashing lights and the movement of the barriers can be defined as the operating time of LC [9]. Considering the previous times, a total operating time of 55 s and 67 s for LCs can be determined.

4 Conclusion

This study presents the framework for the development of the DT system for LC. The main components of the framework for the DT system of LC are the physical system and the virtual component. In addition, the variables that should be included to optimise the LC operating time in the virtual layer and their initial values have been shown. As can be seen, one device that affects the operation of LC is a detection device. Consequently, the operation time of LC depends on the time of activation and deactivation of LC, as well as the location of the detection device.

In railways, track circuits have so far been used as a detection devices. However, with the introduction of moving blocks and virtual coupling concepts, trains can follow each other on the braking distance. With these new concepts, the detection of trains and the (de)activation of LCs is changed from track circuits to balises. The expected challenge is to find the ideal location of the balises and how many balises should be used before LC. Real-time communication between train and balises and on-side equipment about the exact train position can significantly reduce the operation of LC and the waiting time for road users. Taking into account the layout of track circuit on the rail, assumptions about the balises used and their distances and performed analyses assuming a constant speed of the train were carried out. The operating time of LC then depends on the type of train, i.e., the speed at which the train travels over LC and the train length.

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AUTOMODAL - Automation of Inland Container Terminal Cranes Solving People Detection in the Operating Range

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Abstract. The AutoModal project results show the prototypical end-to-end automation of the transshipment terminal. An essential component is the automation of a gantry crane, which was converted for this purpose so that independent automated processes could be carried out. The focus of the work was on the conversion and prototypical operation of the crane automation in a reference terminal. For this purpose, the gantry crane was equipped with additional sensors to ensure safe and reliable detection of persons in the crane environment and to enable automated operation. Suitable solutions were evaluated from a wide selection of sensors and tested on a test model. In parallel, suitable control software was developed, interfaces harmonized and hardware components integrated for operation. The software modules developed was published onto the GitLab Open Source platform. The following article describes the main outcome of the project. AutoModal was carried out as part of the funding programme for innovative port technologies of the Federal Ministry for Digital and Transport Affairs.

Keywords: Freight Transport · Multimodal Transport · Container · Carne · Terminal · Automation · Machine learning · Person recognition

Acronyms

CCTV Closed-circuit Television
LiDAR Light detection and ranging

1 Status Quo and State of the Art

A gantry crane is the most efficient and important handling equipment in combined transport (Arnold et al. 2008, p. 759). In inland terminals, cargo handling with gantry cranes still takes place manually, in contrast to seaport terminals (David and Putz 2014),

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where automated cranes in fenced areas allow a higher performance. But inland cranes work in a mixed used area. They span the water side, the container storage, tracks and loading lanes, where for example the truck driver usually stands beside the truck while loading process. This leads to safety problems in the danger zone of the crane.

The port industry has recognized the potential of automation and, in this context, has also driven the implementation of automated container terminals. These are characterized by use of automated handling equipment for the transport and storage of containers (Speer 2017). The most advanced automated container terminals with high-tech facilities are for example in Hamburg, Rotterdam, Hong Kong and Norfolk USA.

Several projects and companies started to transfer the results to inland terminals. In 2015 the pilot project "STRADegy" started focuses on the introduction of autonomously driving handling vehicles in Wilhelmshaven (Eberlein et al. 2021). Inland terminals already use optical character recognition or radio-frequency identification tags technologies at the terminals' road entrances and exits and in container shifting. Some inland gantry cranes offer for example automated gantry controls with Differential Global Positioning System and onboard sensors that enable precise, real-time positioning and control. But there is no fully automated gantry crane in German inland terminals realized, that can work without a human operator in practice.

In research, several studies focus on the theoretical potential of automation of terminals. For example, Urru et al. (2021) addressed the development of a fully automated intermodal terminal system that uses a roll-on/roll-off processes. Li et al. (2021) analyze the terminal layout of automated container terminals from efficiency, economic and environmental perspectives.

Literature review shows that there is a lot of research done, but there is not yet a solution for the safety problem in the mixed used areas of an automated gantry crane in Europe.

2 Development and Implementation of Automation Solution

The aim was to identify reliable sensors for consistently detecting individuals near a crane. Initially, a detailed requirements survey defined precise technical specifications for the sensor technology. Subsequently, after an exhaustive literature review, in-depth technical discussions with manufacturers and end-users led to a comprehensive evaluation of various sensor types and models in a laboratory environment.

2.1 Person Recognition

2.1.1 Sensor Technology

Sensors should be capable of reliably capturing the crane environment for person detection purposes. To achieve this, a categorized requirements catalogue was developed, encompassing "Measurement Requirements," "Sensor Technology Interfaces and Installation Requirements," "Legal Obligations," "Housing and External Influence Protection Requirements," and "Additional Requirements."

Based on these established prerequisites, four core technologies suitable for the use in AutoModal were identified due to their inherent characteristics: Surveillance Camera/Closed-circuit Television (CCTV), Thermographic Cameras, Ultrasonic Sensors, and LIDAR, Radar, Laser, and similar technologies.

Market research involved the investigation and engagement of over 20 sensor system manufacturers. Their performance was assessed against the defined requirements. Multiple sensor models underwent laboratory and crane-based testing, ultimately revealing that the combination of visual cameras and LiDAR sensors yielded optimal results for person detection.

2.1.2 Positioning on the Crane

Following extensive sensor analyses and testing, a comprehensive detection concept was formulated to achieve thorough person detection within hazardous areas. This concept specifically addresses two critical zones: the vicinity of the trolleys and the area beneath the load. To accomplish this, a total of 8 LiDAR sensors and 16 Closed-circuit Television (CCTV) cameras were strategically deployed within the landing gear area.

2.1.3 Machine Learning Techniques Used

Diverse sensors were integrated to create a dependable person detection system, with one crucial component involving identifying individuals in RGB images captured by the 16 CCTV cameras. This was achieved through the utilization of open-source Machine Learning-based Object Detection algorithms. To facilitate future updates, a dedicated neural module was developed as part of the Sensor and Neural Data Platform (SAND) software, leveraging the open-source Machine Learning API MLCVZoo. A dataset comprising 8,700 images encompassing all three crane levels (s. Fig. 1) and gantry legs was generated for training the final Object Detection model. This dataset was designed to address various real-world scenarios, including bright sunlight, rain, and nighttime conditions, as well as specific tri-modal terminal situations such as obstructed views of persons. During development, the YOLOX algorithm demonstrated the best Speed-Accuracy-Tradeoff, achieving a 97% mean Average Precision (mAP) on the test dataset. The processing time of the complete system (16 CCTV) is approximately 5 frames per second.

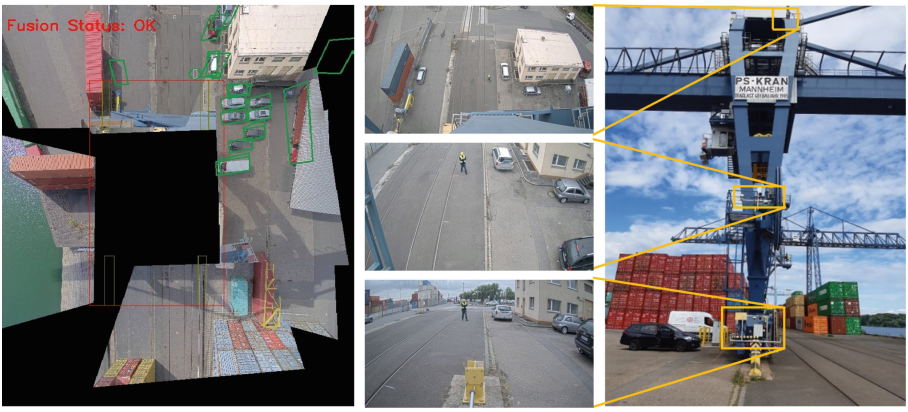


Fig. 1. Frame of Map and single pictures of different 3 levels.

2.1.4 Sensor Fusion and Map Builder

LiDAR sensor data is acquired by the software's LiDAR reader, subsequently routed to both a data recorder for storage and a transformer and filter. The latter processes involve consolidating the data streams from the 8 LIDAR sensors and eliminating redundant image information. The refined data is then transmitted to the "sensor fusion" module and a "map builder."

The crane's camera system captures images, which are handled by a camera reader and forwarded to an enricher and a recorder. The enricher associates camera data with metadata, including timestamps and camera positions (3 levels). Enriched data is then directed to an "image transformer" for conversion into 2D representations.

Within the map builder, this camera data is overlaid with the previously pre-processed LiDAR sensor data, resulting in a 2D map representation. This representation is subsequently disseminated to the crane dashboard through a "publisher" or "combiner."

2.2 Automation Function

To modernize the 1985-built crane for automation, various components were added, including a position detection system for the portal and crane trolley, a final landing system, and a pendulum damping system. Additionally, a supplementary programmable logic controller was integrated into the Crane Control System (CCS). Travel orders originating from the terminal operating system are routed to the internally developed Thing Action Management System (TAMS), where they undergo translation into crane-specific travel order data. Subsequently, this machine-compatible translation of the travel order, which adheres to standardized procedures, is transmitted to the CCS. Within the CCS, it is further converted into machine commands, facilitating corresponding crane movements through the crane control system. If the TAMS functionality is expanded to encompass "Autonomous Guided Vehicle" operations, the interface communication aligns with that of a gantry crane. Additionally, the order processing status is relayed back from the crane to the Terminal Operating System through TAMS. The crane continuously

transmits metadata from its actuators and sensors to a real-time dashboard. This "crane dashboard" consolidates essential data for external crane operators stationed at a control terminal. The operator oversees operational processes and retains the option to intervene or manually operate the crane when necessary. The displayed information encompasses crane movement data, order status, and sensor data from the camera and LiDAR systems.

3 Roadmap Automated Crane Handling

The tested automation elements only assist the crane operator. Before they can substitute the human operator, the safety concerns must be dispelled with an official technical safety approval for the automated crane, which is operated with the SAND person detection system. The developed roadmap to the automated crane shows following options for terminals to realise an automated handling in different steps:

Crane operator assistance. (= preparation for automation) - 1.5 years

Some tested features, which are necessary for an automated crane as a final landing system, assist the crane operator. This can also be retrofitted to old cranes, as shown in the project. The main effect has been seen with the remote-control system. There the operator can control the crane from the office or from the ground next to the crane. The crane operator saves a lot of time as he does not need to climb up the crane to the top cabin in ~28 m height for work. Additionally, an office workplace is a much more ergonomic and attractive workplace for a crane operator.

Automation within a fenced area - 0.5 years

Automation can be activated in not mixed used areas, that are fenced like container stock areas. Within this area the crane operator could use the automated system but must take the control again at the not fenced area. The savings potential of the fenced variant is low as the main work are un−/ loading processes.

Safety approval for automated cranes with person detection - 3.5 years

The safety approval is a long-lasting project of minimum 3.5 years. Even though the developed software SAND offers a technical solution for the problem, it must be extensive tested and approved by public authorities. Then it offers the potential to achieve big economic benefits by allowing one person to monitor multiple cranes at the same time and bringing the vision of an automated inland terminals closer to reality. Here some companies must go ahead to realise the safety approval with the automation technologies supported by the SAND system.

4 Evaluation and Insights

4.1 Evaluation of the Sensor Technology Used

Initially, the size of the danger zone must be defined and the sensors aligned accordingly. Furthermore, a machine learning network is to be integrated into the SAND software for the recognition of persons; various open source networks and the trained network of the AutoModal project are available for this purpose. Depending on the environment, it may make sense to train the network further in order to increase the recognition rate. The success rate is to be determined in tests in different situations for person recognition.

The minimum set enables the detection of persons in danger zone 1 around the travel paths of the gantry crane. It includes 4 visual cameras and 4 LiDAR sensors. The cameras are mounted at a height of about 25 m above the ground and pointed downwards.

The high performance set allows a 360° view and consists of 12 cameras and 8 LiDAR sensors.

4.2 Handling Performance

After completion of the conversion measures, the overall system was tested with regard to performance. The objective was to determine the throughput of the automation technology compared to manual operation. The crane's operating times in automated mode were comparable to those of an inexperienced crane operator. The partial processes were comparable in length in manual and automated mode. During the first test runs, the automated system was prone to errors in the load pick-up and load delivery processes. This was especially true for the accurate pick-up and set-down. However, in the further course of the test runs, the system then worked very continuously. The long-term data evaluation from 2018 on a more modern crane shows Ø 2:31 min for the process of handling in the terminal. This is below the range achieved by the manual operator on the older test crane with weaker drive. These values are considered realistic for this crane, but the times cannot be used as a comparison for all cranes. The exact times with and without automation must be recorded for each crane in a direct comparison.

5 Published Open Source Software

The software modules developed in the AutoModal project has been released as open-source software. This comprises a total of four components. The SAND tool simplifies camera streams by providing an extensible framework for reading, manipulating and republishing images. The TAMS enables manufacturer-independent control of crane systems. The CCS is an adapter to connect the TAMS to the crane control. The "Thing Action Management Interface (TAMI)" is a definition of the interface used to transmit travel orders to the crane system. The components are listed on a project website (Fraunhofer 2023).

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The 5G-RACOM Project: 5G for Resilient and Green Rail COMmunications

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Abstract. The German-French innovation project 5G-RACOM is investigating solutions for the efficient, reliable and sustainable use of the Future Railway Mobile Communication System (FRMCS) and the associated frequency spectrum. FRMCS is foreseen to be the successor to GSM-R and will ensure high-performance and real-time wireless communication between trains and infrastructure based on 5G technologies. FRMCS will deliver the basis for the digitalization and automation of railway operations and is, hence, fundamental to increase rail network capacity. 5G-RACOM has three objectives for a spectrum-efficient, a resilient and a robust FRMCS system design: (1) radio channel modeling studies at 900 MHz and 1900 MHz in different railroad operational scenarios including high-speed lines, tunnels, rural areas, (2) evaluation of the coexistence of GSM-R and FRMCS at 900 MHz and prototype development for technology migration, and (3) solutions for hybrid FRMCS networks in which the private FRMCS network is complemented by public mobile networks, e.g., as a fallback layer or capacity enhancement.

Keywords: FRMCS · 5G · Railway mobile radio · Mission-critical services · Hybrid railway networks · Multipath · Radio channel modeling

1 Introduction

The advancing digitalization of rail operations comes with highly demanding connectivity requirements. As the current 2G based railway mobile communication system GSM-R is not meeting those demands and will become obsolete in the 2030s, the 5G

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based Future Railway Mobile Communication System (FRMCS) is under development at European level [1–3]. FRMCS standardization is driven forward at UIC (International Union of Railways) and ETSI (European Telecommunications Standardizations Institute) within the Technical Committee for Railway Telecommunications (TC RT). Two railway mobile radio (RMR) frequency spectrum bands (at 900 MHz and 1900 MHz) have been allocated for FRMCS deployment in Europe [4] while parts of the radio spectrum are already in use with GSM-R (at 900 MHz). Additional spectrum, e.g., from public mobile network operators (PMNOs) is considered. The FRMCS architecture is based on two main paradigms: (1) Modularity enables separation of the application and the communication system as well as separation of services and pure transport. (2) Relying on standardized components and off-the-shelf technologies. Services are based on the mission critical services framework (MCx), standardized in 3GPP, while the transport is based on 5G with flexibility to integrate other access technologies as well as additional networks.

To make further progress, French and German railway infrastructure managers, telecommunication vendors, research institutes and academia joined forces in the 5G-RACOM project [5], under the "Franco-German Ecosystem for Private 5G Networks" initiative, to drive innovations towards a powerful private 5G network for railways. This project aims at investigating, developing and demonstrating key technologies to achieve a green, resilient, and future-proof FRMCS system by two paths: 1) exploiting the available RMR frequency spectrum most efficiently and 2) extending FRMCS towards additional public frequency spectrum via a hybrid network architecture.

2 Radio Channel Modeling and Co-existence of FRMCS and GSM-R Radios in the 900 MHz Band

Radio channel models will be developed based on trials on tracks along four different types of environments: high speed, intercity, regional and urban lines. These environments vary in terms of vegetation, profile of the terrain, presence or absence of buildings, and trains' speed. These differences have a major influence on radio propagation in the RMR bands. Three complementary MIMO radio channel sounders are considered [6–8]. The measured data will be used to develop 3D stochastic MIMO channel models and Ray Tracing (RT) technique, which is recognized as a good solution to complement stochastic models and emulate spatially-consistent MIMO radio channel properties (e.g., the map-based approach in the 3GPP TR 138 901 model). Channel sounding systems are able to extract the complex impulse response of the channel on a given frequency band in order to extract crucial information such as slow and fast fading distributions, Doppler spectrum, non-stationarity information in the channel, delays, position of the scatters, etc. At the time of writing of the paper, the measurement campaigns are in preparation and preliminary results obtained will be given in the final presentation.

Current GSM-R networks are deployed using FDD mode in a 900 MHz harmonized frequency band of 2 x 4 MHz (876–880 MHz uplink (UL) / 921–925 MHz downlink (DL) – R-GSM 900). While this spectral range is, in Europe, entirely devoted to the needs of GSM-R, some European countries have been authorized to take benefit of a spectral complement. This is particularly the case in Germany, Liechtenstein and Switzerland

where the 873–876 MHz (UL) and 918–921 MHz (DL) frequency bands may also be used for railways needs (ER-GSM Band). In 2020, CEPT concluded the harmonization of the 900 MHz frequency range, allocating 2 x 5.6 MHz, (874.4–880 MHz UL / 919.4–925 MHz DL), operated in FDD mode, for both the current and future railway needs. This band is now allocated by 3GPP as 5G NR band n100, also called "RMR 900". This decision implies that the coexistence issue between current GSM-R systems and the future FRMCS standard should be addressed. To enable this coexistence, a simple approach could be proposed.

Considering the 2 x 5.6 MHz FDD part devoted to railways in the 900 MHz band (Fig. 1), a GSM-R re-farming could be envisaged to release at least a bandwidth of 2 x 3 MHz, in UL and DL parts, on which a reduced 5G system could operate. As illustrated in Fig. 2, a narrowband 5G system [9] is introduced adjacent to the GSM-R carriers that have been re-farmed. This collocated approach using a 5G NR system of approx. 3 MHz system bandwidth is currently under study in 3GPP.

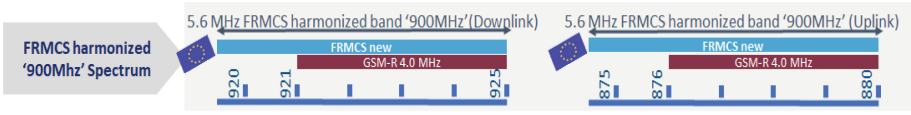


Fig. 1. Harmonized FRMCS 900 MHz spectrum.

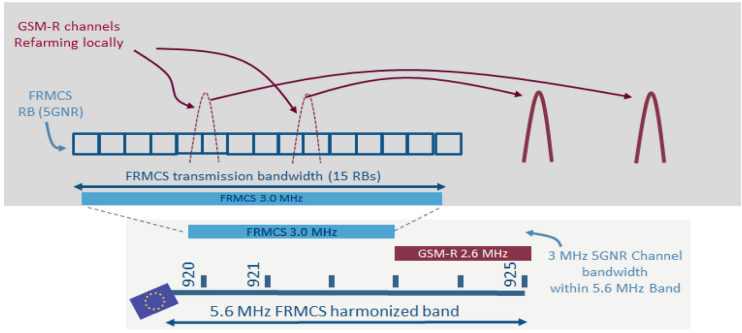


Fig. 2. FRMCS and GSM-R 900 MHz coexistence using "collocation" approach.

Another innovative approach could consist of deploying a 2 x 5 MHz 5G NR system overlapping the current 2 x 4 MHz GSM-R system. This approach is designed to operate in coexistence with the existing GSM-R system by minimizing inter-system interference. This is achieved through advanced scheduling techniques in the base station to protect GSM-R carriers while remaining fully compatible with standard FRMCS handsets and cab radios using 5G NR (meaning no change on mobile devices required, standard RMR 900 UE used). In both approaches, the 5G resources will be limited. The "whitespace" coexistence scheme consists of locating the current GSM-R technology and the 5G NR technology onto the same frequency band. The main goal is to allow a smooth

introduction of the 5G NR RMR 900 inside the GSM-R band without impacting GSM-R performance. The aim is to not allocate additional spectrum nor introducing complex filtering solution to solve RF coexistence problems that would strongly impact the legacy GSM-R system. The proposed method ensures that in a given spectrum (on which GSM-R is already deployed) 5G NR deployment is possible with a maximized capacity not reachable by other methods. The concept consists in reusing the inter GSM-R carriers frequency spaces as follows: Into the 900 MHz harmonized band two railway systems, the current GSM-R 4 MHz standard and the future FRMCS standard based on 5G NR 5 MHz (25 RBs) OFDM technology, for both UL and DL. 5G NR resource blocks (RBs) coinciding with GSM-R carriers are blanked in order to prevent GSM-R carriers from being disturbed by adjacent interferers. The resulting "whitespace" approach is depicted in Fig. 3. Note that in both coexistence approaches, a coordination scheme between radio and computing schedulers in the context of 5G FRMCS is needed to satisfy application QoS requirements (in terms of throughput, processing time, packet loss, etc.).

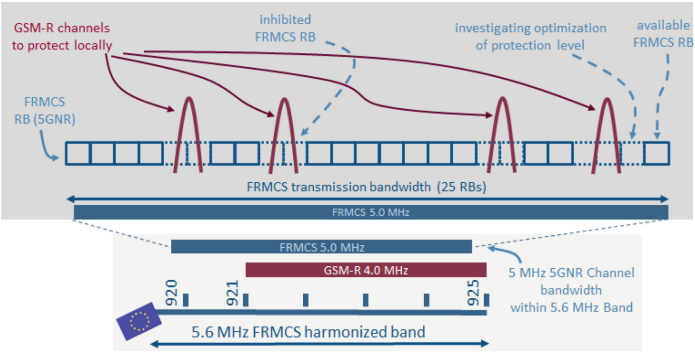


Fig. 3. FRMCS and GSM-R 900 MHz coexistence using "whitespace" approach.

3 Hybrid FRMCS Networks

To increase resilience and availability in railway communications, but also to provide capacity enhancement and improve overall coverage, 5G-RACOM is working on extending the FRMCS network with access to the resources of public 5G mobile networks in a hybrid FRMCS network architecture. The hybrid architecture concept is illustrated in Fig. 4. It is based on the use of selected multipath (MP) technology that will enable railway infrastructure managers to use multiple independent transmission paths to implement individual policies for all railway applications incl. video streaming and group communications. The overall solution as implemented by the 5G-RACOM project shall provide support for the following high-level use cases: 1) application specific path selection, 2) resilience via fallback, 3) resilience via path selection, 4) resilience via duplication, 5) capacity complement and 6) coverage complement.

For the typical FRMCS approach a connection between an application inside the train and its counterpart at the trackside is established with a single network and a single

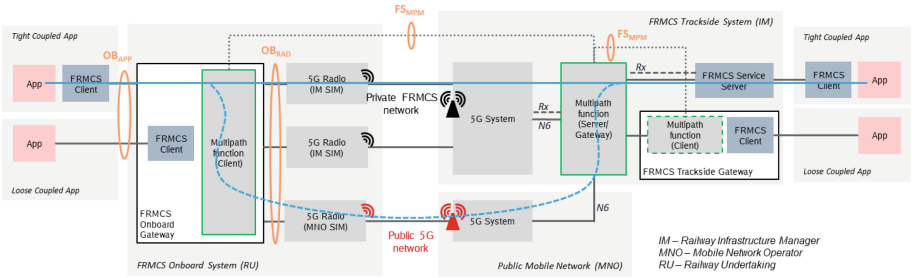


Fig. 4. High-level view of a hybrid FRMCS architecture incl. multipath functions.

onboard radio. The onboard gateway offers that multiple railway applications located inside the train can access the FRMCS network. The service server (i.e., MCx server) at the trackside is managing services offered towards the railway applications utilizing MCPTT, MCData or MCVideo capabilities. 5G-RACOM will interconnect the service server at the trackside also with the public 5G mobile network to provide another connectivity option. At the train side, additional onboard 5G radio(s) will be integrated within the onboard system architecture and connected with the onboard gateway. To utilize both networks flexibly, seamlessly and in a parallel fashion, the MP function needs to be implemented on both the onboard side and the trackside of the FRMCS system and will anchor/aggregate all the traffic. These MP functions would then provide steering, switching and splitting capabilities necessary for using multiple independent transmission paths by railway applications within the hybrid FRMCS network in a transparent manner, see Table 1.

Table 1. Steering, switching and splitting capabilities in multipath functions.

Steering	=	FRMCS	or	Public 5G	=	Best network selection
Switching	=	FRMCS	from/to	Public 5G	=	Seamless handover
Splitting	=	FRMCS	and	Public 5G	=	Network aggregation

MP functions should consider, among others, the availability of the network, the instantaneous quality of the networks as well as the QoS requirements of the specific railway application. Based on such information, MP functions can apply policies as defined by the railway infrastructure manager. Scenarios such as poor radio conditions of the FRMCS network can be compensated by adaptive re-routing of the traffic, whose QoS cannot be supported. In cases of a complete unavailability of the FRMCS network, the complete traffic could be handled by the public 5G network. High volume applications such as video streaming can be offloaded to the public 5G network in case of insufficient capacity of the FRMCS network. For supporting QoS of railway applications also within the public network, a dedicated network slice is envisaged in the public 5G network for which specific service level agreements can be provided by the mobile network operator. The N6 interface in 3GPP 5G networks will be used for the data transfer from/to public 5G

network while no signalling interface will be used between the networks in the project. Different candidate multipath technologies and protocols such as MP-TCP, MP-QUIC, SCTP, load balancing based solution and SD-WAN are under investigation in the project, while the most suitable solution will be selected for conceptualization, implementation and elaboration within a real-world hybrid FRMCS test network. This test network will be realized in the Ore Mountains in Germany, combining a private 5G FRMCS test network from Deutsche Bahn and a public 5G mobile network under joint operation of Vodafone and Technische Universität Chemnitz, that can implement 5G-RACOM's test configurations.

4 Conclusions

Exploiting the frequency spectrum allocated for FRMCS through an efficient and robust system design is essential for the existing mission-critical railway applications to migrate from GSM-R to FRMCS and a key step for future railway operations to be introduced and deployed. 5G-RACOM contributes to this by providing solutions for radio channel modeling, for GSM-R and FRMCS coexistence in the 900 MHz band and for design and realization of hybrid FRMCS system architectures, incl. selection of multipath protocols for optimized routing.

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New Roads Governance Framework Based on Circularity

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Abstract. One of the activities that can most influence climate neutrality is the activity of infrastructure construction.

Some countries already include environmental concepts in the development of their infrastructures, as an approximation to neutrality, but this is insufficient, it is necessary to be more ambitious, and define in a broad and global way, a governance framework that includes this concept in detail, throughout their life cycle.

To this end, a methodology is proposed that defines the neutrality of infrastructures based on circularity, including this concept in governance processes, through circularity indicators.

In addition, to show its validity, it is applied to the contracting in the construction phase of the A-67 Highway project, Capacity Expansion, in Spain.

Obtaining very good improvements in infrastructure governance, thus contributing to climate neutrality.

Keywords: Governance framework · Circularity · Resource efficiency · Carbon footprint · Recyclability · Risks

1 Introduction

To fulfill the commitment of the 2030 Agenda [1] and the objective of achieving climate neutrality in 2050 [2].

Circularity is chosen as the base concept for its fulfillment and definition, since circularity has as its goal the protection of the environment and the protection of the existence of materials, retaining the maximum possible value, for the longest possible time, to thus minimize the use natural resources [3].

By its nature, the infrastructure sector, and more specifically that of roads, meets all the conditions to apply the principle of circularity, both due to the materials they are made of and their installation method.

Thus, it is considered necessary that the concept of circularity must be included in the management of infrastructures and therefore form part of their governance framework.

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2 Circularity Regulatory

To do this, we must know to what extent this concept is developed.

- **Green Public Procurement (2015). Procuring goods** [4]. Acquisition of goods, services and works with a reduced environmental impact throughout their life cycle.
- **RAGTIME, EC (2016)** [5], based on risks, proposes a general infrastructure governance framework.
- **ISO 20400:2017. Sustainable procurement (2017)** [6]. Sustainable procurement — Guidance. It provides guidance to organizations, regardless of their activity or size, on the integration of sustainability into procurement, as described in ISO 26000. It is aimed at stakeholders involved in or affected by procurement decisions and processes.
- **Level(s) – A common EU framework of core sustainability indicators for office and residential," (2017)** [7].
- **FORESEE, EC (2018)** [8], which proposes the management of resilience against climate change, based on risks.
- **Guide des achats durables (2021)** [9], Belgiam Federal Institute for Sustainable Development (IFDD), has developed a sustainable procurement guide that describes technical sustainability criteria, to be included in the purchase specifications of supplies and services, and Belgian Transport Research Center (CRR), has developed a series of sustainability indicators [10] of an environmental, social and economic nature, with the aim of being included in tenders with an easy, simple and objective methodology.
- **Platform CB'23 (2019)** [11], a Dutch initiative within the construction sector, published a framework for assessing circularity in buildings and civil engineering in the Netherlands.
- **CERCOM (2022)** [12], Good practice inventory of current systems and procurement methods (Overview of Research Programs Operations (cedr.eu))

3 Circular Infrastructures Governance. Methodology

Based on and according to all the above considerations, a methodology is proposed based on expressing circularity, as a milestone of infrastructure neutrality, and specifying it through circularity indicators (Table 1).

Table 1. Infrastructure circularity indicators.

Indicators	Definition[a]
$I_{Materials}$	Materials Cost/Direct Cost
I_{Waste}	Waste Cost/Direct Cost
I_{Water}	Water Cost/Direct Cost
I_{Energy}	Energy Cost/Direct Cost
I_{C02}	CO2 emissions cost/Direct Cost

[a]Costs obtained based on project data expressed in €

Indicators obtained based on the definition of the circularity actions proposed in the LIASON project (2023) [13] (Fig. 1).

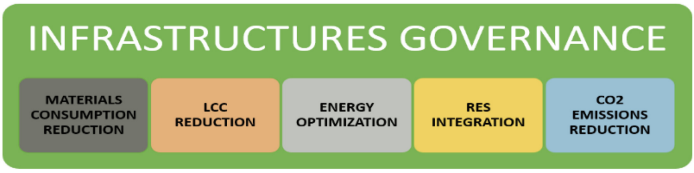


Fig. 1. Actions for the circularity of Infrastructures 13.

- Materials Consumption Reduction. Reduce the use of materials by increasing their durability quantified in uses or years of useful life (resilience against risk) and their recyclability 9Rs [14], of which only those directly applicable to construction materials are used, in addition to paying special attention to waste and water use.
- LCC Reduction. Reduce the life cycle of infrastructure, fundamentally with the union the phases of Project and Construction [7].
- Energy Optimization. Optimize energy through proper planning.
- Integration of renewable energy solutions. Integrate the use of combustion energy with renewable energies.
- Reduction of CO2 emissions. Reduction of emissions based on the operating time of the machinery.

Thus, these circularity indicators, together with the rest of the infrastructure risk indicators, affected by their corresponding project weights, **will form the basis of the governance framework, which determines the infrastructure neutrality processes** (Fig. 2).

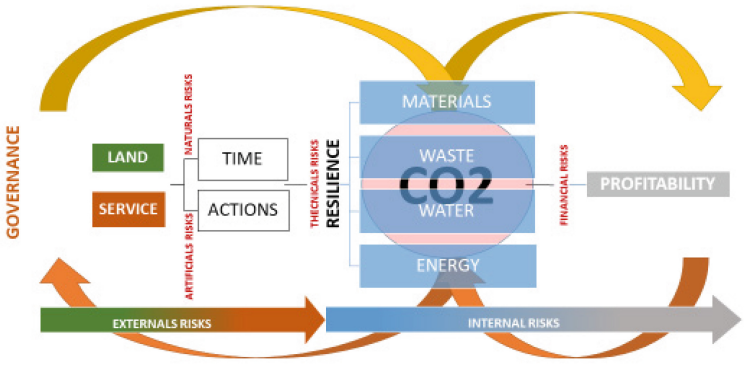


Fig. 2. Neutral Infrastructure Governance Indicators [13].

4 Circularity A-67 Highway Capacity Expansion

From the application of this methodology to the Construction Project of the A-67 Highway Capacity Expansion, SPAIN, the following circularity indicators are obtained (Table 2):

Table 2. Circularity indicators A-67 Highway Capacity Project.

