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Contents

Foreword

The transport sector stands at a critical juncture where the demand for sustainable, data-driven solutions has never been more pressing. This edition of the Journal of Integrated Mobility shares real, practical research transforming how we design, build, maintain, and operate infrastructure across Australia, New Zealand and our region.

Developed in partnership with local governments and state agencies, this new research is revealing a fundamental shift in how we approach transport challenges. From circular economy applications in pavement materials to innovative methods of network assessment, these contributions share a common thread: they move beyond theory to actionable changes and real tools that our industry can adopt today.

Our work in the Kingdom of Tonga exemplifies this practicality. Supporting Pacific nations to build resilient, sustainable transport systems not only strengthens regional connectivity but also provides valuable insights that inform our approach across Australia, New Zealand and the rest of the Pacific.

The advancement of data-rich assessment technologies is completely transforming how quickly the sector can act on assets within their care. When governments can gather comprehensive information about their entire road networks efficiently and effectively, they gain an advantage to make intelligent and timely decisions about maintenance priorities and resource allocation. This leads to the delivery of safer roads for the communities we serve. New technology is enabling us to acquire deeper data sets and on a much faster timeline, making it simpler to action cost effective solutions for the network.

Decarbonisation continues to shape our industry, and the research on recycled materials and sustainable pavement solutions will aid the transport sector to meet environmental goals without compromise. These are the step-change approaches that will define the next generation of infrastructure development.

NTRO's role is to be a bridge, bringing global best practices to our region while contributing homegrown innovation to the international conversation. The Journal of Integrated Mobility serves as a platform connecting researchers, practitioners, and decision-makers across the world who share our determination to solve today's transport challenges while driving the necessary step-changes for tomorrow. Developing innovative solutions backed by rigorous research to achieve meaningful outcomes is exactly what NTRO is built for.

> I invite you to discover how these insights can advance the work you do.

Michael Caltabiano
Chief Executive Officer
NTRO

In this issue

The unifying theme of this issue of the Journal of Integrated Movement is the next generation of researchers and problem solvers. The more experienced echelons of our cohort – or any cohort – often fret about who will keep the flame alight once they have retired. The overarching message of this issue to them is "Have no fear, the future is in good hands". Each paper presented has as its first author a researcher of 15 years or less experience, some of whom were finalists in NTRO's Research Rising Star award 2025.

> The scope of these papers ranges from the infrastructure fundamentals to some of the new and emerging issues of our times.

Dr Thanh Vinh Le's paper presents some pavement engineering and performance research. Dr Qiqin Yu takes a timeless topic (pavement roughness) and puts a modern twist on it by evaluating mobile phones as a means of assessing it. Those who use light rail regularly will have some appreciation for the work that Dr Daniel Ainalis and his co-authors did on the need to mitigate the vibrations and noise associated with light rail transit.

Materials engineering is also a timeless topic, but imperatives surrounding their use are changing. Jaimi Harrison presents a dashboard for recycled materials providers, while Dr Chrysoula Pandelidi presents some thinking around an assessment framework which is suited to non-traditional materials.

Evelyn Wen and Stephanie Yue's papers cover the very real need to think differently about how we travel. Evelyn's paper proposes a means of thinking about first-mile access to promote public transport patronage, while Stephanie's looks at the fast-evolving option e-micromobility and the challenges and opportunities it presents.

We return to 'timeless' with Dr Sepehr Dekhordi's paper – safety – but with a modern twist – automation. The specific application for his work is the improvement of the Australian Level-Crossing Assessment Model (ALCAM).

The paper by Georgia O'Connor addresses the most important question of all – Why? As transport professionals, we exist to serve and uplift communities and make humanity thrive, and her paper describes how this has been applied in the Kingdom of Tonga.

Mike Shackleton
Chief Research Officer
NTRO

Authors

Jaimi Harrison

Jaimi Harrison is a highly motivated and results-oriented researcher in NTRO's Sustainability and Material Performance team. She holds a Bachelor of Science in Chemistry and a Master of Urban Planning and Environment. Recycled materials are Jaimi's current focus and has been leading and participating in projects involving glass, plastics and crumb rubber. Jaimi has worked with the SPARC (Smart Pavements Australia Research Collaboration) Hub, Major Transport Infrastructure Authority team, ecologiQ and in a joint research venture with Arup on the recycled materials in freight rail.

Dr Chrysoula Pandelidi

Dr Chrysoula Pandelidi is a Materials Scientist in the Sustainability and Materials Performance team at NTRO. Chrysoula has expertise in the field of materials processing and performance following her PhD in polymer matrix composite material extrusion additive manufacturing. She has worked in a range of projects in the field of additive manufacturing and since her employment at NTRO in research projects investigating the work health and safety and environmental impacts of recycled plastics in bitumen and asphalt, the digestion potential of different types of crumb rubber, the development of biomaterials for use in pavement applications and the stripping potential of asphalt with liquid anti-stripping agents.

Dr Vinh Le

Dr. Vinh T. Le is a Research Fellow at Monash University. He received his Bachelor's degree with Honours in Civil Engineering from Ho Chi Minh City University of Technology, Vietnam (2017). After graduation, he worked as a geotechnical engineer in industry for nearly two years before completing his PhD at Monash University in 2024. His doctoral research focused on the numerical modelling of fatigue damage in cemented pavement materials (CPMs), aiming to bridge the gap between laboratory testing and field-scale performance. His current research interests include constitutive modelling of geomaterials (CPMs, rock, and soil), computational geomechanics, pavement engineering, and rock fracture and cave mining.

Professor Ha Bui

Professor Ha H. Bui is Head of the Department of Civil and Environmental Engineering at Monash University and an internationally recognised leader in computational geomechanics. His research focuses on computational mechanics and material modelling, with particular emphasis on bridging scales in geomaterial failure and addressing complex multi-physics problems. He is widely credited with introducing the Smoothed Particle Hydrodynamics (SPH) method into geomechanics and establishing it as a mainstream tool for simulating large deformations and failure. Professor Bui is also the founder and lead developer of GeoXPM, a powerful continuum particle-based platform for both academic and industry applications. His contributions have been recognised with numerous awards, including the 2021 ALERT Research Medal, an ARC Future Fellowship, the Scott Sloan Best Paper Award, and the JSPS Fellowship. He serves as Editor of Computers & Geotechnics (Elsevier) and the International Journal for Numerical & Analytical Methods in Geomechanics (Wiley).

Dr Qiqin (Leo) Yu

Dr Qiqin Yu is currently a Postdoctoral Researcher at the City University of Hong Kong. He completed his undergraduate and doctoral degrees at Monash University in Australia, with his Ph.D. research focusing on smartphone-based methods for assessing road roughness. His research emphasises integrating edge computing, artificial intelligence applications, and crowdsourced vehicle data to advance sustainable and data-driven management of urban transportation infrastructure.

Dr Yihai Fang

Dr Yihai Fang is a Senior Lecturer in Construction Engineering and Management at the Department of Civil and Environmental Engineering at Monash University. He received his Ph.D. in Civil Engineering from the Georgia Institute of Technology. Before joining Monash, he worked as a Postdoctoral Associate at the College of Design, Construction and Planning at the University of Florida. Yihai's research interests include Construction Automation and Informatics, Construction Robotics, Digital Twin for Construction and Built Environments, and Construction Safety and Human Factors. Yihai is a member of the American Society of Civil Engineers (ASCE) and Engineers Australia (EA), and is registered as a Professional Engineer in Victoria (RPEV).

Richard Wix

Richard Wix is an internationally recognised expert in the pavement measurement and management of road networks. At NTRO, Richard holds the position of National Technical Leader – Measurement, where he is responsible for overseeing NTRO's needs in relation to infrastructure measurement. During his time at NTRO, Richard has had a strong focus on the collection and analysis of functional and structural pavement condition data for road managers in Australia and New Zealand, and has played a key role in establishing, managing and building NTRO's data collection service into a profitable business.

Yijia (Evelyn) Wen

Evelyn is an Operations Solutions Lead with Transdev New Zealand, specialising in data-driven approaches to public transport scheduling, workforce planning, and performance analytics. She is also contributing to strategic insight initiatives at NZ Transport Agency Waka Kotahi. She has a Bachelor of Science in Mathematics from University of Otago and has recently completed a Master of Mathematical Sciences at University of Canterbury. Her research focuses on applying operations research to real-world transportation systems.

Stephanie Yue

Stephanie is a Senior Engineer in the Safer Smarter Infrastructure team at NTRO, providing integrated multi-modal advice on various transport projects around Australia. With a passion for delivering safer and smarter transport networks, her key areas of specialisation include strategic transport planning, precinct master planning, land use planning, future mobility studies, movement and place frameworks and investment prioritisation frameworks. She has experience managing complex multi disciplinary projects, with demonstrated financial and commercial acumen in project delivery.

Dr Ronny Kutadinata

Dr Kutadinata specialises in transport optimisation, control and automation. His research interests include vehicle and traffic modelling, traffic network control and transport optimisation. Ronny has worked on various projects in the ITS field, including applications of intelligent on-demand mobility, CAV trials and roadmap development. He has also taken a role as an NTRO R&D Program Leader focusing on infrastructure productivity through integrated mobility management and optimisation. He has also been involved in the technical program committees of several international transport conferences and has had many of his technical reports and academic publications published in various world-leading journals and conferences.

Georgia O'Connor

Georgia O'Connor is a SeniorEngineer in the Asset Management Portfolio of NTRO's Asset Performance Team with a background in Environmental Engineering, Governance and Sustainability. Georgia's key focus areas and technical expertise include undertaking vulnerability assessments and developing risk management plans for the impact of climate change and natural hazards on transport infrastructure and developing sustainability strategies for major transport infrastructure projects.

Dr Daniel Ainalis

Dr Daniel Ainalis leads the Life Cycle and Economic Assessment portfolio at the NTRO and has extensive experience across a variety of national and international projects related to the performance, sustainability, and economics of road and freight transport and infrastructure. Prior to joining the NTRO, Daniel was a Senior Researcher and Research Manager of the Centre for Sustainable Road Freight at Cambridge University (UK) and spent time as a Researcher in the Centre for Transport Studies at Imperial College London (UK). He has led and co-authored numerous technical reports, white papers, and academic publications and has presented at several national and international conferences and events. He is a board member of the international Heavy Vehicle Transport & Technology (HVTT) Forum, and an Honorary Research Fellow at the Centre for Transport

Dr Bahareh Nikmehr

Bahareh is a Track & Civil Engineer at V/Line in Melbourne, accredited as a National Engineering Register (NER) and Registered Professional Engineer of Victoria (RPEV). She holds a PhD in advanced concrete research and, with 18 years of experience including two years as a Senior Engineer at NTRO, specialises in rail infrastructure and sustainable materials.

Dr Youli Lin

Dr Youli Lin is a Senior Engineer in the Sustainability and Materials Performance team at NTRO. His background is in geotechnical and pavement engineering. At NTRO, Youli has been involved in a range of projects focusing on sustainability in transport infrastructure construction, accelerated loading facility trials of unbound and cement-modified granular materials, development of technical specifications, and feasibility studies.

Danny Feigen

Danny Feigen commenced employment with NTRO in 2020 as an intern and continued to develop and progress within NTRO. Danny is transport engineer with extensive experience delivering applied research, economic and life cycle analyses, modelling tools and providing expert advice to drive sustainable transport outcomes. By applying lifecycle and cost estimation skills, Danny has developed a program of work across key research bodies, to assess and quantify the benefits of the research programs and calculate the benefit-cost-ratio. Utilising lifecycle estimates and benefit-cost modelling, Danny is able to provide key insights to the viability of different project alternatives and inform option assessment and program allocation decisions

Dr Sepehr Dehkordi

Sepehr is a Principal Engineer within the NTRO's Asset Performance team. Sepehr has a background in Control and Automation Engineering, and researching Connected Automated Vehicles and Intelligence Transportation systems. He conducts interdisciplinary research in the areas of control theory, robotics, transportation, mobility & AI. He fuses sensory data such as radar, LiDAR, cameras, GPS, & V2X communication devices to assess safety and develop decision-making algorithms.

Melanie Venter

Melanie Venter is the NTRO Portfolio leader for Safer Asset Performance, based in Brisbane. She has worked across business sectors including academia, public and private entities in South Africa and Australia. She is often tasked with leading large scale multi-disciplinary projects, with a particular interest in combining innovative technology with road safety. Her latest projects include delivering automation of the Australian level crossing assessment model, and the Bundaberg regional council's network safety plan.

Elliott Tang

Elliott is a Senior Engineer within the Safer Smarter Infrastructure team at NTRO, specialising in traffic engineering and road safety. He has worked extensively across Australia including Queensland, New South Wales, Victoria, Western Australia and the Northern Territory, as well as internationally in Canada and Tonga. His work involves research, technical studies and the development of updated guidelines and policies to support both state and local government road agencies. Elliott's experience covers a wide range of areas, including road safety audits, crash investigations, traffic management and calming schemes, active transport planning, speed limit reviews, and the integration of road design in challenging environments such as mine sites.

Zi Chen

Zi Chen is a Senior Engineer within the Asset Performance team at NTRO. By leveraging his technical expertise and extensive research experience, he actively contributes to various projects where his involvement spans critical areas such as road design standards updates, statistical analysis of treatment effectiveness, AusRAP rating for road networks and standardisation of data collection procedures for multiple levels of government.

Sunand Sudhakaran

Sunand Sudhakaran is a Level Crossing Project Manager Department of Transport and Planning (DTP), Victoria oversees a multi-disciplinary technical program for the Victorian Railway Crossing Safety Steering Committee (VRCSSC). They manage program portfolios supporting the Victorian Rail Crossing Safety Strategy by piloting new technologies, implementing and updating safety standards, addressing safety gaps and evaluating safety upgrades. As the Chair of the Rail Crossing Technical Group (RCTG), their work is aimed at improving safety at public railway level crossings by leading projects in AI, machine learning, digital twin simulation, immersive virtual reality, road and rail signalling, traffic engineering, and human factors.

ARTICLE 01

Practical Tools for a Circular Economy: NACOE's Recycled Materials Supplier Dashboard

Jaimi Harrison, National Transport Research Organisation (NTRO), Australia

The Queensland Department of Transport and Main Roads (TMR) is working toward a more sustainable future, leveraging the principles of a circular economy. To support reducing waste, lowering emissions and promoting the use of recycled materials in infrastructure projects, TMR launched a new initiative in early 2025: the Recycled Materials Supplier Dashboard (National Asset Centre of Excellence 2025).

This publicly accessible, free-to-use digital platform is designed to support both industry stakeholders and TMR project delivery teams in identifying local opportunities for incorporating recycled materials into road construction and maintenance. By making it easier to source sustainable materials, the Dashboard is helping to transform how transport infrastructure is planned and delivered across Queensland.

TMR's commitment to sustainability is demonstrated by its Waste2Resource Strategy **(Queensland Government 2025)**, which outlines a vision for becoming a leader in circular economy practices within the transport sector. This strategy is built around four key objectives:

1. Minimising landfill waste.
2. Achieving resource efficiency through circular economy principles.
3. Fostering market growth for sustainable products.
4. Reducing greenhouse gas emissions associated with waste and resource use.

These goals align with the broader Queensland Government's Waste Management and Resource Recovery Strategy, reinforcing a whole-of-government approach to sustainability **(Queensland Government 2019)**. This Dashboard specifically targets the third objective, creating a space for industry to build market connections.

The Recycled Materials Supplier Dashboard is the result of the multi-year collaboration between TMR and the National Transport Research Organisation (NTRO), under the National Asset Centre of Excellence (NACOE) research agreement. This partnership is focused on delivering research that is not only cost-effective and implementable but also builds capacity and supports collaboration across the transport sector.

Since its inception in 2022, the project has involved consultation with stakeholders across Queensland. Workshops were conducted with local government representatives and other state departments to identify user needs and explore opportunities for future cross-governmental synergy. These engagements revealed an appetite for a tool that could simplify access to information about recycled material suppliers.

The first year of the project focused on research and stakeholder engagement. NTRO worked closely with TMR to understand the technical and practical requirements of the Dashboard. This phase included evaluating software options and gathering input from potential users to ensure the final product would be fit for purpose.

Feedback from industry stakeholders and project delivery teams was that a lack of visibility has been a barrier to the broader adoption of recycled materials in transport projects. Without easy access to reliable, up-to-date information, teams often default to conventional materials because they are more familiar and easier to source. The Dashboard directly addresses this challenge by centralising supplier information and making it accessible in a user-friendly format.

Additionally, the project team conducted a review of existing tools in the industry to inform the Dashboard's development. Notable examples included Sustainability Victoria's Buy Recycled Directory **(Sustainability Victoria 2025)** and ecologiQ's Supplier Map for Victoria's Big Build projects **(State Government of Victoria 2023)**. These tools provided insights into best practices and user expectations, helping to shape a platform tailored to the Queensland context.

In the second year, the team developed an alpha version of the Dashboard, which was tested with industry stakeholders, including both suppliers and end users. Feedback from this phase helped refine the platform, leading to the beta version development and, ultimately, the final product.

The Dashboard is designed to be intuitive and user-friendly, offering a range of features that make it easy to find and evaluate recycled material suppliers across Queensland. Key functionalities include:

- Interactive map where users can explore supplier locations geographically, helping them identify nearby sources of recycled materials. This is important for considering and, potentially, reducing haulage – a significant contributor to emissions.
- Tabulated data view, where users can view supplier information in tables, allowing for easy comparison.
- Search function and filters, where users can look for specific materials, products or suppliers, and narrow down results based on location, material type or specifications.
- Simple charts that help users quickly understand key information about product listings and suppliers.

As of July 2025, the Dashboard features 28 suppliers, with new entries added monthly. These suppliers are from eight TMR districts, with a few interstate businesses that provide products to Queensland. The suppliers include quarries, recyclers and manufacturers of bituminous products.

The range of recycled materials available through the Dashboard is diverse and continues to grow. Commonly listed materials include crumb rubber; crushed brick, concrete and glass; reclaimed asphalt pavement; reclaimed aggregates; fly ash; and recycled water. These materials are used in a variety of applications, including asphalt, bituminous binders and unbound granular material blends.

The Recycled Materials Supplier Dashboard is a strategic tool that supports TMR's broader sustainability goals. By supporting the use of recycled materials, the Dashboard seeks to help reduce the environmental footprint of transport infrastructure projects while also supporting local markets for recycled products.

Further, the platform encourages innovation by making it easier for project teams to find and adopt alternative materials. This will hopefully see a drive in demand for recycled products and supports future innovators.

As Queensland continues to invest in sustainable infrastructure, the Recycled Materials Supplier Dashboard will play a role in ensuring that environmental considerations are embedded in every stage of project delivery, from planning and design to construction and maintenance.

Through the development and launch of the Recycled Materials Supplier Dashboard, there is an aim to see industry stakeholders supported to make more sustainable choices. This project shows the value of research-driven, practical tools.

> By making it easier to find and use recycled materials, the Dashboard is helping to build reliable, cost-effective and sustainable network of suppliers, project teams and contractors.

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ARTICLE 02

A Comprehensive Materials Assessment Framework: Considerations and Implications

Dr Chrysoula Pandelidi, National Transport Research Organisation (NTRO), Australia

1. Introduction

Since 2020, when the Australian Government passed legislation prohibiting the export of waste (DCCEEW 2024), industry and governments have been challenged to provide value-adding alternatives to landfill (DCCEEW 2025). Australia's transport agencies recognised the capacity of the country's expansive transport infrastructure to absorb significant quantities of this waste (Hall et al. 2022).

Furthermore, the scarcity of natural resources has sparked not only the development of innovative substitutes by researchers and industry, such as bio-based alternatives to bituminous binders **(Pandelidi et al. 2025)**, but also a need to understand how to effectively incorporate marginal and non-standard materials **(Austroads 2018)**.

Australia has also committed to decrease greenhouse gas emissions progressively, with a goal to achieve net zero by 2050. The transport sector, however, is increasingly projected to be Australia's largest emitter by 2030 **(DITRDCA n.d.)**. Product stage emissions for standard infrastructure materials alone account for an estimated 5% of Australia's total greenhouse gas emissions and their transportation an additional 0.3% **(Infrastructure Australia 2024)**. Figures specific to sourcing and transporting materials for road construction are not readily available. However, it is recognised that increased uptake of locally available materials will decrease overall project costs and improve sustainability outcomes **(Austroads 2018)**.

There is, therefore, an opportunity for innovation where pathways to decrease transportation distances and resource requirements need to be identified. Efforts so far, though, have shown that the solution to these sustainability challenges is not straightforward. In this context, there are two inherent situations that need to be overcome. Firstly, new materials, whether they are recycled, innovative, marginal or non-standard, introduce an element of the unknown and often require additional assessment for engineering performance, supply chain sustainability, re-recyclability, environmental impacts, and occupational health and safety (OHS) implications **(Zhalehjoo et al. 2025)**. Secondly, the lack of harmonisation of test methods **(Austroads 2023)** and the broad adoption of partially prescriptive specifications across Australia form a barrier to the swift adoption of alternative materials. To enable innovation, test methods and specifications need to be materials-agnostic and outcome-based.

As a first step, a materials assessment framework was developed to provide a structure for the comprehensive and efficient assessment of new materials and to enable their successful adoption in road infrastructure.

2 Framework Approach

The framework was designed to be appropriate for the assessment of recycled, marginal, non-standard and innovative materials, and considers market capacity, potential environmental impacts, potential OHS impacts and engineering performance.

The framework introduces two consecutive levels of assessment. Level 1 seeks to understand available volumes and location and assess any relevant environmental and OHS impacts. The outputs of this assessment include:

- Service regions informed by the location where the new materials are produced and/or processed.
- Sustainable volumes for standard material substitution based on their available quantities and relevant demand within the region.
- Potential environmental impacts and mitigation strategies, where possible.
- OHS impacts and mitigation strategies, where possible.

A hold point follows Level 1 assessment, during which the decision is made on whether the material is safe, sustainable and economically viable. Level 2 outlines the pathway to assessing relevant engineering performance and re-recyclability. During Level 2 assessment, the material and/or mix is tested as/if required to produce an initial comprehensive list of potential applications. This list is then progressively reduced, based on findings from Level 1 assessment.

3. Transformative Value

The evaluation and adoption of recycled, innovative, marginal and non-standard materials in road infrastructure, is not new in Australia. However, it has not been systematic, predominantly focusing on the execution of an expensive laboratory and implementation program, excluding potentially detrimental aspects from the assessment. There has also been a lack of subsequent monitoring and reporting of field evaluation trials, which means that new learnings are not gained, so effort is duplicated.

