NACOE
NATIONAL ASSET CENTRE OF EXCELLENCE

ANNUAL SUMMARY REPORT

A35: Identification of Residual Risk for each Element and Development of a Funding Allocation Methodology of Elements (2018–19: Year 2)

ARRB Project PRA18018

Author/s: Dr Tim Martin, Georgia O'Connor & Ulysses Ai

Prepared for: Queensland Department of Transport and Main Roads

February 2021

Final Report

Version 3

Commercial in Confidence

AN INITIATIVE BY: arrb Queensland Government

SUMMARY

This report summarises the progress and outcomes to date for the National Asset Centre for Excellence (NACoE) Project A35 *Identification of Residual Risk for each Element and Development of a Funding Allocation Methodology of Elements*.

The report encompasses a summary of the project, the project methodology, and the development of the pavement residual risk model (PRRM). The PRRM is based on an analytical hierarchical process (AHP). The AHP applied to the calculation of residual risk was adapted from RIVA, a GIS-based risk analysis tool, used in Germany to account for natural hazards.

The PRRM includes five major risk dimensions, these are:

- access/vulnerability of the road asset due to hazards
- the impact of hazards on stakeholders and the community
- the impact of hazards on the safety performance of the asset
- the impact of hazards on the legislative compliance of the asset
- the impact of hazards on the operations of the asset.

These risk dimensions are comprised of several indicators, based on data which Queensland Department of Transport and Main Roads (TMR) regularly collects for the state-controlled road network. These indicators include:

- Environment and Traffic: Thornthwaite Moisture Index, annual rainfall, traffic (AADT and %HV), terrain, and slope stability.
- Infrastructure Performance and Condition Indicators: drainage condition index (DCI), pavement condition index (PCI), reactive soils, the AusRAP safety rating, the priority of defects, regulation compliance and the impact of loss of access.

Estimates of the pavement residual risk were made with the PRRM, using road segments that were field rated under NACoE Project A26 for the districts from which they were sampled. The preliminary results were weighted to show a range of representative values across the indicators and risk dimensions. These results have been presented both graphically and spatially. At this stage, and with further work, the PRRM appears to be capable of discriminating between the level of risk that different pavement segments have in the network.

ACKNOWLEDGEMENTS

ARRB wishes to acknowledge the collaborative support of TMR staff; Andrew Golding, Michelle Baran, Peter Bryant, Mohan Sharma, Nam Ranatunga and Jared Lester.

ACRONYMS

AADT	Annual Average Daily Traffic
AHP	Analytical Hierarchical Process
ARL	Assessed Risk Level
ARRB	Australian Road Research Board
AusRAP	Australian Road Assessment Program
CLoS	Customer-based Levels of Service
DCI	Drainage Condition Index
HV	Heavy Vehicles
ITS	Intelligent Transport Systems
MPO	Maintenance, Preservation and Operations
NAASRA	National Association of Australian State Road Authorities
NACoE	National Assets Centre of Excellence
NRM	NAASRA Roughness Measurement
PCI	Pavement Condition Index
PMS	Pavement Management System
PRR	Pavement Residual Risk
PRRM	Pavement Residual Risk Model
PRS	Pavement Risk Score
RUL	Remaining Useful Life
TLoS	Technical-based Levels of Service
TMR	Queensland Department of Transport and Main Roads
TNRP	Transport Network Reconstruction Program
TSD	Traffic Speed Deflectometer

CONTENTS

TABLES

FIGURES

1 INTRODUCTION

Queensland Department of Transport and Main Roads (TMR) faces a challenge in addressing the funding needs of multiple asset elements and the impacts on them from traffic use and the environment. Asset performance, and therefore needs and risks, are impacted by a combination of factors, with climate-related factors increasing in importance as evident from Queensland's recent floods. Different parts of the network and specific roads and assets, including structures, slopes, drainage, and signs and lines, are impacted differently. In specific cases, the frequency and scale of impacts effect the risks which can differ from case to case. Road pavements and surfacings, which have been subjected to substantial study, also need to be considered at risk, as there is a need to ensure an appropriate distribution of funding across multiple asset programs.

Therefore, TMR's Maintenance, Preservation and Operations (MPO) Steering Committee has identified a need for a more comprehensive and rational basis for assessing and managing risks. The intent is to allow TMR to better manage its portfolio by more rigorous, risk-based planning and programming, and the provision of clearer guidance to inform implementation.

1.1 OBJECTIVES

This project was created to deliver guidance and tools aimed at supporting a comprehensive, risk-based framework to assist in the allocation of funding to different elements of the road network. The project has drawn on established and recently developed methodologies and solutions in aiming to achieve early success, whilst ensuring the solutions support TMR's needs.

This project required the appropriate use of both a network-level approach and a more road section-based approach, depending on the nature and the geographic distribution of risks. For example, certain impacts have a significant disruptive, potentially catastrophic, effect on a network and impede the flow of traffic, whereas others are more confined and have marginal network impacts. The framework needed to be able to deal with such varied circumstances yet be sufficiently practical so that it could provide clear direction and focus for the individual element management plans.

1.2 PREVIOUS WORK

Directly related other NACoE projects include:

NACoE Project A5: Incorporating Uncertainty in PMS Modelling

Pavement management systems (PMS) require data that faithfully reflects the properties and other operating circumstances of the network. It is a well-known, though frequently ignored, fact that much of the information is uncertain or poorly represented either due to the nature of the data (e.g., environment) or due to the aggregation of the data into disparate segments. Therefore, the approach developed as part of this project expanded the use of existing deterministic models by using the full range (distribution) of the data instead of an aggregated, usually average, representation of the full dataset. Further, this approach utilised a comprehensive set of historical data and forecasted the probability distribution of key dependent variables (Kadar & Sen 2016).

NACoE Project A26: Incorporation of the Pavement Risk Score (PRS) into the Pavement Condition Index

Martin and Hore-Lacy (2017) published a NACoE report detailing the *Incorporation of the Pavement Risk Score into the Pavement Condition Index* as part of the NACoE A26 program. The study was aimed at reviewing, calibrating and incorporating the Pavement Risk Score (PRS) developed by TMR into the Pavement Condition Index (PCI) implemented in TMR's PMS. The PCI was modified by the addition of the

Traffic Speed Deflectometer (TSD) maximum deflection, D_0, that improved prediction of the remaining structural life of pavements (see Appendix B).

Other work in this area includes that on the life-cycle impacts of extreme events, and road performance modelling including the following NACoE and Austroads studies:

NACoE Project A4: Accounting for Life-cycle Costing Implications and Network Performance Risks of Rain and Flood Events

The rain and flood events across Queensland between 2010 and 2013 showed that the road network is more exposed to damage from such events than desirable, with between 23% and 62% of the state-controlled network closed or with limited access over four summers. With increasingly uncertain climatic factors and stretched infrastructure budgets, efficient optimisation and prioritisation of works is critical to the overall network condition.

Historically, works programs were focused on the highest priority treatments, which in some cases resulted in an overall deterioration in network condition over time, as measured by condition indicators such as roughness and seal age. Strategic, timely maintenance and rehabilitation programs are thought to be preferable to one-off major reconstruction programs such as the recently completed Transport Network Reconstruction Program (TNRP).

There was a need to review pavement management, maintenance, and rehabilitation practices to decrease exposure to damage in a cost-effective manner. In order to prove this, this project analysed the life-cycle costing implications of rain and flood events in Queensland through modelling three strategic options across a series of seven case studies.

The analysis also highlighted two critical factors in this discussion: the uncertainty surrounding future extreme climate and weather events in the face of predicted increased climate risks to Queensland and the importance of treating pavements within their target life before the start of accelerated deterioration (Beecroft & Peters 2017).

NACoE Project A34: Customer-based Levels of Service in Road Maintenance (ongoing)

In the context of road maintenance, road agencies have identified that there is a pressing need to relate Customer-based Levels of Service (CLoS) requirements related to road maintenance, to the maintenance intervention measures (roughness, rutting, cracking, potholes, etc.) used by road asset managers, or the Technical-based Levels of Service (TLoS). It is expected that some of these technical measures can be related to customer level of service as these are often not directly observed by the customer. A re-justification of existing levels of service is required to provide a defendable position to TMR in its decision to allocate funds and manage financial risks for the department and potential road user impacts, and the extent to which they are consistent with whole-of-life-cycle costing based funding priorities.

This project aims to determine the existence of relationships between CLoS and TLoS for an agreed set of road categories that will allow the determination of a customer acceptable level of TLoS.

1.3 PROJECT PROGRESS AND CHRONOLOGY

Work commenced on Stage 1 of this project in 2017–18 (Year 1) and continued to Stage 2 in 2018–19 (Year 2) with final completion of Stage 3 currently scheduled for 2019–20.

The work has required collaboration with several TMR departments during the project.

1.4 SCOPE AND CONTENTS OF THIS REPORT

This report is aimed at providing progress on the work undertaken during the year 2018–19 (part Stage 1 and Stage 2) that is particularly focused on the development of the residual risk management tool for pavements. The structure of the report is as follows:

- Section 2 outlines the methodology adopted for this project.
- Section 3 documents the development of the Pavement Residual Risk Model (PRRM).
- Section 4 presents the results of the PRRM applied to a sample of Districts.
- Section 5 presents the conclusions from the work on the PRRM in Year 2.

Other work for the development of the residual risk approach applied to the intelligent transport systems (ITS) and structures (bridges and culverts) assets has also been underway concurrently with the residual risk for pavement assets.

2 PROJECT METHODOLOGY

2.1 STAGE 1 – DEVELOPMENT OF RESIDUAL RISK MODELS

Stage 1 of this project involved the development of a general framework and methodology for determining the level of risk by individual asset types associated with different condition states and operating conditions, with risk quantified in terms of both likelihood and consequence. This work built on an extension of the PRS methodology under NACoE project A26 (Martin & Hore-Lacy 2017), but used the PCI, which was calibrated for road pavements, under NACoE project A26, against the measures employed in the department's PMS, including whole-of-life-cycle–based financial and economic costs. The aim was to:

- review existing element management plan approaches and national and international practice on risk management
- extend the composition and weightings employed in the PCI to reflect the sensitivity of outcomes to changes in key input variables, with the weightings defined as a simplified distribution (with boundary conditions) relevant to each variable, and taking account of estimated time-based changes in distribution, e.g. for climate-related variables
- ensure the estimated level of risk is responsive to different treatment strategies, e.g., where 'full resilience' or 'stitch-in-time' strategies are adopted, or where funding levels are varied, including accounting for different road use (AADT and HV composition)
- assemble evidence to allow the principles of the above 'risk model' approach to be adapted and applied to two non-pavement asset elements, selected in consultation with TMR
- present the proposed prototype model (and supporting illustrations) to the MPO Steering Committee to inform the suitability of the approach and direction for Stage 2.

As part of Stage 1, four different residual risk models were investigated. This involved the Pavement Residual Risk Model (PRRM), the Intelligent Transport Systems Residual Risk Model (ITSRRM), the Structures Residual Risk Model (SRRM), and the environmental Residual Risk Model (ERRM).

2.2 STAGE 2 – TRIAL ASSESSMENT OF PRRM

Stage 2 of this project, detailed in this report, operationalised the PRRM in a trial application on the TMR road network. As mentioned, this project was based on a continuation of the methodology used for NACoE Project A26. Therefore, the trial assessment of the PRRM was completed for road segments which were field rated as part of NACoE Project A26.

The main element of this work was the development of the indicators used to assess each risk dimension. This involved an in-depth review of the data which was available from TMR for indicators which were of a quantitative nature, and an investigation for alternate methodologies for indicators which were of a more qualitative nature.

Once the indicators to be used for the assessment had been finalised, the data was combined, and presented in both a graphical and spatial format (see Section 4.1 and Section 4.2).

2.3 STAGE 3 – NETWORK-LEVEL ASSESSMENT OF PRRM

Stage 3 of this project will involve applying the PRRM to the entire TMR state-controlled road network. In addition, Stage 3 will conclude with the development and dissemination of the technical documentation and resources to support the application of the PRRM for ongoing asset management. Lastly, Stage 3 will investigate avenues for further research and methodologies for the expansion of the ITSRRM and SRRM.

3 PAVEMENT RESIDUAL RISK

Stage 1 of this project involved the initial development of the Pavement Residual Risk Model (PRRM) in Year 1 of the project.

In addition, during Stage 1, work was also progressed on the initial development of the residual risk approach applied to intelligent transport systems (ITS), structures (bridges and culverts) and the environment. The ITS and structures applications of residual risk focused on defining the risk indicators and dimensions that are relevant for these asset types. Further development of the residual risk approach applied to the environment is not planned to proceed under this project. Finalisation of these indicators and dimensions are currently underway in conjunction with TMR. These models will be further investigated as part of a proposed Stage 4 of this project.

3.1 GENERAL

This section of the report details the information used as input for the PRRM. This includes the selection of road segments, the indicators, the rating categories, and the calculation of residual risk.

Specifically, this section of the report is structured as follows:

- Road segment selection (Section 3.2)
- Environment and traffic indicators (causes) (Section 3.3)
  - Thornthwaite Moisture Index (Section 3.3.1)
  - Annual rainfall (Section 3.3.2)
  - Traffic (Section 3.3.3)
  - Terrain (Section 3.3.4)
  - Slope stability (Section 3.3.5)
- Infrastructure performance and condition indicators (Section 3.4)
  - Drainage condition index (DCI) (Section 3.4.1)
  - Pavement condition index (PCI) (Section 3.4.2)
  - Reactive soil impact (Section 3.4.3)
  - Asset safety (Section 3.4.4)
  - Regulation compliance (Section 3.4.5)
  - Priority of defects (Section 3.4.6)
  - Loss of action/function (Section 3.4.7)
- Risk dimension rating categories (Section 3.5)
  - Access vulnerability (Section 3.5.1)
  - Stakeholders and community 3.5.2)
  - Safety performance (Section 3.5.3)
  - Legislative compliance impact potential (Section 3.5.4)
  - Operations impact potential (Section 3.5.5)
- Calculation of residual risk (Section 3.6)

The PRRM is based on an analytical hierarchical process (AHP), as outlined in Figure 3.1. The AHP applied to the calculation of residual risk was adapted from RIVA, a GIS-based risk analysis tool, used in Germany to account for natural hazards (Klose 2017). In 2014, Auerbach and Herrmann (2014) outlined a risk analysis approach for adapting the road infrastructure to climate change, which formed the initial basis for the RIVA work.