Indicators		Values	
$I_{Materials}$	$I_{R2\ Reduce}$	**0.49**	**0.68**
	$I_{R3\ Reuse}$	**0.41**	
	$I_{R4\ Repair}$	**0.30**	
	$I_{R5\ Refurbish}$	**0.57**	
	$I_{R8\ Recycle}$	**0.49**	
I_{Waste}		**0.01**	
I_{Water}		**0.00**	
I_{Energy}		**0.60**	
I_{C02}		**0.14**	

Indicators that express the circularity of the project, and are the basis for the selection process for the construction of the neutral infrastructure, which the A-67 Highway can become.

5 Conclusions

As a final result, this infrastructure circularity methodology,

1. Proposes simple concepts of circularity.
2. It applies to the entire infrastructure life cycle.
3. It defines neutral infrastructure governance indicators, based on circularity, easily incorporated into current project management tools.
4. Complete the digitalization of infrastructure governance, based on risks.
5. Finally, it defines a simple infrastructure governance framework to achieve climate neutrality by 2050.

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CEMBOX. Digital Twin Oriented Infrastructure Asset Management Platform

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Abstract. CEMBOX Digital Twin oriented Platform has been conceived to address the pressing needs in terms of design, maintenance, retrofitting and digitisation in the fields of infrastructure and mobility. The Platform's Digital Twin is conceived as a real-time replica of the infrastructure that enables (i) the visualisation of assets in an interoperable BIM-GIS environment, (ii) the inspection of the state of infrastructure assets, integrating advanced inspection and monitoring technologies by means of IoT systems and other ICT enablers, and (iii) infrastructure condition analysis by means of Artificial Intelligence and advanced structural health monitoring algorithms, analysing the evolution of condition state over time, so as to support asset management decision-making.

Following the needs of infrastructure asset inspection, maintenance, and management, CEMBOX has been orchestrated into four main services described in this article: Management, Inspection, Monitoring and Planning.

Keywords: Digital Twin · BIM · GIS · Internet of Things · Artificial Intelligence · Structural Health Monitoring

1 Introduction

In the current context of maturity and high-level service within the European infrastructure sector, investments in transport infrastructure are primarily focused on managing existing assets. A significant portion of European transport infrastructures were constructed between the 1960s and 1970s and were designed with a lifespan of 50 years. As a result, a high percentage of existing assets have exceeded their design lifespan and require maintenance and actions to preserve their functionalities and adapt to new technical and service requirements.

In addition to regular maintenance tasks, the aging existing infrastructure requires significant upgrading efforts. Furthermore, the fight against climate change underscores the need to reduce emissions in all aspects related to road infrastructure management. In this context, the smart preservation of pavements, tracks, structures, and other road network assets can significantly reduce associated CO_2 emissions [1].

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Thus, Industry 4.0, with the rise of robotics, digitisation and artificial intelligence, added to the actual climate crisis, have shifted the perspective of technical road requirements and the techniques to be employed for its preservation. The sector requires technologies for the management and preservation of road infrastructures that are capable of: (a) enhancing services in terms of safety and connectivity, (b) reducing costs resulting from the high volume of necessary conservation activities in the coming years, (c) increasing the European network capacity by making a more intelligent use of it, and (d) enabling sustainable asset management, moving towards decarbonisation in line with the European Green Deal [2].

2 Platform: Concept, Objectives and Impact

The main objective of the research hereby presented is the development of an Intelligent Asset Management Platform which aims to improve, digitalise, and automate the management processes of transport infrastructures, focusing on linear infrastructure.

The Digital Twin oriented Platform has been conceived as a tool that enables a centralised approach to address the new needs in the field of transportation and mobility, encompassing maintenance, rehabilitation, digitisation, and technological development. The Digital Twin is conceived as an updated replica of the infrastructure that allows [3]:

- Visualization of assets in an interoperable BIM-GIS environment.
- Analysis and prediction of the infrastructure's state, integrating advanced inspection and monitoring technologies using IoT (Internet of Things) systems, among others.
- Simulation of scenarios regarding asset behaviour, enabling optimisation of maintenance planning using Artificial Intelligence (AI) and advanced optimisation techniques, among others.

Based on the various inspection, maintenance, and management needs of transport infrastructure assets, the so-called CEMBOX Platform has been organised into four main services: Management, Inspection, Monitoring, and Planning (this last one still under development). The different services are formed by different modules that will be detailed in the following sections.

The integration of all the described developments and services into CEMBOX aim to generate a significant impact on transport infrastructure asset management across various aspects such as mobility service improvement, traceability, cost reduction and safety enhancement.

3 Platform: Use Case and Functionalities

The functional architecture of the Asset Management Platform follows a continuous improvement process and it is, at this stage of development, based on three services (Management, Inspection and Monitoring), while the Planning service is still under development. Several modules integrate each of the aforementioned services with specific objectives and applications that are described in the following subsections.

3.1 Management

The Management service is used to coordinate all the assets and activities to be carried out in a particular transport infrastructure application, organised on a client, project or asset basis. This provides an inventory for documentation; actions, costs and deadlines (for maintenance and monitoring); or BIM and FEM models, among others.

This service constitutes the basis on which the rest of CEMBOX's functionalities are built. The service is developed based on a SAP® Back-End, based on previous internal developments of CEMOSA, for which two modules have been parametrised, among other tools:

- The **PS (Projects System) module** to adapt its standard functionality to the needs of infrastructure asset management.
- The **ZOBRA application**, developed to allow the recording of infrastructure data and the calculation of infrastructure condition state following a set of algorithms developed in the TECH4INFRA project [4].

Thus, this service enables a **Common Data Environment (CDE)** for the Digital Twin. The CDE allows the exchange of all information from the Asset Management Platform with the different stakeholders of a project, since it includes documentation, BIM models, plans, management of actions, tasks or project milestones. The Front-End applications of the Management service have been implemented using SAP Fiori®, as well as APIs and tools provided by Autodesk BIM 360®, Autodesk Platform Services® and ESRI®.

This service enables the information from the BIM-GIS models and the dynamic information stored in databases such as SAP HANA® (among others) to be jointly managed and used for various purposes such as inspection, monitoring or testing, among others.

3.2 Inspection

The Inspection service is composed by a data entry module, the so-called Visits module, based on a field survey application developed by CEMOSA [4]; and three visualisation and interaction modules related to pavements, point clouds and pathologies.

The **Visits module** is an application that enables the recording, processing and management of infrastructure inspection information for its use on the Platform. In accordance with the planning of the inspections and the visits registered in the Management module, inspection data is recorded, employed to calculate the condition state indexes of the inspected elements and stored in real time in a SAP HANA® database.

Thus, the module is built on web applications that have been developed in SAP Fiori® to allow them to be executed on any mobile device and communicate bidirectionally and in real time with the Management module implemented in CEMBOX's SAP® Back-End.

The **Pavements module** (focused on road infrastructure applications) provides an environment for the visualisation of georeferenced information on road segments, such as information related to IRI, SFC or deflections. This module allows coordinated use of the information from the GIS models (using the ESRI API for visualisation) and the dynamic information stored in the database. The module allows bidirectional communication

between the model information, located on the left-hand side of the interface, and the commands and information referenced on the right-hand side of the interface.

Figure 1 shows the pavement module from the inspection service which focuses on the GIS information providing the road condition parameters. On the left-hand side of the interface, the interactive viewer allows the navigation, while the right-hand side panel displays the related road segment information.

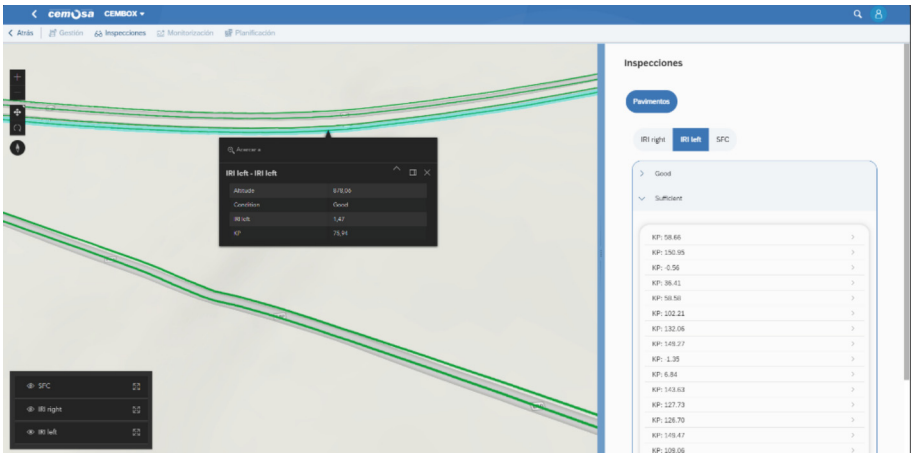


Fig. 1. Pavement module from Inspection service.

The **Point Cloud module** allows the interaction with infrastructure inspection and scanning campaigns through point clouds. Based on the Management service, these point clouds are organised by project and asset, which enables the survey of works, (visual) condition status and damages.

Finally, the **Pathologies module** manages the information regarding the damages inspected over time through the aforementioned Visits module, and organises the information based on project and asset. These features enable a traceable monitoring of the identified defects in a specific asset. The module aims to display the information related to pathologies in an asset in a clear and understandable way for the end-user. Thereby, it relates the BIM-GIS model of the infrastructure and all its defects referenced as families of BIM elements to all the information registered about these defects over time, stored in a SAP HANA® database.

3.3 Monitoring

The Monitoring service has the objective of providing information on the state of the infrastructure through data captured in real time by IoT devices such as accelerometers, inclinometers or strain gauges. This Platform service is made up of three modules related to the installed devices, the data received and the subsequent analysis of this data.

The **Devices module** includes information regarding the sensors installed on specific assets, establishing a hierarchical relationship among them. The module shows the location of the sensors on the BIM model, in addition to information related to the device,

including the serial number, the type of sensor or the sampling strategy: acquisition period, acquisition time in an event and frequency of sampling. The Platform allows various strategies for the deployment of sensors, using gateways or edge nodes for the communication as well as different protocols, such as MQTT. The information from the devices can be stored either in databases such as SAP HANA® or in other databases (such as those provided by Microsoft Azure) depending on the requirements.

The **Data module** is closely linked to the devices and provides the information captured in real time by the sensors.

Finally, the **Analysis module** processes the data from the two previous modules and their respective databases to provide information on the status of a monitored infrastructure asset.

One example is the case study related to Structural Health Monitoring (SHM) of bridges. This module uses algorithms to carry out the processing and analysis of the recorded signals, as discrete monitoring events, to provide information according to the specific requirements, such as:

- Maxima and other statistical calculations oriented to comfort evaluation.
- Frequency Domain Decomposition (FDD) analysis to determine the frequencies and modes of vibration of a bridge, as well as their evolution over time.
- Based on this information, Machine Learning and advanced optimisation techniques are being applied to analyse the evolution of the modes of vibration and the condition state, and provide a basis for the prediction and prognosis of the structural health of the asset.

Figure 2 shows the Analysis module from the Monitoring service. As per the previous cases, the BIM-GIS interactive visualisation is shown in the left-hand side, while the information relative to the analysis (e.g. modes and evolution) is shown on the right.



Fig. 2. Analysis module from Monitoring service interface.

4 Conclusions

This article has presented the Asset Management Platform developed by CEMOSA within the framework of several research and innovation projects, including TECH4INFRA [4], OMICRON [5] and IN2TRACK3 [6]. The Platform is involved in a continuous improvement process where, at this stage of development, it integrates three main services:

- The **Management service**, which is the basis for the rest of services since it defines the common data environment for the intelligent management of infrastructure assets.
- The **Inspection service**, with the aim of integrating different tools for the periodic and regulated survey of assets.
- The **Monitoring service**, with the objective of capturing, storing, and processing real-time information on infrastructure assets.

These services host different modules that provide different functionalities such as (i) asset information management and inventory; (ii) infrastructure inspection using traditional and aerial systems; (iii) management of models (e.g. BIM, FEM) related to an asset and its damages; (iv) monitoring and evaluation of the structural health of assets; (v) evaluation of infrastructure condition state; and (vi) access and visualisation of information through a Digital Twin Platform.

New developments relative to prognosis based on Machine Learning techniques are planned to improve the analytical capabilities of the Platform. These will be employed in the fourth service of the Platform, the Planning service. This service will process the stored information from the various sources presented earlier as well as the results from the different algorithms to support maintenance multi-criteria decision-making and asset intervention planning.

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Using the Analytical Hierarchy Process (AHP) to Prioritize Network Benefits When Applying Novel Traffic Management Strategies

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Abstract. Continuous developments in computer technology and communications and their application in traffic operations have led to the development of several Traffic Management Strategies (TMS). This study applies the Analytical Hierarchy Process (AHP) to gather and consolidate stakeholder preferences, allowing for the identification of the most important network benefits obtained from implementing four emerging TMS. AHP provides a robust, cost-effective and popular framework for making similar decisions in complex, multi-stakeholder decision situations. To apply the AHP, we have solicited ten stakeholders of various backgrounds (private and public operators, transit authorities etc.) from four European cities: Athens (Greece), Manchester (UK), Lisbon (Portugal) and Rennes (France). Stakeholders were individually requested to express their preferences through pairwise comparisons across four axes (objectives): Service Performance, Network Efficiency, Economic Performance, and Environmental Performance. Each objective was linked to a scenario-specific KPI, which was communicated to stakeholders and allows for concrete TMS performance measurement, ex-ante (e.g. through simulation), or ex-post, on the field. It is derived that stakeholders prioritize differently the potential benefits arising from the implementation of each TMS.

Keywords: AHP · MCDM · Traffic Management Strategies · Multi-Stakeholder Decision-Making

1 Introduction

Advancements in computer and communication technologies have led to the evolution of various Traffic Management Strategies (TMS), such as transit signal priority systems, adaptive signal control, and congestion pricing schemes. Selecting the appropriate TMS in cities is a well-researched topic with proven benefits: various implementations of TMS in cities globally have demonstrated their effectiveness in facilitating the movement of urban traffic flows across various modes [1]. The configuration or parameterization of the TMS is equally crucial, since different configurations can significantly affect traffic flows and yield different performance levels regarding objectives such as decreasing congestion and/or greenhouse gas emissions, increasing the efficiency of the overall

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network etc. And, more often than not, it is not possible to increase performance in one objective without decreasing it in a different one, in an environment of where various stakeholders hold different and often highly conflicting views on the relative importance of each of them [2].

To assist decision makers in cases where multiple objectives must be evaluated concurrently from multiple stakeholders, Multi-Criteria Decision-Making (MCMD) techniques have evolved as a subset of operations research [3]. Among them, the Analytic Hierarchy Process (AHP) is one of the most widely used as it offers an intuitive, consistent, and axiomatically founded mathematical framework which delimits the scope of the decision-making environment into the evaluation of a number of criteria (objectives). It also guides decision-makers into expressing their preferences in a natural way, by comparing the relative importance of objectives in a pairwise manner [4]. In the transportation sector, where there is a continuous need for decision-making for selecting the optimal policy, infrastructure or project in a strategic, tactical, and operational level, the application of the AHP is wide and lauded [5]. In this context, the main objective of the present study is to present an AHP-based decision support tool for the identification of the relative importance of conflicting transport network objectives, in the case where four novel TMS are applied.

2 Methodology

The four TMS which are of interest in the context of this work are defined below:

- **Signal-Vehicle Couple Control (SVCC)**: SVCC aims at the joint optimization of the Connected and Automated Vehicles' (CAV) routes and signalization (e.g. signal timings).
- **Synchronization of on-demand and transit modes (DRT-PT)**: DRT-PT pertains the dynamic synchronisation of the transfer between on-demand and regular public transit services.
- **Dynamic congestion pricing (DCP)**: DCP refers to various dynamic congestion pricing schemes. The dynamic nature of the system refers to their capacity to adjust the toll price in response to real-time or near-real-time variations in traffic flows.
- **Synchronization of public transport and traffic control (PTTC)**: PTTC aims at the joint optimisation of transit assignment (e.g., service headways, fleet allocation/capacity) and signalization (signal timings).

The selection of the optimal TMS configuration is determined based on specific performance standards tied to recognizable societal concerns. In this work, four objectives are identified: Service performance (SP), Network efficiency (NE), Economic performance (EP) and Environmental performance (ENV).

Each objective has been associated with a specific Key Performance Indicator (KPI). Each KPI can be perceived as a concretization of what each objective actually corresponds to in the context of each TMS. It also enables the concrete measurement of the performance of each TMS, ex-ante (e.g. through simulation), or ex-post, on the field. For each objective and TMS, the indicators are included in Table 1.

Table 1. Selected KPIs for each Objective and TNM.

Problem	SP	NE	EP	ENV
SVCC	Total travel time difference between CAVs and conventional vehicles	Congestion at selected axes	Energy consumption of CAVs	Emissions reduction
DRT-PT	Total passengers served	Passenger travel time	Operational costs of the DRT fleet	Emissions of the DRT fleet
DCP	Congestion within the congestion charging zone	Congestion outside the congestion charging zone	Total profit from the tolls	Emissions reduction
PTTC	User costs for selected bus lines	Congestion at selected axes	Public transport operational cost	Emissions reduction

2.1 The AHP Framework

A set of n objectives $X = \{x_1, \ldots, x_n\}$ is defined and let the significance or relative importance of x_i in relation to x_j be represented by a_{ij}. Additionally, the following conditions are met: $a_{ij} = 1/a_{ji}$, for $i \neq j$ and $a_{ij} = 1$ for $i = j$. Preference relations for all pairs of objectives are collected in the matrix $A = (a_{ij})^{n \times n}$, called the reciprocal preference matrix.

To elicit a_{ij}, decision-makers are asked to express a graded comparative judgment of two objectives x_i, x_j on a semantic scale. The most frequently used scale is Saaty's 1 to 9 rating scale (Fig. 1).

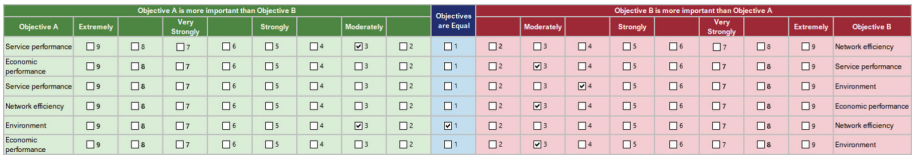


Fig. 1. Elicitation of pairwise preferences for a given TMS.

When all judgements on pairs of objectives have been collected, the goal of the AHP is to obtain the scale of priorities for the n objectives, or the n-dimensional vector $w = w(A) = (w_1, w_1, \ldots, w_n)'$ obtained from matrix $=(a_{ij})^{n \times n}$, such as w_i faithfully captures the relevant importance of objective x_i among all objectives in X.

Using the Maximum Eigenvalue (ME) method [6], the vector w can be obtained by solving a linear system of equations, proven to have the unique solutions $\overline{w} = (\overline{w}_1, \overline{w}_2, \ldots, \overline{w}_n)'$ [7].

2.2 Data Collection

To achieve the creation of an evidence-based tool based on actual stakeholder input, data was collected through a structured survey which was addressed to decision-makers in four European cities: Athens (GR), Lisbon (PT), Manchester (UK) and Rennes (FR). The survey has targeted officials with knowledge of the decision-making, cooperation and communication patterns between stakeholders involved in traffic management. Respondents could represent various public and private stakeholders. For the elicitation of preferences, experts evaluated every objective against all others in a pairwise way, resulting 6 evaluations of the 4 objectives per decision-maker and per TMS (Fig. 1).

The total number of collected questionnaires amounted to 10 questionaries from an equivalent number of experts.

3 Results

The resulting objective weight for each TMS are reported in Table 2.

Table 2. Number of opinions for each TMS.

Objective	SVCC	DRT-PT	DCP	PT-TC
Service Performance	0.23	0.36	0.41	0.22
Network Efficiency	0.36	0.28	0.32	0.32
Economic Performance	0.15	0.17	0.12	0.19
Environmental Performance	0.27	0.19	0.16	0.27

For SVCC, Network Efficiency ranks as the top priority with a weight of 0.36, followed by Environmental Performance at 0.27. The potential that CAVs bring in optimizing traffic flow and reducing emissions (through efficient platooning, speed harmonization, improved lane utilization, intersection management, and ride-sharing) is being widely reported [8]. Participating decision-makers seem to agree with this view when expressing their preferences. The ranking is completed by Service Performance and Economic Performance, which rank as 3rd and 4th respectively.

For DRT-PT, Service Performance, approached as the total served passenger by the system, ranks as the most important objective (0.36). This result is intuitive in its context, since the primal aim of the synchronization of on-demand modes and public transit is the solution for the first/last mile problem [9], particularly in less populated areas with sporadic public transport. In this context, on demand modes can serve as connectors or gatherers for public transit and act as an alternative to infrequent public transit lines (usually bus lines), with vehicles running almost empty. If the system can cater to a large number of passengers, it means it is effectively addressing the transportation needs of the community. Network Efficiency ranks as the second most important objective (0.28), again intuitively since passenger travel time is a common consideration when

designing a multimodal transit system [10]. The ranking is completed by the objectives of Environmental Performance (0.19) and Economic Performance (0.17).

For DCP, Service Performance ranks as the most important criterion (0.41). Given that the corresponding KPI is related to the congestion within the congestion charging zone, we conclude that, unsurprisingly, stakeholders evaluate more favorably the main pursuit of such a system, which is the discouragement of car users from passing through the city center, and shift to peripheral streets or public transport [11]. The ranking is complemented by the objectives of Network Efficiency (0.32), Environmental Performance (0.16) and Economic Performance (12).

Finally, for PTTC, Network Efficiency (0.32) ranks as the most important objective. Given that this objective is related to the KPI "Congestion at selected axes", we read this result as a concern for the possible increase of waiting times for non-bus traffic which can also lead an increase in emissions and fuel consumption (the Environmental Performance objective ranks 2nd with a weight of 0.27). The ranking is followed by Service Performance (0.22) and Economic Performance (0.19), which, as with the evaluation of all previous TMS, it is regarded as the least important objective.

4 Conclusion

The aim of this work is to showcase the methodological approach and primary outcomes of implementing the AHP to quantify and understand the most important network benefits obtained from implementing four emerging TMS. Our specific goal was to determine a consolidated ranking regarding the relative importance of four transport network objectives when the strategies are applied. The study reveals interesting insights on the priorities of stakeholders, which prove to be different for each TMS and can be used to select the network configuration that optimally corresponds to their priorities. Our methodology is problem-agnostic and can be applied to uncover and quantify the consolidated, consensus-based priorities of expert in different sectors, as long as the decision-making problem is structured like ours. In further research efforts, other MCDM methods such as TOPSIS, SAW or the Analytic Network Process (ANP) can be evaluated and their results can be compared with the ones presented here. A further, interesting research avenue is the application of the novel Consensus Reaching Process (CRP) paradigm, which relies on the same input and models the formation of a consensual preference through interaction with a mediator.

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Comparing Random Forests and Multinomial Logit Models for Urban Travel Mode Choice Under Innovative Traffic Management Strategies

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Abstract. This study explores the factors affecting travel mode choices upon the implementation of two innovative Traffic Management Strategies in an urban setting, namely a Transit Signal Priority system and a Congestion Pricing scheme. To gather the necessary data, a stated preferences survey was conducted in three major European cities: Athens (Greece), Lisbon (Portugal), and Manchester (United Kingdom), aimed at the elicitation of individuals' preferences when selecting travel modes. The collected data from each city were used to develop and calibrate multiple mode choice models, including econometric Discrete Choice (DC) models such as the Multinomial Logit (MNL), as well as state-of-the-art Machine Learning models like the Random Forest (RF) classifiers. Through the evaluation and comparison of the models' results, we present an analysis of the factors influencing mode choice and we highlight the similarities and differences in the performance and interpretation of parametric and non-parametric models. The findings from this study can inform the development of sustainable transportation systems and contribute to more efficient decision-making processes in urban mobility management.

Keywords: Mode choice · Traffic Management Strategies · Machine learning · Random Forests · Multinomial logit

1 Introduction

The ongoing advancements in Information and Communication Technologies (ICT) have opened up possibilities for the creation of novel Traffic Management Strategies (TMS), aimed at enhancing mobility management and operations within urban areas [1, 2]. Among the plethora of the recently proposed TMS for arterial streets and grid networks, Transit Signal Priority (TSP) and Congestion Pricing Schemes are some of the most promising [2]. In this context, this study aims at the investigation of the decision-making process behind travel mode choices, under the occurrence two innovative Traffic Management Strategies: a Transit Signal Priority System and a Congestion Pricing

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scheme. To collect the necessary data, a stated preferences survey that elicits individuals' preferences when choosing travel modes was conducted in three major European cities: Athens (Greece), Lisbon (Portugal), and Manchester (United Kingdom).

The collected data from each city were used to develop and calibrate multiple mode choice models, including traditional Discrete Choice (DC) models such as the Multinomial Logit (MNL), as well as state-of-the-art Machine Learning models like the Random Forest (RF) classifiers. Their results were then evaluated and compared, leading to a comprehensive discussion on the factors that affect mode choice and the similarities and differences between parametric (such as the MNL model) and non-parametric (like the RF classifiers) models.

The study was carried out within the scope of TANGENT, a Horizon 2020 project that aimed at the development of innovative tools that optimize traffic operations across different modes of transportation, promoting coordination and adaptability. It is financially supported by the European Commission's Research and Innovation Programme.

2 Methodology

The procedure outlined below was followed to develop the models presented in this study (Fig. 1).

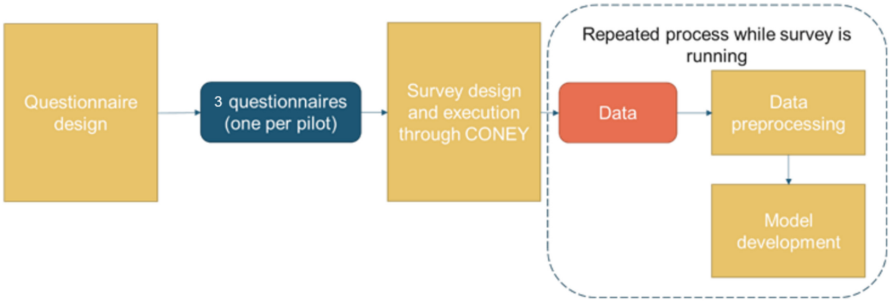


Fig. 1. Modeling pipeline.

The collection of the necessary data was achieved by designing and executing a thorough travel behaviour survey. The survey builds upon the stated preference technique, where respondents were presented with hypothetical mobility scenarios and they were invited to choose their preferred transportation mode among the alternatives.

Two different scenarios were developed, each linked to a specific TMS.

In the first scenario, "Synchronisation", a TSP system is applied leading to an increase of bus speeds. In this case, survey participants are presented with the case of a hypothetical trip from the suburbs to the city centre,where the two available transportation modes are the private car and public transport. The options are differentiated with respect to cost, and in-vehicle and waiting times.

In the second scenario, "Pricing", a CP scheme is implemented; commuters who want to enter to the city centre are required to pay a toll. Respondents are presented with three alternatives for a hypothetical trip to the city centre: use their private car and pay the toll, use their private car and bypass the tolled area by making a longer trip around the city centre or take the public transport. Each alternative is differentiated in terms of mode, trip cost, and trip time.

Data were collected using using *Coney Toolkit*, an innovative toolkit designed to enhance the user experience in surveys completion. *Coney Toolkit* exploits an intuitive conversational approach where survey questions are asked by an interactive chatbot. The tool is available at https://coneytoolkit.cefriel.it/. A total of 1612 valid (excluding incomplete and fault answers) responses were collected for the three pilot cities (553 valid responses were collected for the case of Athens, 632 for Lisbon and 427 for Manchester).

Upon data collection, mode choice models were developed and calibrated for each city using both parametric and non-parametric (Machine Learning) techniques. For the parametric approach, Multinomial Logistic regression (MNL) models were utilized. Random Forest (RF) classifiers were selected as the non-parametric method.

Logit regression models are some of the most commonly used tools in mode choice analysis. In the case of travel related choices, the models assume that commuters possess a utility for each alternative and that they will always adopt the alternative that maximizes it. The estimation of the models' coefficients depends is achieved using the maximum likelihood method [3].

RF machine learning models on the other hand are ensemble models that combine a set of multiple Decision Tree predictors (which form the 'forest'). Each tree is trained on a subsample which is selected randomly from the training dataset using bootstrapping. Each time, a random set of explanatory variables is selected, a technique also known as "feature bagging". The final classification result is determined by applying the majority voting rule, i.e. by selecting the individual tree that is predicted most frequently [4].

A total of eight models were trained. A MNL and a RF model were developed for "Synchronisation" in each of the three cities, amounting to six models. Additionally, two models from both types were created to study the impact of congestion pricing schemes on mode choice in Athens ("Pricing").

Finally, the performance of all algorithms was measured in terms of their Precision, Recall and the F1-score, all of which are commonly adopted metrics in classification tasks [5].

3 Results

Estimation results of the MNL for the "Synchronization" scenario for each of Athens, Lisbon and Manchester are presented in Table 1. For each independent variable considered in the model, the table reports its coefficient. To conclude whether an independent variable is statistically significant, the alpha level threshold for the p-value was set at 0.05 or 5%. Only the significant variables are reported. In this scenario, selection of a private car is designated as the reference category. As such, the calculated coefficients describe how the independent variables affect the probability of choosing a public transit mode over a private car.

Table 1. Coefficients of MNL model for "Synchronisation".

Variable	Athens	Manchester	Lisbon
Intercept	0.199	−0.480	0.986
In vehicle time of PT (Cont.)	−0.070	−0.082	−0.036
Waiting time for PT (Cont.)	−0.100		−0.065
Trip cost for PT (Cont.)	−0.248		−0.329
Age of individual (Cont.)	−0.130	−0.169	−0.075
Income of individual (Cont.)	−0.618	−0.880	−0.588
Satisfaction with PT Service (1–5)	0.318	0.170	0.205
Commuting during peak hours (Yes/No)	−0.277		

For "Pricing", the models have been calibrated only on Athens data and the equivalent estimation results of the MNL model are reported in Table 2. The option of selecting the car and bypassing the congestion charging zone is designated as the reference group, affected only by the three alternative-specific variables of the stated preference scenarios (trip time, cost and distance). The coefficients for the two other outcome groups (selection of car with toll payment - CARTOLL and selection of public transport - PT) are estimated according to this class.

Table 2. Coefficients of MNL model for "Pricing" in Athens.

Variable	CARTOLL	PT
Trip time (Cont.)	−0.600	−0.600
Trip cost (Cont.)	−0.169	−0.169
Intercept (Cont.)	−0.735	0.795
Satisfaction with PT Service (1–5)	−0.090	0.187
Commuting during peak hours (Yes/No)	−0.262	0.451
Being employed as a government employee (Yes/No)	0.529	0.570
Being a student (Yes/No)	−0.122	0.868
Being retired (Yes/No)	−1.204	−0.330

Given that Machine Learning models normally do not provide a readable output of model estimation parameters which could support a similar argumentation, they are evaluated using the performance measures, presented in the following section.

3.1 Comparative Assessment

To compare the performance of the two calibrated model families, performance measures, namely the models' accuracy (Table 3), precision, recall and F1-score were calculated. For that, the dataset was separated into a train and a test set, comprised of 80% and 20% of the total entries respectively.

Table 3. Accuracy of developed models for each city.

City	Model	Synchronization	Pricing
Athens	MNL	0.69	0.48
	RF	0.75	0.52
Lisbon	MNL	0.83	–
	RF	0.83	–
Manchester	MNL	0.71	–

The accuracy of each model is presented in Table 3. We observe that, for "Synchronisation", both models score consistently between 69% and 83%, suggesting that they are capable of identifying correctly most classes. "Pricing" models on the other hand show a lower accuracy of around 50%. We also note that RF models score consistently better than the equivalent parametric models, something that can be attributed to their ability to capture complex, non-linear dynamics in data that cannot be captured by linear models.

The classification results in terms of their precision, recall and F1-score are presented in Table 4 for "Synchronisation". It is observed that the RF Classifier performed better than the MNL in almost every case and for all three datasets, as it has higher precision, recall and F1-score values.

The equivalent results for "Pricing" are presented in Table 5. In this case, the performance of ML models is roughly on par on par with the performance of their parametric equivalents, while no sample unbalances are observed.

Table 5. Classification results for RF and MNL models for "Pricing".

Class	Precision		Recall		F1-Score		Number of Samples
	MLN	RF	MLN	RF	MLN	RF	
Athens							
CAR w/o toll payment	0.513	0.504	0.406	0.476	0.453	0.489	143
CAR w. toll payment	0.478	0.430	0.413	0.419	0.443	0.425	155
Public Transport	0.541	0.581	0.686	0.618	0.605	0.599	191

Table 4. Classification results for RF and MNL models for "Synchronisation".