The developed framework has considered all relevant factors and proposes an efficient and robust pathway to assess new materials minimising effort, redundancies and duplications.

4. Recommendations for Future Research

It is recommended that the assessment framework is further developed into an online platform, where the user can provide three inputs (namely, material type, available quantity and state or territory) and is given an optimum assessment program. The user may be called to progressively select from a list of potential applications generated after all controls have been applied. To develop this online platform, a database needs to be built in the background, including:

- Demand per material type per state/territory.
- Environmental testing requirements and allowable limits per state/territory.
- OHS requirements and allowable limits per state/territory.
- Physical and chemical tests per material type.
- Testing methods and requirements per specification per state/territory.

Importantly, although the developed framework can be adopted with existing test methods and standards in place, it is recognised that unless performance-based specifications are developed, its impact will inevitably become limited. The development of appropriate test methods and reliable performance-based specifications will require:

- Review and development of test methods suitable to assess the performance of materials per material type, including aggregates, binders, fillers and additives.
- Review and development of sample preparation methods in the laboratory.
- Review and development of test methods for mixes including unbound granular, stabilised, concrete and asphalt.
- Determination of the minimum performance requirements.
- Development of representative performance criteria for mixes.
- Development of appropriate quality control and assurance practices.

> Lastly, **Pandelidi and Grenfell (2024)** identified that methods suitable for the environmental and OHS implications of new materials are yet to be developed, with available tests being unsuitable for roading materials.

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ARTICLE 03

Mechanistic Framework for Shift Factor Development in Cemented Pavement Materials

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1. Background

Cemented pavement materials (CPMs), also known as cement-stabilised pavement materials (CSPMs) or cement-treated bases (CTBs), are mixtures of granular aggregates, water and cementitious binders such as Portland cement, lime or other chemical agents (Austroads, 2017). Widely used in road construction and rehabilitation, CPMs are valued for their cost-effectiveness and ability to enhance pavement strength. However, like all structural pavement layers, CPMs deteriorate over time, primarily due to fatigue damage caused by repeated vehicle loading. Fatigue cracks typically initiate at the bottom of the CPM layer and propagate upward, progressively degrading the pavement's load-carrying capacity. To evaluate and predict fatigue performance, laboratory tests, such as unconfined compressive strength (UCS), indirect tensile (IDT) and four-point bending (4PB) tests, are commonly used to assess mechanical properties and fatigue life (Austroads, 2020; Pai et al., 2022; Richard, 2012; Zhang et al., 2022). Despite their usefulness, laboratory tests cannot fully replicate the complex conditions experienced by CPMs in the field. Field conditions often differ significantly from laboratory settings in terms of boundary constraints, stress and strain states, loading modes, and variations in material properties, among other factors. As a result, predictions based solely on lab data often fail to reflect actual field performance.

To bridge this gap, shift factors (SFs) – numerical adjustments to laboratory results – are used to estimate field fatigue life. SFs are central to mechanistic-empirical design standards **(Austroads, 2017; SANRAL, 2013)** and remain a focus of ongoing research. However, SF values reported in the literature vary widely, largely due to the inconsistency in experimental methods and fatigue failure definitions **(Al-Qadi & Nassar, 2003; Ma et al., 2019; Mateos et al., 2011; Prowell, 2010)**. Laboratory fatigue failure is often defined by modulus reduction, while field fatigue failure is typically identified by surface cracking. Furthermore, differences between laboratory-prepared and in-situ materials add to this variability **(Austroads, 2008b)**. To address these issues, a more robust and transparent approach is needed – one that applies consistent failure criteria across scales and captures the mechanisms driving the shift in performance between them. Numerical modelling offers a promising solution by simulating key fatigue behaviours, including modulus reduction, fatigue life and crack growth, while accounting for failure mechanisms, boundary and loading conditions. Compared to purely experimental approaches, numerical methods provide greater certainty and deeper insights. Building on these advantages, this study introduces a mechanistic methodology for developing lab-to-field shift factors. By combining rigorous fatigue modelling with a consistent failure criterion (i.e., modulus reduction), this framework offers a more reliable means of predicting the fatigue performance of CPMs in the field **(Le et al., 2024)**. To ensure accessibility for a broad audience, this paper focuses on the motivation, key findings and practical implications of the study, rather than technical details, aiming to inform both decision-makers and technical professionals interested in implementing these insights.

2. A Mechanistic Approach to Developing Lab-to-Field Shift Factors

This section outlines a mechanistic methodology that links laboratory and field fatigue performance through fatigue damage modelling and a consistent failure criterion, as illustrated in Figure 1. The approach begins with a two-scale fatigue model **(Le et al., 2023)**, calibrated against four-point bending (4PB) test data on Australian CPMs – namely, siltstone and hornfels **(Austroads, 2008c)**, as described in Section 2.1. The model captures key fatigue behaviours observed in the lab, including modulus reduction curves and fatigue crack growth, offering a reliable basis for predicting field performance **(Le et al., 2024)**. After validation with laboratory tests, the model is applied to simulate in-situ performance using full-scale accelerated loading facility (ALF) test data **(Austroads, 2008a, 2008b)**, detailed in Section 2.2. Crucially, the same fatigue failure criterion (modulus reduction) is applied consistently at both scales, ensuring meaningful comparisons. By explicitly accounting for differences in strain states and boundary conditions between laboratory and field conditions, the methodology quantifies the intrinsic shift in fatigue performance without entirely relying on empirical adjustments, as discussed in Section 3. This provides mechanism-based shift factors that are both reliable and practical for engineering applications.

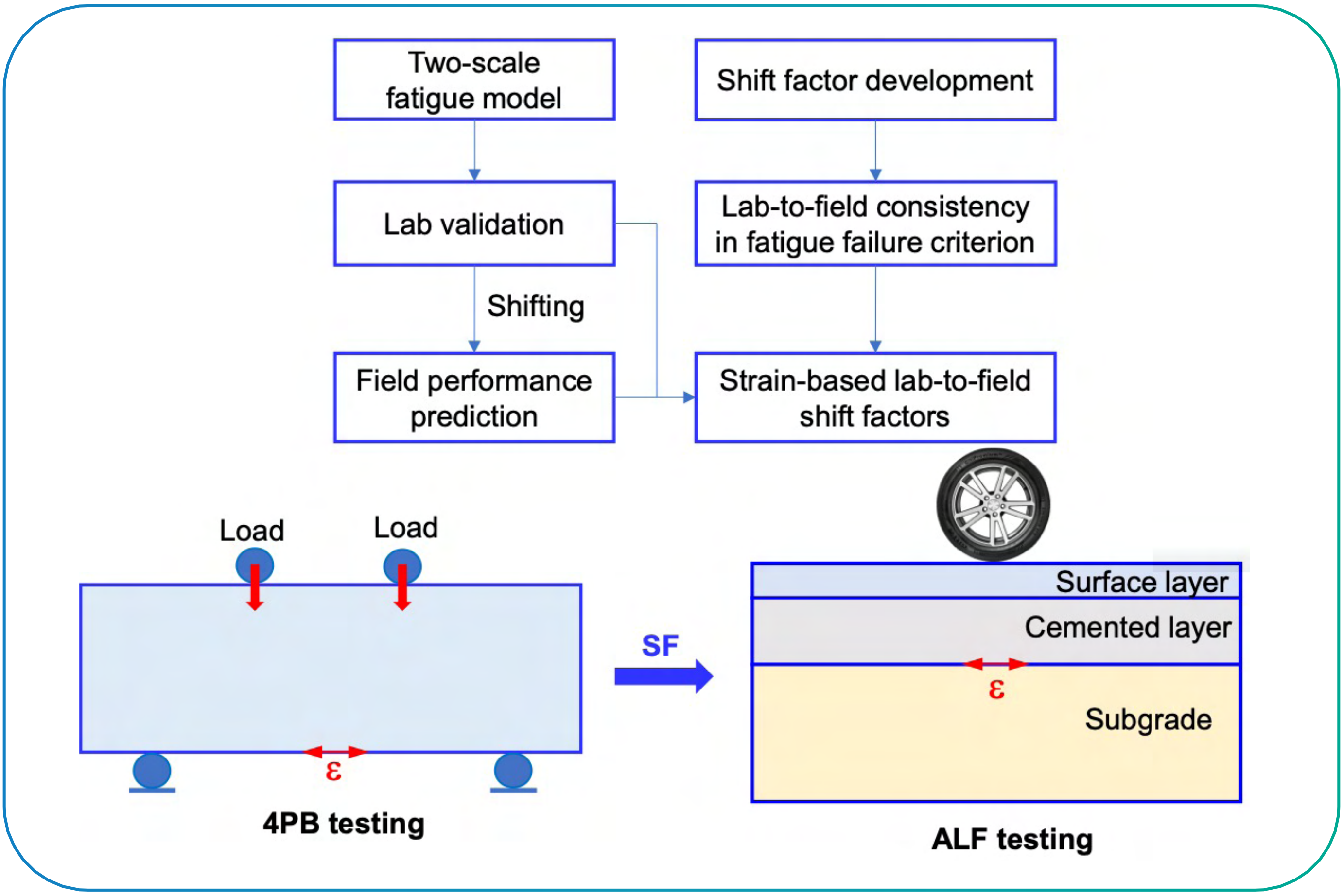


Figure 1: Proposed methodology for SF development (Le et al., 2024).

2.1 Validation of CPMs' Fatigue Characteristics at Laboratory Testing

This section focuses on evaluating the fatigue behaviour of CPMs in the laboratory using the developed fatigue model developed by **Le et al. (2023)**. The model was implemented in the commercial software ABAQUS and applied to simulate two-dimensional 4PB tests on two typical CPMs: siltstone and hornfels **(Austroads, 2008c)**. To assess the model's ability to predict fatigue performance under different stress levels accurately, simulation results were compared against experimental data, as shown in Figure 2. The comparison examines the relationship between the initial micro-tensile strain – measured at the mid-bottom of the beam (see Figure 1) – and the corresponding fatigue life, expressed as S-Nf curves. Here, fatigue life Nf is defined as the number of load cycles required for the material's modulus to decrease by 50%, following **(Austroads, 2014a)**. The results show that the model successfully captures the strong influence of stress level on fatigue life, demonstrated by the close agreement between the simulation trend line and the experimental observations.

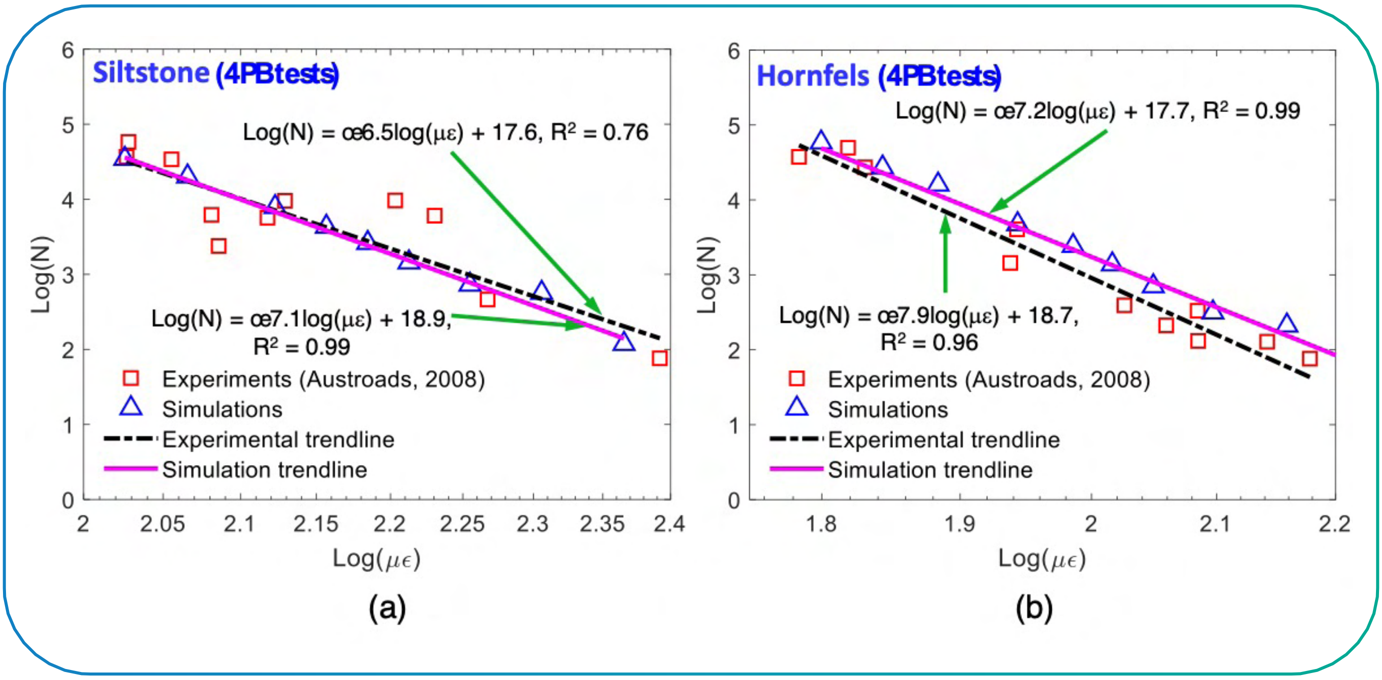


Figure 2: Comparison of initial micro-tensile tensile strain versus fatigue lives (S-N_f curves) between simulation and experiments: (a) Siltstone materials; (b) Hornfels materials (Le et al., 2024).

2.2 Prediction of CPMs' Fatigue Characteristic at Full-Scale Testing

Based on the calibrated fatigue model parameters presented in Section 2.1, this section predicts the full-scale fatigue performance of CPMs. To do so, two-dimensional simulations were conducted, replicating full-scale testing under ALF loading conditions **(Austroads, 2008b)**. Notably, the CPMs used in the 4PB laboratory tests were identical to those used in the ALF experiments **(Austroads, 2008c)**. The experimental layout of the ALF tests, conducted by the former Australian Road Research Board (ARRB, now the National Transport Research Organisation, NTRO) **(Austroads, 2008b)**, is shown in Figure 3. Two pavement sections were constructed using different CPMs: siltstone and hornfels. Each experimental layout consisted of 7.5 m wide by 45 m long cemented pavement sections, allowing for up to six ALF experiments per CPM type. Before loading, the hornfels and siltstone layers were cured for four and seven months, respectively. The test sections were subjected to continuous rolling loads using a dual-wheel half-axle, with applied loads ranging from 40 to 80 kN. All experiments were conducted indoors under dry conditions to eliminate environmental influences.

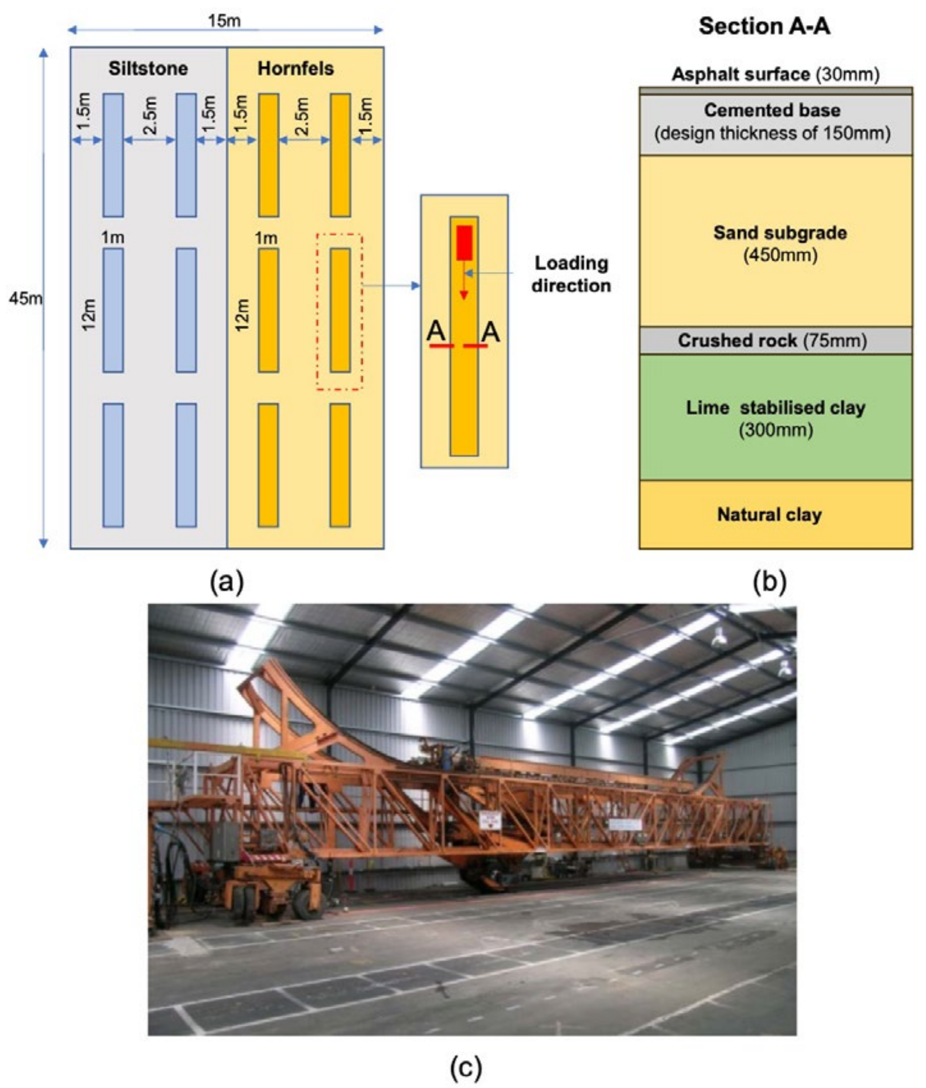


Figure 3: ALF tests: (a) Experiment layout; (b) Test pavement structure (Le et al., 2024); (c) The Australian ALF operating indoors at Dandenong, Victoria (Austroads, 2008b)

To evaluate the model's quantitative performance, S-Nf curves derived from both the simulations and experiments are compared in Figure 4. The comparison shows a consistent trend, with simulated fatigue lives falling within the range of the experimental data. However, the simulation trend line slightly overestimates the initial strain relative to the experimental observations. This discrepancy is likely due to differences in how the initial tensile strain was calculated. The experimental results assume an elastic pavement structure under axisymmetric conditions, whereas the simulations compute the initial strain under plane stress conditions. Additionally, differences in the assumed modulus and thickness of pavement layers in the ARRB's elastic modelling, compared to the calibrated subgrade modulus in the simulations, may also contribute to the observed variation.

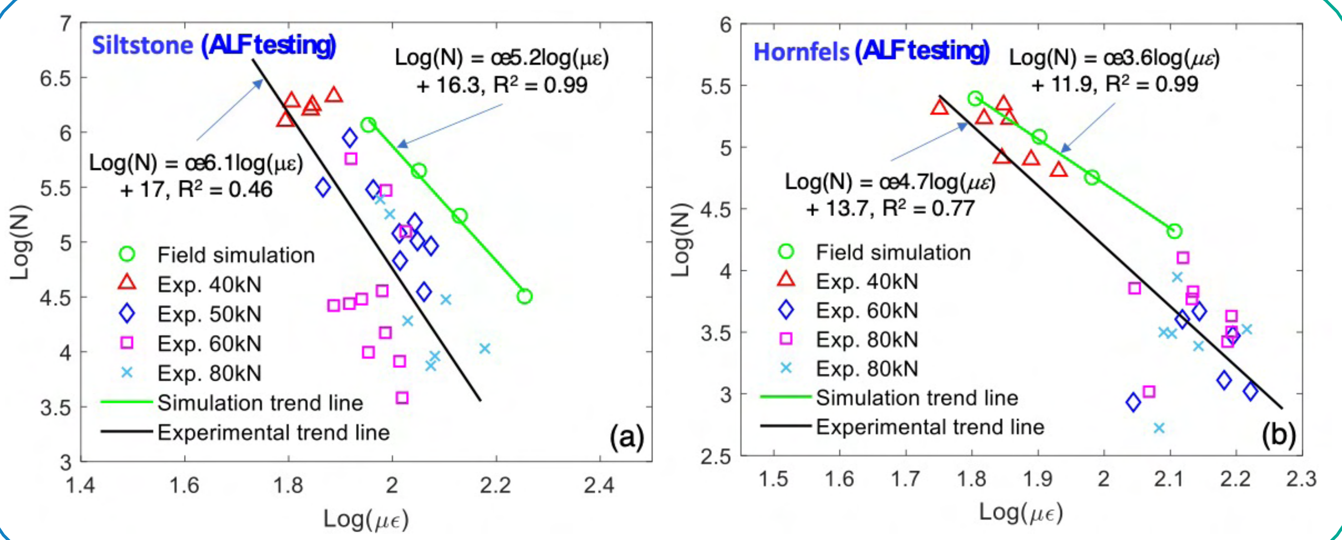


Figure 4: Comparison of initial micro-tensile strain versus fatigue lives (S-Nf curves) between field-scale simulation and ALF experiments for: (a) Siltstone materials; (b) Hornfels materials (Le et al., 2024).

3. Fatigue Shift Factor Development and Implications for Design

The primary goal of this study is to bridge the gap between laboratory and field fatigue performance of CPMs by deriving reliable shift factors (SFs). To this end, S-Nf curves from simulations of both laboratory-scale (4PB tests) and field-scale (ALF tests) fatigue performance are plotted on a logarithmic scale in Figure 5a and Figure 5c. As shown, a clear shift appears in the log(Nf)–log(με) relationship when moving from laboratory to field conditions, mainly due to differences in boundary conditions and resulting failure mechanisms **(Le et al., 2024)**.

Austroads (2014b, 2017) has long recommended a strain-based fatigue equation, proven effective in both laboratory and accelerated loading data and forming the basis of their design procedures for decades.