Another methodology (Nicolosi, Augeri & Soccodato 2019) for allocating funding across assets is available but was not used for this project. In this case, Nicolosi et al. (2019) used a hybrid framework combination of top down/bottom-up multi-objective approaches. Typically, most asset funding allocation approaches struggle to quantify some of the factors influencing the allocations. In addition, the adoption of a risk-focused quantitative approach to allocation of funding needs a substantial database encompassing all the factors contributing to the risk.

The PRRM shown in Figure 3.1 uses a set of indicators for the causes, such as traffic and the environment and another set of indicators for the effects of risks, which are the performance and condition of the infrastructure. The indicators are aligned to different risk dimensions to estimate a residual risk at each sub-component level. Finally, the residual risks of each sub-component are combined using various pre-determined weightings to estimate an aggregated residual risk for each road segment.

The indicators for causes and effects rely on quantifiable measures that are accessible and regularly updated in the TMR database, which was the source for the indicators on each road segment. The definitions and details of these indicators are outlined in the following section.

3.2 ROAD SEGMENT SELECTION

The road segments used for the PRRM calculation were selected based on the previous NACoE Project A26 *Incorporation of the Pavement Risk Score (PRS) into the Pavement Condition Index (PCI).* NACoE Project A26 sought to calibrate (and adjust) TMR's PRS methodology with field observations, and a whole-of-life-cycle costing methodology applied in the PMS.

Within NACoE Project A26, the pavement condition index (PCI) for samples of road segments, from differing districts across Queensland, was calculated. In addition, many of these road segments were field rated for their condition. Road segments which had the PCI calculated, and were field rated, formed the basis of the dataset.

A list of the road segments, and the associated districts, included in this project are provided in Appendix A.

3.3 ENVIRONMENT AND TRAFFIC INDICATORS

Environment and traffic indicators refer to those which are generated by environmental factors, and factors related to traffic/road usage. For this project, this included: the Thornthwaite Moisture Index (TMI) (Thornthwaite 1948), annual rainfall, annual average daily traffic, AADT, commercial/heavy vehicle traffic (%HV), terrain and slope stability. Each of these indicators are detailed in the following sections.

3.3.1 THORNTHWAITE MOISTURE INDEX

TMI is a reflection of the aridity or humidity of the soil and climate of an area. It is calculated by analysing the collective effects of precipitation, evapotranspiration, soil water storage, moisture deficit and runoff (Austroads 2004).

TMI can be used to classify various climate types according to the moisture index limits, which are outlined in Table 3.1. The distribution of TMI is shown in Figure 3.2.

Figure 3.1: Pavement residual risk model (PRRM)

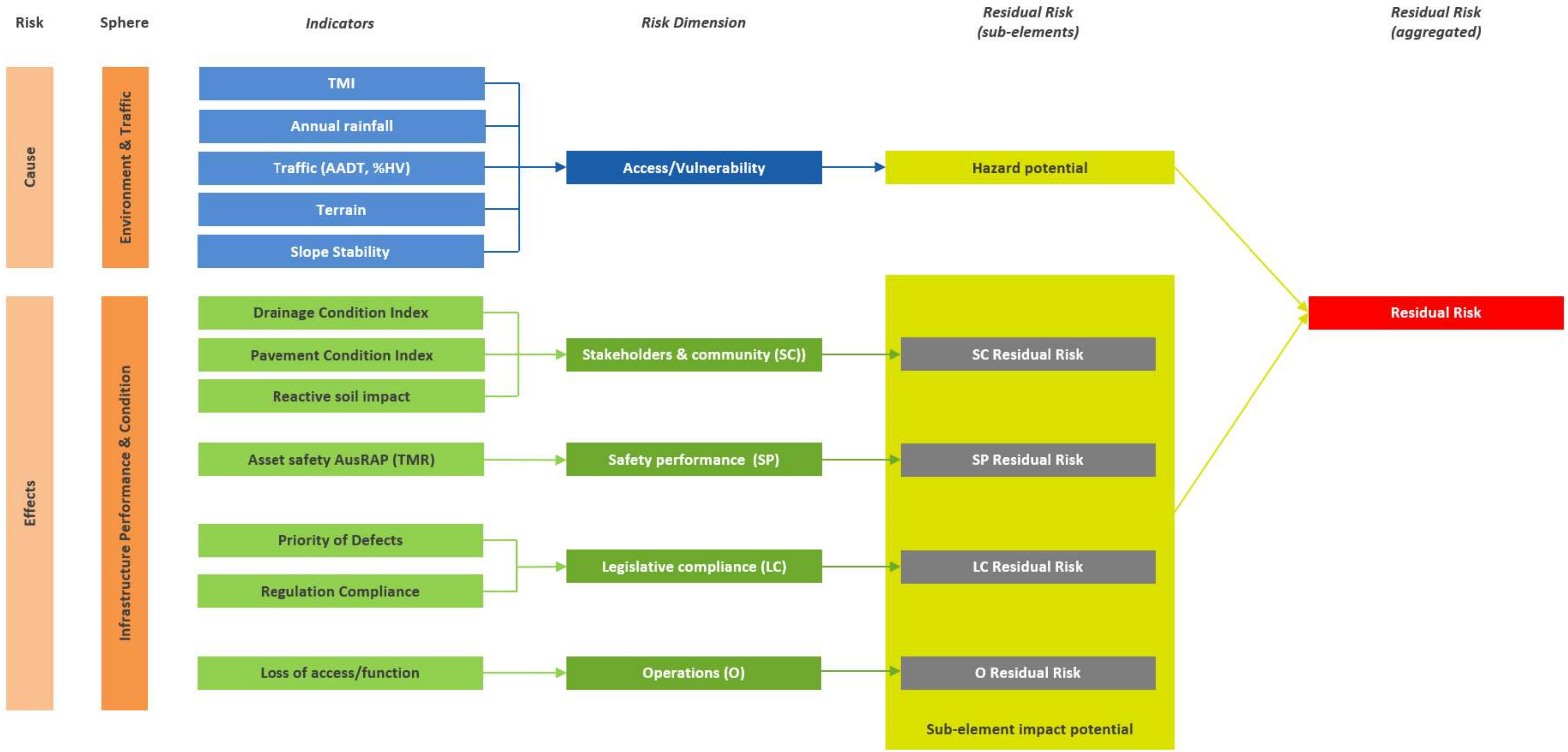
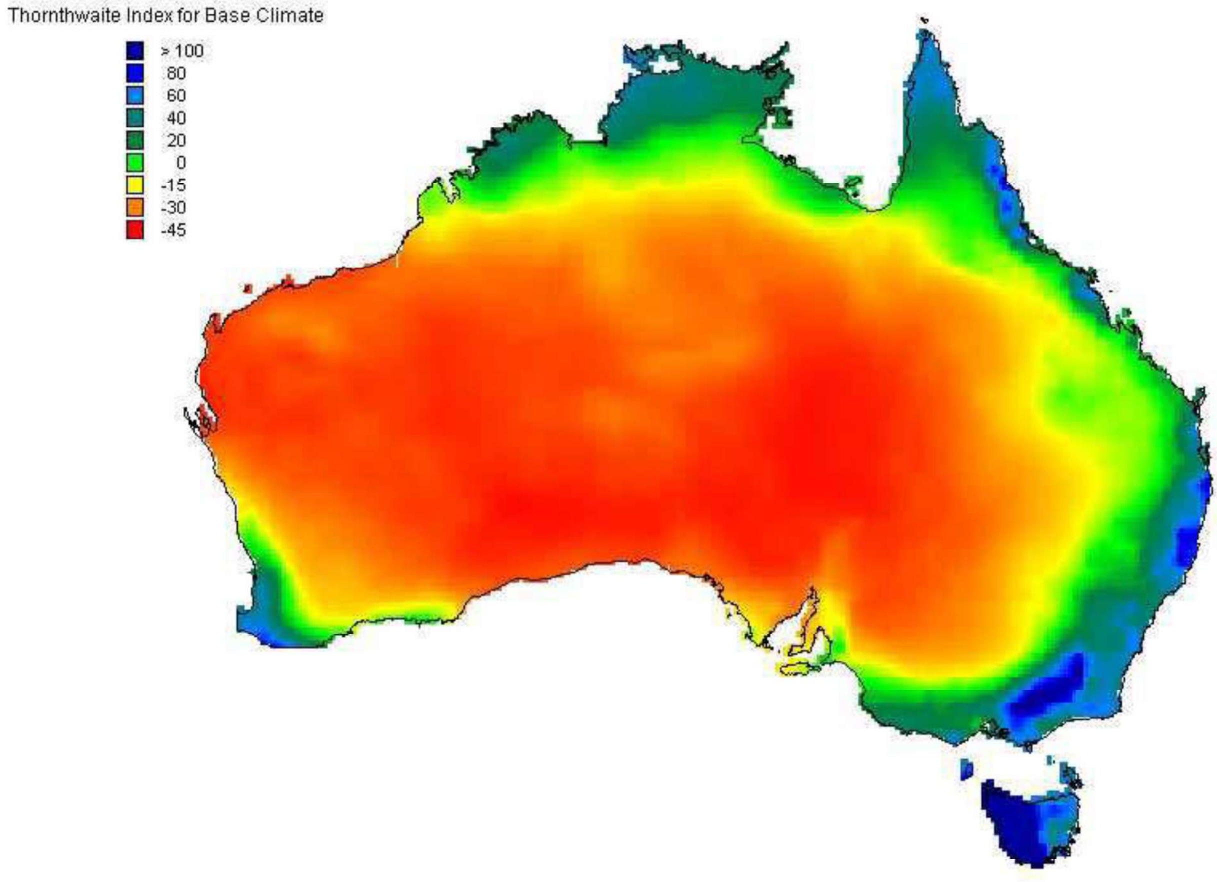


Table 3.1: Thornthwaite's climate type classifications

Thornthwaite climate type		Thornthwaite Moisture Index
Grid type	Unit	Range
A	Perhumid	>100
B4	Humid	80 to 100
B3	Humid	60 to 80
B2	Humid	40 to 60
B1	Humid	20 to 40
C2	Moist subhumid	0 to 20
C1	Dry subhumid	−20 to 0
D	Semi-arid	−40 to −20
E	Arid	−60 to −40

Source: Thornthwaite (1948).

Figure 3.2: Thornthwaite Moisture Index for Australia in 2000



Source: Austroads (2004).

Data on the TMI for each of the locations assessed as part of this project was obtained from the A26 dataset, which as mentioned, was used as the basis for the road list in this project.

3.3.2 ANNUAL RAINFALL

The annual rainfall indicator is defined as the long-term average annual rainfall for a location. The long-term average annual rainfall for each location was calculated by averaging the annual rainfall of the most recent 30-year period, 1988–2018.

The annual rainfall for each road segment location was generated using data from the Bureau of Meteorology (BOM). Based on the chainages of the road segments, the nearest town was identified. This town was entered into the BOM's search engine to locate the closest weather station. Relevant towns, and associated weather station characteristics were recorded. Weather stations were selected based on their proximity to the town, and the amount of data available. Ideally, weather stations with 30 years of rainfall data were selected.

3.3.3 TRAFFIC (AADT/%HV)

The impact of traffic on residual risk was calculated for two separate indicators, AADT and %HV for traffic using the road. Both these indicators were obtained from the data provided by TMR. The data used was relevant for 2018.

3.3.4 TERRAIN

The terrain indicator refers to the physical features of the land across which the road traverses. TMR defines terrain into three categories, level, rolling and mountainous. The terrain category associated with each of the road segment locations was provided by TMR.

3.3.5 SLOPE STABILITY

The slope stability indicator refers to the stability of the batter and cutting slopes along the road. The batter and cutting slopes are the uniform side slope of the road batter and cutting, which is distinct from grade, and is expressed as a ratio of the horizontal distance to vertical slope height (Austroads 2015). The stability of the batter and cutting slope is important as it contributes to the structural resilience of the road pavement, including shoulders. The batter and cutting slopes contribute to the ability of the road to shed water by providing a stable base for its table drains to drain runoff from rain and flood events.

Slope stability is measured by TMR with an assessed risk level (ARL). This ARL value is a number from 1 to 5 with 5 being a stable slope, and 1 being an unstable slope. Data on the stability of slopes was provided by TMR. This data included the ARL, the slope type, the slope height, the slope angle, location information and whether or not the slope has a management plan.

3.4 INFRASTRUCTURE PERFORMANCE AND CONDITION INDICATORS

Infrastructure performance and condition indicators refer to the elements of the asset itself which effect the level of service it provides. In this project, this includes the following indicators that were used to build the risk dimensions:

- drainage condition index (DCI)
- the pavement condition index (PCI)
- impact of reactive soils
- AusRAP asset safety rating
- priority of defects, set by TMR's corporate priorities in the Routine Maintenance Guidelines (TMR 2017)
- regulation and compliance
- loss of access which would occur due to closure of the asset.

3.4.1 DRAINAGE CONDITION INDEX

Drainage refers to the natural or artificial means of intercepting and removing surface or sub-surface water usually by gravity (Austroads 2015). DCI in this context refers to the portion (percentage, %) that drainage culverts are blocked with detritus reducing the effectiveness of the culvert. The DCI was originally developed by Austroads (2011) and was revised to an indicator that can be assessed on ARRB expert opinion, using the soil type information provided by TMR.