Class	Precision		Recall		F1-Score		Samples
	MLN	RF	MLN	RF	MLN	RF	
Athens							
CAR	0.620	0.706	0.492	0.598	0.549	0.648	189
PT	0.717	0.769	0.810	0.843	0.761	0.804	300
Manchester							
CAR	0.623	0.743	0.611	0.694	0.617	0.718	108
PT	0.760	0.817	0.769	0.850	0.764	0.833	173
Lisbon							
CAR	0.706	0.655	0.089	0.267	0.158	0.379	135
PT	0.820	0.846	0.991	0.966	0.897	0.902	564

4 Conclusions

In this paper, eight models from two model families were developed to predict mode choices when two novel traffic management strategies are introduced in an urban setting. For each strategy, parametric, multinomial logit models and machine learning, Random Forest models were developed. The models we calibrated and evaluated on stated preference data collected in three major European cities: Athens, Lisbon, and Manchester. The models where proven to fit the data well and provided interesting insights regarding the factors affecting mode choice for different user categories at the occurrence of novel traffic management strategies.

Our comprehensive analysis of demand shifts in different cities using both machine learning and econometric models highlights the distinctive advantages and applications of each method. By comparing their outcomes, we have derived interesting insights on machine learning's ability to handle complex patterns, and econometric models' strength in interpreting causal relationships. The development of a robust modelling pipeline, which leverages both approaches, offers a versatile framework that can be adapted to understand and predict demand dynamics across various contexts. Moreover, the use of stated preference scenarios to elicit commuters' mode choice behaviour in hypothetical policy environments further demonstrates the potential of these models to inform proactive transportation planning. The findings from this study can inform the development of sustainable transportation systems and contribute to more efficient decision-making processes in urban mobility management. Closing, future research could explore merging stated preference data with revealed preferences to leverage the strengths of both types of data for more accurate outcomes.

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Data Communication System for Remote Train Operation on Regional Lines, Including Video Integration

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Abstract. In modern transportation, the railway plays a crucial role in connecting societies. The evolution of railway transportation towards automation and digital infrastructure prompts innovative advancements, notably in remote train control. This transition is effectively revolutionizing the transportation system and represents a significant stride toward achieving fully autonomous trains on regional line operations. This study explores the critical role of data communication systems in enabling the remote driving of trains. It addresses the prerequisites of data communication in railway remote driving and emphasizes the necessity for real-time, reliable, and low-latency communication between trains and control centers. The study assesses the fulfillment of existing and planned railway mobile communication systems (GSM-R, FRMCS) with the requirements. It also examines the strengths and limitations in meeting the demands of remote driving scenarios with video support. The study underscores the significance of video communication within railway infrastructure and draws insights from other sectors to enhance safety, security, and operational efficiency.

Keywords: railway operations · trains · remote driving · digital transport infrastructure · teleoperation, data communication

1 Introduction

1.1 Study Background

European governments aim to enhance the reliance on trains, necessitating innovative approaches in the railway sectors. Among these new innovations is the push for further automation, particularly remote control of trains and Automatic Train Operation (ATO). This has the potential to alter staff roles, enhance safety, and optimize the capacity utilization of the lines. The trend towards automation in the railway is on the rise, with many metro systems operating driverless. The successful implementation of high grade of automation (GoA4) in metro is attributed to closed working environment, while on regional lines there is ongoing effort to prepare for different grades of automation. Open world environment nature of mainlines makes implementation arduous since it has complexity due to larger interconnected networks and diversified operating environment compared to closed world environments of metro lines [1, 2].

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The focus of this study is centered on the data communication of a remotely controlled demo that can successfully transmit high-quality video to a control center, which, in turn, will be able to safely operate the train's basic actuators. This paper addresses the following research questions "What are the requirements of data communication for railway remote driving with video support and "how do the existing and planned railway mobile communication systems fulfill these requirements".

1.2 Railway Remote Driving

Due to rising passenger demand and the high cost of railway infrastructure, building new tracks is neither a practical nor a timely solution. The most feasible option is to expand the capacity of existing tracks by introducing advanced automation systems, such as remote driving. Railway remote driving has emerged as a promising solution for achieving advanced automation on mainlines, as implementing advanced automation (such as autonomous trains) in open environments like mainlines is not feasible in the near future. In remote driving operation, humans remain part of the control loop, which allows for the harnessing of both human and automated capabilities, as human input is still essential, especially in addressing novel situations, due to their problem-solving skills and adaptability.

Before fully deploying autonomous trains on main lines, remote driving serves as a crucial intermediary stage [1, 3].

Railway remote driving can serve as a backup system in case of autonomous train (GoA4) failure. However, according to the definition of (GoA4) excludes remote train control, creating confusion about response actions in case of train failures [1].

In socio-economic perspective, passengers tend to accept remote driving more readily than fully autonomous driving [4].

With remote driving, it is feasible to streamlining the decision-making among staffs in the event of disruptions, thus enabling efficient and well-coordinated train operations management.

2 Railway Mobile Communication Systems

The railway communication system comprises infrastructure, a network of technologies, and protocols that enable seamless communication and coordination among different components within a railway system [5]. Its significance lies in guaranteeing the safe and efficient operation of trains and the overall management of railway infrastructure. A robust railway communication system is essential for successful remote train control [6]. The expected necessities for railway remote control in mobile data communication standpoint are presented in the following.

Reliable and low latency communication. Remote driving demands real-time data exchange between the control center and the train. Therefore, the communication system should offer low latency and high reliability to ensure swift and accurate command transmission [7, 8]. The data transfer delay (both directions) is caused by the train's distance from the remote-control center, the bandwidth available for information transfer, and the specific mobile communication system employed [6].

High-Bandwidth for Data Transfer. Video streaming, sensor inputs, and other critical data from the train require high-bandwidth capabilities to ensure a smooth flow of information. Adequate bandwidth is essential to avoid delays and ensure timely decision-making by operators [7, 9]. Moreover, for video streaming need, the location of the camera and its depth perception significantly influence the information gathered and the accuracy of distance estimation [6]

Secure Data Transmission. As remote driving involves controlling critical infrastructure which carries passengers and freights, data security is of utmost importance. Robust encryption and authentication mechanisms are required to safeguard against unauthorized access and potential cyber threats [5, 7, 8].

Resilience to Interference. The railway systems traverse diverse terrains, including tunnels and remote regions, where network coverage may be restricted or prone to interference [10]. Data communication system needs to possess strong resilience against interference and sustain connectivity to ensure reliable communication [11].

Redundancy and Failover Mechanisms. To ensure reliability, availability and fault tolerance, redundancy and failover mechanisms is of key importance the data communication system for railway must have. These mechanisms are essential in maintaining uninterrupted operations and preventing service disruptions, especially in critical applications like train remote control. Having duplicates servers, network switches and power supplies can be considered as hardware redundancy. Software and data redundancy can also be employed for the purpose of creating backups and enhancing overall system reliability [11].

Compatibility. The communication infrastructure for remote driving must be adaptable to both current and upcoming railway-related mobile communication systems. This compatibility ensures smooth integration and future-proof functionality.

2.1 Railway Mobile Communication Networks

The wireless communication in the railway network uses a dedicated system derived from the public network (e.g., GSM, LTE, 5G). These networks are responsible for seamless, reliable, and efficient data transfer processes. However, as railway technology advances, it introduces demands that surpass the capabilities of the current network infrastructure. Notably, these demands encompass, the need for video communication, high transfer rates, low latency, and robust communication. The following section provides an overview of railway-specific communication systems.

Global System for Mobile Communications—Railway (GSM-R). It is a specialized version of the GSM wireless communication system designed for the needs of the railway industry. GSM-R is based on the GSM standard, which is commonly used in mobile phones, but it operate at 876–880 MHz uplink and 921–925 MHz downlink, 200 kHz channel bandwidth, time-division multiple access (TDMA) as access scheme, and it can achieve data rates up to 21.4 kb/s [12, 13]. It offers low latency, secure and reliable connectivity, which is suitable for basic train control and signaling operations [12, 14]. However, it might not be optimal for highly demanding real-time applications such as remote driving with high-definition video streaming because of limited bandwidth [12,

14]. GSM-R provides redundancy in its network infrastructure, ensuring backup communication channels and minimizing the risk of communication failures [14]. GSM-R antennas suffer [7] from undesired transient signals (interference) stemming from various sources, such as the universal mobile communication system, public GSM communication [10, 12, 14], or electromagnetic disturbances (arcing) generated by moving parts like the catenary system and pantograph [7, 15].

Terrestrial Trunked Radio (TETRA). It is a digital mobile radio communication widely used in various industries, including railways (e.g., Kazakhstan National railway company). It operates at 300 MHz and higher, access scheme as GSM-R, channel bandwidth of 25 kHz and the peak rate of data channel is 7.2 kb/s [13]. In railway communication, TETRA provides excellent speech quality, redundancy system, high data transmission rates, ensures secure and encrypted connections than GSM-R [16]. While GSM-R is expected to become obsolete by 2030, TETRA, in contrast, exhibits a prolonged life cycle and has demonstrated a continuous evolution with an upgrade path to align with anticipated future trends, also offers direct mode operation which serves as an advantage in train-to-train communication [13, 16].

Digital Mobile Radio (DMR). Digital Mobile Radio (DMR) finds applications in various aspects of communication in railways such as siding shunting and station operation. It operates at 30 MHz–1 GHz, 12.5 kHz channel bandwidth, use the same access scheme as GSM-R, peak transmission rate 4.8 kb/s [13]. DMR technology in the railway industry provide reliable, secure, and efficient voice and data communication, which is essential for the safe and smooth operation of trains and railway systems.

Long-Term Evolution for Railway (LTE-R). LTE-R is based on LTE standard. It is a newer technology that provides advanced communication capabilities [12, 14, 17]. LTE-R is designed to grasp the benefits of 4G LTE technology and is considered a potential replacement for GSM-R in the future [7, 14, 17]. It operates at 5855–5925 MHz, 1.4–20 MHz channel bandwidth, peak transmission rate 30 Mb/s [13]. LTE-R offers lower latency, more reliable, more secure [18] and higher bandwidth thus higher data transfer rates compared to GSM-R or any other currently operating [14, 17], making it more suitable for applications requiring near-real-time responsiveness, including aspects of train remote driving. LTE-R shows great promise in delivering high-definition video streaming [14], handling larger data volumes, which in turn holds significant importance for remote driving applications. LTE-R networks designed with redundancy to provide backup communication paths in case of system failure.

Future for Railway Mobile Communication Systems (FRMCS). The FRMCS is the next generation wireless technology for railway, that aims to revolutionize the way trains communicate with each other and with the control center. The system will enable faster, more reliable, and more efficient communication between trains, trackside equipment, and control centers. It therefore has the potential to be a valuable system for supporting autonomous or remote driving. FRMCS could possibly be powered by a 5G or later satellite communication system [13]. In FRMCS, Optical Wireless Communication, both Free-Space Optical and Visible Light Communication, can serve as a complementary network to address coverage gaps, particularly in tunnels. By deploying OWC in these

areas, communication can be enhanced and extended to provide reliable connectivity where conventional wireless networks might face limitations [7].

3 Remote Driving with Video Support

The EU Funded FutuRe project (FP6) task 3.1 is developing a scaled prototype of a train that will be remotely controlled by an operator in a distant control center. The prototype will feature cameras and a range of sensors to send live video and other relevant data to the control center, facilitating operational control. This remote operation will be supported by a data communication system utilizing public networks. Real-time communication, between the train and the remote center, will play a pivotal role in enhancing safety and security. It will enable operators to remotely monitor trains using real-time data, facilitating swift responses to potential issues or emergencies. Also through dedicated network, LTE-R and FRMCS are promising options for enabling video communication within railway infrastructure due to their wideband system, higher data rates, and minimal latency [15]. The remote driving technology, presently employed across diverse sectors including mining, automotive, aviation, marine, and even metro lines can be extended to regional railway domain particularly in areas such as communication and data transfer and remote operation of larger haul trucks (e.g., Rio Tinto).

4 Conclusion

The railway industry is moving towards increased automation to improve safety, efficiency, and operational management. The remote driving technology is seen as intermediate step towards fully autonomous trains. The first research question addressed in this paper relates to what are the requirements of data communication for railway remote driving with video support. To achieve successful remote driving, a robust and reliable communication system is essential. The communication system must offer low latency, high bandwidth, secure data transmission, and resilience to interference. A second research question was how the existing and planned railway mobile communication systems fulfill these requirements. Existing mobile communication systems (i.e GSM-R, TETRA) may not fully meet the demanding requirements of remote driving. Emerging technologies like LTE-R and FRMCS show promise with their advanced capabilities, including higher bandwidth and reduced latency, making them more suitable for real-time applications like video streaming in remote driving scenarios. The railway industry can learn valuable insights from other sectors, where remote driving technology is already in use, recognizing its potential applicability and transferability to the realm of railways. However, challenges related to safety regulations, infrastructure compatibility, human-machine interface design, and cybersecurity must be carefully addressed before implementing remote driving on a larger scale.

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Modelling Probabilistic Digital Twins of Complex Inland Waterway Transportation Systems Using Bayesian Networks

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Abstract. The Horizon Europe Project, ReNEW, uses the digital twin concept to simulate and model the complexity and interdependencies of the Inland Waterway Transport (IWT) system. This concept is used to design novel strategies to ensure network functionality despite climate change impacts on IWT. A digital twin is an accurate copy of a real object/item/system with associated characteristics in the digital world. Digital twin models can be developed using physics or statistics or combining the two. They can be used for simulation, classification, prediction, optimization, and more. This work proposes probabilistic digital twin modelling of complex IWT networks using Bayesian networks. Bayesian networks are statistical models that can address the complexity and uncertainty of the physical world. The availability of new data/information facilitates model updates, resulting in more accurate estimates.

Keywords: Bayesian Networks · Digital Twins · Inland Waterways Transport · Resilience · ReNEW

1 Introduction

Climate change is already having a substantial impact on inland waterway transportation (IWT) systems [1], and this trend is predicted to continue/worsen [2]. Disruptions to the normal operation of IWT networks may have serious consequences for people, businesses, and the local and regional economies [3–7]. Hence new climate-neutral and climate-resilient solutions must be designed, evaluated, and implemented to ensure the successful operation of the IWT [8].

The complexity and interdependencies of IWT systems must be addressed to achieve resilience. ReNEW, a Horizon Europe Project, seeks to address the dynamicity, heterogeneity, and complexity of IWT systems and provides a blueprint for enhancing smart, green, sustainable, and climate-resilient IWT systems. Digitalization is considered a

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driving force for sustainable transportation solutions, which may enhance resilience solutions as well as provide economic, environmental, and societal advantages [9]. Modelling complex systems, such as IWT systems, with Digital Twins (DTs), provides substantial benefits, particularly in forecasting how those systems will react to predicted and unexpected occurrences [10]. Processes and operations can be optimized in real time using DTs, yielding better outcomes than traditional methods [11].

A digital twin model can be physics-based, statistical-based, or a hybrid of both. A Bayesian network is proposed in this paper for the development of probabilistic digital twins that can mathematically represent high-level dependencies in IWT infrastructure. Using field data and expert opinion, Bayesian Networks (BN) are used to model the interdependencies between system components. A Bayesian Network Model can be updated as new (field) data becomes available from monitoring and other remote data sources, resulting in more accurate estimates.

2 Digital Twins

A digital twin (DT) is a precise replica (or model) of a physical system. It includes both historical records and the present state of the system. A digital twin is distinguished from other digital models by the automated exchange of information with its physical counterpart. There are many purposes for a digital twin, including classification, prediction, optimization, and so on. A DT could be a digital model of an element (e.g., a bridge pier), a subsystem (e.g., a bridge), a system (e.g., IWT infrastructure), or a network (e.g., the entire IWT network).

A digital twin model can be based on physics, statistics, or a combination of the two approaches. Bayesian networks are statistical tools for modelling complex systems. In Digital Twin modelling, Bayesian networks are used to address the uncertainty introduced by unknown or missing data, as well as the uncertainty of the model itself.

3 Bayesian Networks

3.1 What Is a Bayesian Network?

A Bayesian Network is a direct acyclic graph (DAG) used to depict the interdependencies of a set of stochastic variables and their conditional probabilities [12]. A BN consists of two components, one qualitative and one quantitative. The qualitative component of a BN shows how variables in a system are interdependent. They are associated with a set of functions that represent numerical quantities. Probabilities are associated with every node in the graph, which represent a collection of conditional probabilities describing how the predecessors affected the node.

Figure 1 shows a graphic structure of a BN. The network is a collection of nodes that represent objects, variables or elements in a system, and links that represent their relationships. Each node has a certain number of states representing the condition of each element of the system. For example, node C has two possible states – True and False – and is probabilistically dependent upon the state of nodes A and B. Nodes A

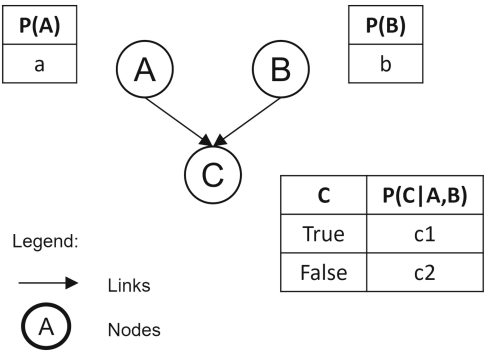


Fig. 1. Example of Bayesian network with conditional probability tables.

and B are called parents of node C. An empirical conditional probability table (CPT) is attached to each node, representing discrete conditional probabilities.

Bayesian networks are based on Bayes' Theorem (also called Bayes' law or Bayes' rule) – see Eq. 1. According to Bayes' theorem, prior probability is the probability that a stochastic parameter will be in a given condition state. The conditional probability is the likelihood of a parameter's state given the states of its parents. Given the prior probability, conditional probability, and the statistical principles that specify their interdependencies, the likelihood that the parameter will be in a specific state can be estimated, and this is known as the posterior distribution.

$$P(A|B) = \frac{P(B|A) \times P(A)}{P(B)} \tag{1}$$

where:

P(A|B) is the posterior (or conditional) probability.
P(A) is the prior (or marginal) probability.
P(B|A) is the likelihood.
P(B) is the normalizing factor, and the Total Probability Theorem states that:

$$\mathrm{P(B)} = \mathrm{P(B|A)} \times \mathrm{P(A)} + \mathrm{P}\left(\mathrm{B}|\bar{\mathrm{A}}\right) \times \mathrm{P}\left(\bar{\mathrm{A}}\right) \tag{2}$$

When new data is observed, the model can be updated as follows:

$$\mathrm{p}(\theta|\mathrm{D}) = \frac{p(D|\theta) \times p(\theta)}{p(D)} \tag{3}$$

where:

θ is parameter of the model.
D is new (or observed) data used as evidence.

3.2 Applications of Bayesian Network

Bayesian networks can be used to assess the risk, safety, and reliability of large, interconnected systems. Diagnostics, reasoning, causal inference, decision-making under

uncertainty, anomaly detection, automated insight, and prediction may all be done with BN. These activities require investigating numerous research hypotheses, which can be conducted in a variety of ways employing a BN and according to the user's preferences and expectations. These consist of identifying the threats (events) and the probability of occurrence; assessing the likelihood that certain events will threaten essential assets and observing the impact on other variables of the system (e.g., there are events with 100% probability of occurrence); and monitoring the probability of the entire network without affecting individual nodes.

A sample application of Bayesian Networks for risk assessment is illustrated in Fig. 2. The IWT network is broken down into systems (e.g., infrastructure, vessel, port, etc.), subsystems (e.g., bridge, lock, etc.), and elements in Fig. 2a. To evaluate the current state of the elements, data and expert opinion are used. Each damage state is coupled with a collection of damage metrics that will assist in building the CPT. Figure 2b depicts a basic Bayesian Network used to estimate the probability of the subsystem failing.

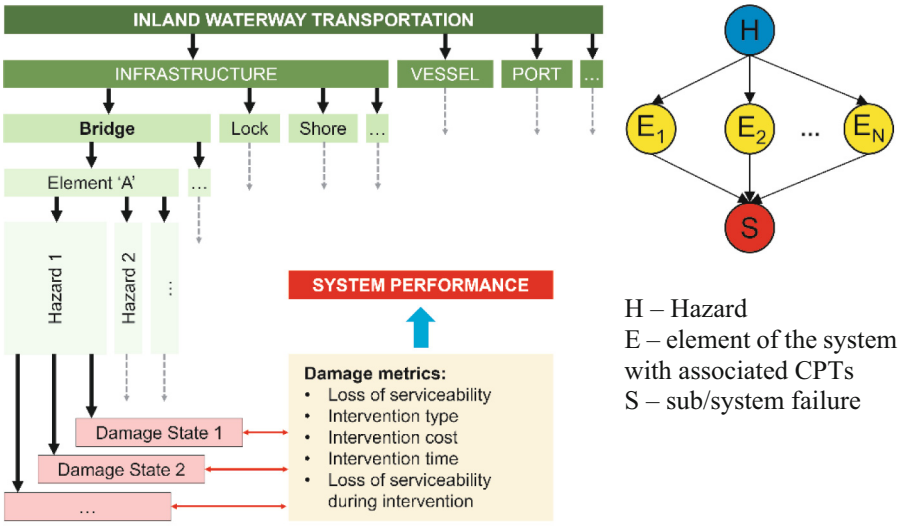


Fig. 2. Bayesian Network for risk assessment: a) data and/or expert opinion derived loss metrics for each element damage state; b) BN graph model for risk assessment.

3.3 The Benefits and Limitations of a Bayesian Network

Bayesian networks have several applications in a variety of disciplines. However, when compared to other probabilistic techniques, Bayesian Networks have significant benefits and limitations. One of the most notable benefits of using a BN is that the system knowledge can be represented graphically. They are intuitive and efficient when working with large amounts of data, and aid in the decision-making process. BNs account for uncertainty and allow for model updates as new information becomes available. A BN can model several interdependencies and identify important components. However, there are

practical limitations on the type of distributions and statistical dependence. For systems with a large number of stochastic variables and states, a BN is computationally intensive.

4 Conclusions

Climate change has significant implications for IWT networks. To ensure the IWT's effectiveness, smart, green, and sustainable solutions are necessary. There are several advantages associated with digitalization in sustainable transportation, which include enhancing resilience and providing economic, environmental, and societal benefits. This paper proposes using Bayesian Networks for probabilistic digital twin modelling of complex inland waterways transportation networks. A digital twin is an approach used to create a digital model of a real-world object. Statistical models, such as the Bayesian network, are employed to deal with the complexity and uncertainty inherent in real-world applications like IWT. Moreover, the probabilistic twin model can be updated as new data becomes available, leading to more accurate estimates.

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Using Accelerometers on an In-Service Train to Detect Bridge Damage and Repair

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Abstract. One pier and two spans of Malahide Viaduct (Dublin, Ireland) were replaced in 2009 due to bridge scour failure. The new (replaced) parts of the structure are considerable stiffer than the rest of it. An in-service passenger train, instrumented with accelerometers, collected vibration data as it crossed the repaired bridge that serves the Dublin-Belfast railway line. This paper reports on an analysis of the bogie vertical acceleration data. Vibration data collected from 41 train crossings were analysed in the time and frequency domains. Results show that there is (visual) evidence that the stiffened spans vibrate less than the rest of the bridge as the train crosses. Multiple signal responses, grouped by train velocity, add to the evidence of a stiffer section of the bridge where two spans were replaced. Moreover, the observed signals have good spatial repeatability, despite the fact that the effect of load is also acknowledged to have an impact. Overall, the results suggest that instrumented trains can be successfully used for continuous condition monitoring of the railway infrastructure and, consequently, for detecting damage or rehabilitation needs.

Keywords: Bridge · Indirect Monitoring · In-service Train · On-board Sensors · Railway · Structural Health Monitoring

1 Introduction

Trains are becoming more popular as countries seek to reduce the carbon footprint of transportation. Most rail networks rely heavily on railway bridges [1]. Bridges are, however, complex structural systems susceptible to degradation in a variety of circumstances, including improper maintenance, inadequate inspections, and harsh environmental conditions [2]. Network outages have major consequences for both users and network operators [3]. The collapse of the Malahide estuary viaduct in Dublin, Ireland [4], in 2009, is an example where a bridge collapsed unexpectedly, with serious consequences for users and owners. Early damage detection results in more effective and efficient interventions and the prevention of catastrophic failures [5].

Rail networks [6, 7] and bridges [8, 9] are increasingly being monitored by sensors on trains (or other railway vehicles). Bridge damage can be identified by analysing the

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dynamic responses of bridges acquired by these sensors [10, 11]. It has been observed in [8] that there is a need to emphasize on the applicability and efficacy of such methods and this paper attempts to further focus on the repeatability and consistency of possible detection of features of interest in a bridge from multiple drive-by measurements from trains. To assess the condition of the bridge, damage-sensitive characteristics can be extracted from acceleration data using signal processing techniques. However, it is still challenging to fully validate these approaches in the field. Most of the time, this is the result of a lack of tests involving instrumented trains crossing bridges with known damage or repair history.

This paper presents results from an accelerometer placed on an in-service passenger train that travelled more than 50 times over a repaired bridge. The objective was to determine if the stiffened spans could be detected from the on-board measurements, thereby demonstrating that on-board sensors can monitor the bridge condition. The results indicate that instrumented trains can be successfully used for the monitoring of condition and to identify the need for repair or rehabilitation when it arises. This full-scale approach provides insights into the impact of a stiffer foundation at one pier and greater flexural rigidity in two spans of the viaduct, for which experimental evidence is rarely available. The work also identifies some of the challenges of such detection, such as accurate positioning and variability in the speeds of the passing trains.

2 Data Collection

2.1 Malahide Viaduct

The Malahide Viaduct is a 12-span railway bridge just North of Dublin in Ireland. In 2009, a pier and two spans collapsed due to scour failure of the foundations. They were replaced with a stiffer pier and spans with greater flexural rigidity. The existing structure extends over 175 m in 12 simply supported spans and is roughly 9.0 m wide (Fig. 1). The precast concrete beams are 15.85 m long (spans 3–10) and 12.2 m long (spans 1, 2, 11 and 12). The beams are supported by cut-stone masonry piers. The new pier is made from in-situ reinforced concrete with a precast bearing shelf.

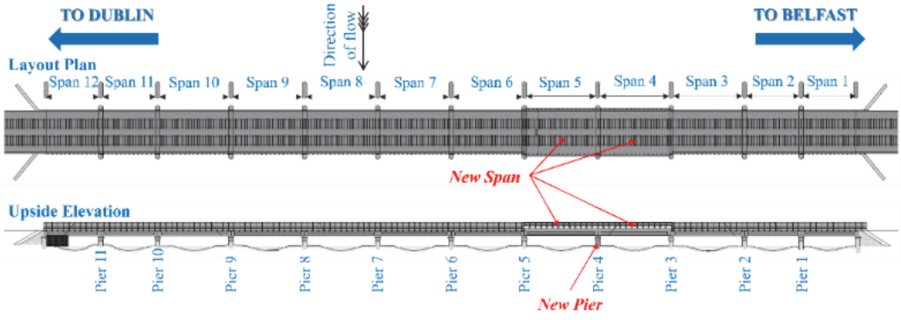


Fig. 1. Plan & elevation of the Malahide Viaduct showing the replaced pier and spans.

2.2 Instrumented Railway Vehicle

Multiple accelerometers and a Global Positioning System (GPS) were installed on an Irish Rail 22000 InterCity DMU Unit (passenger service) [8, 12]. The accelerometers were attached to the leading car's front bogie. The GPS antenna, installed near the passenger door, recorded the location of the train. An existing unused coupler box housed the data logger, and the entire system was powered by a supply located at the back of the car. Figure 2 shows the configuration of the system.

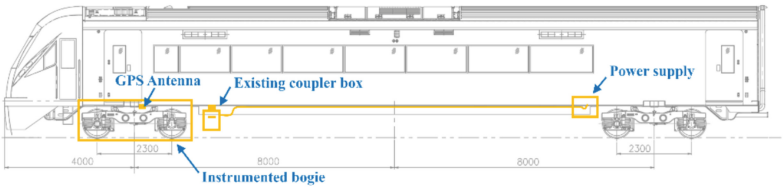


Fig. 2. System configuration (adapted from [8]).

3 Field Observations

In 2016, bogie vertical acceleration was recorded on 54 Dublin-Belfast train journeys over the course of 5 weeks. The velocity of the train at the entrance of the bridge ranges from 85 to 120 km/h. In this study, data from 41 train travelling with velocity ranging from 95 to 110 km/h were evaluated. These velocities are depicted in Fig. 3 and can be seen to be increasing as the train passes the bridge. The train velocities were divided into three clusters, as shown, for a more accurate evaluation of the bogie vertical acceleration.

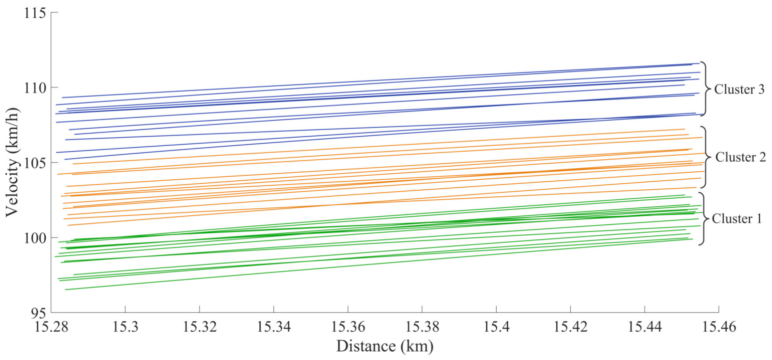


Fig. 3. Train velocity on the bridge – 41 train journeys as three clusters of data.

Figure 4 depicts a sample of the bogie's unfiltered vertical acceleration signal. The signal was filtered using a 6th order Butterworth lowpass filter with a cut-off frequency of 15 Hz, with the filtered signal shown in Fig. 5. The grey region highlights on-bridge part of the signal. Vertical lines represent the old piers, the centre pier, and the new pier. The stiffened spans are also highlighted. The amplitude of the acceleration signal

recorded as the train crosses the replaced (stiffer) spans appears (visually) to be less than that of the rest of the bridge. This is taken to be the effect of greater flexural rigidity at this location.

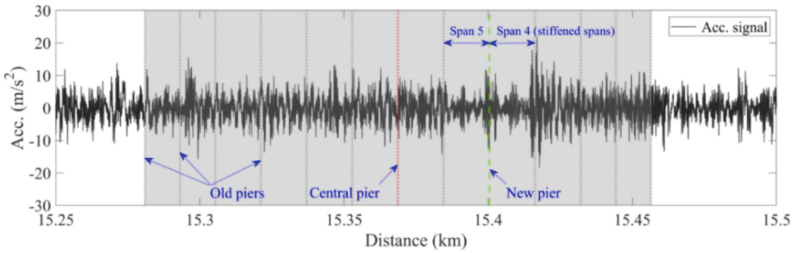


Fig. 4. Sample of unfiltered bogie vertical acceleration signal.

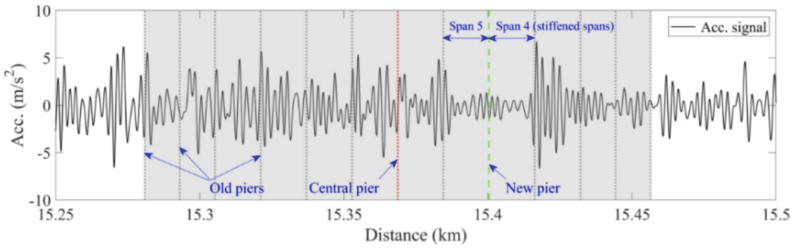


Fig. 5. Sample of filtered bogie vertical acceleration signal.

The filtered signal and a continuous wavelet transform of it is illustrated in Fig. 6. There is clearly less vibration in the stiffened spans, particularly for the dominant frequencies/scales. It is acknowledged that a second region of low vibration is evident toward the end of the bridge where the spans have not been stiffened.

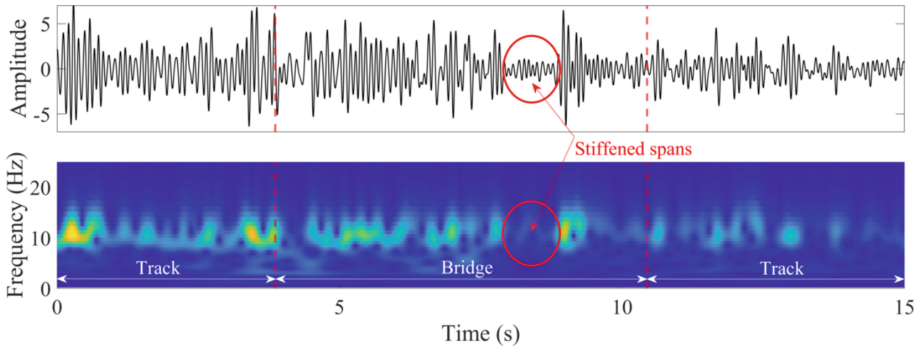


Fig. 6. Acceleration signal and Continuous Wavelet Transform, track and bridge.