This equation is expressed as:

$$N = \left(\frac{k}{\mu\varepsilon}\right)^{12}$$

where

N	=	the allowable number of load repetitions from fatigue testing
με	=	the load-induced tensile strain at the base of the test beam or cemented layer (microstrain)
k	=	a fatigue constant

The strain damage exponent (SDE) of 12 in Equation 1 represents an average value derived from a large dataset of laboratory fatigue tests on various CPMs and is adopted in this study. Using this SDE, mechanism-based shift factors (M-SFs) of 1.19 and 1.21 were determined for siltstone and hornfels, respectively, as shown in Figure 5b and Figure 5d. These SFs are the outcome of a rigorous fatigue modelling approach, validated comprehensively at the laboratory scale and shown to predict field performance reasonably. Importantly, applying a consistent fatigue failure criterion across laboratory and field conditions makes these M-SFs more reliable and distinguishes them from previously proposed SFs for CPMs. It is also worth noting that the M-SFs in this study are derived within the strain-fatigue life space, explicitly addressing the strain differences between laboratory and field conditions (see Figure 1). The resulting M-SFs are lower than the strain-based SF of 1.9 recommended by **(Austroads, 2014b)**, which was derived empirically from Mulgrave ALF tests and based on a threefold reduction in modulus (as detailed in Sections 3.1 and 7.4 of **Austroads (2014b))**. That original SF of 1.9 was later adjusted to 1.8, reflecting a revised definition of in-service fatigue life as one-fifth, rather than one-half, of the initial modulus. In practice, this empirical SF converts laboratory results – obtained from well-cured beams with minimal micro-cracking and high modulus – into design models using a design modulus equal to one-third of the 90-day laboratory value. In contrast, the M-SFs presented here aim to capture the intrinsic shift in fatigue performance from laboratory to field scale. They are derived from simulations calibrated with laboratory fatigue relationships reported in **(Austroads, 2008c)**, which were influenced by micro-cracking due to disruptions during moist curing. Therefore, the M-SFs of 1.19 and 1.21 for siltstone and hornfels, respectively, should be interpreted as applicable to weaker field areas that may have experienced some micro-cracking before loading.

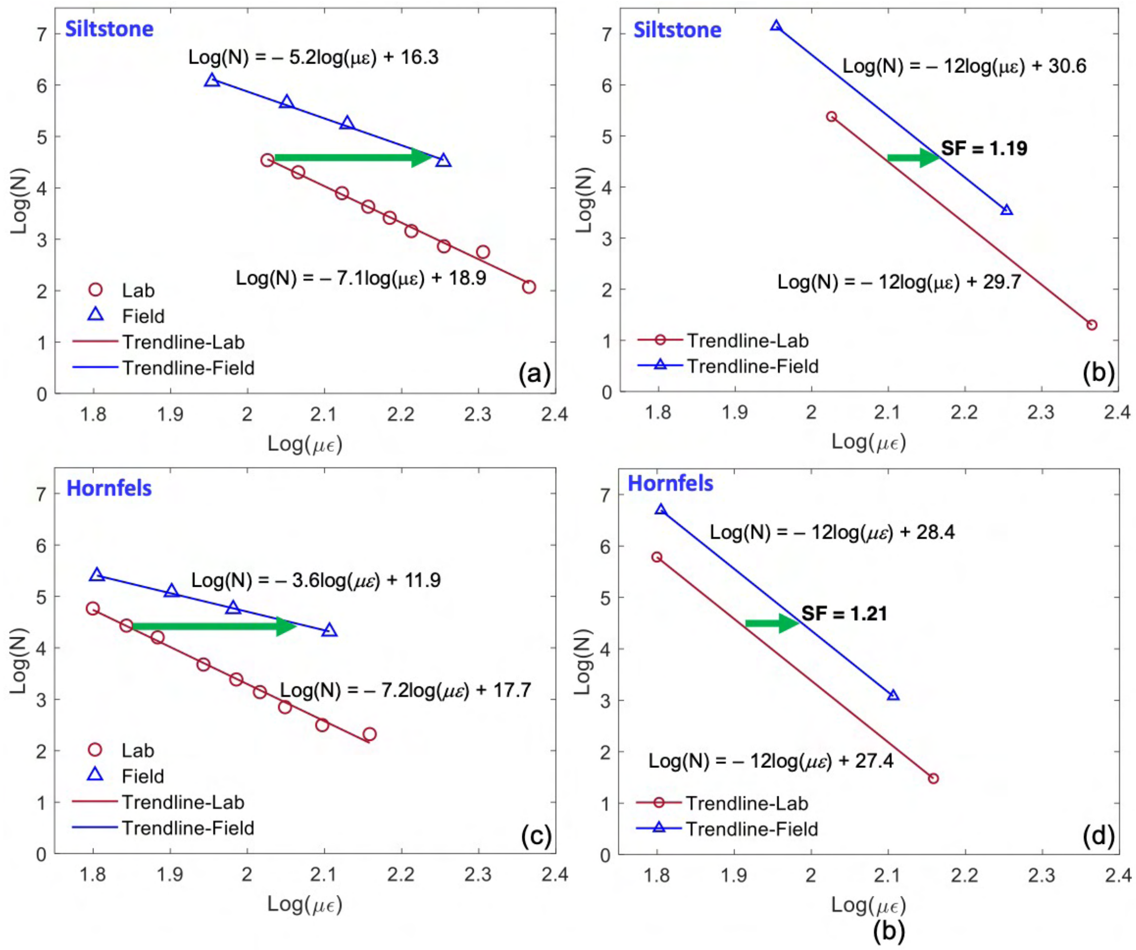


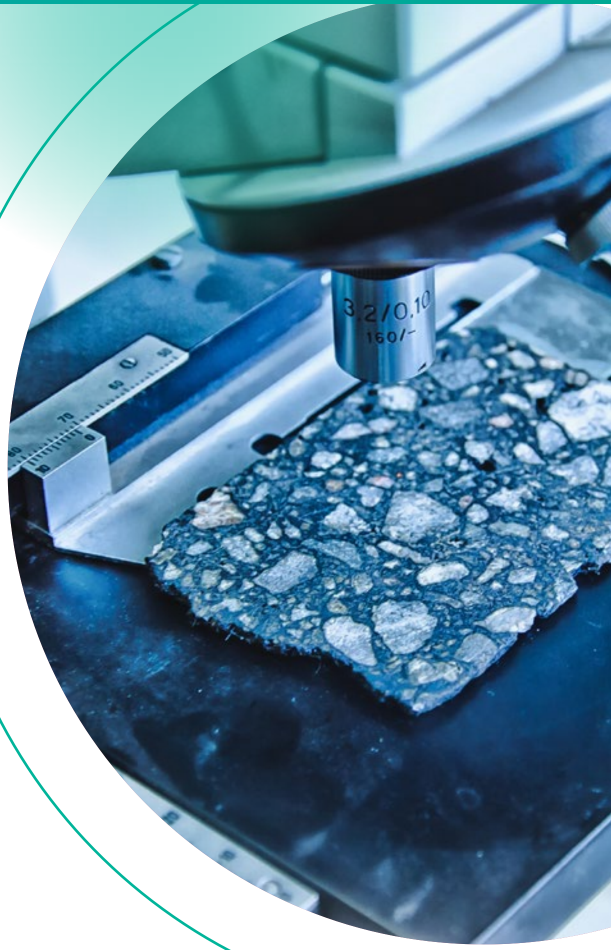
Figure 5: Shifting in strain and fatigue lives from lab to field scale: (a) Lab-to-field shifting for hornfels; (b) Lab-to-field SF for hornfels using SDE of 12 (Le et al., 2024).

4. Conclusion and Future Works

This study demonstrates that a mechanistic, modelling-based methodology can reasonably develop the translation of laboratory fatigue test results into field performance predictions for CPMs. By combining laboratory calibration, field validation and a consistent failure criterion, the approach produces reliable and practical shift factors. The strain-based lab-to-field shift factors derived here – 1.19 for siltstone and 1.21 for hornfels – represent the intrinsic mechanical differences between laboratory and field conditions rather than traditional empirical factors. This enhances confidence in fatigue life predictions and supports more informed pavement design and maintenance decisions.

Although developed for CPMs, the methodology is adaptable to other pavement materials and conditions, offering a pathway toward more resilient and cost-effective road infrastructure. Future research should aim to develop more generalised shift factors by accounting for additional influences, such as moving loads, traffic wander, and increasingly extreme environmental conditions, which differ markedly between laboratory and field settings.

> Finally, developing methods to integrate individual shift factors – each representing different contributing mechanisms – into a single and comprehensive factor, remains an important area for further investigation.



5. Acknowledgements

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ARTICLE 04

Characterising pavement roughness using smartphone-collected vehicle response data

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1. Introduction

Roads are key to a nation's transportation and maintaining their condition is crucial for ensuring user safety and vehicle ride comfort. Monitoring pavement roughness is therefore essential for informed decision-making in maintenance planning and remedial works. As digital technologies advance, the monitoring of road roughness has begun to incorporate more ubiquitous sensing technologies. In addition to conventional professional pavement survey instruments, public vehicles (i.e., vehicles owned by the general public) travelling on road networks can also serve this purpose. Pavement roughness causes vibrations in the vehicle body, which can be measured using smartphone sensors. These sensors have the potential to be a prevalent tool for collecting vehicle-based response data. However, smartphone-based systems are affected by variations in practical factors, including travelling speed, vehicle type and mounting configurations. These inconsistencies and uncertainties result in significant differences in measurements among different users. Hence, this research investigated the impact of these practical factors and developed methods for characterising pavement roughness considering these factors, by leveraging crowdsourced public vehicles.

We first developed a standardised evaluation framework to systematically assess the performance of three commercial smartphone-based roughness index estimation apps. Next, we investigated the impact of smartphone mounting configurations on smartphone-collected vehicle response data. A laboratory vibration test was conducted to obtain the response function of the mounting configurations. Frequency-domain correction functions were developed to mitigate their impact, which was evaluated in field tests. Subsequently, the research developed a method to estimate the roughness profile using vehicle body response sequences, taking into account vehicle parameters such as weight and suspension characteristics. Details are highlighted in the following sections.

2. Evaluating existing smartphone-based roughness estimation systems

The review suggests that an understanding of the performance of the state-of-the-art smartphone-based roughness index estimation (sRIE) systems is lacking, with no standard procedures for validating their performance. Multiple sRIE systems have become available recently. However, there is no framework to evaluate the performance of sRIE systems in a systematic and repeatable manner. This work aimed to develop and validate a framework for evaluating sRIE systems for pavement roughness assessment. It is the first attempt to integrate practical factors that affect sRIE systems into the evaluation framework. Using these factors, an evaluation framework was established and the computation of the statistical test measures explained. A field experiment then evaluated three existing sRIE apps side-by-side, as shown in Figure 1 and Figure 2.

Figure 1: Evaluating the performance of the existing Apps

Figure 2: NTRO survey vehicle

The proposed framework was used to validate the sRIE systems' repeatability and accuracy against conventional measurement instruments. The statistical measures have shown that the sRIE systems' performance becomes less robust when tested on gravel pavement. Two of the three sRIE systems depend on survey speed, vehicle type and mounting variations. However, the third system can provide consistent measurements regardless of practical factor variations, and the results are demonstrated in Figure 3.

The results have proved the validity of the proposed framework to assess the performance of the tested systems. The general performance of current sRIE systems was found to have an R2 value in the range of 0.5 to 0.7, when tested on sealed pavement. Building on these findings, the next section focuses on quantifying the impact of the mounting configuration on the response of the smartphone and developing a correction function to mitigate its impact.

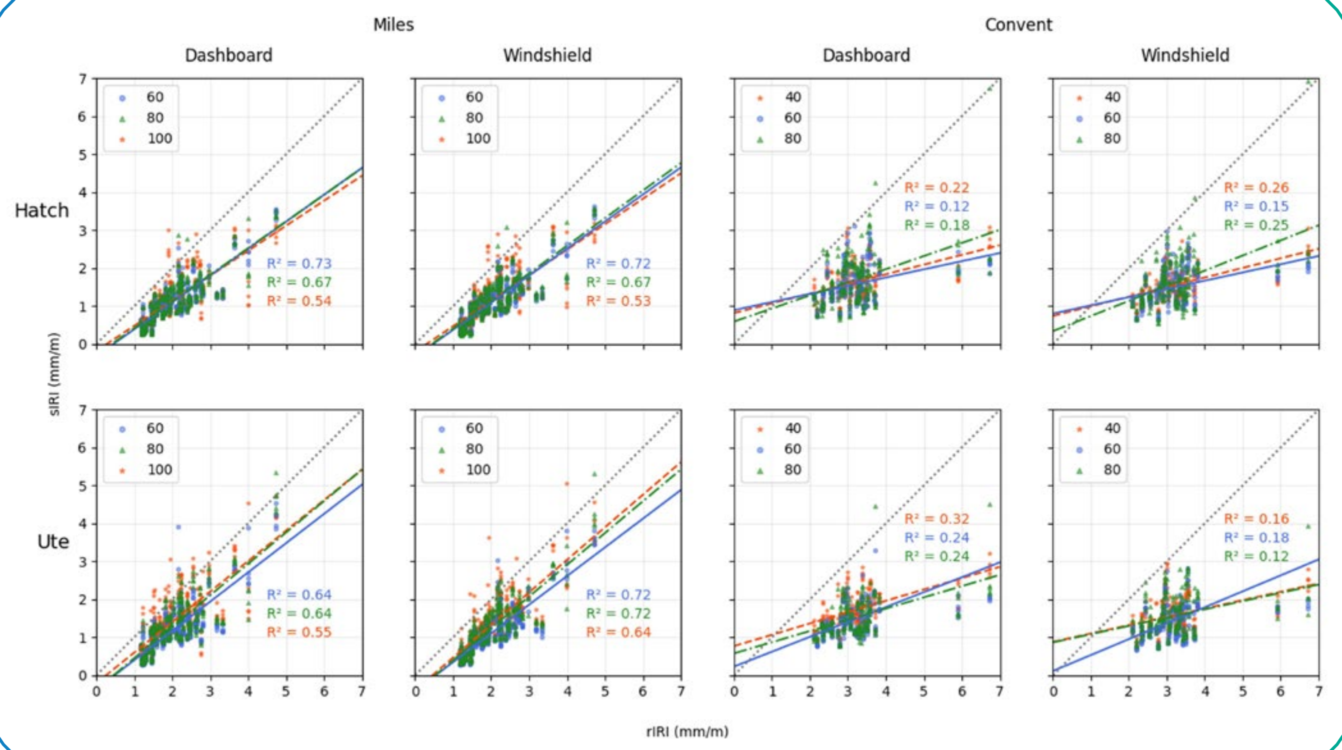

Figure 3: Performance of the existing sRIE system (Yu, Fang & Wix, 2023)

3. Quantifying and mitigating the mounting-induced impact on the smartphone-collected vehicle response

The results from the field experiments of the existing sRIE Apps have shown that they do not consider the different systems used to mount the smartphone. As a result, the measurements obtained from different smartphone mountings are significantly inconsistent. Among the practical factors that affect the smartphone-collected data, the mounting type has been underexplored, despite its significant influence on the smartphone-collected vehicle response data.

This section aims to quantify the effects of four typical mountings on smartphone-collected response data and develop a method to correct their measurements to accurately reflect the vehicle-body response. As shown in Figure 4 , an empirical-based correction function was obtained from a laboratory vibration test and validated using real-world vehicle response data. This study found that the mountings amplify the signals in a 7-20 Hz frequency band, depending on their arm length and rigidity, while attenuating the amplitudes of vibrations above 30 Hz. The proposed method reduces the differences caused by different mountings through amplitude correction in frequency bands.

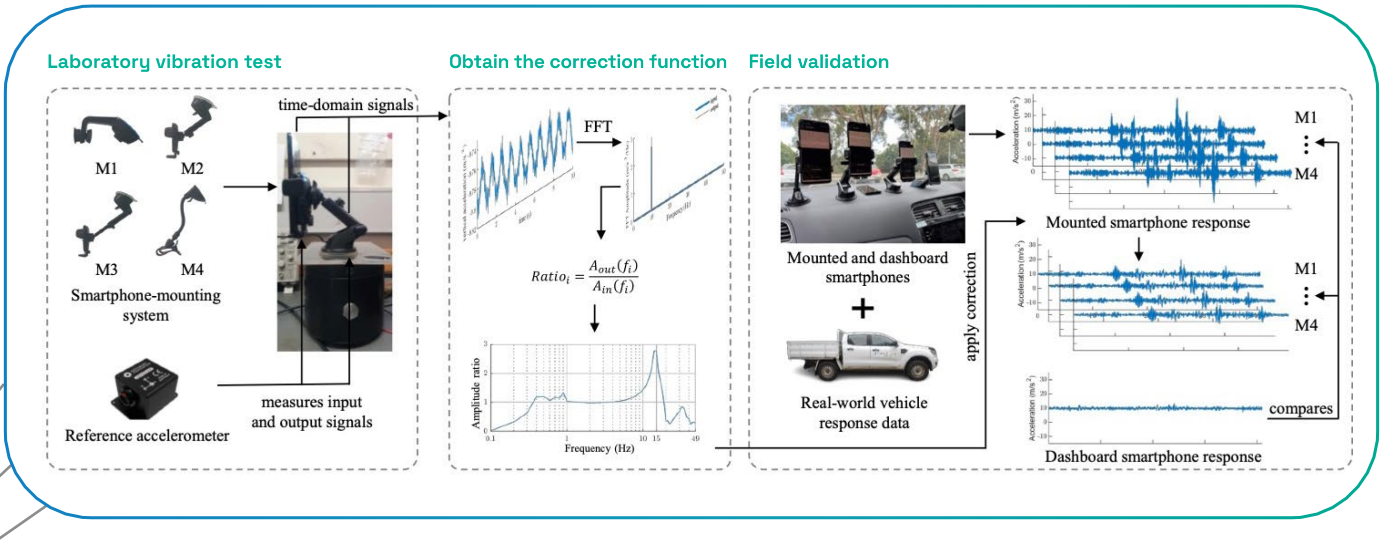

Figure 4: Schematic flowchart of the mounting correction method

3.1 Laboratory vibration experiment

The experimental set-up comprises the smartphone-mounting system, a dedicated accelerometer, vibration instruments, and a flat mounting platform. The vibration instruments include a waveform generator, a power amplifier, and a vibration exciter that is predominantly used for calibrating accelerometers. The vibration signal was first created in the wave generator, then passed to the amplifier. The amplifier increases the power of the signal so the exciter moves vertically in a pattern that reflects the generated signal. Connected to the exciter, the flat platform provides a base for the smartphone mountings to sit on. The platform was fastened to the exciter using screws, ensuring the effective transfer of vibrations. The schematic representation and a photo of the actual set-up are shown in Figure 5 (a) and (b) respectively.

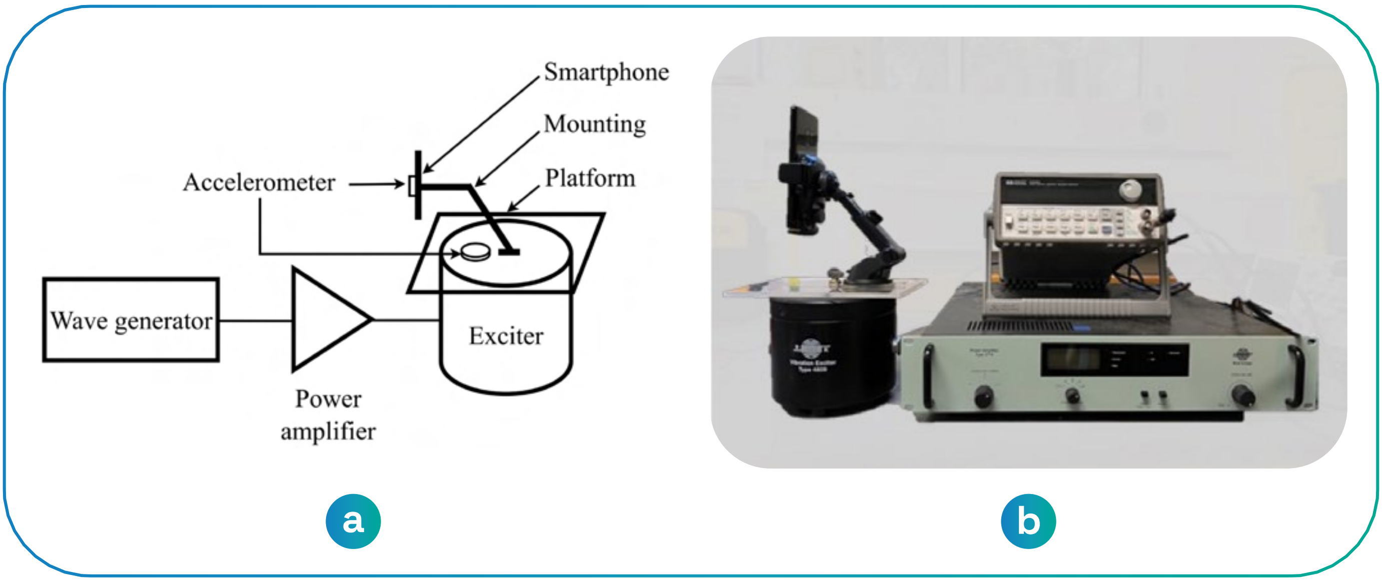

Figure 5: Schematic plot and Exciter set-up

As shown in Figure 6, four different smartphone-mounting systems were installed on the dashboard of the vehicle cabin using a suction mount, while the smartphone that collects the reference signal was mounted to the dashboard using double-sided tape.

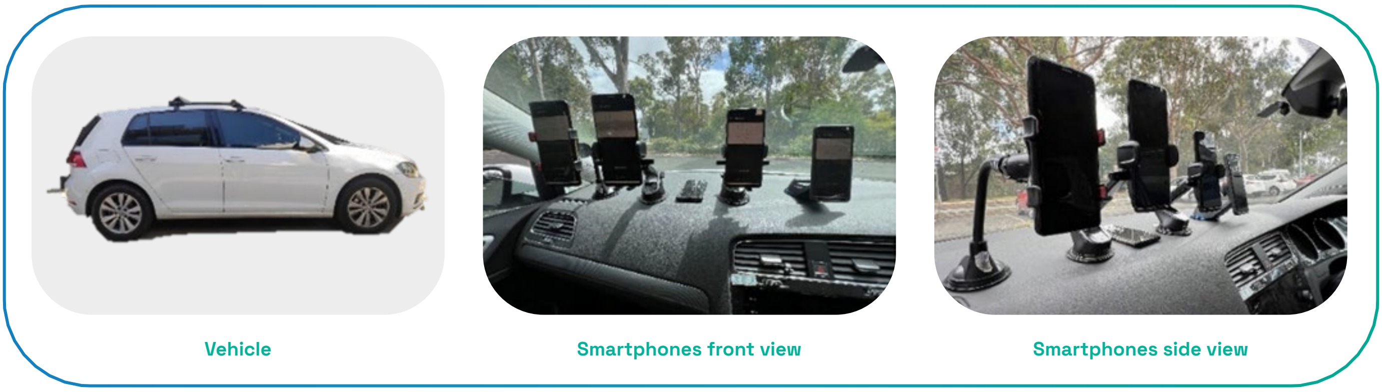

Figure 6: In-cabin set-up

3.2 Validation of the mounting correction function

The bandpower plots for the full 1.05 km of response data were calculated for each mounting type to demonstrate the performance of the correction function.

