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Foreword

Our transport industry and NTRO stand at an inflection point. An upwards move will lead to safe, sustainable and resilient transport spanning land, sea and air. A downwards move is not an option worth considering. The key to the desired upwards direction of that inflection depends on a number of things.

First amongst them is seizing the opportunities which data and AI offer. Importantly, though, data is not an end in itself, but a means of creating the insights needed to drive effective solutions and system improvements. At NTRO we see this as being so important that we have invested significantly in the space and are re-platforming the organisation around these digital capabilities.

While pursuing the new, we must not lose sight of the long-term outcomes which the community and leaders expect from transport systems. Safety, sustainability, resilience and value for money have been and will be at the top of that list. Our elected members are seeking heightened economic productivity and social connection from the transport system.

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I am looking forward to seeing how the digital trajectory can help us solve some of the intractable and enduring problems that we face.

Michael Caltabiano

Chief Executive Officer
NTRO



In this issue

This issue addresses two defining threads of today's transport landscape: one longstanding and persistent (road safety), and the other emerging and transformative (data and data-driven solutions).

Road safety remains the transport sector's unending fire. It is now abundantly clear that the 2030 target to halve road deaths and serious injuries will not be achieved. Current trends point to increasing, rather than decreasing, fatalities and hospitalisations. This is despite the transport profession's immense goodwill, expertise, commitment and focus, and an estimated \$10–20 billion invested in road safety since 2020. New approaches are needed to complement existing efforts.

While the future of data may be uncertain, two things are clear: there is a vast amount of it, and it continues to grow rapidly. Conservative—though necessarily speculative—estimates suggest humanity held around 0.1–0.3 zettabytes (300 million terabytes) of recorded information in 2000. Today, the global stock is approximately 180–220 zettabytes, representing a thousand-fold increase. It is growing by around 20–25% annually, adding roughly 40 zettabytes each year and doubling every three to four years.

This issue focuses explicitly on solutions enabled by the availability and application of diverse data sources.

The issue starts with a mini focus of four papers on road safety and follows up with several solutions-focussed papers.

Tran's opinion paper examines the wicked problem of the growing road toll and argues for a deeper systems-thinking approach. Fox and Hand then outline NTRO's initiative to tackle transport safety across the Asia Pacific region through a broader systems lens.

Chen et al. revisits 30 years of crash data to assess the suitability of the traditional five-year analysis window. Green presents a new approach for improving safety at high-speed rural intersections.

Four papers focus on data-driven improvements to infrastructure performance and management more broadly. These solutions cover a range of aspects from real-time monitoring of rail ballast health (Lin et al.), to use of residual risk approaches to improve asset management practice (Kurian and O'Connor), to optimisation of bridge maintenance (Kutadinata et al.) and system-focussed data frameworks for network-wide road monitoring (Wang et al.)

Finally, in an invited paper from Chile, Associate Professor Alvaro Gonzalez outlines a road dust management system for mine haul roads, drawing on his extensive experience with these specialised environments.

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Data itself is not the goal; its value lies in generating insights that lead to new and better solutions.

Mike Shackleton
Chief Research Officer
NTRO



Dr Ronny Kutadinata
Editor-in-Chief
NTRO



Authors



Phuong Tran

Phuong is a transport and road safety professional with over five years' experience turning data and design into practical insights that improve how people move through cities and regions. She specialises in infrastructure risk assessment, corridor and network planning, and policy development, supporting evidence-based decisions for government and industry. At NTRO, she has contributed to major initiatives including the Safe System Crash Review Framework, speed-zoning policy, and adapting the Movement and Place Framework. She also developed a Data Assessment Framework for MRWA. Phuong collaborates closely with stakeholders to deliver practical, future-focused transport outcomes.



Paul Fox

Paul is the Executive Director of NTRO's Centre for Transport Safety Asia Pacific. He is also a Visiting Fellow with UK-based Cranfield University & the Regional Manager Asia Pacific for Cranfield's Safety & Accident Investigation Centre. Prior to joining Cranfield, Paul was a Senior Industry Fellow (Aerospace and Aviation) with RMIT University, where he was instrumental in establishing a partnership between the Australian Transport Safety Bureau (ATSB) and RMIT. Paul's previous roles include Deputy Chairman & Executive Director of the national industry association – Aviation/Aerospace Australia, Regional Director Asia Pacific with the USA-based Flight Safety Foundation, and General Manager with the Australian Davos Connection – an Australia-based leadership think tank, affiliated with the World Economic Forum.



Guy Hand

Guy Hand is head of communications at NTRO, and part of NTRO's wider Marketing and Communications team. A former award-winning journalist, Guy is involved with producing content and in-house marketing material, website production and writing, social media content, videos and podcasts, internal and external communications within the organisation.

Guy has worked at NTRO/ARRB since 2018, and before that spent 25 years as a journalist working for major news organisations such as the BBC, Australian Associated Press (AAP) and News Corp across print, digital, television and radio. He has also worked in sports administration, event production, digital media, public relations and other communications roles – liaising regularly with local government and statutory bodies as part of those roles.



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.



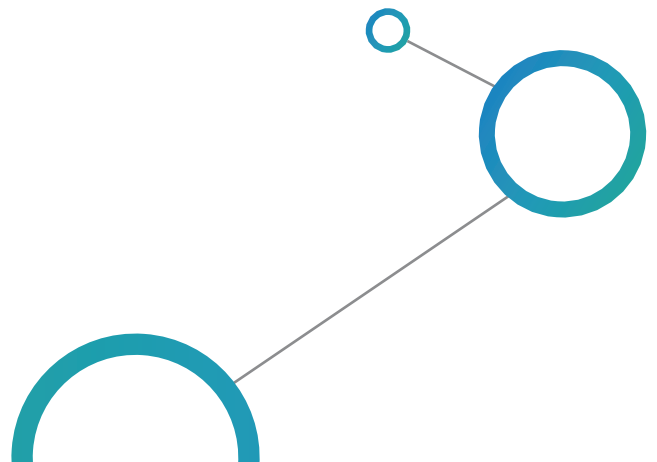
Gavin Lennon

Gavin Lennon is Director and lead Crash Reconstruction Expert at CrashLab Solutions. A physicist with more than 17 years' experience in transport safety and investigations, he has led hundreds of collision investigations across road, rail, maritime and aviation sectors. ACTAR-accredited since 2017, Gavin regularly provides expert evidence in legal proceedings and delivers specialist training, drawing on experience with police, transport agencies and major safety projects across Australasia.



Melanie Venter

Melanie Venter is a Principal Engineer at NTRO, where she is focussed on new methods and solutions aimed at reducing the road toll in Australia , New Zealand and across the Asia-Pacific region. She has worked across business sectors including academia, public and private entities in South Africa and Australia. She has led several large scale multi-disciplinary projects, with a particular interest in combining innovative technology with road safety. Her latest projects include working towards automation of the Australian level crossing assessment model, and the Bundaberg regional council's Network Safety Plan.





David Green

David Green is a qualified civil engineer and Principal Professional at NTRO, with over 20 years of experience across the road and traffic industry. His work spans public and private sectors, focusing on network operations, intelligent transport systems, road safety, freight and multimodal policy, connected and autonomous vehicles, public transport priority, and electric mobility.



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.



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 Engineering and Modelling, Imperial College London, UK.



Tom Turvey

Tom joined NTRO in 2026 as a graduate scientist in the Sustainable Infrastructure Materials portfolio. Since joining he has worked in a range of project areas including recycled pavement materials specifications, accelerated loading facility testing and rail ballast assessment. He graduated from Monash University in 2025 with a Bachelor of Science Advanced – Research (Honours), completing an extended major and honours in chemistry. His honours thesis explored the use of electrochemical techniques for the recovery of valuable metals from waste lithium-ion batteries.



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 Javad Yaghoubi

Dr Javad Yaghoubi is a Principal Engineer at the National Transport Research Organisation (NTRO) and a Registered Professional Engineer of Victoria (RPEV). He has more than 16 years of experience across research, industry, and higher education in pavement, geotechnical, and transport infrastructure engineering. His work focuses on sustainable infrastructure, including the use of recycled materials and industrial by-products to support circular economy outcomes. At NTRO, he leads projects involving technical specification development, practitioner training, feasibility studies, and field trials. Over the past four years, he has expanded his expertise into rail infrastructure, drawing on a strong foundation in road infrastructure engineering and research.



Dr James Grenfell

James is a principal pavement engineer leading the Sustainable Infrastructure Materials Portfolio within Sustainability and Materials Performance group and NTRO. James has more than 20 years of experience in pavement engineering and pavement materials spanning the UK and Australia. He has researched a variety of road construction types including bituminous binders, asphalt, concrete, unbound granular and stabilised materials. Since arriving at NTRO 8 years ago, his work has focused on sustainable construction techniques and the beneficial use of recycled materials in transport infrastructure.



Rohit Kurian

Rohit is a civil engineer with over five years' experience across local government, consulting and construction. He specialises in asset management, construction management and pavement performance. At NTRO, he has delivered major asset management projects for Austroads, TMR, MRWA, DTP and local councils, applying cost-risk-quality frameworks to improve performance and reduce whole of life costs. His work supports national initiatives on low and zero emission heavy vehicles and network level remaining life. With strong technical, analytical and communication skills, Rohit links strategic asset management with practical implementation to deliver clear, actionable insights.



Georgia O'Connor

Georgia O'Connor is a Senior Engineer 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 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.



Colum McGovern

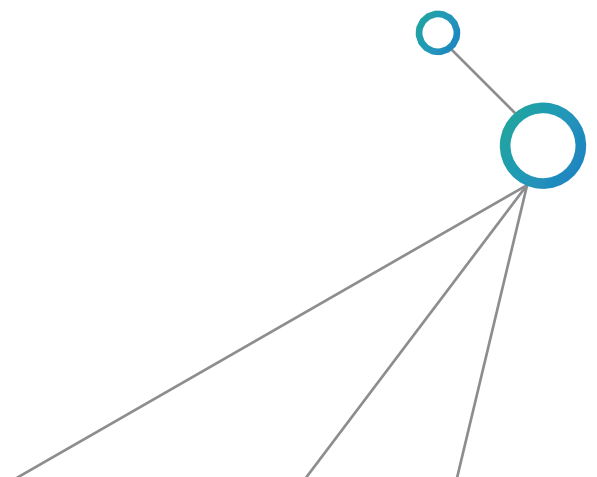
Colum McGovern is a Structural Engineer with NTRO's Asset Performance – Structures team, where he has been involved since 2023. With over six years of experience spanning structural design, asset management, and research, Colum brings both technical expertise and practical insight to the management of transport infrastructure.

Before joining NTRO, Colum worked as a consulting engineer, gaining a strong foundation in structural analysis, design, and project management. He also has extensive field experience conducting bridge inspections across Ireland and Australia, assessing structural condition and recommending remedial measures.



Kaiwen Liu

Kaiwen Liu is a Master of Information Systems student at the University of Melbourne and an engineering exchange student at Harvard University. Building on his Bachelor of Economics background, he takes a cross-disciplinary approach to applying advanced computing and analytical methods to complex problems. His technical and applied experience spans generative AI system design, database modelling, and full-stack software engineering. His work at NTRO focused on designing data-driven decision support system for strategic asset management. Kaiwen is interested in building intelligent, scalable systems at the intersection of robust engineering and applied economics.





Nigel Powers

Nigel is a business and industry leader with over 25 years experience in the planning, design, construction, maintenance and management of transportation infrastructure. He has been working in various roles across NTRO for the last 7 years and is currently the National Technical Leader – Structures.

Outside of NTRO, Nigel has over 18 years experience in the Victorian public service including VicRoads/DoT/DTP and Major Road Projects Victoria/VIDA Roads. Nigel's technical focus is bridges and other road structures with experience throughout the lifecycle of a structure and is acknowledged nationally and internationally for this work. His experience includes design, inspection, assessment, asset management, network management, construction, maintenance and operation.



Trevor Wang

Trevor Wang is a Senior Professional Engineer in NTRO's Mobility Futures team. After graduating from the University of Queensland with the qualification in Civil and Environmental engineering, his internship with ARRB/NTRO was directly related to the industry of traffic engineering. This work instilled experience in traffic management and planning, and showcased Trevor's ability to handle complex projects relating to road designs and traffic operations.



Dr Sepehr Dehkordi

Sepehr is a Senior 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.



Neil Beckett

Neil brings over 25 years of experience as an asset engineer, working mainly in the client space in New Zealand. A Chartered Member (Engineering Technologist) with Engineering NZ, he has extensive knowledge of road maintenance and operations. His consulting and government experience helps him apply practical, cost effective and sustainable solutions. Neil's skills include asset and information management, emergency response, structures management, pavement condition surveys, customer focussed delivery and people leadership across multiple disciplines. He is driven by doing the right thing safely, in the right way, and at the right time, whilst recognising the impact on customers and communities.



Associate Professor Alvaro Gonzalez

Alvaro is Civil Engineer, MSc, PhD, and Associate Professor at Universidad Católica de Chile, with over 20 years of experience in academia and industry. His research focuses on road engineering, sustainable materials, and technologies to improve productivity in the road sector. He specializes in road materials and soil stabilization, promoting efficient and sustainable infrastructure development.



The Problem with ‘The Problem’: Road Trauma as a Wicked Problem and the Case for Systems Thinking in Road Safety

Phuong Tran, National Transport Research Organisation, Australia

Abstract

Road trauma in Australia remains a persistent public health challenge, with 1,313 road deaths recorded in the 12 months to January 2026—a figure sitting above the trajectory required to meet the targets of the National Road Safety Strategy 2021–30. This paper argues that the gap reflects not only a failure of implementation but a deeper issue in how road safety has been understood and defined. Drawing on systems thinking and wicked problem literature, it examines road trauma as a complex sociotechnical problem in which crashes emerge from the interaction of infrastructure, behaviour, institutional arrangements and wider societal conditions.

This paper reframes road trauma as a wicked problem in the tradition of **Rittel and Webber (1973)**, where competing stakeholder framings, interconnected causes and the absence of any single correct solution make targeted and conventional responses insufficient on their own. It then examines how systems thinking can extend and strengthen existing approaches, including the Safe System framework, by drawing attention to the feedback relationships, governance structures and cross-sector dynamics that shape safety outcomes at the system level.

Practical applications including systems mapping, causal loop analysis, backcasting and collaborative approaches are discussed as tools for translating systems thinking into practice. The paper concludes with a call for road safety strategy, policy and professional practice in Australia to move toward a more systemic understanding of risk, one that reflects the true complexity of the system it is trying to change.

1. Introduction

Road trauma remains a persistent public health challenge in Australia, with current trends indicating that progress toward Vision Zero targets is off track. In the 12 months ending January 2026, 1,313 people were killed on Australian roads, equating to a fatality rate of 4.8 deaths per 100,000 population (**DITRDCA 2026**). While this reflects a slight reduction in the fatality rate, the total number of deaths has increased, and recent reporting confirms that no jurisdiction or road user group is currently on track to meet the targets set out in the National Road Safety Strategy 2021–30 (**AAA 2024**).

These national figures also conceal significant variation across jurisdictions, road user groups and demographics, indicating that road trauma is unevenly distributed across the system. Such patterns suggest that road safety outcomes are shaped by a range of interacting factors rather than a single cause. Transport systems are widely recognised as complex sociotechnical systems, where safety outcomes emerge from interactions between infrastructure, vehicles, road users, policy and institutional decision making (**Salmon et al. 2012**). Figure 1 presents this uneven distribution of road trauma across Australia and reinforces the limitations of relying on national aggregates to understand patterns of risk.

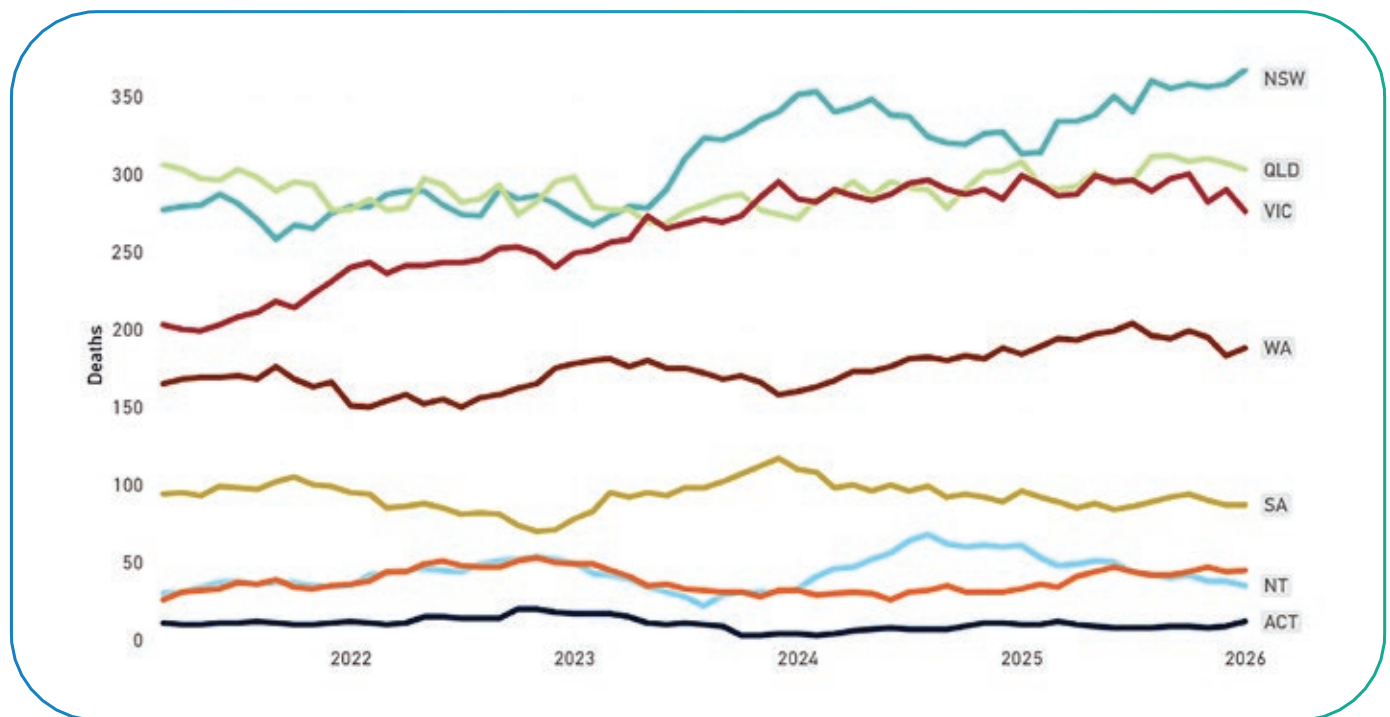


Figure 1: State comparison of total deaths

Source: DITRDCA 2026.

Within this context, systems thinking offers a way to better understand how these elements interact and contribute to risk. Not replacing existing approaches, it provides an additional lens through which to examine the limitations and blind spots of current practices. Frameworks such as Safe System have already advanced road safety by shifting focus towards shared responsibility and injury minimisation. However, systems thinking can complement these approaches by helping identify relationships, feedback loops and underlying system conditions that influence how safety outcomes emerge over time.

This paper explores how systems thinking can support a more integrated and holistic understanding of road safety and how it can be used alongside existing frameworks to strengthen analysis, decision making and intervention design.

2. Road Trauma as a Wicked Problem

The patterns visible in Australian road safety data suggest that road trauma cannot be presented as a single, clearly defined problem with a manageable solution. It reflects a set of interconnected issues spanning infrastructure design, road user behaviour, vehicle technology, policy decisions, and wider social and environmental conditions. This aligns with the concept of “wicked problems” introduced by **Rittel and Webber (1973)**, which describes complex societal challenges that are difficult to define and do not have a single, agreed solution.

Unlike problems in the natural sciences and engineering where goals are clear and solutions can be verified, wicked problems are shaped by competing perspectives and rely on judgment instead of definitive answers. **Rittel and Webber (1973)** argue that such problems cannot be solved, only addressed repeatedly over time. A feature of wicked problems is that how the problem is defined influences how it is approached. One of their observations

was that wicked problems have no definitive formulation; understanding the problem and figuring out how to address it happen at the same time, because the problem cannot be entirely defined without already thinking about solutions (**Rittel and Webber 1973**). This is relevant to road safety, where different stakeholders frame road trauma in different ways depending on their roles and priorities.

For example, engineers may focus on infrastructure, public health practitioners on exposure and risk, enforcement agencies on compliance, and planners on land use and mobility patterns. Each perspective leads to a different set of interventions, yet none wholly captures the problem on its own. As a result, reaching a shared definition is challenging, since each framing implies a different response (**Rittel and Webber 1973**). Figure 2 illustrates the key characteristics of wicked problems.

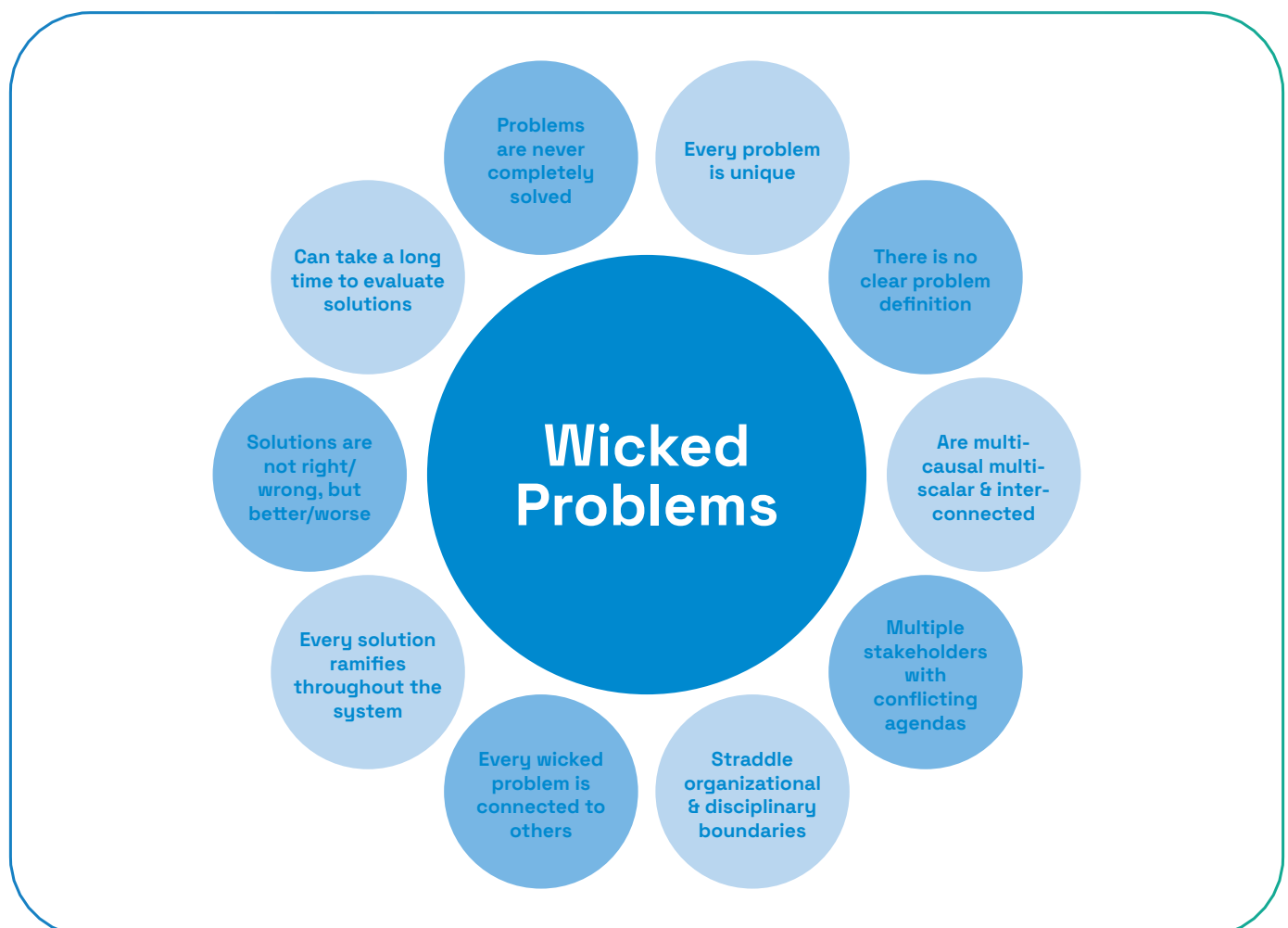


Figure 2: Summary of the complexity of wicked problems

Source: CMU Transition Design, Irwin & Kossoff based on Rittel & Webber 1973.