Multiple responses of the traversing train signals are indicative of the existence and location of a stiffer part of the viaduct where the two spans were replaced. Despite variations in loaded mass, there is good spatial repeatability in the measured signals, particularly when they are grouped by speed – see Figs. 7, 8 and 9.

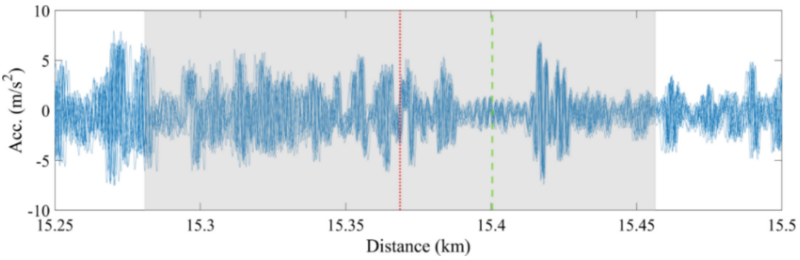


Fig. 7. Acceleration signals of Cluster 1 (15 train journeys – see Fig. 3).

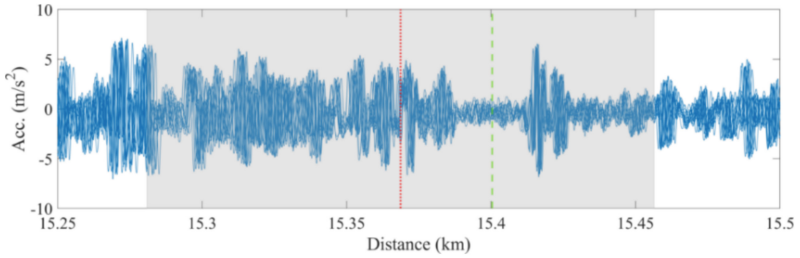


Fig. 8. Acceleration signals of Cluster 2 (13 train journeys – see Fig. 3).

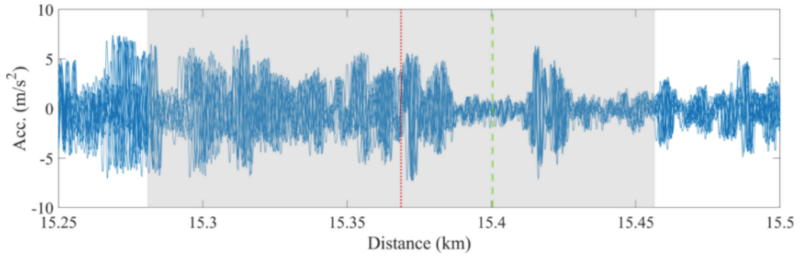


Fig. 9. Acceleration signals of Cluster 3 (13 train journeys – see Fig. 3).

4 Conclusions

This paper introduces a full-scale field experiment of drive-by bridge structural health monitoring. An in-service passenger train, instrumented with accelerometers, collected vibration data as it travelled multiple times over the same bridge. The bridge under consideration has undergone repairs after foundation scour caused two spans and one pier to collapse. The new parts of the structure are significantly stiffer than the old parts.

Acceleration responses collected by the instrumented train are used to identify stiffness variations in the replaced/new spans of the viaduct. Measured acceleration signals demonstrate good spatial repeatability despite fluctuations in loaded mass, especially when they are clustered by speed.

Acknowledgments. The authors gratefully acknowledge the EU Atlantic Region-funded SIRMA project (Strengthening Infrastructure Risk Management in the Atlantic Area – Grant No. EAPA\826/2018) and Science Foundation Ireland for supporting this research under the Industry Fellowship Programme, ID 19/IFA/7433. Vikram Pakrashi would like to acknowledge SFI TraIn project NCF 22/NCF/FD/10995 and SFI. Abdollah Malekjafarian would like to acknowledge the financial support of Science Foundation Ireland under Grant number 20/FFP-P/8706.

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Field Validation of Damage Detection in a Railway Bridge in Ireland Using Sensor Redeployment

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Abstract. Accelerometers on a bridge can be used to extract dynamic properties such as mode shape which are known to be damage-sensitive. However, as bridges are often physically large, this can require a significant number of sensors. In this paper, the concept of re-deploying a small number of sensors is proposed, building up the mode shape from a series of field acceleration measurements. Frequency Domain Decomposition is used to find segments of mode shape in each measurement, using a different train as the source of excitation in each case. In numerical simulations of a simply supported beam, it is shown that a minimum of two accelerometers can be used to construct two points of a mode shape, the first mode being the one most sensitive to excitation. Mode shape amplitudes are calculated in segments which are then stitched together to obtain the global mode shape. In numerical simulations, failure of the support bearings is represented as an increase in rotational spring stiffnesses. This is shown to have a significant effect on the shape of the first mode. The concept was tested in a field trial, before and after the bridge was repaired. The measured mode shape, represented as an envelope of possible shapes, was seen to change significantly when the support system was rehabilitated, and new bearings installed.

Keywords: Bridge · re-deployable · damage detection · structural health monitoring · bearing damage

1 Introduction

Numerous techniques have been proposed for Bridge Health Monitoring (BHM) that aim to assess the structural condition of bridges [1]. These techniques encompass both direct or indirect approaches, which rely on the use of sensors on the bridge, or on the vehicle crossing the bridge, respectively [2]. In direct approaches, sensors are strategically placed at various locations on the bridge to measure structure responses. Acceleration responses are commonly used to extract valuable information such as bridge natural frequencies [3–5] and mode shapes [3, 6–8]. However, a notable limitation of this approach is that it is less effective at detecting minor damage, as the frequencies only exhibit subtle changes in such cases [9]. Another form of direct BHM involves measuring the bridge strain

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responses to the passage of vehicles, utilizing concepts like Bridge Weigh-in-Motion [10]. While these methods offer reasonable accuracy and sensitivity to bridge damage, they require strain sensors to be located very close to the damage site. This results in the need for extensive arrays of distributed sensors on the bridge, which can be both time-consuming to install and disruptive to traffic.

To address these challenges, researchers have explored modal estimation techniques using bridge accelerations [1]. These techniques have gained significant attention over the past two decades for developing effective health monitoring systems and identifying key bridge properties. The sensitivity of accelerations to bridge damage makes them a valuable resource for understanding structural change [10]. Traditional modal testing methods and output-only modal techniques typically involve deploying a large number of accelerometers across the bridge [11, 12], making these systems costly and complex to maintain [13]. Nevertheless, the research in this area has evolved, with a focus on novel modal concepts like "modal curvature" [14] and the "modal energy method" [7]. Mode shapes have proven to be particularly sensitive to bridge damage. However, there is a challenge in measuring curvature, as it involves differentiating bridge accelerations, which can introduce errors. To overcome this limitation, [14] proposed using strain responses to measured bridge curvature with greater precision. Yet, like other strain-based systems, this approach necessitates a significant number of sensors on the bridge, posing implementation challenges. Others [15, 16] proposed a method for extracting mode shapes by visually measuring bridge displacements using drones and applying a natural excitation technique for eigen-system realization. This involves recording videos of the structure to detect the displacement of identifiable markers on the bridge. Small groups of these markers are then used to estimate global mode shapes. [17] proposed the use of a decentralized modal estimation approach to estimate the bridge mode shape under variable loading conditions with a small number of accelerometers that redeploy from one segment to the next, until completely covering the full length of the bridge. This redeployable sensor strategy has been assessed to detect common bridge damages, e.g., bearing seizure and scour.

In this paper, the redeployable sensor strategy is validated and tested in field conditions to detect bridge bearing seizure. Bearing damage is a common issue in bridges, with bearings usually having a shorter lifespan than the bridge girders themselves. Bearing damage can lead to a significant increase in rotational stiffness at the supports, affecting the overall structural integrity [14, 17]. This approach allows for a high-density array of measurement points to be monitored using a relatively small number of sensors. The Frequency Domain Decomposition (FDD) technique is applied to the bridge accelerations from each segment to calculate segments of mode shape. These segments are subsequently stitched together using common locations to form a global mode shape. This approach is shown to work effectively with just two accelerometers, eliminating the need for numerous sensors to be installed on the bridge. To assess the effect of bearing damage on bridge mode shape, the authors analysed eigenvalue mode shapes of a simply supported beam with rotational springs at the supports to mimic bridge bearing stiffness. The approach s tested in the field on a railway bridge in the Republic of Ireland. The results from these field tests provides evidence of the effectiveness of the moving

sensors concept in detecting bridge bearing damage. The concept of utilising redeployable sensors has shown promise in overcoming several limitations of traditional health monitoring methods, while still providing accurate information about bridge condition.

2 Redeployable Sensor Strategy

The concept of redeployable sensors is based on the estimation of bridge modal properties using a sequence of measurements from a small set of accelerometers that are moved from one end of the bridge to the other [15]. In this study, accelerations from just two accelerometers are used at any one time. These accelerometers are redeployed to different bridge nodes at different points in time. The FDD concept is applied to the accelerations from each stage to obtain segments of the mode shape for any desired frequency. A detailed description of this approach is given in [17]. In each stage, FDD gives a vector of mode shape amplitudes for a segment of mode shape. It should be noted that to implement the concept of redeployable sensors, neighbouring segments must have one location in common to allow the segments to be scaled and combined into a global mode shape. This means that one accelerometer stays fixed in a segment when the other moves to the next segment.

2.1 Field Setup and Test Plan

The redeployable sensors' strategy was tested on a steel railway bridge. The Oranmore bridge (UBG165) (Fig. 1) is an 18.3 m long single-span skewed deck. It carries one operational rail track and is located in County Galway, in the Republic of Ireland. The bridge consists of 2 primary longitudinal, 8 secondary transverse and 4 tertiary longitudinal steel beams with a thin steel plate deck. There was uncertainty about the support conditions and the bridge was rehabilitated on 26th October 2019. The ends of the deck were repaired, as necessary, and new bearings and abutments installed (see [17] for more details). Redeployable accelerometers were used to assess the bridge before refurbishment on 15th/16th of October and then again after refurbishment on 12th/13th November. The field tests will apply the moving sensors concept using bridge accelerations induced by passing trains, from before and after the replacement of support bearings, to measure the 1st bridge mode shape.

The abutments were replaced with a precast concrete transition slab and elastomeric bearings fitted at the beam ends. Other minor repairs were carried out on rusted areas of the bridge. The bridge was out of operation for 2 days while the rehabilitation took place. Figure 2 shows the bridge abutments after the rehabilitation [17].

Two triaxial wireless MEMS accelerometers were used to record the deck accelerations due to passing trains before and after the rehabilitation. These sensors were calibrated before the field test by testing them on a calibrated beam in a laboratory setup. For the field testing, six measurement locations were selected on the primary beam on the North side. Testing was carried out in 5 stages, each involving sensors at two locations on the beam, while always keeping one location in common with the neighbouring segment/stage. The accelerometers were attached to the beam web at each location using magnetic mounting bases and accelerations were recorded at a scanning



(a) (b)

Fig. 1. The Oranmore Bridge: (a) North side from the South; (b) top of the bridge from the West.



(a) (b)

Fig. 2. After rehabilitation condition of the bridge supports – (a) lift of bridge via crane, and (b) new bearings under primary beams.

rate of 256 Hz. For each stage of measurement, the accelerations in response to 3 passing trains were recorded and transmitted wirelessly to a base station near the bridge. Recording was continued for two seconds of free vibrations after the passage of each train [17].

3 Results and Discussion

Damage in bridge bearings impacts the boundary stiffness of the beams – they lose their ability to rotate freely. Any change in the rotational stiffness of the supports, causes a global change in the modal parameters of the bridge by adding extra rotational constraints at the support. The 1st mode shape of the bridge is used to detect the bearing damage at the supports.

For the field test, the acceleration data from each stage is analysed using FDD to obtain a segment of the 1st mode shape. For each stage, the mode shape segment is calculated three times, once for each of the passing trains. Over five stages, with three segments of mode shape per stage, there are (3^5=) 243 possible ways in which the segments can be combined. All 243 estimates of the mode shape are normalised and averaged for the pre- and post-rehabilitation measurements of the 1st mode shape. Using

a 4th degree polynomial fit, a finer resolution of the measured mode shape is calculated and shown in Fig. 3. The post-rehabilitation fitted mode shape is seen to be a good fit to a numerical finite element model (refer to [17] for more details) with pinned conditions and is reasonably different from the pre-rehabilitation shape (that resembles the fixed condition mode shape of the numerical analysis).

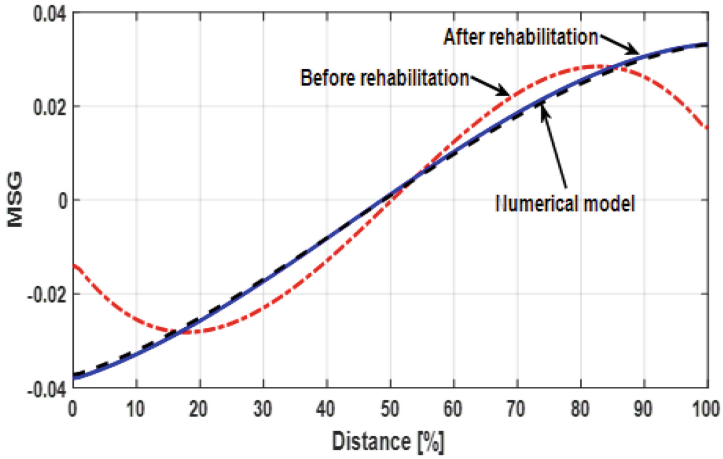


Fig. 3. Damage indicator - mode shape gradient (MSG) of the first mode shape.

4 Conclusion

In this paper, a novel redeployable (moving) accelerometers concept that determines bridge mode shapes using low number of sensors, is presented and validated in field conditions. The bridge mode shapes contain important structural condition information and are sensitive to global as well as local changes in structure responses. To estimate the mode shapes with a low number of sensors, the concept of redeployment is used and tested. Segments of mode shape are found from each stage of deployment using FDD and stitched together to form the 1st global mode shape. A field test of a bridge was carried out which experienced bearing failure due to age and loading. This bridge was repaired/rehabilitated to renew the support bearings. The bridge was instrumented before and after its bearings and abutments were replaced. Two accelerometers were used to demonstrate the moving sensors concept. The field analysis illustrated that the post rehabilitation 1st mode shape closely resembles the numerically generated mode shape with pinned supports (healthy). The mode shape is used as a damage indicator, and successfully indicates the change in support conditions due to rehabilitation.

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Asset Information Management for a Communications Network in Ireland

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Abstract. A major public asset owner in Ireland sought to collate structured asset information that could be used for improving future decision making in respect of a communications network. Due to the lack of an organization-wide standardized approach to asset information management, the authors proposed a vendor-neutral, standards-based approach, with machine-readable rules and instance data using Web technologies. Clearly defined use cases were elicited from end users such as maintainers and operators. A sub-set of these use cases was selected to identify information needed for each asset type, focusing on the most important information. To define the machine-readable rules, ontologies and validation scripts were developed iteratively through use case testing on small data sets. A proprietary site inspection mobile application was used to gather data, which was also supplemented through desktop study of as-built records. The data was then exported, post-processed, transformed, automatically validated, and uploaded to the database. The agreed use cases were achieved and demonstrated to the asset owner. The work presented various technical challenges, including software functionality, availability of information, post-processing of collected data, communicating the outcomes. However, the prospective benefits warrant due attention by public asset owners seeking to futureproof their data and systems.

Keywords: Asset information management · Knowledge graphs · Compliance checking · Geospatial · Use case

1 Background

A highway infrastructure project in Ireland required installation of new power and communications cables. These cables necessitated construction and modification of a network of ducts and chambers. Historically, as-built records from such projects would comprise documents in unstructured data formats (e.g., PDF, CAD). However, Transport Infrastructure Ireland (TII), a major public asset owner, sought to collate structured asset information that could be used for improving future decision making.

TII did not have an overarching data strategy at the outset of the project. Further, TII did not have an asset information management system (AIMS) for duct, chamber, and cable asset information.

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The aim of this paper is to provide an overview of the technical solution adopted by the authors, both in terms of technology choices and business processes, and the technical challenges and benefits elicited from the outcomes. The paper does not deal with the strategic and organizational level challenges for asset information management, which are well covered by literature.

2 The Approach

2.1 Proposed Solution

The authors proposed a vendor-neutral, standards-based approach to asset information management, with machine-readable rules and instance data using linked data and semantic web technologies. Such an approach was recommended by the CEDR INTERLINK project in 2018 [1] and adopted by highways asset owners is some countries. The proposed approach was intended to futureproof the data such that it could be consumed by any adopted AIMS. Further, demonstration of the approach itself was intended to inform the stakeholders of the potential technical benefits and disbenefits of its adoption across other areas of the asset network or other asset types.

2.2 Systematic Process

A systematic approach was followed throughout the project. Clearly defined use cases were elicited from end users such as maintainers and operators through meetings and workshops. A sub-set of these use cases was selected to identify information needed for each asset type.

Lessons learnt internationally showed that seeking to record all 'nice-to-have' information about each instance of an asset type significantly increases the risk of poor outcomes. Often, this is due to information being incomplete relative to the requirements or the maintenance of the information being uneconomical. Accordingly, a minimum viable product approach was taken, retaining focus on the most important information and functionality.

A top-level ontology was developed based on a draft version of EN 17632-1 [2]. (The standard has since been published.) The project team created a 'chambers, ducts and cables' ontology using proprietary software. A small set of instance data was loaded into a triple store along with the ontologies, and test queries were run to ascertain if the agreed use cases were met. This resulted in some refinement of the ontologies prior to extending instance data collection to the whole project.

2.3 Data Collection and Post-processing

The ontologies formed the basis for configuration of a proprietary site inspection mobile application, used to gather data such as location, duct orientation, and photographs. Asset data was supplemented through desktop study of as-built records. The data was

then exported in JSON format, post-processed using Python, and converted into RDF.[1] SHACL validation was run on the dataset to confirm compliance with the ontologies and with W3C standards prior to upload to the triple store.[2] The adopted triple store presented query results in XML, tabular, image, or map formats. The triple store also facilitated GeoSPARQL, which enabled queries typical of geospatial information systems. The agreed use cases were achieved and demonstrated to TII.

Figure 1 indicates the information flow from site and desktop-based data collection through automated data transformation and validation onto the triple store, with the proprietary applications and standardized formats identified.

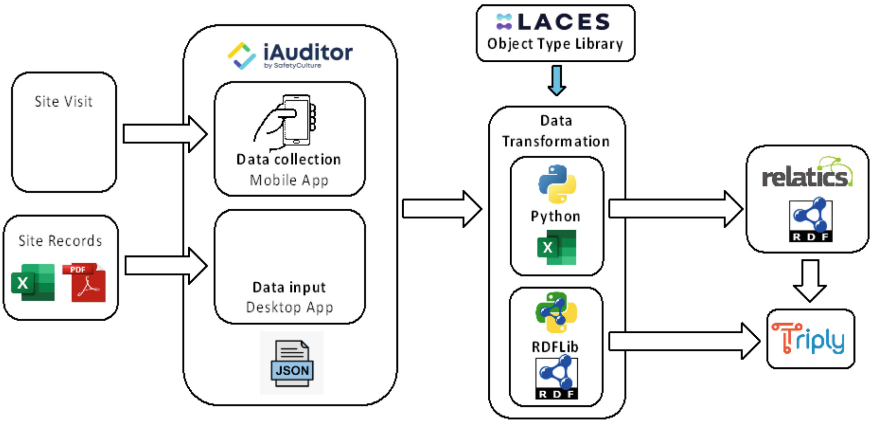


Fig. 1. Data collection and post processing.

3 Outcomes

3.1 Challenges

The work presented various technical challenges which are not insurmountable but may justify reluctance of an asset owner to adopt the approach on a larger scale across other asset types in the short term. Typical challenges are set out below.

Software Functionality: Popular CAD, geospatial and asset information management software applications have limited functionality for reading or writing RDF. Also, they usually store data in a relational database rather than a graph database, and exchange or sharing of information between both types is not facilitated currently by many off-the-shelf software applications. Vendors may not introduce these functionalities until such a time as there is sufficient market demand for same.

[1] The World Wide Web Consortium (W3C) has standardized various models and languages for representing and querying data in graph databases including RDF, OWL, SHACL and SPARQL [3].

[2] A triple store is used to store and access graph databases.

Complexity Related to Below-Ground Assets: Managing information about below ground assets is difficult, even during the construction stage. Table 1 shows the feasibility of selected data queries due to relative effort for gathering and post-processing data. Awareness of such a challenge is important when asset owners are considering the anticipated costs and benefits of enabling certain data queries. This difficulty is a function of the use cases addressed in the project rather than the technology choices.

Table 1. Feasibility of selected data queries for new build assets.

Query	Data availability[a]	Data management[b]
For a plinth, return the schematic of that plinth	Good	Low
For a chamber, return any available photographs and / or schematic	Good	Medium
List all available ducts running through a specified chainage and return their GIS geometries	Fair	High
Return the GIS route for a certain cable	Fair	High
Return duct location based on related chamber location	Fair	High
Return the mandrel test result and record sheet for an existing duct	Good	Medium

[a]The relative ease of gathering information to enable the query
[b]The relative effort needed to post-process the information to enable the query

Multi-step Post-processing of Collected Data: Some aspects required significant human effort to map the relationships between assets, e.g., which cables go through which series of ducts, with multiple ducts running between any pair of chambers. This could be addressed with refined data collection software and further automation, although such software development was outside the scope of the project. It could also be addressed by simplifying certain use cases.

Communicating the Outcomes: The project did not include the development of a user-friendly interface for interrogating the data. As such, results were presented through a proprietary front end to the triple store. This was very useful to those who were familiar with the technologies but not user friendly for day-to-day interrogation by end users. Therefore, it was difficult to communicate the technical benefits of the solution to the asset owner and other stakeholders.

3.2 Prospective Benefits

Irrespective of the challenges encountered, the prospective technical benefits of the approach are clear to the authors. Some are elaborated below.

Information Requirements Based on Use Cases: In the authors' experience, asset information requirements often list extensive attributes that should be populated for

each asset type instance by a design, contractor, supplier and or maintainer throughout the life cycle of an asset. In practice, significant resources are needed to populate all attributes for each asset instance, to validate the information at handover, to manipulate the information into an asset information management system, and then to maintain the information. The value derived is unlikely to outweigh the costs of procurement. Conversely, the approach adopted by the authors resulted in only a small number of attributes needed for each asset type based on the authors' understanding of the asset manager's and maintainer's priorities. This requires detailed engagement with the end users of the desired information, but avoids waste.

Modularity and Scalability: Graph databases enable relatively straightforward reuse of ontologies, rules, validation tools and data sets. For example, this project used ontologies from W3C (inherent in the choice of using OWL, RDF and RDFS) and from EN 17632-1, which had been produced by others. Simple reference to those ontologies enabled reuse of the full benefits of same. This means that if the public asset owner chooses to extend their ontologies to cover other asset types and use cases, then much of the challenging data modelling work would have already been completed and could be reused. Such an approach has been adopted by other highways asset owners in Europe. Also, because datasets can be related to each other through RDF triples, rather than necessitating extension to relational database tables, scalability is high. This does come at a cost of complexity, with less available expertise in graph databases when compared to relational databases. Accordingly, governance rules for the ontologies and data sets are vital if the technologies are to be adopted at scale.

Standards Based and Machine Readable: All data was structured in accordance with international web standards. As such, software tools that were developed for other domains and use cases could be plugged into the project data quite easily. Further, the semantic richness of the data enabled various applications to automatically understand the meaning of the data. This was especially apparent when using tools for interrogating and visualizing the data. It contrasts with common historical approaches to asset information management, where data is often structured in a proprietary manner, specific to the asset owner or even to separate departments within an organization, with no overarching machine-readable rules to control data entry.

4 Conclusions

The project was challenging but provided value even if the technologies are not further adopted by the asset owner in the short term. The validated asset data was transformed and exported into a relational database for future use, albeit with the loss of some semantic richness. The prospective technical benefits presented above warrant due attention by public asset owners seeking to futureproof their data and systems.

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A Data-Driven Framework for Detecting Railway Maintenance Needs Using Acceleration Data Collected from Passing Trains

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Abstract. There is a fast-growing need for maintenance of railway track systems due to increasing the number of passengers and freight transport in the past few years. In this paper, a novel data-driven method is proposed to detect different maintenance needs of railway track systems using vertical acceleration data collected from an operational passenger train. The framework contains four modules. Firstly, a data pre-processing and cleansing is performed to extract useful data from the whole dataset. Then, condition-sensitive features are extracted from the raw data. In the third module, the best subset of measurement features that characterize the state of the tracks are selected using Analysis of Variance (ANOVA) algorithm which eliminates irrelevant characteristics from the time domain feature set of responses. Finally, a multilabel classification algorithm based on the Support-Vector Machine (SVM) is used to classify the type of maintenance needs of track. An open-access dataset from a field study in the United States is used in this study for validation of the proposed method. Results show that when an SVM is used, a higher accuracy can be achieved for detecting tamping and surfacing needs in comparison with k-Nearest Neighbors (KNN) and Decision Tree (DT). In addition, the impact of using different features selection methods, different classification algorithms and different accelerometer types (uniaxial and triaxial accelerometers) on the accuracy of the proposed approach is studied.

Keywords: Indirect railway monitoring · Data driven · Rail maintenance

1 Introduction

Railway infrastructure networks are among the most important transportation assets and have served the worldwide growth of industry and civilization for hundreds of years [1]. It is very important for railway owners to keep these systems well maintained and operational [2].

Railway infrastructure monitoring systems currently rely on two main approaches: visual inspection and the utilization of specialized track recording vehicles (TRV). However, both methods are labor-intensive and time-consuming [1]. Consequently, innovative and cost-effective techniques for monitoring the health of railway infrastructure have

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been developed in recent years. In this context, the Structural Health Monitoring (SHM) of railway systems can be accomplished through two primary methods: model-driven or data-driven approaches [3]. The main premise behind the first approach is the use of an accurate analytical or numerical model of the train and track [3]. Some limitations and difficulties such as the requirement of a highly detailed model make the data-driven techniques a more feasible option [1].

As data-driven SHM techniques rely on actual measured data, most of them have adopted statistical pattern recognition paradigms within a framework of combining feature extraction and statistical decision-making [3]. However, these methods still have certain constraints and shortcomings. For instance, in a study conducted by Kerrouche et al. [4], they employed fiber Bragg grating (FBG) sensors for monitoring railway track behaviors. This necessitates a substantial number of sensors for monitoring the entire railway network, which would be inordinately expensive. In response to these challenges, researchers [1, 3] have explored alternative monitoring strategies, wherein the health status of railway infrastructure can be assessed indirectly through the dynamic response of a passing train that is in service itself. This paper aims to investigate the feasibility of detecting various maintenance requirements of railway tracks through the analysis of vibrations transmitted to the train from the interaction between the wheel and rail.

To do this, a four-step data-driven framework is proposed. Firstly, the acceleration responses of the track are acquired using the sensors mounted on the train. Then the features of these responses are extracted using signal-processing techniques. In the next step, the best subset of features is selected using Analysis of Variance (ANOVA) as feature selection algorithm [5]. Finally, the railway maintenance needs are classified using Support Vector Machines (SVM) [5]. This paper has two main contributions (1) extracting all time domain features and then selecting the best subset of features that captures the characteristics of the different maintenance needs and (2) detecting multiple maintenance needs simultaneously using SVM.

2 Experimental Data Set

The DR-Train dataset, originally introduced by Liu and colleagues [2], is a publicly available dataset containing measurements obtained from two Light Rail Vehicles (LRV) situated in Pittsburgh, Pennsylvania. In addition to vibration data recorded through accelerometers, this dataset includes GPS coordinates, relevant environmental parameters (such as temperature and weather conditions), and maintenance logs that have been verified by the Port Authority of Allegheny County (PAAC) [2].

As described in [2], the sensing module comprises two single-axis accelerometers inside the train cabin for measuring vertical vibrations, one tri-axial accelerometer mounted on the central wheel-truck (bogie), and a BU-353 GPS antenna positioned just below the roof.

Liu et al. [2] gathered data from numerous complete journeys covering the 42.2 km rail network, sampling continuously from the GPS at 1 Hz and from the accelerometer at 1.6 kHz [3]. Since the purpose of this paper is to classify rail maintenance needs, a specific location should be selected where multiple types of maintenance work have

been done on it. The location of interest selected for this study is a location with the description: Denise crossover and Glen-bury crossover. This location has a recorded maintenance work of tamping and surfacing. Surfacing refers to the maintenance of the tracks in order to have the correct surface elevation, such as raising or lowering the track structure. Also, tamping refers to the work that is done to pack the track ballast underneath the track itself [3].

3 The Proposed Framework

The proposed framework comprises four primary stages, elaborated in detail in Fig. 1. In Step 1 (Data Pre-Processing), the recorded sensor acceleration responses undergo a cleansing and alignment process based on the GPS dataset. To achieve this, the passes are initially synchronized with the ground truth track coordinates, utilizing the Iterative Closest Point (ICP) algorithm, as outlined in Liu et al.'s methodology [2]. Passes that have incorrect GPS positions are subsequently filtered out.

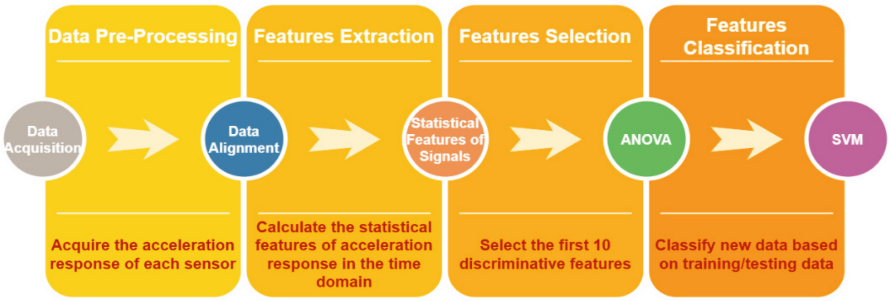


Fig. 1. The detailed flowchart of proposed framework.

In the second step (Features Extraction), to reduce the length of the data and extract meaningful information from the responses, statistical features of signal are extracted from a raw acceleration signal. These features (such as Root mean square, Variance, Mean, Shape factor, Crest factor, etc.) are computed in the time domain and provide a summary of the statistics of the signal over a time window with a specified length.

When the feature set is extracted, a feature selection method called ANOVA is used to reduce the dimension of the problem. ANOVA test and rank the features based on their level of variance across the damage states and then a percentage of ANOVA-ranked features are used as the input vector to the damage classification algorithm.

In the final step (Features Classification), the classification algorithm based on SVM is trained. The input of SVM is 10 of high ranked features, and the output is the track maintenance needs. The different maintenance needs that can be identified include tamping (Class 1), surfacing (Class 2), both (Class 3) or no maintenance (Class 4).

4 Experimental Results

According to the process explained in Sect. 3, the response of the train at the location of interest is extracted from the available dataset of all regions. After extracting the response of sensors on the train, The acceleration data are aligned with the ground truth tack coordinates using the ICP algorithm [2]. The aligned data is then used to extract salient features.

4.1 Feature Extraction and Selection

The results for various accelerometer directions are presented in Table 1. Notably, in the transverse direction, which is perpendicular to the railway, there is a slight performance advantage compared to the vertical direction. This result aligns with the logic that tamping and surfacing maintenance activities aim to achieve a smoother ride. The more unnecessary movements occurring in any other direction indicates that maintenance is needed. It also can be seen that a method based on triaxial accelerometer dataset, performs better than the uniaxial accelerometer (only vertical direction) dataset.

Table 1. Classification results of different accelerometer direction and type.

Sensor Direction	Acc	Sensor Type	Acc
x-axis (longitudinal)	81.90%	Uniaxial	85.90%
y-axis (transverse)	88.90%	Triaxial	92.31%
z-axis (vertical)	86.90%		

4.2 Feature Classification

In the final step of proposed framework, the fivefold cross-validation manner is applied to compute the classification accuracy (Fig. 2). Confusion matrix of SVM for classification of various maintenance needs of railway track. illustrates the confusion matrix depicting the classification outcomes achieved by the SVM model. The model exhibits its highest level of accuracy when categorizing instances under the ‘tamping’ class. Conversely, the worst performance of the model is when it tries to classify the passes that need ‘surfacing’. In this case, in 18.2% of passes, the detected class is ‘taming’. Meanwhile, it can be an acceptable result because it shows that the track needs maintenance and it does not classify them as ‘no-maintenance’. Balanced accuracy classification score for SVM is 92.31% that shows SVM able to be used for multiple maintenance needs detection.