Before correction. As illustrated in Figure 7(a), the dashboard reference (in grey) exhibits consistently lower bandpower amplification across all frequency ranges compared to smartphones mounted on various arms. Each mounting setup amplifies vibrations most prominently within a specific frequency range, generally between 5 and 25 Hz. Specifically, the short and medium length arms exhibit strong amplification around 17 Hz, while the longer and flexible arms peak in the bands of 9 Hz and 7 Hz, respectively.

After correction, the recalculated bandpowers, shown in Figure 7(b), indicate that the previously high peaks have been successfully reduced and now align more closely with the reference signal. Variations in bandpower among the different arm mountings are significantly lower. In particular, all four mount types show a greater consistency with the reference within the 0–10 Hz range, with no major peaks or dips. However, some discrepancies remain: the medium length arm shows elevated bandpower in the 15–25 Hz range; and the short arm still peaks in 17 Hz. Overall, the correction function effectively lowers the Root Mean Square Error across each of the setups, reducing the deviation from the reference data set and enhancing the accuracy of the responses in relation to the vehicle body's behaviour, regardless of the mounting configuration.

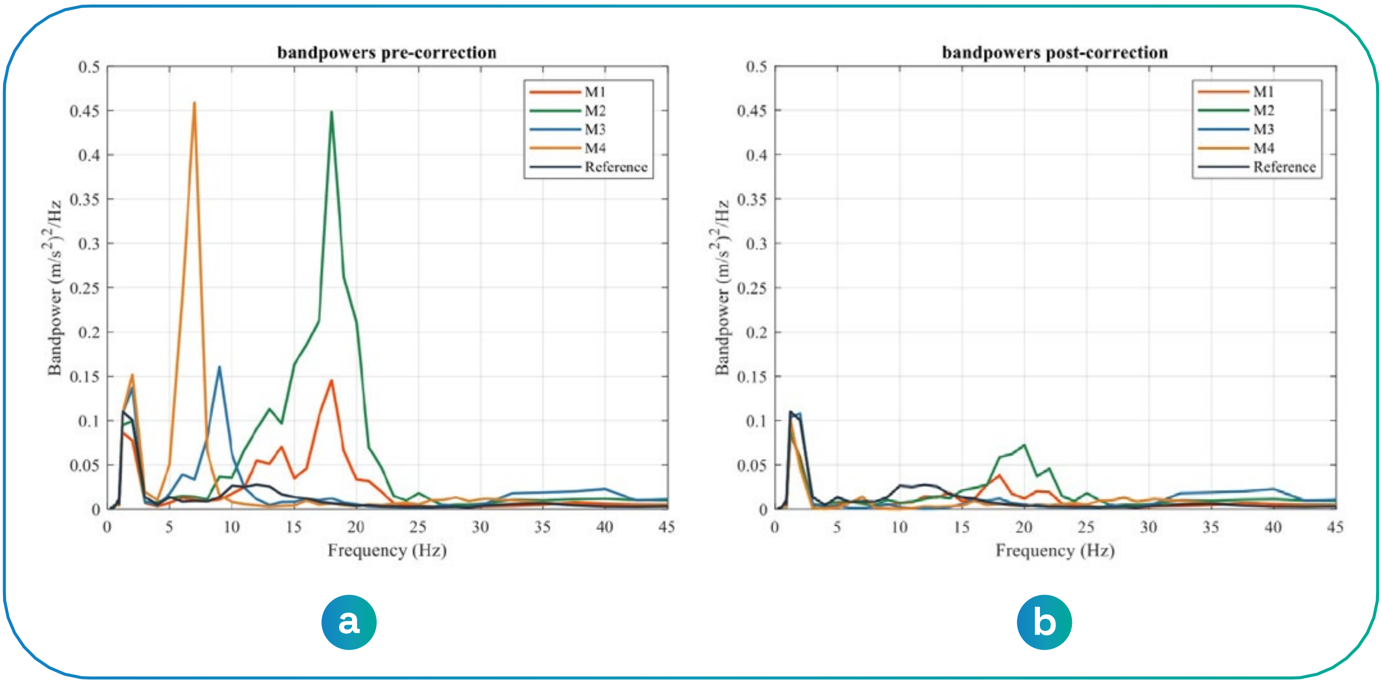

Figure 7: Bandpower of the signal from mounted smartphones – pre correction (a); post correction (b)

4. Develop a profile estimation method considering vehicle specifications

The previous section investigated and quantified the impact of the mounting mechanism on the vehicle response to the pavement profile measured by the smartphone. This section aims to address another critical factor that introduces a significant amount of uncertainty into the measurements made by the smartphone: vehicle type. To develop a robust roughness characterisation method, it is essential to investigate the impact of vehicle type on response data collection and to develop a roughness profile estimation method based on vehicle body response. As demonstrated in Figure 8, this section presents a method for reconstructing the roughness profile that considers the vehicle specification. Real-world speed and roughness profiles, and simulated vehicle responses, were used in the training and validation procedures.

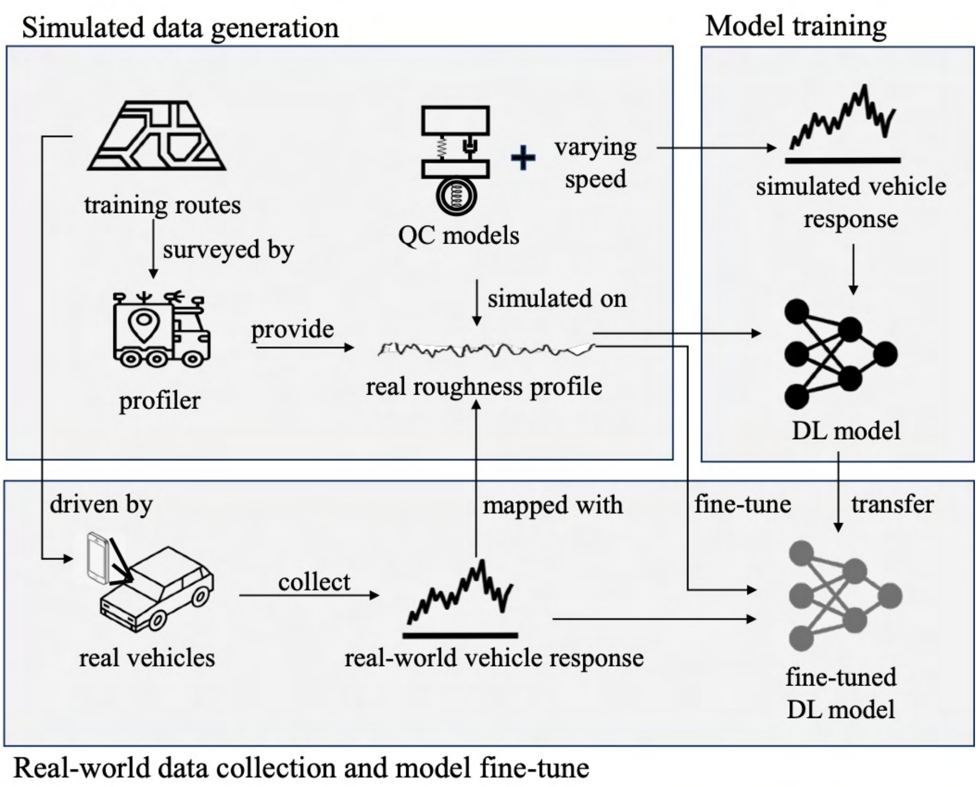

Figure 8 Schematic flowchart of the vehicle-based roughness profile estimation

The IRI of the estimated profiles across a 1000 m segment of the testing route is demonstrated. With a reporting length of 10 m, Figure 9 presents IRI measurements for two different vehicles (Sedan and SUV) traversing the same road section versus their respective reference profile. The colour shading indicates the percentage of differences between the estimated IRI (eIRI) and the real IRI (rIRI), with the blue indicating differences of > 10 % and the orange indicating > 20%. Where there is no shade, it suggests a < 10% difference between the two.

In general, the eIRI shows a high level of agreement with the rIRI, with no drastic differences between the two vehicles' performances. Notably, the two eIRIs pick up the peak at chainage 200 m, as well as the moderate peaks at chainage 600 - 800 m. Meanwhile, the eIRIs correlate well with the rIRIs in the < 5 IRI segment, including chainage 0 - 150 m, 250 - 600 m, and > 750 m. It was also noted that the changes in speed do not affect the accuracy, though noticeable deviations are shown in the 600 - 800 m segment where there is a significant speed drop. Judging by the shaded background, the performance of the two vehicles across the entire testing route is close, as evidenced by the similar R2 values in the range of 0.58 to 0.65. Nonetheless, it is worth noting that a significant deviation happens at chainage 650 m for both vehicles. In fact, similar deviations happen along the testing route occasionally. This is likely due to the unusual measurements in the response sequence, attributed to factors beyond the roughness conditions.

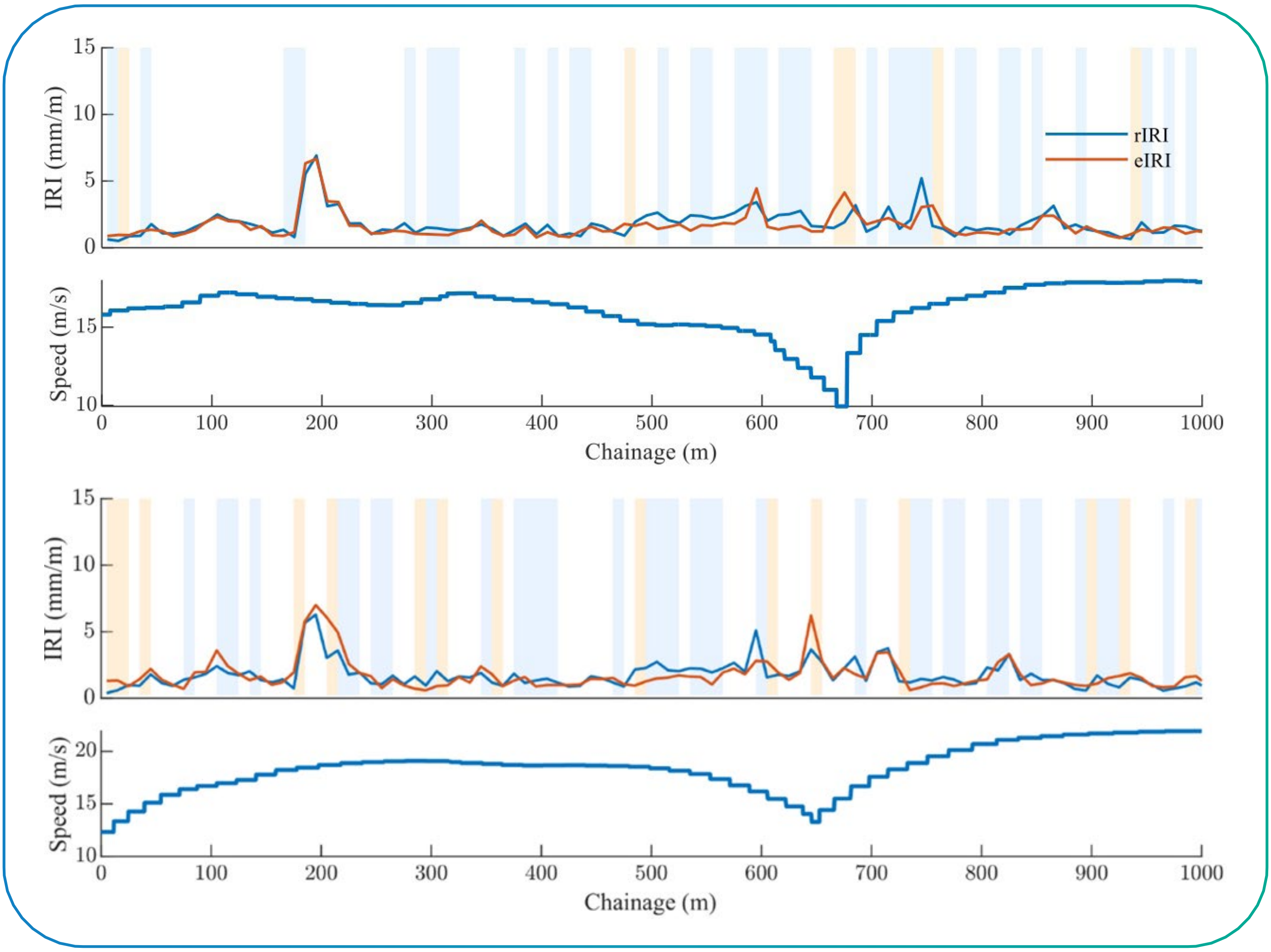

Figure 9 Estimated IRI from the vehicle response (above SUV; below Sedan)

5. Conclusion

The modern methods of roughness monitoring aim at engaging public drivers, with vehicle-mounted smartphones used to collect response data from public vehicles. While a number of existing studies have developed methods of estimating the roughness index from the smartphone-collected response data, the issue of practical uncertainty has not been addressed. The accuracy and consistency of the current smartphone-based approaches are affected by practical factors including speed, vehicle type and mounting configuration. Our work aims to understand how variations in different practical factors affect the smartphone-collected vehicle response data, and to develop methods of mitigating such impacts and characterising roughness conditions more accurately.

First, an evaluation framework was developed to validate smartphone-based roughness index estimation (sRIE) systems, introducing 6 metrics to assess their accuracy and consistency. Field tests on three commercial sRIE Apps revealed that their R-squared values against the ground-truth IRI ranged from 0.5 to 0.7, indicating significant limitations in robustness against mounting and vehicle variations. We then focused on understanding the impact of smartphone mounting on collecting vehicle response data. Empirical-based correction function was obtained from a laboratory vibration test and field validated using real-world smartphone-collected responses. The correction of the 4 typical mounting configurations provides a viable approach to mitigate the mounting's impact on transferring vehicle body response data, as evidenced by bringing down the powerbands of the smartphone-mounting systems closer to that of the reference signal. Next, the vehicle factor was studied. The variation of the vehicle model imposes variations to the vehicle collected response excited even by the same roughness profile and, as a result, causes inconsistency in the estimated roughness index. Therefore, our research aims to accommodate the vehicle factor by taking into account the vehicle specification in estimating the roughness index. The estimated IRI reached an R2 of 0.72 compared to the reference IRI.

The research contributes to the body of knowledge of accelerometric-based pavement roughness characterisation by: 1) providing a comprehensive evaluation framework for sRIE systems; 2) developing correction functions to mitigate mounting's interference in practical data collection and; 3) proposing a roughness profile reconstruction approach considering vehicle specifications.

> Ultimately, this study advances pavement condition monitoring by integrating ubiquitous sensing and public vehicles.

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ARTICLE 05

Reimagining First-Mile Access: A Cost-Neutral Parking Strategy to Promote Public Transport Usage

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Poor first-mile access limits public transport use in many urban regions. By changing how parking works, we propose a first-mile solution to increase train ridership and service quality. It is cost-neutral, with generated revenue offsetting the anticipated costs, achieving a net-zero financial impact. Using Wellington Metro Railway Network in New Zealand as a case study, this article evaluates its potential impact on travel modal shift, revenue growth and equity gains, contributing to a more sustainable urban mobility framework.

1. Introduction

Public transport systems are crucial for urban mobility. New Zealand Government (2024) emphasises enhancing them for sustainable urban development. However, connectivity challenges between public transport networks and passenger origins/destinations often deter users, leading to a preference for private vehicles over public transits. Greater Wellington Region features a typical spatial separation between commercial and residential areas. A significant portion of Wellington City employees commute from its outskirts, including Porirua City, Lower Hutt City and Upper Hutt City (Wellington Regional Growth Framework, 2020). Wellington Metro Railway Network covers these major commuting demands.

This study proposes an innovative, cost-neutral parking model for the Wellington Metro Railway Network, focusing on daily commuting. It combines free carpooling facilities and paid single-occupancy parking that charges $5 on weekdays, promoting shared rides to local train stations and regular train commutes. This first-mile solution anticipates additional revenue from paid parking and increased train ridership. This revenue could be reinvested into rail infrastructure maintenance and peak-hour service frequency increases, ultimately supporting a self-sustaining cycle of commuter growth and service enhancements. This concept is globally transferrable to cities with similar spatial characteristics.

Beyond the rail ecosystem, this proposed solution may be beneficial to easing traffic congestion, lowering carbon emissions, as well as reducing road accidents and maintenance costs **(Greater Wellington Regional Council, 2022)**. Figure 1 illustrates the policy concept. The $5 charge is also illustrative of how this system could work and may be replaced by another amount in real-life practice.

The initial investment to roll out the programme involves the costs for regulatory and policy assessment; smart parking technology, including camera monitoring systems and system integration to support monitoring logistics; signage and road markings to clearly designate carpooling and paid single-occupancy spaces; as well as public-awareness promotion through targeted social media and station-based marketing. The overall cost is estimated to be under NZ$2,000,000 and can be proposed as a small project within the Value for Money (VfM) programme as part of the investment portfolio of NZ Transport Agency Waka Kotahi.

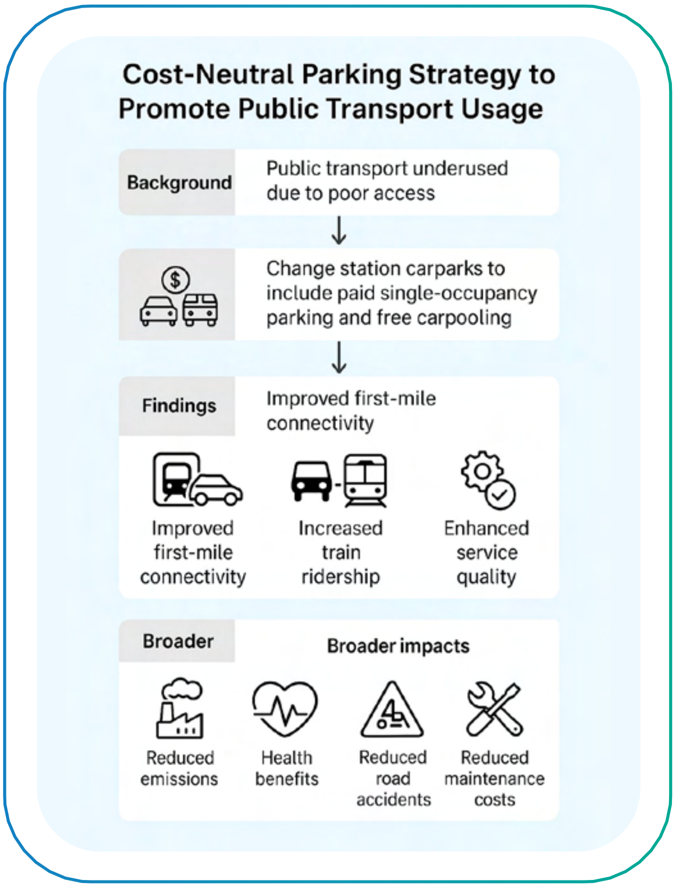

Figure 1: Illustration of the concept of the proposed parking policy

2. Modelling Patronage Fluctuations

The core concept is to transform existing carparks at local train stations into an active policy lever. It encourages commuters to shared riding through cost incentives and increases train ridership through easier station access. It provides rail agencies with a modest, stable income stream to enhance service quality, such as increasing peak-hour frequency without major capital investments.

The rail patronage is studied to obtain an expected patronage trajectory over the next two years without the proposed carpooling intervention. It serves as a baseline for predicting carpool usage fluctuations.

2.1 Analysing Past Patronage

Figure 2 displays weekly rail patronage from November 2022 to June 2024, with troughs during holiday periods. For the rest of the year, the weekly ridership largely remains between 125,000 and 175,000.

A multivariable regression identifies the number of days off work, average atmospheric visibility and rail service reliability during the week, as key drivers of past patronage variations. A local level model with explanatory variables and seasonal component, under the state space time series model schema, captures the unobserved dynamic evolution of patronage over time. It shows that atmospheric visibility resonates with patronage seasonality. Poor visibility reduces train ridership. Rail service reliability also causes patronage fluctuations, though with a more consistent pattern.