Crilly (2025) adds a useful insight into wicked problems by arguing that wickedness is not a fixed property of a problem but something that varies depending on who is dealing with it and under what conditions. Instead of a binary categorisation of wicked or not wicked, the degree and form of wickedness can shift across stakeholders and over time. In road safety, this helps explain why different agencies and practitioners can look at the same problem and reach very different conclusions about what needs to change.

Viewing road trauma through this lens helps account for why it may appear that little progress is being made despite improvements in parts of the system. Improvements in one area, such as a reduction in drink-driving fatalities or gains from improved vehicle safety standards can co-exist with deterioration elsewhere, and interventions addressing one dimension of the problem may generate unintended effects in another. This provides the basis for examining why systemic approaches are necessary and what they need to account for that more conventional approaches do not.

3. Systems Thinking and Road Safety

3.1. Understanding Systems Thinking

Systems thinking offers a way to work with the complexity of road safety by focusing on the relationships, feedback loops and interactions between elements of a system, and how they collectively produce outcomes (**Allen and Kilvington 2025**). Unlike conventional approaches, cause and effect in complex systems are not linear but iterative, meaning actions continue to shape future outcomes in ways that are difficult to predict from any single intervention (**Kim 1999**). This is reflected in road safety as current deterministic approaches to this challenge, including those focused primarily on driver behaviour, enforcement or infrastructure treatments, do not completely account for the complexity of transport systems or the full range of factors shaping behaviour (**Salmon et al. 2016**).

While interventions such as education and enforcement have contributed to significant reductions in road deaths over time, it has been argued that they may have reached a ceiling in terms of their effectiveness (**Larsson et al. 2010 cited in Salmon et al. 2016**). Crashes are better understood as emergent outcomes of a complex system, shaped by the interaction of road design, vehicle technology, human behaviour, regulatory settings and institutional decision making across multiple levels, from individual road users to the agencies responsible for planning, regulation and enforcement (**Guy et al. 2025**). It is the interaction of these elements together that produces safety outcomes.

This perspective does not diminish and replace targeted interventions but places them within a broader system context, where the structure and operation of the transport system must also be considered.



3.2 Expanding Safe System Thinking Through Systems Approaches

The Safe System approach is widely adopted in road safety policy. It is based on the premise that human error cannot be eliminated and that systems must be designed to account for human vulnerability (**ITF 2022**). Responsibility is shared across those who design, manage and regulate the network, with roads, vehicles, speeds and behaviour addressed collectively. This represents a shift away from traditional approaches that focused primarily on road user behaviour.

In practice, however, a gap can emerge between the principles of the Safe System approach and how it is implemented. The Australasian College of Road Safety (**ACRS 2024**) has noted that the concept of shared responsibility is still vague and has not removed the tendency to focus on road users as the primary source of the problem. The emphasis on pillars, as shown in Figure 3, and related interventions also encourages treating components in isolation, when safe or unsafe outcomes result from interactions between different components and participants across the whole system.

Systems thinking adds value by focusing on how safety outcomes emerge from interactions between technical, organisational and societal factors beyond the traditional Safe System pillars (**ACRS 2024**). It highlights how governance, policy and institutional arrangements shape decision making and influence outcomes across the system (**Guy et al. 2025**). Rather than viewing interventions in isolation, it considers how they interact over time. This perspective also supports more adaptive approaches by recognising feedback processes within the system. Reinforcing and balancing dynamics help explain why some interventions lead to sustained improvements while others do not, and where more fundamental change may be required (**Guy et al. 2025**).

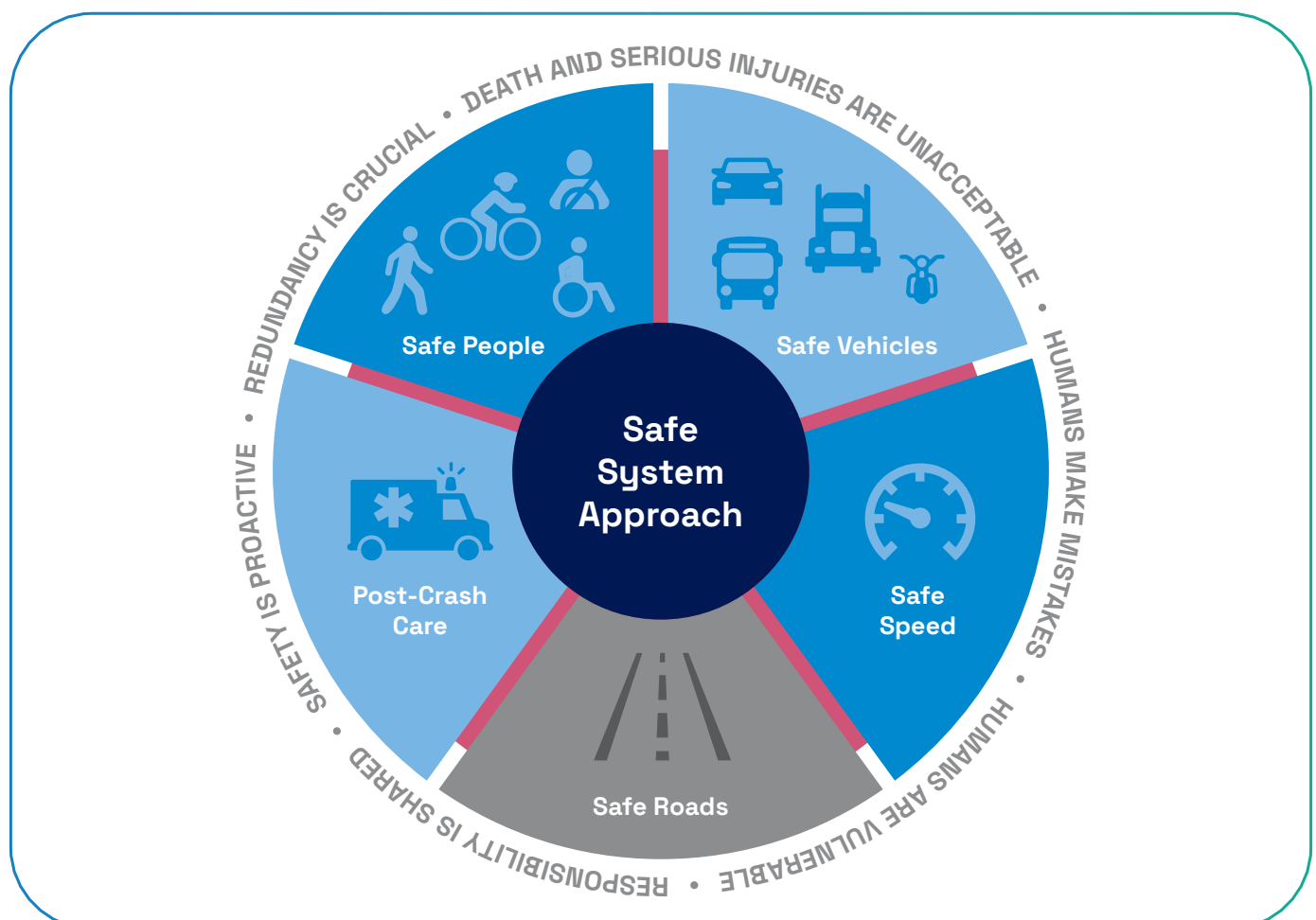


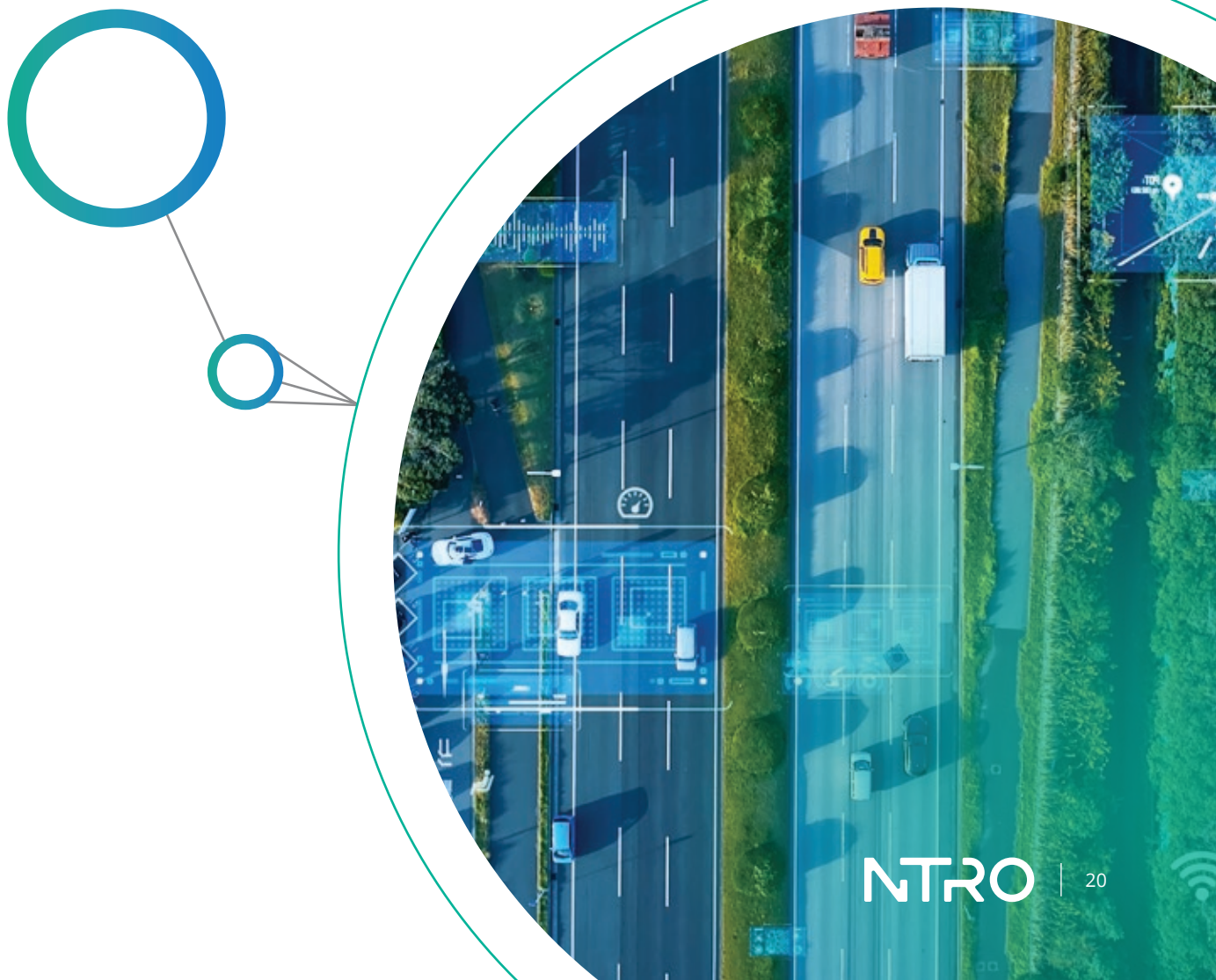
Figure 3: Safe System Pillars

Source: U.S. Department of Transportation.

4. Applying Systems Thinking Methods in Road Safety

Systems thinking in road safety draws on a range of methods that examine how risk is produced across the system as a whole. Some approaches discussed in Sections 4.1 to 4.4, include systems mapping, causal loop analysis, backcasting, and participatory stakeholder engagement. These methods are not exhaustive, but represent common approaches used to understand complex problems and identify points for intervention. The main shift is in how the problem is framed: rather than responding to individual incidents after they occur, these approaches examine the conditions and structures that give rise to risk in the first place, supporting more proactive and coordinated responses across the system.

They also extend how learning occurs within the system. For example, in aviation and healthcare, learning extends to structured reporting on near misses and system failures, not just incidents where serious harm has already occurred. Road safety in contrast, continues to rely heavily on post-crash analysis. Expanding learning to include near misses and system-level patterns could reveal how risk accumulates over time, not only how it presents at the point of failure (**Guy et al. 2025**).



4.1 Systems Mapping and System Structure

Systems mapping offers a way to examine how different elements of the road transport system interact and collectively produce safety outcomes. The focus is on the relationships between infrastructure, behaviour, policy and the environmental conditions that create the circumstances in which crashes occur, not just the crash itself. It is worth noting that systems thinking tools have already been applied in road safety to some extent. Accimaps have been used to analyse crash causation across system levels (**Salmon et al. 2012**), and **Salmon et al. (2016)** used STAMP (Systems Theoretic Accident Model and Processes) to map the control structures and organisational relationships within the Queensland road transport system. These focus on specific incidents or defined relationships rather than providing a broad picture of how road users, infrastructure, institutions, and policy interact across the system as a whole. An expansive systems map does not yet exist for road safety in Australia.

Figure 4 is included to illustrate what one looks like in practice, drawn from transport and climate change planning, and to give a sense of the complexity involved. It shows part of a systems map that looks at how a city like Paris might respond to climate change. It focuses on how different transport choices influence each other. For example, increased use of public transport and cycling can make car use less attractive. It also shows how more cycling can lead to greater use of bike lanes, which then changes how appealing cycling and other transport options feel. The map highlights how these relationships shape behaviour across the system (**Slattery and Kaufman n.d.**). Building an equivalent map for road safety would be a valuable next step for the sector.

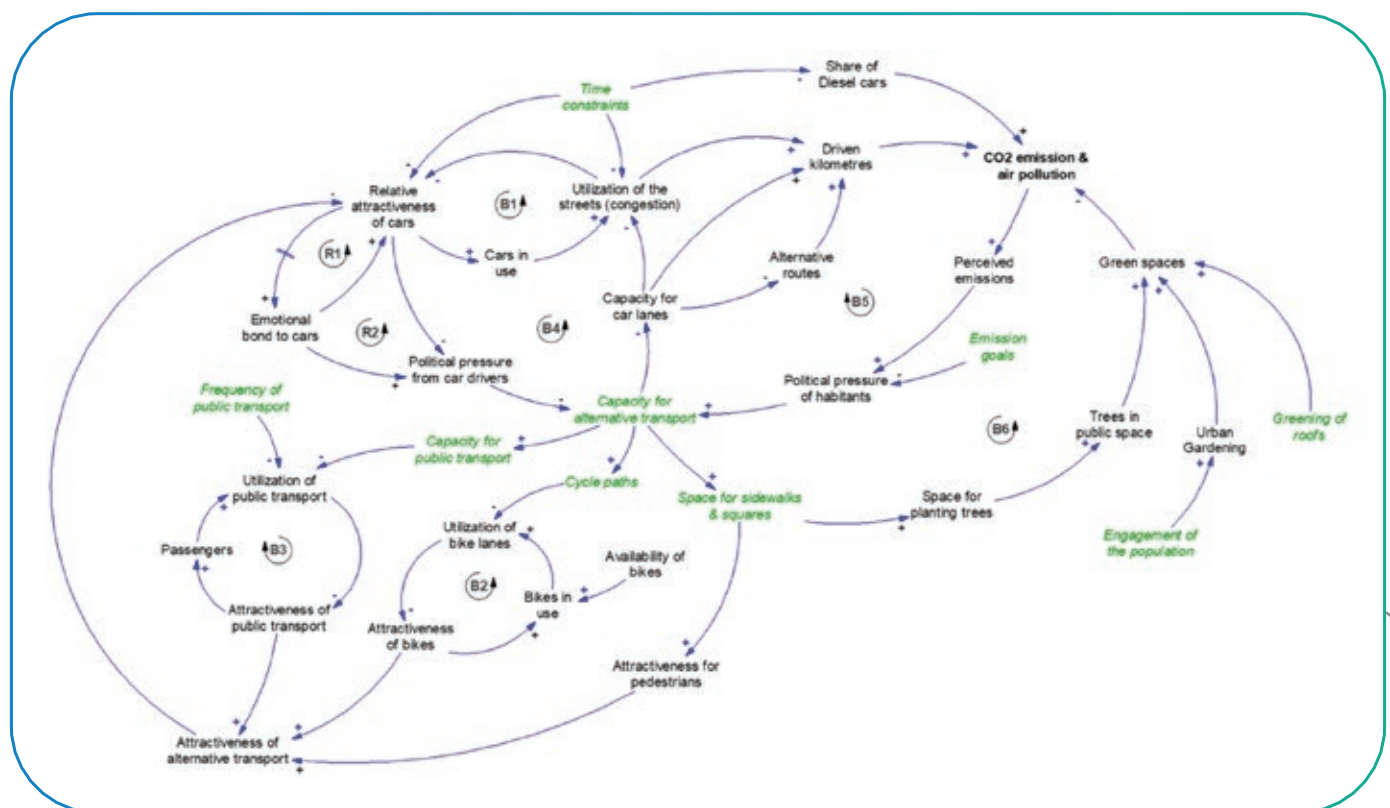


Figure 4: Sample Systems Map (Addressing Climate Change in Paris)

Source: Slattery and Kaufman n.d.

On a regional highway network, for example, a systems map might reveal how long-distance commute patterns, limited rest stop infrastructure, inadequate public transport and employer scheduling practices combine to increase the likelihood of fatigued driving. Mapping these relationships reveals how the conditions that produce fatigue are embedded in work arrangements, land use patterns, and the absence of alternatives to private vehicle travel, rather than in individual driver decisions alone. This kind of analysis tends to lead toward more systemic responses, such as expanding rest stop provision, adjusting employer scheduling practices, and improving regional transport options alongside traditional enforcement measures (ACRS 2024).

At a strategic level, systems mapping can reveal how funding structures, performance metrics and institutional responsibilities shape decision making across the network. Where investment consistently prioritises travel time efficiency over safety outcomes, this can reinforce system conditions that increase risk. Making these structural drivers visible is often a requirement for shifting attention away from treating symptoms and towards addressing underlying causes (Guy et al. 2025; NetZeroCities 2020).

4.2 Feedback, Causal Loops and System Behaviour

One of the most valuable contributions systems thinking makes to road safety is helping explain why patterns of harm persist even when interventions appear to be working. Causal loop diagrams provide a way to map the feedback relationships within the system and to understand how these relationships produce outcomes that are difficult to sustain or reverse over time (Barbrook-Johnson and Penn 2022; Guy et al. 2025).

The relationship between speed enforcement and driver behaviour illustrates this: increased enforcement may reduce speeding in the short term, lowering crash severity; however, over time, reduced perceived risk of detection or changes in traffic conditions may allow speeds to drift back towards previous levels, while road design and vehicle capability continue to enable speeds that exceed what the posted limit was intended to represent. This balancing dynamic helps explain why short-term enforcement gains are often difficult to sustain.

Induced demand (such as increasing road capacity through new roads or road widening) offers a further example of how reinforcing dynamics can undermine safety gains. Expanding road capacity may relieve congestion initially, but tends to encourage more vehicle travel over time, thereby restoring traffic volumes and with them, crash exposure. Mapping these dynamics helps explain why some interventions appear effective in the short term but do not translate into lasting improvements (Allen and Kilvington 2025; Guy et al. 2025). Understanding these feedback structures allows practitioners to identify where their interventions may be counteracted by other parts of the system and where more fundamental change is required.



4.3 Backcasting and Long-Term System Change

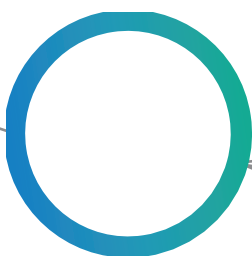
A persistent challenge in road safety policy is ensuring that short-term actions contribute meaningfully to long-term goals rather than accumulating as a collection of disconnected measures. Backcasting addresses this by starting from a desired future state and working backwards to identify the changes required to get there, instead of projecting current trends forward (**Guy et al. 2025**). In road safety, this typically involves starting from a goal such as eliminating fatalities, and identifying the necessary changes across infrastructure, policy, behaviour and governance. This approach is consistent with the normative commitments of Vision Zero and the Safe System philosophy, both of which treat safety as a design challenge rather than a compliance problem (**ITF 2022**). While backcasting is a specific planning methodology applied within these frameworks rather than a principle that underlies them, it offers a practical means of operationalising their long-term goals.

By working backwards from a defined endpoint, it becomes possible to assess whether current actions are genuinely on a path towards long-term outcomes, and to identify where the gaps between the goal and trajectory are largest.

4.4 Participatory Approaches and Cross Sector Coordination

Road safety is not the responsibility of any single organisation, and the conditions that generate risk in the network are shaped by decisions made across transport agencies, land use planners, enforcement bodies and health services. Because of this, systems mapping is most useful when developed collaboratively. The process of building a map together challenges assumptions, exposes gaps in shared understanding and helps stakeholders see how their actions connect to those of others within the system (**NetZeroCities 2020**).

In practice, this can take the form of workshops where stakeholders collectively map system structure, identify where their understanding diverges and explore where intervention may have a meaningful effect. These processes do more than improve analysis of the system and how risk is generated. They also build shared ownership of both the problem and the response, which is often a prerequisite for the kind of coordinated action that road safety requires (**Guy et al. 2025**).



5. Going Forward

The research and ideas discussed in this paper suggest that improving road safety outcomes in Australia requires more than refining existing approaches. While current strategies have delivered meaningful gains, recent trends indicate that progress is slowing. This reflects not only how interventions are implemented, but how the problem itself has been framed. Approaches centred primarily on individual behaviour and targeted treatments can only address part of a broader system.

Systems thinking does not replace established frameworks such as the Safe System approach, nor does it dismiss interventions that have proven effective. Instead, it adds another layer of analysis by examining how the wider system shapes outcomes. It highlights the role of governance, institutional arrangements, funding decisions and cross sector coordination in determining whether interventions are effective and sustained.

For Australia, this points to the need to look more closely at how road safety is understood and approached in practice. This includes paying more attention to near misses, patterns of behaviour and how decisions made across different parts of the system influence outcomes. It also suggests the need to broaden how road safety performance is considered. Focusing only on fatality numbers can overlook the role of governance, coordination and investment decisions that shape those outcomes.

In practice, methods such as systems mapping and causal analysis offer ways to explore these relationships more directly, but they are not yet widely embedded in standard approaches. At the same time, funding cycles, organisational boundaries and limited capacity for collaboration are constraints that can make it difficult to apply these methods consistently. Engaging with these realities will be important if systems-based approaches are to be applied more meaningfully across Australia.



There is an opportunity to move beyond a reliance on post-crash analysis and place greater emphasis on how risk develops across the system over time.

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Centre of Transport Safety Asia Pacific

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1. Introduction

Whether a journey is by car, plane, train or any other mode of transport, it begins with a simple assumption – that we will safely get to where we are going. We buckle a seatbelt, check a timetable, print out a boarding pass, then step forward with trust in systems, strangers and the unseen choices of others. Despite having safer vehicles than ever before, as well as safer networks and technology around them, government funding commitments, well-meaning initiatives to keep travellers safe and the best endeavours of transport safety practitioners, not every journey ends safely. That is why NTRO has established the Centre for Transport Safety Asia Pacific with the support of its strategic partner – world-renowned Cranfield University from the UK.

2. When Routine Journeys go Wrong

For some, a routine trip becomes a defining moment – and not in a good way. A moment's distraction, an error, a mechanical or system failure, or a decision made in haste can unravel lives in an instant through death or injury on our transport networks.

Some do not make it home at all. In some modes and jurisdictions, that number is growing year on year – in Australia, there were 1,326 road deaths in the 12 months prior to March 2026, 3% higher than the same time the previous year (**Department of Infrastructure, Transport, Regional Development, Communications, Sport and the Arts 2026**). For aviation, the Asia Pacific region's accident rate has increased significantly to 1.62 per million departures in 2024 from 0.78 in 2023, with the International Civil Aviation Organisation (ICAO) saying the increasing number of accidents and fatalities serve as a stark reminder of the need to continue ensuring the safety of air travel amidst increasing growth and complexity (**ICAO 2025**).

For many others, their lives are reshaped by injury, loss or trauma that lingers long after the wreckage is cleared and the headlines fade.

3. The Case for a Cross-Modal Approach

Transport safety is usually defined and designed by modes: road; rail; aviation; and maritime. The lessons learned in one transport mode are rarely applied to another and there has never been a formal mechanism for sharing them across modes.

NTRO and UK-based Cranfield University believe that needs to change. The Centre for Transport Safety Asia Pacific is a new initiative of NTRO, developed with the support of Cranfield, which aims to drive significant and lasting improvements in transport safety for all transport domains across the Asia-Pacific region.