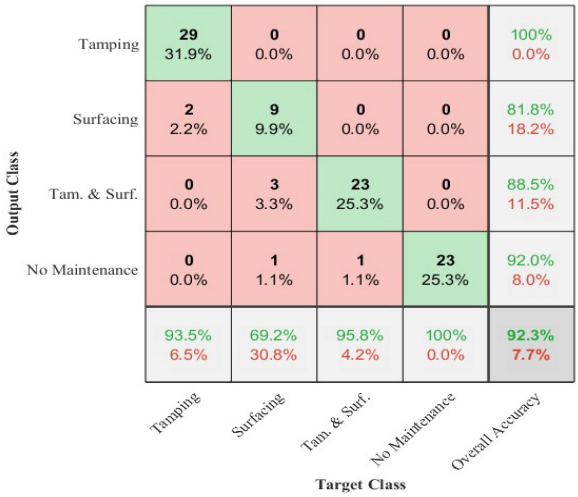


Fig. 2. Confusion matrix of SVM for classification of various maintenance needs of railway track.

To compare the performance of SVM with other machine learning (ML) algorithms, two well-known algorithms of K-Nearest Neighbors (KNN) [6], and Tree [6] are selected, and the same framework as SVM is implemented for them. Furthermore, the capability of the ANOVA as feature selection algorithm for distinguishing between various maintenance needs is assessed by comparison of its performance by two other methods: Minimum Redundancy Maximum Relevance (MRMR) algorithm [7] and ReliefF [7]. Comparison results for three feature selection methods and three classification algorithms can be seen in Table 2.

Table 2. Comparison of different feature selection/classification algorithms in identifying the maintenance needs of railway track.

Feature Selection Method	Number of Features per Each Sensor Direction	KNN	Tree	SVM
MRMR	10	85.80%	85.90%	91.20%
ReliefF	10	81.00%	82.20%	89.32%
ANOVA	10	82.40%	83.50%	92.31%

All methods perform effectively, with the SVM classifier demonstrating higher accuracy in most combinations. Furthermore, ANOVA shows better performance in selecting the features with high discriminability scores between various maintenance needs of track. It is important to highlight that this study exclusively addresses two specific maintenance tasks: tamping and surfacing. In practice, railway tracks may undergo various other forms of maintenance work. Considering these maintenances can be an extension to this study.

5 Conclusion

This paper proposed an adaptive framework for identifying the maintenance maintenance requirements of railway systems. This objective is achieved through the recording of acceleration responses from moving trains, followed by their classification based on the subset of features extracted from the raw signal data. Results showed that multiple maintenance needs can be detected simultaneously using SVM. In addition, the comparison results between MRMR, ReliefF, and ANOVA as feature selection algorithms show that ANOVA performs better in distinguishing between different categories of maintenance needs. It should be noted that this study focused solely on two maintenance requirements, specifically tamping and surfacing. Nevertheless, it represents a significant step towards the development of an early warning system for the detection of railway track maintenance needs. This methodology offers a straightforward approach that is well-suited for implementation in regions with a history of maintenance activities.

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Enhancing the Performance of Emergency Vehicles Through Reinforcement Learning Based DVSL Control Systems

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Abstract. Variable Speed Limits (VSL) have been used to dynamically control traffic via the adaptation of vehicular speed with the aim to mitigate congestion, enhance safety and traffic flow performance. Recent studies have demonstrated the effectiveness of employing Deep Reinforcement Learning (DRL) techniques for VSL controllers, resulting in improved safety, efficiency, and environmental sustainability on highways. However, the conventional RL models for VSL control systems have not been trained to prioritize and facilitate the movement of emergency vehicles. This paper proposes a deep deterministic policy gradient (DDPG) algorithm which utilizes an actor-critic model by training the DVSL controller and a novel reward function to optimize the time loss of emergency vehicles across a highway weaving section. The results show that the proposed approach outperforms the baseline method with no VSL in terms of the accumulated waiting time, accumulated time loss, average time loss of emergency vehicles and the average travel time of all the vehicles.

Keywords: Differential Variable speed limit control(DVSL) · Connected Automated Vehicle (CAV) · Intelligent Transportation System (ITS) · Reinforcement Learning (RL) · Mixed traffic

1 Introduction

Congestion closure due to ramps normally result in reduced levels of service (LOS), compromised safety, and higher fuel consumption. This is particularly important when Emergency vehicles (EVs) are present and must deliver first aid and rescue personnel to the scene of an accident. A shorter response time is associated with a lower fatality rate. Therefore, ensuring a fast and reliable response time of emergency vehicles (EVs) has become a primary objective in the development of emergency management systems [1]. However, EVs often encounter obstacles such as other vehicles on normal road segments, which can force EVs to slow down or even come to a complete stop [2].

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Intelligent Transportation Systems (ITS) offer viable solutions through the implementation of traffic control systems such as Variable Speed Limits (VSLs)[3], which calculates speed limits based on the current traffic conditions using up-to-date information collected from the vehicles on the highway [4]. Such information can be obtained from the infrastructure, or communicated by the vehicles. Automated vehicles(AV) and Connected Automated vehicles(CAV) can collect traffic information from a variety of sensing and communication technologies integrated within the vehicle, such as cameras, sensors, radars, lidars, and 5G [5].

DVSL is an incorporation of Differential Speed Limit (DSL) and VSL. DSL is utilized in two cases: The DSL control system can implement different speed limits for various vehicle types, such as lower speed limits for trucks and buses and higher speed limits for passenger cars. Additionally, it can set different speed limits for different lanes on freeways, such as higher speed limits for the left lanes and lower speed limits for the right lanes[6]. The DVSL control among lanes is executed by imposing dynamic and distinct speed limits among lanes. To process such information and make decisions (i.e., set a speed limit) in real time, interactive algorithms such as deep reinforcement learning (DRL) have shown promising results. DRL facilitates the development of autonomous control agents for problems that were previously considered intractable using reinforcement learning [7]. This approach is repeatedly employed to effectively manage unforeseen conditions[8,9]. Similar to other areas of research, some studies have utilized DRL approaches to address the objectives of Emergency Vehicles (EVs)[10]-[11]. RL agent learns from the consequences of its actions in the environment. A Deep Reinforcement Learning (DRL) model was proposed in [7] for DVSL control, where dynamic and distinct speed limits can be imposed among lanes. To train the DVSL control, different reward signals, such as total travel time, bottleneck speed, emergency braking, and vehicular emissions are used. The idea of our research is inspired by the mentioned article; however, in this research, we focus on the movements of EVs and adjust the reward function for this objective. Although some works have shown promising improvement in this domain, they have not studied the impact of their method on potentially present EVs' performance. These challenges are addressed in this paper through its following contribution.

- A DVSL system is designed and trained to facilitate the movement of EVs using a Deep Deterministic Policy Gradient (DDPG) algorithm.
- The proposed approach is then compared with a no-VSL baseline and the findings of this comparison are presented.

The remainder of this article is organized as follows. Section 2 presents the system model and background of this research. Section 3 presents the experimental setup. Results and discussion are described in Sect. 5, followed by conclusion in Sect. 6.

2 Background and the Proposed System

This section demonstrates how our proposed system was designed to assist the EV in trajectory. We also described our proposed system in this section.

2.1 Deep RL for Differential Variable Speed Limit

The proposed RL applies Markov Decision Process (MDP) to create an optimal policy for an agent to interact with the environment and maximize its cumulative reward. Considering an MDP characterized by a tuple of (S, A, P, R, γ), where S represents the set of agent's states, A is the set of possible actions taken by the agent to transition from one state to another. Let $P(s, s')$ denote the transition probability when the agent takes action, R is the expected accumulated reward in each state-action pair, and $\gamma \rightarrow [0, 1]$ is a discount factor that determines the importance of future rewards relative to immediate rewards. In the proposed model we utilize a deep neural network in the RL design due to its multi-layer and function approximators. The deep RL model uses the actor-critic system to generate and evaluate the actions for the DVSL problem. We formulate the actor of the deep RL as[12];

$$\begin{aligned} f_\theta^\pi : R^{m_l+u_l+o_l} => R^{c_l} => A \\ f_\theta^\pi(s^t) = a_t \\ g(a_t) = int(clip(a_t, 0, M)) \end{aligned} \tag{1}$$

where the function f_θ^π, which is parameterized by θ^π, maps from the state space $R^{m_l+u_l+o_l}$ to the action space R^{c_l}. Assuming there are M different types of speed limits for each lane, we are required to map "a_t" to an element within the valid action set A. The critic also is defined as follows:

$$\pi_\theta(s) = argmax_{ag(f_\theta^\pi(s)} Q_\theta^Q(s, a) \tag{2}$$

In which Q_θ^Q is the estimated value function and Q^θ and Q^π represent the parameter of the critic and the actor, respectively.

2.2 Deep Deterministic Policy Gradient(DDPG)

DDPG is a deep RL algorithm, which integrates the classical actor-critic RL approach [13] with the Deterministic Policy Gradient proposed by [14]. The policy gradient theorem for a stochastic policy $\pi(s, a; \theta)$ was initially proposed in [13]. The neural network actor, denoted as $\pi(s; \theta^\pi)$, approximates a deterministic policy (as opposed to a stochastic one). It takes the environment state s as input, parameterized by weights θ^π. On the other hand, the critic is implemented by a separate network Q(s, a; θ^Q), updated using the Bellman equation, similar to the Deep Q-Network (DQN) formulation:

$$Q(s_t, a_t) = E_{r_t, s_{t+1}}[r(s_t, a_t)] + \gamma Q(s_{t+1}, \pi(s_{t+1}))] \tag{3}$$

To update the actor, the chain rule is applied to the loss function, and the weights θ^{π} are updated by following the gradient of the loss with respect to them. The loss function is as follows:

$$L(\theta) = E[(y - Q(s, a; \theta))^2] \tag{4}$$

To update critic, the loss will be minimized:

$$L = 1/N \Sigma_i (y_i - Q(s_i, a_i | \theta^Q))^2 \tag{5}$$

The actor also will be updated using the sampled policy gradient:

$$\nabla \theta^{\pi} L = 1/N \Sigma_i \nabla_a Q(s, a | \theta^Q) \nabla_{\theta^{\pi}} \pi(s | \theta^{\pi}) | s_i \tag{6}$$

2.3 DVSL Environment Modelling

The proposed DVSL environment includes the following: **Agents**, which are the DVSL controllers of the system. **State** (s_t), that is defined as $R^{m_l + u_l + o_l}$, which is occupancy rates collected from loop detectors and m_l, u_l and o_l are the number of lanes of the merging area, the upstream mainline, and the on-ramp respectively. **Action** (a_t) at time t, which is the speed limit generated for each lane by VSL control. $a_t \in R^{c_l}$ and c_l is the number of lanes at a section.

State transition probability $\mathrm{p}(s_{t+1}|s_t, a_t)$: which is probability of an agent to change the state to another state is conducted from SUMO.

Reward Modelling. In this research the reward signal that we have considered "r_t" is accumulated time loss of EVs, which the accumulated time lost due to driving slower than desired. Since accumulated time losses are large numbers, b is also used to scale the reward to smaller values. So the reward function is: $r_{t+1} = r_t - tl_t/b$

3 Experimental Setup and Results

The Network Setting: Simulation of Urban MObility (SUMO) is selected for the simulation analysis as a powerful tool for evaluation purposes of traffic networks. The traffic mix in this simulation experiment is composed of 5 types of vehicles. The first 2 types are heavy vehicles (comprising 20% of the total numbers of vehicles, with the length of 8 m). The second 2 types are passenger cars (containing79% of the vehicles, with length of 3.5 m). For these mentioned vehicle types, we considered two different car following models ("Krauss" and "IDM". The last type of vehicles is Emergency vehicle with length of 5.5 (m) (1% of vehicles). In this simulated section of the motorway, as depicted in Fig. 1, vehicles enter from two different origins of the network (mainline and on-ramp) and exit from two edges to their destinations (mainline and off-ramp). The presence of EVs induces changes in the behavior of traffic flow, since downstream vehicles are forced to implement lane changes to clear the way for emergency vehicles. Figure 1 shows the traffic network of this study. As it is shown in the picture, vehicle V1 changes the lane from L1 to L2 and clear the lane for emergency vehicle EV1.

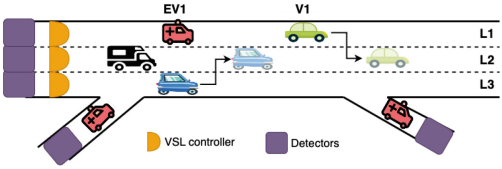


Fig. 1. An illustration of the EVs and elements of the traffic and infrastructure in the network.

To investigate the performance of the DRL algorithm on DVSL control, a freeway section composed of 3 lanes, including an on-ramp and off-ramp is considered. 3 DVSL controls are considered in the upstream of bottleneck area. There are three groups of detectors in the upstream and downstream of the mainline lanes and another group in the on-ramp which provide traffic counts that feed into the VSL algorithm.

Since all 99% of the vehicles are CAVs, they can be designed in order to comply with the speed limits. The compliance with speed limits is modeled using a normal distribution ("normc(1,0.1,0.2,2)") as a speed factor for these CAVs. This distribution ensures that CAVs adopt the speed limits which will be updated during simulation via TraCI. However, EVs ignore speed limits , as they operate with a speed factor of 1.5. The duration of simulation is 2 h and the agents are trained by 20 episodes of simulation.

Performance Criteria: The effectiveness of the learned control policy is evaluated by metrics outlined below. Average accumulated time loss of EVs, average mean time loss, and the average travel time of all types of vehicles and average accumulated waiting time of EVs all in seconds. The values for these metric for both proposed method and baseline are presented in Table 1.

Results: The simulation results are compared with a baseline scenario in which the posted speed limit on the mainline lanes is 65 mi/h and no VSL control is implemented [7]. The average values obtained from 5 runs and are compared to the performance of the baseline. As summarised in Table. 1, a significant improvement of 32.4% in accumulated time loss of EVs in DVSL approach is achieved. The proposed approach decreases other metrics such as accumulated waiting time and mean time loss of EVs. In addition, it improved Average Travel Time of all types of vehicles.

Table 1. Average performance of different models on 20 episodes of 5 run simulation

Metrics	No VSL	DVSL	Improvement
Average Accumulated time loss of EVs(s)	1112640	1646053	32.40%
Average Meantimeloss of each EV(s)	54	55	1.80%
Average Travel time of all types vehicles(s)	102	104	1.90%
Average Accumulated waiting time of EVs(s)	40	41	2.40%

4 Conclusion

In this research, a DDPG algorithm is used to train DVSL controllers to adjust speed limits for approaching vehicles to the bottleneck area. The proposed method used an actor-critic architecture, imposing speed limits to the all types of vehicles, except for emergency vehicles, which has been given priority to pass the mentioned area. Significant improvements are achieved by the proposed method compared to results of the baseline, across various metrics. The DVSL approach achieved a remarkable 32.4% reduction in accumulated time loss for EVs when compared to the no VSL scenario. Additionally, improvements in other key metrics such as mean time loss of EVs and accumulated waiting time, indicates a better traffic flow and reduced congestion. These findings demonstrate the effectiveness of the DVSL approach in optimizing traffic management strategies, particularly in scenarios that involve emergency vehicle prioritization. By utilizing advanced algorithms and dynamic control mechanisms like DDPG, traffic control systems can adapt in real-time to varying traffic conditions, leading to higher safety, more efficient mobility within congested areas and work zones.

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Software Patterns and Architectural Decisions for a Next-Generation Traffic Management System in the TANGENT Project

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Abstract. This paper introduces the TANGENT project and how it is exploring Dynamic Management of Multimodal Traffic in four European cities. It focuses on how specific software patterns and architectural decisions are contributing to the success in creating and trialling a Simulation powered Next-Generation Traffic Management System. It starts by exploring the motivation behind a TANGENT API where a REST API coexists with a Message Queue Broker and how they synergize to cover the different needs of distinct data producers and consumers within and around the TANGENT project. It then explores a generic approach for the different pieces of the TANGENT API. How incoming data handling from the message queue service is implemented generically in the TANGENT API, how the REST API is implemented with this same approach and how the OpenAPI documentation of the REST API is produced. Highlighting the central role of the JSON Schemas and meta-data stored in TANGENT Schema catalogue and how it is simple to add new data sources with this approach as opposed to custom handling the individual data sources.

Keywords: Next-Generation Traffic Management System · Transport APIs · Multimodal Traffic Management

1 Introduction

The TANGENT project [1] is exploring Dynamic Management of Multimodal Traffic in four European cities (Athens, Manchester, Lisbon and Rennes) by creating and trialling a Simulation powered Next-Generation Traffic Management System.

Data is a first-class citizen in the TANGENT project. It originates in data sources from a myriad of entities and services covering the four case study cities. In a first step, Service 0 (S0 in Fig. 1 below), is responsible for the collection, harmonisation and fusion of these data sources. It uses a Data Catalogue and an internal RDF-based Meta-model to achieve this. This Meta-model is based on transportation standards like Datex II [2], SIRI [3] and NeTEX [4]. It then outputs data in a JSON serialisation that is used by the TANGENT API in Service 1 (S1). All data elements sent from Service 0 to Service 1 are JSON serialized, and each type of data element follows a JSON Schema that is directly derived from the RDF Meta-model.

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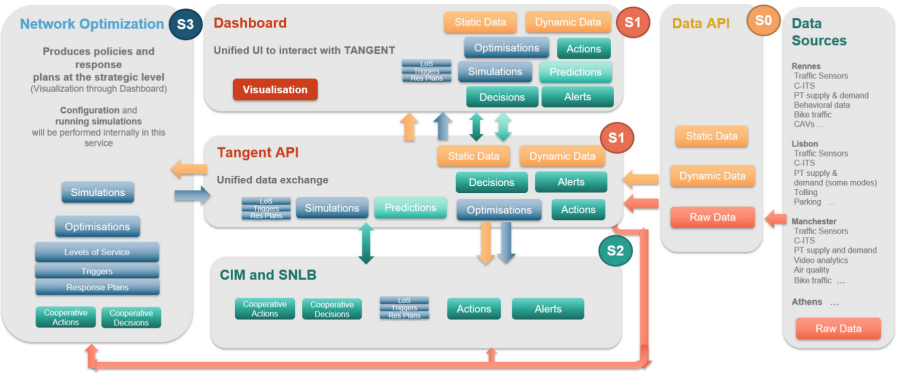


Fig. 1. TANGENT Project Data flow diagram.

TANGENT Services (S0-3), their data flows and the main data entities involved are depicted in Fig. 1 below.

The TANGENT API from S1 is responsible for all internal and external project data exchange. This service also includes a User Interface component, denominated the TANGENT Dashboard. With the data originally coming from Service 0, the TANGENT Dashboard can provide multiple integrated visualisations, be it in maps, tables or KPI summary views. Services 2 and 3 complement the visualisation functionality with the ability to detect, analyse, plan, and implement responses to network disruptions and incidents in a multimodal, cooperative fashion. Response plans are prepared through the creation of templates that identify the detection conditions for network disruptions/incidents, characterize the incident and include a transport simulation model that can produce an optimised response plan for the given situation. A simulation engine runs the transport model for each template and produces optimisation results which are stored. When the Response Plan is activated due to degrading conditions on the network, the optimisation results in the template are presented to users in the Dashboard and cooperatively they will decide to change or directly apply the optimisation results to address the degraded conditions. These results can range from changes to Public Transport scheduling to changing traffic light plans and priorities, combining changes to several modes of transport in the city to produce an optimised response.

The TANGENT API is a central element in this project, exchanging data between the different Services. This includes both data coming originally from the cities as well as data supporting communication between the different Services to provide more advanced functionality, such as creating and implementing Response Plans. This central role is illustrated in the diagram of the TANGENT Tool architecture at Fig. 2.

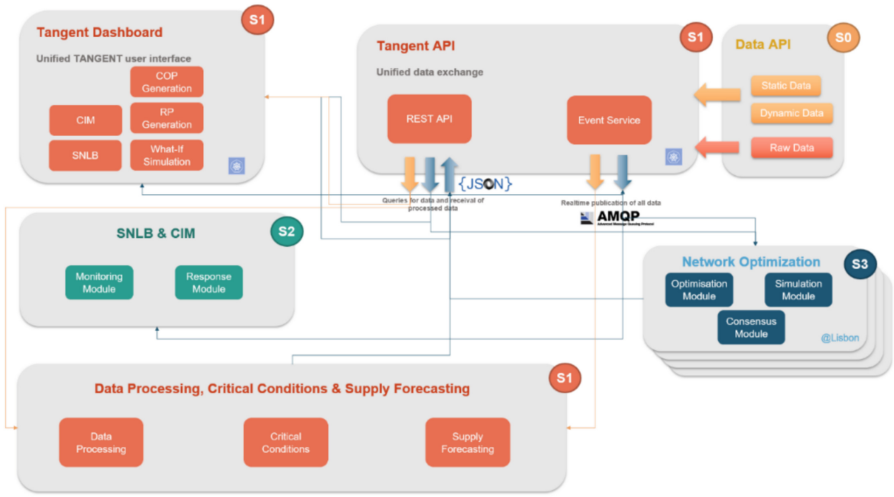


Fig. 2. TANGENT Detailed Technical architecture.

2 Complementing REST and AMQP Services

The entire TANGENT API is implemented both as REST services and, correspondingly, as messages in a Message Queue service (using AMQP). The message queue service provides real-time capabilities used by multiple services, including the User Interface. The REST services provide an OpenAPI documented interface where data can be fetched and delivered as needed. The messages exchanged follow the same JSON Schemas in both technologies. The JSON Schemas for the data coming from the cities are produced from the RDF Meta-model that is central to Service 0. The remaining JSON Schemas, namely those used for inter-service communication, are automatically produced from data samples in JSON and reviewed and enhanced manually.

Most Open data APIs for multi-modal transportation, and generally, Open data APIs, are implemented as REST services, offering queryable data sources in formats such as JSON, CSV and XML. The reason for this is probably because it's easier to implement user applications based on queryable data sources (as offered by REST services) instead of real-time messaging services (as offered by message queues).

A user application typically opens an entry screen with live information about a transport network / city and offers a set of planning functionalities, such as finding the best routes to a destination or determining the best time to leave work so you can arrive home or somewhere else before a certain time. This usage pattern fits well with queryable data sources, where the application can fetch live data and execute queries for the desired routing and other functionality as needed.

This rationale behind user applications was also part of the motivation behind offering the TANGENT API as a REST OpenAPI documented interface using only well-documented JSON payloads. This allows the TANGENT API to fit well with the existing Transport and Smart city API ecosystem and positions the TANGENT API as a potential source of data for User Applications. The queryable data source pattern offered by the

REST part of the TANGENT API also fits well with most of the needs of the TANGENT Dashboard, namely fetching the data to feed to live transport data widgets on a user's Dashboard.

But data displayed on the TANGENT Dashboard is not static. It typically changes periodically and it needs to be updated on the user interfaces. This is one use case where the REST services model shows its limitations. There are a few ways to overcome this limitation in REST APIs, namely Long pooling, Webhooks, Server-Sent Events or opting altogether for a different integration method such as Websockets. Most of these solutions involve setting up a dedicated permanent communication channel and, in some cases, involve exposing services from the client-side, which may be cumbersome and undesirable from the networking perspective.

The real-time update of data is not the only TANGENT Tool requirement not adequately covered by the REST API. A more advanced functionality such as Incident Management, involves the system monitoring a set of predefined conditions that will identify an occurring Incident, such as traffic occupancy or public transport occupancy surpassing a given threshold,. It is crucial to evaluate these conditions as soon as the data behind them changes. Other such situations exist, namely having to generate calculated data and produce forecasts once new live information is available.

The fundamental technical limitation with the REST API that had to be overcome to adequately support all the previous use cases was the same, the lack of a real-time communication channel from the API towards its clients. This is where the Message Queue principle came into play. Unlike most ways used to overcome this limitation with REST APIs, message queues do not involve the need to setup a listening endpoint on the client side and decouple the connection between API producers and consumers / clients, allowing for a large number of distinct message producers and consumers.

Also, adopting a Message Queue to coexist with REST on the TANGENT API, allowed offering a native event driven solution alongside a queryable data solution, providing the TANGENT API clients with the best of both worlds.

Data is published directly to the Message Queue by distinct producers in Service 0 through to Service 3. It is persisted by a TANGENT API Service that subscribes to all known topics of the message queue, and that is how data becomes available for the REST API. Internal TANGENT API consumers will use the Message Queue primarily as they are either data producers, data transformers (subscribing to data that they enhance or use to produce up-to-date forecasts) or offer asynchronous services (such as optimising an incident response plan).

The TANGENT API REST component is used by the TANGENT Dashboard to fetch data to display in its widgets and by third-party applications that can benefit from TANGENT's harmonised data.

In terms of architecture quality, a pure solution would not include the overlapping functionality of AMQP and REST. It would be a cleaner approach to evolve to a purely Message Broker based solution. Still, we do not envision that to be the best solution for the TANGENT API because of the queryable data nature of the REST API which is more natural for many applications and due to the lack of formal documentation mechanism in Message Queues, such as OpenAPI in REST APIs. Thus, we predict that, for the time-being, the duality of the TANGENT API will be an asset.

3 A Generic Data-Driven API

All the data flows coming from Service 0 to the TANGENT API involve indexing and storing the received data. TANGENT components that need to act on data once it becomes available, subscribe to the appropriate message queue topics. For instance, a triggering mechanism for the Response Plans, in Service 2, subscribes all the topics in the message queue for the data elements that it is monitoring. The event component of the architecture, based on the native events of the Message Queue, allows for a generic implementation of the main data processing services.

This motivated the development of generic approaches for incoming data handling from the message queue service in the TANGENT API, for the implementation of the REST API and for producing the OpenAPI documentation of the REST API from the JSON Schemas and meta-data stored in TANGENT.

This is not a new concept and has been promoted by works such as [5] and [6]. Handling data from different sub-domains is not an intrinsically distinct task. For TANGENT all data must be indexed and persisted; whatever actions need to be done, based on the data, can be defined through handlers for subscriptions to the message topic, namely updating the Dashboard or evaluating conditions regarding Incident detection.

The central element behind all generic approaches for the TANGENT API is the meta-data that lists all integrated data sources, identifying the message queue topics they arrive to, their REST base URL, their JSON schema, the database collections where the data should be stored, the permissions needed by users who can access each data source and several other specific aspects that provide distinguishing behaviour to the different data sources.

The service that handles incoming messages to the Message Queue simply has to listen to all the data source topics, indexing and persisting any received messages in the respective collection.

The REST API is a generic service that handles all request paths and validates them against the possible paths for the different data sources. Once matched, and access is validated, the respective action can be performed in a generic way, either read or store data.

The REST API is documented using the OpenAPI standard. Although the REST API implementation is generic, the OpenAPI documentation needs to include the signature of all the Data Requirements covered by the API. To this end, our solution uses the meta-data, where the URLs, JSON Schema, allowed operations, and parameters are defined to produce the OpenAPI documentation. JSON Schema objects will be converted into OpenAPI Schema Objects. The remaining elements of the OpenAPI Schema for each data source will be produced through Templates based on the remaining configuration elements present in the meta-data.

Instead of creating a custom API for each of the Data Sources supported in the TANGENT project, we opted for this generic solution. This allowed to systematically identify the common requirements of the data handling process, implement a generic solution covering these requirements and now it is straightforward to integrate new data sources without having to implement new code.

Our generic approach extended also into the Data Visualisation strategies, a topic which will be explored in future works.

4 Conclusions

As a Next Generation Traffic Management System, the TANGENT Tool will offer a multimodal view of urban transportation systems. It will also allow the cooperative management of network disruptions and incidents using optimised response plans obtained by simulations.

The composition of the TANGENT API as a combination of REST and a Message Queue allows dynamic choice between queryable data sources and event driven ones, delivering a robust and versatile integration platform for a wide spectrum of use cases.

Implementing the Tool through Generic API services allowed to focus on the data being exchanged and how it is displayed on the User Interface, instead of having to program the API specifically for each data source being handled. Adding new data sources became only a matter of configuration and testing.

Being generic, the API can also cater to new data source needs. It will capture these needs as configuration aspects and provide a generic solution to handle them, meaning it can be applied to other future data sources sharing the same need.

In the end, the ability to combine data from different modes of transport, the inclusion of forecasts and cooperatively implementing Response Plans based on simulation, overcome limitations of the vertical segmented systems operating transportation in most cities.

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Tolling Dematerialization Use Cases

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Abstract. Road User Charging, Dynamic Congestion Pricing, Emissions Charging, and Urban Access Control are appearing worldwide as examples of more complex, dynamic, or rule-based types of road pricing. The existing tags/transponders or video recognition tolling solutions do not scale adequately for these use cases, whereas more dematerialized solutions such as Mobile Tolling, GNSS Tolling, or Vehicle to Everything (V2X) Tolling do. This paper describes A-to-Be's research and development for these advanced use cases, how Mobile Tolling accuracy was enhanced using Bluetooth, how the V2X software stack was adapted to tolling and the overall trials with Mobile Tolling and V2X Tolling prototypes.

Keywords: Road-User Charging · Mobile Tolling · GNSS Tolling · V2X Tolling

1 Introduction

The Future of Tolling and Access Control is dematerialized, seamless and cost-effective. This dematerialization is of utmost importance because it greatly decreases the use of heavy infrastructures and equipment (channeled lanes, booths, payment machines, gantries, in-pavement sensors, etc.). This downsizing benefits both IOOs (Infrastructure Owners and Operators), with the huge reduction of installation and maintenance costs, and society on its own, with the large decrease in material footprint.

In most countries, with the increasing digitalization of services accelerated by the COVID-19 pandemic, and the urge to deal with congestion environmental costs, plaza tolling is converging towards a Multi-Lane Free Flow (MLFF) / Open Road Tolling (ORT) model, where the tolling transaction is performed without hindering the traffic flow, as opposed to the Stop&Go or Slow&Go pace of plaza operations [1]. The most common MLFF implementations are the All-Electronic Tolling (AET) ones, where the transactions are fully processed electronically, with customer identification normally made via tags/transponders and/or video recognition (most commonly through Automatic License Plate Recognition - ALPR). AET helps operators save money, reduce greenhouse gas emissions, improve traffic safety, and keep vehicle traffic flowing. However, there are still many complex and large infrastructures dependent on toll plazas, with gates, booths, and/or automatic payment machines, where the user passes and, in some cases needs to stop, to carry out the transaction and interact with a machine/toll booth. The co-existence of these large infrastructures with the new systems under deployment creates a hybrid ecosystem requiring adjustments to infrastructure and operation

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to ensure a smooth painless integration for both plaza and MLFF scenarios. This transformation comes with a set of challenges: (i) capture the vehicle's ID in a cost-efficient way; (ii) match that ID to a registered customer (data quality and cleansing is an essential lever to avoid revenue losses); (iii) trace down violators, send out fines and collect the payment driving profitability.

Nowadays, the challenge of matching the ID to a registered customer, is most commonly achieved by re-enforcement, by overlaying two independent validation events – namely through passage identification with tags/transponders and through image recognition (ALPR), to achieve a high level of operational efficiency. Computer Vision algorithms applied to vehicle classification for axle counting and/or volumetric analysis, complemented with re-identification and fingerprinting techniques, are allowing to create unique vehicle signatures with high accuracy rates. These advances in image-based automated validation processes will allow progressing video tolling into a single validation event, as computer vision techniques evolve and data engineering is consolidated, improving validation rates, thus allowing the reduction of operational costs (from tags and logistical/processing costs). Thus, video tolling is one of the main technology pathways to forward dematerialization, by allowing the elimination of the identification equipment of each vehicle, which nowadays accounts for billions of tags/transponders.

As smartphone ownership has become worldwide spread (6 billion worldwide in 2021 [2]), Mobile Tolling is the other prime technology pathway for transponder elimination. Leveraged by embedded mobile technologies, it can catalyse the dematerialization of tolling, by providing passage identification, real-time connected services, and account management services to road users, while increasing revenue assurance for operators [3]. Most Mobile Tolling solutions available nowadays are simply account management platforms for AET, resorting to passage identification through tag/transponder and/or ALPR, with that passage being cross-referenced with registered customers and, when a match is found, charging the client via the app's default payment method. In some instances, the app may also verify the vehicle's current location (using geolocation) as an adjuvant method. A-to-Be's development work in the field since 2020, deepens the concept to make it a truly different type of tolling, resorting to GNSS and/or Bluetooth (BT) technology for passage identification.