Soil group data was provided by TMR, based on 2014 survey results. There were 62 different soil types included in the data. These were grouped into categories and assigned assumed blocking percentages based on Table 3.2.

Table 3.2: Soil grouping and assumed DCI

Soil type	Assumed Drainage Condition Index (DCI)
Sandy or loamy	0% blocked
TC* soils	1–10% blocked
Non-cracking clays	11–25% blocked
Cracking clays/expansive	26–50% blocked
Waterlogged/silt	> 50% blocked

Note: *Tertiary colluvial

3.4.2 PAVEMENT CONDITION INDEX

PCI is calculated based on various individual condition indices (CI). The PCI is an aggregate of these individual CIs, based on the concept of a 'weighted maximum', i.e., instead of using an average of the CIs, the maximum (worst) dominates the overall index (COST 2008). The current composition of the CIs to calculate the PCI used by TMR is outlined in Table 3.3.

Table 3.3: Composition of the TMR PCI

Attribute (CI)	Description
NAASRA Roughness (NRM)	Counts per km with separate limits defined by traffic level and speed zone
Rutting	Mean rut depth (mm), with separate limits defined by traffic level, climate, and speed zone
Cracking	Area (%) of all cracking
Remaining useful life (RUL)	RUL of the road pavement in years
Surface age	Age of the latest surfacing in years
Skid deficiency	% less than investigatory skid resistance

Source: Martin and Hore-Lacy (2017).

In order to express the overall condition of an asset in terms of a PCI, the above condition indices are aggregated (Martin & Hore-Lacy 2017). The estimation of the RUL attribute is detailed in Appendix B.3. The RUL is based on the traffic speed deflectometer (TSD) measurements of maximum pavement deflection (Martin & Hore-Lacy 2017).

> Engineering decisions are usually made based on the worst condition, e.g., a structurally very weak, but a perfectly smooth road would have an average (say 2.5) pavement condition index. Treatments, however, would be decided based on the worst condition, in this case the structural weakness. The proposed PCI is shaped by the engineering decision-making approach, consequently it gives greatest weight to the worst condition, whilst the other condition indices are also accounted for as minor adjustments.

The PCI is calculated by applying Equation 1, as follows:

$$PCI = MAX(w_i \times Index_i) + p\left(\frac{SUM(w_i \times Index_i) - MAX(w_i \times Index_i)}{\sum(w_i) - Avg(w_i)}\right) \quad (1)$$

where

PCI = pavement condition index

w_i = weight for individual condition criteria, including cracking, roughness, rutting and surface age

$Index_i$	=	index value for individual condition criteria, including cracking, roughness, rutting and surface age
p	=	condition factor (the current value is 0.1).

It should be noted that the weights (w_i) must be relatively close to 1 to avoid significant distortion of the index.

As mentioned, the PCI was calculated for many road segments as part of NACoE Project A26. These segments were also field rated as part of that project.

3.4.3 REACTIVE SOIL IMPACT

The reactive soil impact indicator refers to the effects of the environmental zone through which the road traverses. Reactive soils are based on the type of soil they are composed of which can cause them to swell when wet and shrink when dry, i.e., they are reactive to water. TMR classifies their soils into four environment zones, including: dry reactive, wet reactive, dry non-reactive and wet non-reactive.

3.4.4 ASSET SAFETY – AUSRAP

The AusRAP indicator is from the Australian Road Assessment Program. AusRAP provides safety ratings for roads, where roads are assigned a score from one star (least safe) to five stars (most safe). In this context AusRAP is a useful indicator for the safety risk dimension.

AusRAP uses four complementary methods – or protocols – for assessing the safety of roads: risk mapping, performance tracking, star ratings and safer roads investment plans (SRIPs). Risk maps use detailed crash data to illustrate the actual number of deaths and injuries on a road network. Performance tracking enables the use of star ratings and risk maps to track road safety performance and establish policy positions. Star ratings provide a simple and objective measure of the level of safety provided by the road design. SRIPs draw on proven road improvement options to generate affordable and economically sound infrastructure options for saving lives (Australian Automobile Association (AAA) 2013).

The AusRAP star rating for the road segments, used as input for this project, was used as the indicator for safety.

3.4.5 REGULATION COMPLIANCE

The regulation compliance indicator has been defined broadly as being the compliance of the road to the roughness intervention levels defined by TMR. Road segments were categorised by the percentage to which the road is either compliant with the 'desirable' roughness intervention level or whether it exceeds the roughness intervention level. Table 3.10 is a summary of TMR's roughness intervention levels based on the AADT.

Table 3.4: TMR roughness intervention limits

AADT range	NAASRA roughness
< 500	130
< 500 & < 1 000	110
>=1,000 & <10 000	95
>=10 000	80

3.4.6 PRIORITY OF DEFECTS

Priority of defects refers to the corporate priorities assigned by TMR to each of the defects recorded on a road segment. There are six categories of corporate priorities that are summarised in Table 3.5. These corporate priority ratings were grouped together to generate the residual risk ratings.

Table 3.5: TMR corporate priority defects categories

Corporate priority	Description
Priority 1 – Hazard	Defects where the likelihood of harm occurring is greater than a safety defect determined by the hazardous defect identification procedure
Priority 2 – Ordered works	Work undertaken in accordance with the Principal's order and directions
Priority 3 – Safety	Defects that are an issue of safety
Priority 4 – Legislative	Defects that are required to be repaired by legislation
Priority 5 – Preventative	Defects that if treated will reduce the asset's rate of deterioration
Priority 6 – Appearance/Usability	Defects that are a nuisance or unsightly

Source: TMR (2017).

3.4.7 LOSS OF ACCESS/FUNCTION

Originally two indicators, the loss of access and loss of function contributed to the operations risk dimension and refer to an event in which the entirety of the road segment is not functional, and therefore cannot provide access. This indicator was generated by calculating the percentage increase in the distance required to be travelled if a road is closed.

This category is based on the number of alternate routes available to travel to a destination, if a road is closed. This is a high-level assessment, using a route application such as Google maps. Table 3.6 shows the basis for establishing the ratings for loss of access/function. These percentage increases in distance travelled can be coarsened to reflect the reality of the increases in distances travelled in Queensland.

Table 3.6: Ratings for loss of access/function

Ratings	Loss of access/function
1	< 5% increase in distance travelled
2	5–10% increase in distance travelled
3	10–20% increase in distance travelled
4	> 20% increase in distance travelled
5	No alternate route

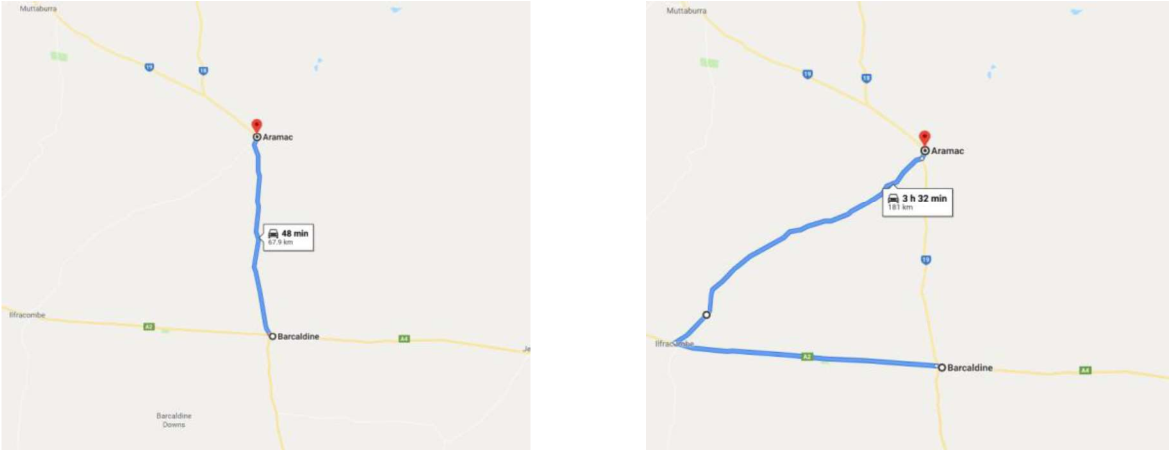
This approach to the ratings was applied to Road 573 as shown in Table 3.7 and

Figure 3.3. As can be seen from Table 3.7, this category does not apply a different rating to each road segement, rather, it assumes the whole road segemnt has been closed so the same redirected route option is applied.

Table 3.7: Example calculation of loss of access/function indicator for Road 573

Road section ID	Dist start	Dist end	Run no.	Traffic (AADT)	Road length	Alternate route length	Percentage increase in distance travelled	Rating
573	9.7	9.8	4693	180	67.9 km	181 km	166.57%	4
573	9.8	9.9	4693	180	67.9 km	181 km	166.57%	4
573	9.9	10	4693	180	67.9 km	181 km	166.57%	4
573	10	10.1	4693	180	67.9 km	181 km	166.57%	4
573	45.6	45.7	4693	180	67.9 km	181 km	166.57%	4
573	45.7	45.8	4693	180	67.9 km	181 km	166.57%	4
573	45.8	45.9	4693	180	67.9 km	181 km	166.57%	4
573	45.9	46	4693	180	67.9 km	181 km	166.57%	4

Figure 3.3: Example calculation of loss of access/function indicator for Road 573



(a) Road 573 Direct Route (b) Road 573 Alternate Route

Source: Google Maps

3.5 RISK DIMENSION RATING CATEGORIES

3.5.1 ACCESS VULNERABILITY

The access vulnerability dimension refers to the extent to which a road is susceptible to, or unable to cope with, the adverse effects of the environment and traffic. The indicators included in this category are the TMI, annual rainfall, traffic, terrain and slope stability.

The TMI and the annual rainfall represent the impacts of climatic events on the road infrastructure. These affect access as extreme weather events commonly cause road closures due to damage, and associated repairs. Further, the retention of water in the environment, caused by rainfall, can lead to network disruption due to flooding. Similarly, the slope stability is of importance regarding access, as unstable slopes can cause road closures.

Traffic contributes to access vulnerability as, with increasing traffic comes increasing road congestion, and higher road congestion reduces the accessibility service that a road can provide. In addition, traffic increases the wear on the road.

Terrain contributes to access vulnerability as roads on a level terrain provide a higher level of access service than those on a mountainous terrain. This is because roads on a mountainous terrain are more likely to be affected by rainfall, land subsidence, etc. As noted above, slope stability can impact on access to close the road with unstable slope material covering the road. Lastly, the combination of terrain and slope stability leads to the risk of landslides, which affects the availability of road for users.

The rating categories for indicators in the access vulnerability risk dimension category are outlined in Table 3.8. Each of these elements has been weighted to a value of one. Based on likelihood, the risk of flooding would rate more highly than the risk of landslides. Further, the risk of these environmental hazards is more likely than a loss of access based on damage to the road.

Table 3.8: Rating categories for the indicators that affect asset vulnerability

Indicators	Category/Rating					Weight
	V Low (1)	Low (2)	Fair (3)	High (4)	V High (5)	
TMI	−50 to −25	−24.9 to 0	0.1 to 30	30.1 to 60	60.1 to 100	0.25
Annual rainfall (mm)	< 250	251–500	501–800	801–1500	> 1 500	0.25
Traffic (AADT)	< 250	251–1 000	1 001–10 000	10 001 – 15 000	> 15 000	0.05
Traffic (%HV)	< 25	25–100	101–300	301–1 000	> 1 000	0.12

Indicators	Category/Rating					Weight
	V Low (1)	Low (2)	Fair (3)	High (4)	V High (5)	
Terrain class	Level	–	Rolling	–	Mountainous	0.17
Slope stability (ARL rating)	Inert (ARL = 5)	Stable (ARL = 4)	Mod. Stable (ARL = 3)	Mod. Unstable (ARL = 2)	Very unstable (ARL = 1)	0.17

3.5.2 STAKEHOLDERS AND COMMUNITY

The stakeholders and community dimension connects the pavement's performance and condition to the road users and general community. Pavement performance and condition should be assessed in response to road use and the pavement's interaction with the environment.

The PCI indicator accounts for several factors including roughness, rutting, cracking, RUL, surface age, and skid deficiency. Several of these elements are heavily influenced by environmental factors. For example, if the soils below the road do not drain properly, then the road is more susceptible to cracking. Further, these indicators can greatly affect the economic viability of a pavement, as they can lead to high maintenance costs in returning the pavement to its expected level of service.

The DCI measure assesses the ability of the sub-surface soils to deal with water. This, in turn, is the ability of the soils to cope with the environmental conditions of the area, and therefore, refers to the environmental sustainability of the asset.

As described, the impact of reactive soils refers to the shrinkage and expansion of soils in wet and dry environments, respectively. Similarly, this is an environmental impact and, therefore, contributes to the environmental sustainability of the asset.

The rating categories for indicators in the stakeholders and community risk dimension category are outlined in Table 3.9. Each of these elements has been weighted to a value of one. The risk factors here are based on the condition of the road, the PCI, and the amount of water that the road is exposed to due to the functionality of the drainage, measured by the DCI. A road in poor condition is susceptible to an increased rate of deterioration that is proportional to the amount of water in the immediate environment (i.e., if a road is cracked and subject to minor flooding, the subgrade is more likely to be damaged).

The DCI and the reactivity of the soils contribute equally to the risk of expansion in the soil. If the soils are reactive and drainage is poor, these factors will amplify one another. Conversely, the impact of poor drainage is reduced if the soils are non-reactive. The impact of these factors on this risk dimension are dependent on one another, and thus share equal contribution to the risk.