Cranfield is a global leader in transport safety education and training across aviation, marine, rail and road. It is trusted by defence forces, government regulators, investigation agencies, aircraft manufacturers and large-scale enterprises, and works with 1,500 organisations across 40 countries. The collaboration between NTRO and Cranfield is an example of the power of sharing knowledge and of partnership, with the joint venture already delivering training in Australia.

4. No Competitors in Safety

In establishing the Centre, NTRO has drawn on a profound principle: that there are no competitors in safety. This was first articulated by William (Bill) Voss, former CEO of the Flight Safety Foundation and former Director of the Air Navigation Bureau at the International Civil Aviation Organization (ICAO), and it captures one of the foundation values of the new Centre for Transport Safety Asia Pacific of an industry-wide, cross-domain, collaborative approach.

One of the Centre's highest priorities is to create a platform and environment where collaboration and the exchange of knowledge, experience and ideas can take place. NTRO's structure and status make it a logical and appropriate host for an initiative of this kind.

NTRO is independent, not-for-profit, owned by the governments of Australia and New Zealand at State and Federal levels and the Australian Local Government Association, and has a footprint in the Asia-Pacific region through its work in Australia, New Zealand, India, Tonga, Fiji and Vanuatu.

The Centre will coordinate with organisations responsible for or affected by transport safety, including government and regulatory authorities, industry and industry bodies, research bodies and universities. Together, they will work to improve transport safety across all modes in the Asia-Pacific region.

As transport volumes continue to grow across the already busy Asia-Pacific region, the Centre is a timely way for NTRO and Australia to support neighbouring countries.



5. Six Pillars for Safer Transport

The Centre for Transport Safety Asia Pacific will focus its work through six core pillars:

1. Applied safety research.
2. Standards development and management.
3. Professional development and education.
4. Advisory and implementation services.
5. Safety data and Intelligence
6. Technology and infrastructure innovation.

The Centre will also foster thought leadership and whenever necessary, convene or prompt difficult conversations on the issues that need to be discussed. The Centre aims to become the central repository for knowledge and expertise around transport safety and the sharing of that knowledge across all sectors.

6. Early Priorities and Practical Action

Facilitating applied research and sharing knowledge across jurisdictions and transport modes are central to the Centre's purpose and long-term value. The Centre's first activity was delivering the Cranfield Aviation Safety Investigation short course in Melbourne in April 2026, with attendees from the commercial airline industry, the defence sector, the general aviation sector and the emergency services.

The Centre is in the process of scheduling similar courses in rail safety investigation and road safety investigation. One of its next major priorities is to develop a national, no-blame road crash investigation standard, which will be a major step forward for the road safety agenda in Australia. The Centre will undertake the initial development work on the standard, followed by comprehensive engagement with all applicable government and industry stakeholders. Once this feedback is consolidated, Australia's first national standard for no-blame road crash investigations will be published.



7. A 2030 Vision for the Region

By 2030, the Centre aims to have moved the dial in a positive way for transport safety. Its aims include:

- A downward trend in accidents, fatalities and serious injuries across the board.
- A more coordinated approach to safety policy frameworks, strategy and funding across each region in which the Centre works, including stronger alignment between jurisdictions such as states and territories.
- A much more efficient use of funding for safety-related initiatives, with funding guided by risk modelling backed by sound and targeted applied research.
- A more professional workforce standard for transport safety and accident investigation professionals in the region, supported by targeted, risk-informed training and a credible accreditation framework.
- Better access to transport safety research data and intelligence (i.e. how the Centre uses the data).

- Creating lasting mechanisms that become part of the 'operations normal' methodology for sharing knowledge across transport domains.

There is a clearly identified demand and need for improved safety standards, intelligence and skills throughout the region and across all transport domains. Bringing together leading expertise from across the transport safety sector will deliver significant and lasting benefits.

The Centre for Transport Safety Asia Pacific is a mechanism for positive change. It is a world-first concept dedicated to saving lives, preventing serious injuries, as well as reducing the emotional and economic impacts on individuals and our society at large. The Centre is actively seeking partners and subject matter experts to support its critical mission: a safer transport future.

“

The next step is clear: no competitors, just collaboration and a shared commitment to radically improving transport safety outcomes.

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Re-evaluating the 5-year crash analysis window: Insights from 30 years of data

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Many road agencies worldwide, including in Australia, recommend a 5-year period for crash analysis. However, with the ever-growing demand for more in-depth insights as a result of advancements in data collection technology and the increasing sophistication in modelling, would this timeframe of 5 years still be appropriate?

1. Introduction

The Queensland Department of Transport and Main Road's (TMR's) primary method for investing capital funding for road safety projects is through the Targeted Road Safety Program (TRSP). A common feature across TRSP's suite of subprograms and initiatives is the use of a benefit-cost ratio (BCR) as a principal metric for evaluating the eligibility of funding submissions. This method also enables individual submissions from TMR and/or local government across the state to be prioritised or 'ranked' against each other. Currently, BCR calculations for all TRSP subprograms are based on the examination of a 5-year crash period for injury-related crashes.

The intent of this project was to test whether a 5-year crash period is universally appropriate for gauging the risk of fatal crashes occurring at a given location. Specifically, the project's aim was to investigate and evaluate the applicability of different time periods for such a scenario.

For example, in any sample of crash locations, only a few are likely to have had even a single fatal crash occur over a 5-year period. Under the current approach, all these sites would be assessed as an equal risk of a fatal incidence occurring. However, given the nature of probability, it is possible that some of these locations may have another fatal crash occurring through outside of the 5-year window (perhaps 8 or 10 years apart), arising from the same underlying infrastructure deficiencies or crash mechanisms.

The literature scan indicated that there is limited published information or transport agency guidance on the use of a 5-year time period for crash data analysis and reporting in Australia. There was no literature found that identified significant benefits in using a longer time period nor any specifically relating to fatal crashes. Accordingly, this study sought to evaluate whether the current reliance on a fixed 5-year crash period is appropriate for assessing fatal crash risk or whether alternative temporal windows may provide a more accurate and equitable representation of the underlying safety risk.

This study was done as part of the National Asset Centre of Excellence (NACOE) program, and the content of this paper is drawn from the R154 project report (**Chen et al. 2025**).



2. Methodology

This study incorporated 30 years of crash data on the TMR road network and conducted the following 2 studies:

- **a volume trend analysis**, where changes in crash trends over long periods of time were investigated
- **a frequencies at locations analysis** that focused on the ability to capture recurrence of fatal crashes with various analysis time windows.

The 30 years of fatal crash data were integrated into the Queensland Risk Assessment Model (QRAM) data. The QRAM data includes road lengths, annual average daily traffic (AADT), and speed limit information. Some roads were excluded from the analysis (50 out of 590), as their governing authority was transferred from the state to local councils over the past 30 years.

2.1 Volume Trend Analysis

The fatal crash trend over an extended time period, past the standard 5-years, was analysed by plotting historical fatal crashes for the following contexts:

- the entire state road network across Queensland
- subsets grouped by different regions across Queensland
- subsets grouped by roads with different speed limits across Queensland.

Fatal crash rates are calculated by dividing the total number of fatal crashes by the length of the road section (where fatal crashes occurred) and then further dividing that number by the AADT, which is then multiplied by 365 days. This calculates fatal crashes per VKT (Vehicle Kilometers Travelled), which is a standard unit used in transport safety analysis.

Yearly fatal crash rates per VKT were illustrated using 2 charts, with one bar chart indicating fatal crash counts for a particular year and the other showing the cumulation of crash counts through a line chart. The cumulative charts normalised the total fatal crashes for the entire period of analysis to 1, aiding visualisation of how fatal crash occurrences have evolved over the years. A comparison of the benefits of each chart type is summarised in Table 1.

Category	Fatal crash counts per year (bar chart)	Cumulative fatal crash counts over years (line chart)
Trend analysis: yearly vs long term	Clear representation of yearly variability, which makes it easier to spot annual fluctuations or sudden 'spikes' in fatal crash occurrences.	Smoother graph for trend analysis because short-term fluctuations are reduced, making it easier to identify overall trends without being distracted by year-to-year variability.
Short-term vs long-term objective analysis	Better for short-term evaluations, such as seasonal analysis, or if the focus is on a recent event, such as policy or infrastructure changes.	Better for long-term comparison between different settings, especially when normalised.
Magnitude vs pattern identification	Easier to compare absolute values, also making it easier to identify peak or low occurrence years.	Can assist with detecting anomalies, as a sudden change in slope would indicate a change in the trend.

Table 1: Benefit of different chart types

Source: Chen et al. (2025)

The shape of the cumulative line chart, as shown in Figure 1, revealed certain information in relation to the fatal crash trend as summarised below:

- Straight line: the rate of change of fatal crash occurrence has been at a consistent rate over the years, and there has been no significant change in the rate of increasing or decreasing.
- Concave: this pattern indicates that the rate of decline in fatal crash occurrence has increased in the recent years compared to the past.
- Convex: this pattern indicates that the rate of decline in fatal crash occurrence has decreased in the recent years compared to the past.

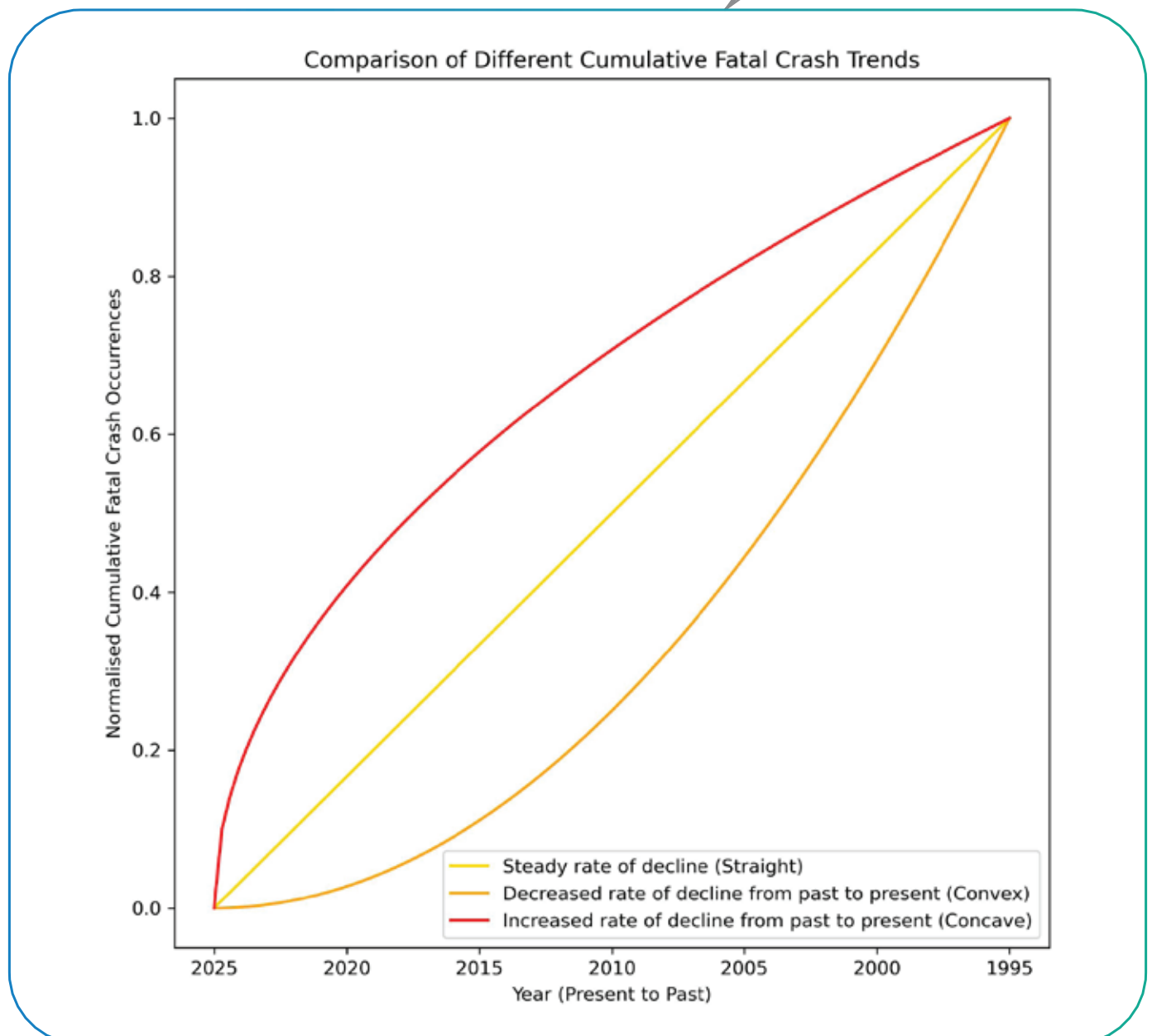


Figure 1: Comparison of different cumulative fatal crash trend lines

Source: Chen et al. (2025)

2.2 Frequencies at Locations Analysis

A key part of this project was determining the ideal number of years (time period) for which fatal crash data should be analysed to capture all locations with a significant fatal crash history. To do this, it was imperative to analyse the frequency at which these locations experience fatal crashes.

2.2.1 Historical Cumulative Segment Analysis

This analysis tracked the cumulative count of individual road segments that have experienced 2 or more fatal crashes, with a progressively expanding analysis time window from the current year to the earliest available data. For each analysis window, which starts from 2025 and extends backward in time, additional segments meeting the threshold (≥ 2 fatal crashes) were added to the cumulative total only if they were not previously counted in the timeframe dating to its previous year. Additionally, this method was applied using 3 segment lengths - 1 km, 3 km and 5 km.

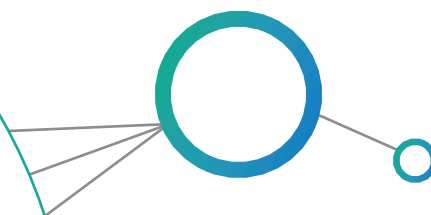
After performing the above steps, it was possible to fit a quadratic curve for each of these data plots using the formula shown in Equation 1:

1

$$y = ax^2 + bx + c$$

Then, the team reviewed the following 4 parameters of the fitted quadratic curves.

- Growth rate coefficient **a**: For a quadratic curve, the rate of change will change over time. The rate of change accelerates/decelerates as the variable increases/decreases. It should be noted that the selection of a longer timeframe will greatly enhance the results due to the quadratic nature of this coefficient.
- Linearity coefficient **b**: This relates to the location of the vertex of the parabola and will represent the slope of the line as it crosses the y-axis, controlling the linearity of the curve. The larger the coefficient b is, the greater the horizontal shift (left for positive, right for negative values) of the quadratic curve.
- Intercept term coefficient **c**: This corresponds to the intercept of the curve with the y-axis. The larger the coefficient c is, the greater the vertical shift of the parabola. A negative value means that the parabola will intersect the y-axis at a negative value, indicating the model is less reliable at shorter time periods.
- Coefficient of determination **R²**: This represents the proportion of variance in the dependent variable that is predictable from the independent variable(s). The higher the value (closer to 1), the better the fit of the model to the data.



2.2.2 Fatal Crash Recurrence Pattern Analysis

This analysis investigated the impact that different time periods between successive fatal crashes, or crash pairs, had on the ability to detect recurring fatal crash patterns on any road segment.

For a road segment where 2 or more fatal crashes occurred, the time period between each fatal crash, in years, was recorded for 1 km, 3 km and 5 km segment lengths. For those segments where more than 2 fatal crashes occurred, the time period between each successive crash was recorded separately.

For each segment length, a negative binomial model, as per Equation 2, was fitted to each data plot.

2

$$\log \mu = \beta_0 + \beta_1 \text{ year_gap}$$

where

μ

=

the expected number of fatal crashes

β_0

=

the intercept

β_1

=

the slope

A negative binomial regression model is often used when the data exhibits overdispersion, meaning the variance is greater than the mean. Furthermore, the parameters of the model are described below:

Intercept (β_0): The intercept term represents the log of the expected count when all predictors in the model are zero. The intercept provides a baseline or reference point for the model's predictions, helping to understand the average count expected when no other factors are considered.

Slope (β_1): The slope term indicates the change in the log of the mean count when the predictor (in this instance, years between consecutive fatal crashes) increases by one unit, i.e. one year.

Dispersion: Dispersion is a parameter that allows the model to account for overdispersion in the data. It acts as a 'tuning' parameter, influencing how much the variance exceeds the mean. When the dispersion value approximates 1, the variance of the data is equal to its mean, meaning that the data is not over dispersed. In this case, the negative binomial distribution essentially behaves like a Poisson distribution.



3. Findings

3.1 Volume Trend Analysis

Overall, fatal crashes on the Queensland state-controlled road network have reduced at a relatively constant rate over the entire 30-year timeframe. Figure 2 presents the bar charts showing the fatal crash count and the cumulative crash chart over the past 30 years. Upon inspection of the data at a more granular level, as shown in the fatal crash count bar chart, it becomes apparent that there are clearly defined 'spikes' in the data at regular intervals. These 'spikes' are accompanied by subsequent reductions in fatal crash numbers, appearing as step changes that drive the overall reduction in the number of fatal crashes. Ideally, to account for these apparent step changes in the number of fatal crashes, any study should use a timeframe that spans across homogeneous temporal periods, separated by these critical shifts in fatal crash numbers, to ensure a more accurate and meaningful analysis.

The cumulative fatal crash curve exhibits a concave shape, indicating that the change in annual fatal crash rate has generally declined over time. In the context of a cumulative line chart, it means that earlier years (right-hand side) contribute more heavily to the total, while more recent years (left-hand side) add smaller increments due to lower per-year crash rates. Should earlier years be excluded, the implication will be a disproportionately large loss of total observed crashes. In other words, the reduction in cumulative counts from shortening the analysis period is non-linear, with longer-term data capturing substantially more crash information. Therefore, the finding of this analysis supports the use of an extended crash analysis timeframe, as shorter periods may omit a significant portion of the underlying crash history.

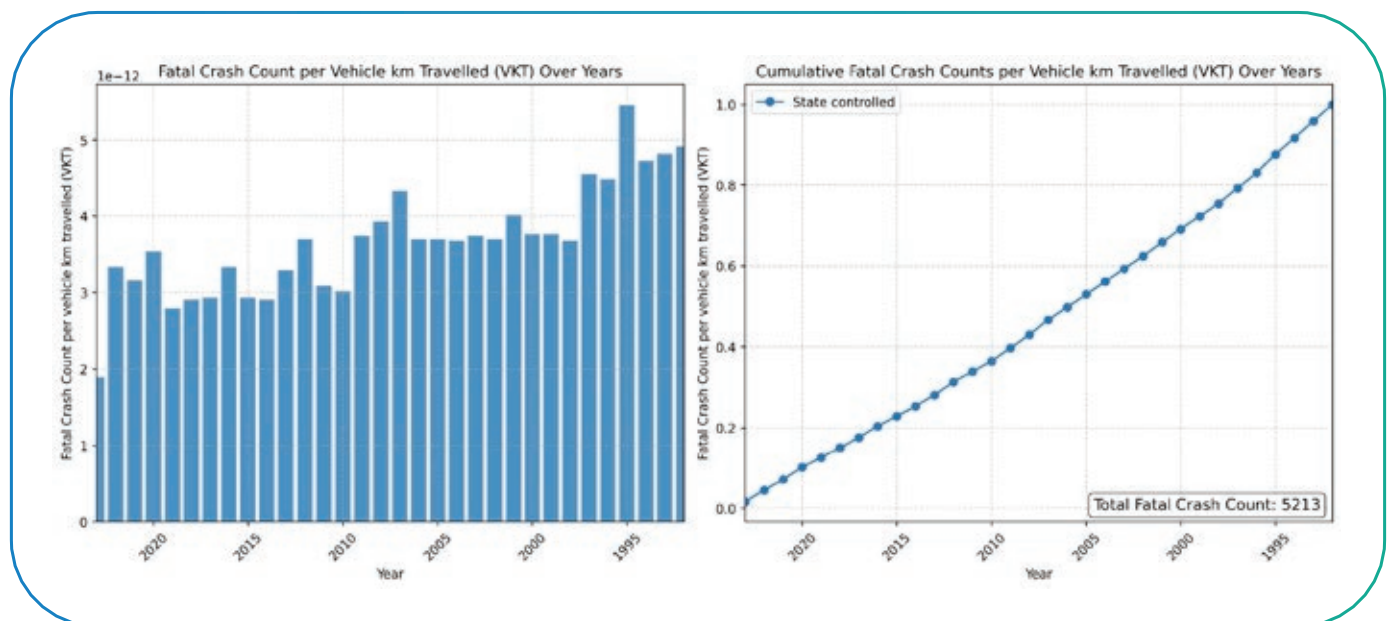
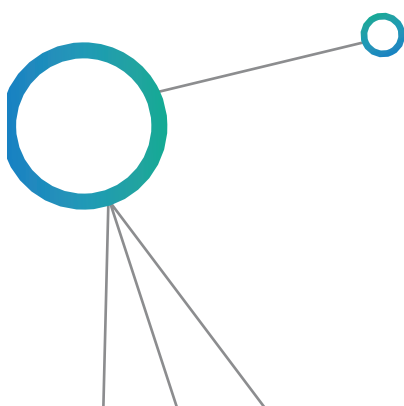


Figure 2: Fatal crashes per VKT for the state-controlled road network

Source: Chen et al. (2025)



Due to the decreasing number of fatal crashes on the Queensland state-controlled road network, the number of fatal crash recurrences on any given section of road reduces the closer the data is to the current day. This means that for the purposes of identifying new locations that may have a high risk of a fatal crash occurring, the timeframe of analysis needs to be extended to successfully capture

the true trend pattern for that location, with the number of years required to identify a trend reducing as the segment length is increased. Conversely, the reliability of the model is predicated on the selection of the time period being sufficient to accurately establish the trend. Figure 3 shows the fatal crash count for various regions in Queensland.

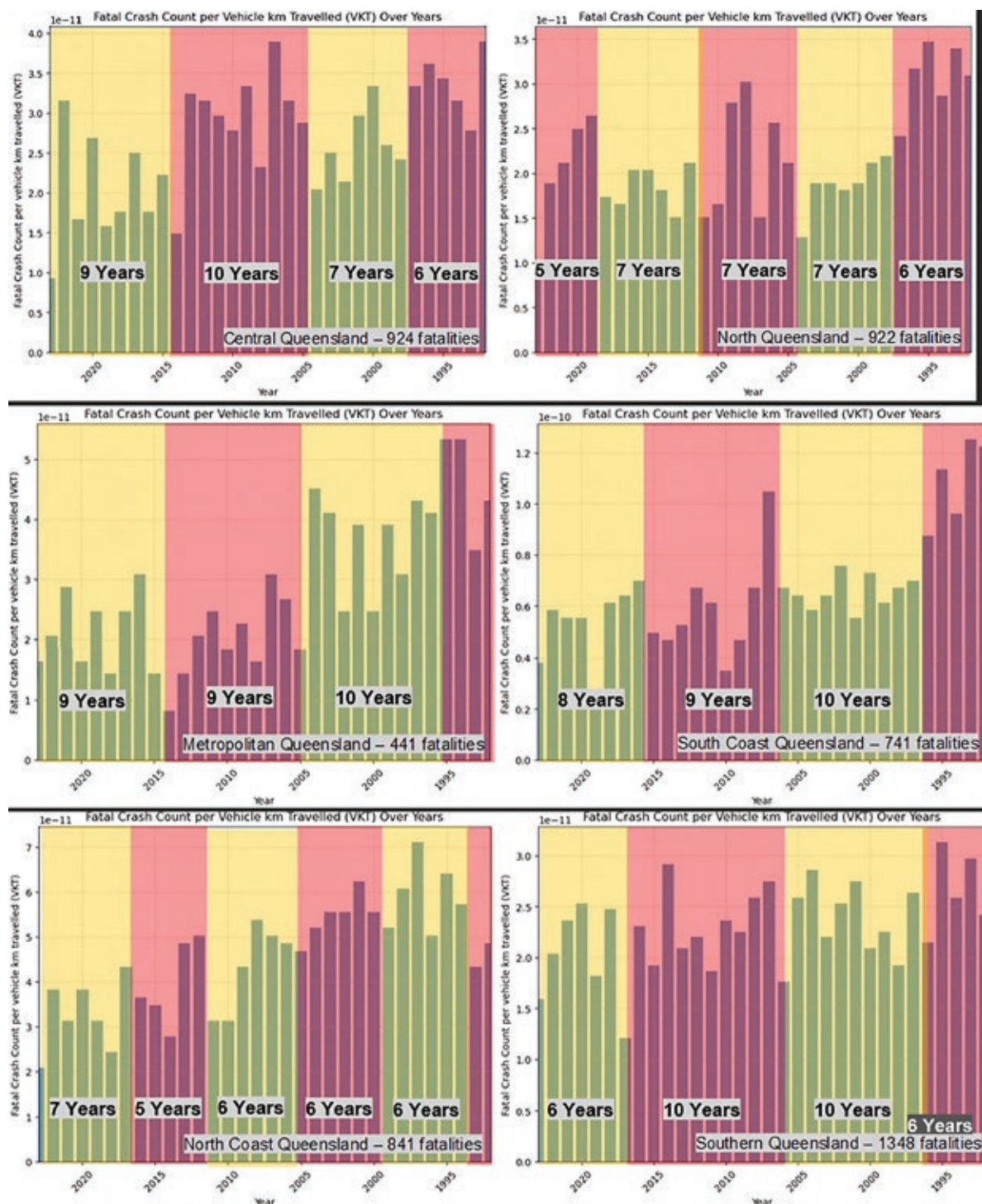


Figure 3: Fatal crash count per VKT over years

Source: Chen et al. (2025)

The following observations can be made by analysing the plots from Figure 3:

- 'Spikes' in fatal crash occurrences appear consistently within a 4- to 6-year time span.
- Following a 'spike', there is a subsequent reduction in fatal crash occurrences compared to the localised average preceding a 'spike'.
- The combination of time between fatal crash occurrence 'spikes' and the subsequent reduction compared to the localised average preceding a 'spike', constituting a step change, occurs generally within a **7- to 10-year** period.