Traditionally, road user charging was a straightforward transaction between the driver and the tolling authority, where the road user would remunerate for access to a paid roadway, with the concessionaire or governing body assuming responsibility for road maintenance and safety. However, the transport paradigm shift is altering road usage and payment mechanisms. Contemporary electronic tolling methods not only focus on fee collection but also target to contribute to the optimization of roads operation and management. Advanced tolling methodologies aim at leveraging data from various sources, including Bluetooth, Cellular, or V2X technologies, for precise identification, localization, and vehicle classification. In anticipation of the near future, automotive Original Equipment Manufacturers (OEMs) are diligently striving to establish continuous communication channels with their vehicles on the road. For instance, the activation of in-car payments stands as a strategic objective [4] and this initiative holds the potential to establish the groundwork for location-aware tolling methods such as V2X Tolling. Standardization discussions are in progress, and V2X protocols like SAE - J3217 [5]

are currently being piloted. A-to-Be, as a road infratech provider, aiming at positioning itself at the forefront of technology, has implemented two V2X Tolling prototypes.

Besides traditional tolling, connected technology can provide other added-value services, such as Dynamic Pricing (DP), with values adjusted by the minute, based on real-time traffic Key Performance Indicators (KPIs) or Advanced Traffic Management functionalities, by providing real-time information collected from roadside sensors and recommendations from the IOOs.

Figure 1 summarizes the envisioned evolution of tolling technologies just presented.

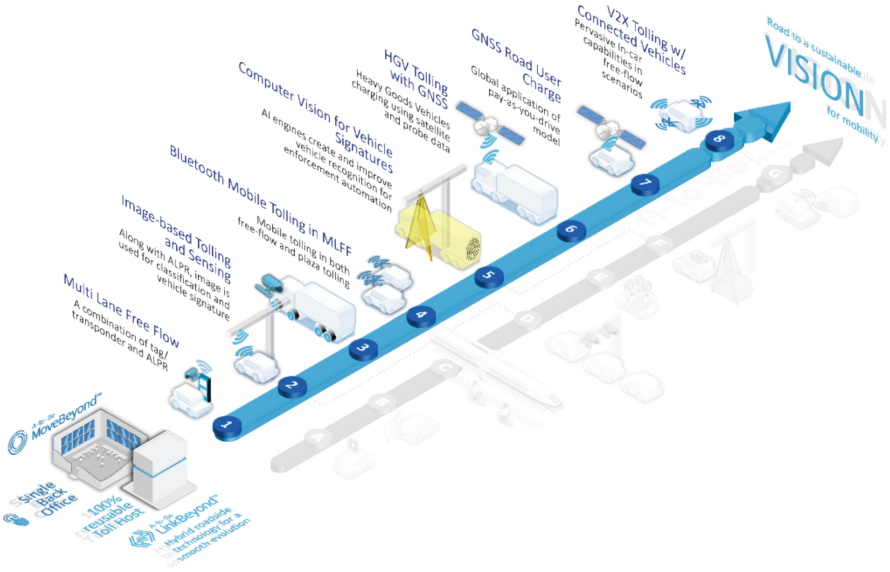


Fig. 1. Tolling Technologies evolution.

2 Dematerialized Use Cases

Although one of the main end goals of both Mobile and V2X Tolling is tag/transponder dematerialization, a main technical challenge needs to be solved. Existing on-board unit (OBU) transponder solutions rely on directional antennas able to identify the vehicle location up to the lane level. Both Mobile and V2X Tolling solutions rely on GNSS positioning. This means tolls can be defined virtually anywhere but also that, in some cases, GNSS accuracy will be an issue to correctly pinpoint the road user inside the tolling location. To address this, A-to-Be developed a BT based complement for Mobile Tolling. This is an intermediate step in terms of dematerialization, since it uses BT emitters located at the infrastructure, but which can enhance the positioning accuracy for the more demanding positioning use cases, e.g., lane detection. Enhancing trip reconstruction accuracy using interpolation techniques is also under exploration.

More advanced scenarios supported by dematerialized solutions, such as Dynamic Pricing, require providing information to the road user about dynamically changing prices. In these cases, in-vehicle integration of the dematerialized solutions (either

Mobile or V2X) is necessary. There are several increasing levels of integration: (i) Smartphone user interface; (ii) Smartphone app integration with vehicle media system (e.g., Apple CarPlay, Android Auto); (iii) In-vehicle app (e.g., Android Automotive).

2.1 Mobile Tolling

A-to-Be is developing a Mobile Tolling solution based on Bluetooth, resorting to BT technology embedded in all commercial smartphones, BT Local Access Mediators (LAMs) installed at the road infrastructure, and a mobile App/SDK designed for user identification and remote payment processing. The developed prototype uses an App installed on the user's smartphone, which can detect periodic beacons transmitted by the BT-LAMs strategically placed at tolling locations. These LAMs facilitate communication between the App and the operator's infrastructure through Bluetooth Low Energy (BLE). The App autonomously detects the user's proximity to a toll point, triggering the entire payment process seamlessly. Users would have previously configured their vehicle profile and preferred payment method within their user account area, ensuring a smooth and unobtrusive experience while driving. To guarantee streamlined communication between smartphone and payment system and address the issue of the App not being actively running during toll approach, geographic regions in the form of Bluetooth beacon IDs are configured in the smartphone. This approach not only enhances driving safety, as the driver is not required to interact, but also conserves battery life as the App need not be active prior to toll detection. The solution operates in both online and offline modes, incorporating mechanisms to guarantee payment security and authenticity. In offline mode, toll detection data is securely stored within the App and transmitted to the backend once a connection is reestablished.

In 2020, a first proof-of-concept was implemented, integrating a LAM with the payment system present in toll booths, with the communication between the user's smartphone and the cabin equipment enabling the payment method for Stop&Go and Slow&Go scenarios, where a barrier needed to be opened. In 2021, MLFF tolling, characterized by intrinsic higher vehicle velocities, was explored. The initial approach involved the App emitting beacons detectable by LAMs at the infrastructure. The LAMs would continuously monitor the presence of beacons in its proximity and a successful transaction would occur whenever the LAM captured a beacon broadcasted by the smartphone, which would act as the vehicle locator, eliminating the need for establishing a BT connection within limited space and time. To avoid requiring users to manually activate the App at the beginning of their journey, a specialized LAM was positioned prior to the MLFF location emitting periodical Beacon messages. This would wake up the user's phone before reaching the toll and start emitting the beacons to be detected back by the LAM, subsequently communicating it to the backend system. However, privacy limitations imposed by Apple smartphones restricted the transmission of BT beacons when awakened by an iBeacon. To address this challenge, A-to-Be deployed multiple LAMs within the toll zone, allowing the App to receive beacons from different sources and producing an estimation of the vehicle location by averaging these signals with weighted filters. Due to limited success, in 2022 A-to-Be set to explore cost-effective firmware modifications to the LAMs to periodically emit beacons and place them on opposite roadsides in combination with directional antennas. This configuration could

allow unambiguous lane detection by analyzing the unique radiation patterns of signal sampling over time (tracking the vehicle movement on the road). In 2023 this methodology was expanded by periodically spacing modified LAMs at a road gantry. This lane detection mechanism is being tested in road trials to assess its effectiveness and limitations. Integration with tolling backend systems and frontend portals is underway and demo pilots with Portuguese and U.S. clients are currently under consideration.

2.2 V2X Tolling

V2X communications have been developed with a focus on road safety. Many other information services and advanced use cases can also benefit from the connectivity capabilities of vehicles, roadside infrastructure, and other road users, namely V2X tolling and other charging procedures. V2X Tolling has many advantages. Figure 2 summarizes the most immediate ones. Additionally, it may also provide secure proof of vehicle characteristics for classification and streamline onboarding, such as enabling the activation of a rental vehicle through a personal tolling account.

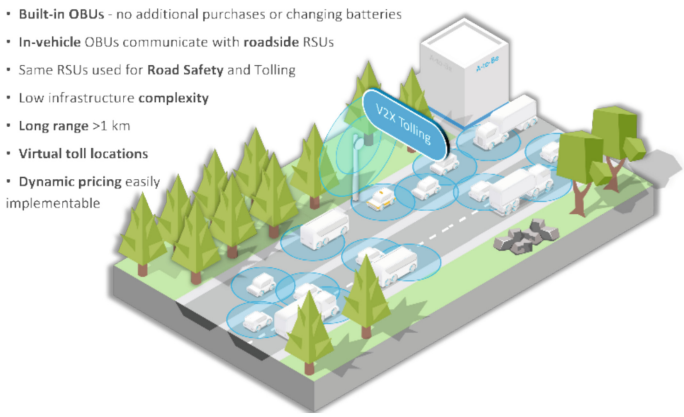


Fig. 2. V2X Tolling Roadside.

While Mobile Tolling is appearing worldwide with some production apps available, V2X Tolling is still at an earlier stage with limited prototypes and trials. In Europe, known efforts have been undertaken by the French SANEF road operator and published as an ETSI Technical Report [6]. In the US, SAE proposed a standard systematizing V2X Tolling and other V2X charging applications [5]. The ongoing standardizations are key factors, ensuring native interoperability, one of the bottlenecks of the previous AET methods.

In 2021, A-to-Be started implementing two V2X Tolling prototypes, one closer to the architecture of [5], and the other closer to [6]. In the latter, denominated TLS-V2XT, customized V2X facilities-level tolling messages (Tolling Payment Messages - TPM) were defined, to execute the tolling transactions and run these on top of a Transport Layer Security (TLS) channel over ITS-G5 V2X communications. TPM uses Service Announcement Essential Messages (SAEM) for roadside units (RSUs) to announce the

tolling service and provide the necessary information for in-vehicle OBUs to establish the TLS channels with the RSUs (this way providing authentication and encryption capabilities). A second, simpler approach, denominated GN-V2XT, also resorting to SAEM and taking advantage of the fact that ITS-G5 already has a powerful encryption feature inside GeoNetworking (GN) was implemented. In this prototype, TPM messages were sent directly over Basic Transfer Protocol (BTP) and GN, but using GN native encryption and signing features, and implementing a retransmission mechanism for messages that get no reply. In this approach, the security options (ECDSA for authentication and ECIES for encryption) followed [5]. Both V2X Tolling prototypes were integrated into A-to-Be′s Mobile Tolling backend, showcasing the suitability of V2X Tolling across DSRC (WAVE and ITS-G5) and revealing viability over Cellular V2X.

3 Conclusions

The tolling landscape is evolving, driven by the need for downsizing its material and equipment footprint and accelerated by advancements in Road User Charging technologies, particularly Mobile Tolling and V2X Tolling. Tolling dematerialization entails a simplification of tolling processes, enhancing convenience for road users, streamlining infrastructure management, and offering several direct benefits such as cost reduction and simplified maintenance. Mobile Tolling and V2X Tolling solutions enable a range of advanced, sustainable, secure, and safety-enhancing features. Notably, these solutions eliminate the need for road users to halt or decelerate at toll points, eschew manual payment transactions, eliminate the purchase and upkeep of OBUs, while providing additional functionalities such as real-time safety, services notifications and, most importantly, enabling new, necessary, use cases that are not supported by existing technology.

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Simulating the Effects of Connected and Automated Vehicles on Traffic Management

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Abstract. Automation in road traffic is reshaping our future lives, and mobility. Autonomous cars require new approaches from a road operator in all activities, including traffic management. Next generation of traffic management should go hand in hand with the development of autonomous cars via open road tests. An ongoing Hungarian research project is focusing on realizing a transport ecosystem using state-of-the-art technology to develop a comprehensive solution to support autonomous vehicles in cooperation with the infrastructure. The solution builds up an external environment model in the cloud. The system will utilize all information from both vehicle and infrastructure side by fusing data from both sources together in a cloud based, real time digital twin. The scope of the project is to provide a platform for road infrastructure related cloud-based services for connected and automated vehicles. The new test environment is going to be a perfect location to simulate and evaluate the effects of Connected and Automated Vehicles (CAV) on traffic management.

Keywords: Digital infrastructure · Digital twin · Vehicle-to-everything (V2X) · cloud control · Autonomous vehicle testing · traffic management

1 Introduction

1.1 CAV Testing

Connected and highly automated vehicles will be real game changers, but we still have to wait for their mass production. After various stages of testing in the loop, and the controlled proving ground, test vehicles have to pass in a limited public road environment, too (See Fig. 1) [1]. In order to facilitate this process, many countries have opened all or part of their public road network for autonomous vehicle testing. In addition to this some countries have implemented Co-operative Intelligent Transport Systems (C-ITS) and services for testing V2X communication [2], and several smart highway developments are in operation, too, but there are only a few sites, where roadside equipment and features were designed to support automotive testing on public road sections.

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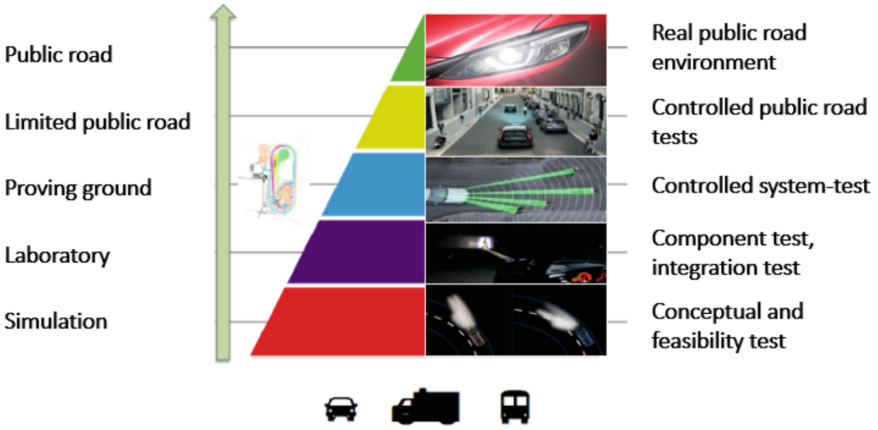


Fig. 1. Levels of vehicle testing [3].

A recent literature review has studied three interesting and unique test ecosystem with different scopes and concepts [4]. This non-exhaustive survey presents two small-scale test sites in Europe, already operational since 2017, and a recent large-scale project in China (PRC). Aside from the differences we can observe some common features among these locations (See Table 1).

Table 1. Table captions should be placed above the tables.

FEATURES OF SELECTED CAV TEST FACILITIES			
	Providentia++ (Germany)	Aurora (Finland/Norway)	Vehicle-road-cloud (PRC)
Sensor infrastructure	+	+	+
HD map	+	+	+
Digital twin	+		+
Data fusion	+	+	+
Open test ecosystem	+	+	
Cloud control			+

The most significant difference between these setups is that traffic management is not a key issue at the European sites. In contrast other companies in the field of vehicle automation, the Chinese Mogo AI is not focusing solely on vehicles, but also to create an integrated platform including infrastructure sensors, and the central traffic management. Besides the country's first large scale autonomous driving trial in the city of Hengyang (Hunan) cited in the study, based on its industry-leading platform Mogo has launched a vehicle-road-cloud integration project in Tongzhou (Beijing), and an intelligent tourism project in Dali (Yunnan) [5].

1.2 Future of Traffic Management

The purpose of traffic management is to improve infrastructure performance, road safety, and to reduce adverse environmental impacts. Traffic management solutions are evolving together with technology and communication constantly opening up new possibilities, like the vehicle-to-everything communication that has recently come into focus. Lately the main concept for vehicle guidance is based on the vehicle's perception system extended by the infrastructure's and other vehicle's sensor information. Cooperative perception service based on the V2X communication channel enables creating a more detailed, comprehensive picture of the surrounding space, even from the blind spots that are not visible for sensors of the ego vehicle. It seems that there is a huge potential in building up a central cloud system to create the digital representation of the real world, all static objects, and moving entities (vehicles, people) in a real time digital twin. Based on these digital twins the next generation of central traffic management might even take over the control of a vehicle.

2 Planned Open Road Test Environment

2.1 Central System Project

Central system was one of the Austro-Hungarian R&D and innovation initiatives in the field of connected and automated driving launched in 2019. The initial phase concentrated on the specifications of a central cloud architecture, and a unique measurement campaign was carried out on a highway section nearby the town of Csorna, too. The measures were taken on a real road section with the exclusion of normal traffic. Participating test vehicles were using Real-Time Kinematic (RTK) correction service to enhance accuracy, and keeping the measurement error below 5 cm. The data collection frequency was 100 Hz to provide accurate trajectories, even at higher speed levels. Recorded GPS data contained time, position, heading and quality information. For the latter the standard deviation and the number of available satellites were given, too. Prior to the campaign, an Ultra High Definition (UHD) map was created for the whole road segment [6, 7].

The ongoing follow up phase of the central system project is focusing on the implementation of the ecosystem elaborated in the initial phase, including state-of-the-art infrastructure sensors, and the central cloud architecture. The platform provided for testing cloud-based services for connected and automated vehicles runs in a Kafka based cluster, and supports leading industrial standards (e.g. Sensoris, ASAM OSI), and a few standardized interfaces based on gPRC and Kafka protocol. The selected test section for the demonstration is one of the main urban-interurban interfaces of Budapest, with complex traffic situations (merging sections, on-ramps/off-ramps) and traffic volumes over 120.000 veh/day Annual Average Daily Traffic, on 4–5 lanes per each direction [8].

2.2 Data Collection

The Central system solution uses an external cloud based global environment model supporting individual vehicles with a comprehensive representation of the surrounding

space. The system collects all available data from both vehicle and infrastructure sensors and fuse them in a real time digital twin [9]. The cloud-based map contains the following features:

- Static map (3D representation, vectorized data, material properties)
- Semi static and semi dynamic content (like weather or lighting conditions, road conditions...)
- Full dynamic data (vehicles, pedestrians, and all relevant dynamic information)

The sensor installations are ongoing, the first setups are planned to be operational in Q1 2024 along. Sensors will be mounted on gantries along this section the common section of M1-M7 highways near to Budapest (Hungary). The mounting position and angle were defined by using Dspace ASM simulation software (Fig. 2). Sensor sets to be deployed at the 5 gantries along the 1.2 km-long section consist of:

– 2 Short range LiDARs (one per direction)
– 2 Long range LiDARs (one per direction)
– 2 Thermal cameras (one per direction)
– 2 Wide-angle (~60°) cameras (one per direction)
– 2 Narrow-angle (~30°) cameras (one per direction)
– 1 Fish-eye camera
– 2 Radar sensors (one per direction).

The largest gap between planned "sensor islands" is 510 m, the shortest distance is only 110 m.

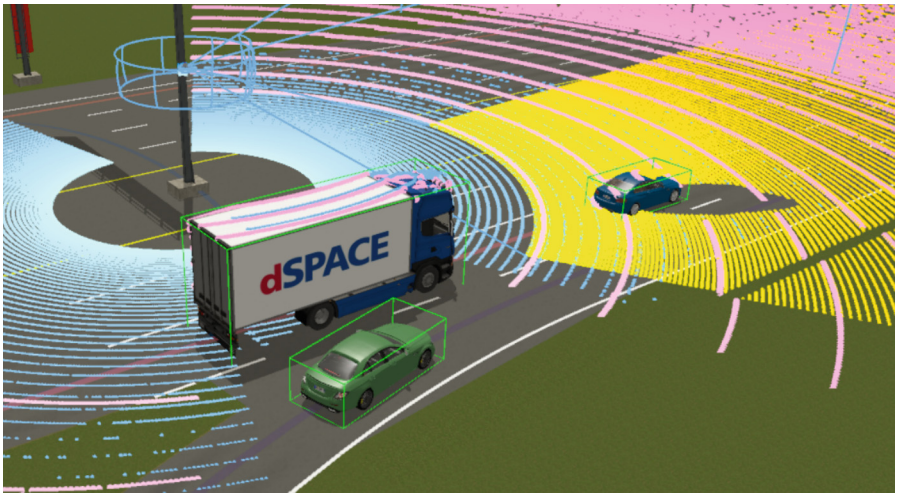


Fig. 2. Optimization of sensor mounting position by simulation [8].

3 Central Cloud Architecture

3.1 Link to Traditional Traffic Management

Traditional traffic management basically sets rules for human drivers using a number of unified signs. There are some significant differences between humans and machines that requires a different approach in the future, e.g., humans can easier cope with incomplete information or unexpected situations. Machines still require quality-controlled information for the proper operation [10]. Besides the traffic rules, and traffic information it is necessary to define the actions to be taken, too. Though traditional traffic management often gives an advice linked to the actual traffic information/regulation e.g., *reduce speed, or drive carefully* this is only a general recommendation and the driver is responsible for adapting to the circumstances. The information need of a highly automated vehicle is far more sophisticated. We need an accurate, high resolution digital representation of the real world, a real time digital twin containing all static, and dynamic elements.

3.2 Digital Twin

The generated digital twin model based on data provided by sensors deployed in the infrastructure might be utilized to enhance the traffic safety as well as to optimize the traffic flow through a given road section (covered by various types of infrastructure sensors such as cameras, lidars, radars). By using various fusion methods operating on the data of such type of sensors a digital twin model - accurate enough to fulfill the requirements posed by services implementing the above-mentioned traffic safety and traffic flow enhancing capabilities - can be generated. Based on the digital twin model the traffic participants might be informed in advance in case of potential hazardous situations and might be provided with vehicle specific instructions to minimize the possibility of their occurrence. In the framework of the ongoing Hungarian research project which is focusing on realizing a transport ecosystem using state-of-the-art technology to develop a comprehensive solution to support autonomous vehicles in cooperation with the infrastructure one of the goals is to test the applicability of digital twin model to support traffic safety increasing solutions and traffic flow optimalization.

4 Conclusion

Progress and change in traffic management should accompany the development of Connected and Automated Vehicles right from the early (open road) testing stage, and there is a need for the contribution of road operators to ‘pave the way’ for Autonomous Vehicles. Even before CAVs will appear in large numbers, it is worth investing in the implementation of smart roads, i.e., digital infrastructure, as the increasing amount and detail of information available from various sources and the huge amount of raw and processed data from modern sensors can provide a much more detailed picture of the current traffic situation. This also means that much better models can be built that are more accurate, and on this basis better forecasts can be done. In addition, digital infrastructure and V2X communications enable the implementation of a range of C-ITS services that can significantly improve safety and efficiency and can contribute to the testing and development of new or upgraded automated driving functions.

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Enhancing Public Transportation Operations Through Service Reinforcement, Bunching Detection and Data-Driven Analysis

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Abstract. This paper introduces a system designed to assist a public transport operator, in identifying services requiring reinforcement, predicting or detecting service bunching, and refining schedules based on historical data analysis. In routes with low frequency, the system analyzes factors such as occupancy, punctuality, punctuality trend, and the percentage of completed routes to generate a prioritized list of services that could benefit from additional vehicles for reinforcement. For high-frequency routes, the system examines the distances between consecutive vehicles and their behavior to identify groups of services that may result in bunching scenarios. Furthermore, a regression study is conducted to uncover punctuality patterns that may necessitate a reevaluation of official schedules.

Keywords: computational geometry · graph theory · Hamilton cycles

1 Introduction

Public transportation is crucial for modern society due to its efficiency, democracy, and sustainability in reducing congestion and improving air quality. It plays a pivotal role in making cities more livable and eco-friendly. However, reliability is a critical concern for public transportation, especially in high-frequency services. For that, fleet supervisors must manage the allocation of backup resources to ensure adherence to schedules and reduce service bunching, making their decision-making process complex.

Like in other works [1], in this study, we demonstrate how our system assists fleet supervisors in identifying services requiring reinforcement in advance, predicting or detecting service bunching, and refining official schedules based on

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historical data analysis. The system primarily processes messages (stop passes and GPS position mainly) from the public transportation fleet. Additionally, it incorporates the daily schedule, which outlines the expected times for each service to pass through each stop.

Upon receiving these messages, the system updates its status, enabling the supervisor to monitor real-time information. This includes a list of services that may require reinforcement and situations where the predicted time difference between two or more services is diminishing. Moreover, the system enables analysis beyond real-time monitoring and offers a thorough evaluation of the services' performance. This includes comparing them to historical data from previous days and extracting further valuable insights.

2 Related Work

Extensive research in the field of operations research and transportation science has made noteworthy progress in tackling the issue of bus service reliability. An effective strategy involves implementing headway-based control, a methodology centered around regulating the time intervals between buses to achieve a consistent and balanced service frequency [2]. In the context of bus bunching, the utilization of headway-based solutions enables a precise evaluation of traffic conditions, road congestion, and various factors that have a substantial influence on bus operations and contribute to the phenomenon of bunching [3]. For low-frequency transportation lines where the next service is too distant to resolve the problem, specific reinforcements address punctuality or occupancy issues that arise in particular services [4].

Numerous studies have underscored the significance of timetabling and vehicle scheduling. Gkiotsalitis et al. [5] present an alternative approach that integrates rescheduling and bus holding strategies to improve passenger waiting experience, specifically addressing excessive waiting times (EWT) at bus stops. Wagale et al. [6] employ an optimization approach that incorporates real-time data event parameters, such as bus stop departures, arrivals, and bus traffic costs, to enhance the bus scheduling process.

3 Service Reinforcement

Our system provides the supervisor with a roster of services that necessitate reinforcement. To do this, the system creates a ranking of services to be reinforced ordered by a parameter (called susceptibility to reinforcement) that considers several factors extracted from the data received from each service.

This is the defined formula for susceptibility to reinforcement parameter:

$$S = R(\alpha O + \beta P + \gamma T)$$

where S is the susceptibility to reinforcement, R is the percentage of the route remaining, O is the vehicle occupancy parameter, P is the punctuality of the

service, T is the trend of the service in punctuality and α,β,γ are weights of the linear formula. All described parameters go from 0 to 1.

Note that the percentage of the path remaining, R, appears by multiplying the linear combination comprising all the other parameters. If this value is close to 0 (the service is close to ending), it does not make sense for this service to be reinforced, and therefore this value of R must cancel the entire formula, no matter how high the other parameters are.

3.1 Percentage of Route Remaining

Depending on the type of communication received from the vehicle, the percentage of the remaining route is calculated in two different ways. If the data received is from one stop to the next, the percentage between the distance traveled to that stop, and the total distance is calculated. On the other hand, if the data is a GPS position, the distance between the previous stop and the point received is calculated. Thus, this distance is added to the total distance to the last stop and then divided by the entire service length.

However, it is different to reinforce a service close to garages (where the reinforcement vehicles rest) or one that will need a long time to be reinforced. If the route is very far, the service may have ended when the reinforcement arrives.

So, in the calculation of R, the percentage of the remaining route, if a service needs reinforcement at some point on the route, we will have to consider that the reinforcement will take time to reach the next stop, and it will have to be done before the service arrives (in theory). Therefore, using the estimated times from depots to each stop, we will take the first stop where the reinforcement comes before the service. Thus, in the general formula, instead of multiplying the percentage of the missed route, we will multiply the percentage of the missed route from the stop where the reinforcement would start. If a reinforcement cannot arrive on time for any stop of the route, it would take 0 value.

3.2 Vehicle Occupancy

People getting on and off the vehicle are known at each stop. With these data, the system updates the number of passengers traveling in each vehicle. To convert this number into the parameter O, which goes from 0 to 1, a threshold is defined (different for each type of vehicle), and penalization begins once that value is exceeded. Therefore, the parameter is 0 below the threshold and at the threshold itself and increases proportionally to 1 (maximum capacity of the vehicle).

3.3 Service Punctuality

Of the four parameters in the formula, two are related to the punctuality of the vehicle: P and T. This punctuality is calculated simply when the message is a stop pass since we also have the theoretical stop pass. However, when the message received is a GPS position, this information must be converted to a punctuality

value. The GPS point is placed in a segment of the shape corresponding to the route that the vehicle is carrying out. Then, the distance between the previous stop and the point and between the point and the next stop are calculated. In this way, we can obtain the percentage made between the stops, and knowing the theoretical time between these two stops, the time remaining for the vehicle to reach the next stop is proportionally calculated.

Then, the deviation of the route from the theoretical route, p, is first calculated. Then, to have the final parameter P inside the interval $[0, 1]$, we compute $P = 1 - e^{-ap}$ where a is a parameter to modulate the penalization due to the lack of punctuality.

With this formula, we get that when punctuality is good, the difference between the expected time and the real-time is 0, and the value of the parameter P is 0. The value increases with the minutes lost until it approaches 1.

3.4 Service Punctuality Trend

When it comes to the punctuality of the service, we must consider if the service is getting more and more delayed, it is stuck in a constant delay, or it is recovering part of its delay. Those that are doing worse will be more likely to be reinforced.

Therefore, the moving average of punctuality is calculated with a window of length k. The difference between the last moving averages is the one marked by the T parameter. If this difference exceeds a given threshold, it will begin to penalize, and below it will be 0.

4 Bunching Detection

As previously mentioned, on high-frequency routes, the spacing between services takes precedence over punctuality. The EWT serves as an indicator to comprehend the status of a particular route or the entire fleet concerning this aspect. However, the objective of our system is to pinpoint the specific services that require corrective action with greater precision.

Therefore, we define a parameter PB (predisposition to bunching) that will serve to order services regarding their need for corrective actions:

$$PB = \mu CD + \nu BT$$

where μ and ν are scalar parameters that can be defined by the public transportation operator based on their experience and their needs. CD is the current inter-service distance and BT is the bunching trend.

4.1 Current Inter-service Distance

When identifying a vehicle v_n that has to modify its service, we consider the distance from the previous vehicle, v_{n-1}, and the distance to the subsequent vehicle, v_{n+1}. The objective of the operator is to maintain both distances aligned with the theoretical distance t.

In Fig. 1 three different bunching situations are shown. The first one is the ideal one (both distances equal to t). In the second one, even though v_n is too close to the previous services, it seems that it is v_{n-1} the service that has to be modified because the second distance is correct. In this case, the system will detect the problem when computing PB for v_{n-1}. In the third situation, v_n is the vehicle that is causing the bunching and the one that should be corrected.

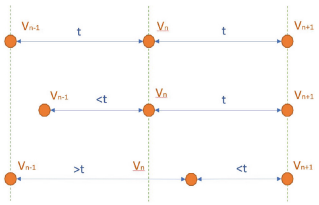


Fig. 1. i) no bunching, ii) bunching due to v_{n-1}'s delay, iii) bunching due to v_n's delay.

Following these principles, we define $CD = |dist(v_{n-1}, v_n) - t| + |dist(v_n, v_{n+1}) - t|$. This way, CD will be 0 in ideal situations and any deviations from neighboring services will increase its value. Additionally, this prioritizes situations such as the third one depicted in Fig. 1 over the second one.

4.2 Bunching Trend

Currently, corrective actions for addressing bunching are initiated upon a driver reporting an issue via radio, such as expressing lateness or visually observing the preceding service. The objective of this bunching detection is to proactively anticipate the problem by considering the trend of bunching.

Thus, a moving average of the inter-service distance is employed to penalize services that progressively deviate from the expected distance they should maintain. This is crucial since a small deviation typically deteriorates rapidly.

5 Historical Data Analysis

The points pictured in Fig. 2 show the historical behavior of the services on a route. We analyze how the punctuality of the service varies concerning the percentage of the route completed, that is, how punctuality varies in the different areas of the route.

As can be seen, the punctuality of the service is not independent of the percentage of the route. The punctuality of the different services follows a general pattern that can be used to model each route. Thus, a polynomial regression model can give us good results. However, we have to evaluate the goodness-of-fit, since not all the routes have such clear behaviors.

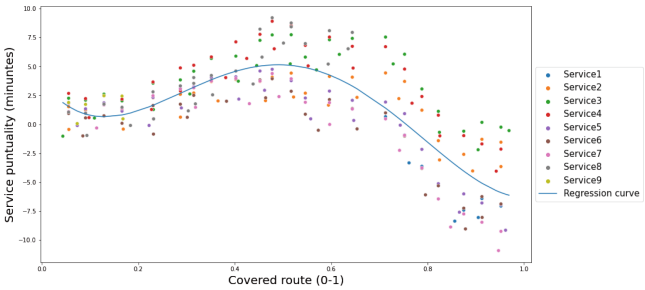


Fig. 2. Regression curve for the analysed route.

In the Figure, we show the polynomial regression carried out. Once the regression was done, the obtained polynomial was tested with new data (for the same route) and we checked that the behavior extracted from previous data was valid.

Historical data can help to improve the theoretical value of stop passes since it can detect permanent punctuality patterns. We compare in Fig. 3 the theoretical value, the corrected theoretical value, and the real value of the steps made by the services of a given route.