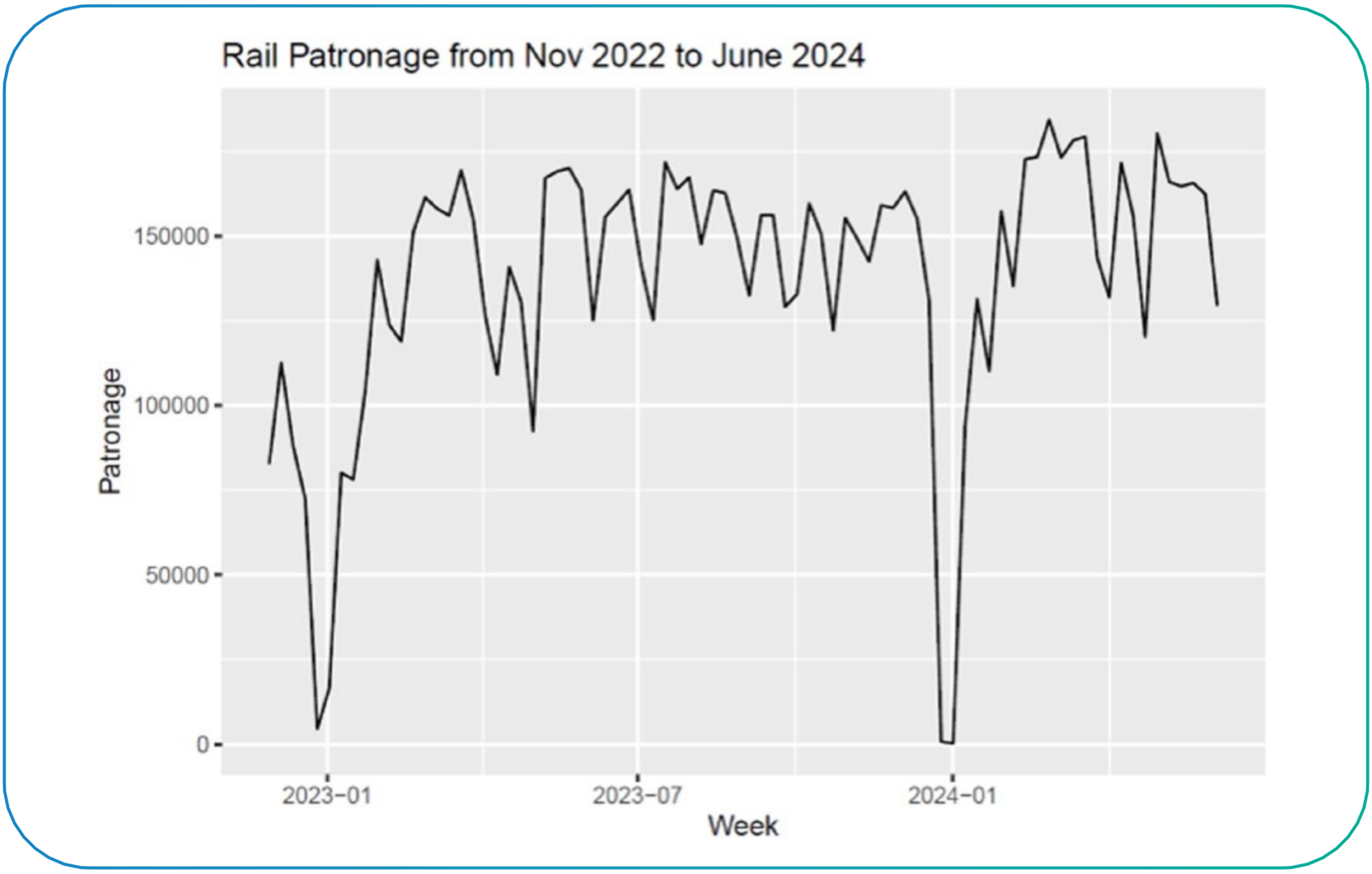

Figure 2: Time series plot for past rail patronage

2.2 Predicting Future Patronage

Building on the identified trend and seasonality patterns, a stochastic differential equation model is developed to forecast future rail patronage. It leverages underlying historical noises to account for stochastic fluctuations without explicitly requiring future data. This feature is critical due to the unavailability of future weather and rail performance data.

Without the carpooling intervention, Figure 3 forecasts a generally increasing trend of rail patronage over a two-year horizon. The weekly patronage is predicted to be largely between 170,000 and 200,000. Patronage shown in the figure was scaled for parameter interpretability.

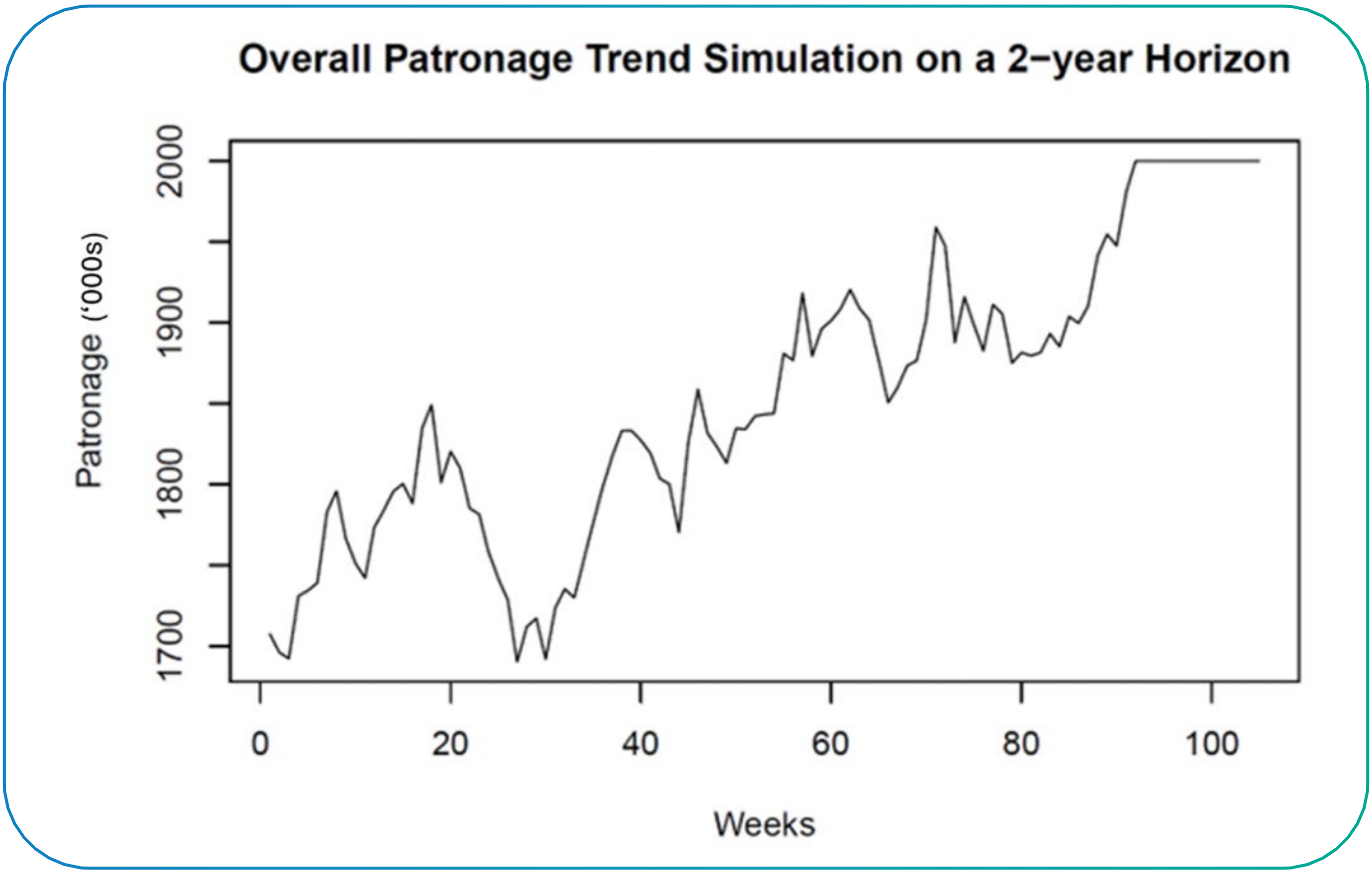

Figure 3: Future rail patronage simulation without carpooling interventions

3. From Parking Spaces to Behavioural Shifts

The 2018 New Zealand Census presents population data by main means of travelling to work in each suburb **(Statistics New Zealand, 2018)**. Here, the main commuting means are categorised as train, driving and other. A multivariable regression model has identified that commuters are significantly influenced by cost sensitivity, exceedance probability and additional multimodal commuting time compared to optimal driving.

- **Cost sensitivity.** There are several possible pricing schemes for the existing carparks at local train stations to support multimodal commuting. We define three boundary options:
  - All carparks are free, assuming all parked vehicles are single-occupancy.
  - All carparks charge $5 on weekdays, assuming all parked vehicles are single-occupancy.
  - All carparks are for carpooling passengers only on weekdays, assuming that all parked vehicles are shared by two commuters.

These three boundary pricing schemes are used to determine the cost sensitivity for commuters in each suburb, which measures how significantly their commuting cost responds to price changes.

- **Exceedance probability.** This measures the likelihood of single-modal driving with traffic delays exceeding multimodal commuting time for each suburb.

3.1 Localising Carpool Ratios

Suburbs have distinct commuting characteristics for cost sensitivity and exceedance probability. Thus, segmenting them into groups that share similar characteristics helps tailor the proportion of carpool parks at each local train station.

In Figure 4, Cluster 1 (red) suburbs have lower cost sensitivity and exceedance probability, and Cluster 2 (blue) suburbs are to the contrary. Commuters from Cluster 2 suburbs may be more likely to adopt multimodal commuting for cost- and time-savings, suggesting more free carpool parks at their local train stations may be more effective in expanding railway usage.

Strategically, local train stations for suburbs in Cluster 1 and 2 are baselined with 20% and 40% of the carparks converting to carpool parks on weekdays, respectively. The remainders are for single-occupancy carparks that charge $5 on weekdays.

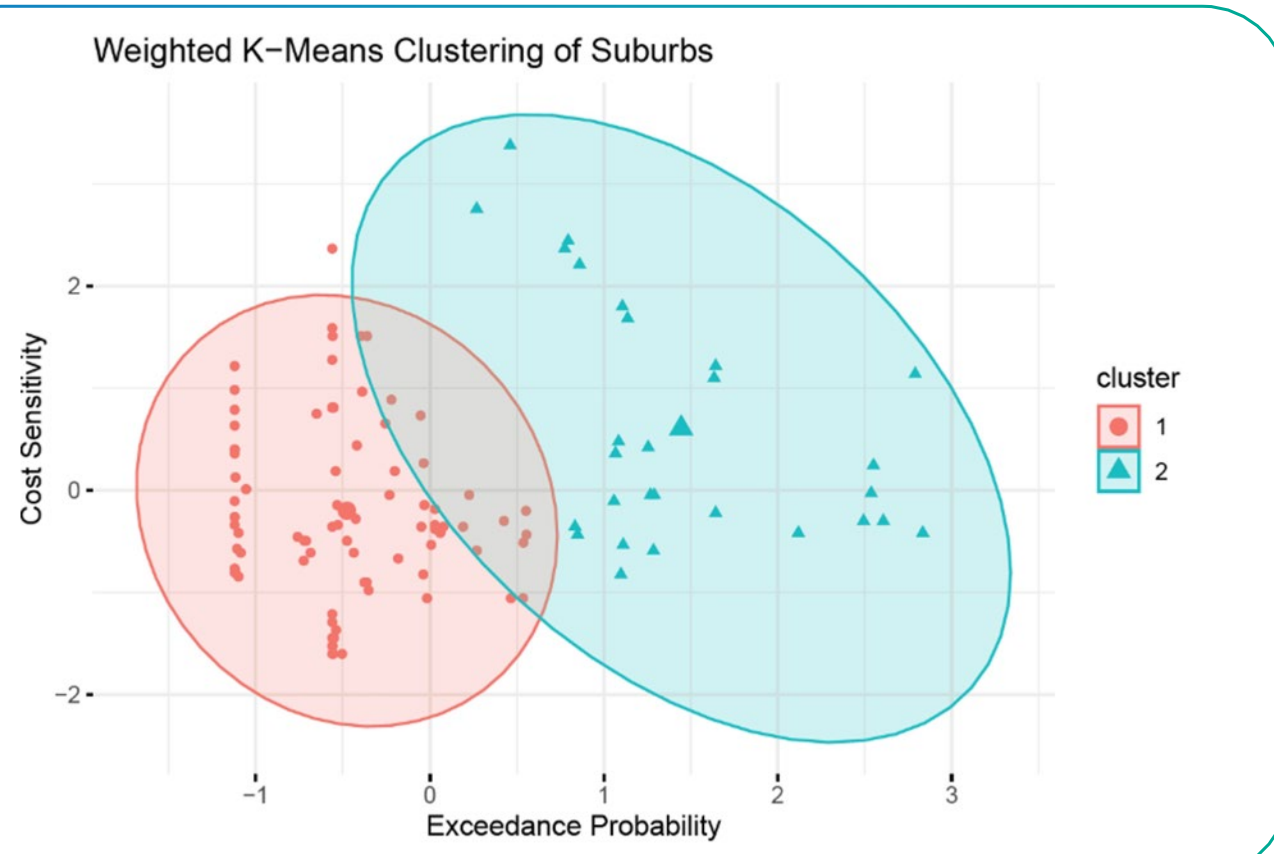

Figure 4: Two clusters of suburbs of distinct commuting characteristics

3.2 Forecasting Carpark Usage

In addition to cost sensitivity and exceedance probability, there are other behavioural nuances that impact commuters' decision making. For example, commuters may not fully perceive vehicle maintenance and fuel costs as part of their daily commuting expenses. They may be discouraged by the coordination efforts to carpool with other commuters **(van Kujik, et al., 2022)**, despite monetary savings. Introducing paid single-occupancy carparks may initially lead to avoidance, such as driving directly to work and working from home. Possible illicit behaviours, such as parking at nearby residential areas, may intensify community dynamics **(van Ommeren, et al., 2011)**. Over time, acceptance may follow as commuters start comparing the options rationally.

This adoption process of carpark usage is modelled by an S-curve, assuming growth in the first year and stabilisation in the second year, as illustrated in Figure 5.

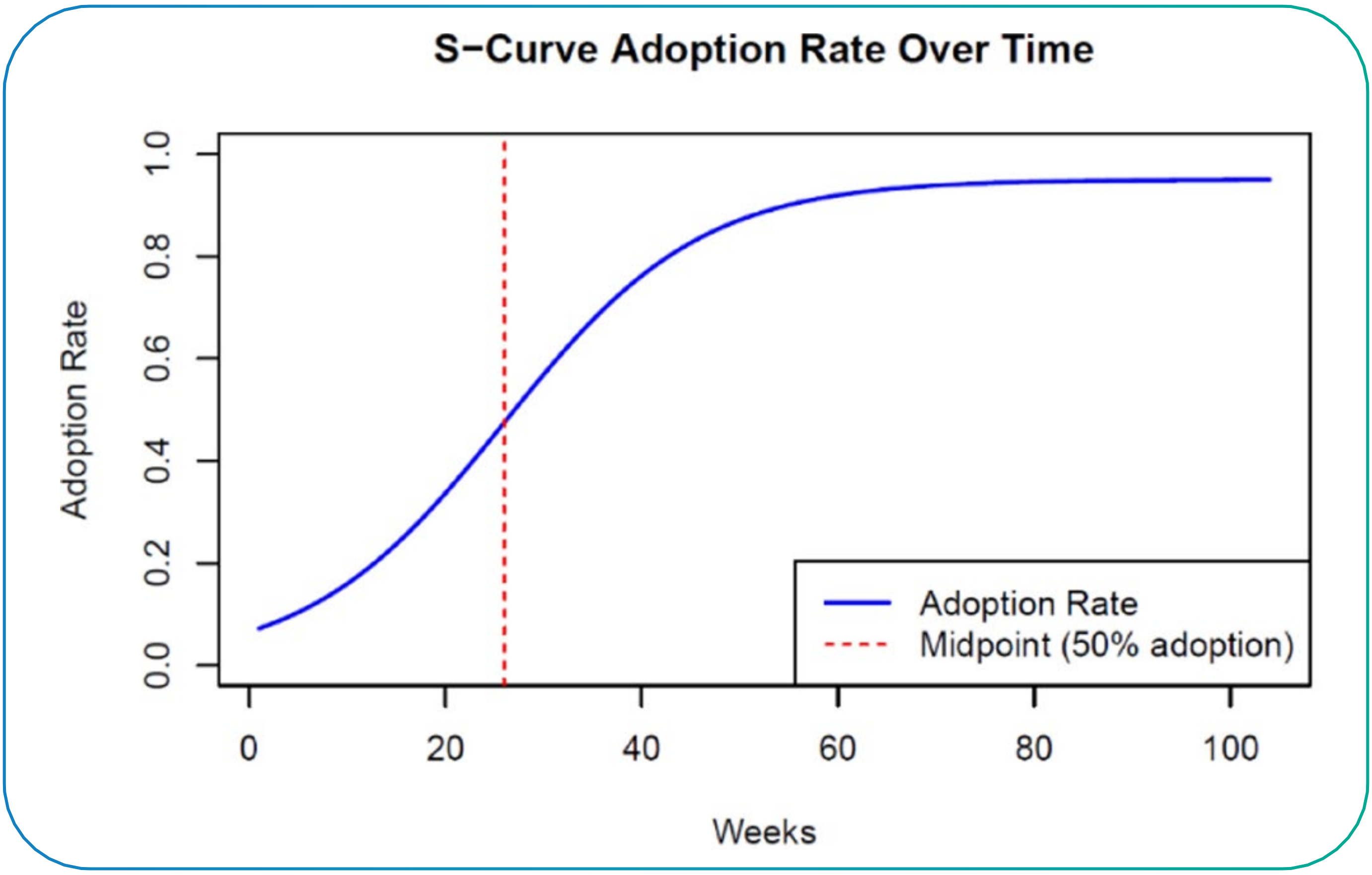

Figure 5: A defined S-curve carpark adoption rate for each local train station

Commuters in the catchment areas of each station are presented with the following five options: single-modal driving; multimodal commuting with single-occupancy driving to local train stations; or multimodal commuting with carpooling with 1, 2 or 3 other commuters to local train stations. A SoftMax function-based random utility model estimates the probability of commuters choosing each mode, incorporating cost, inconvenience, penalty and randomness. Input of the model includes the number of commuters and available carparks at each station, sourced from 2018 Census and Metlink website, respectively.

The estimated probabilities inform adjustments to baseline carpool ratios: 10% for stations with no significant carpooling incentive influence; 20% for those with limited multimodal commuting choices; and 30%-60% based on the relative proportions between single-occupancy and carpooling commuters.

Adjusted carpool ratios allow estimation of single-occupancy and carpool park usage in the first two years of implementing the proposed parking policy.

Fluctuating the carpark usage with the rail patronage evolutions modelled in 2.2, the forecasted outcome for a sample station, Melling, is presented in Table 1. There are 187 carparks at Melling Station, with 113 allocated carpool parks and 74 single-occupancy carparks.

Week	Single-Occupancy	Carpool_2	Carpool_3	Carpool_4
1	6	6	3	0
13	16	15	6	2
26	34	33	13	5
39	56	54	22	8
52	65	64	25	10
78	73	71	28	11
104	74	73	29	11
...				

Source: R Studio Output

Table 1: Forecasted carpark usage for Melling Station in Wellington

4. From Behavioural Shifts to Service Enhancements and Social Benefits

With the forecasted carpark usage and a $5 daily charge for single-occupancy carparks, the additional revenue from parking fares and increased train ridership in the first two years of this policy implementation is forecasted at $11.58 million. $3.70 million is forecasted in the first year and $7.88 million is in the second year.

To improve the network stability for service frequency increase, it is more cautious to reinvest the $3.70 million from the first year in rail infrastructure upgrades, such as the fragile turnouts and signal systems. The $7.88 million from the second year is to be reinvested in more services.

Following **Burdett and Kozan (2006)**, the absolute capacity of each line can be determined in accordance with various factors, such as the impact of freight services and long-distance commuter services, signalling capacity and dwell times.

The operating cost of Wellington Metro Railway Network is approximately $66.44 per kilometre **(Ministry of Transport, 2023)**. Operational costs for additional trains are estimated by multiplying this unit cost by line segment length.

An optimisation problem is formulated to determine the optimal allocation of additional services. The objective is to maximise the revenue usage. The constraints are the network capacity and the balance of morning and evening services for timetable symmetry. This problem may be solved by integer programming to determine the number of additional services on each line during peak hours.

With these additional services and increased patronage, the following social benefits may be expected:

- **Environmental sustainability.** The reduction of vehicles on roads would lead to the reduction of carbon emissions.
- **Health benefits.** This research addresses the first mile through the carpooling incentive and leaves the last mile for commuters to walk in the city centre. Physical inactivity is a major health concern in New Zealand and walking offers an easy improvement **(NZ Transport Agency Waka Kotahi, 2020)** to enhance overall public well-being.
- **Road to Zero.** Road to Zero is a previous government's road safety vision, for which no one in New Zealand should be seriously injured or killed in road accidents **(NZ Transport Agency Waka Kotahi, 2021)**. Encouraging public transport usage reduces private vehicles and traffic density, thereby lowering risk of accidents caused by congestion, driver fatigue and reckless driving, particularly during peak commuting hours.
- **State Highway maintenance.** Reduced vehicle traffic slows pavement deterioration, decreasing the demand for reactive maintenance and positively influencing predictive maintenance. This extends the lifespan of state highway infrastructures, delaying major road renewals and reducing long-term government financial burdens.

5. Closing Remarks and Limitations

Repricing station carparks offers a practical strategy to public transport usage without requiring major capital investments for new infrastructures. It is cost neutral and helps the transport authorities operate under budget constraints. Through behavioural modelling and reinvestment optimisation, the proposed strategy shows potential for public transport systems to attract new users, generate self-sustaining revenues, enhance service frequencies and achieve social benefits.

Though grounded in Wellington data, this framework is highly transferable. It suits cities with a similar spatial structure, where jobs concentrate in the centre and housing sprawls outwards.

> Ultimately, a targeted parking policy is key to make public transport more accessible.

A key limitation is the reliance on 2018 Census data, which does not account for post-COVID-19 impacts. Moreover, predictable commuter responses are assumed to the parking modification and service upgrades. However, actual behaviours are influenced by more complex socio-economic factors and personal preferences that are not fully captured. Thus, projected benefits are indicative and will depend on stable commuter behavioural patterns and sustained carpark system adoption.

Since reinvestment decision making is arguably a complex topic, it is simplified in this article as a proposed optimisation problem without precise solutions. Further exploration of investment decision modelling is outside the scope of this article but may be addressed in future work or through integration with the Value for Money (VfM) framework.

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ARTICLE 06

E-micromobility Challenges and Opportunities: Research in Practice

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1. Introduction

The emergence of e-micromobility in Australia has been gaining momentum since the early 2010s, with its uptake surging in popularity during COVID-19 as people sought avoid public transport for social distancing purposes. By 2020, most major cities had, or were considering, shared/'for hire' e-micromobility trials. This required all levels of government to seriously consider how best to regulate these new services to achieve the best public outcome from a safety and planning perspective. Similar to the challenges faced by the introduction of ridesharing, governments were faced with a contest in which technology was advancing faster than policy and regulation. It is therefore important to better understand the challenges and opportunities presented by this emerging mode of transport to ensure future policy directions are targeted and enable the potential of e-micromobility to be unlocked without detriment to urban planning and road safety outcomes.

2. Understanding the challenges and opportunities created by e-micromobility

The appeal of private and shared e-micromobility is undeniable, given its popularity as a convenient and cost-effective mobility solution. It has also garnered the attention due to regulations (and even bans) around its usage in various cities around the world. There are valid reasons for these bans that could be attributed to safety concerns due to the behaviour riders, and other road users, have exhibited in the use of these personal mobility devices.

Emerging concerns around the use of private and shared e-micromobility can be broadly centred around three key factors:

1. Unsafe user behaviour during rides (e.g., joyriding, riding at high speed in shared areas, riding without a helmet or riding on roads and footpaths).
2. Unsafe behaviour of other road users around e-micromobility users (e.g. inattention/unawareness of drivers, higher vehicle speeds).
3. Negative urban planning outcomes caused by the parking or placement of the devices (e.g. footpath clutter).