Table 3.9: Rating categories for the indicators that affect stakeholder & community

Indicators	Category/Rating					Weight
	V Low (1)	Low (2)	Fair (3)	High (4)	V High (5)	
Drainage condition index (DCI)	V Good (0% blocked +ve slope)	Good (1–10% blocked)	Fair (11–25% blocked)	Poor (26–50% blocked)	V Poor (> 50% blocked −ve slope)	0.25
Pavement condition index (PCI)	V Good (PCI = 0–1)	Good (PCI = 1.001–2)	Fair (PCI = 2.001–3)	Poor (PCI = 3.001–4)	V Poor (PCI = 4.001–10)	0.5
Reactive soil impact	Non-reactive dry	–	Non-reactive wet	Reactive dry	Reactive wet	0.25

3.5.3 SAFETY PERFORMANCE

The safety performance dimension of an asset refers to the ability of the asset to provide public safety and minimise harm to the environment. As the environment is covered by the access vulnerability dimension, this dimension mainly refers to public safety for this project.

As mentioned, the AusRAP indicator can provide safety ratings for roads, where roads are assigned a score from one star (least safe) to five stars (most safe). As AusRAP generates a safety rating for the road, based on several indicators, this covers most of the issues which need to be considered in this dimension. Table 3.10 provides the rating for the indicators for the safety performance dimension.

Table 3.10: Rating Categories for the Indicators that affect Safety Performance

Indicators	Category/Rating					Weight
	V Low (1)	Low (2)	Fair (3)	High (4)	V High (5)	
Safety (AUSRAP)	V Good (AusRAP = 4–5)	Good (AusRAP = 3–3.9)	Fair (AusRAP = 2–2.9)	Poor (AusRAP = 1–1.9)	V Poor (AusRAP = 0–0.9)	1

3.5.4 LEGISLATIVE COMPLIANCE – IMPACT POTENTIAL

The legislative compliance dimension refers to the level to which an asset conforms to the regulations outlined by the TMR standards and specifications. Differing from access vulnerability, stakeholders and community, and safety performance, this dimension is quite qualitative in nature. Table 3.4 shows the roughness intervention limits used to determine compliance to roughness conditions. In addition, this category includes the priority of defects, as specified by TMR's corporate priorities in routine maintenance.

Table 3.11 provides the ratings for the indicators for the legislative compliance dimension. Each of these elements has been weighted to a value of one. Both of these indicators are related to the condition of the road, and as they represent deterioration or damage in the pavement, they were weighted equally.

Table 3.11: Rating categories for the indicators that affect legislative compliance

Indicators	Category/Rating					Weight
	V Low (1)	Low (2)	Fair (3)	High (4)	V High (5)	
Roughness compliance (% meeting NAASRA roughness limit)	100% compliant	> 90% compliant	90–80% compliant	80–70% compliant	< 70% compliant	0.5
Priority of defects	No recorded defects	Assigned corporate priority of 6 (appearance/ usability)	Assigned corporate priority of 4 or 5 (legislative or preventative)	Assigned corporate priority of 2 or 3 (ordered works or safety)	Assigned corporate priority of 1 (hazard)	0.5

3.5.5 OPERATIONS – IMPACT POTENTIAL

The operations impact potential dimension refers to the indicators that will affect the asset's ability to operate to a normal functional standard. Differing from access vulnerability, stakeholders and community, and safety performance, the loss of access/function indicator can be quantified as noted in Section 3.4.7. Table 3.12 provides the ratings for the indicator for the Operations dimension.

Table 3.12: Rating categories for the indicator that affect operations

Indicator	Category/Rating					Weight
	V Low (1)	Low (2)	Fair (3)	High (4)	V High (5)	
Loss of access/function	< 5% increase in distance travelled	5–10% increase in distance travelled	10–20% increase in distance travelled	> 20% increase in distance travelled	No alternative access route	1

3.6 CALCULATION OF RESIDUAL RISK

As detailed above, there are five risk dimensions associated with the PRRM which include:

- access/vulnerability of the road asset due to hazards
- the impact of hazards on stakeholders and the community
- the impact of hazards on the safety performance of the asset
- the impact of hazards on the legislative compliance of the asset
- the impact of hazards on the operations of the asset.

Each of these is weighted prior to being included in the calculation. The weightings are outlined in Table 3.13. The potential for hazards involved with the indicators as part of the access and vulnerability risk dimension are the most prevalent, as these indicate whether the road is useable. Further, usability is also greatly impacted by the impact potential of the operations of the road. Therefore, these two categories have been given the second highest weightings. Safety performance has been given the highest weighting, as road fatalities have the greatest social impact. Roads need to be safe for road users to travel on, and therefore this is a high priority in estimating residual risk. The remaining categories are comprised of indicators which are aspects of physical factors affecting the road. These are aspects which can be managed as part of routine maintenance. Therefore, these have been weighted lower.

Table 3.13: Combination of rating categories

Risk dimension	Index weight[1]	Indices	Variable name
Access/vulnerability	$w_1 = 0.25$	Hazard potential	AV
Stakeholders and the community	$w_2 = 0.09$	Impact potential	SC
Safety performance	$w_3 = 0.33$	Impact potential	SP
Legislative compliance	$w_4 = 0.08$	Impact potential	LC
Operations	$w_5 = 0.25$	Impact potential	O

Note: 1. Weighting is an initial assessment.

The PRRM results are calculated by summing the index weights multiplied by each risk dimension, as shown in Equation 2, which can have a minimum value of 1 and a maximum value of 5.

$$Pavement\ Residual\ Risk = w_1 * \mathrm{AV} + w_2 * \mathrm{SC} + w_3 * \mathrm{SP} + w_4 * \mathrm{LC} + w_5 * \mathrm{O} \quad (2)$$

3.7 OTHER CONSIDERATIONS IN THE RESIDUAL RISK

The residual risk is a combination of many elements which are generally considered by road asset managers, as they cause major network disruption issues which affect the sustainability of an asset. Many of the indicators which have been discussed as part of the development of this project, are those which are influenced by the information which has been included.

A key concern for road asset managers is the exposure to legal redress caused by management practices. This is something which has been included in the PRRM as part of the priority of defects indicator. As mentioned, within TMR's Routine Maintenance Guidelines, there is a provision for the classing of defects into corporate priorities. Defects which are classed as a priority of 4, are defects that are required to be repaired by legislation.

A further concern is that defects which are unrepaired will not meet the technical levels of service set in place by TMR, or the customer-based levels of service which are expected by the road user. Currently within the NACoE Program, Project A34 *Customerbased Levels of Service in Road Maintenance*, is seeking to address these inconsistencies. Once A34 is complete, TMR will have the ability to use the relationships identified to build a levels of service framework, which could be used in conjunction with the residual risk framework.

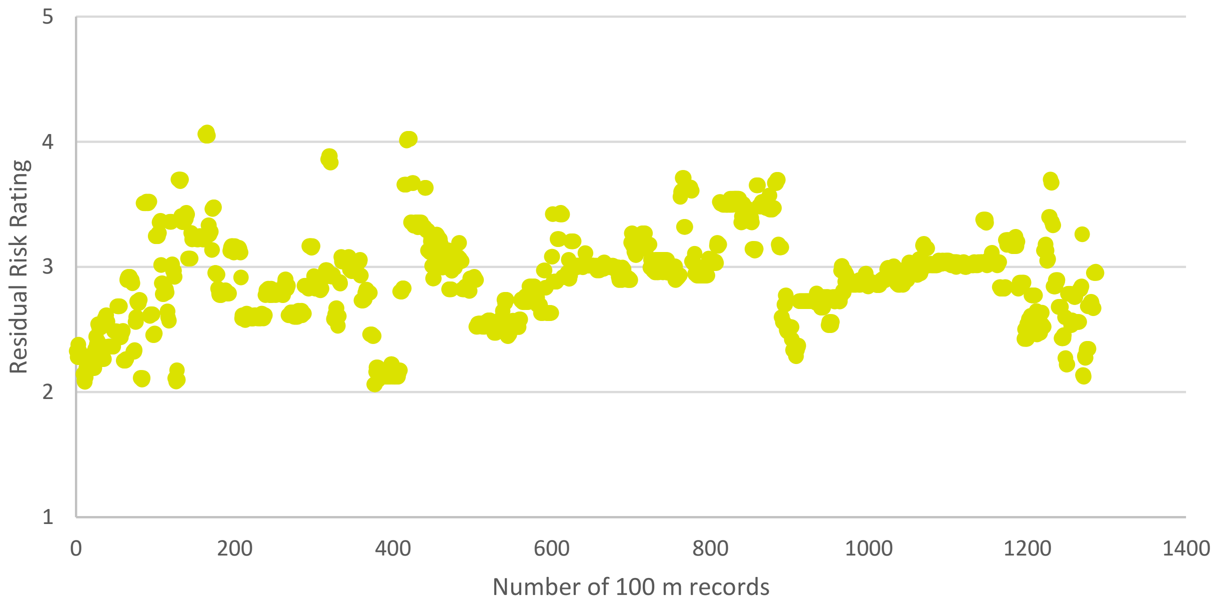
4 PRESENTATION OF PRELIMINARY RESULTS OF PRRM

This section details the PRR score estimates based on the TMR road segment data set used for NACoE A26 (Martin & Hore-Lacy 2017). The PRR score as defined in Section 3.1, was estimated using the indicators described in Section 3.3 and Section 3.4, which were used to calculate the risk dimensions described in Section 3.5. As noted, there are some indicators which required further evaluation and replacement due to the challenges with obtaining the data as outlined in Section 3.7.

4.1 PAVEMENT RESIDUAL RISK RESULTS

Figure 4.1 provides an overview of the weighted PRR score rating estimates for the A26 dataset that was field rated. This graph presents the number of 100 m road sections which have been assessed, which fall into each residual risk category. As can be seen from the graph most of the residual risk values fall between 2 and 4.

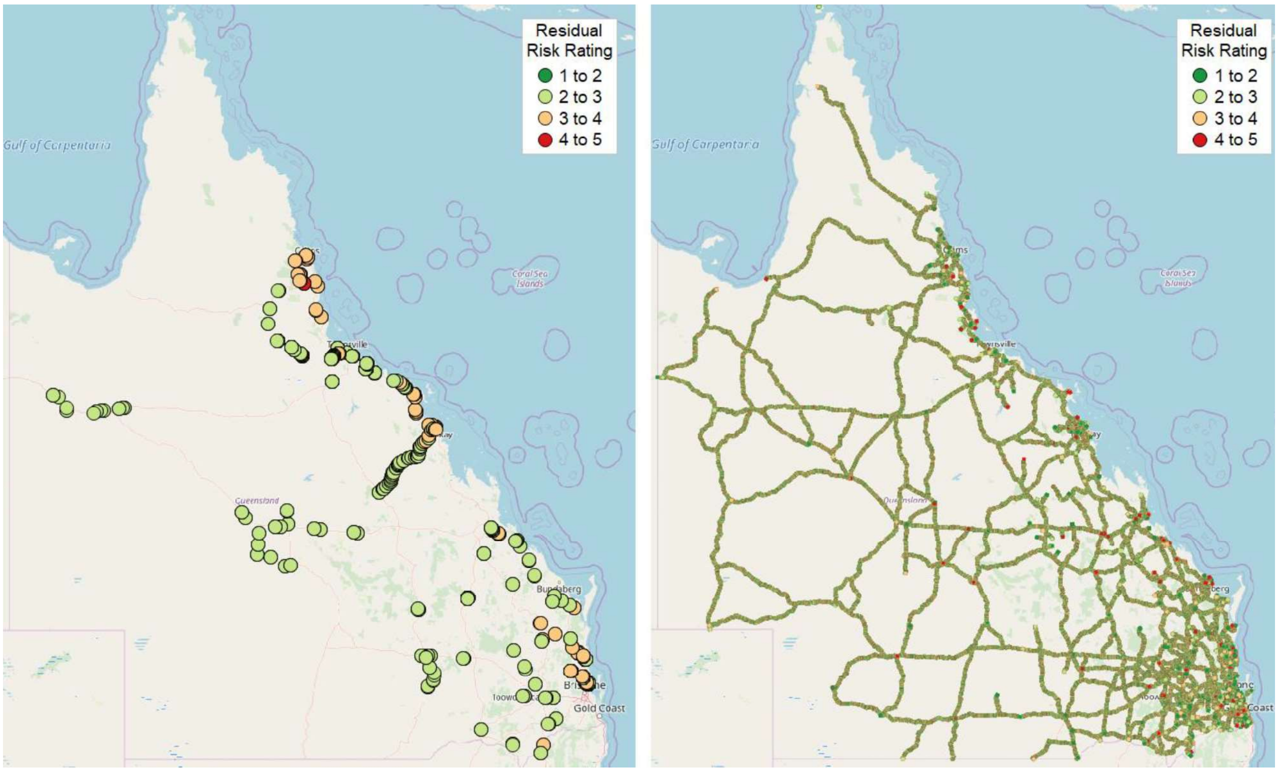
Figure 4.1: Pavement residual risk model weighted results



4.2 VISUAL REPRESENTATION OF PRRM RESULTS

Figure 4.2 provides a visual map representation of the PRR score estimates from the analysis, based on the weighted PRR score estimates to display the full range. Due to the 'scattered' and limited nature of the dataset, the results were difficult to present visually as shown in Figure 4.2(a). Figure 4.2(b) has been 'filled-in' with the sampled PRR score estimates. This expansion was undertaken for demonstration purposes only.

Figure 4.2: Map of Queensland showing the location of the residual risk sites with coloured risk ratings



(a) Results in dataset (b) Results repeated to fill out entire network

Source: TMR

4.3 COMPARISON OF RESULTS BETWEEN DISTRICTS

The mean weighted PRR scores were estimated for each district. Another assessment of overall residual risk, such as an advanced maximum, could be used. As can be seen in Table 4.1, the average conceals much of the variation in the residual risk data. For example, it will hide the road segments with a very high residual risk value, if the majority of the other road segments are low.