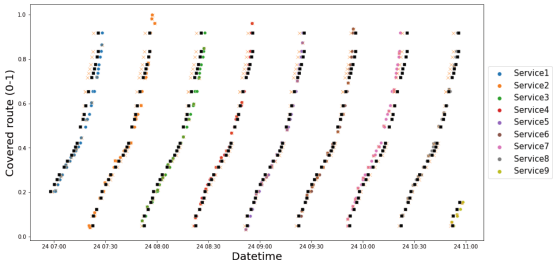


Fig. 3. Theoretical steps (crosses), corrected theoretical steps (squares), and real steps of the services of a route.

In this case, in most of the routes, the corrected step is closer to reality than the theoretical one.

6 Conclusions

Within this paper, we have unveiled a support system for fleet supervisors overseeing public transportation operations. The system works as a guide to supervisors concerning low-frequency routes, suggesting potential reinforcement with additional vehicles, as well as high-frequency routes, signaling the need for corrective actions performed by the vehicles themselves. In addition to providing

real-time assistance, the system also enables the analysis of historical data to uncover punctuality patterns that could warrant schedule adjustments.

Contrary to expectations, it remains compulsory that the supervisor is responsible for making decisions and communicating corrective actions via radio. Furthermore, certain corrective actions, including determining the number of stops to skip in order to regulate service distance, are performed by drivers independently, without any supervision.

Therefore, the forthcoming stages in advancing our system will not be related to automating decision-making. We will focus on enhancing the support provided by the system to the supervisor. Regarding the detection of bunching, we believe that occupancy plays a significant role in the gradual delay of a service and the advancement of the subsequent service. Thus, we intend to incorporate occupancy as one of the influencing factors in measuring the predisposition to bunching.

On the other hand, when it comes to historical data analysis, we plan to conduct a more detailed study to identify patterns of punctuality during peak and off-peak hours.

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Service Orchestration and Network Function Virtualization for Information Systems Maintenance Service in Railway Systems

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Abstract. Information and Communication Technologies can support the progressive digitalization of the railways sector improving its efficiency and sustainability. In particular, Service Orchestration and Network Function Virtualization can push forward a paramount evolution of railways Traffic Management Systems (TMS) allowing remote operations of their different components, reducing their complexity and improving their effectiveness and scalability.

In this paper the architecture of a new generation TMS based on micro-services supported by Service Orchestration and Network Function Virtualization is presented. It allows highly flexible and re-configurable networks and services, through the implementation of a service as a general replicable function available in a Virtual Machine or a container within a remote data center or a local general purpose fog node, improving the efficiency of railways control and management systems.

Keywords: Railways systems · Maintenance · Network Function Virtualization · Traffic Management Systems · ERTMS · Service Orchestration

1 Introduction

The progressive digitalization of the railway sector is part of a great transformation driven by the application of Information and Communication Technologies (ICT) capable of providing advanced and innovative tools to improve the efficiency and the effectiveness of the railway systems. The advent of Service Orchestration and Network Function Virtualization (NFV) can sustain and push forward the evolution from a strictly "in presence" to remote operations of different components of railways Traffic Management Systems (TMS), such as the Information Systems Maintenance Service (ISMS), with the aim to reduce their complexity, improve their effectiveness and scalability [4,5].

The TMSs, whose reference in Europe is the European Rail Traffic Management System (ERTMS), deal with the management of the complex railways

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systems composed both by the railways infrastructure and the convoys, supervising the state of the railways network and the circulation of the trains respecting strict requirements about the safety of passengers and convoys and the efficiency of the service. To do that TMS are based on a hierarchical distribution of the intelligence in different layers, where at the top the Control Rooms manage the overall systems using the information about trains and infrastructure collected and partially elaborated by the components of the lower layers: track-side and on-board equipment that collect the information about trains and infrastructure and exchange such information with the intermediate level components, the Intermediate Points. From its side, ISMS is a key service of TMS, directly impacting on their safety and efficiency, supervising the functioning of the equipment that regulate the railways occupation (level crossing and switches) and the strictly related maintenance activities. Its efficiency is based on an easy access to the data and on the rapid deployment of preventive and proactive actions suitable to prevent failures and guarantee a reliable recovery of the system under fault. Such distribution of functions and components lends itself well to being rethought and enriched through the introduction of resource virtualization.

In this paper the architecture and the design of a modern TMS based on micro-services along with a possible use case will be presented, with a particular focus on the maintenance service/ISMS.

Dealing with the paradigm of Network Function Virtualization, the proposed architecture aims to distribute the services provided by the core of the TMS and whose related to the different Rail Business Services (RBS), into physical and virtualized resources. The NFV paradigm allows highly flexible and re-configurable networks and services, providing a service as a general replicable function available in a Virtual Machine (VM) or a container within a remote data center or a local general purpose fog node. This allows the application of programmable service-chained functions to specific traffic flows, improving the efficiency of railways control and management systems.

2 Architecture

Railways TMS are based on a complex systems of components whose interaction allows the management of railways convoys and infrastructure. This is possible through the intense exchange of information about convoys and infrastructure provided by track-side and on-board equipment from one side and the central management unit (the Control Rooms) from the other side. The different TMS applications relies on Railways Business Services such as Interlocking (IXL) that is based on the signalling equipment to prevent trains movement conflicts, Radio Block Center (RBC), which supervises the distancing of the trains, Maintenance Management, Energy Management, but also on external services such as Passenger Information Systems (PIS) and Weather Forecast that use this information to deliver their services. The applications of new generation TMS, whose general architecture is illustrated in Fig. 1, communicate seamlessly with these services with a communication layer which uses standardised data structures, and the services are connected to peripheral field entities like switches,

traffic lights, encoder, energy substations, etc., through dedicated and secured links, which use specific communication protocols with high safety standards (e.g. SIL4). The communication layer ensures interoperability to support the interaction with different TMS. An example of such architecture was designed and implemented in the context of the H2020 Shift2Rail OPTIMA project [1,3], that introduced an Integration Layer suitable to work as a middleware allowing seamless communications. The demonstrator for new generation TMS developed during this project was based on standard interfaces and on a Common Data Model to support the exchange of information from different sources and to ease scalability and future evolution [2]. This general architecture can be further advanced treasuring the paradigm of Network Function Virtualization, as shown in Fig. 2: the proposed architecture aims to distribute the services provided by the core of the TMS and whose related to the different RBS into physical and virtualized resources. Going into details of this advanced architecture, TMS and Traffic Control (TC) applications as well as Maintenance applications are hosted in Virtual Machines or containers that can run in a dedicated data center. The same approach is adopted for the different services (RBS and external) allowing a complete virtualization of the service applications. These two sets of applications and services interact by means of an interoperable communication network.

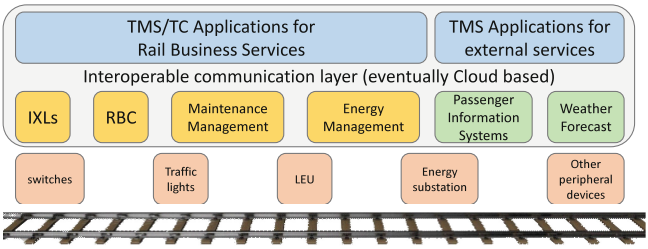


Fig. 1. Building blocks of a general architecture for modern TMS services.

This approach paves the way to the introduction of micro-services, based on the isolation of single applications that are hosted in VMs or containers. The objectives of a TMS based on orchestration of micro-services are:

- providing resource management to ensure high availability issue;
- providing central monitoring and configuration to allow an overall vision of the deployed components;
- allowing separation of big monolithic applications into many fine grained micro-services taking over the responsibility for fail-over, controlling, and monitoring of them.

This improves the efficiency, reliability and availability of the system. These functionalities can be covered by different existing software solutions on the market, but none of them provides a standardized Application Program Interface (API) or an agreed set of data structures for TMS applications. Therefore,

a software wrapper layer around Commercial off-the-shelf (COTS) software is needed to provide specific functionalities and standardized data structures to this TMS. The implementation of the new TMS paradigm requires that each service or micro-service shall have its own run-time environment. This is possible by using COTS software that provides hypervisors to run isolated VM and software containers, a software manager to manage the instances of the services, and a virtual network stack to connect them. A proper virtualization management environment lets to hide the complexity of managing the virtualized TMS applications and RBS services and can provide standardized run-time environments and an easy to use interface for the Infrastructure Manager. Moreover, it lets to control the main life cycle functions such as deployment, start/stop instances, monitoring, and removal.

In particular, the NFV paradigm allows highly flexible and re-configurable networks and services, providing a service as a general replicable function available in a Virtual Machine or a container within a remote data center or a local general purpose fog node. This allows the application of programmable service-chained functions to specific traffic flows, improving the efficiency of railways control and management systems. The service instantiation is managed by means of a Network Function Virtualization Orchestrator (NFVO) considering the underlying network, infrastructure physical and software resources. The Wireless Infrastructure Manager (WIM) of the NFVO allocates the required network resources (slices), whereas the Virtual Infrastructure Manager (VIM) deals with the involved fog nodes and Virtual Machines. This method also allows to manage the access restrictions related to the devices accessible by the technician, whereas a VM or a container installed by the VIM in the technician board provides a dedicated desktop with all the settings that he is authorized to perform. With this application it is possible to deploy configuration software without pre-installing it. Furthermore, also the peripheral devices can be implemented as virtual and physical devices, as depicted in Fig. 2, distributing their functionalities into on-site physical equipment and remote virtual resources. Such devices, in general, are proprietary devices provided by a restricted number of companies and are designed as customized equipment for the railways field. The integration of resource virtualization can allow the use of more “dump” physical devices, demanding some of the services delivery to VM or containers.

3 Results and Discussion

The illustrated architecture can be applied to the maintenance of the track-side railways components (such as Balises, Encoder, Line-side Electronic Unit - LEU, track circuits, ect.) that are used to monitor state and position of trains and condition of the railways infrastructure. Currently their maintenance is based on the physical on-site intervention of a technician that accesses the device and does the necessary controls and configuration. This approach requires an accurate planning of the intervention to preserve the railways capacity, limiting the impact on the availability of the railways lines and, consequently, on the trains scheduling,

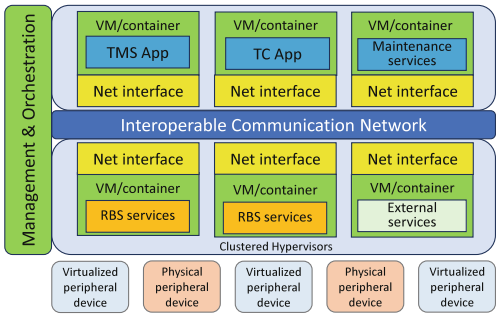


Fig. 2. Architecture of TMS based on clustered hypervisors and connected to Virtualized and Physical peripheral devices.

without jeopardizing the safety of technicians at work. Through the introduction of the proposed architecture the technicians can do these operations remotely from the maintenance office without requiring to physically reach the device to control or configure. Furthermore, in the case of device failure, the technician can immediately do a preliminary remote check of the device and, when possible, also opportunely reconfigure it, for example recovering the fault activating standby devices already present on premises. This centralization and remote control of the maintenance operations can positively impact on the time required for the maintenance activities reducing the disruption time and the recovery time of the service, saving the operational costs.

An use cases for testing this new architecture paradigm is related to the continuous updating of the train status information and the information related to the track/platform occupation. In an operational rail network there may be multiple sources for data relating to train status and position, and track/platform occupancy, depending on the type of signaling system, train control and any additional systems. This information is available in the OPTIMA project demonstrator, derived for example from different network sources such as network topology, signals, switches and crossings, track circuits, routes and closures. This information is continuously published by several independent subsystems in the virtualized communication network, and can therefore be easily monitored. To validate the system thus designed, ad hoc software was developed to verify that the information received on the virtualized communication network is consistent and intact compared to what is transmitted by the peripheral entities. The testing method used consists in 1) feed the recorded train position data via the Rail Business Service into the communication layer, 2) read data published on the communication layer from dedicated applications running in the operator workstations connected to the communication layer 3) save a log file of what is received and verify the correctness of the data, then 4) calculate the proportion of correct data. Therefore, this test validates the delivery and correctness of the received information about the status of network elements (i.e. related to the train position) to a test application at the operator's workstation. The

results of these tests showed that the testing application is able to listen to the communication layer and retrieve all the data that has been published by the dedicated RBS. It has been verified that the recorded data is identical to that transmitted by the original sources, as shown in Fig. 3. Therefore, the analysis of the input and output data shows that this demonstrator is able to communicate information on the state of the network elements, and relating to the position of the trains, even in a virtualized environment.

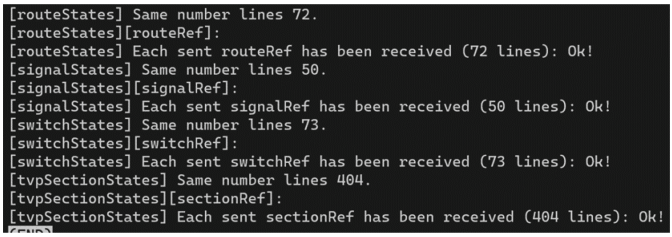


Fig. 3. Test results of the communications in virtualized environment.

4 Conclusions

The introduction of Service Orchestration and Network Function Virtualization can further evolve Traffic Management Systems (TMS) allowing remote operations of their different components, reducing their complexity and improving their effectiveness and scalability. In this paper the architecture of a new generation TMS based on micro-services supported by Service Orchestration and Network Function Virtualization is presented. It is based on the implementation of the different services, (TMS-TC applications from one side and Rail Business Services and external services from the other side), as a general replicable function available in a Virtual Machine or a container within a remote data center or a local general purpose fog node. This allows highly flexible and re-configurable networks and services, improving the efficiency of railways control and management systems. Finally, this architecture can be applied in the general field of Intelligent Transportation Systems, in the Advanced Traffic Management System not only in the railways domain but also to metro systems or road traffic management systems.

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Dynamic 2D Scene Analysis Inside Train Compartments Using Deep Learning Techniques

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Abstract. This paper presents a comprehensive study on scene analysis inside a train using computer vision and deep learning techniques. The primary objective is to develop a dynamic 2D representation of the perceived scene by continuously projecting passengers onto a 2D plan. The research contributions focus on detecting abnormal situations inside a train, such as passenger discomfort and forgotten luggage. To achieve optimal results, we rigorously tested cutting-edge deep learning techniques, including convolutional neural networks (CNN) for object detection and tracking. Through fine-tuning pretrained models on annotated datasets, our system achieves precise localization of individuals, enabling accurate estimation of their actions. Additionally, temporal analysis is used to moderate anomaly detection mechanisms for identifying situations requiring attention. The AI-based system has undergone rigorous real-time evaluation using RGB cameras installed in an actual train car. Through an onboard train sever, our system proactively identifies potential abnormal situations and sends alert to a supervision application. During testing sessions on the train, several scenarios involving unattended luggage and passenger discomfort were successfully identified in real-time, with high confidence rates.

Keywords: Scene analysis · dynamic 2D representation · abnormal situations · passenger discomfort · unattended luggage

1 Introduction

This work is part of a research project led by SNCF, in collaboration with multiple partners, with the objective of conducting tests on an autonomous passenger train. However, building such a powerful machine requires the integration of not only an automated driving system but also several other innovative components. Indeed, an autonomous train must rapidly understand the exterior environment as well as the interior of the compartments. This involves the integration of various sensors (e.g. camera, lidar) and the use of AI-based computer vision algorithms to extract meaningful insights from data captured by the sensors. In this context, extensive efforts are dedicated to monitor the external environment [1] with the aim to replicate the role of a human driver in detecting rails, pedestrians, obstacles, etc. Nevertheless, works aimed at assessing inside train

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perception are less common [2] and the limited existing studies only focus on passenger detection, tracking and counting [3]. These findings assert the pressing need for studies on scene analysis inside a train.

Automatic inside train or in-train perception consists of monitoring several events that may occur during a train travel. The research in [4] estimates passenger action using SVM classifier trained on HOG descriptors to predict three classes : sit, stand and in-between. However, to ensure the safety, it is necessary to anticipate atypical actions such as passenger falling. Moreover, prior work [5] has not considered in-train scene analysis, especially with the aim of projecting the observed scene onto a 2D plan. Such representation enables a clearer understanding of the events inside the train and provides optimal visualization without compromising people's right to privacy. Motivated by these considerations, we initiated this research with the goal of filling these gaps. The proposed approach aims to analyze visual content within the train, enabling real-time detection of critical scenarios through object detection and tracking techniques. Detected passengers are projected through a homographic transformation. In addition, the use of temporal analysis enables the prediction of actions, with a particular focus on falls, thereby allowing for the identification of passenger discomfort.

In the field of deep learning-based object detection, the most commonly used architectures [6] include R-CNN and YOLO. The R-CNN is initially known for its region-of-interest selection and CNN-based feature extraction. In contrast, YOLO follows a single-stage approach by dividing frames into cells and making prediction for each cell. Both architectures were enhanced, resulting in the development of efficient object detectors. The Faster R-CNN [7] and Yolov7 [8] are ones of those powerful models that significantly improved speed and accuracy. Tracking techniques are also considered in this work, particularly Sort and its variants Deep-Sort [9] and Bot-Sort [10]. In the field of computer vision applied to safety, significant approaches were proposed to address the public health issue of human fall detection. Among these, the research in [11] analyzed motion characteristics using 3D positions of human joints to the human torso motion model (HTMM). It detects falls by monitoring real-time changes in the torso angle and centroid height for each individual. Another work [12] presented the called normalized shape aspect ratio (NSAR) based on camera variability and motion speed. The approach can perform fall detection in multiple direction, which is efficient for both indoor and outdoor environments.

The rest of the paper is as follows: the next section details our approach including scene analysis and critical events detection. Afterwards, results and discussions are presented. Finally, we conclude with key findings and future research directions.

2 Proposed Approach for in-Train Monitoring

This research was designed to meet the project needs and the railway challenges. The proposed methodology for monitoring in-train perception and identifying atypical events is presented in Fig. 1.

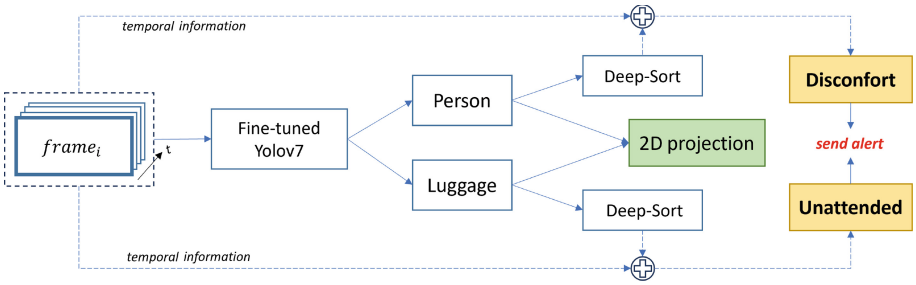


Fig. 1. Illustration of the proposed approach for in-train monitoring.

2.1 Passenger Detection and Tracking

Representing passengers on a plan requires a precise detection. In our approach, to select the appropriate model, we conducted extensive tests and comparisons, evaluating not only the detectors but also their combinations with trackers. The detectors considered are Faster R-CNN [7] and Yolov7 [8], while the trackers used are Deep-Sort [9] and Bot-Sort [10]. During the project, multiple videos were recorded, serving to generate various datasets. Based on a first set of 5.000 images from different cameras, the combination of Yolov7 with Deep-SorT proved to be the most suitable for our context. However, we found that actual pretrained models weakly detect desired objects and need to be fine-tuned depending on the context. Therefore, using a second collection of 15.000 images, the Yolov7 model is fine-tuned to detect two classes: person and luggage. The annotation step is performed using the pretrained model followed by a cleaning step, where wrong detections are removed. Accuracy on validation sample reached 98%, enabling precise and real-time detection, thus making temporal analysis meaningful for identifying critical events.

2.2 Compartment Analysis and 2D Representation

To enable in-train perception, multiple cameras were installed in a train car, including the lower and upper cabin. Unfortunately, as observed in Fig. 2, there is a blind spot in the middle, which excludes multi-camera processing. Therefore,

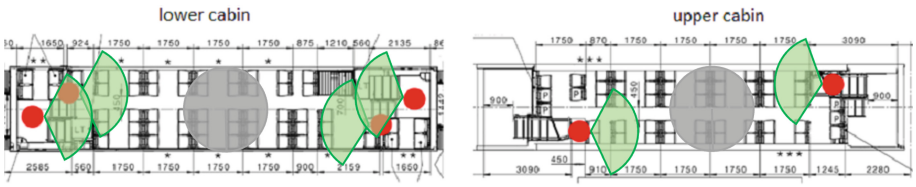


Fig. 2. Location of RGB cameras installed in a compartment of a French regional train (Regio2N). Field of view is depicted in green and blind spot in gray.

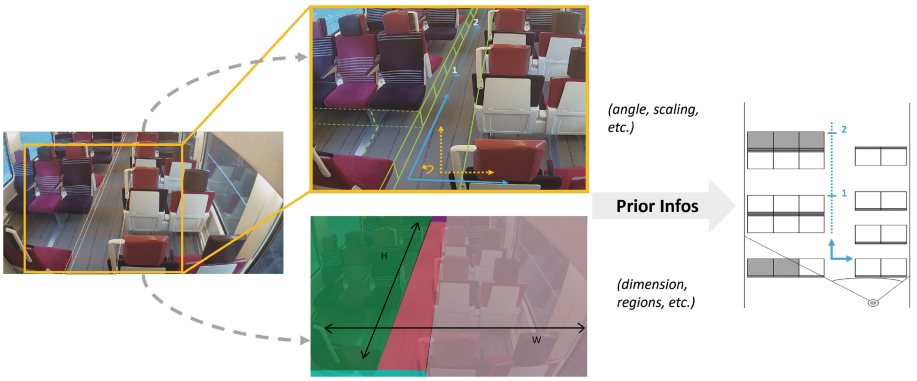


Fig. 3. Analysis of train compartment and camera field of view for 2D representation.

this research was carried out using a single camera and object detection to represent each passenger on a 2D plan. For this purpose, several information were calculated in advance. In the initial phase, compartment dimensions are used to generate a 2D plan which is truncated to fit the camera's field of view (CFV). The angle between the image axis and the ground axis is estimated and a unit is defined depending on the ground axis, as illustrated in Fig. 3. Moreover, the image is divided into regions, including hall, left and right seats, based on the defined unit, in order to adjust the perspective. For each region, a transformation matrix is calculated to project objects, depending on the location of the lower-center point of the bounding box. As a consequence, the density is calculated using the number of persons and the CFV area, where three classes are considered: low, medium, and high density.

2.3 Temporal Analysis for Critical Event Detection

Based on detection and tracking, several features can be inferred using temporal analysis such as the evolution of position and dimension. Therefore, using simple rules, basic actions can be estimated, particularly distinguishing between standing and sitting. The detection of fall events among passengers is achieved through the implementation of NSAR [12]. We assume that discomfort occurs when the passenger remains falling during a short time, defined as fall duration $d_f = \frac{n_f}{fps}$ (e.g. 3 s, 5 s). Then we calculate the fall detection ratio $r_{fd} = \frac{n_{ff}}{n_f}$ by dividing the number of frames where a fall is detected n_{ff} by the fall duration d_f in frames n_f. The closer this ratio is to 1, the higher the probability of discomfort occurring. The identification of unattended luggage is achieved by detecting isolated objects within train compartments, during a predefined time. By linking each luggage to an owner, unattended luggage counter c_{ul} starts when the owner leaves the CFV. Another use case can be the inconvenient luggage which is detected based on the predefined regions and luggage tracking.

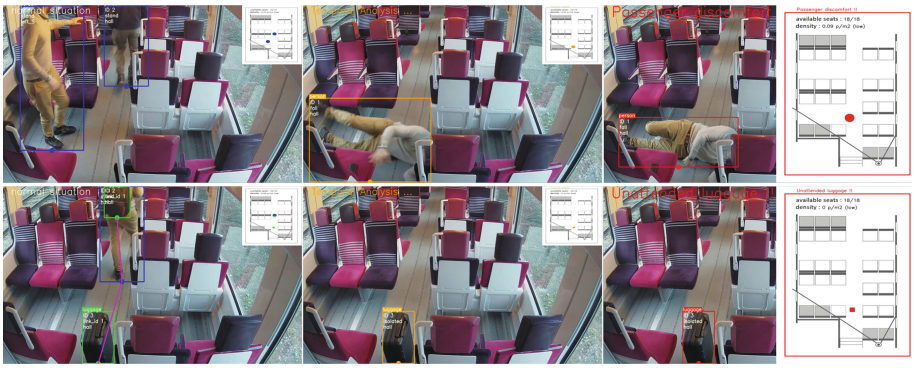


Fig. 4. Sample of results obtained for critical event detection. Row 1 shows passenger discomfort and Row 2 unattended luggage. Dynamic 2D mapping is also represented.

Table 1. Obtained results for critical event detection, during test sessions

Critical events	P	R	F1	FPS
Passenger discomfort	95	96	95	45
Unattended luggage	92	91	91	55

3 Results and Discussions

During test sessions, various scenarios of passenger discomfort and unattended luggage were played and detected in real-time. The AI-based program was continuously running in a server with GPU Quadro RTX 6000 24Go and Cuda 11.4. For performance evaluation, we used 3 h of videos, including 85% of normal situations and 15% of critical events. The overall average of precision (P), recall (R), F-score (F1) and time processing (FPS) are presented in Table 1. This demonstrates the efficiency of our approach in classifying temporal segments in real-time. Indeed, the results reported in Table 1 concern critical events during time, regardless to detection and tracking results.

Based on a predefined counter, temporal analysis turns out to be efficient for critical event detection, as illustrated in Fig. 4. However, this may lead to missed shots when the tracking is incorrect, which involves a restart of the counter. For passenger discomfort, the counter starts when a fall occurs, while for unattended luggage, the counter starts when the link between the luggage and its owner is lost, as seen in Fig. 4. In our experiments, we tested several values of parameters that impact the performance such as d_f, n_{ff}, r_{fd} and c_{ul}. For passenger discomfort, we observed that false detections tend to increase with a low value of n_{ff} while a high value may result in missed shots. For unattended luggage, in some cases, occlusions break the link between a luggage and its owner, which results either in a false detection or a missed shot.

4 Conclusion

The proposed approach is designed to meet the project needs and the railway challenges. In-train scene analysis using fine-tuned Yolov7 and DeepSort allows for a 2D representation and rapid identification of critical events. The test sessions served as a crucial validation step of our approach which showed high performance in real-time conditions. Further works will consider multiple camera processing and monitoring of real-world train travel. Furthermore, the identification of other critical events such as violence detection is under study.

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Traffic Regulations in the Digital Age

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Abstract. This paper describes our insights from a collaboration project on digital and machine-readable traffic rules – what it is, why it matters and how we get there. Traffic rules are typically written in text intended for humans. We argue that traffic rules, in the future, must be understood by machines as well. In a digital world we need data on traffic rules. Road users, citizens, companies, and other actors in our society would benefit from such data. Innovative forms of transportation, not least automated vehicles, depend on such data. Relying on e.g. road signs is not sufficient for automated vehicles in order to follow all traffic rules. In the project, we investigated what is needed to reach machine-readable traffic rules in Sweden. The work was conducted as a policy lab. We found that the way forward is an amendment to the legislation that requires decision-making authorities to digitalize their traffic regulations.

Keywords: digitalization · traffic rules · policy lab · regulation · autonomous vehicles · connected and automated vehicles

1 Introduction

The transport sector is becoming increasingly connected, digitalized, and automated, which has great potential to improve the transport system in several areas (safety, efficiency, environmental impact, and accessibility). But to meet this development, we need a detailed digital representation of the road network, including digital and machine-readable traffic rules. Traffic regulations are traditionally analogue and paper-oriented (although published online in pdf format). They are written in text intended for humans. In the future, traffic rules must be understood by machines as well. 'Traffic rule' refers to a legal rule that determines the behavior of road users in traffic. A traffic rule originates from a traffic regulation or other legislation.

In our research, we have explored how to reach a future system with machine-readable traffic rules in Sweden [1]. We need to accelerate the digitalization in this area, since many actors in the society need this data. Significant work has already been done to digitalize a large proportion of traffic regulations in Sweden. Even though we have come far, compared to most countries, we still have work left to do.

Internationally, there are several ongoing initiatives to address machine-readable traffic rules, but these do not focus enough on capturing data close to its source, which is key to ensuring reliable data on traffic rules.

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2 Related Works

Our work partly builds on results from previous research, government investigations and other initiatives.

In Sweden, digital infrastructure is a central part of the national digital policy, which aims to promote the opportunities that digitalization brings for society: for individuals, businesses, civil society, and public administration.

The Swedish government has tasked the Agency for Digital Government (DIGG) to establish, together with several other authorities, a joint administrative digital infrastructure for information exchange as well as a national framework for basic data. Several basic data domains on national level are about to be introduced and a transport data domain is also being developed [2].

Over the years, the Swedish government has appointed several investigations [3, 4] to examine the need for legislation in relation to the development towards a more connected and automated road transport system. These investigations have proposed measures within digital infrastructure, including digitalization of traffic regulations.

In the 1990s, the National Road Database (NVDB) was introduced in Sweden. Over time, the Swedish Transport Administration has had several projects to increase the quality in NVDB by improving the transfer of traffic rule data to the database. However, they have repeatedly encountered limitations as traffic regulation processes as such need to be improved to ensure a more qualitative data transfer.

A project [5] in 2018 stated that there are more than 300 decision-making authorities in Sweden that decide on traffic regulations and their processes are not standardized. Standardized and automated processes were mentioned as a way forward.

Another project [6] suggested a public-private partnership platform to accelerate the implementation of physical digital transport infrastructure. Policy and regulation were identified as important to accelerate the implementation of digital infrastructure.

There are also ongoing EU initiatives that are pushing the issue and that may require Sweden and other Member States to do more in the future. In February 2022, the European Commission adopted a new delegated act on real-time traffic information (RTTI) to the ITS Directive (2010/40/EU) and there is also an ongoing revision of the ITS Directive which suggests that Member States must in future ensure that certain traffic information, including certain types of traffic rules, are available in machine-readable format [7]. Furthermore, the EU initiative of a common European mobility data space (EMDS) aims to facilitate access to and sharing of data in the transport sector.

3 Methodology

3.1 Policy Labs and Policy Lab Methodology

In this collaboration project, we have applied policy lab processes to identify challenges and opportunities related to implementing a future system for digital and machine-readable traffic regulations in Sweden.

The use of policy lab processes has increased in Sweden and other countries to accelerate the adaptation of regulations to emerging technologies and innovations [8]. The challenges for society that lie ahead require radical changes to, among other things,

the transport system, which can be supported by new digital technology. In this context, the existing legislation is often seen as a barrier. To address this perceived conflict between technological innovation and legislation, a participatory policy lab methodology can accelerate the process from the first experience of a regulatory barrier to the resolution of the problem.

There are different ways to organize policy labs. RISE Research Institutes of Sweden has, since 2017, worked with policy lab methodology in collaboration projects with stakeholders from public and private sector to frame, discuss and solve policy barriers. Policy lab, as an idea, has its origins in the question "Can we work with policy and regulatory development in a better way than today?" This question should be seen in the light of reality becoming increasingly complex and challenging to grasp, which leads to the need to find new ways and tools that can be used to meet the challenges facing our society [9–11].

Policy labs usually include several working methods that are typical of design, for example design thinking methods. The purpose of using different work methods is to expand the toolbox to boost the innovation work and complement other approaches such as technology-driven and business-driven processes. This can speed up the process from the identification of a need for a new policy or new rule to its implementation. Policy labs can also create policies and regulations that are adapted to the needs of users by involving more people in the process. A policy lab also offers a neutral meeting place where participants from business, academia, authorities and others can meet and discuss policies and regulations [9, 11, 12].

3.2 This Policy Lab

Our work described in this paper was conducted as a policy lab with a series of workshops with many participants from private and public sector, academia, and research. In parallel, we conducted literature studies and interviews with project participants and external experts. We also arranged a hearing with other stakeholders and the general public. Moreover, we did a survey study with a comprehensive questionnaire to municipalities, which as decision-making authorities for traffic rules at local level would be very much affected by a changed system.

We gathered information about 1) the current system of traffic regulation, 2) needs and benefits for different users and use cases of data on traffic rules, 3) challenges and possibilities related to changing the current system, 4) related initiatives in Sweden, EU and internationally, and 5) how other countries do. This helped us understand the current situation, identify a desired situation and how to get there.

In our work, we have primarily started from a Swedish context. Nevertheless, our results are in many respects useful outside Sweden, as many countries have similar systems in terms of traffic regulation, i.e. general traffic rules at national level which are supplemented or replaced by special traffic regulations decided by various authorities at local or regional level. The use cases for data on traffic rules are also similar in many countries.