2.1 E-micromobility: a threat to safe urban mobility?

Between 2020 and 2024, injuries involving e-mobility devices more than doubled in some Australian states and territories **(Berecki-Gisolf and Hayman 2024)**. In 2025 alone, a 69-year-old man in Victoria was struck and killed while crossing the road by an illegally modified e-bike travelling at 80km/h **(Bicycle Network 2025)**. In Perth, a 51-year-old man was struck and killed by a foreign student on an e-scooter travelling with over three times the legal blood alcohol content **(Ho 2025)**.

In a recent NTRO submission to a WA Parliament inquiry on the use of e-rideable devices, the following safety challenges were discussed.

2.1.1 Increase in injuries relating to e-micromobility and liability

Health departments across Australia are recognising the severe impact that e-rideables are causing with regards to trauma patients presenting at hospitals. As an example, the Jamieson Trauma Institute launched the Electric personal MObility DEvices Surveillance (E-MODES) Patient Survey Study to better understand the true extent of the safety issue and its related costs to health departments, which is only possible through accurate case identification and thorough information recording **(Vallmuur et al. 2023)**. To date, this remains the most comprehensive source of information regarding e-mobility injuries in Queensland.

The insurance landscape for e-micromobility usage in Australia remains complex and inconsistent **(Polaris Lawyers 2022, Mini EVs n.d.)**. Traditional motor vehicle schemes, such as that offered by the Transport Accident Commission (TAC), typically exclude coverage for unregistered vehicles like e-scooters. Furthermore, personal insurance coverage varies considerably across jurisdictions and providers, with e-scooters sometimes classified as motor vehicles requiring motorcycle insurance and in other cases treated as low-powered bicycles. This lack of uniformity creates substantial uncertainty regarding liability and compensation following an accident. This underscores the pressing need for clearer, more comprehensive insurance frameworks to ensure adequate protection for all road users.

Local Government must be actively engaged and involved in the planning, delivery and management of e-micromobility initiatives, as they are predominantly used on local roads and streets that they are responsible for.

2.1.2 Usage of e-micromobility in dense, mixed traffic environments and urban precincts

The use of e-micromobility in dense, mixed traffic environments, including highly pedestrianised areas or other urban precincts, poses a significant road safety issue due to the conflicting mix of motorised vehicles and vulnerable road users such as pedestrians.

Complete separation through dedicated infrastructure is not always feasible or possible, so there needs to be rationalisation of the threshold of e-micromobility-volumes-to-pedestrian mix, which warrants investigating the need for dedicated infrastructure. There is a need to understand how to differentiate separation of infrastructure in highly pedestrianised areas, whereby streets provide an environment for people to congregate and dwell (also referred to as streets with 'high place significance'). This also involves ensuring adequate end-of-trip facilities, such as parking, are provided in a way that ensures undesirable and unsafe kerbside clutter is avoided.

2.1.3 Compliance and classification of e-micromobility devices

The previous sections outline genuine and emerging issues that warrant further investigations on the best approach to regulate the use of e-micromobility devices and, equally importantly, the policing and enforcement of these regulations. Similarly, compliance and associated enforcement of e-micromobility is two-fold:

1. Compliance of rider behaviour – ignorance of the law is no defence; being unaware of regulations and user responsibilities are not acceptable reasons to justify dangerous use of e-micromobility. However, governments can do more to consider how critical information around the safe use of e-micromobility is conveyed to the public through improved education, awareness campaigns and information/signage to encourage improved behaviour.
2. Compliance of the device – understanding what types of e-micromobility devices are permissible under current jurisdictional legislation and how to police the illegal modification and import of non-compliant devices into the market.

> This can be challenging when the regulatory frameworks governing the use of e-micromobility are unclear and data supporting the use of these modes of transport is not easily monitored and reported on.

2.2 The benefits offered by e-micromobility

It is not all bad news; there are many opportunities and important benefits that e-micromobility can deliver to the community when used responsibly and safely.

Jurisdictions such as NSW have been tackling the challenge of ensuring the safe usage of e-micromoblity on their road networks. In October 2024, **Transport for NSW (2024)** published their E-micromobility Action Plan that outlines key opportunities that are, and can be, unlocked by this mode of transport. The Action Plan outlines how permissible e-bikes can be safely used on public roads (noting that private e-micromobility is still only legal for use on private property in NSW).

The notion of a '15-minute city' is an emerging concept in urban planning that can be enabled by the creation of multiple, distinct hub-and-spoke centres. To support this vision, e-micromobility has the potential to be a solution to fill the first- and last-mile gap, to ensure effective public transport integration.

From a sustainability perspective, an increased use of e-rideables will result in overall reduction in carbon emissions by creating a mode shift from private vehicles to active transport. Like any form of active travel, e-rideables are not subject to congestion, fuel or registration costs, providing added economic benefits as a cost-effective transport alternative.

Electric personal mobility aids, which could be categorised as a subset of e-micromobility, provide an opportunity for people with various accessibility needs, which are not able to drive as an example, to have equal access to employment, education, healthcare and wider community life.

To unlock these opportunities and benefits, the emerging road safety challenges outlined previously must be tackled in earnest, by both public and private sector transport and planning practitioners.

3. E-micromobility challenges and opportunities in practice

To better understand the motivations for the use of e-micromobility, and test some of the challenges and benefits outlined in Section 2 in practice, the NTRO rolled out the Shared E-micromobility Staff Pilot Program at the head office in Port Melbourne. This project was co-funded by Fishermans Bend Innovation, Diversity, Experimentation and Activation (FB IDEAs), with microFleet as the supplier partner.

The pilot program broadly involved:

- A run period between February and June 2025.
- The provision of 2 e-bikes and 2 e-scooters for NTRO staff to use.
- Devices that could be used for any trip purpose and even borrowed overnight for commuting trips.
- Participants signing a user agreement and procuring an appropriate rider insurance to be able to register.
- Pre-trip checklists completed and recorded in Donesafe safety compliance platform.

During the pilot program, there were two data collection activities. Firstly, geolocation data was collected from the e-micromobility devices that provides information on the trips made. Secondly, a staff survey was conducted to collect insights into the perception of staff members on the trial, as well as to understand their behavioural decision on their mode choices and participation in the trial. The survey collected responses for two weeks in July. There were 36 responses received, six of which were from users of the devices.

The project resulted in three major learnings.
These learnings are on: (i) the safety challenges in establishing such operation; (ii) analysis of the usage patterns; and (iii) the findings from the staff survey.

3.1 Safety is at the centre of everything

The project found three key aspects of safety when establishing such a program, namely: facility safety; vehicle safety; and rider safety.

- **Facility Safety.** This aspect relates to the measures taken to manage the safety risk if a fire occurs due to the e-micromobility devices and the charging equipment. This aspect determines the storage location of the e-micromobility devices and equipment, depending on the fire isolation, proximity to the appropriate fire extinguishers, evacuation path and any other existing safety requirements. Additionally, the building owners may have guidelines/requirements related to electric vehicle charging, which need to be adhered to.
- **Vehicle Safety.** To ensure the safety of the e-micromobility device, it needs to comply with relevant safety standards, particularly those related to the battery and the charger. Additionally, a pre-trip safety check (e.g., brake and tyre check) needs to be done before every trip to ensure the device is suitable for use. Finally, regular maintenance of the devices needs to be carried out and appropriate insurance is required to cover any damages to the device.
- **Rider Safety.** The current regulatory framework on e-micromobility relies on each user's responsibility to do the right thing, such as following the road rules, riding responsibly and ensuring their riding skills are appropriate. For this, a user agreement was professionally drafted to ensure clear and well-defined roles and safety responsibilities. Additionally, trips on e-micromobility devices are not covered under Workcover. 'For hire' schemes, including the NTRO E-micromobility Staff Program, rely on riders' insurance from a reputable provider to cover any injuries or damages due to incidents involving the use of e-micromobility devices.

Our experience from the program provides a glimpse into the potential mechanisms to better enforce compliance, mainly through technology. The NTRO e-micromobility devices are equipped with GPS trackers, from which trajectory data can be extracted, which provides some insights into the device movements. Coupled with appropriate booking and user account systems, such frameworks can potentially be used to monitor user behaviour and act accordingly if any non-compliance to road rules is detected. There is still work to be done to further develop and test various technologies for such use, e.g., understanding the impact of GPS accuracy on the accuracy of movement monitoring.

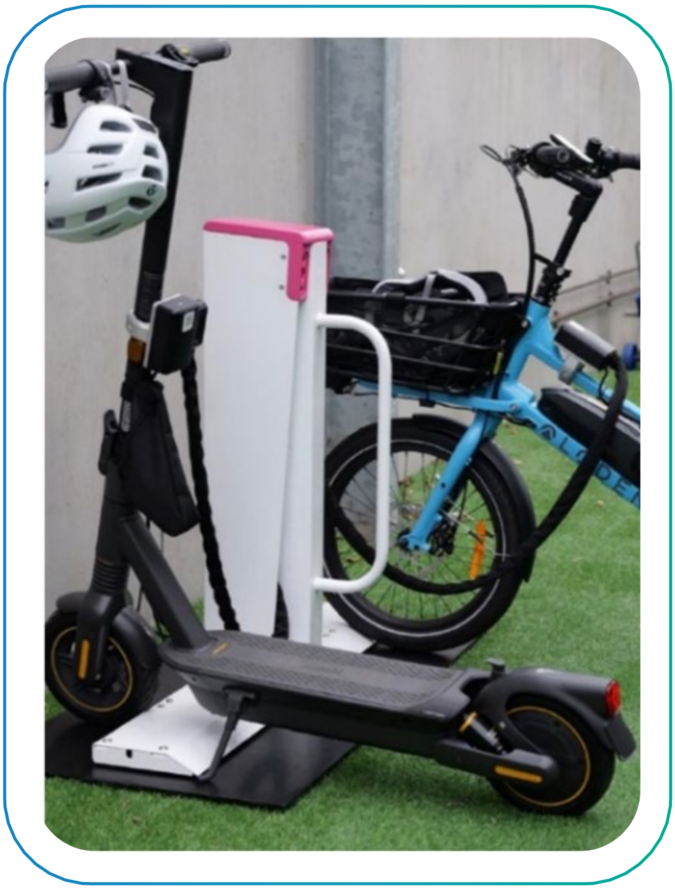


Figure 1: NTRO e-micromobility

3.2 Use cases: short commute or recreational trips

There were six unique users who made a total of 55 bookings, with two regular users contributing 87% of those bookings. Of those 55 bookings, 53 were overnight bookings used to commute from/to work (plus the occasional trips to other activities such as shopping). Furthermore, looking at comparisons with other modes (Table 1), e-micromobility devices offer a better travel option when compared to public transport. However, the travel times by private car are much shorter on both trips, specifically for User 1. This highlights that e-micromobility is more suited to shorter trips. Finally, it is worth noting that these two users were active transport users.

These findings indicate that e-micromobility option is more likely to be competitive for commuting over a relatively short distance. Unfortunately, the project also finds that e-micromobility is more likely to replace active transport rather than cars, as evidenced by the fact that the regular users of this program were already active transport users. This aligns with a recent study in Poland that found that e-bike sharing schemes mostly replace public transport, not car trips **(Bieliński et al. 2021)**. Combining this with the fact that e-micromobility is inherently less active compared to active transport modes **(Payne et al. 2025)**, our findings point to the need to have a more careful deployment strategy to ensure better transport outcomes.

Regular users' trips	Trip details	Car trip comparison	PT trip comparison
User 1 (e-bike)	55.5 minutes 17.4 km	20.6 minutes 23.5 km	1h 40min, including 29min walking
User 2 (e-scooter)	27.3 minutes 9.2 km	17.2 minutes 9.1 km	1h 5min, including 22 minutes walking

Table 1: Comparison of the taken e-micromobility trips with other modes

3.3 Potential detractors

The staff survey collected a cross-sectional data on perceptions of the e-micromobility option for their trips. Firstly, the top six factors influencing the respondents' mode choice were travel time, reliability, connectivity, affordability, comfort and safety. Non-users tended to favour travel time, reliability, comfort and safety, whereas users were more likely to consider affordability and connectivity as important (Figure 2). This further reveals the appeal of driving in addition to trip time, which is the perceived safety, comfort and reliability.

Secondly, it was found that the top three most common reasons for not participating in the trial were: unwillingness to pay for insurance; there being no need to use the e-micromobility option; and there being interest but no usage (i.e., there was no urgency to use e-micromobility). Digging deeper into the issue of cost, it was found that the maximum daily cost the respondents are willing to pay was relatively low (Figure 3).

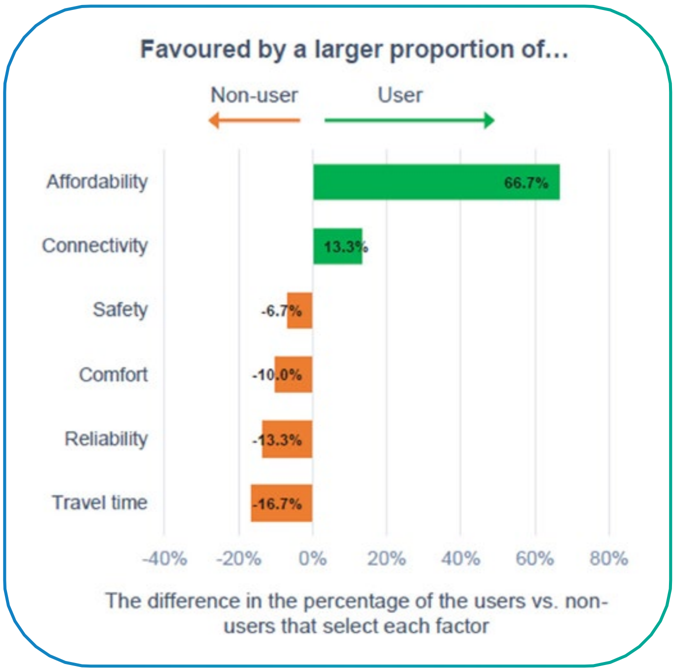
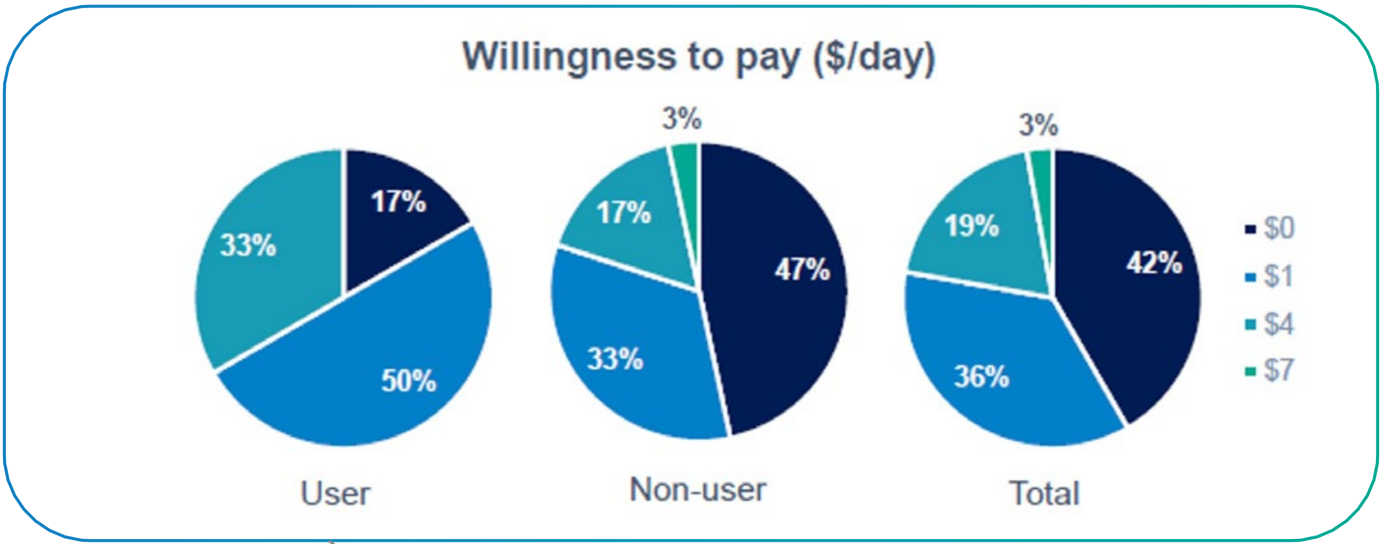


Figure 2: Difference in the important of factors affecting mode choice between users vs. non-users



Source: NTRO analysis

Figure 3: Willingness to pay for the use of e-micromobility

4. Concluding remarks

The trial revealed the many challenges associated with establishing a widely adopted staff e-micromobility sharing program. The legal requirements and the attractiveness of other modes, such as private cars, have proven to be hurdles that need to be overcome before we see widespread adoption of e-micromobility devices. To combat this, more support from employers may be required to help drive uptake, e.g. by providing financial support for the insurance costs and a more streamlined process (e.g., automated documentation). More generally, transport networks in many Australian cities are still geared for car travel. As such, the attractiveness of active transport is generally lacking when compared to private car use and there is inadequate justification to switch to active transport modes.

The rise in injuries, inconsistent insurance coverage, as well as regulatory ambiguity, all underscore the urgent need for robust policy frameworks and infrastructure planning. While e-micromobility presents significant opportunities for enhancing urban mobility, sustainability and accessibility, its integration into existing transport systems demands careful and coordinated action. Broader industry practitioners from other sectors such as local government, health departments, law enforcement and private industry, must also come to the table, alongside transport agencies, to address safety concerns, ensure compliance and educate the public on responsible usage.

> Only through comprehensive regulation, thoughtful urban design and inclusive planning, can the full potential of e-micromobility be realised: delivering safer, cleaner and more equitable transport options for all members of the community.

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ARTICLE 07

Empowering the Kingdom of Tonga: A Strategic Leap Towards Resilient and Sustainable Transport Infrastructure

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With a clear desire to improve local technical skills, gain independent materials science accreditation, increase infrastructure resilience and transport network sustainability, the Kingdom of Tonga engaged the National Transport Research Organisation (NTRO) to partner with them on a long-term *Strategic Transport Infrastructure Advisory Program* (STIAP).

This transformative initiative tackles the challenges of a dispersed island nation by examining ways to modernise road and aviation networks, to optimise the use of local materials, and to empower the Ministry of Infrastructure through data-driven infrastructure understanding. Critically, it also has a central focus on capacity building.

From advanced infrastructure assessment across road and aviation networks to in-field roadworks analysis, review of transport network plans, in-country tailored training programs, detailed analysis of materials science laboratory processes and advanced planning for a new transport materials research and laboratory centre, as well as policy advisory work for emerging major projects in Tonga (including the design and development of the new Fanga'uta Lagoon Bridge), the first year of STIAP has laid the foundation for a new infrastructure future for Tonga.

The program has set a new benchmark for infrastructure development across the Pacific.

1. Introduction

The Kingdom of Tonga, a Pacific Island nation comprising 169 islands, faces unique challenges in maintaining and developing its transport infrastructure. Geographic dispersion, limited local resources and technical skills, contested finances and increasing climate-related risks, necessitate a strategic and sustainable approach to infrastructure development. In response, the National Transport Research Organisation (NTRO), in partnership with Tonga's Ministry of Infrastructure (MOI), launched the *Strategic Transport Infrastructure Advisory Program* (STIAP) in March 2024.

The program was purposefully designed as a comprehensive, multi-year initiative to assess, enhance and future-proof Tonga's transport infrastructure across road, maritime and aviation sectors. The program also included a determined effort to build local capacity, improve asset management practices, and align infrastructure development with global sustainability goals. With Year One program works now completed, this article reflects on the program's objectives, individual program streams and long-term aspirations.

The STIAP program was structured around four strategic objectives:

- **Infrastructure baselining** to ascertain the current condition and capacity of Tongan infrastructure across road, maritime and aviation assets;
- **Improving standards** to help uplift and develop Tonga infrastructure standards to ensure infrastructure is stronger, sustainable and resilient in the context of a changing pacific environment;
- **Financial value** by realising significant financial savings through advanced infrastructure understanding and targeted asset management/maintenance planning;
- **Capacity building** to increase the practical and technical skills of the Tongan people (public and private sectors), with the aim of increasing self-reliance.

These objectives were pursued through a series of ten interlinked program workstreams, with each playing their role in advancing the transformation of Tonga's transport infrastructure.

Figure 1: NTRO Team Members with the Deputy Prime Minister for Tonga, the CEO of the Ministry of Infrastructure, the Director of Civil Aviation, and key members of the MOI Team.