Table 4.1: Mean residual risk by district

District	Mean weighted residual risk
Central West District	2.36
Darling Downs District	2.84
Far North District	2.94
Fitzroy District	2.64
Mackay Whitsunday District	2.92
Metropolitan District	3.01
North Coast District	3.23
North West District	2.48
Northern District	2.93
South West District	2.58
Wide Bay Burnett District	2.75

Therefore, histograms were generated for each district to show the distribution of the PRR scores (weighted residual risk) and are shown in Figure 4.3 to Figure 4.13. These histograms show the number of 100 m segments which fall into each of the residual risk categories (1 to 5) for each district.

Figure 4.3: Histogram of PRR for Central West District

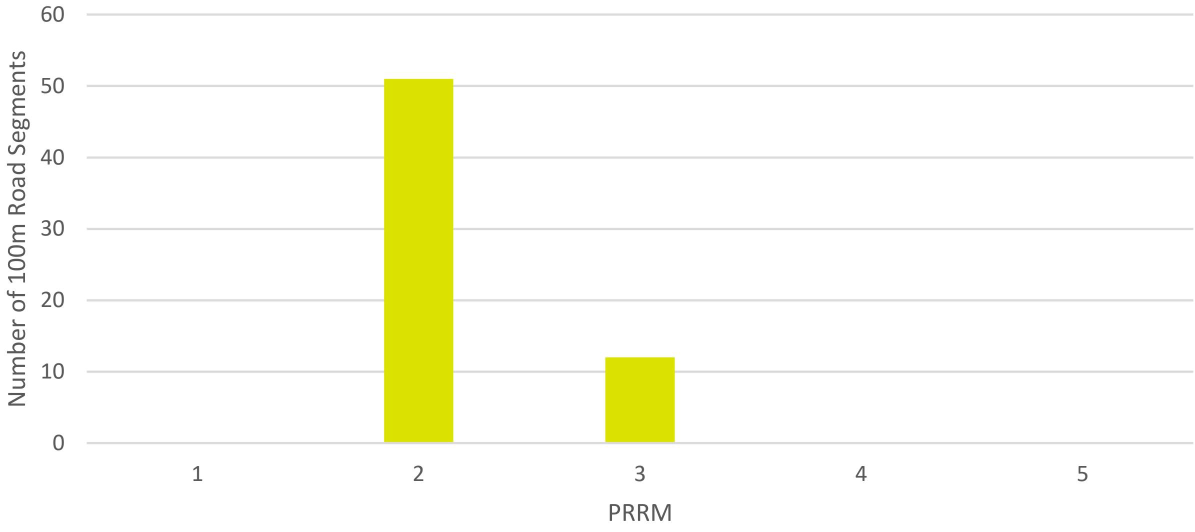


Figure 4.4: Histogram of PRR for Darling Downs District

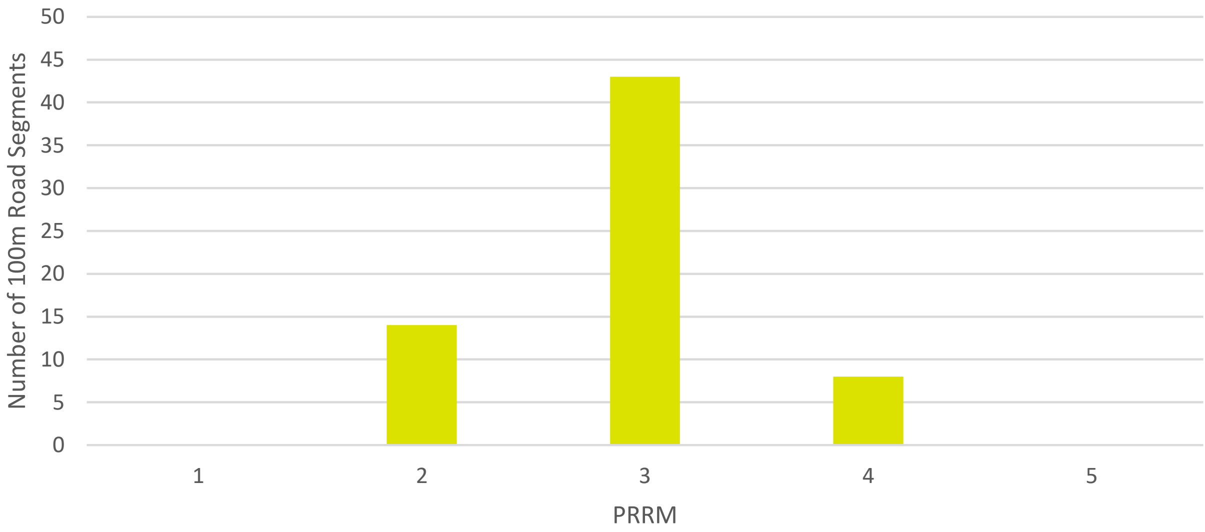


Figure 4.5: Histogram of PRR for Far North District

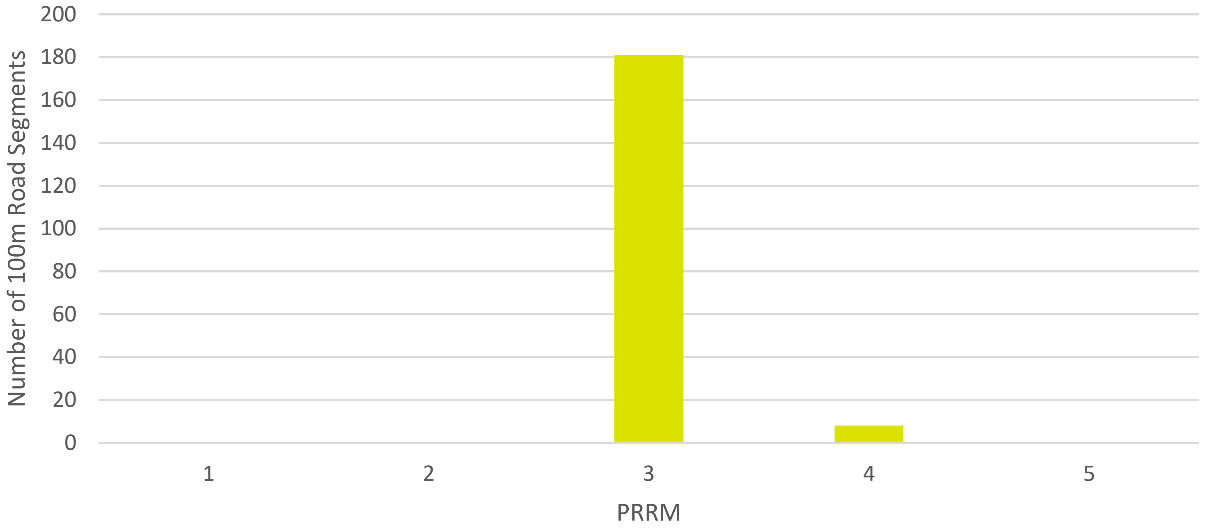


Figure 4.6: Histogram of PRR for Fitzroy District

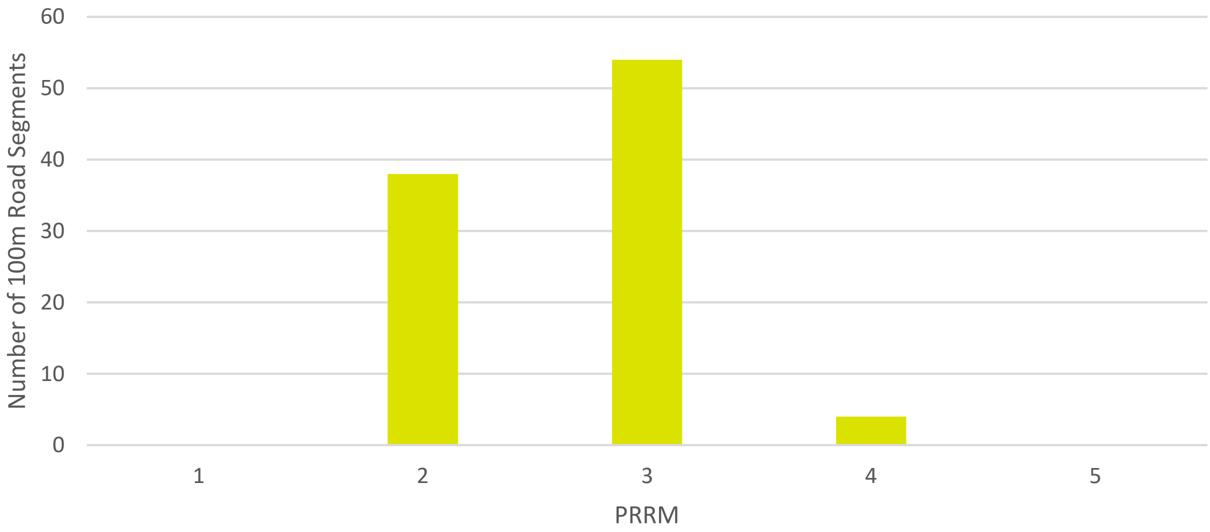


Figure 4.7: Histogram of PRR for Mackay Whitsunday District

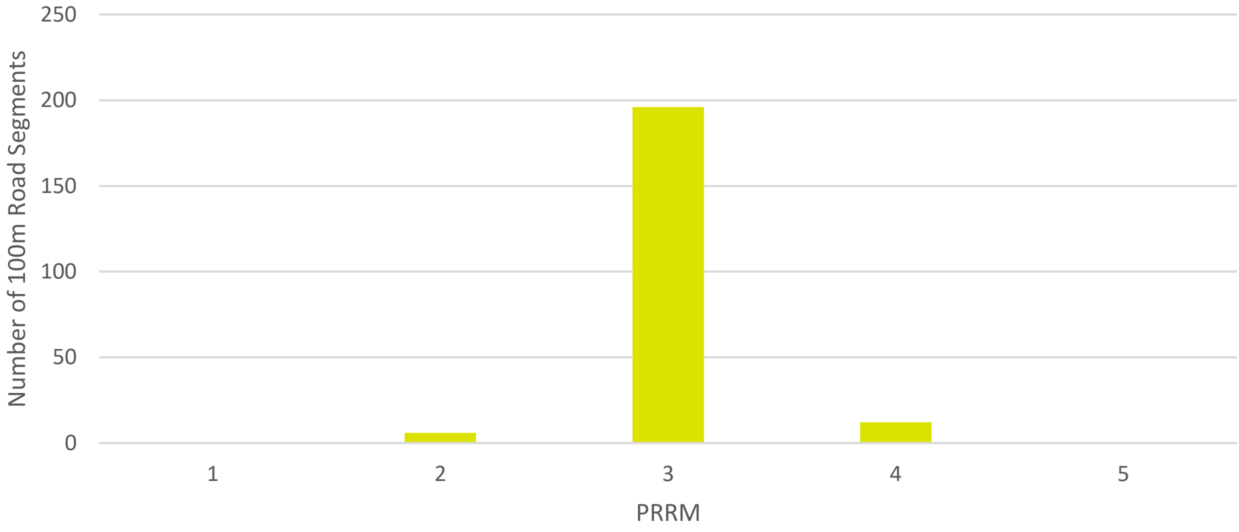


Figure 4.8: Histogram of PRR for Metropolitan District

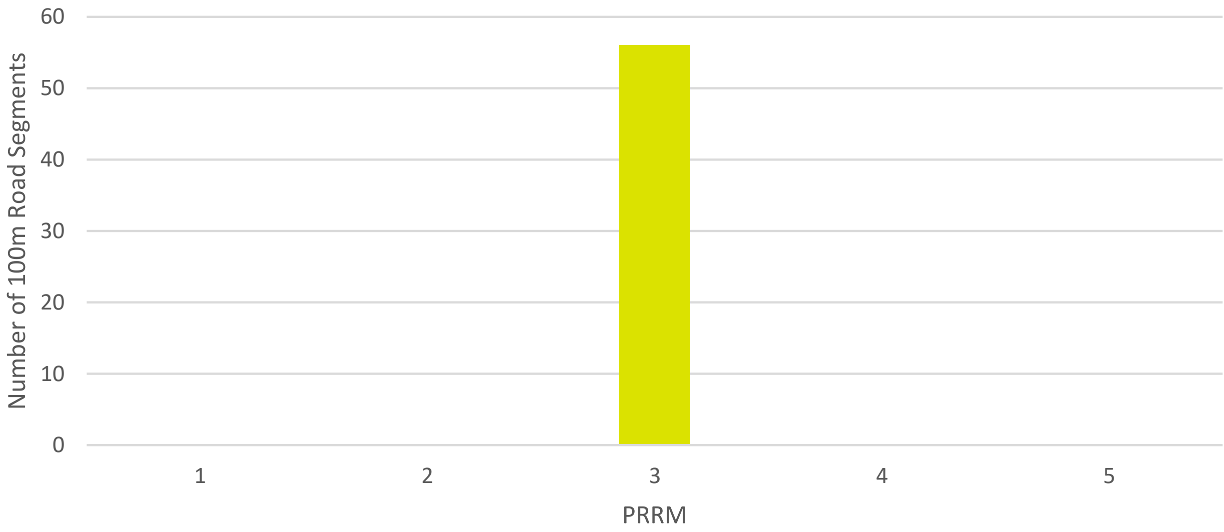


Figure 4.9: Histogram of PRR for North Coast District

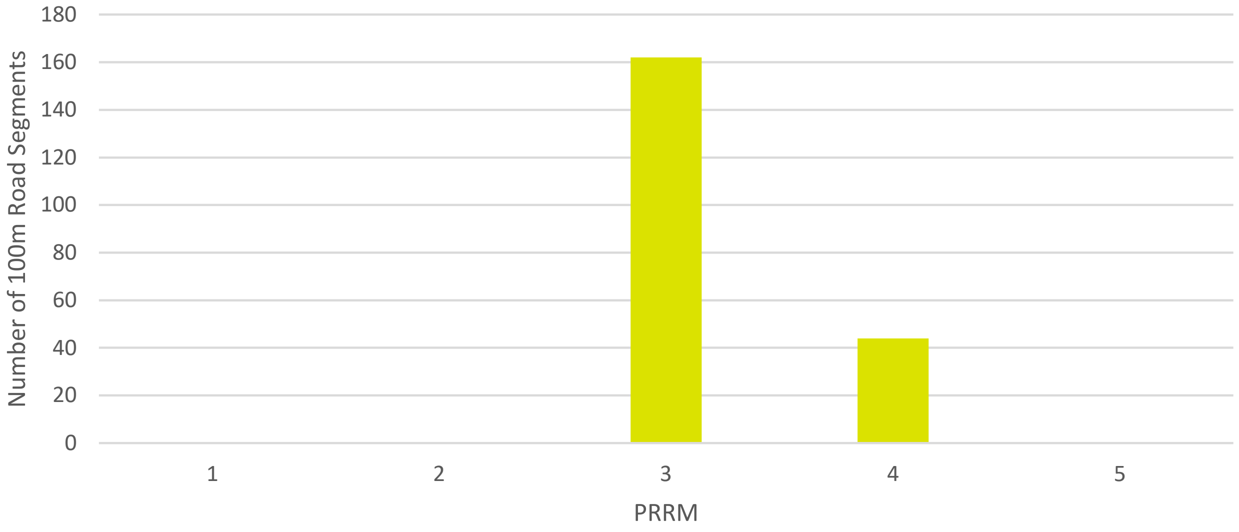


Figure 4.10: Histogram of PRR for Northern District

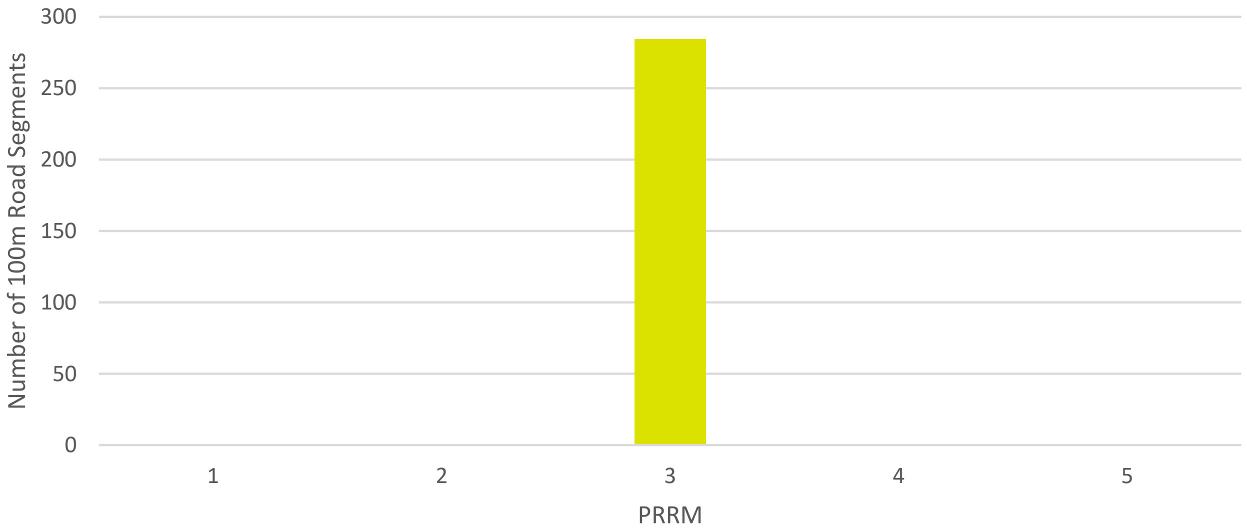


Figure 4.11: Histogram of PRR for North West District

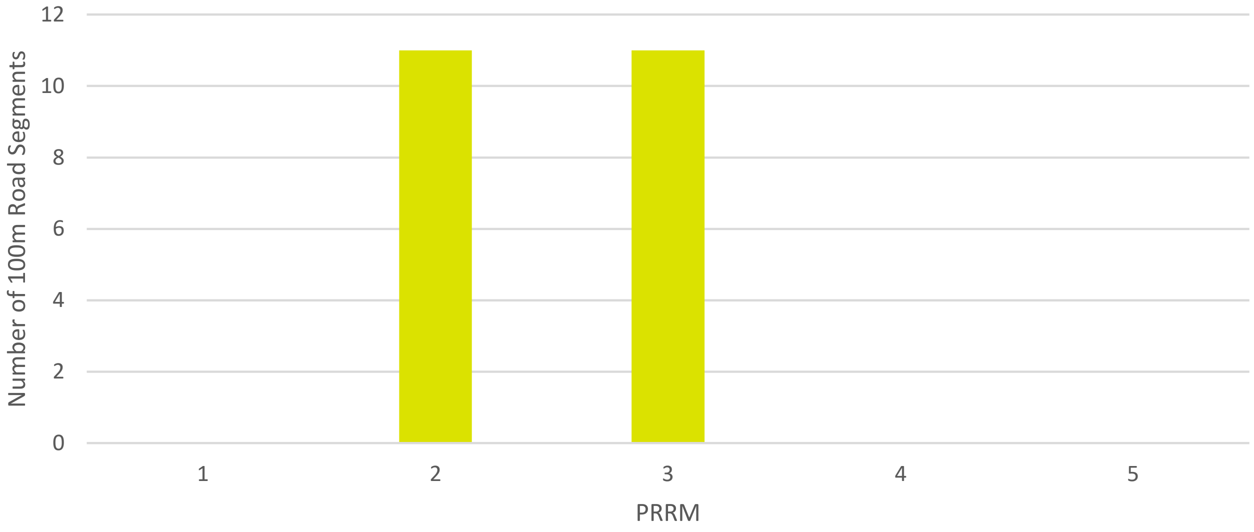


Figure 4.12: Histogram of PRR for South West District

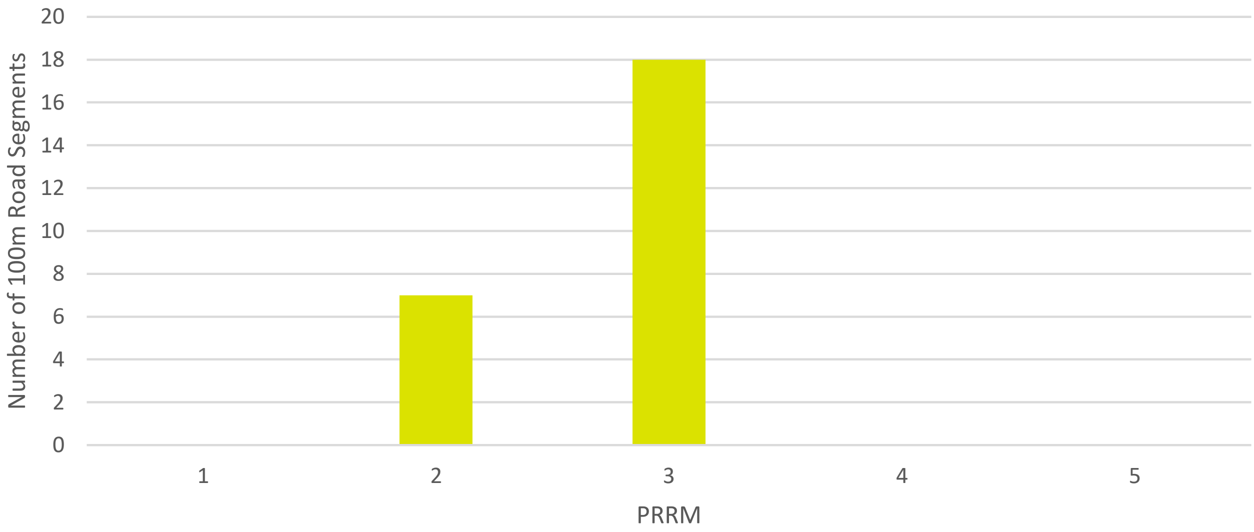
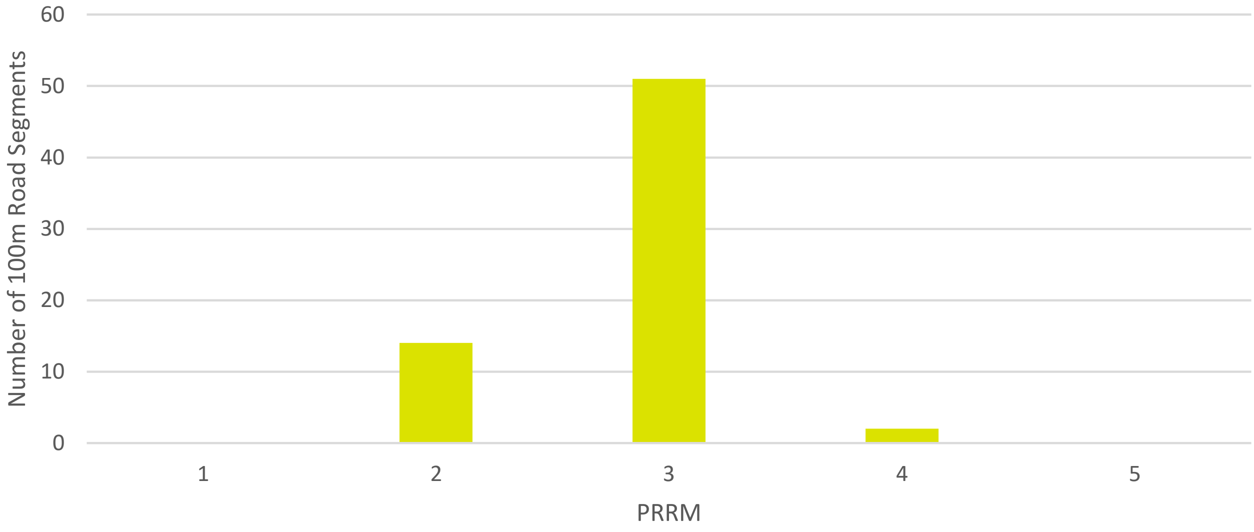


Figure 4.13: Histogram of PRR for Wide Bay Burnett District



5 CONCLUSIONS

5.1 SUMMARY

The development of an analytical hierarchical process (AHP) as the basis of an approach for objectively estimating values of residual risk applied to road segments shows promising potential for the allocation of annual asset management program funding. The approach outlined in this report shows the potential to estimate values on the relative residual risks associated with road segments located in different geographical and geological areas subject to differences in traffic and environmental impacts. Critically, the approach relies on an extensive and well-maintained database from the road agency.