We have chosen not to focus primarily on the general traffic rules outlined in the traffic legislation, but instead on the traffic regulations of various kinds decided by authorities and municipalities and electronically announced on the website www.stfs.se (e.g. speed

limits, weight/length/width restrictions, environmental zones, etc). These encompass all local and special traffic regulations concerning a certain road, road section or area. These account for the largest share of traffic regulations in Sweden (as in several other countries too). In the long run, however, all traffic rules decided on both national and local level must be digitalized.

In this work, we have particularly had to consider that there are many decision-making authorities at state, regional and municipal level writing traffic regulations in different ways, with different tools and with different roles in the traffic system.

We have not at all dealt with issues such as what traffic regulations we should have in the future (i.e. what behaviours should be allowed and what not) but only focused on how the traffic regulations should be designed.

4 Results and Discussion

Data on traffic rules are crucial for a variety of applications, including navigation, routing, and intelligent speed adaptation. This data also simplifies access to information on where to park, load and charge an electric vehicle, in an increasingly complex society. Furthermore, it enables future applications such as automated driving. As the road transport system becomes more automated and connected, the demand for reliable and easily accessible digital information on traffic rules increases.

We could not quantify the societal benefits in monetary terms in this project, but we described their potential significance. Some effects would also be difficult to calculate in monetary terms but are nonetheless substantial.

There is also inherent value for decision-making authorities in working digitally in traffic regulation, as the generated data can be used for various purposes within a municipality's or authority's area of operation.

Both national and EU-level initiatives are pushing for increased digitalization in society, including digitalization in public administration based on citizens' needs.

Sweden has made significant progress in this area, but there is still work to be done. Complete and reliable data on traffic rules are lacking considering the entire road network. An important reason is that there are 290 municipalities and several state authorities that decide on traffic regulations, and their processes are neither standardized nor harmonized. Some of them use digital tools (dedicated IT systems for the preparation, digitalization, and publication of traffic regulations), while others do not. There is also a significant flexibility in how traffic regulations can be written, resulting in substantial variation in their design at local and regional level. There is room for improvement.

However, we have a good starting position in Sweden to achieve digital and machine-readable traffic rules. Tools for this already exist, and many municipalities as well as the Swedish Transport Administration already utilize these opportunities.

5 Conclusions

Significant efforts are needed for traffic rule data to become more complete and more reliable across the entire road network. Neither the market nor a central authority like the Swedish Transport Administration can satisfactorily address this alone. More decision-making authorities must digitalize their traffic regulations, and their processes need to be harmonized.

Taking action around this involves costs. However, our research suggests that the benefits greatly outweigh the societal costs, even though we were not able to quantify the benefits in monetary terms in our project.

In the project, we discussed stimulating measures such as information and practical support as well as financial compensation from the state as a way to accelerate voluntary digitalization among decision-making authorities. However, many project participants, including those from the municipal sector, expressed that we have moved beyond the stage where such measures would be effective. Instead, it is time for new requirements that enforce digitalization. We also considered financial incentives for voluntary digitalization, but such instruments would have a lower potential effect compared to mandatory requirements, and designing such incentives for maximum effectiveness may also be challenging.

New requirements for decision-making authorities could be introduced, for example, in the Regulation on electronic announcement of certain traffic regulations (förordning [2007:231] om elektroniskt kungörande av vissa trafikföreskrifter), which already includes a few mandatory requirements regarding when, where, and how traffic regulations should be announced. A regulatory change that entails mandatory digitalization can be expected to have a significant effect in increasing digitalization, for the simple reason that it becomes mandatory to digitalize, i.e. every decision-making authority must do so.

Restrictions on local self-government can be made if they are proportionate and if municipalities are compensated by the state (due to the proportionality and financing principles that must be considered when the state introduces new or expanded tasks for municipalities).

Measures such as information and practical support can increase interest and facilitate digitalization, but their effect on increased digitalization is likely to be low. However, they can be essential when combined with regulation.

The "zero-alternative", i.e. taking no action, means that the situation with insufficient digital information persists, and that societal benefits are delayed.

In summary, a regulatory change mandating digitalization stands out as the best option. Thus, the way forward is through an amendment to the legislation that requires decision-making authorities to digitalize their traffic regulations.

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UAV Integration into Airport Infrastructure Inspection Procedures—Case Study Zagreb Airport

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Abstract. Within the EU project OLGA (Holistic & Green Airports), one of the main objectives is to reduce emissions and develop decarbonizing solutions for airside operations. In this paper, we will describe the proposed methodology and newly developed procedures for the usage of unmanned aerial vehicle (UAV) for the inspection of airport airside areas. Such an approach may bring significant benefits: i) Reduction of air pollution (in line with European Green Deal policy), ii) Better efficiency of infrastructure inspection and higher accuracy of detection of anomalies on operational surfaces, iii) Multiple measurements (inspection) per one drone operation and iv) Improvement of the Safety Management System at the airport.

To enable safe and secure usage of UAV in a daily routine inspection, it was necessary to develop a workflow for the integration of UAV into airport operations, which included the development of AD-HOC structure / procedure. The analysis of the whole process, which includes the collaboration between air traffic control, civil aviation agency, airport operational and asset management, is presented in the paper. The application of UAV for the inspection of the airside areas is analysed and presented with the aim of assessing the feasibility, capability, cost efficiency and environmental impacts of the implementation of UAV into daily, monthly and/or annual inspection procedures at the airports.

Keywords: UAV · airport infrastructure · visual inspections · monitoring

1 Introduction

The airport maintenance process consists of different procedures and inspections to achieve an adequate level of safety for aircraft operations. These inspections include operational surfaces on the airport airside, and the process is performed manually with

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traditional technologies (with vehicles). The new approach is to use automated technologies in order to improve efficiency and reduce operational costs and greenhouse gas emissions. An unmanned aerial vehicle represents a potential alternative technology to replace traditional processes.

Runways are particularly exposed to considerable loading and require daily inspections and monitoring because of high safety standards. The inspector should look for objects, contaminants, anomalies on the runway surface, that may endanger the safe landings and take-offs of aircraft such as: i) foreign object debris (FOD); ii) contaminants on the runway surface such as water, snow, spilled oil or fuel, or rubber deposit etc.; iii) cracks and potholes on the runway surface; iv) birds and wildlife on or in the vicinity of the runway. Instead of using vehicles for all operations, the intention is to replace some of them with UAVs. Such an approach may bring significant benefits: i) reduction of air pollution (in line with European Green Deal policy); ii) better efficiency of infrastructure inspection and higher accuracy of detection of anomalies on operational surfaces; iii) multiple measurements (inspection) per one drone operation; and iv) improvement of the Safety Management System at the airport.

The aim of this paper is to describe the workflow for the integration of UAV into airport operations, which included development of AD-HOC structure/procedure, in order to enable safe and secure employment of UAV in a daily routine inspection. The proposed workflow is demonstrated on the Zagreb International Airport in Croatia. After the introduction, Sect. 2 outlines various previous research regarding the UAVs application for runway visual inspection. Furthermore, Sect. 3 describes current procedures for airport operational runway inspection which are performed physically by a vehicle on the on-site locations. The proposed workflow for the integration of UAV into daily inspection processes in defined in the Sect. 4. Finally, some concluding remarks are given in Sect. 5.

2 UAVs Application for Runway Visual Inspection

Sappington et al. in [1] presented the use of a drone to monitor airport runway in order to identify potential cracks and potholes. The proposed method is based on the image processing technique to single out areas of interest. Histogram plots of the images, along with setting a threshold for variance values, proved to be a potential solution for runway inspection. The group of authors propose [2] the UAV application for the following procedures: runway inspection, bird control and a tactical component for future Surface Manager Systems. Maloka et al. [3] highlight the development of drone technology over the past few years and its potential application in the aviation industry. The authors conducted a survey questionnaire to the selected participants based in 20 major airports in South Africa. The purpose of their research is to determine the willingness of the South African airport industry to apply drone technology [3].

Several attempts and ongoing research projects have been made to use UAVs for different purposes in the infrastructure and security sector [4–7]. Groupe ADP is one of a pioneer in the utilization of drones at its airports, e.g., to inspect terminal buildings or for the calibration of air navigation equipment. In August 2016, ADP selected German company Airsight to conduct the first large-scale inspection of Paris Charles De

Gaulle Airport (CDG) using an untethered drone. This mission aimed to determine if drone-based pavement inspections, as developed and already used by Airsight at German Airports since 2015, could be used in conjunction with conventional on-site visual inspections performed by Groupe ADP personnel driving the runway. More than 200 thousand square meters of surface were captured during the inspection. To minimize impacts on capacity, the overall net flight time of approximately 1 h and 45 min was split into nine individual flight segments to take advantage of lower traffic periods. Due to the good preparation and close collaboration of all stakeholders (airport and ATC), the maximum runway occupancy time for a flight segment was 18 min.

In the H2020 European project ASHVIN "Assistants for Healthy, Safe, and Productive Virtual Construction Design, Operation & Maintenance using a Digital Twin", GIS integrator for digital-twin-based asset management was developed. The tool aims to integrate all of the data related to monitoring, condition assessment and maintenance of infrastructures into GIS for asset management on all levels and to categorize and quantify damages of the assets under study. A specific tool was developed for condition assessment, categorization, and quantification of damages and demonstrated on use case airport in Zadar, Republic of Croatia [8, 9].

The major elements of the developed tool, start with the data collection using cutting-edge technology and a drone fitted with a high-resolution camera. The examination of images that show the main categories of damages is used to determine the asset's condition. The images are also employed in the creation of a 2D or 3D model of the asset. For the purpose of developing and training a damage detection model, damages are categorized and labeled based on failure mechanisms (such as cracks) and predefined threshold values. After applying the created damage detection model to the asset's 2D or 3D model, the outcome is the geo-positioned defects. Figure 1 shows the process of imprinting the expert knowledge judgment into captured images. The visual inspection specialist labels a certain amount of images with the defined damage categories. Labeled images are then used to train the damage detection model which is further tested with the deployed dataset of images [10].

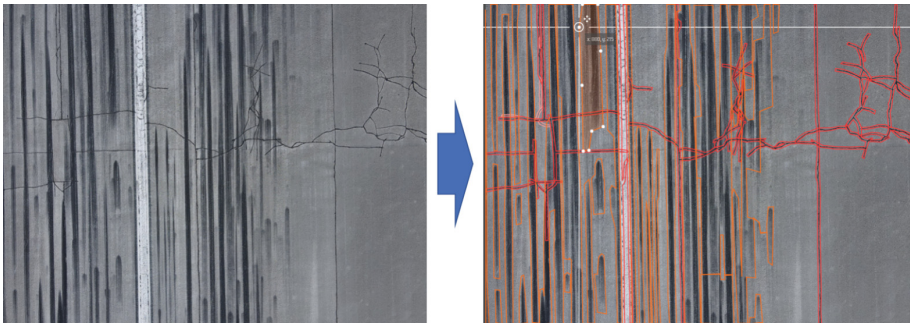


Fig. 1. Preprocessing damage labelling of images captured with a UAV equipped with high resolution camera.

3 Current Procedures for Airport Operational Runway Inspection

Regular inspection of the airport operating area, additional facilities and radio navigation devices is a fundamental prerequisite for quality maintenance to achieve maximum safety of aircraft operations. To support safe aircraft operations, operation personnel must perform several times a day (mainly before traffic peaks) an inspection of operational surfaces (runways, taxiways, aprons, security fences) and all other infrastructure.

These activities are performed physically by a vehicle on the on-site locations, and operational personnel must manually collect information (by visual observation and by taking photographs) about infrastructure conditions. The frequency of these inspections depends on the purpose and the activity and can vary from several times a day (usually four times) to once a year. Because of high safety standards, runways are particularly exposed to considerable loading and require daily inspections and monitoring.

The provision of ADR.OPS. B.015 of Regulation (EU) 139/2014 and the Air Traffic Act defined the obligation to control the operational area at the airport. Regular visual inspections of the runway from a vehicle are usually conducted at the following times: dawn, morning, afternoon, and dusk inspection. Each airport determines the frequency of inspections based on its infrastructure complexity and traffic schedule.

The inspector should look for objects, contaminants, and anomalies on the runway surface, that may endanger the safe landings and take-offs of aircraft, such as:

- foreign object debris (FOD);
- contaminants on the runway surface such as water, snow, spilled oil/fuel, rubber deposit, etc.;
- cracks and potholes on the runway surface;
- horizontal and vertical signage, markings,
- and birds and wildlife on or in the proximity of the runway.

4 The Workflow for the Integration of UAV into Daily Inspection Processes

Generally, the procedure for the integration of UAVs into airport inspection procedures should include regulatory and operational preconditions but also approval and support from the Air Navigation Service Provider. Here, the workflow for the integration of UAV into daily inspection processes is demonstrated on the Zagreb Airport case study (Fig. 2). The main stakeholders involved in integrating UAVs into the Zagreb Airport's daily operations are the Zagreb International Airport (Airport Operator), external experts, the Air Navigation Service Provider (in Croatia CROCONTROL), and the Croatian Civil Aviation Agency (CCAA), an independent and non-profit legal entity founded by the government of the Republic of Croatia, responsible for air traffic safety-related tasks, especially certification, oversight, supervision, and other air traffic-related activities defined under the Air Traffic Act. Zagreb International Airport initiates the process and is responsible for issuing the remote pilot and UAV operator certificates under the EU regulation (EU) 2019/947 and EU regulation (EU) 2019/945. Also, Zagreb International Airport performs site prechecking, which includes available geographical information on the location and the operational constraints of the environment. The external

experts determine the survey objectives (data requirements for the area that should be inspected) based on which flight parameters will be determined. Details and the whole workflow process are given in Table 1. Based on the predefined survey objectives and flight parameters, CROCONTROL performed a safety study for the ground and air risks of the drone's environment. EASA recommends the usage of the Specific Operations Risk Assessment (SORA) methodology, but other complementary methodologies, such as MEthoDology for the U-Space Safety Assessment (MEDUSA) developed under the SESAR program, could be usable in the future. CCAA approved SORA and ad hoc airspace structures under specific categories according to the EU regulation 947/2019. The final step implies integrating ad hoc structure into an airport and ATM environment and performing procedures on a scheduled basis.

Airport	- initiates the process - responsible for issuing the remote pilot and UAV operator certificates - performs site prechecking
↓	
External experts	- determine the survey objectives (e.g. crack detection) - determiine flight parameters (e.g. image resolution, height, speed)
↓	
Aeronautical Navigation Service Provider (ANSP)	- performs a safety study for the ground and air risks of the UAV's environment
↓	
Civil Aviation Authority	- approves Specific Operations Risk Assessment (SORA) methodology - approves ad hoc airspace structures under specific categories
↓	
Airport ANSP External Experts	- integration of ad hoc structure into an airport - integration of ad hoc structure into ATM environment - performing inspection on a scheduled basis

Fig. 2. Overview of the workflow for the integration of UAV into airport operations.

5 Conclusion

In this paper, as part of the OLGA EU research project, the focus is on integration of UAVs for visual inspection of airport infrastructure. In order to enable safe and secure usage of UAV in a daily routine inspection, it is necessary to develop workflow for the integration of UAV into airport operations, which included development of AD-HOC structure / procedure. The analysis of the whole process, which includes the collaboration between air traffic control, civil aviation agency, airport operational and asset management, is presented in this paper. The application of UAV into daily, monthly and/or annual inspection procedures for the inspection of the airside areas is under development and the procedures are being analyzed with the aim to assess feasibility, capability, cost efficiency and environmental impacts of the implementation of UAV.

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Author Index

A
Abdelmuhsen, A. 195
Abou, Roland 503
Adesiyun, Adewole 815
Adey, Bryan T. 31
Afonso, Joao L. 445
Ahmed, Abubeker 351, 358, 365
Akker, Marjan van den 534
Alario, Raquel 567
Aleksa, Michael 285
Alpiarça, Carlos 111
Al-Tabbaa, Abir 264, 292
Aluko, Oluwasegun Oluyemi 160
Alvarado, Unai 541, 636
Alves, Rodrigo 708
Amditis, Angelos 746
Amokrane-Ferka, Kahina 243
Anagnostopoulos, Lemonia 694
Anastassiadou, Kalliopi 78
Andersson, Jeannette 815
Andrews, Louis 619
Androls, Mattias 651
Antoniou, Maria 644
Antunes, Vítor 317
Anvo, Nzebo Richard 264, 292
Anwar, Usama 773
Arandia, Iker 933
Aribisala, James Olugbenga 160, 167
Arnesen, Petter 794
Arokia, Marshall 84, 104
Arregui, Harbil 933
Arts, Jos 513
Arvidsson, Anna 527
Aschauer, David 331
Asgarpour, Sahand 599
Asplund, Matthias 90
Avril, Bertrand 497
Ayfantopoulou, Georgia 739, 746

B
Baasch, Benjamin 541, 636
Backendorf, Fabia 188
Bah, Fatoumata 72
Bakloekk, Leif J. 181
Ballance, Éamonn 331
Ballis, Haris 644
Bandarian, Fatemeh 906
Bartolt, Raphaël 503
Basso, Paolo 462
Bauer, David 828
Bauschert, T. 835
Bendraou, Youssef 948
Berbineau, M. 835
Bergiers, Anneleen 58
Berthou, Hervé 243
Besbes, Mariem 174
Bharathi, Dhivya 666
Bhreasail, Áine Ní 619
Bles, Thomas 250, 372
Boesiger, Lukas 132
Bogojevic, Bojan 90
Böhm, Mathias 24
Boistault, G. 835
Bolletta, Fabio 462
Bon, Philippe 605
Bordado, João 111
Bott, Frederick 188
Böttger, Berit 580
Bouhouras, E. 429
Bourgeois, Vincent 174
Bowe, C. 887
Bowe, Cathal 379, 438, 880
Bracic, Matija 961
Breidbach, Matthias 787
Brink, Anna-Carin 310
Broek, Roel van den 534
Bruhin, Peter 132
Brunat, Mathis 243
Brunel, Julien 139
But, Boris 815
Buursma, Douwe 541
Bygvraa, Dspoina Andrioti 694

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C
Cademartori, Marcello 462
Canow, Kristina 277
Cappi, Cyril 72
Carey, Jude 651
Carroll, Páraic 118
Castro-Fresno, Daniel 125, 216
Cecchetti, Gabriele 941
Chailleux, Emmanuel 392
Cheimariotis, Ilias 409
Cieren, Emmanuel 452
Clarke, Jeremy 619
Clausen, Uwe 828
Clément, Philippe 573
Coen, Mick 331
Collart-Dutilleul, Simon 605
Connolly, Lorcan 118, 223, 874
Connolly, Mark 416
Corazza, Maria Vittoria 586
Corbally, Robert 385
Corre, Y. 835
Costa, André Amaral 920
Cotterill, Sarah 474
Cunha, Jose 445
Czmil, Victor 174

D
d'Avigneau, Alix Marie 52, 264, 292
Dabaj, Anas 72
Dais, Sofoklis 739, 746
Daleiden, Jerome 687
Danaher, Michael 400
de Groen, Frederique 372
de Groot, Bert 513
De Guio, Pascal 483
de Guio, Pascal 490
de Jonge, Anoek 250
De Maio, Florencia Victoria 462
de Miguel, Javier Camacho 541, 636
de Paor, Caitriona 223, 250, 874
de Picado Santos, Luís 111
De Silva, Lavindra 52
De Stefano, Rita 462
de Vos, Peter 146
de Weerdt, Mathijs 534
Debbech, Sana 781
Delafuente-Navarro, Christopher 125
DeLaFuente-Navarro, Christopher 216
Denner, Jon 400
Develter, Marc Georges 139
Dias, Tiago 913, 920
Díaz, María López 629
Didier, Paul 483
Dinegdae, Yared 358, 365
Djordjevic, Boban 822
Doenitz, Friederike-Chantal 17
Dolic, Tomislav 38
Dollevoet, Rolf 90
dos Santos, Fabio Marques 409
Dosch, Gion 132
Dubey, Mayank 701
Duffy, Liam 237
Dumančić, Sebastijan 534
Dunne, David 331
Dybkjaer, Stine 250

E
Eiband, Agnes 828
El Idrissi Raghni, Sami 452
Elekes, Gabriel-Martin 132
Ende, A. 835
Eraña, Rubén 842
Erlingsson, Sigurdur 344, 365
Eudes, O. 835
Eustachio, João Henrique Paulino Pires 724

F
Fafoutellis, Panagiotis 732
Fargeon, Rodrigue 767
Fecarotti, Claudia 31
Feighan, Kieran 230, 237
Ferreira, Adelino 153
Filho, Walter Leal 724
Finck, Tobias 554
Fischer, Marie 483
Fish, Paul 400
Fjendbo, Simon 527
Floquet, Romain 483
Fochesato, Donatella 651
Foley, Ross 773
Fonseca, Alvaro 250
Fontul, Simona 111
Fort, Mathias 243
Fröidh, Oskar 822
Free, Matthew 619
Freire, Ana Cristina 111, 317
Freitas, José 111
Friedman, Miles 257
Friedner, Saul 808

Fritzsche, R. 835
Fuggini, C. 97
Fuggini, Clemente 462

G
Gaboriau, Joséphine Boisson 72
Galea, Edwin 694
Galhano, Rui 111
Gallego-Gueto, Juan 847
Galvão, Teresa 708
Ganic, Emir 961
Garcia-Sanchez, David 250
Geier, U. 835
Geisler, Flavien 392
Georgoulas, Dimitris 423
Ghiasi, Ramin 379, 899
Ghosh, Bidisha 659, 666
Gieske, Hanneke 513
Giouroukelis, Marios 854, 860
Girolami, Mark 52, 264, 292
Gkoumas, Konstantinos 409
Glaser, Florian 24
Gläser, Ute 202
Goel, Pragati 680
Golpayegani, Fatemeh 906
Goodwin, Leonard 773
Gordan, Meisam 118
Goubert, Luc 58
Gregersen, Ida Bülow 250
Grønskov, Leif 104
Grosso, Monica 409
Gueguin, Maxime 452
Guy, Ianto 815
Gyamfi, Eric 906

H
Hadjichristodoulou, Christos 694
Hadjidemetriou, Georgios M. 264
Hadjidemetriou, Georgios 52
Hadjidemetrious, Georgios M. 292
Hahn, Matthias 38
Hallisey, Ronan 400
Hanou, Issa K. 534
Haouchine, Lokmane 468
Hardwell, R. 331
Harries, Leandro 271
Hart, Johannes 787
Hartmann, Andreas 599
Hecht, Markus 760
Hellman, Fredrik 344
Hendriks, Jurjen 90
Herbold, Michael 828
Hernando, Mª. Antonia Pérez 842
Holfeld, B. 835
Holfeld, Denise 202
Hora, Joana 708
Horn, Alfons 271
Hu, Aihui 673
Hula, Andreas 38, 285

I
Ihamouten, A. 195
Indacoechea-Vega, Irune 125, 216
Ingrosso, I. 97

J
Jacob, Bernard 503
Jaffrezic, Claire 72
Jafino, Bramka Arga 644
Jetlund, Knut 794
Jimenez-Redondo, Noemi 847
Jokela, Tero 717
Jordan, Hanna 338
Jović, Marija 580

K
Kahil, Sirine 452
Kalliovaara, Juha 717
Kandiri, Amirreza 548
Kanellopoulos, Ioannis 746
Kapoor, Sidharth 277
Karabinos, T. 835
Karakikes, I. 429
Katzilieris, Konstantinos 732
Keenahan, Jennifer 45
Keneghan, Damien 400
Keou, Oceane 644
Khan, M. A. 887
Khan, Muhammad Arslan 379
Khelladi, Nassiba 781
Kirwan, Andy 651
Klein, Jörn 694
Kluenker, Carmo S. 554
Kmar, Prashant 694
Ko, Ili 118
Kokot, Darko 527
Kolb, Juergen F. 694
König, Sandra 118

Konstantinou, Christos 860
Kornejad, Behzad 822
Kortenhaus, Andreas 746
Kourkoulis, Rallis 644
Krawczyk, Charlotte M. 787
Krebs, Miriam 188
Kremer, Felix 828
Krmac, Evelin 822
Kuchly, Philippe 490
Kunz, Bernhard 132
Kwapisz, Maciej 801

L

Lakra, Savita 701
Lamb, Martin 250
Lampin, Denovan 324
Lancaster, Emma 338
Lanselle, Romain 468
Laoide-Kemp, David 612, 808
Largo, A. 97
Larsson, Magnus 351
Lastra-González, Pedro 125, 216
Laubrock, Michael 605
Lavaud, Stéphane 392
Le Corre, Pierre 767
Leendertse, Wim 513
Leopold, Philip 801
Leveque, Matthieu 304
Li, Zili 90
Lipus, Martin Peter 787
Liu, William Zhendong 277
Lodi, Chiara 409
Lohbreier, Julian 760
Loli, Marianna 644
Lopez-Arevalo, Paula 847
Lötscher, Dominique 132
Loyo, Estíbaliz 933
Luceri, D. 97
Lundahl, Jenny 955
Lynch, Alan 392
Lynch, Cian 400

M

Mac an tSearraigh, Cathal 257
Madadi, Bahman 815
Mahitthiburin, Kornpong 209
Mahler, Sébastien 243
Mahmut, Vincent 483
Mair, Richard 651
Majd, Amin 717
Majka, Michal 438
Makhoul, Nisrine 299
Malekjafarian, Abdollah 379, 385, 880, 899, 906
Malmgren-Hansen, David 104
Mangan, Cathal 331
Mannion, Rory 659
Mantouka, Eleni 854, 860
Marino, Clara Grahal 651
Marotta, Alessandro 409
Marquard, Marco 629
Marqués, Antonio 567
Märtens, Tammo 828
Martinez-Covarrubias, Juan 416
Martinez-Pastor, Beatriz 593, 673
Mayolle, Quentin 324
Mazzoni, Henry 132
McCarthy, John 815
McCrum, D. 887
McCrum, Daniel 118
McEvoy, John 331
McGowan, Ray 230, 237
McHenry, Helen 593
McPherson, Kevin 527, 815
Meddeb, Maroua 243
Mehranfar, Hamed 31
Meine, Lennart 188
Micu, Alexandra 223, 874
Micu, E. Alexandra 379, 880
Miera-Dominguez, Helena 216
Milbredt, Olaf 17, 24
Mintsis, Evangelos 906
Mitsakis, Evangelos 906
Mitschele-Thiel, A. 835
Mock, Peter 787
Moghtadernejad, Saviz 31
Monteiro, Vitor 445
Mooren, Sander 599
Moosavi-Anchehpoli, Seyed-Saeid 468
Moraal, Jan 90
Moreno, Christian 842
Morvant, Camille 452
Moser, Thomas 801
Mößner, K. 835
Mouchtouri, Varvara A. 694
Moura, Lara Trigueiro 920
Moura, Lara 913
Mujika, Andoni 933
Mullard, Hubert 573

Müller, Rainer 580
Murray, Catherine 416
Myhrvold, Øyvind T. 867
Mykoniatis, Georges 605

N
Navaratnam, Piraba 612, 808
Navaratnarajah, Shobanraj 612, 808
Neumann, Thorsten 541, 636
Neves, José 111, 317
Nicodeme, Claire 304
Nogal, Maria 548
Nosal, Michael 271
Núñez, Alfredo 90

O
O'Brien, Eugene 874
O'Connor, Alan 874
O' Sullivan, Barry 520
O'Cinneide, Cian 331
O'Connor, Alan 223, 230, 237, 250
O'Connor, John 257
O'Keeffe, Aonghus 893
O'Keeffe, Billy 338
O'Pray, Declan 392
OBrien, E. J. 887
OBrien, Eugene J. 379
OBrien, Eugene 880
Ogundipe, Olumide Moses 160, 167
Oguntayo, Daniel Oluwafemi 160, 167
Olsson, Nils O. E. 867
Oorni, Risto 815
Osmani, Saimir 462
Otten, Maximilian 828
Ozturk, Cemalettin 520

P
Paavola, Jarkko 717
Pajusco, P. 835
Pakrashi, V. 887
Pakrashi, Vikram 880
Palic, Sandra Skaric 961
Palin, Damian 264, 292
Papadimirtiou, Stratos 423
Papaioannou, G. 429
Papataxiarhis, Vassilis 694
Parny, Christophe 468
Parsons, Simon 808
Pehrsson, Helene 84, 104
Pereira, Hélder 746
Perez, Carles Soriano 372
Petit, Anne 72
Petton, Pierre-Yves 767
Phusakulkajorn, Wassamon 90
Polydoropoulou, A. 429
Popa, Andrei 17, 24
Pouget, Simon 392
Pouligny, Philippe 490
Poulikakos, Lily 132
Pritchard, Oliver 338
Pulver, Thierry 651

R
Rahman, Shafiqur 344
Ralbovsky, Marian 285
Rengaraju, Sripriya 264, 292
Renoir, Nicolas 243
Renzi, Giulia 746
Ripke, Burchard 202
Robinson, Matthew 586
Rodenburg, Arjen 724
Rodriguez-Arana, Borja 541, 636
Rousseau, Tom 243
Rövid, András 927
Ruane, Tom 331
Ruscelli, Anna Lina 941

S
Sá da Costa, Margarida 111
Saad, Elie 174
Saba, Rabbira Garba 181
Saberi, Mogens 527
Sabra, A. 835
Said, Safwat 351
Samson, Henk 636
Sánchez, David García 842
Sanchez-Guerrero, Jose 847
Sarma, Hrishikesh Dev 593
Saulnier, Loïc 72
Sauni, Mikko 651
Sauter, Moritz 828
Schatzl, J. 65
Schauer, Stefan 118
Scheffers, Evelien 146
Schellenberg, Urs 132
Schellert, Maximilian 828
Schmidt, Bjarne 687
Schmidt, F. 195

Schmidt, Franziska 299
Schönbach, Torsten 271
Schott, Lucas 243
Schouenborg, Björn 344
Shen, Chen 90
Siilin, Niko 694
Silva, Ana V. 913, 920
Silva, Thaynara 139
Silvano, Ary P. 815
Simonin, J.-M. 195
Simonsen, Erik 344
Smit, Godfried 746
Snilsberg, Brynhild 181
Sobiech, Cilli 955
Solari, C. 97
Solis-Hernandez, Jose 847
Song, Yeonjung 416
Soroudi, Mona 118
Spielhofer, Roland 38
Sreenivas, Puneeta 474
Staub, Stefan 78
Stavroulakis, Peter J. 423
Stell, Marvin 188
Stępniak, Marcin 409
Stewart, Laura 619
Stimac, Igor 961
Stipanovic, Irina 961
Sumathi, Siddharth Suresh 277
Szymczak, Sonja 188

T
Tabakovic, Amir 392
Taefi, Tessa T. 724
Taha, Hussameldin M. 264, 292
Tamagusko, Tiago 153
Tangrand, Kristoffer 794
Taunay, Lionel 468
Teixeira, Rui 548, 593
Tetley, Simon 687
Thiébaut, Alain 497
Thidevall, Niklas 955
Tica, Marin 961
Tiecken, Jacques 541, 636
Tihanyi, Viktor 927
Tomaschek, Tamás Attila 927
Torrado, David 893
Treacy, Joanne 338
Tremblay, Julien 490
Tsioumas, Vangelis 423
Tundis, Andrea 629

U
Ubi, Ofem Ofem 160
Unsiwilai, Siwarak 90
Urassa, Patrick 867
Urbieta, Itziar 933

V
Vaggelas, G. 429
Vaidya, Gaurav 680
Van Geem, Carl 58, 527
van Ginkel, Kees 372
van Marle, Margreet 250, 372
van Wyk, Riaan 310
Vanheeghe, Philippe 324
Vanvliet, Dave 392
Ventikos, Nikolaos P. 694
Vincze, Zsolt 927
Vlachakis, Christos 264, 292
Vlahogianni, Eleni I. 732, 854, 860
Vlieghe, Valentin 324
Voort, Paul van der 534
Vorwagner, Alois 801
Vosinakis, Geogos 694
Vuitton, Jonas 760

W
Wacker, Bastian 787
Waldemarson, Andreas 358
Walsh, Geraldine 666
Weber, Mara 554
White, Greg 3, 10
Winterlich, E. 392
Wolf, Franziska 724
Wollin, Christopher 787
Woning, Mike 372
Wooles, Joanna 619
Wright, Alex 815

Y
Yeganeh, Ali 527
Yetik, Gorkem 773
Yildiz, Irfan 828
Young, Scott 10

Z
Zaumanisa, Martins 132
Zeng, Yuanchen 90
Zeybek, Hulya 561
Zhang, Fengqiao 527

Zhang, Yiming 52
Zhu, Jiqing 358
Ziani, Smail 468
Zoeteman, Arjen 90
Zolghadri, Marc 174
Zouzou, Nada 468
Zreik, Rawya 452