- Step changes, when looking at the fatal crash occurrences based on a regional analysis, appear to occur within a **6- to 10-year** period.
- Step changes, when looking at the fatal crash occurrences based on speed environment, appear to occur within a **6- to 8-year** period.

Based on these points, it can be argued that the use of the traditional 5-year period for fatal crash analysis has some limitations, as it may fail to capture long-term cyclical patterns, step-change behaviours and the broader temporal dynamics that shape fatal crash trends across regions and speed environments.



3.2 Frequency at Locations Analysis

In addition to the temporal patterns observed, the historical cumulative segment analysis further reinforced the sensitivity of fatal crash identification to both timeframe selection and segment length. The parameters of the fitted quadratic models can be found in Table 2. The 1 km segment analysis (also visualised in Figure 4) demonstrated the strongest model fit and highest growth (acceleration) rate, indicating that shorter segments are more responsive to increases in analysis period and require longer timeframes to reliably capture recurring fatal crash patterns. In contrast, 3 km and particularly 5 km segments exhibited more linear behaviour with lower growth rates,

suggesting that extending the analysis period has a more consistent but less pronounced effect on identifying high-risk locations. However, the negative intercepts observed for longer segment lengths indicate reduced reliability when shorter timeframes are used, reinforcing the need for sufficiently long analysis periods regardless of spatial aggregation. Collectively, these findings highlight a trade-off between spatial resolution and temporal requirements, where shorter segments provide greater sensitivity but demand longer time horizons, while longer segments offer stability but may mask localised risk patterns.

Segment length	a	b	c	R ²
1 km	0.728	-1.9	1.854	1.000
3 km	0.684	8.5	-23.058	0.997
5 km	0.473	16.675	-37.237	0.996

Table 2: Quadratic curve coefficients and R²

Source: Chen et al. (2025)

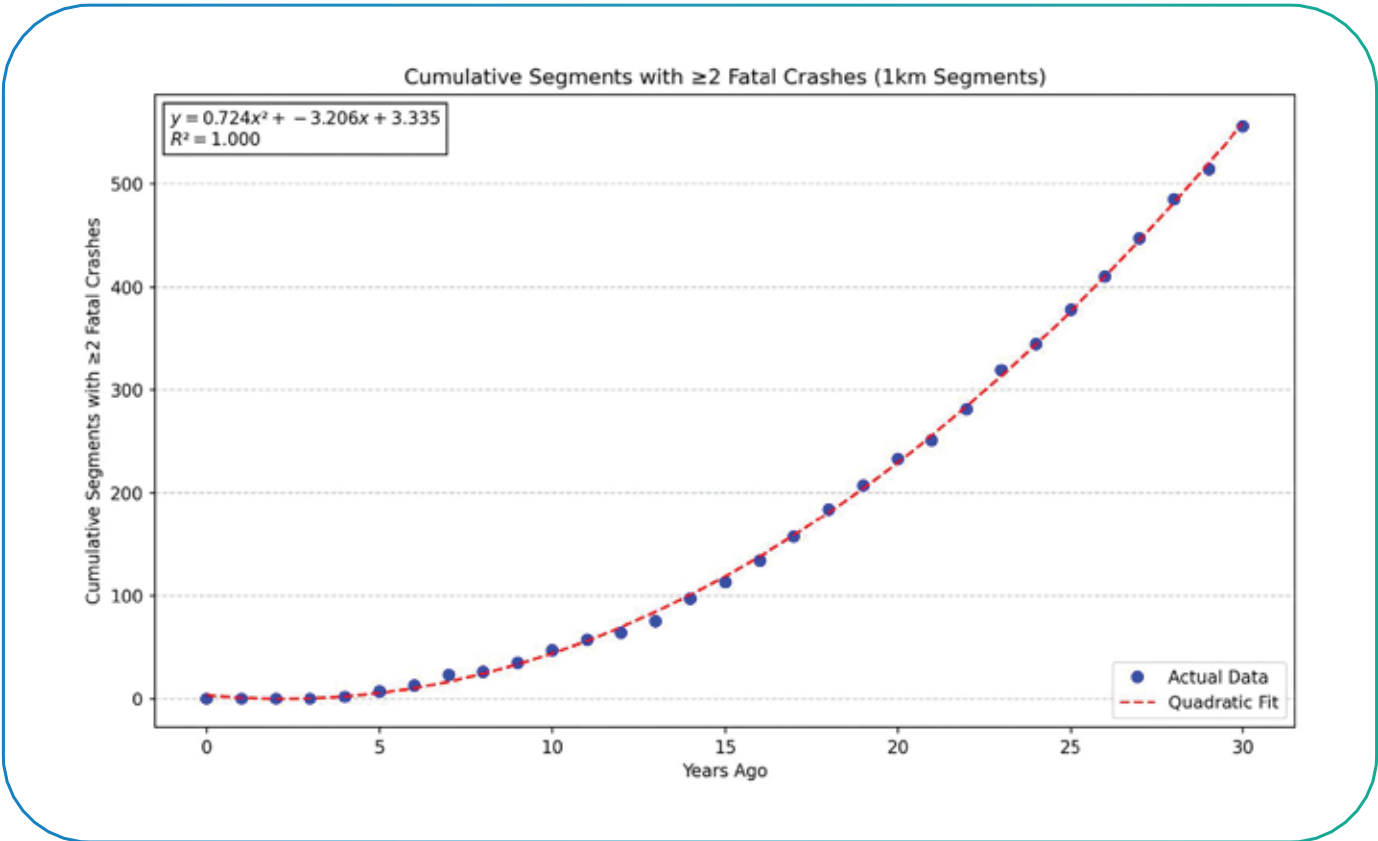


Figure 4: Cumulative 1 km road segments with multiple fatal crashes

Source: Chen et al. (2025)



Table 3 shows the coefficient values of the fitted binomial model as part of the fatal crash recurrence pattern analysis, as outlined in Section 2.2.2. Firstly, the resulting dispersion values are 1, indicating that they behaved like a Poisson distribution. Furthermore, it is apparent that, as the segment length gets larger, the intercept term β_0 also gets larger. This is expected as it indicates that fatal crash pair counts occur at shorter durations when a larger segment distance is considered. Similarly, as segment length increases, the slope term β_1 also gets larger, indicating a faster rate of exponential decay. This implies that the duration required to capture any given percentage of fatal crash pairs reduces as segment length increases.

Segment length	β_0	β_1	Dispersion	Deviance	Degrees of freedom residual
1 km	4.43	-0.11	1	1.6	26
3 km	5.30	-0.15	1	1.8	26
5 km	5.69	-0.17	1	2.4	26

Table 3: Negative binomial model coefficient fitted to the consecutive fatal crash interval charts for 1 km, 3 km and 5 km segment lengths

Source: Chen et al. (2025)

Figure 5 shows the time period required for capturing 95%, 90%, 80% and 70% of all recurrent fatal crashes, for 1 km, 3 km and 5 km segment lengths, along with the percentage of recurrent fatal crashes captured for a 5-year period. These time periods are indicated by vertical lines drawn across the x-axis at the corresponding time periods. The following observations can be made:

- Only between 47% (at 1 km intervals) and 61% (at 5 km intervals) of crash pairs are captured using a 5 year period between successive crashes in a pair.
- When the separation time between crash pairs is increased to 12 years, over 80% of crash pairs are identified for all segment lengths.

- Beyond a separation window of **9 to 12 years**, the number of crash pairs being detected decrease significantly with every extra year, indicating diminishing returns from additional analysis period.

In summary, a strict 5-year analysis timeframe captures only around 47–61% of recurrent fatal crash pairs. Extending the timeframe to approximately 9–12 years increases coverage to over 80%, indicating that a longer analysis period is necessary to adequately represent recurrent crash patterns. A 9- to 12-year timeframe is therefore considered appropriate, as it achieves substantial coverage while avoiding diminishing returns beyond this range.

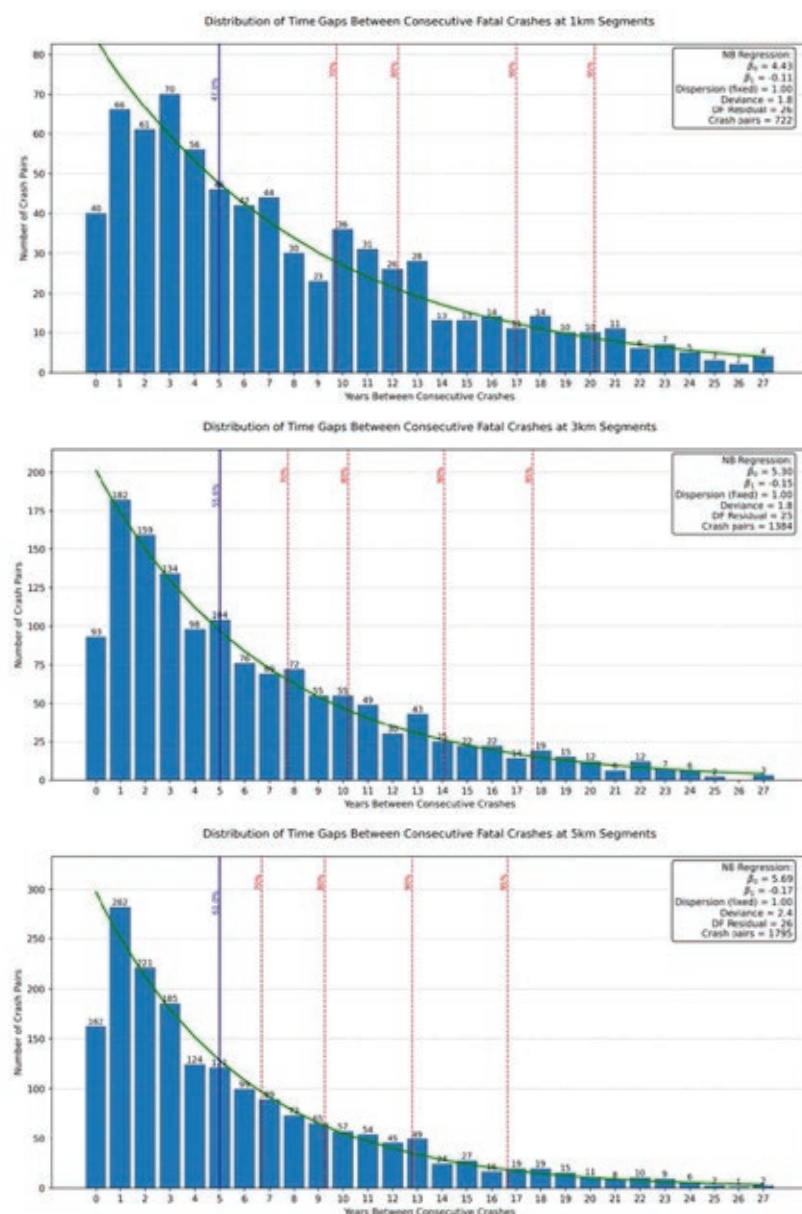


Figure 5: Time elapsed between successive fatal crashes for 1 km, 3 km and 5 km segments

Source: Chen et al. (2025)

4. Conclusion

In conclusion, it was found that a longer time period than 5 years should be considered for fatal crash analysis, albeit it is not possible to pinpoint an exact applicable timeframe. The selection of the exact timeframe to be used should be informed by the time when the analysis data was captured, with consideration of its temporal context relative to the current date and the length of segmentation utilised to identify specific crash locations.

“

A time period between 7 and 12 years is suggested to identify road segments that could be at higher risk for fatal crash incidences, which considers fatal crash history and the general rate of recurrence of fatal crashes.

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Template-Based Tool for Improving Safety at High-Speed Rural Road Intersections

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High-speed rural intersections contribute significantly to fatal and serious injury crashes. This article provides an overview of a template-based Safe System Intersection (SSI) assessment tool, adapted from the Federal Highway Administration methodology. The template-based tool enables an objective comparison of 33 common intersection layouts. This article outlines the tool's motivation, methodology and application to support safer intersection decision-making.

1. Introduction

High speed rural road intersections (example shown in Figure 1) present a significant safety concern for road and transport managers. Due to the high approach speeds at these intersections, when crashes occur, the kinetic energy involved often exceeds human tolerance, resulting in a high likelihood of fatal or serious injury (FSI) outcomes.

Australian road and transport agencies have increasingly adopted Safe System principles, recognising that road environments should be designed to accommodate human error while minimising the severity of crashes.

Historically, practitioners have relied on professional judgement, simplified conflict counts, operational performance metrics and, where available, historical crash data to compare intersection layout options. While each approach provides valuable insights, they do not directly quantify the severity potential of different conflict configurations. Additional considerations regarding land space and funding availability compound the complexity for building the intersection. As a result, practitioners within the same agency can reach different conclusions on which intersection layout is preferred from a safety perspective for a given location.

Main Roads Western Australia (Main Roads WA) identified this challenge, noting that disagreements around the relative safety of alternative layouts often arose, particularly where trade offs existed between operational efficiency, land take and perceived crash risk. This highlighted the need for a tool that was not only grounded in Safe System principles but was also objective, transparent and practical.

The work presented in this paper responds to that need by describing the development of a template based Safe System for Intersection (SSI) tool that enables practitioners to compare the relative FSI risk of high speed rural intersection layouts in a consistent and defensible manner.

Figure 1: Example high-speed rural road intersection



2. From Traditional Conflict Analysis to Safe System Intersection Scoring

2.1 Shortcomings of Conventional Approaches

Traditional conflict point analysis assumes that all conflicts pose a similar risk, but this is often not the case. For example, a right angle crossing conflict at 100 km/h does not pose the same injury risk as a merging conflict.

Predictive crash models using crash modification factors provide a more sophisticated analysis alternative but rely on established calibration datasets. They are, therefore, best suited to comparing well defined intersection types and are less effective for comparing innovative or hybrid designs, which may be considered on rural highways.

Safe System assessment frameworks provide a holistic lens for evaluating exposure, likelihood and severity of crash types. However, these frameworks are typically qualitative and depend heavily on practitioner judgement, limiting their repeatability and usefulness when comparing closely competing design options.

2.2 Safe System for Intersections (SSI)

The SSI method, developed by the United States Federal Highway Administration (US FHWA) (**Porter et al. 2021**), represents a significant advancement in intersection safety assessment. The method was based on previous Australian developments including the kinetic energy management model (KEMM) (**Corben et al. 2010**) and the extended kinetic energy management model for intersections (X-KEMM-X) (**Austroads 2017**).

The FHWA SSI method links conflict identification with exposure, impact speed, collision angle and movement complexity to estimate the probability of an FSI outcome. However, the method requires practitioners to work through a detailed series of formulas and calculations that are documented throughout a large guidance report, which some practitioners may find challenging to follow.

Main Roads WA recognised the potential value of the SSI method but also recognised that, without adaptation, it may be difficult to get practitioners to adopt and follow the process consistently.



3. Development of the Template based Tool

The National Transport Research Organisation (NTRO) used the FHWA SSI method to develop a template based tool, hosted in Excel. The final tool incorporates 33 predefined high speed rural intersection layouts, covering common 4 way intersections (e.g., Figure 2), T intersections, wide median treatments, roundabouts and restricted movement designs such as J turns.

Prior to developing the template-based tool, NTRO had converted the FHWA SSI method into an Excel-based spreadsheet that could be applied to individual intersections, with practitioners required to input details for each conflict at the intersection. This approach made the FHWA SSI method easier to apply, as it had all formulas and equations embedded within the spreadsheet. However, it was time-intensive to complete, typically taking several hours per intersection, due to the need to identify conflicts and enter all required inputs.

The subsequent development of the template-based tool, with all conflict elements predefined, has dramatically reduced the assessment time while preserving the analytical integrity of the SSI framework.

Converting the method into a template-based tool included undertaking a series of targeted modifications to the process. These included conversion to metric units, adoption of Australian FSI probability relationships, alignment with left hand traffic conventions and terminology changes to better reflect local practice.

For each layout, conflict points (e.g. Figure 2), collision angles and movement characteristics were predefined using consistent assumptions. This means practitioners are only required to input location specific variables such as traffic volume, speed environment and vulnerable road user activity. The tool produces an SSI score for each of the 33 intersections layouts. This allows for an SSI comparison score across layouts.

In addition, using Excel and standard Excel formulas (rather than macros), allows for easier maintenance and adjustments if required by Main Roads WA.

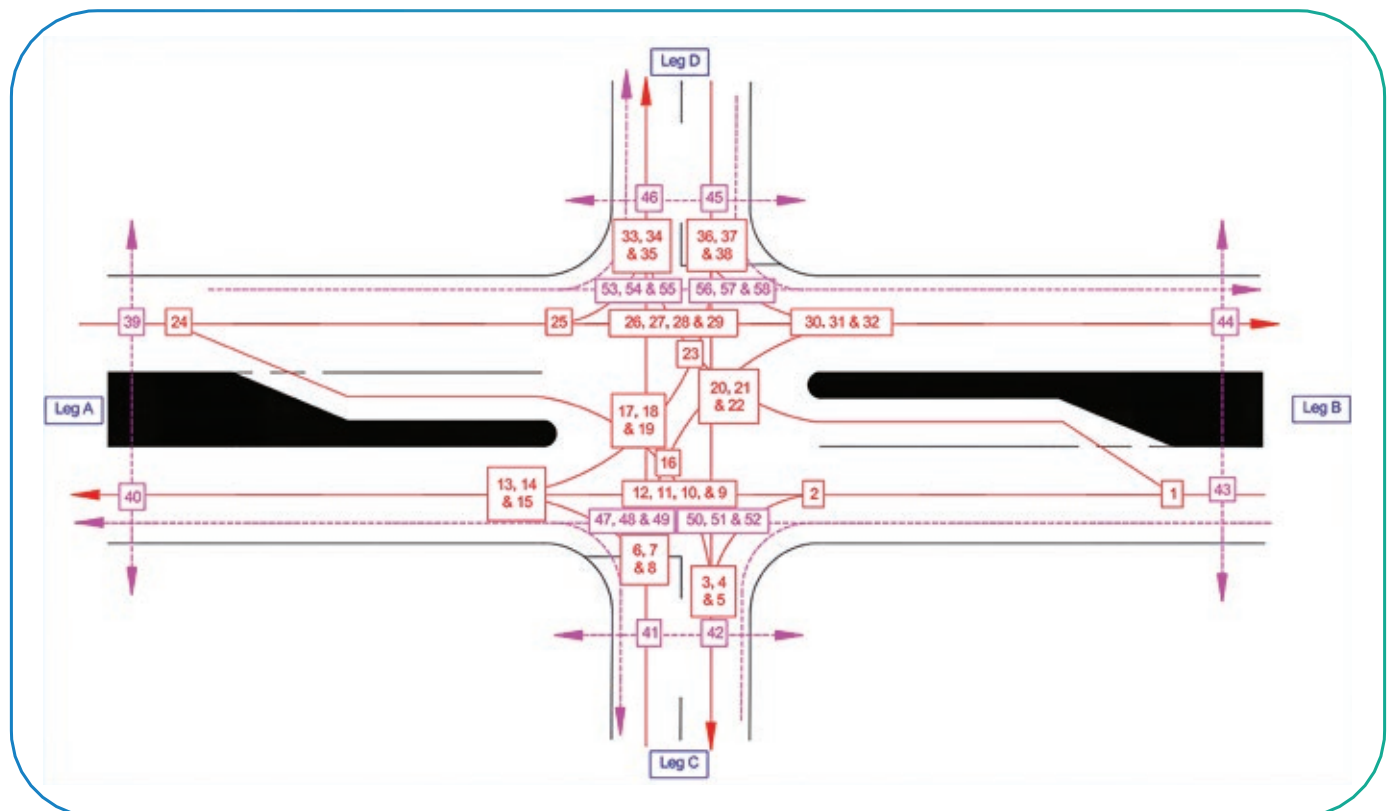


Figure 2: Four-way intersection with conflict point identification

4. Application and Findings

4.1 Sanity Testing of Common Intersection Layouts

Prior to finalising the tool with 33 intersection layouts, a sanity test was undertaken, and the tool was initially applied to a set of representative high speed rural intersection layouts that had previously been assessed by Main Roads WA using existing simplified methods. The intersection layouts that were tested included a conventional 4 way intersection, a wide median treatment, a restricted right turn with median U turn layout and a roundabout.

The results aligned closely with practitioner expectations. Conventional 4 way intersections consistently returned the lowest SSI scores, reflecting their high number of severe crossing conflicts. Layouts that reduced or eliminated right angle conflicts performed better. Roundabouts achieved the highest scores in motor vehicle-only scenarios due to their lower impact speeds and reduced conflict severity, whereas wide median and restricted movement treatments occupied an intermediate position. This demonstrated the suitability of the template-based tool prior to its full-scale development.

4.2 Sensitivity to Vulnerable Road Users

When vulnerable road user movements were introduced, the tool demonstrated appropriate sensitivity, particularly at roundabouts where pedestrian and cyclist crossings interact with circulating traffic. This detail allows the practitioners to explore how changes in crossing demand influence the intersection's overall safety performance.

4.3 Early Evidence of Robustness

Subsequent application of the tool by Main Roads WA has indicated positive results. As part of work examining right turn warrants at seagull intersections (example layout is shown Figure 3), Main Roads WA investigated a range of potential explanatory variables for FSI crashes, including sight distance, gap acceptance, delays and queue lengths. When the template-based tool was applied, Main Roads WA observed a moderate correlation between the SSI score produced by the tool and actual FSIs. It was noted by a Main Roads WA practitioner that:

- This correlation had not been previously observed with other methods used by Main Roads WA.
- This result suggests that the SSI score produced by the tool may be one of the more effective leading indicators currently available to Main Roads WA for identifying locations with elevated FSI crash risk.