Estimates of the pavement residual risk were using the PRRM for road segments that were field rated under NACoE Project A26 (Martin & Hore-Lacy 2017) for the districts from which they were sampled. The preliminary results were weighted to show a range of representative values across the indicators and risk dimensions. These results have been presented both graphically and spatially.

5.2 CHALLENGES

There have been several challenges noted in collating the data required to quantitatively assess all the indicators requested as part of this project. Several of the issues were overcome through the assistance of the Road Asset Data team, and other members of TMR staff who were able to assist in acquiring and managing the required datasets.

However, several of the indicators requested were not specific types of data which TMR records, as these indicators were more qualitative in nature. The issue with these categories is that these tend to be flow-on effects from other impacts, which are already included as indicators. Therefore, there is the potential to double-up on datasets. It was determined that these indicators would be excluded from the PRRM.

5.3 NEXT STEPS

Residual risk estimates can be made either for a sample of road segments, as was done in this report, or a complete road network of defined road segments provided sufficient and accurate data is available for all risk dimensions. Stage 3 of this project will comprise an assessment of the entire TMR state road network. The outcomes of estimating the PRR scores for the whole of TMR's arterial road network will be documented in a summary report. The final stages of this project will include a fully documented report, including a spreadsheet calculator, which will enable TMR to apply the residual risk approach routinely to the TMR road network.

5.4 RECOMMENDATIONS FOR FURTHER RESEARCH

This project is currently planned to finish after Stage 3. Consequently, it is recommended that the residual risk models for ITSRRM and SRRM be undertaken as further research in part of Stage 4 of this project to estimate residual risks for ITS and structures assets, respectively. These two models would be assessed using a similar AHP methodology to what was used for developing the PRRM.

Figure 5.1 and Figure 5.2 outline the proposed approach to estimating the residual risk using the ITSRRM and SRRM models, respectively.