2. Program Streams and Year One Outcomes

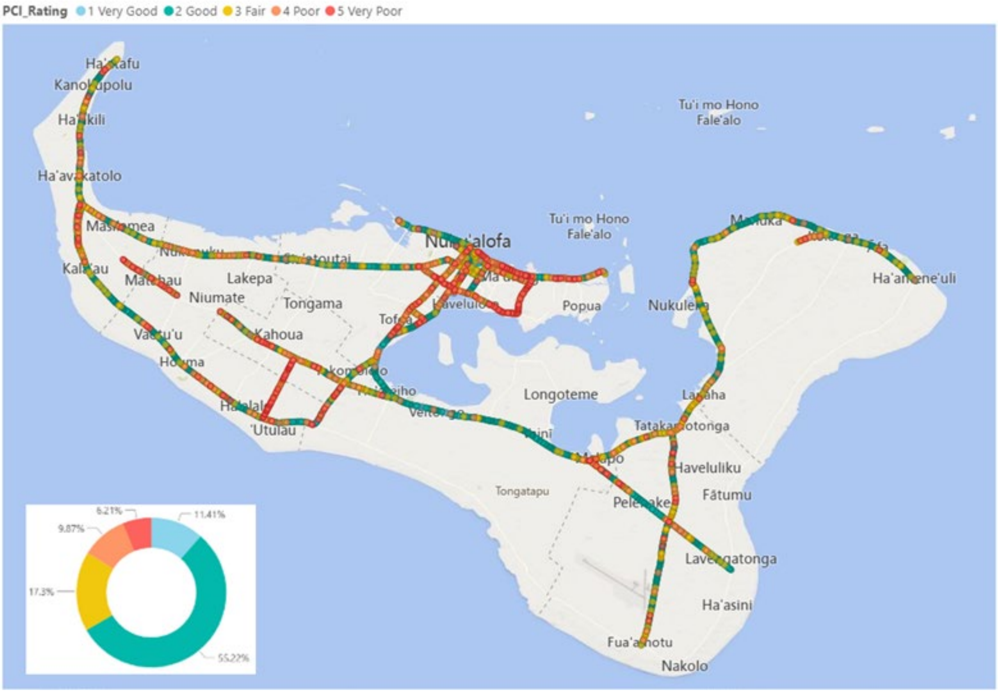
2.1 Infrastructure Measurement

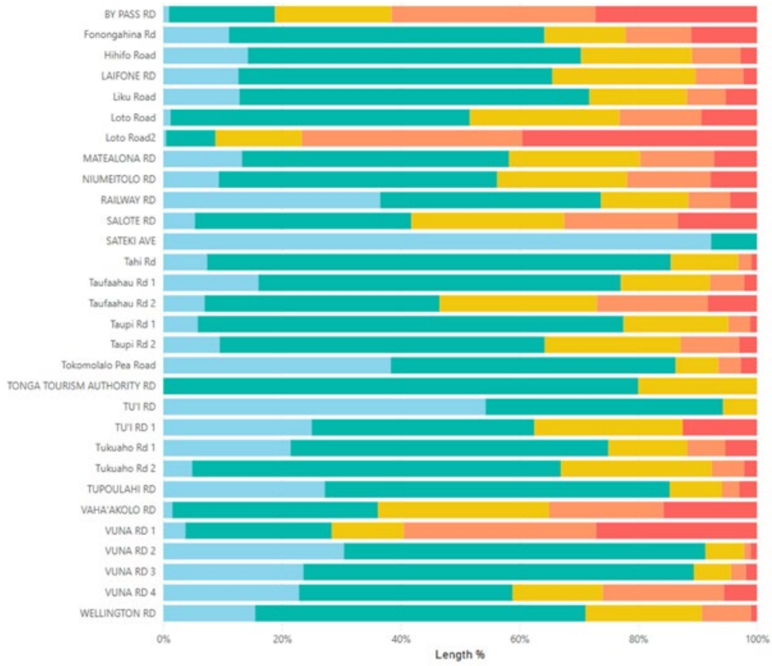
The foundational component of STIAP was the comprehensive measurement and assessment of existing infrastructure.

NTRO deployed its Network Survey Vehicle (NSV) to collect high-resolution data on road conditions across Tongatapu, Vava'u and the two major airports Fua'amotu International Airport and Lupepau'u International Airport. The NSV captured metrics such as surface roughness, rutting, macro-texture and road geometry, supported by a multi-camera imaging system for asset inventory. This data formed the basis for all subsequent planning and design activities, ensuring that interventions were grounded in objective, up-to-date information.

The comprehensive measurement of Tonga’s road and aviation infrastructure provided the first-ever digital baseline of asset conditions across the Kingdom. This initial data set now empowers MOI and other government entities (such as Tongan Airports Limited (TAL)), to consider evidence-based decisions, prioritise maintenance and plan future investments with increased confidence. Limited road and aviation maintenance funds can be directed to priority areas.

Figure 2: NTRO NSV on Tongatapu Island





The use of NTRO's NSV introduced advanced data collection capabilities for the first time in Tonga.

The use of NTRO's NSV introduced advanced data collection capabilities for the first time in Tonga.

The NSV is now permanently based in Tonga so that annual surveys (or more regular if required) can be undertaken. Equally, the NSV can also now easily be deployed to neighbouring Pacific nations, fostering regional-wide collaboration to uplift baseline infrastructure understanding through the capture of data-rich information of both sealed and unsealed road networks, as well as regional airport pavements.

2.2 Asset Performance and Management

The transformation of raw data into actionable insights was a key success of the STIAP program in Year One. NTRO's Asset Performance and Management team worked closely with MOI to integrate survey data into their asset management practices. This information enabled the generation of network condition reports and visual maps and will allow for the development of predictive maintenance models.

For roads, this meant the development of tailored Levels of Service (LoS) and the creation of surface and pavement condition indices. These tools allowed MOI to prioritise maintenance activities, estimate budgets and plan forward works with greater confidence.

In the aviation sector, baseline assessments were conducted for all six of Tonga's airports, including two international and four domestic airfields. These assessments covered both airside and landside infrastructure, providing a detailed picture of pavement conditions, drainage systems, lighting, and terminal facilities.

NTRO also supported the conversion of runway ratings from Pavement Classification Number (PCN) to Pavement Condition Rating (PCR), aligning with international best practices and improving safety and compliance. The development of runway PCR results at the two international airports, signalled the first of its kind in the Pacific Region.

Figure 4: NTRO team undertaking (a) road inspections, (b) runway pavement inspections, and (c) FWD testing on runways for PCR assessment

2.3 Materials Science and Laboratory Services

Tonga's reliance on coral limestone as a primary construction material presented both opportunities and challenges. STIAP included a dedicated stream focused on materials science, with NTRO conducting resource investigations into quarry materials, geotechnical exploration activities in the northernmost remote islands (Niuafo'ou and Niuatoputapu) and evaluating the performance of local aggregates and concrete.

The program developed engineering guidelines for the optimal use of coral limestone, addressing issues such as premature aging of bitumen binders and the limitations of sprayed seals. These guidelines were informed by laboratory testing and field performance data.

To support ongoing quality assurance, NTRO is also providing special advisory services regarding the redevelopment of laboratory facilities at MOI headquarters in Tonga'tapu. Work has included site planning, building design and layout advisory services, recommendations regarding necessary upgrades to laboratory equipment including new equipment, training for laboratory staff, and steps toward international accreditation.

The evaluation and optimisation of local materials, particularly coral limestone and harder basaltic materials potentially available in the northern islands, will reduce Tonga's dependence on costly imported construction materials. This not only lowers project costs but also supports local industries through resources payment and enhances supply chain resilience.

Upgrading MOI's laboratory facilities will ensure that Tonga can independently verify material quality, improving construction standards and enabling international recognition of its testing capabilities.

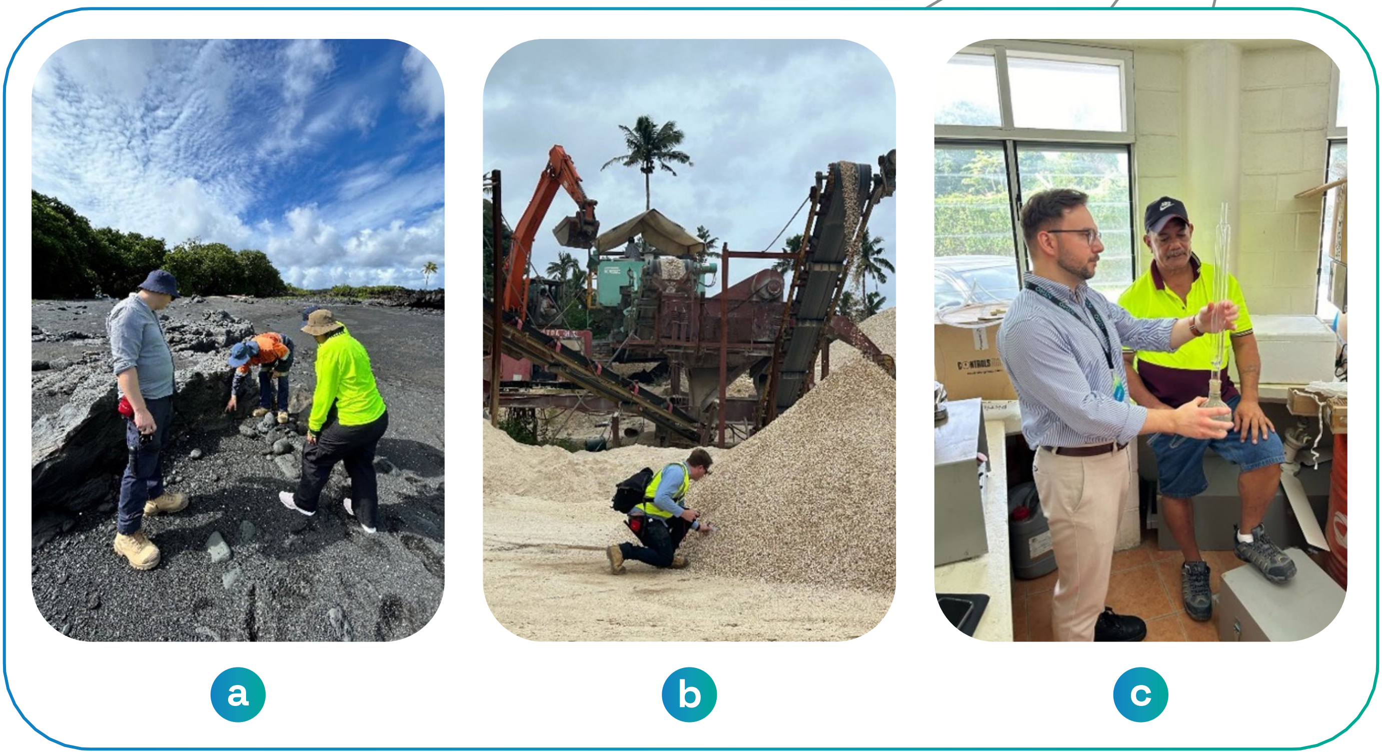


Figure 5: (a) NTRO & MOI undertaking geotechnical explorations, (b) NTRO undertaking quarry investigations, and (c) NTRO undertaking laboratory investigations

2.4 Transport Safety

Improving road safety is a central concern of the Tongan Government. During the first year of the program, NTRO's transport safety specialists conducted a comprehensive review of crash data, traffic volumes and existing safety plans. This was followed by in-country site visits to observe road user behaviour, intersection performance and school-zone safety.

The team identified several quick-win interventions, including improved line marking, enhanced signage and targeted upgrades at high-risk intersections. These measures were designed to deliver immediate safety benefits while informing a longer-term road safety strategy.

The identification of short-term safety improvements has immediate life-saving potential. Longer-term strategies developed under STIAP will help reduce crash rates, improve traffic flow and create safer environments for all road users. These improvements also support tourism and economic activity by making travel safer and more reliable for a broad range of users.

Future stages of the program will focus on embedding these improvements through training, pilot projects and the development of a national road safety framework.

2.5 Infrastructure Sustainability

Sustainability was embedded throughout STIAP, with the United Nations Sustainable Development Goals (SDGs) serving as a guiding framework. NTRO developed a dedicated STIAP Sustainability Analysis tool to track progress against relevant SDGs, including those related to infrastructure, climate action and economic development.

Annual sustainability reports are being produced, highlighting achievements such as reduced reliance on imported materials, improved resilience to climate impacts, and increased local employment through training and capacity building.

NTRO also worked with MOI to prioritise SDG actions most relevant to Tonga's context, ensuring that sustainability efforts were both meaningful and achievable.

Figure 6: NTRO & MOI team undertaking sprayed seal inspections

2.6 Pavement Design and Resilience

Tonga's diverse terrain and exposure to extreme weather events require innovative approaches to pavement design. NTRO's pavement engineering team collaborated with MOI to develop designs that optimise durability, reduce maintenance costs and enhance climate resilience.

Key activities included:

- Assessing the suitability of local materials for pavement construction;
- Spending time in-country during maintenance operations with local road crews, examining construction and maintenance practices and procedures;
- Initial investigations into accounting for flooding, sea-level rise and temperature extremes;
- Conducting in-country training workshops to transfer knowledge to MOI engineers and contractors.

This dedicated road pavement stream is designed to assist the MOI develop and maintain robust pavement structures that are better suited to Tonga's environmental conditions and long-term needs.

Ultimately, this will reduce costs and disruptions (due to lower intervention events) while improving connectivity across islands. Training MOI staff in new construction and maintenance techniques will ensure that the benefits are sustained over time and that future projects are designed with resilience in mind.

2.7 Infrastructure Advisory and Standards

Through this program stream, NTRO provided expert advisory services for several high-profile projects, most notably the Fanga'uta Lagoon Bridge. NTRO continues to support MOI through all project phases, from option assessment and tender negotiations to specification development and construction readiness.

Under this program stream, Year One activities also included the development of Tonga-specific infrastructure standards and specifications. These were co-designed with MOI staff and tailored to local conditions, materials and construction practices.

> Two national standards were completed during the program, with a roadmap for future standard development established.

2.8 Training and Development (Capacity Building)

Capacity Building is the cornerstone of STIAP.

During Year One of the program, NTRO delivered structured training and development programs for MOI staff and private sector stakeholders.

Training was delivered both online and in-country, covering topics such as asset management, pavement design, laboratory testing and project management.

A *Capability Development Framework* was created to guide future training efforts, ensuring that skills development remains a priority beyond the life of the program.

Feedback from participants indicated high levels of satisfaction and a strong desire for continued professional development.

Figure 7: NTRO Team undertaking training sessions with MOI

3. Conclusion

Although in its infancy, the STIAP has already delivered a transformative impact on Tonga's transport infrastructure sector. Through a comprehensive, collaborative and capacity-focused partnership, the program has made significant progress in:

- Establishing a robust evidence base for infrastructure planning and maintenance;
- Improving the quality, resilience and sustainability of road and aviation assets;
- Reducing long-term costs through better asset management and local-material use;
- Enhancing road safety through targeted interventions and strategic planning;
- Building institutional capacity within MOI and the broader infrastructure sector;
- Aligning national infrastructure development with global sustainability goals.

As Tonga continues to address the challenges of climate change (including the increasing severity of storm and natural weather events), economic development and regional connectivity, the NTRO will continue to partner with MOI – with a focus of building in resilience, rather than locking in continuous vulnerability.

> Year One of the program has not only delivered immediate improvements but also laid the foundation for a more resilient, self-reliant and sustainable transport infrastructure future.

ARTICLE 08

Mitigating noise and vibration in embedded light rail tracks: A multi-criteria assessment of infrastructure solutions

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1. Introduction

Noise and vibration from rail traffic is a growing concern in urban areas across the world, causing discomfort to passengers and nearby residents and superficial and structural damage to adjacent buildings (McIntosh 2015, Hosseinzadeh et al. 2024). The rail-wheel interaction generates rolling noise, often amplified by rail roughness, up to 20 dB higher on tramways than ballasted tracks (Sun et al. 2020). Light rail noise mainly arises from rolling contact, wheel squeal and impact noise. It also generates vibration that can impact nearby buildings, particularly historic structures in urban areas (Hosseinzadeh 2024). These vibrations stem from dynamic effects such as moving loads, irregularities in track and wheel surfaces, and localised defects at rail joints, switches and crossings (Kouroussis 2021).

NTRO performed a desktop study to investigate commercial infrastructure-based mitigation measures for noise and vibration, including embedded components. We assessed a range of solutions such as embedded components (pads, matting), wear-resistant rails and external sound barriers. Each option was assessed for its suitability in both new construction and retrofit scenarios through a comprehensive desktop review, multi-criteria analysis and stakeholder consultation.

2. Desktop Review

A desktop review of commercially available infrastructure solutions for mitigating noise and vibration in light rail systems identified six primary types of solutions (Table 1).

No.	Type of Solution	References
1	Rail encapsulation in embedded rail system	**Pandrol n.d., edilson)(sedra 2020, Sealable n.d., STRAILastic 2021**
2	Under-slab track matting	**edilson)(sedra n.d.**
3	Rail pads	**edilson)(sedra n.d.**
4	Friction modifiers	**Loram n.d., AirLube Rail 2025, RS Clare & Co Ltd 2025, LB Foster n.d.**
5	Green track systems (grass or vegetation surrounding the track)	**STRAILastic 2021**
6	High wear-resistance rail	**Voestalpine n.d.**

Table 1: Identified infrastructure-based solutions to reduce noise and vibration for light rail systems

3. Assessment of Solutions

To evaluate and compare solutions for reducing noise and vibration in light rail tracks, a multi-criteria assessment framework was applied. This process involves four key stages:

1. Defining the problem and assessment structure.
2. Assigning weights to evaluation criteria.
3. Scoring each alternative against the criteria.
4. Calculating weighted scores based on criterion importance.

In this study, all criteria were equally weighted. Each solution was rated on a scale from 1 (least desirable) to 5 (most desirable) across the following categories:

- **Installation feasibility.** The ease of installing the system, the extent of disruption to operations/general traffic during installation, and the requirements of the machinery used in installation (such as power, water, etc.)
- **Noise mitigation.** A relative assessment of how effective the solution is at mitigating noise.
- **Vibration mitigation.** A relative assessment of how effective the solution is at mitigating vibration.
- **Lifecycle costs.** A qualitative assessment of how costly the option is, including the purchase of materials, installation, maintenance and decommissioning compared to other solutions.
- **Technology maturity.** The extent to which the solution has been used or tested in Australia or internationally.
- **Maintenance and longevity.** How extensive the maintenance requirement of this solution is and how long the system will last before needing to be replaced.
- **Risks.** An assessment of any potential safety risks to pedestrians and vehicles (e.g. flange gap risk, fire resistance).

Solution	Installation feasibility	Noise mitigation	Vibration mitigation	Lifecycle costs	Technology maturity	Maintenance & longevity	Risks	Total score	Rank
Under-slab track matting	✓✓✓✓ Easy in new tracks; difficult for retrofits	✓✓✓✓✓ Significant ground-borne noise reduction	✓✓✓✓✓ Significant ground-borne vibration reduction	✓✓✓✓✓✓ Low cost; rare high-cost replacement	✓✓✓✓✓ Widely used (e.g., Sydney L3)	✓✓✓ High replacement cost	✓✓✓✓ Fire risk	31	1
Rail pads	✓✓✓✓ Easy in new tracks; difficult for retrofits	✓✓✓✓ Reducing structure-borne noise by 3 to 6 dB	✓✓✓✓ Reducing structure-borne vibration by 3 to 6 dB	✓✓✓✓✓ Low lifecycle cost	✓✓✓✓✓ Internationally adopted and considered for renewal in the Yarra Trams rail network	✓✓✓ Replacement cost is high	✓✓✓✓ Water ingress risk between rail and pad	29	2
Rail encapsulation	✓✓✓ Easy on-site; retrofit and welding complex	✓✓✓✓✓ Effective for ground-borne noise but not for squealing or airborne noise	✓✓✓✓✓ Significant ground-borne vibration reduction	✓✓✓ Medium; high maintenance costs	✓✓✓✓✓ Used globally and in Sydney and Canberra Light Rail networks	✓✓✓ High replacement cost; complex maintenance	✓✓ Heat, water and salt sensitivity; thermal expansion concerns	26	3
High wear-resistance rail	✓✓✓✓ Labor- and cost-intensive to implement	✓✓✓ Structure-borne noise reduction	✓✓✓ Structure-borne vibration reduction	✓✓✓ High initial cost; lower lifecycle cost	✓✓✓✓ Widely adopted internationally	✓✓✓✓✓ Reduces the maintenance and increases the service life	✓✓✓✓ Higher wheel wear; environmental impact from heat treatment	26	3
Green track systems	✓✓✓ Not suitable for shared roadways	✓✓✓✓✓ Ground-borne noise reduction	✓✓✓✓✓ Ground-borne vibration reduction	✓✓ High cost; regular upkeep	✓✓✓✓✓ Used nationally and internationally, including tram lines in Sydney, Adelaide and Melbourne	✓ Regular maintenance, irrigation, fertilisation and mowing required	✓✓✓ Reduced visibility of defects, moisture retention, allergens	24	4
Friction modifiers	✓✓✓ Easy to retrofit; not for shared roadways	✓✓✓✓✓ Squealing noise reductions average around 10 dB, with potential reductions up to 22 dB	N/A	✓✓✓ Medium; requires ongoing supply and checks	✓✓✓✓✓ Internationally and nationally used (case study on St Kilda Road)	✓ Needs training, regular inspection	✓✓✓ Lubricant runoff, sensitivity to weather, risk of failure	20	5

Table 2: Assessment of solutions

Comparing the solutions based on their ranking, under-slab track matting ranks the highest with a score of 31, standing out for its significant noise and vibration mitigation, low cost and suitability for new tracks. However, it is less ideal for retrofitting due to installation complexity and high replacement costs. Rail pads scored 29 and ranked second in the assessment, offering strong noise and vibration reduction with low costs, though their use in existing tracks is limited by installation challenges and risks such as water ingress. Rail encapsulation and high wear resistance rail ranked third with a score of 26. High wear resistance excels in lifecycle cost reduction and maintenance benefits but involves high initial costs and labour-intensive installation. Rail encapsulation significantly reduces ground-borne noise and vibration and offers the benefit of a low initial cost; however, repairs are costly and challenging.

Green track systems ranked fourth with a score of 24, as these provide environmental benefits but require extensive maintenance and are unsuitable for mixed rail traffic. Friction modifiers were the lowest ranked option, with a score of 20, as although they are easy to install on existing tracks and offer significant squeal noise reduction, they require regular maintenance, have a high environmental sensitivity, while the potential for lubricant run-off reduces their practicality.

4. Guidance

The next step is to ensure the key considerations are made for performing a feasibility assessment of the solution. Table 3 presents a detailed analysis for implementing the most practical rail noise and vibration mitigation solutions trial in existing rail track, including necessary considerations and relevant recommendations for each key aspect based on the review of literature and stakeholder consultation. For installation in new track systems, the key aspects, considerations and recommendations for implementing rail noise and vibration mitigation measures are outlined in Table 4.

Aspect	Considerations	Recommendations
Site evaluation	• Source(s) of noise • Source(s) of vibration	• Finding the noise sources such as wheel-rail interaction, impact noise from rail joints, switches, squeal from tight curves. • Finding vibration sources such as track irregularities, subgrade conditions, ground-borne vibration, etc.
Noise and vibration impact evaluation	• Noise and vibration level • The impact of noise and vibration on nearby residential and commercial areas	• The reduction in noise and vibration levels for each solution is discussed in Table 2. • Noise complaints, night operational restriction and operational description due to speed restriction etc., should be considered when evaluating the impact of noise and vibration.
Technical feasibility	• Case-by-case evaluation of each solution according to the track types and the type of the noise and vibration	• According to the site evaluation and noise/vibration source analysis, the most suitable solution is determined based on track type and technical considerations. The recommended solutions for retrofitting are evaluated in detail in Table 2.
Compliance with regulations	• Meet regulations • Meet railway safety standards • Being type approved	• Rail infrastructure managers (RIMs) to modify the specifications and guidelines based on information relevant to noise and vibration minimisation solutions. • Risk to safety for using the solutions shall be assessed. • RIMs to type approve the solutions for the installations in the rail corridor.
Cost benefit analysis	• Estimate the cost of the implementation and operation while considering budget constraints • Compare the costs to the benefits of improving rail operation and reducing noise/vibration levels	• The comparative lifecycle costs and the level of the noise/vibration mitigations are outlined in Table 12. The general benefits of noise and vibration reductions are as follows: – decreased noise complaints from residents near rail corridors. – maintained or increased night operations, allowing off-peak scheduling, reducing daytime congestion and optimising logistics. – higher travel speeds without increased noise – reduced track and infrastructure wear caused by vibrations, leading to lower maintenance costs and extended asset lifespan.
Community engagement	• Engage with local communities to gather their feedback and address concerns about the proposed project	• Collect and feedback through interviews and surveys to inform appropriate solutions.