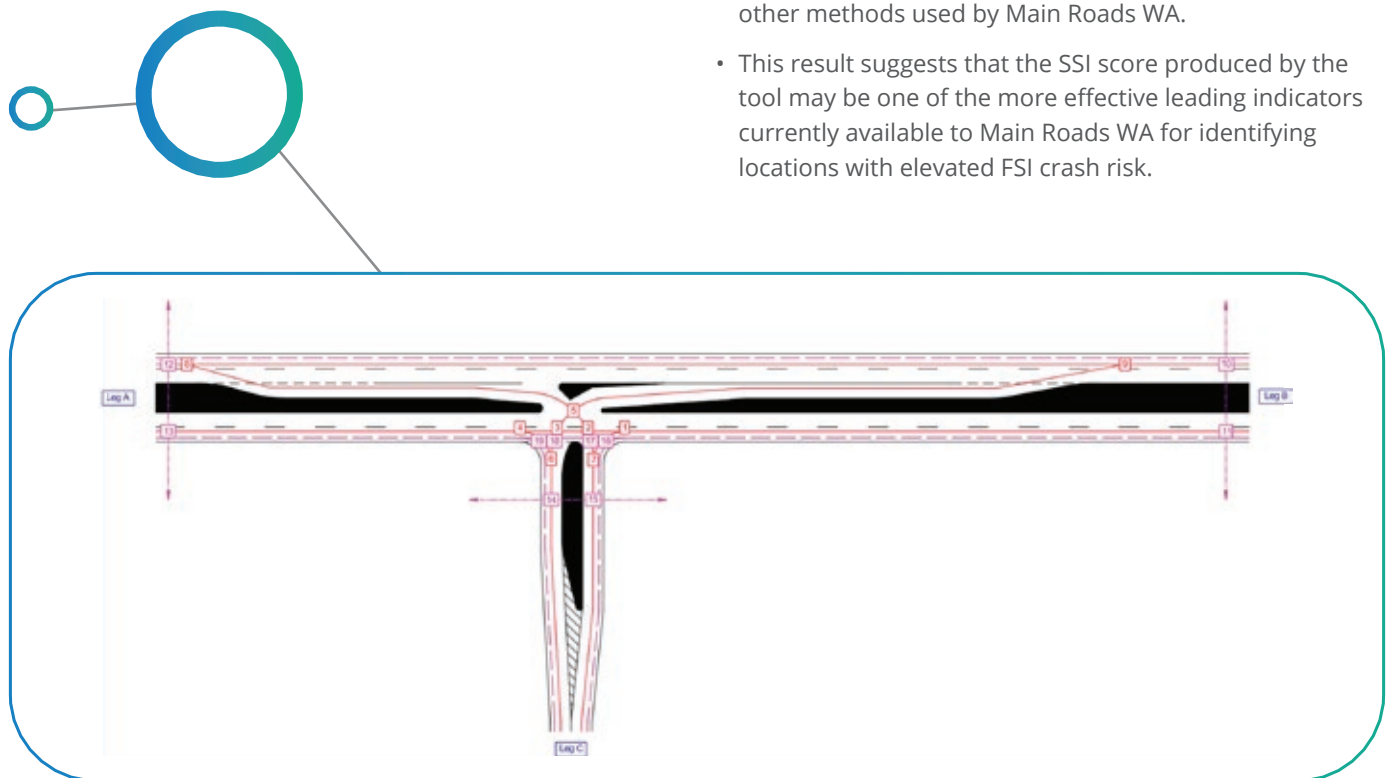


Figure 3: Example of a seagull island treatment intersection

5. How the Tool Can Be Used in Practice

The key value of the template based SSI tool lies not in producing an absolute measure of safety, but in enabling a consistent, objective comparison between alternative intersection layouts.

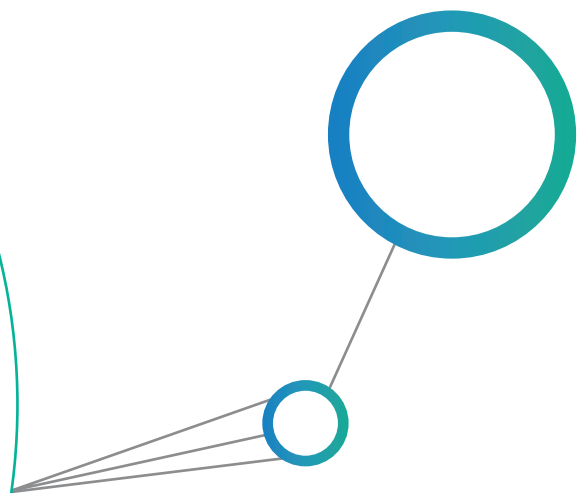
In practice, the tool is best applied at the concept and options assessment stage, when intersection layouts are being shortlisted. Applying the tool early allows agencies to focus detailed design effort on options with inherently lower FSI risk.

The tool is not intended to replace road safety audits, operational modelling or economic evaluation. Rather, it complements these processes by embedding Safe System thinking at the point where strategic layout decisions are being made.

Used appropriately, the tool provides a common language for discussing intersection safety across engineering, planning and policy disciplines, improving transparency and defensibility of decisions.

While the template based SSI tool represents a significant step forward, it needs to be acknowledged that the tool focuses on conflict based severity potential and does not directly account for behavioural adaptation, enforcement or post crash care. It is also sensitive to the assumptions embedded within predefined templates, which may not capture all site specific nuances.

Main Roads WA is developing internal guideline material that establishes policy guardrails around when and where the tool should be applied and how its outputs should be interpreted within the broader project development process. This would be supported by training to ensure practitioners understand how the tool can be used and how its results should be interpreted. This positions the tool as a decision support mechanism rather than a prescriptive design rule.



6. Conclusions

High speed rural road intersections present complex safety challenges that cannot be addressed through subjective judgement alone. The template based SSI tool developed for Main Roads WA demonstrates how advanced Safe System methodologies can be translated into practical, implementable tools when supported by clear guidance and training.

Early application suggests that the SSI score provides a defensible leading indicator of elevated FSI risk, complementing traditional safety and operational measures.



More broadly, the work illustrates a pathway for embedding Safe System thinking more consistently into rural intersection planning and design.

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Real-Time ballast health assessment with instrumented ballast particles

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Ballast condition and rail track formation stiffness play a critical role in railway safety, performance and asset life, yet remain challenging to measure using existing inspection and monitoring techniques. Conventional approaches, including visual inspections and ground-penetrating radar, are limited in their ability to capture real-time, particle-scale behaviour and are often costly or operationally disruptive. In response to these limitations, recent research has explored the novel monitoring approach of using instrumented ballast particles to record the dynamic response of individual ballast particles under train loading. These fabricated particles are shaped to replicate the characteristics of real ballast with built-in monitoring instrumentation.



1. Introduction and Background

Ballast structural condition is a primary driver of track deterioration, with poor ballast condition leading to track settlement. Among the various components of the substructure, the ballast settles faster over time than either the sub-ballast or subgrade. A standard track formation for a ballast track and its various components is shown in Figure 1 below.

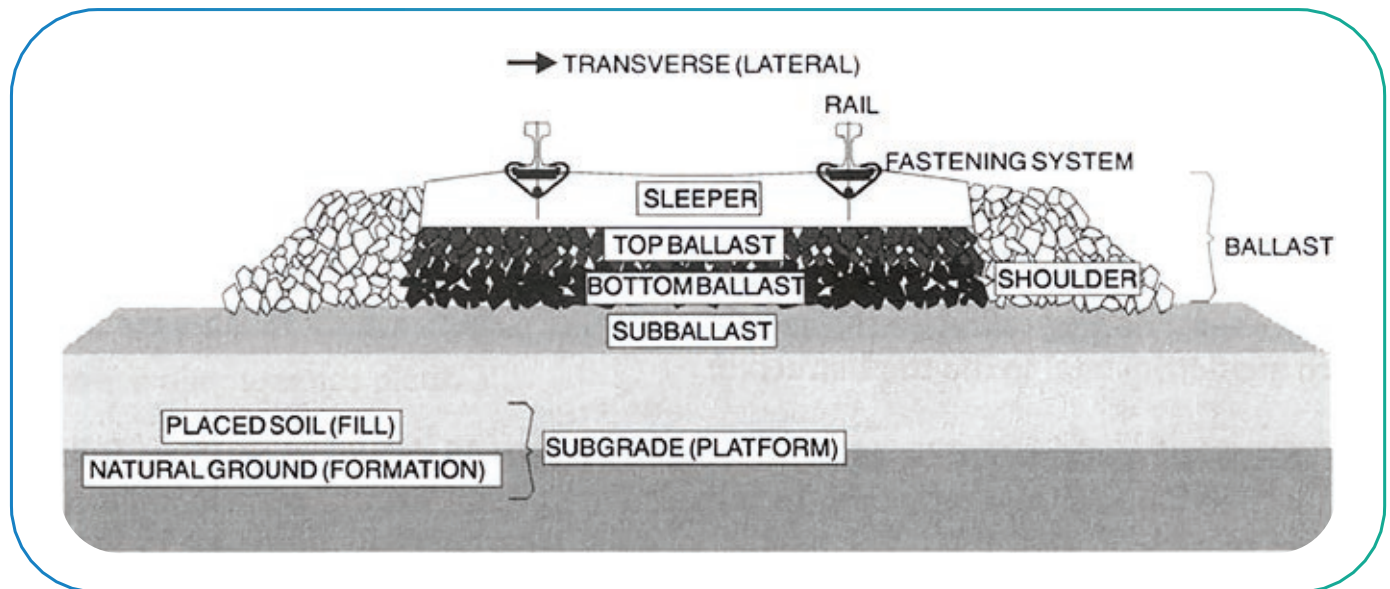


Figure 1: Cross-section view of typical ballast track components

Source: Alabbasi and Hussein (2021)

Ballast layer stiffness is a key parameter that can be used to assess ballast condition and monitor track degradation. The track tends to move both vertically and laterally. The vertical movement is known as 'top' track deterioration, where the rail level becomes irregular due to the ballast formation being compacted by train loads over time. Australian Rail Track Corporation (ARTC) Standards set a recommended vertical elastic deflection limit of 6.35 mm (ARTC 2025). Exceeding this transient deflection limit is usually due to ballast breakage and continual rearrangement, and is a common sign for required maintenance. More broadly, track stiffness is a useful diagnostic for substructure issues, as it reflects the combined behaviour of rail, pad, sleeper, ballast, sub-ballast and subgrade.

Given the difficulty of directly assessing ballast condition beneath the track, a range of monitoring approaches have been developed, including instrumented ballast particles (IBPs), which enable real-time, in situ measurement of ballast behaviour. As such, the primary objective of this project was to assess the feasibility and requirements of IBPs for field testing, which was achieved through a practice review of literature and prior research, informed by stakeholder feedback and a proposed design for a future field trial.



2. Summary of Practice Review

Track stiffness has an important role in the stability and safety of train operations. It has a significant influence on the dynamic behaviour of the railway system, impacting trains, track geometry and component lifespan. Monitoring track stiffness requires measuring both force and displacement or acceleration, which is challenging to measure across any considerable length of railways (Wang et al. 2016).

Conventional approaches to ballast condition monitoring, such as ground-penetrating radar or visual assessment, also have similar limitations. They often rely on expensive or disruptive equipment and are typically unable to show real-time particle movement. To overcome this, researchers have focused on the development of IBPs. IBP typically incorporates different types of sensors such as tri-axial accelerometer, tri-axial gyroscope, and tri-axial magnetometer capable of recording translation, rotation and orientation, respectively. IBPs can be embedded in a ballast layer and used to perform measurement and monitoring ballast behaviour under railway loading.

The review identified several IBPs used to study dynamic ballast behaviour, but the measurements were limited to recordings of translational and rotational movement (particle vibration). Several opportunities for improving the existing IBPs were identified through the review, noting that existing IBPs are constrained by:

- limited recording time due to battery capacity
- challenges in data transfer and communication under varying environmental/operating conditions
- limited measurement resolution and frequency range
- a lack of comprehensive evaluations across different fouling levels, particle geometries or railway layers.

The review concluded that it was feasible to build an improved IBP device and to test it in a laboratory environment. A group of Central Queensland University (CQU) researchers (Tahmoorian et al. 2021, Tahmoorian et al. 2022) designed and constructed several prototype IBPs according to their outline of requirements for an improved IBP device, which focused on 5 main subsystems: structure, sensing, processing, communication and power. The developed prototype IBP (Figure 2) is a 3D-printed shell similar in size and shape to a real ballast particle and contains:

1. a tri-axial accelerometer, for recording translation
2. a tri-axial gyroscope, for recording rotation
3. a tri-axial magnetometer, for recording orientation.

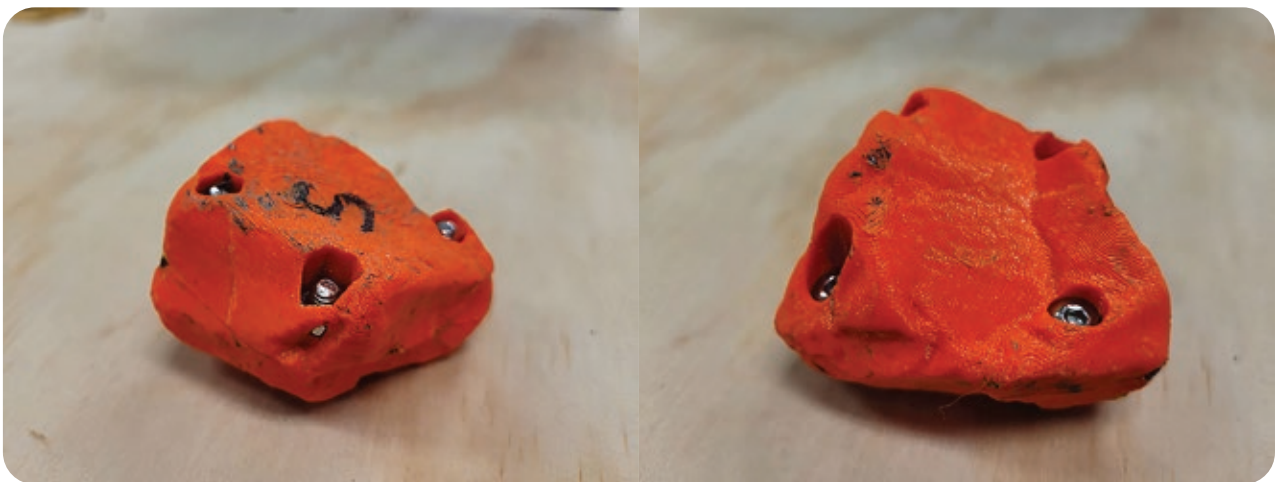


Figure 2: Photographs of the CQU-designed instrumented ballast particles after laboratory testing

Source: Tahmoorian et al. (2022).

The designed IBP device needed to replicate an individual ballast particle with similar characteristics and be placed in a suitable location within the ballast layer. Table 1 outlines the proposed IBP specifications.

The laboratory tests demonstrated the device’s ability to measure particle accelerations and displacements at higher frequencies and forces. However, for a practical field device, there are several requirements that need to be considered, including the sampling frequency, measurement sensitivity and range suitable for measuring the movements present in the ballast. Power consumption of the device is also crucial to ensure sufficient data is collected over the operational life of the sensor.

Parameter	Range
Particle size	20–65 mm
Frequency range of interest	150–300 Hz
Maximum displacement magnitude	200 µm
Resilient modulus	140–550 MPa
Layer depth	200–500 mm
Depth of maximum stress experienced	0–200 mm

Table 1: Ballast layer and particle geometric and mechanical properties

Source: Tahmoorian et al. (2021).

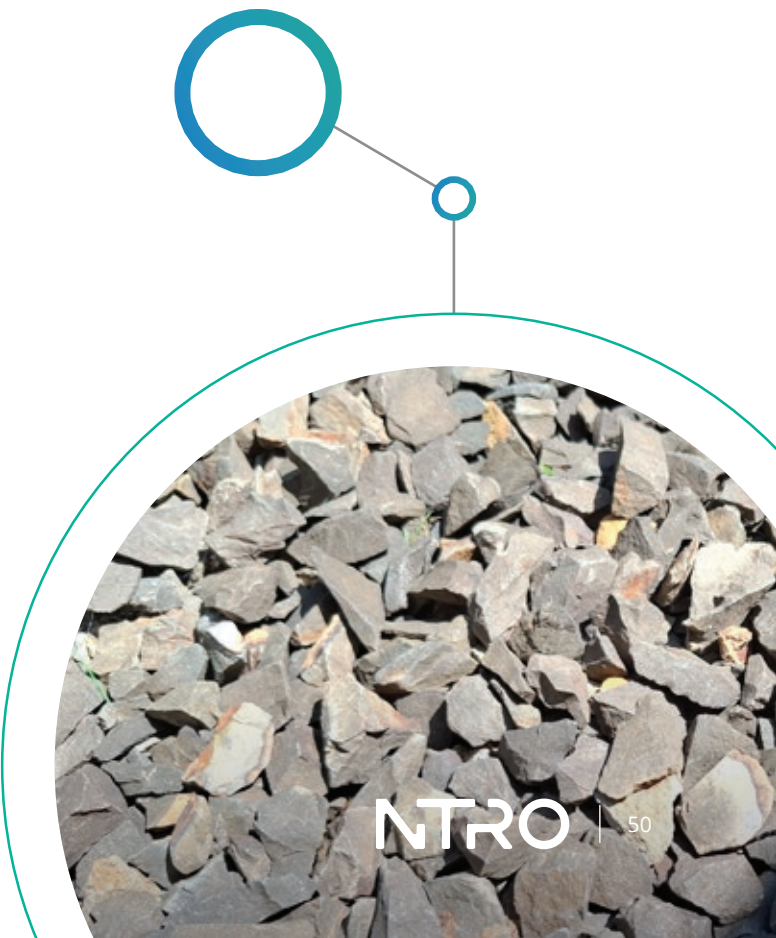
3. Consultation Insights and Feedback

Following the practice review, key stakeholders, primarily railway infrastructure managers (RIMs), were invited to provide their insights and feedback relating to their experience with assessing ballast condition and their potential interest in IBPs. The feedback also provided a better understanding of the requirements for IBPs’ use in live operational conditions.

The insights and feedback obtained from the key stakeholders is summarised as follows:

- Triggers for ballast maintenance/reconstruction are due to a multitude of factors such as drainage problems, subgrade and formation issues, ballast degradation, poor construction or renewal practices and sleeper-related issues.
- There are several notable limits to current detection methods for ballast condition monitoring.
- The maturity level for the use of IBPs in Australia is low, but there was high openness to trialling them:
 - All stakeholders were open to participating in field trials of IBP sensors, and some suggested locations where deployment could be prioritised (e.g. track sections with known recurring track geometry faults).
 - The key factors that would influence the uptake of IBPs were cost, resourcing, life cycle considerations, and practical and safe deployment.
 - Operational and safety challenges such as battery life and repeatability of measurement results would need to be addressed.

The stakeholder consultation confirmed that IBPs are not currently available as a commercial solution and that confidence in the technology will depend on demonstrated performance under operational conditions. The stakeholders indicated a willingness to support field trials, with priority sites identified as track sections with known recurring geometry faults and transition zones, and newly reconstructed track where degradation pathways can be clearly observed.



4. Field Trial and Outcomes

The recommended field trial would aim to validate IBPs as an in situ method to monitor ballast condition deterioration over time and to determine the accuracy and robustness of the indicators derived from the IBP measurements with observed changes in ballast condition under real-world operational factors.

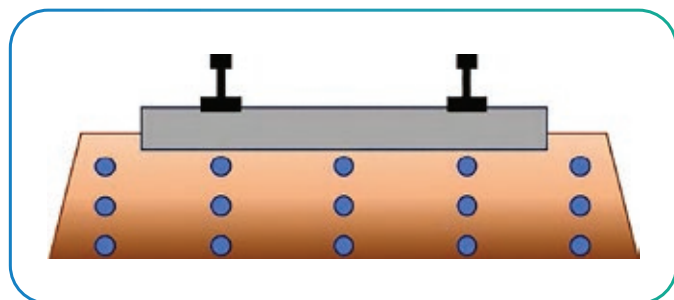
4.1 Proposed Trial Details and Setup

A minimum trial duration of 12 months is recommended to sufficiently capture seasonal climatic variability (e.g. temperature and rainfall), ensuring progressive ballast degradation processes can be adequately assessed. Multi-site deployment is preferred due to the ability to cover different failure conditions and track locations to enable a robust comparative analysis and support generalising the findings across different network conditions with a view of their use in normal operations. However, it was acknowledged that if only a single trial location is feasible for the field trial, a newly constructed track or site is preferred, where the track and ballast have undergone significant reconstruction to monitor degradation from good conditions.

A minimum of 15 IBPs per site is recommended to provide adequate spatial coverage, redundancy and robustness for data interpretation. This quantity would enable deployment across multiple lateral and vertical positions while allowing for potential device loss or failure over the trial's duration. IBPs should be installed at varying depths and lateral locations within the ballast layer to capture representative mechanical and environmental responses. As shown in Figure 3, typical deployment locations include:

- lateral positions: shoulder ballast, crib ballast and beneath sleepers
- vertical positions: near the top, middle and base of the ballast layer.

Alongside the IBP measurements, the field trial should be supported by environmental monitoring, operational data collection and ground-truth condition assessments. These datasets will provide confidence in the IBP response to known loading, climatic drivers and maintenance activities.



4.2 Trial Results and Future Work

The outcome of the proposed field trial would provide a number of recommendations to ensure it delivers clear and actionable outcomes. These should encompass:

- $\geq 80\%$ IBP survival over the 12-month deployment
- $\geq 90\%$ usable data capture days per device
- demonstrated enclosure integrity and in-field performance consistent with laboratory observations
- documented failure modes and lessons learned
- statistically meaningful correlations between IBP metrics and environmental and moisture conditions, observed ballast fouling and particle degradation
- maintenance interventions, with identifiable before and after signatures
- safe and repeatable deployment and retrieval processes, acceptable to the RIM
- reporting outputs that are interpretable and usable by engineers.

The successful achievement of these metrics would represent a milestone toward wider acceptance of IBPs, inform further device refinement and enable a proactive, data-driven ballast management approach for RIMs.

Figure 3: Proposed instrumented ballast particle sensor locations for field trial

Source: NTRO (2026).

5. Concluding Remarks

The implementation of IBPs is emerging as a novel method for in situ monitoring of ballast condition and track performance. This project provided further supporting evidence that while ballast degradation is widely recognised as a key contributor to track geometry faults, ballast degradation is caused by a multiple of factors, reinforcing the need for monitoring approaches capable of operating within the ballast layer itself.

The laboratory testing of IBPs developed by CQU demonstrated that the devices are sufficiently robust and sensitive to record ballast particle response under representative cyclic loading, particularly at frequencies and load amplitudes associated with degraded or vulnerable track conditions. While limitations exist, particularly in relation to operating life and displacement estimation, the results indicate that IBPs have matured to a point where controlled field validation is both feasible and necessary.

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This work proposes a field trial framework that identifies important practical considerations for real-world application, including power management, communication reliability and repeatability of measurements.

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Embedding Residual Risk in Asset Management: A Case Study from Main Roads Western Australia

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We propose a data driven, stakeholder refined asset management framework that quantifies pavement residual risk across Western Australia's sealed road network and turns it into actionable planning intelligence.

1. Introduction

Residual risk represents the level of risk remaining after existing controls are considered. In an operational road asset management context, it reflects combined influences related to vulnerability to environmental factors, pavement condition, road user safety, and customer and reputation considerations. Embedding residual risk within asset management enables consistent comparison of diverse locations, clearer links between risk signals and treatment options, and improved transparency for prioritisation of funding allocation decisions.

Residual risk frameworks provide a structured way to understand the level of risk that remains after design, treatment and management controls have been applied across the life of an asset. In the context of road pavements, such frameworks support transparent, repeatable decision making by integrating condition, performance, consequence and uncertainty into a single risk-informed view. This article describes the rationale, structure and practical application of a pavement residual risk framework, including how diverse data sources can be synthesised into an interpretable residual risk measure to support asset management, prioritisation and governance. The framework is illustrated using the Main Roads Western Australia (Main Roads) approach as a case study, where a pavement residual risk model was developed to operationalise whole-of-life, risk-based asset management for sealed road pavements.



2. Framework Overview

The Pavement Residual Risk Methodology (PRRM) developed for Main Roads follows an Analytic Hierarchy Process (AHP) structure comprising 4 risk dimensions: Asset Vulnerability, Asset Preservation, Asset Safety, and Customer & Reputation. Seventeen indicators are combined using agreed weightings to calculate a pavement residual risk (PRR) score on a 1 (very low) to

5 (very high) scale. Weightings reflect Main Roads' risk appetite and were refined through structured stakeholder workshops. The approach provides a consistent method while allowing future updates to the indicators' weightings as organisational priorities evolve. The details for the framework are outlined in Figure 1.