Figure 5.1: Intelligent transport systems (ITS) residual risk model (ITSRRM)

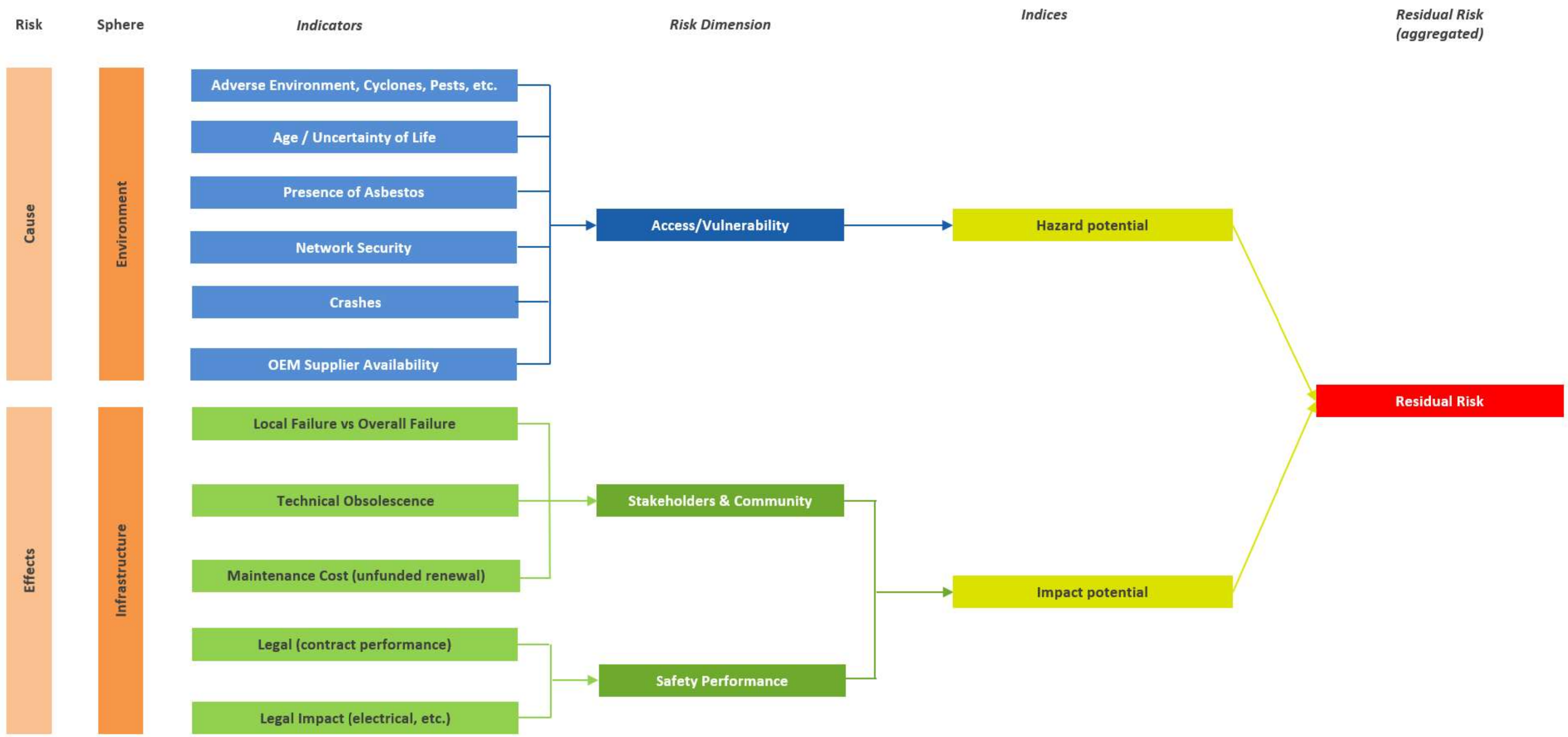
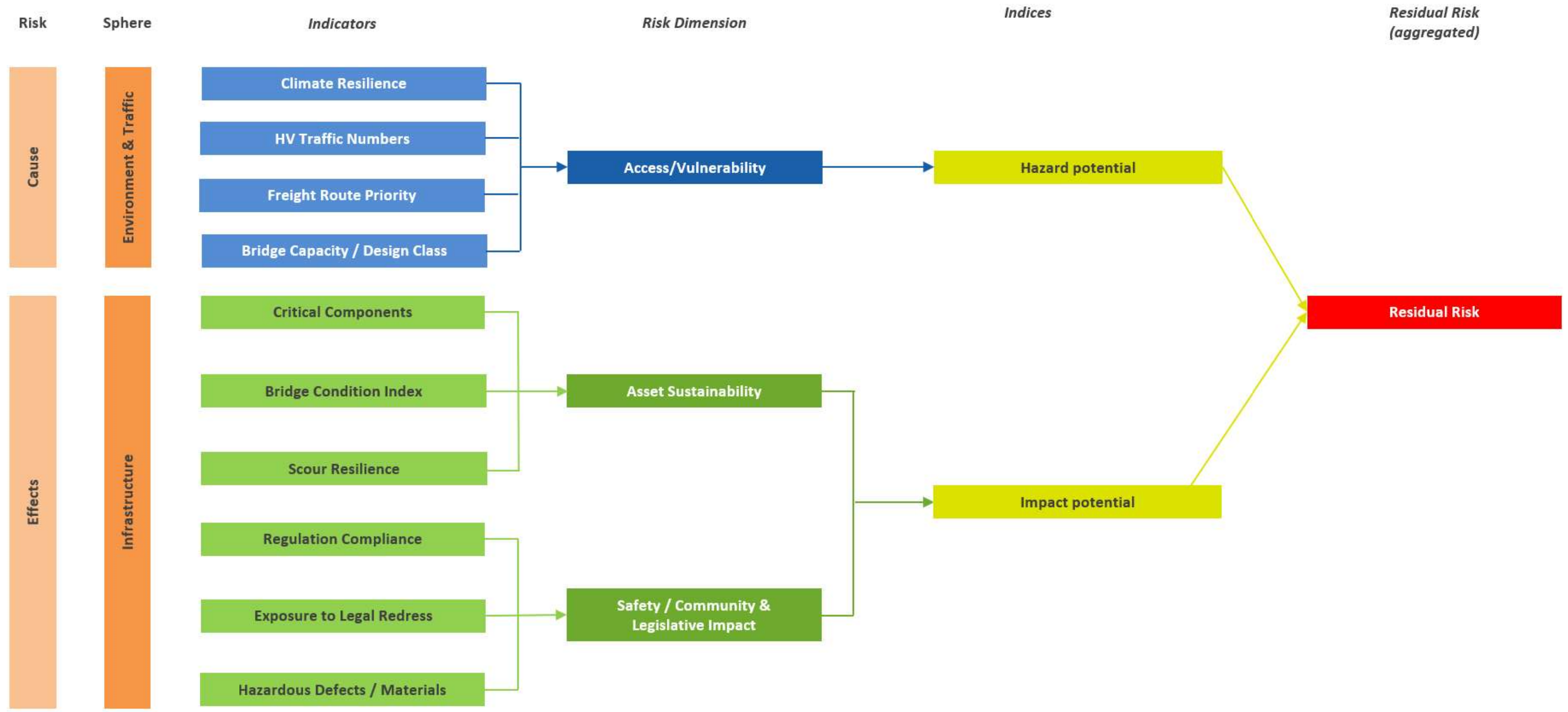


Figure 5.2: Structures residual risk model (SRRM)



REFERENCES

Australian Automobile Association 2013, *Australian Road Assessment Program (AusRAP) star rating of Australia's national; network of highways*, AAA, Canberra, ACT.

Auerbach, M & Herrmann, C 2014, 'Adaptation of the road infrastructure to climate change', *Transport research arena proceedings*, Paris, France, 10 pp.

Austroads 2004, *Impact of climate change on road infrastructure*, AP-R243-04, Austroads, Sydney, NSW.

Austroads 2008, *Technical basis of the Austroads design procedures for flexible overlays on flexible pavements*, AP-T99-08, Austroads, Sydney, NSW.

Austroads 2011, *Network performance indicators – next generation*, AP-T176-11, Austroads, Sydney, NSW.

Austroads 2015, *Austroads glossary of terms*, AP-C87-15, Austroads, Sydney, NSW.

Beecroft, A & Peters, E 2017, *Accounting for life-cycle costing implications and network performance risks of rain and flood events (2013/14 – 2015/16),* project A4, National Asset Centre of Excellence (NACoE), Brisbane, Qld.

Brown, LC 2002, *Statistics for environmental engineers*, 2nd edn, CRC Press, Boca Raton, FL, USA.

COST 2008, *The way forward for pavement performance indicators across Europe*, action 354, COST (European Cooperation in the field of Scientific and Technical Research), Austrian Transportation Research Association, Vienna, Austria.

Deighton Associates Limited 2014, *Deighton's Total Infrastructure Management System,* (dTIMS), software, version 9, Deighton Associates Limited, Canada.

IPWEA 2015, *International Infrastructure Maintenance Manual*, (IIMM), 5th edn, Institute of Public Works Engineering Australia, Sydney, NSW.

Kadar, P & Sen, R 2016*, Incorporating uncertainty in PMS modelling - phase 1 (year 1 – 2013/14 and year 2 – 2014/15)*, project A5, National Asset Centre of Excellence (NACoE), Brisbane, Qld.

Klose, M 2017, 'Resilience and assessment of climate risk: experiences from road infrastructure in Germany', *paper presented at the PIARC workshop on International Climate Change Adaptation Framework for Road Infrastructure, Cuba, Technical Committee 1.4, PIARC, France*.

Lee, J 2016, 'Benefit of traffic speed deflectometer data in pavement analysis', contract report 010554, prepared for Queensland Department of Transport and Main Roads, ARRB Group, Vermont South, Vic.

Martin, T & Hore-Lacy, W 2017, *Incorporation of the pavement risk score into the pavement condition index*, project A26, National Asset Centre of Excellence (NACoE), Brisbane, Qld.

Nicolosi, V, Augeri, MG & Soccodato, 2019, 'Multi-objective approaches to cross-asset resource allocation in transportation asset management', *Routes/Roads,* no. 381, pp. 37-44.

Queensland Department of Transport and Main Roads 2017, *Routine maintenance guidelines*, TMR, Brisbane, Qld.

Thornthwaite, CW 1948, 'An approach toward rational classification of climate', *Geographical Review*, vol. 38, no. 1, pp. 55-94.

APPENDIX A ROAD LIST

Table A.1 details the roads which were included in the analysis for this study. As mentioned, this road list is based on the roads which were analysed as part of NACoE Project A26. Some roads from the A26 road list were removed due to lack of available data in the indicator categories required for this study.

Table A.1: TMR state-controlled roads included in study, sorted by district

Districts	Road name	Road section ID	PRR score
Central West District	Barcaldine – Aramac Road	573	2.28–2.38
	Isisford – Ilfracombe Road	715	2.08–2.29
	Isisford – Blackall Road	716	2.19–2.54
	Landsborough Highway (Barcaldine – Longreach)	13E	2.26–2.61
	Landsborough Highway (Longreach – Winton)	13F	2.36–2.36
	Capricorn Highway (Emerald – Alpha)	16C	2.49–2.69
	Capricorn Highway (Alpha – Barcaldine)	16D	2.25–2.49
Darling Downs District	Gatton – Helidon Road	314	2.87–2.92
	Toowoomba– Cecil Plains Road	324	2.32–2.6
	Oakey – Cooyah Road	417	2.71–2.74
	Chinchilla – Wondai Road	426	2.1–2.11
	Malanda-Atherton Road	645	3.51–3.52
	Cunningham Highway (Ipswich-Warwick)	17B	2.46–2.62
	Warrego Highway (Ipswich-Toowoomba)	18A	3.02–3.37
	Warrego Highway	18D	2.55–2.87
	New England Highway (Warwick – Wallangarra)	22C	2.92–3.36
	Leichhardt Highway (Miles – Goondiwindi)	26C	2.09–2.17
Far North District	Bruce Highway (Ingham-Innisfail)	10N	3.36–3.7
	Bruce Highway (Innisfail-Cairns)	10P	3.07–3.07
	Captain Cook Highway	20A	3.22–3.27
	Palmerston Highway	21A	3.22–4.08
	Kennedy Highway (Cairns-Mareeba)	32A	3.26–3.33
	Kennedy Highway (Mareeba-Ravenshoe)	32B	3.14–3.48
	Kennedy Highway (Mt Garnet-The Lynd)	32D	2.94–2.95
	Charters Towers – Lynd	98C	2.58–3.17
	Kennedy Developmental Road	99A	2.93–2.98
Fitzroy District	Millaa-Malanda Road	641	3.84–3.89
	Bruce Highway (Gin Gin – Benaraby)	10D	2.53–2.94
	Bruce Highway (Benaraby – Rockhampton)	10E	2.73–3.08
	Carnarvon Highway	24E	2.45–2.77
	Leichhardt Highway (Westwood – Taroom)	26A	2.06–2.83
Mackay Whitsunday District	Bruce Highway (Mackay-Proserpine)	10H	3.12–4.02
	Bruce Highway (Proserpine-Bowen)	10J	2.82–3.26
	Bruce Highway (Bowen-Ayr)	10K	2.81–3.19
	Peak Downs Highway (Clermont-Nebo)	33A	2.45–2.84
	Peak Downs Highway (Nebo – Mackay)	33B	2.63–3.43
Metropolitan District	Brighton Redcliffe Road	122	2.97–3.11
North Coast District	Redcliffe Road	120	2.9–3.27
	Maroochydore Road	136	2.9–3.06
	Eumundi Kenilworth	484	3.32–3.71

Districts	Road name	Road section ID	PRR score
	Bruce Highway	10A	2.93–3.55
	D'aguilar Highway	40A	3.13–3.7
	D'aguilar Highway	41B	3.13–3.7
North West District	Flinders Highway	14E	2.56–2.9
	Barkly Highway	15A	2.29–2.52
	Barkly Highway	15B	2.29–2.52
Northern District	Ayr – Dalbeg	545	2.68–2.79
	Ross River Road	612	2.54–2.76
	Ayr – Townsville	10L	2.8–3.01
	Townsville – Ingham	10M	2.97–3.01
	Flinders Highway	14A	2.56–2.9
	Hervey Range Road	83A	2.83–3.38
South West District	Inglewood – Texas Road	231	2.43–2.5
	Warrego Highway	18E	2.55–2.87
	Carnarvon Highway	24B	2.45–2.77
	Carnarvon Highway	24C	2.45–2.77
Wide Bay Burnett District	Maryborough – Hervey Bay Road	163	3.13–3.18
	Murgon – Gayndah Road	439	3.05–3.4
	Gympie – Brooloo Road	483	3.33–3.7
	Bruce Highway (Gympie – Maryborough)	10B	2.85–2.9
	Bruce Highway (Maryborough – Gin Gin)	10C	2.43–2.68
	Isis Highway (Bundaberg – Childers)	19A	2.22–2.6
	Isis Highway (Childers – Biggenden)	19B	2.79–2.79
	Burnett Highway (Gayndah – Monto)	41C	2.54–2.57
	Burnett Highway (Biloela – Mt. Morgan)	41E	2.56–2.76
	Wide Bay Highway	44A	2.82–3.26
	Bunya Highway (Dalby – Kingaroy)	45A	2.12–2.29
	Bunya Highway (Kingaroy – Goomeri)	45B	2.33–2.69
	Dawson Highway (Gladstone – Biloela)	46A	2.67–2.96

APPENDIX B PAVEMENT CONDITION INDEX

This appendix provides information on the Pavement Condition Index (PCI). This information is extracted from NACoE Project A26 *Incorporation of the Pavement Risk Score into the Pavement Condition Index* (Martin & Hore-Lacy 2017).