Table 3: Feasibility analysis for installation of infrastructure solutions in existing track systems

Aspect	Considerations	Recommendations
Site evaluation	• Source(s) of noise • Source(s) of vibration	• Assess potential noise sources in the planned track alignment and design for noise minimisation. • Evaluate subgrade conditions and select suitable track structures to minimise vibration.
Noise and vibration impact evaluation	• Potential noise and vibration level and their impacts on surrounding areas	• Conduct predictive modelling for noise and vibration impact on surrounding areas. • Integrate mitigation measures discussed in Table 2 into the initial design to minimise long-term impact.
Technical feasibility	• Design and incorporate suitable mitigation measures in the track layout and construction plans	• Choose cost-effective and durable solutions that align with project constraints, based on the assessments in Table 2. • Conduct pilot testing before full-scale implementation.
Compliance with regulations	• Meet regulations • Meet railway safety standards • Being type approved	• RIMs to obtain necessary approvals for integrating noise control measures in new rail corridors. • The safety risk assessment for using the solutions shall be conducted. • RIMs to type approve the solutions for the installations in the rail corridor.
Cost benefit analysis	• Evaluate the cost implications of integrating noise/vibration control in track design • Compare initial construction costs vs. long-term maintenance savings and operational benefits	• Prioritise solutions with a strong return on investment and minimal maintenance requirements based on the assessments in Table 2. • Balance upfront costs with long-term benefits.
Community engagement	• Gather community feedback on noise/vibration expectations for the new track alignment	• Conduct surveys, meetings and stakeholder engagement sessions to ensure community support. • Ensure community concerns are integrated into the design phase.

Table 4: Feasibility analysis for installation of infrastructure solutions in new track systems

5. Conclusions

> Each light rail mitigation solution was evaluated through a multi-criteria assessment framework, considering installation feasibility, mitigation effectiveness, lifecycle cost, maintenance requirements and associated risks.

Stakeholder engagement was conducted to validate and enhance the findings derived from the desktop review. The assessment outcomes can be used to support decision-making for upgrades and future planning in noise and vibration sensitive light rail environments:

- Under-slab track matting emerged as the most effective solution for noise and vibration mitigation. However, its installation in existing tracks poses significant challenges.
- Rail pads are cost-effective and commonly used to address structure-borne noise and vibration. Contrastingly, they are vulnerable to water ingress.
- Rail encapsulation demonstrated strong performance in mitigating ground-borne noise and vibration but is hindered by complex maintenance and repair requirements.
- High wear-resistant rails offer moderate noise and vibration reduction, along with substantial lifecycle cost savings and maintenance advantages. These benefits are offset by high upfront costs and labour-intensive installation.
- Green track systems contribute positively to urban integration and environmental aesthetics while providing noise and vibration mitigation. Nonetheless, they demand intensive maintenance and are less suitable for mixed traffic conditions.
- Friction modifiers effectively reduce squeal noise and are easy to apply on existing tracks. However, their sensitivity to weather, potential for lubricant runoff and elevated risk of failure, limit their practicality for long-term use.

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ARTICLE 09

Automation Improvements for the Australian Level-Crossing Assessment Model

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1. Introduction

To evaluate the safety risks at Australian railway level crossings, the Australian Level Crossing Assessment Model (ALCAM) is employed. Traditionally, ALCAM assessments utilise information obtained through manual inspections undertaken by authorised personnel. As such, the process can be time-consuming, resource-intensive and limited by funding and inspector capacity/availability. This can result in level crossings being inspected inadequately (e.g. once every seven years), limiting the availability of up-to-date data for risk management and informed decision-making.

To address the current limitations of the ALCAM process, NTRO was engaged in 2022 to lead and deliver a collaborative multi-stage project funded by the Department of Transport and Planning (DTP) Victoria. This project sought to investigate how the ALCAM process could be optimised via the integration of modern technologies (see Figure 1), including automated data collection, virtual inspection techniques and machine learning. Delivery of this project would reduce resource-dependency and facilitate more frequent delivery of inspection data, making up-to-date and accurate inspection data available to stakeholders to utilise in managing risks and prioritising safety risk at level crossings.

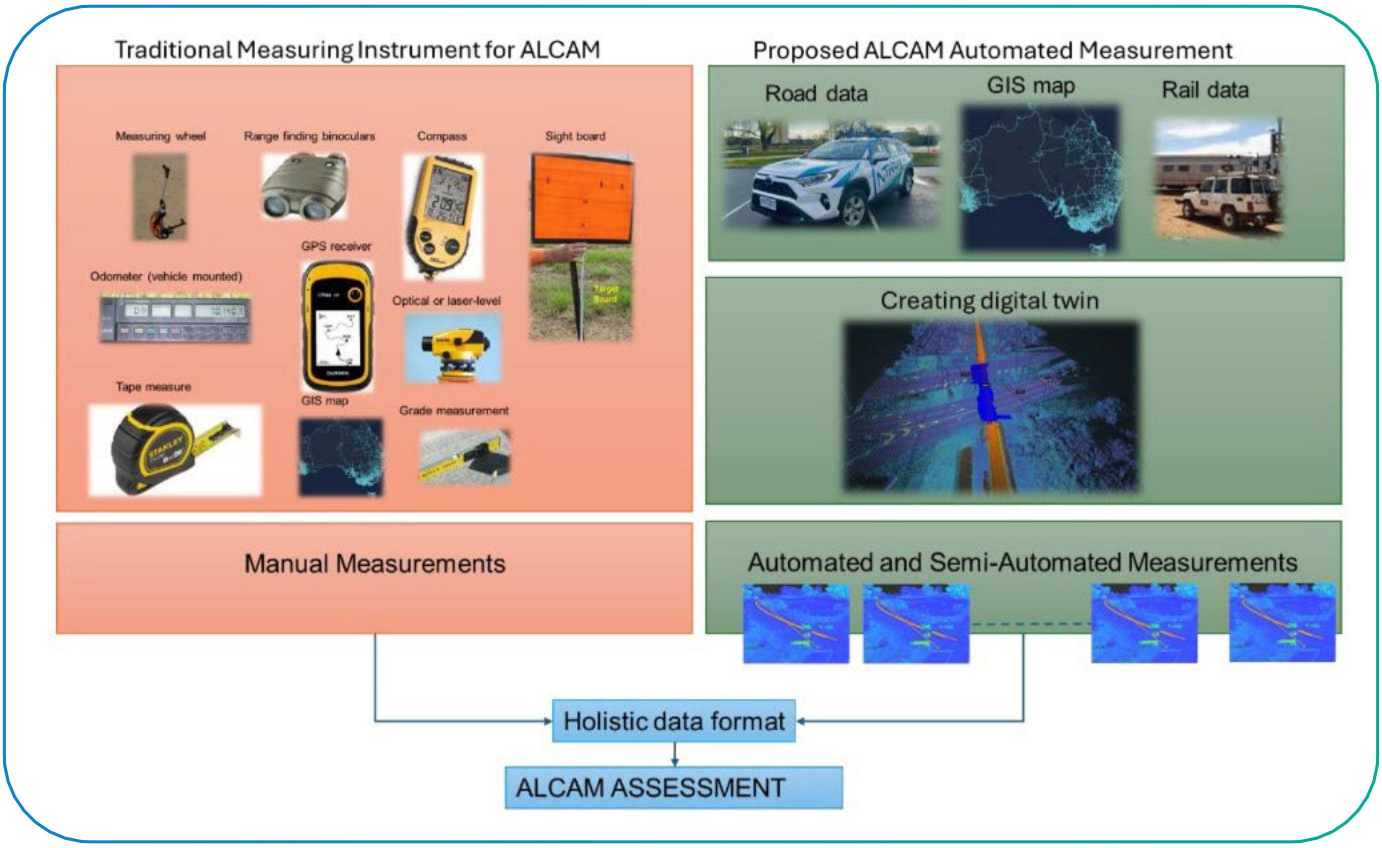

Figure 1: ALCAM Automation concept to streamline sight measurements for ALCAM surveys

2. Project Overview

The work to improve the ALCAM process was scoped as a three-stage process:

1. **Stage 1:** a desktop review of current ALCAM practices, highlighting inefficiencies and areas for improvement.
2. **Stage 2:** initial integration of technology to assess feasibility, including data collection and proof-of-concept trials for semi-automated inspections.
3. **Stage 3:** continuation of the feasibility assessment of integrating technology to reduce manual effort, improve efficiency and uphold safety standards.

2.1 Stage 1

Stage 1 of the project was undertaken in 2022/2023 and focused on a desktop assessment of the current ALCAM approach. The existing ALCAM process was assessed to identify any potential untapped efficiency gains (e.g. optional alternative data sources to mitigate the need for on-site assessment data collection). Applicable technologies were also identified and investigated to understand associated costs and potential for use.

Outcomes of the literature review in this stage revealed the following:

- The ALCAM input parameters for each component of the model are gained from an on-site assessment and then inserted into a level crossing management (LXM) portal from which the ALCAM risk score is calculated.
- Some parameters are auto-populated based on other manual inputs (either entered by the ALCAM assessor or imported from an appropriate file).

Following the literature review, stakeholder and industry consultation was undertaken to identify and prioritise which ALCAM characteristics and LXM input parameters are time-consuming/difficult to assess on-site and would benefit greatly from automation. Six such characteristics (which correlate to 23 primary LXM input parameters and a further 100 secondary LXM input parameters) were identified as follows:

1. Sight distance.
2. Crossing signage/marking.
3. Size limit/clearance.
4. Crossing layout.
5. Vegetation management.
6. Train situation.

To facilitate automation of calculating the above parameters, technology currently utilised in the rail and road sector was reviewed in consultation with industry experts in data collection also including visualisation, software development and AI model development. The outcomes of this investigation indicated the following technologies (generally in various combinations to allow for calculation of ALCAM characteristics) are most applicable to this project:

- Aerial and satellite imagery (including Interferometric Synthetic Aperture Radar).
- High-resolution digital cameras mounted to road/rail vehicles.
- Light Detection and Radar (LiDAR) units mounted to road/rail vehicles.
- Global Navigation Satellite System (GNSS) units required for georeferencing data.

The applicability of these identified technologies, in various combination (examples given in Table 1), were assessed to then determine the viability of undertaking AI model proof-of-concept trials in Stage 2 of the project. This assessment yielded a decision to develop AI models using LiDAR & video data from NTRO's iScan vehicle to assess sight distance, signage/markings and clearance widths.

Example	Technology	ALCAM Parameters	Brief Description of Application
1	Aerial/satellite imagery.	Sight distance calculation and determination of signage/ markings.	Develop AI models to calculate site distance and determine signage/markings using obtained imagery.
2	Video, LiDAR & aerial/satellite imagery.	Sight distance calculation and determination of signage/ markings.	Develop AI models for site distance calculation and signage/ marking recognition using obtained aerial/satellite imagery, and a fusion of LiDAR and video footage from rail/road corridor.

Table 1: Examples of technology for proof-of-concept trials

2.2 Stage 2

Stage 2 of the project was undertaken in 2023/2024 with the aim of developing and implementing AI-based models for feasibility assessment to optimise ALCAM processes. This stage of the project involved data collection, manual assessment, virtual assessment and the development and refinement of AI models.

Within this stage, ten Victorian locations, covering a diverse range of control types, mechanisms and traffic layouts, were identified to be surveyed and assessed. These locations were subject to both manual inspection and NTRO iSCAN vehicle (video and LiDAR) data collection methods, to gather information reflective of current industry practice and for the potential automated practices. This information was then supplied to collaborating partners to begin development of AI models for selected ALCAM/LXM parameter inputs. The development of the AI models broadly included:

1. Processing NTRO's iSCAN data and comparing this with the manually collected data.
2. Georeferencing the collected road/rail data points.
3. Preliminary development of AI models based on selected ALCAM parameters (critical parameters identified as sight distance measurements, signage/marking identification, and clearance width).
4. Comparison of AI models with manual and virtual assessment outcomes.
5. Refinement of AI models for feasibility assessment.

In developing these models, a couple of challenging aspects were identified and addressed to ensure quality and accuracy of the resultant models and their outputs. These challenges were most notably:

- Ensuring the quality and accuracy of collected data for training the AI models.
- Addressing potential inaccuracy in the data collection and model development processes.

At the end of Stage 2, the process for developing a digital twin framework for the ALCAM process was refined by evaluating the feasibility of automation through assessing the developed AI models and identifying attributes that require more detailed analysis. Continued refinement of these models was undertaken in Stage 3.

2.3 Stage 3

To improve consistency, efficiency and safety in support of reducing incidents at level crossings, Stage 3 of the project (2024/2025) undertook testing of integrating the digital twin model, as well as formulating a roadmap towards full automation of the field survey process. The focus on full automation in this stage of the project set out to:

- Assess the feasibility of automated system development for field data collection to integrate with existing ALCAM processes.
- Test and validate an automated system at various level crossings across Victoria.
- Propose methods for completing the system design, alongside recommendations for its application across the national rail network.
- Demonstrate clear benefits to stakeholders (e.g. faster data collection, reduced costs and decreased manual surveying by which improved worker safety is achieved).

This continued investigation into the feasibility of modernising and automating the assessment process for railway level crossings in Australia assessed the practicality, effectiveness and efficiency of the proposed solutions/ interventions using a structured methodology as outlined in Figure 2.

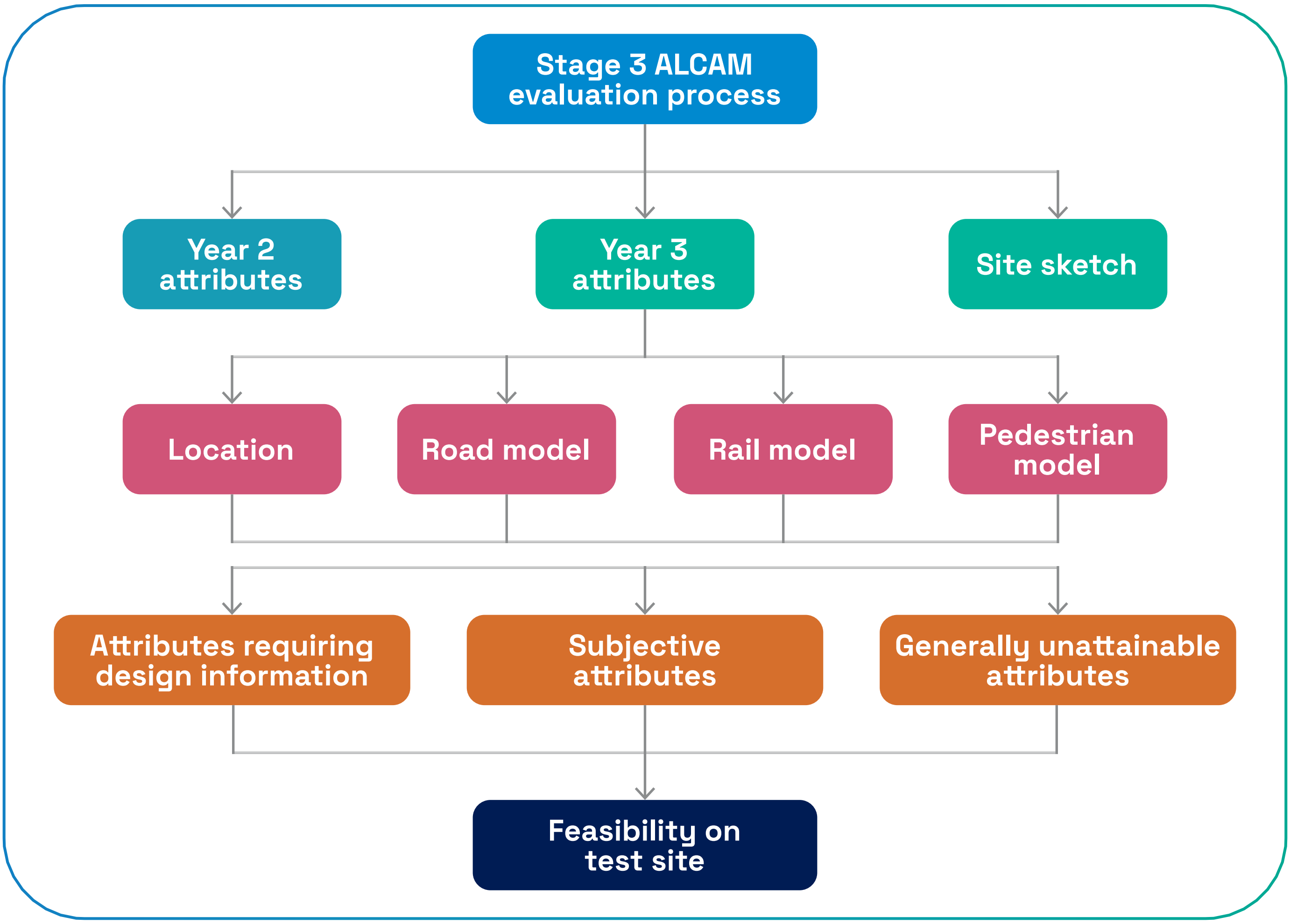

Figure 2: Stage 3 ALCAM Methodology Flow Chart

The ALCAM evaluation in Stage 3 focused on refining the automation feasibility of attributes identified in earlier phases, as well as broader attribute categories applicable across different models. It considered attributes requiring design data, subjective interpretation or those currently unattainable due to data gaps. Feasibility testing at selected sites assessed the practicality of automating data collection, particularly for challenging attributes, using a mix of field studies, simulations and stakeholder input. Both qualitative and quantitative methods were applied to identify risks, limitations and improvement opportunities. Each attribute was evaluated across road and pedestrian level-crossing models, for their relevance, data needs and automation potential to streamline future ALCAM assessments. A total of 222 attributes were reviewed and categorised as follows:

1. **Inputs and outputs of the road and pedestrian models:**
   - Road model: proximity to intersections, number of lanes, road surface conditions, visibility, signage and sun glare.
   - Pedestrian model: proximity to stations, schools, event venues, and condition and safety of pedestrian pathways, signage and visibility.
2. **Automation feasibility** (focused on attributes that can be collected systematically or inferred from existing data sources, reducing the need for manual data entry):
   - Data sources: digital maps, LiDAR and imagery used to extract attributes such as proximity to intersections, visibility and signage.
   - Subjectivity and attainability: some attributes require manual intervention or review due to a lack of data, which are noted for future consideration.
3. **Extended list for automation feasibility:**
   - Specific attributes, such as road level-crossing model inputs (e.g., proximity to stations, visibility of traffic control) and pedestrian crossing model inputs (e.g. pathway gradients, lighting and signage) were prioritised for feasibility testing.
4. **Attributes requiring historical data:**
   - Examples of these type of attributes are heavy vehicle proportion, maintenance effectiveness, train patterns and traffic volumes, which require sources such as digital map information and crowdsourced data, e.g. the traffic layer of digital maps.

Over the course of Stage 3, the methodologies applied to achieve meaningful outcomes from the feasibility testing covered the following steps:

1. **Raw data processing:** collecting, aligning and preparing raw data (including aerial maps, rail data and vehicle data) for processing (e.g. georeferencing and point cloud stitching) and analysis.
2. **Development of automation modules:** analytical modules to achieve automation of traditionally manual tasks to identify, quantify and categorise conditions and constraints related to level crossings, pedestrian walkways, and visibility and clearance parameters. These modules included precision mapping through laser scanning and triangulation, asset and defect detection via computer vision, and level crossing traffic performance assessments through proposed integration of crowd-sourced data.
3. **Measurement of qualitative attributes:** Translating subjective qualities into measurable data via clear criteria and rating systems.
4. **Decentralisation of ALCAM attribute measurement:** Proposal of a standardised/holistic data structure and methodology to enable ALCAM task distribution among vendors based on expertise in various ALCAM attributes.

By the end of stage 3, the key findings were noted as follows:

1. **Automation feasibility:**
   - The study demonstrated the potential of automated tools, including laser scanning and AI-driven analysis, to accurately measure many ALCAM attributes.
   - A semi-automated approach, blending manual expertise with technological innovations, is recommended for the short term due to challenges in automating subjective assessments.
2. **Challenges:**
   - Attributes requiring subjective interpretation or historical design data remain complex to automate.
   - Variations in automated reporting across vendors highlight the need for standardisation and accreditation processes.
3. **Data standardisation:**
   - The adoption of a holistic data format has been pivotal in ensuring compatibility, efficiency and scalability across multiple vendors and technologies.
4. **Efficiency and scalability:**
   - Automation and structured data formats enabled faster assessments, with a significant reduction in the need for manual field surveys.

3. Conclusions

> Overall, this project represents a major advancement in automating and modernising ALCAM, demonstrating through feasibility testing that technologies such as LiDAR, computer vision and digital twins can significantly enhance safety assessments at level crossings.

However, further work can be done to continue advancing ALCAM automation, such as:

1. **Accelerated development of semi-automated models:** broaden the use of semi-automated tools to handle subjective attributes, with a gradual shift toward full automation where viable.
2. **Standardisation of data collection protocols:** invest in consistent data formats to ensure interoperability across technologies and vendors.
3. **Focus on a technology-agnostic solution:** design systems that can integrate emerging tools such as AI and crowdsourced data without being bound to specific platforms, ensuring long-term adaptability.

In addition to these recommendations, the project also establishes a foundation for an Accelerated and Automated ALCAM (A-ALCAM) model, where the term "acceleration" refers to approaches that enhance the accessibility and availability of ALCAM surveys, including the use of semi-automated and automated methods leveraging digital twin technology, machine learning and AI systems. As such, the project presents a strong case for future development focusing on:

1. Testing and validating scalability of semi-automated tools across more sites.
2. Methods to quantify and integrate subjective and qualitative attributes into automated assessments.
3. Establishing automated system accreditation frameworks to ensure accuracy and regulatory compliance.

For more information

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