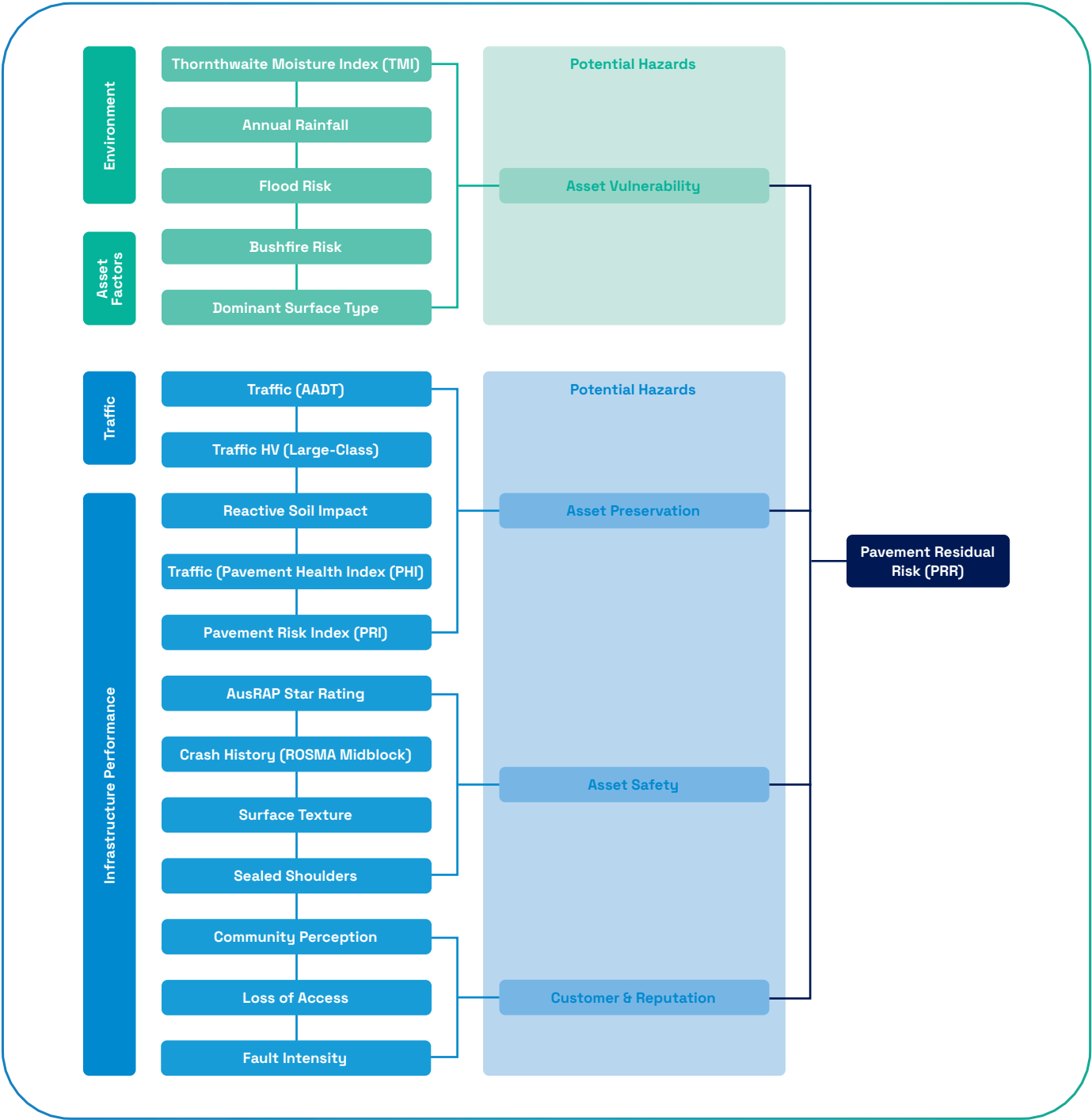


Figure 1: Main Roads Pavement Residual Risk Framework analytical hierarchical process flow chart

The framework was implemented through a detailed technical report, a Microsoft Excel-based PRRM tool and a Power BI dashboard for visualisation of outputs. The Power BI interface was selected to support adoption of the framework into Main Roads WA practice by enabling practitioners to explore high-level network and regional patterns as well as road segment-level details without the use of specialist software. The framework and selected tools enable risk scores to be analysed at both network and individual road segment levels, supporting strategic decision making and funding allocation decisions. The final framework reflects both technical rigour and practical relevance, with sensitivity testing confirming its robustness across varying scenarios.

Stakeholder engagement played a pivotal role in developing the framework. A series of structured workshops were conducted to validate terminology, select relevant indicators, determine preferred weightings for indicators and dimensions, and establish rules for managing missing or duplicate data. This collaborative approach ensured the framework reflected Western Australian conditions, aligns with Main Roads' current practice and can be maintained through regular data refreshes and governance checkpoints.

2.1 Risk Dimensions and Indicators

A total of 17 indicators were used to calculate the composite PRR score using the AHP methodology. The indicators contained within each risk dimensions are outlined below:

- Asset Vulnerability: climate and hazard exposure such as rainfall, Thornthwaite Moisture Index (TMI), flood resilience, bushfire risk and dominant surface type
- Asset Preservation: traffic loading, pavement health and structural performance indices, and environmental/soil influences
- Asset Safety: network-level road safety attributes, historic crash information, surface texture for sealed roads and sealed shoulder provisions
- Customer & Reputation: historical road closures and macro-level community sentiment.

2.2 Data, Tools and Governance

The data preparation used defined spatial and attribute matching rules to align disparate sources (e.g. rainfall, traffic, safety and pavement condition datasets) to consistent road segments. Governance considerations included data ownership, annual refresh cycles, and controlled updates to thresholds and weightings to maintain alignment with policy and practice.

For each segment, indicators were scored on a 1–5 scale and aggregated within each dimension using indicator weightings. Dimension scores were then combined using dimension weightings to produce a PRR score for each road segment. Scores were classified into Very Low, Low, Moderate, High and Very High categories based on defined thresholds, supporting prioritisation without prescribing specific treatments.



3. Operationalisation and Key Insights

Pilot implementation across 2 Main Roads regions informed refinements to terminology, indicator definitions, treatment of missing data and conservative rules when multiple values were present. Following the pilot implementation, the subsequent statewide rollout demonstrated that the methodology is scalable and repeatable. The supporting tools, such as the Microsoft Excel-based PRRM tool and Power BI dashboard, enhance the usability of the framework by enabling interactive exploration of results from the network to individual road segment levels. An example of a dashboard visualisation illustrating the overall PRR score for a representative Main Roads region is shown in Figure 2. When investigating the dashboard at a more granular level, the risk dimensions may exhibit different levels of variability across road sections. These patterns highlight the value of combining safety-related attributes, environmental exposure and pavement condition in a single view while maintaining transparency on the specific risk drivers at each location.

The framework is designed to complement existing Main Roads asset management planning and programming processes. Practical applications include:

- annual works programming: a consistent signal to help identify candidate locations for investigation and scope development
- ten-year network delivery planning: a defensible, system-wide view of residual risk that supports scenario testing and long-term prioritisation
- asset management plans: a common language to connect technical indicators with policy objectives and stakeholder communications
- funding discussions: transparent aggregation of road asset performance factors into a single score, with drill-down to the underlying evidence.

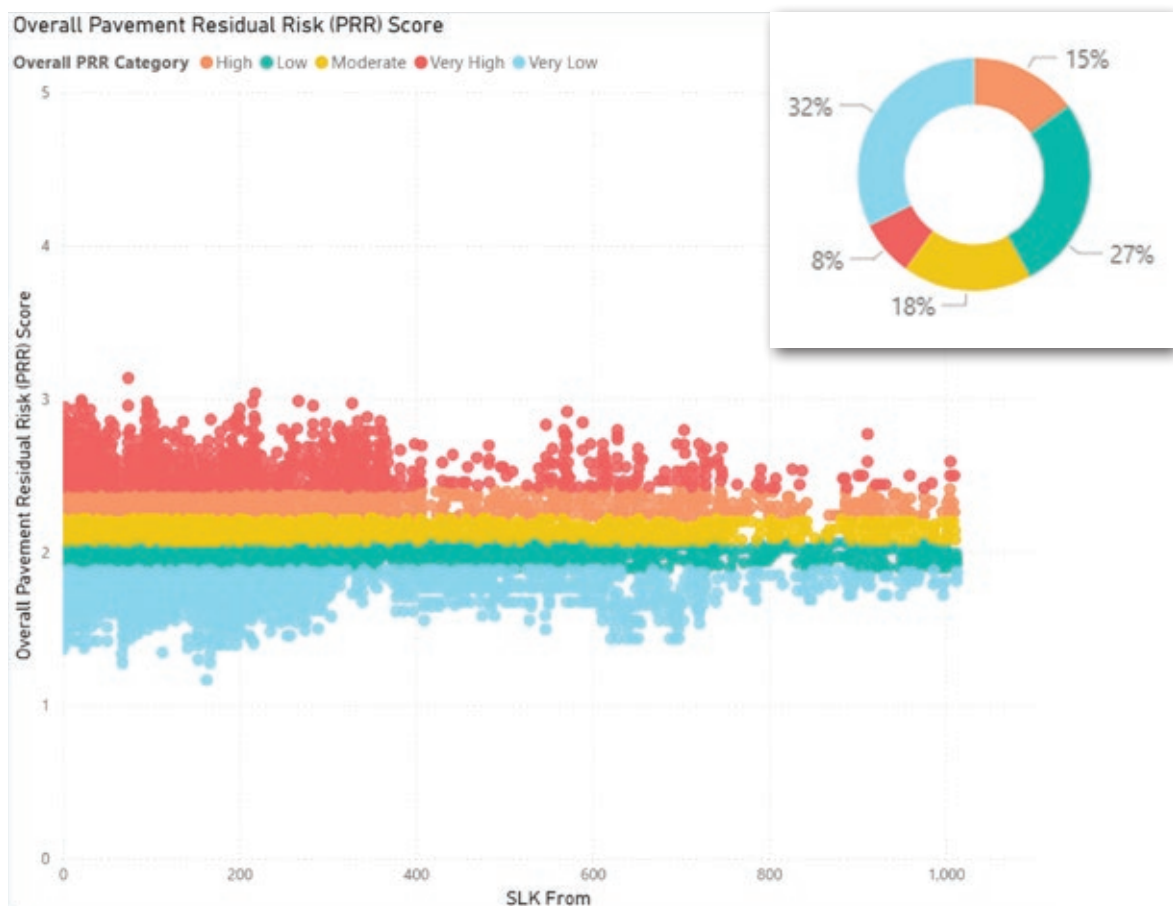


Figure 2: Overall PRR score for all individual road segments in an example Main Roads region

3.1 Value Proposition

The framework adds value to asset management practitioners by providing a common, data-driven basis for prioritisation that is easily explained to technical and non-technical audiences. Key benefits include:

- consistency and transparency: uniform scoring and clear linkages between indicators and outcomes support defensible decisions
- efficiency: targeted investigation of the highest-signal segments enables better use of limited budgets
- scalability: the method scales from local assessments to statewide views without loss of traceability
- adaptability: indicators and weightings can evolve as datasets improve and policy priorities change
- integration: alignment with risk management guidance and asset-planning artefacts strengthens end-to-end governance.

3.2 Practical Implementation Considerations

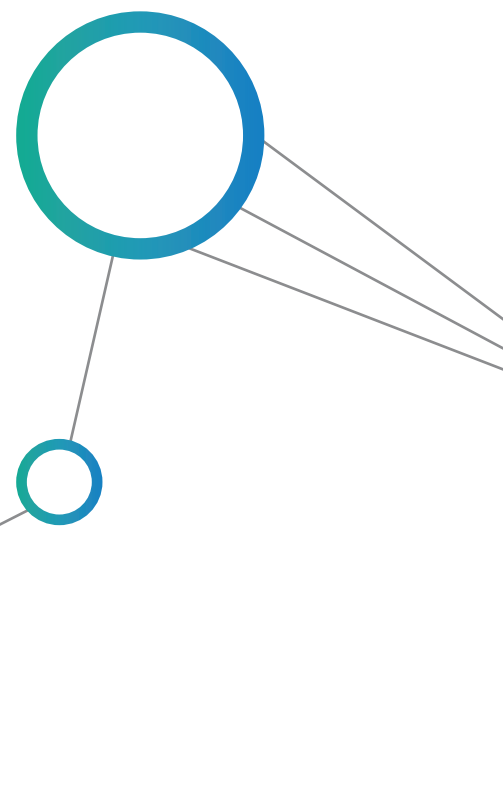
Experience from the pilot and statewide deployment highlights several considerations for sustained effective use of the framework:

- data stewardship: involving nominated data owners for each indicator, with annual refresh schedules and validation steps
- threshold review: reviewing scoring bands and indicator weightings periodically to reflect updated datasets and policy changes
- documentation: a concise methodology pack covering definitions, scoring rules and governance arrangements may assist onboarding
- feedback loop: maintaining practitioner feedback channels to capture local insights and inform refinements.

3.3 Opportunities for Enhancement

Further enhancement and broader application of the PRRM may be supported through several future development pathways. These opportunities reflect areas where additional research or expanded datasets could strengthen the overall analytical capability of the framework.

- extension to additional asset classes: the residual risk approach could be adapted for other asset groups, such as structures, to promote a consistent risk-assessment methodology across the wider Main Roads asset portfolio
- alignment with climate-related investigations: work undertaken through related WARRIP projects may offer opportunities for alignment, particularly where climate-related indicators are shared
- refinement of customer and community impact measures: additional datasets such as anonymised telematics or community sentiment indicators may offer opportunities to develop more granular customer experience measures
- further refinement of weightings and sensitivity testing: broader sensitivity testing may help explore the relative influence of various indicators and support future calibration activities
- long-term monitoring and validation: ongoing monitoring of identified higher-risk segments may support continuous improvement of the model.





4. Conclusions and Opportunity

The PRRM introduces a consistent, data-driven method for assessing residual risk across Main Roads' assets. It integrates multiple datasets to generate technical risk indicators, refined through stakeholder input to ensure they reflect Western Australian conditions. Using an AHP-based structure, the model consolidates complex risk information into a single PRR score while maintaining transparency about the contribution of each risk dimension, such as safety, environment, pavement condition and community impacts. This supports more defensible and consistent prioritisation of maintenance and investment decisions.

Pilot testing in 2 Main Roads regions confirmed the model's ability to identify spatial risk patterns, highlight region-specific drivers and reveal data gaps. Once validated, statewide implementation showed the methodology is scalable and repeatable. The supporting tools, such as the PRRM calculator workflow and a Power BI dashboard, enhance the usability of the framework by enabling interactive exploration of results from the network to individual road segment level.

Extensive stakeholder engagement across several workshops refined indicators, terminology, weights and assumptions, ensuring the model aligned with organisational practices and was trusted by practitioners. The project demonstrates that a structured, data-centric approach can meaningfully quantify residual pavement risk, improve transparency in funding decisions and strengthen the link between risk, maintenance planning and long-term asset sustainability.

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This project lays a foundation for extending risk-informed asset management to other asset classes in the future.

While developed in the context of Main Roads, the residual risk framework described in this article is readily applicable to other transport agencies seeking to strengthen risk-based asset management practices. The methodology is intentionally modular, allowing agencies to tailor indicators, weightings and governance arrangements to reflect local policy priorities, data availability and risk appetites while retaining a consistent and transparent structure.

By providing a defensible way to synthesise disparate condition, safety, and environmental and customer datasets into an interpretable residual risk signal, the framework supports clearer prioritisation, improved communication with stakeholders and stronger alignment between technical evidence and strategic decision making.

As transport agencies increasingly face constrained budgets, growing climate exposure and heightened accountability, embedding residual risk in asset management offers a practical pathway to more resilient, explainable and whole-of-life investment decisions across diverse network contexts.



Acknowledgements

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Data-Driven Optimisation of Bridge Maintenance Program

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1. Introduction

Bridge inspections play a critical role in supporting the safe and effective management of transport infrastructure. Across local government and state road networks, inspections are routinely undertaken to identify defects, assess safety and asset condition, and develop maintenance recommendations. These recommendations may range from routine maintenance activities, such as vegetation management and drainage cleaning, through to structural repairs and capital renewal works.

While inspection programs provide valuable information regarding asset condition and maintenance needs, asset managers are often faced with the challenge of prioritising a large number of competing maintenance activities within constrained budgets. As infrastructure networks continue to age and maintenance backlogs increase, there is a growing need for data-driven approaches that can support consistent, transparent and risk based decision making for maintenance prioritisation.

While there have been previous works on decision support frameworks for bridge maintenance (**Frangopol & Liu 2007**), there has been very limited practical implementation of such frameworks in Australia and New Zealand. Thus, as asset systems grow in scale and interdependence, conventional maintenance prioritisation approaches are increasingly struggling to deliver efficient, data-driven decision-making. In particular, the following points elaborate the specific challenges faced by asset owners in Australia:

- Complexity of resource allocation: Maintenance planning requires the simultaneous consideration of numerous competing factors, including budget constraints, prioritisation requirements and road hierarchy classifications. The interaction between these constraints creates a highly multidimensional problem space that is difficult to resolve accurately through manual calculations.
- Scalability limitations associated with traditional tools: Spreadsheet-based approaches and other manual methods lack the computational capability and efficiency needed to process large volumes of asset data. As a result, these tools are not well suited to managing complex infrastructure networks in a timely and responsive manner.
- Difficulty in quantifying risk: Conventional maintenance methodologies often lack robust mechanisms for modelling how risk evolves over time. This makes it challenging to anticipate deterioration patterns, assess long-term impacts and prioritise interventions based on risk exposure.
- Data quality and dependency: Maintenance programs rely heavily on input data, and when this data is incomplete, inconsistent, or poorly defined, the resulting outputs are less precise and less effective. In addition, the reliance on vague or subjective inputs can lead to suboptimal decision-making and reduced overall performance of maintenance strategies.

This study develops a risk-based optimisation framework for bridge maintenance planning, structured as an integrated decision support system. The framework is designed to support asset managers in prioritising and scheduling maintenance interventions under budget constraints while maintaining network performance and safety.

2. Optimisation Framework

The proposed optimisation framework consists of 3 sequential steps (as shown in Figure 1):

1. risk-based prioritisation using a multi-level Analytic Hierarchy Process (AHP)
2. data-driven deterioration modelling and delay risk quantification
3. optimisation through Integer Linear Programming (ILP).

The main purpose of the first two steps is to generate the required data to formulate the ILP optimisation in Step 3. The data required consists of information related to how the decision variables (i.e. the scheduling of the maintenance actions) will impact on the constraints (i.e. the budget and the urgency of the maintenance task) and the optimisation goal (e.g. minimising deterioration).

These steps are detailed in the following subsections.

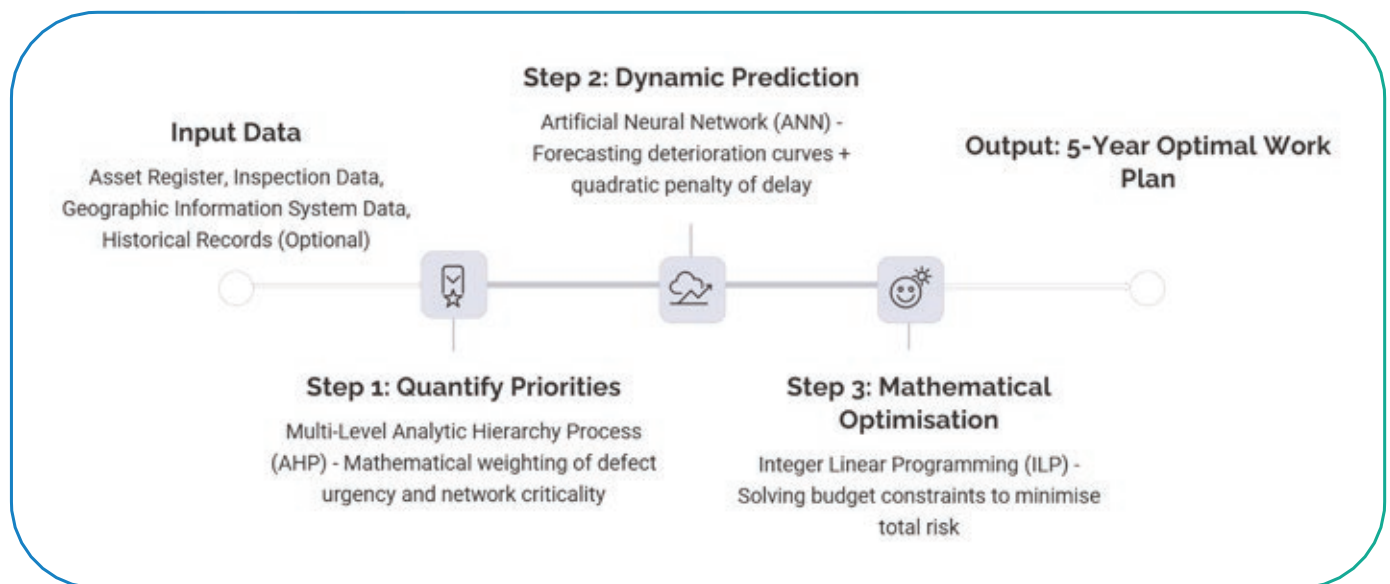
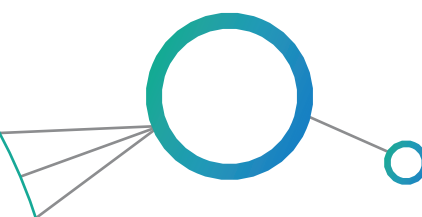


Figure 1: 3-step framework for optimisation of bridge maintenance program



2.1 Input Data

The optimisation framework relies on the outputs of Level 2 structural inspections undertaken. In this study the outputs utilised are in accordance with the Queensland Department of Transport and Main Roads' (TMR) Structures Inspection Manual (SIM). These inspections provide the fundamental asset condition, defect and maintenance recommendation data required to support risk-based maintenance planning.

Inspection data from a Level 2 structural inspection includes component condition ratings, identified defects, recommended maintenance actions, estimated repair costs and assigned maintenance priorities. Maintenance recommendations are developed by experienced bridge inspectors based on observed defects, engineering judgement and condition state triggers defined within the inspection methodology.

The recommended maintenance actions are grouped into 4 urgency categories:

1. Urgent actions require intervention within 6 months.
2. High priority actions require intervention within 12 months.
3. Medium priority actions require intervention within 2 years.
4. Low priority actions require intervention within 5 years or as resources allow.

These priority classifications form a key input to the risk-based prioritisation process.

The framework is applicable to a broad range of road structures, including bridges, major culverts and retaining walls. The maintenance actions represented within the dataset range from routine maintenance works, such as vegetation management and drainage cleaning, through to structural repairs, scour remediation works and larger capital interventions.

Maintenance costs are estimated during the inspection process using publicly available rates and industry cost information. While these estimates provide a suitable basis for network-level planning and optimisation, it is expected that asset owners will review and calibrate the rates against local delivery costs and procurement arrangements prior to implementation.

Road hierarchy information is incorporated using the client's existing council road classification system. This allows maintenance activities associated with strategically important routes and prioritised heavy vehicle networks to be differentiated from those on lower-order roads, ensuring that network criticality is appropriately reflected within the optimisation process.



2.2 Step 1: Risk-Based Prioritisation Using Multi-Level Analytic Hierarchy Process

In order to formulate the ILP optimisation and consider the risk associated with delaying maintenance tasks, there needs to be a quantification of such risks in the form of risk scores. The risk of a maintenance task considers both the defect urgency and network criticality. However, there is no existing universally accepted weighting standard in academic literature to quantify the risk based on these aspects. Therefore, a multi-level AHP approach is adopted to convert expert judgements into consistent numerical weights. In the literature, AHP has been used for quantifying prioritisation for bridge maintenance (**Bukhsh et al. 2019; Dabous & Alkass 2008; Wakchaure & Jha 2012,**), indicating its reliability for this purpose. Another benefit of using the multi-level AHP approach is that it allows the model to assign importance to different priorities based on experts' judgement.

The proposed multi-level AHP approach evaluates Defect Urgency (Layer 1) and Road Hierarchy Priority (Layer 2) to calculate mathematical weights for different situations. At the first level, maintenance action urgency is assessed across 4 categories: urgent, high, medium and low. The second level evaluates network criticality based on road hierarchy and heavy vehicle usage. Roads are classified into 4 priority levels (P1–P4), incorporating factors such as traffic volume, structural demand and National Heavy Vehicle Regulator (NHVR) route designation.

To perform the AHP, a pairwise comparison matrix is constructed for each level to evaluate the relative importance of each category. The 2 matrices (one for each level) were distributed to NTRO experts who filled the comparison matrices using Saaty's 1–9 scale (**Saaty 1980**). These comparison scales were converted into a set of weightings by computing the normalised eigenvector of the matrix. Finally, the 2 sets of weightings were combined to generate the final risk score for each combination of maintenance action urgency and road hierarchy priority. A weighted average was used to combine the weightings, where the scaling factors were set up so that the defect urgency dominated the prioritisation, while network criticality provided secondary differentiation. This formulation ensures that high-severity defects are always prioritised over lower-severity issues, regardless of location.



2.3 Step 2: Data-Driven Deterioration Modelling and Delay Risk

Due to budget constraints, there would potentially be maintenance actions that need to be delayed beyond the recommended time limit. Therefore, the purpose of the second step is to introduce a predictive model to estimate deterioration and quantify the cost of delaying maintenance actions.

A previous study found that a polynomial function of time (t^n) is commonly used to simulate the deterioration of the bridge condition (Srikanth & Arockiasamy 2020). While this mathematically penalises delay, it assumes a uniform deterioration rate for all assets; it fails to distinguish between a 50-year-old timber bridge on a heavy vehicle route and a newly constructed concrete culvert.

To address this, an artificial neural network (ANN) model was trained on historical bridge inventory data capturing the condition states (CS) of various structural assets. The input data is shown in Table 1. The ANN model was able to learn the specific degradation patterns of different structural types, allowing for precise, asset specific forecasting, while assuming appropriate maintenance

(Huang 2010). The core of the ANN model is a Multi-Layer Perceptron regressor, which uses 2 hidden layers of 100 and 50 neurons with Rectified Linear Unit activation functions. This allows the model to capture non-linear interactions, such as the accelerated degradation of timber structures when subjected to high traffic volumes (Assaad & El-Adaway 2020).

The output of the model is the adaptation of the condition state rating, which is traditionally recorded as discrete categories (CS1 up to CS4, with CS1 being the best condition). The ANN model will output the Condition Index (CI), which is a continuous numerical value between 1 and 4, simulating the continuous physical deterioration process (Huang 2010).

Based on these generated CI values, the future conditions of the asset associated with each maintenance action are generated through an iterative simulation over a 5-year planning horizon, divided into 6-month periods. A monotonic constraint ensures that the condition does not improve without intervention, maintaining engineering realism.

Bridge Age	Stress Factors	Structural Attributes	Environmental Context
Age of construction	- Average daily traffic - Heavy vehicle percentage (reflecting the NHVR route status)	- Superstructure material - Structure type - Dimensions (length/width)	Road hierarchy

Table 1: Input layer of the ANN model

2.4 Step 3: Optimisation via Integer Linear Programming

The final phase formulates the scheduling problem as ILP. The objective is to minimise the total penalty across the planning horizon, combining both delay risks and prioritisation weights.

The penalty value of scheduling a maintenance action within a certain time period is mainly based on the computed CI values and is differentiated depending on whether the maintenance action is done before or after the deadline. A pre-deadline penalty is simply equal to the computed CI value. Beyond the deadline time window, the penalty value will grow quadratically and will be multiplied

with the risk score from Step 1. The penalty value for each maintenance action, if it were undertaken in each possible time period, is generated, which is then collected into a penalty matrix to be used in the ILP optimisation.

The optimisation is subject to budget constraints, which limits total expenditure within each period. By solving this optimisation problem, the model generates an optimal maintenance schedule within the planning horizon, minimising the penalty while adhering to the budget constraint.

3. Outcomes

The optimisation framework was applied to a regional Queensland local government transport network comprising 167 structures, including 55 bridges and 112 major culverts. The network is managed under a risk based inspection and maintenance program, with Level 2 inspections undertaken in accordance with TMR SIM requirements.

The inspection program identified approximately 350 maintenance actions spanning routine maintenance, structural repairs and capital improvement works. The estimated maintenance costs exceeded \$600k which is higher than the typical annual maintenance budget, highlighting the challenge faced by asset managers in prioritising competing maintenance demands within constrained budgets.

Maintenance actions were assigned urgency categories and associated completion timeframes based on inspection outcomes, while network criticality was determined using the council's road hierarchy classification. The optimisation framework was then used to develop a 5-year maintenance program over a planning horizon consisting of 10 6-month periods.

Figure 2 shows the maintenance cost over a 5-year period using 2 different examples of budget constraint. It is evident that the program could be completed earlier given more budget, as the optimisation process is able to schedule maintenance actions so that the budget cap is almost fully utilised in each period. Additionally, with limited budget (left figure, \$80,000/period), the framework prioritises more urgent maintenance actions, as evidenced by the mean delay of each defect urgency category. Urgent maintenance actions are never delayed, whereas medium urgency action have higher mean-delay compared to high urgency actions.

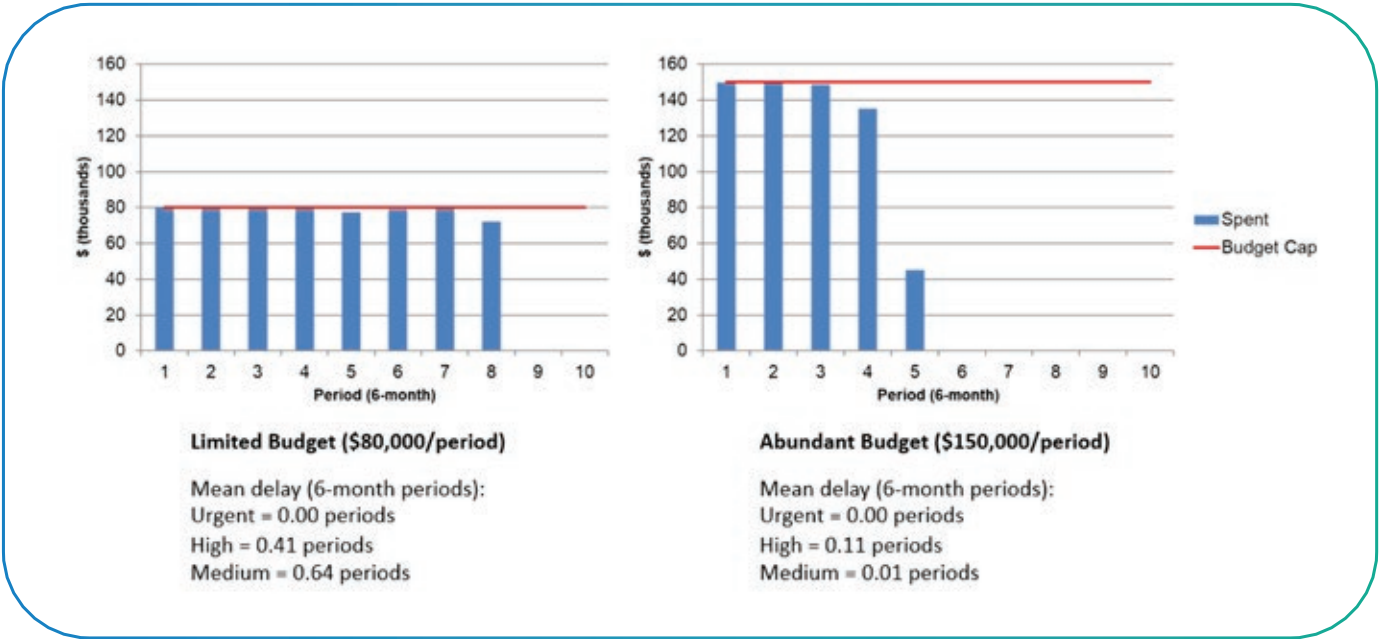
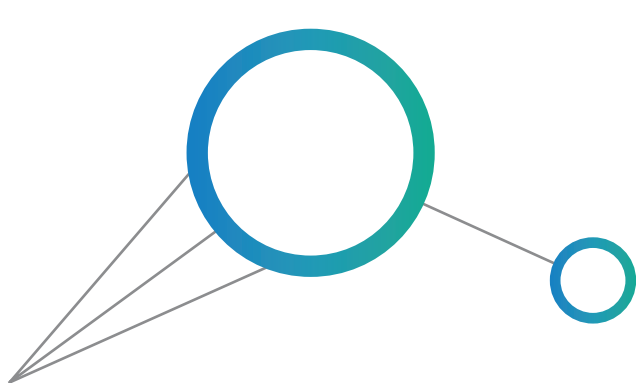


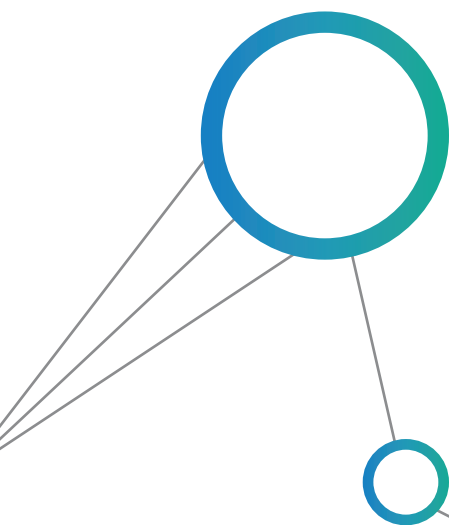
Figure 2: Outputs from the optimisation framework using two different budget limits

Note: An action is considered delayed if it was done beyond the deadline/time limit. For example, a medium urgency action with one period delay implies that the task was done within a 4–4.5-year period.



The results above show that the adoption of advanced analytical and computational methods can fundamentally transform asset management practices, enabling more efficient, scalable and transparent decision-making processes. Relating back to the challenges faced by asset owners in Australia, the proposed framework demonstrates substantive advancements and benefits in the following areas.

- The framework's capability to automate budget allocation enables the systematic balancing of multiple, interdependent constraints to minimise total network risk. This includes integrating budget limitations, asset criticality and prioritisation rules into a structured optimisation framework to generate an optimal, evidence-based 5-year maintenance schedule.
- The proposed method provides the opportunity for superior computational scalability when compared to traditional spreadsheet-based tools. Such an approach enables the analysis of thousands of assets simultaneously, significantly improving processing speed, reliability and consistency.
- The incorporation of dynamic risk quantification further enhances decision-making. By leveraging ANN-based deterioration models and quadratic penalty functions, the proposed model allows for a more refined representation of how safety risks escalate as asset conditions deteriorate, which in turn enables proactive intervention planning.
- With the conversion of inspection data into traceable and objective mathematical outputs, the decision-making process becomes more transparent and reproducible. This reduces reliance on subjective judgement and vague inputs, thereby enhancing the credibility, consistency and defensibility of maintenance planning outcomes.



4. Conclusion

This study presents the development and application of an optimisation framework for bridge maintenance planning, integrating condition assessment, deterioration modelling and decision optimisation into a unified approach. By quantifying trade-offs between cost and risk, the framework supports more informed and defensible decision-making.

While the framework is robust and adaptable, its effectiveness depends on the availability and quality of input data. Continued efforts to improve data collection, model calibration and integration with asset management systems will further enhance its applicability.

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Overall, the developed optimisation framework represents a meaningful advancement in bridge asset management, providing a structured and scalable solution to the challenges of maintaining ageing infrastructure under constrained budgets.

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Data Framework for Smart Network-wide Road Monitoring System

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Enhanced surveillance and real-time monitoring via remote sensors are crucial for improving response times to network disruptions and reducing the risk to network users and communities. Implementing a unified platform enables quicker targeting and response to affected sites, ultimately transitioning isolated data silos into a proactive, resilient and highly visible infrastructure management network.

1. Introduction

Currently, Waka Kotahi NZ Transport Agency (Waka Kotahi) deploys a large number of sensors across their various remote monitoring systems to provide visibility over broader infrastructure networks in New Zealand. However, these remote monitoring systems operate in isolated data silos. This fragmentation, combined with limited geographic coverage and data transmission delays, prevents operators from achieving a centralised, real-time view of the network. Because these systems cannot proactively cross-reference data or alert teams to network-wide status changes, operators remain unable to detect disruptions automatically. Consequently, teams still depend heavily on reactive public reports, meaning critical issues in remote areas often go unnoticed until someone physically encounters them. To build a truly resilient transport network, Waka Kotahi must transition from these siloed, delayed systems to an integrated framework that provides continuous, real-time surveillance across all remote sensors.

To build a resilient transport network, enhanced surveillance and continuous monitoring are essential to improve incident response times. Implementing a centralised real-time monitoring enables quicker targeting and faster responses to affected sites. The primary motivation for this work was to understand Waka Kotahi's current monitoring systems and the needs of the Waka Kotahi teams and to develop a supplementary data management framework tailored to different applications across the network. Addressing these needs would ensure that critical disruptions and network risks are identified and mitigated swiftly, thereby enhancing the overall resilience and safety of Waka Kotahi's transport corridors.



2. Understanding the Current State and Needs

The project conducted a desktop review and held a series of workshops that were structured to extract insights from the diverse perspectives of key stakeholders across Waka Kotahi's teams. These discussions focused on exploring the diverse purposes for which monitoring data is used in each department, identifying the wide range of monitoring sensors currently deployed and understanding the challenges, limitations and potential opportunities associated with the existing remote monitoring systems.

The stakeholder engagement sessions included representatives from the following teams within Waka Kotahi:

- Asset Management Data Standard (AMDS)
- Auckland System Management (ASM)
- Milford Road Alliance (MRA)
- Asset Management (AM)
- Weather
- Auckland Traffic Operation Centre (A-TOC)
- Wellington Traffic Operation Centre (W-TOC)
- Network Management
- Digital Lead
- Intelligent Transport System (ITS)
- Emergency Works (EW)
- Geotech
- Pavement
- Rail & Crossing
- Structures.

This collective approach facilitated a comprehensive understanding of both the current state and future requirements for remote monitoring systems.

2.1 Current Practices in Australia

As part of the desktop review, the practices of 3 major Australian transport agencies were analysed to inform best practice:

- **The Queensland Department of Transport and Main Roads (TMR)** integrates all third-party sensors with STREAMS through an API system-to-system interface. STREAMS is a software platform that integrates various traffic management components, including signal control, incident management and communication with field devices. For example, roadside flood warning signs and water level sensors interface with the STREAMS server via regular data updates (**TMR 2023, 2024**).
- **VicRoads, Victoria** implemented the Smarter Roads Program to enhance journey reliability and to manage congestion. This initiative uses 700 traffic cameras on busy routes for real-time monitoring by emergency, signal and media teams. Furthermore, 120 vehicle detectors send real-time and historical data on traffic volume, speed and density to the Transport Operations Centre. A network of 400 sensors provides average journey times to identify disruptions, feeding into 43 live travel signs (**VicRoads 2011, 2024**).
- **Transport for New South Wales (TfNSW)** employs a vast array of intelligent systems, including CCTV for incident detection, telematics for vehicle diagnostics, Bluetooth/WiFi sensors for travel times and AI-enabled drones for infrastructure inspections. These are integrated into the Intelligent Congestion Management Program (ICMP), an adaptive system that uses machine learning to detect traffic patterns and to generate congestion alerts (**Transport for NSW 2022, 2023**).

2.2 Current Data Framework at Waka Kotahi

Under Waka Kotahi's current monitoring framework, the Digital Lead team intakes raw data, which includes third-party data, CCTV footage, crowdsourced data and sensor data. This raw data feeds into an inventory database that requires continuous monitoring. End users, primarily those from the teams related to maintenance and operations,

can either access the inventory database directly or request specific datasets from the Digital Lead team. Waka Kotahi is currently transitioning to a new integrated GIS platform named Te Paparanga Amiki, led by the Research and Analytics team, to provide a unified application interface.

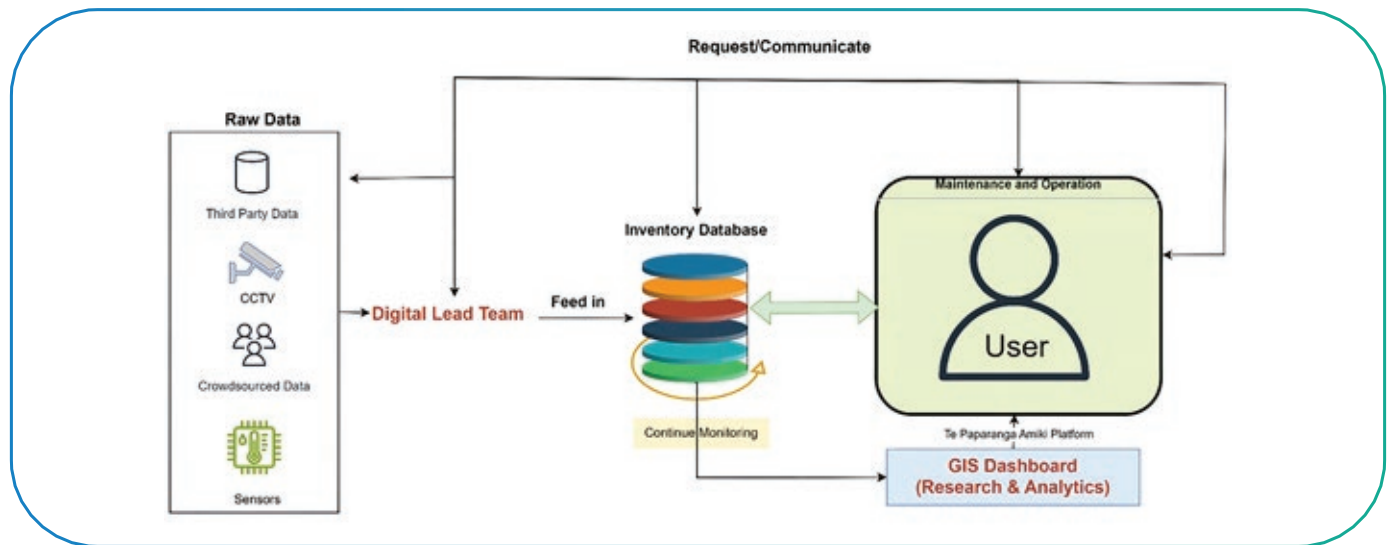


Figure 1: Current framework

2.3 Key Needs from Stakeholder Workshops

The interactive workshops revealed the requirements across the different teams, highlighting both shared and specific needs. A recurring theme was the need for a unified platform or dashboard to consolidate data that is currently scattered across various sources. The specific requirements identified include:

- **Network management and data standards (ASM & AMDS):** A strong demand for scalable IoT solutions that provide extensive sensor coverage for large-area management, underpinned by a mature data model and a unified platform for integration.
- **Operations and incident response (ITS, A-TOC, W-TOC, EW, Rail & Crossing):** These critical operational groups emphasised the need for unified dashboards, highly reliable real-time data integration solutions and adaptable systems to manage dynamically changing conditions during emergency works. Improved sensor and camera integration is vital for extensive network monitoring, alongside improved ITS integration for rapid emergency response.

- **Environmental and geotechnical (Weather, MRA, Geotech):** Key requirements included enhanced real-time data accuracy for high-stakes weather decisions (such as avalanche control), improved data accessibility, strategic placement of weather stations and systems capable of proactive management and real-time alerts for land instability.
- **Digital and long-term planning (Digital Lead & Pavement):** Digital Lead stakeholders require a comprehensive data integration platform to convert physical information into digital formats. Meanwhile, Pavement teams are looking to leverage data primarily for long-term analysis of asset performance.

Ultimately, these findings underscored the need to develop a cloud-based, centralised data stream to make monitoring data universally accessible, supported by a comprehensive metadata inventory of all monitoring assets across the network.

3. Framework Design

The findings from the stakeholder engagement indicated a critical need for a unified platform to access various types of sensor data. An efficient data management framework is required primarily for teams that need access to large historical datasets for network management, as well as for those that need real-time inference for emergency response.

To address the diverse and complex needs revealed during workshops, a proposed additional framework (Figure 2) was developed to run alongside the existing inventory database. This framework was designed to streamline and consolidate the collected data through a highly structured architectural flow that bridges raw data sources with end-user applications. The framework has a layered structure, which prevents selective data extraction and ensures that Maintenance and Operation users receive fully contextualised, actionable intelligence.

As illustrated in the framework model, the architecture relies on a clear pipeline moving from raw data ingestion to user-facing dashboards. To ensure long-term viability, this ingestion process must be designed for reliability, observability and scalability to handle various types of network sensor data. While the raw data feeds the standard inventory database, it is also routed into the new framework's dedicated capture and ingest module via the layered data hubs.

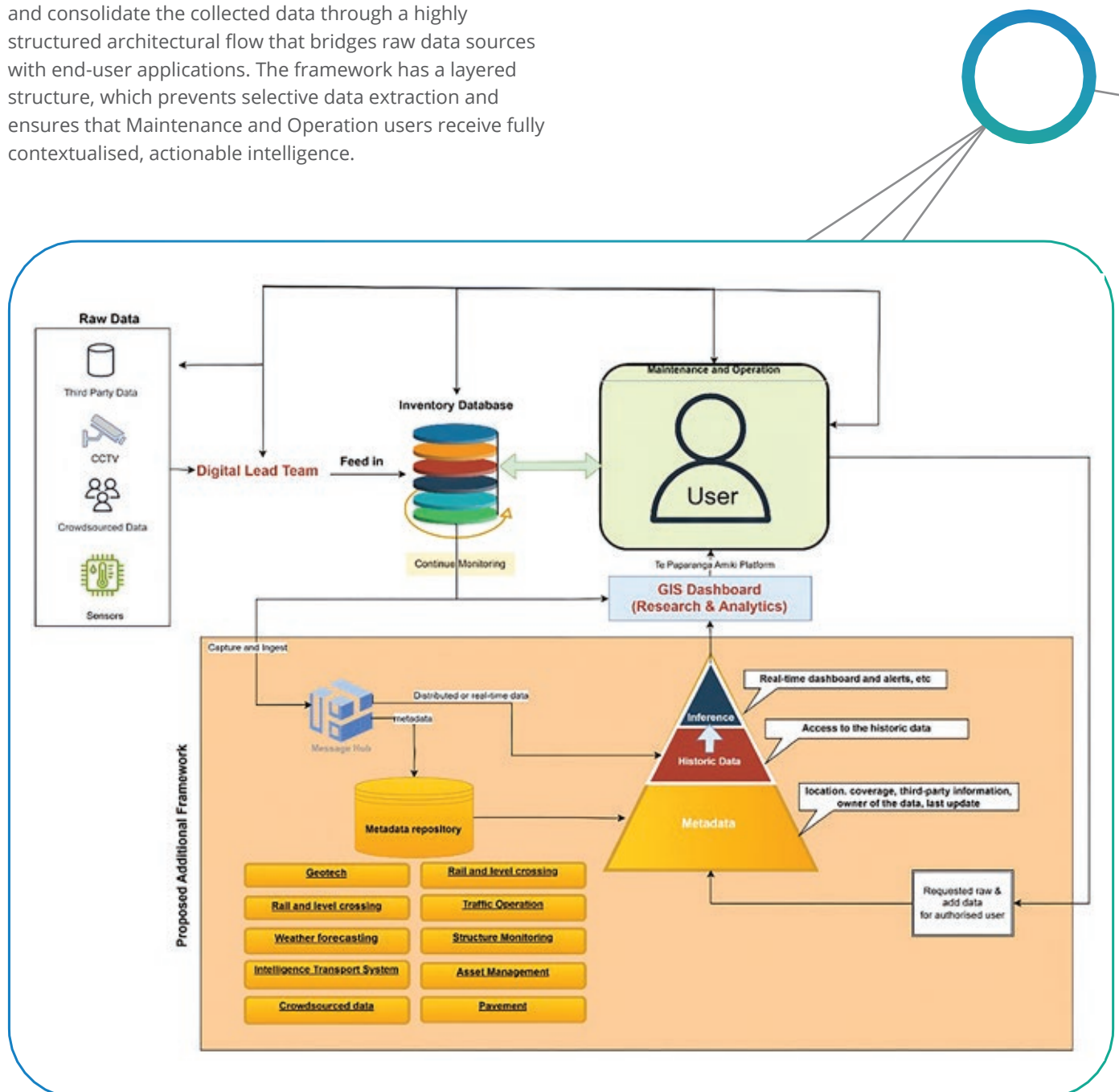


Figure 2: Proposed framework

3.1 The Layered Data Hubs

The layered data hubs make up the core of the proposed framework. They are structured into 3 distinct tiers to serve different operational requirements:

- 1. The metadata layer** serves as the foundation and offers critical details about the data's content and context. It includes information regarding location, coverage, third-party accessibility, asset ownership and update frequency. Users can filter the metadata source based on their project objectives to ensure they access the most relevant information.
- 2. The historic data layer** houses historical data, such as long-term incident and maintenance records, and is presented as time-series data. This allows network management and pavement stakeholders to analyse past trends and patterns to inform long-term smart investment decisions and predictive analytics.
- 3. The inference data layer** is positioned for immediate, real-time decision-making and provides users with access to a dynamic dashboard. This layer promptly flags and highlights specific incidents relevant to users' applications, enabling instant responses to critical events and optimising overall operational efficiency.

The message hub is a specialised data routing and processing engine that is essential for capturing and ingesting all input data, including distributed real-time data from various inventory systems. Metadata is automatically extracted from this hub and saved to the metadata repository. At the same time, relevant teams can directly access the real-time data that is subsequently distributed to the historic data layer. Nine metadata categories have been identified for this metadata repository: geotechnical, rail and level crossing, weather forecasting, intelligence transport system, crowdsourced data, traffic operation, structure monitoring, network management, and pavement.

This data integration platform serves as the bridge between physical infrastructure information and actionable digital intelligence, a primary requirement identified by the Digital stakeholders.



3.2 Proposed Framework Development Roadmap

To transition this framework from a conceptual model to a practical application, it was essential to outline the deployment roadmap. The successful development of a remote monitoring framework requires first assessing and addressing the needs of the current data inventory and then building the proposed framework directly from it. The practical rollout of the framework involves 10 key steps (Figure 3) designed to ensure adaptability to future needs.



Figure 3: Proposed framework development roadmap

4. Roles and Practical Responsibilities

To effectively apply these steps, specific roles have been assigned to maintain and grow the framework.

The digital lead team leads the overall development in collaboration with other stakeholders by:

- assessing the monitoring tools and exploring global best practices
- providing current and future API development
- maintaining the inventory database and the layered data hub.

The research and analytics team gathers ongoing operational requirements from different teams and translates those needs into practical applications by developing GIS dashboards.

The operations teams (ITS, EW, A-TOC and W-TOC) act as the primary end-users of the inference data layer by using real-time dashboards and alerts to actively manage the network and coordinate emergency responses.

The network management stakeholders (AMDS, Pavement) apply the historic data layer to practical use cases and leverage the data to predict asset deterioration, assess performance and make informed, long-term investment decisions.

By prioritising the development of the metadata layer as the robust foundation of this roadmap, Waka Kotahi can ensure a structured overview of data availability. Adhering to standards such as the ANZLIC guidelines (**ANZLIC 2011**) provides a clear path to creating a repository that will effectively analyse and enhance the resilience of transport corridors well into the future.



5. Conclusion

The development of a smart monitoring framework is a vital step toward enhancing Waka Kotahi's visibility and responsiveness in infrastructure networks. Through detailed stakeholder consultations, it was identified that improved sensor coverage, rigorous real-time monitoring and centralised data integration are critical for supporting effective, proactive decision-making. The proposed supplementary framework – comprising a message hub, a metadata repository and a structured layered data hub – serves to consolidate data for a wide variety of immediate and long-term applications.

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By adhering to a clear development roadmap and clearly defining team responsibilities, Waka Kotahi can achieve a unified, efficient platform that drastically enhances network resilience, optimises operational efficiency and ensures public safety across all corridors.

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A road dust management system for surface mining operations

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This article highlights a data-driven road dust management system for unsealed mine roads that integrates continuous monitoring, inventories and performance thresholds. By linking field measurements with maintenance decisions, it enables targeted dust control, evaluation of suppressants, reduced costs, improved safety and more efficient, sustainable mining road operations.

1. Introduction

Dust emissions from unsealed roads are a major environmental, occupational and operational challenge in surface mining. Haul truck traffic generates large quantities of airborne particulate matter (PM) which normally are classified by its diameter.

Dust particles are typically classified as PM₁₀ and PM_{2.5} (i.e., particles with maximum diameters of 10 and 2.5 microns, respectively), as these size fractions can penetrate the respiratory system and pose significant health risks due to the presence of respirable silica and heavy metals (Kavouras et al. 2009). Moreover, road dust is typically one of the dominant sources of particulate emissions in open-pit operations, accounting for up to 90–97% of total emissions (Kashi 2025).

Beyond health implications, dust adversely affects productivity and safety. Reduced visibility increases accident risks and limits vehicle speeds, which increases production costs, while the loss of fine particles accelerates road deterioration and increases maintenance costs (De Silva et al. 2023). Dust generation from haul roads is controlled by a complex interaction of factors that include traffic intensity and vehicle speed, the physical characteristics of the road material such as grading and fines content, environmental conditions including temperature, relative humidity and wind, as well as the current state of the road surface and its maintenance history. These variables interact dynamically, making dust emissions highly variable both spatially and temporally.

Many road dust suppressants made from polymers, bioproducts, salts and other materials are available worldwide (Zhang 2025; Zhou et al. 2018). Some dust suppressants are effective, but to really measure its efficiency and cost-benefit it is important to monitor their performance and use reliable data to make unbiased decisions on application rates and frequency of application. Moreover, road dust measurement systems are not widely established, and traditional methods, such as static samplers, are still commonly used, despite their limited ability to capture real-time dust emissions and their spatial variability.

This article proposes a road dust management system that could be adopted to not only efficiently reduce dust and dust suppressant costs in surface mining operations but also to measure the effectiveness of the dust suppressants (Gonzalez et al. 2019). The system is an adaption from traditional infrastructure management systems (de Solminihac et al. 2018) that have been widely implemented in conventional sealed and unsealed roads and other type of infrastructure.



2. Road dust management system

2.1 Road dust management system overview

The management of road dust in surface mining operations differs significantly from conventional road management due to several factors. One of the most critical differences is the magnitude of applied loads. While legal load limits for trucks on conventional roads are typically around 45 tonnes in many countries (with exceptions like Australia), haul trucks operating in mining environments can impose loads of up to 600 tonnes (**Douglas 2016**). Additionally, traffic patterns in mining operations are highly dynamic. A given road may experience intensive use for a short period, followed by extended durations of little or no traffic, depending on operational requirements. Traffic may also be redirected to previously unused routes to meet production demands.

Another unique characteristic is that mining roads are generally unsealed and constructed using locally available materials. The unsealed nature of these surfaces introduces significant challenges, as their condition can change rapidly in response to traffic loading and climatic conditions. Under dry conditions, these roads are major sources of airborne dust emissions (**Thompson et al. 2018**). Furthermore, the performance of mining roads is largely governed by the behaviour of the unsealed surface layer, making a thorough understanding of soil mechanics essential for evaluating and managing road performance effectively.

The objective of a road dust management system is to maintain the dust generated by road vehicles below a certain threshold while minimising the costs associated with dust suppression, increasing the productivity of the mining operation. The necessary steps to implement a road dust management system are described below.

2.2 Setting Up an Expert Team and Building an Inventory

The first step is to establish an expert team, which should consist of specialists from multiple disciplines where the foundation is road engineering. The team should have staff both in the field performing road surveys and at the desk analysing data from the field measurements. Knowledge on instrumentation, data analysis and code development is essential within the team. It is fundamental to have at least one vehicle (light truck) in the field to conduct the road measurements (Figure 1).

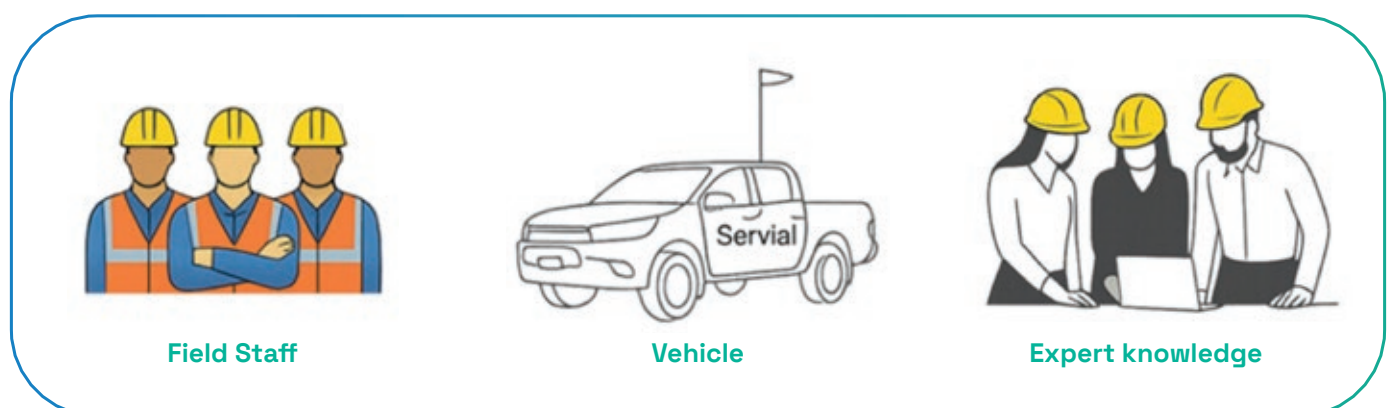


Figure 1: Interdisciplinary team as part of the road dust management system

The next step is creating a database or inventory of the mining roads. In surface mining, the road segments range from a few hundred meters to kilometres. Ideally, the road dust management system should use the same road names adopted by the mining operation to avoid confusion. Basic information like type of surface (unsealed, treated with dust suppressant, stabilised, etc.), road use (haul, service), traffic and any other relevant information should be added to a database. The inventory should be displayed in a map using geographic information systems (GIS) where the road names and basic information are visible (Figure 2).

Once the expert team is settled and the road inventory has been created, continuous dust monitoring should be carried out by the team in the field.

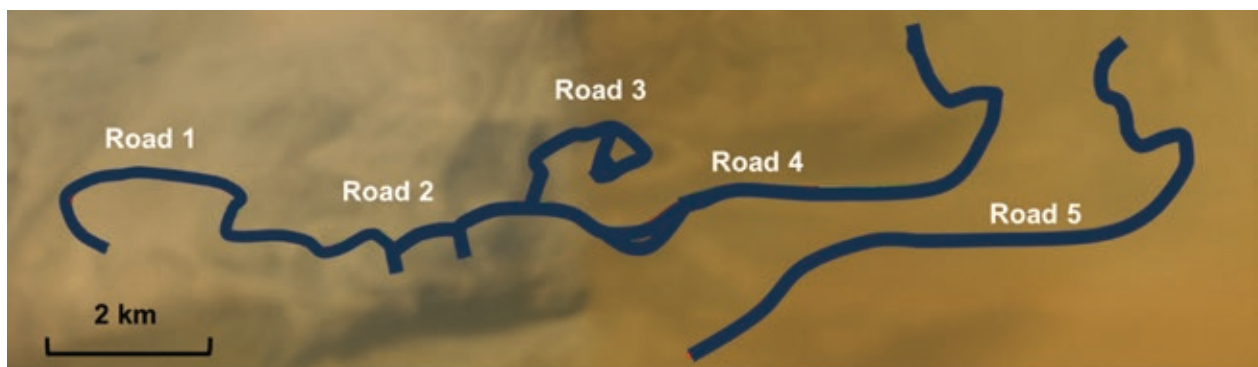


Figure 2: Example of inventory map with road names



2.3 Monitoring Road Condition and Setting Up Thresholds

2.3.1 Background on Road Dust Measurement

Traditional measurement methods exhibit several important limitations. Static dust collection techniques, for instance, provide limited spatial representation and are highly sensitive to local wind conditions. Gravimetric sampling approaches, although accurate, are often labour-intensive and normally do not allow continuous monitoring. Similarly, laboratory-based testing methods do not totally capture real-world operational conditions, particularly the dynamic interaction between traffic and road surfaces. Even though laser-based monitoring systems have improved the accuracy of dust measurements, they are frequently applied without integration into a structured decision-making framework, reducing their practical value in operational environments.

2.3.2 Modern Road Dust Measurement Methods

A few road dust measurement methods have been developed in recent decades to better represent the performance of unsealed roads. The road dust management system proposed in this paper adopted the dust measurement method originally developed by **Thenoux et al. (2007)**, although other methods could also be adopted (for example, **EPA 2015**).

The proposed system integrates several key components, including a laser-based optical sensor capable of detecting PM10 and PM2.5 particles, a GPS module for spatial referencing and a data acquisition system for continuous recording (Figure 3). Normally, the dust is measured in number of particles (PM10 or PM2.5) per cubic centimetre (cm³) of air, although the traditional unit to quantify dust is in micrograms per cubic metre (µg/m³). The air collection system is mounted behind the rear wheel of the survey vehicle used by the field team (Section 2.2) to ensure that it captures the dust plume generated by the vehicle in motion, normally at a target speed of 40-50 km/h (**Gonzalez et al. 2019**). The measurement system is repeatable, but one of the main disadvantages is that it highly depends on the driver positioning the vehicle at different transverse positions of a wide mining road and drive at different speeds.

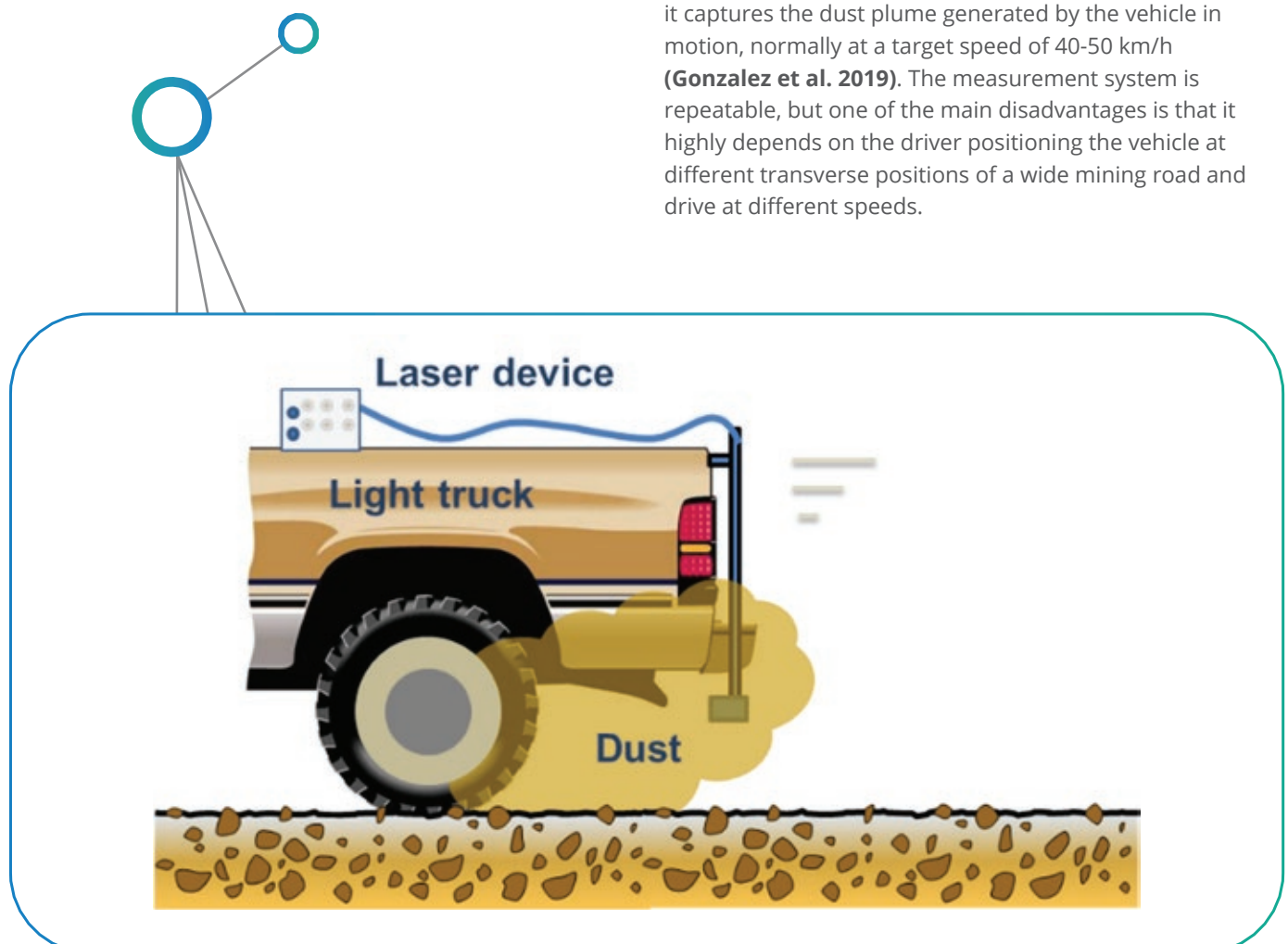


Figure 2: Example of inventory map with road names

2.3.3 Setting Up Level of Service of the Roads

Once the dust measurement system is installed, it becomes possible to quantify dust emissions across the road network. In addition to collecting measurements, it is essential to define thresholds associated with the expected level of service of unsealed roads. For example, a good level of service may correspond to PM10 values below 1000 particles/cc, a fair level between 1000 and 2000 particles/cc, and a poor level above 2000 particles/cm³.

It is useful to associate these service levels with a colour scale. In this case, 3 categories are defined, represented by green, yellow and red for good, fair and poor conditions, respectively. Figure 4 presents a 27.5 km road dust measurement obtained using the system described in Figure 3.

The results reveal significant variability along the road, with some sections showing near-zero particle concentrations, while others exceed 4000 particles/cm³.

The level of service is visualised using coloured segments along the route.

Although the information presented in Figure 4 is valuable, it is more effective to visualise the level of service on a map (Figure 5). Map-based representations allow the expert team to clearly identify road sections requiring additional dust suppression or maintenance interventions, such as grading, placement of unbound granular material or crossfall adjustments.

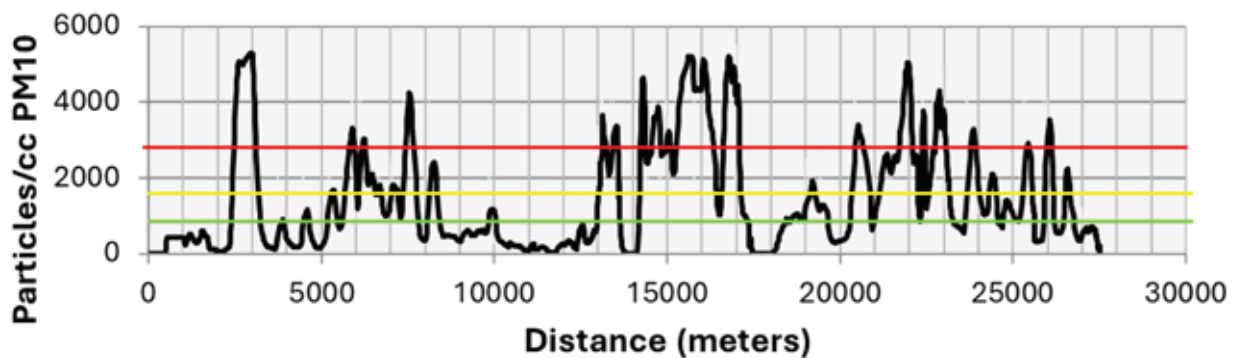


Figure 4: Example of a one-day road dust measurement, where 27.5 km were monitored



Figure 5: Example of a one-day road dust measurement displayed on a map

2.4 Maintenance Plans

Once several days or weeks of measurements have been collected, it is recommended to store the information in a web-based system that allows for systematic data management and analysis. The expert team can then design and advise the mining operation on the application of dust suppressants based on the collected data, considering factors such as traffic, soil type, climate and other relevant conditions.

Although application frequency depends strongly on field conditions—particularly traffic intensity and climate—reapplications of dust suppressants are typically spaced over periods of weeks. By implementing a road dust management system, it becomes possible to schedule applications based on predefined thresholds, ensuring that dust suppressants are applied only when necessary. Some chloride-based dust suppressants are highly effective; however, their hygroscopic behaviour may lead to excessive moisture absorption from the atmosphere, potentially reducing tyre-surface friction. Nevertheless, methodologies have been developed to quantify and mitigate the risk of reduced friction on unsealed roads treated with chlorides (Gonzalez et al. 2015).

Figure 6 illustrates the type of information that can be generated for a specific road segment using the proposed system. In this example, a threshold of 1500 PM₁₀ particles per cm³ is defined. At week 1, dust measurements are approximately 600 particles/cm³. Over the following weeks, dust levels increase, reaching the threshold at week 3, indicating that the application of a dust suppressant is required. After treatment, dust levels decrease to approximately 250 particles/cm³, before gradually increasing again over time.

The system also enables the evaluation and comparison of different dust suppressants. For instance, at week 7, an alternative dust suppressant can be applied to the same road segment, allowing its performance to be assessed under similar conditions.

Overall, the information generated through this system supports the development of optimised maintenance plans for mining operations and provides a systematic record of the performance and effectiveness of different dust suppression strategies.

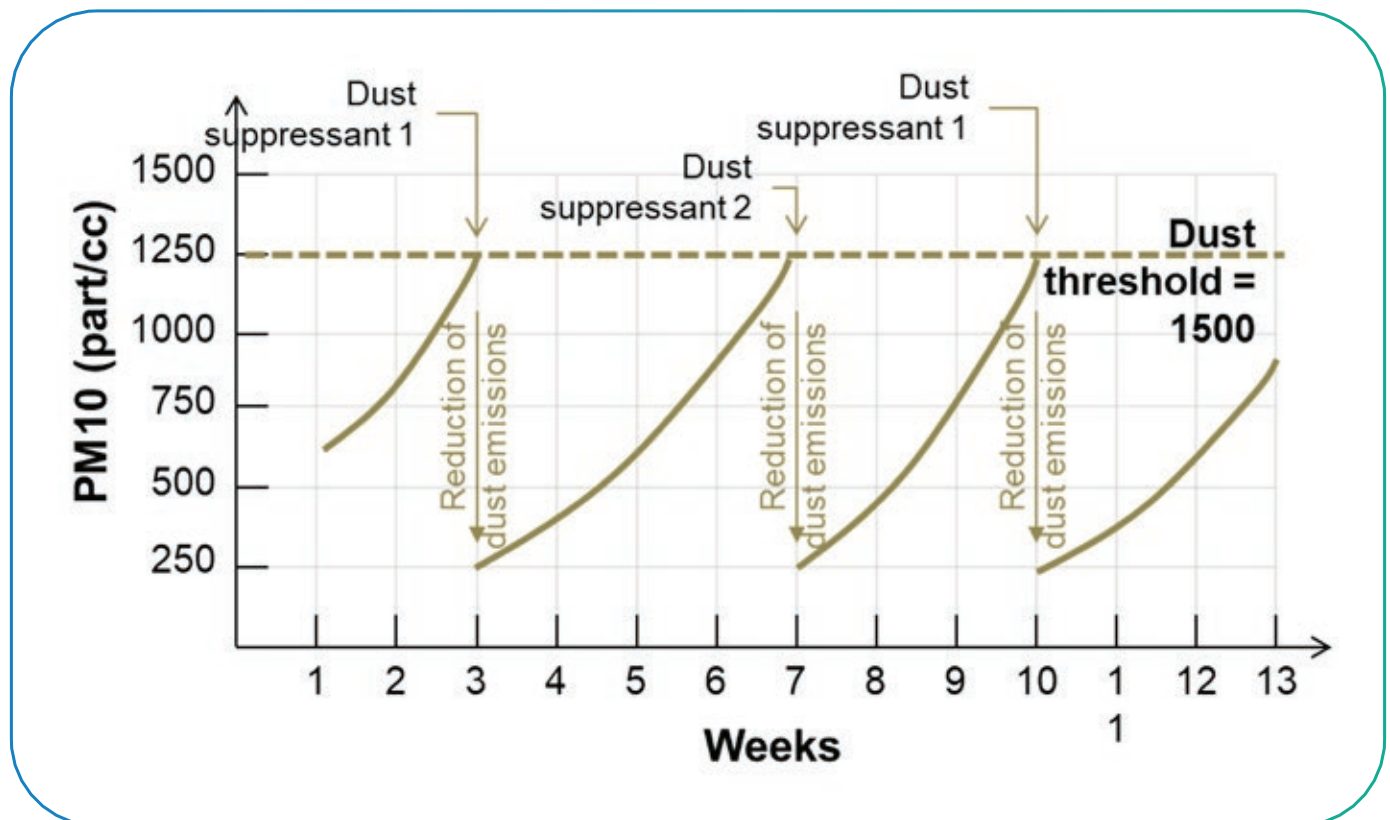


Figure 6: Example of data plot for a road segment



3. Conclusions

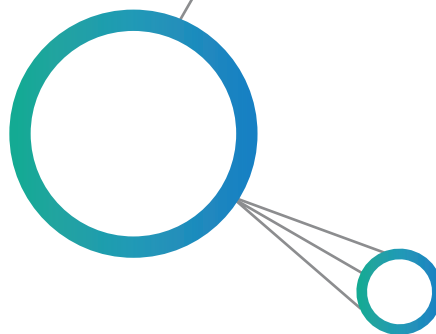
The following conclusions can be drawn:

- A road dust management system integrating continuous monitoring, GIS inventories and performance thresholds provides a structured, data-driven approach for managing unsealed mining roads.
- Dust emissions are highly variable and controlled by the interaction of traffic, environmental conditions and road surface characteristics, requiring adaptive management rather than fixed strategies.
- The integration of measurement systems with decision frameworks enables the identification of high-dust emission zones and supports targeted, efficient application of dust suppressants.
- The use of thresholds allows optimised scheduling of maintenance and treatments, reducing unnecessary applications and lowering operational costs.

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Overall, the system improves road performance, safety, and sustainability, offering a scalable solution for effective dust management in surface mining operations.





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