B.1 DESCRIPTION AND APPLICATION

The need for representing the overall condition of an asset in a succinct and effective manner has always been recognised from the early days of asset management. The overall condition was widely used in management and technical reports as well as for supporting funding requests.

The PCI described here represents a formulation of a general descriptor of the asset condition based on the combination of local experience and the European Cooperation in Science and Technology (COST) Action 354 (COST 2008).

The condition of an asset may be described by many parameters. These can be physical measures or index (typically rated) values. To compare or aggregate the various parameters, they must be on the same scale, which is best achieved by normalising or formulating index values. To distinguish the normalised index parameters from measured parameters, they are referred to as condition indices (CI).

The CI offers several advantages, such as:

- It is easily understandable by non-expert stakeholders: a simple scale or even a 'star rating' conveys the condition clearly without demanding any subject knowledge.
- The index value can be converted back to a physical measure, so the content remains accessible for technical requirements.
- The index value expresses the desired and actual level of service (LOS); hence it is a vehicle for measuring performance.

In a pavement management system (PMS) the CI can be used for setting intervention trigger levels and can have a direct impact on treatment selection. This is the most direct way to link agency policies to work program development. At the same time, the budget necessary to achieve the desired LOS can be easily determined.

The combined index (in this case the PCI) can be used as an optimisation target, e.g., to deliver the best overall condition with the available budget.

The following Section is a summary of the key steps in the development and implementation of the PCI incorporated within the Deighton's Total Infrastructure Management System (dTIMS) (Deighton Associates Limited 2014) established for the Queensland Department of Transport and Main Roads (TMR) in South East Queensland.

The scale adopted is consistent with the International Infrastructure Maintenance Manual (IIMM) (IPWEA 2015), and the overall approach is also consistent with the review of network performance indicators for Austroads (2011), where both individual and combined performance indicators are considered.

B.2 FORMULATION OF A CONDITION INDEX

Definition: Condition index (CI): one property (e.g. roughness) expressed as an index number on a fixed scale.

A CI is calculated by converting the measured parameter to an index value. There are several ways to transform a measured value from one scale to another. For estimating the CI, a series of linear transformations was selected to reflect the value judgement of both the asset manager and the asset owner.

Performance indicators may be formed by using measured or rated parameters, and ought to meet the following requirements:

- All condition indicators should be on the same scale; the identical scale assists in interpreting and communicating the condition.
- All condition indicators should go in the same direction, e.g., the maximum representing the worst and the minimum representing the best condition.
- A CI should express a value judgement suitable for the given circumstances and parameters, e.g., what is 'good' in one instance may only be 'fair' under different conditions.
- A CI should have a direct link from top management level to operational level, i.e., it must exercise real control over performance. If the outcome of an operation (e.g., maintenance work) cannot be controlled or influenced by a CI, the CI is ineffective as a management tool.

The selected scale of the CI and PCI for the South East Queensland dTIMS is 1–5, where 5 represents a very poor condition and 1 represents a very good condition.

B.3 REMAINING USEFUL LIFE (RUL) INPUT INTO PCI ESTIMATION

B.3.1 DEFLECTION, D_0, AND TRAFFIC LOAD CAPACITY, CAP, RELATIONSHIP (RL3)

The following traffic capacity relationships (Equation A1 to Equation A5) using D_0 and D_{200} (from iPAVe measurements) were extracted from Austroads (2008) for asphaltic (AC) and granular (GN) pavement bases. It should be noted that these capacity relationships were for the design of granular and asphaltic overlays on in-service pavements.

$$CAP_{AC} = [\, 3.1077 / (D_0 - D_{200})\,]^{4.415} \quad \text{for } WMAPT \leq 25 \qquad \textbf{A1}$$

$$CAP_{AC} = [\, 2.6898 / (D_0 - D_{200})\,]^{5.105} \quad \text{for } WMAPT > 25 \qquad \textbf{A2}$$

$$CAP_{GN} = 10^{(3.666 - D_{0\,95})/0.422} \quad \text{for } D_{0\,95} \geq 1.134 \qquad \textbf{A3}$$

$$CAP_{GN} = [\, 91.2 / (D_{0\,95} - 0.731)\,]^{1/0.3924} \quad \text{for } 0.8 \leq D_{0\,95} \leq 1.134 \qquad \textbf{A4}$$

$$CAP_{GN} = 100{,}000{,}000 \quad \text{for } D_{0\,95} \leq 0.8 \qquad \textbf{A5}$$

where

WMAPT	=	weighted mean annual pavement temperature (^{0}C)
D_0	=	iPAVe (TSD) maximum deflection (mm)
$D_{0\,95}$	=	95th percentile of maximum estimated iPAVe deflection, D_0 (mm)
D_{200}	=	estimated mean iPAVe deflection 200 mm from the maximum iPAVe deflection (mm)

For granular pavements, the iPAVe D_0 was converted to an FWD D_0 via the following relationship in Equation A6 (Lee 2016) as Equations A3, A4 and A5 are based on FWD deflections:

$$D_{0\text{-FWD}} = 0.9 \times D_{0\text{-iPave}} + 13.8 \quad \textbf{A6}$$

The 95th percentile of the maximum deflection, D_0, can be estimated via the coefficient of variation, COV, for the Austroads long-term pavement performance (LTPP) and long-term pavement performance maintenance (LTPPM) sites which was found to be 40%. The 95th percentile of a cumulative distribution, in this case the D_0 distribution, is as follows in Equations A7 and A8 (Brown 2002):

$$D_{0\ 95} = 1.645 \times \sigma + \mu \quad \textbf{A7}$$

$$D_{0\ 95} = 1.658 \times \mu \quad \textbf{A8}$$

where

COV = σ / μ

σ = standard deviation of the deflection, D_0, distribution for each 100 m segment

= COV $\times$ μ

μ = mean of the deflection, D_0, distribution for each 100 m segment.

Remaining life, RL3, in terms of years, using a known annual traffic loading, $MESA_{annual}$ was estimated as per Equation A9 using the appropriate capacity estimate (CAP_{AC}, CAP_{GN}).

$$RL3 = CAP / MESA_{annual} \quad \textbf{A9}$$

where

MESA = millions of equivalent standard axles per lane per year

Table B.1 is a preliminary assessment of the pavement risk score (PRS) and pavement condition index (PCI) ratings against the remaining life estimates. This will need to be reviewed in the light of forthcoming work on residual risk. Note that the remaining life in Table B.1 is expressed in terms of service life which is more relevant than the design life.

Table B.1: Initial assessment of PCI ratings for remaining life (RL) estimates

PCI rating	Expected RL (years)
1	Full service life1 (20–60)
2	75% service life (15–45)
3	50% service life (10–30)
4	25% service life (5–15)
5	< 5

Note: Service life is usually greater than the design life (up to a factor of 2).

Position/Title: **TMR Agreement Manager**	Position/Title: **ARRB Agreement Manager**
Date: / /	Date: / /

Summary

This report summarises the progress and outcomes to date for the National Asset Centre for Excellence (NACoE) Project A35 *Identification of Residual Risk for each Element and Development of a Funding Allocation Methodology of Elements*.

The report encompasses a summary of the project, the project methodology, and the development of the pavement residual risk model (PRRM). The PRRM is based on an analytical hierarchical process (AHP). The AHP applied to the calculation of residual risk was adapted from RIVA, a GIS-based risk analysis tool, used in Germany to account for natural hazards.

The PRRM includes five major risk dimensions, these are:

- access/vulnerability of the road asset due to hazards
- the impact of hazards on stakeholders and the community
- the impact of hazards on the safety performance of the asset
- the impact of hazards on the legislative compliance of the asset
- the impact of hazards on the operations of the asset.

These risk dimensions are comprised of several indicators, based on data which Queensland Department of Transport and Main Roads (TMR) regularly collects for the state-controlled road network. These indicators include:

- Environment and Traffic: Thornthwaite Moisture Index, annual rainfall, traffic (AADT and %HV), terrain, and slope stability.
- Infrastructure Performance and Condition Indicators: drainage condition index (DCI), pavement condition index (PCI), reactive soils, the AusRAP safety rating, the priority of defects, regulation compliance and the impact of loss of access.

Estimates of the pavement residual risk were made with the PRRM, using road segments that were field rated under NACoE Project A26 for the districts from which they were sampled. The preliminary results were weighted to show a range of representative values across the indicators and risk dimensions. These results have been presented both graphically and spatially. At this stage, and with further work, the PRRM appears to be capable of discriminating between the level of risk that different pavement segments have in the network.

ACKNOWLEDGEMENTS

ARRB wishes to acknowledge the collaborative support of TMR staff; Andrew Golding, Michelle Baran, Peter Bryant, Mohan Sharma, Nam Ranatunga and Jared Lester.

Acronyms

AADT	Annual Average Daily Traffic
AHP	Analytical Hierarchical Process
ARL	Assessed Risk Level
ARRB	Australian Road Research Board
AusRAP	Australian Road Assessment Program
CLoS	Customer-based Levels of Service
DCI	Drainage Condition Index
HV	Heavy Vehicles
ITS	Intelligent Transport Systems
MPO	Maintenance, Preservation and Operations
NAASRA	National Association of Australian State Road Authorities
NACoE	National Assets Centre of Excellence
NRM	NAASRA Roughness Measurement
PCI	Pavement Condition Index
PMS	Pavement Management System
PRR	Pavement Residual Risk
PRRM	Pavement Residual Risk Model
PRS	Pavement Risk Score
RUL	Remaining Useful Life
TLoS	Technical-based Levels of Service
TMR	Queensland Department of Transport and Main Roads
TNRP	Transport Network Reconstruction Program
TSD	Traffic Speed Deflectometer

Contents

Tables

Figures

1 Introduction

Queensland Department of Transport and Main Roads (TMR) faces a challenge in addressing the funding needs of multiple asset elements and the impacts on them from traffic use and the environment. Asset performance, and therefore needs and risks, are impacted by a combination of factors, with climate-related factors increasing in importance as evident from Queensland's recent floods. Different parts of the network and specific roads and assets, including structures, slopes, drainage, and signs and lines, are impacted differently. In specific cases, the frequency and scale of impacts effect the risks which can differ from case to case. Road pavements and surfacings, which have been subjected to substantial study, also need to be considered at risk, as there is a need to ensure an appropriate distribution of funding across multiple asset programs.

Therefore, TMR's Maintenance, Preservation and Operations (MPO) Steering Committee has identified a need for a more comprehensive and rational basis for assessing and managing risks. The intent is to allow TMR to better manage its portfolio by more rigorous, risk-based planning and programming, and the provision of clearer guidance to inform implementation.

1.1 Objectives

This project was created to deliver guidance and tools aimed at supporting a comprehensive, risk-based framework to assist in the allocation of funding to different elements of the road network. The project has drawn on established and recently developed methodologies and solutions in aiming to achieve early success, whilst ensuring the solutions support TMR's needs.

This project required the appropriate use of both a network-level approach and a more road section-based approach, depending on the nature and the geographic distribution of risks. For example, certain impacts have a significant disruptive, potentially catastrophic, effect on a network and impede the flow of traffic, whereas others are more confined and have marginal network impacts. The framework needed to be able to deal with such varied circumstances yet be sufficiently practical so that it could provide clear direction and focus for the individual element management plans.

1.2 Previous Work

Directly related other NACoE projects include:

NACoE Project A5: Incorporating Uncertainty in PMS Modelling

Pavement management systems (PMS) require data that faithfully reflects the properties and other operating circumstances of the network. It is a well-known, though frequently ignored, fact that much of the information is uncertain or poorly represented either due to the nature of the data (e.g. environment) or due to the aggregation of the data into disparate segments. Therefore, the approach developed as part of this project expanded the use of existing deterministic models by using the full range (distribution) of the data instead of an aggregated, usually average, representation of the full dataset. Further, this approach utilised a comprehensive set of historical data and forecasted the probability distribution of key dependent variables (Kadar & Sen 2016).

NACoE Project A26: Incorporation of the Pavement Risk Score (PRS) into the Pavement Condition Index

Martin and Hore-Lacy (2017) published a NACoE report detailing the *Incorporation of the Pavement Risk Score into the Pavement Condition Index* as part of the NACoE A26 program. The study was aimed at reviewing, calibrating and incorporating the Pavement Risk Score (PRS) developed by TMR into the Pavement Condition Index (PCI) implemented in TMR's PMS. The PCI was modified by the addition of the Traffic Speed Deflectometer (TSD) maximum deflection, D_0, that improved prediction of the remaining structural life of pavements (see Appendix B).

Other work in this area includes that on the life-cycle impacts of extreme events, and road performance modelling including the following NACoE and Austroads studies:

NACoE Project A4: Accounting for Life-cycle Costing Implications and Network Performance Risks of Rain and Flood Events

The rain and flood events across Queensland between 2010 and 2013 showed that the road network is more exposed to damage from such events than desirable, with between 23% and 62% of the state-controlled network closed or with limited access over four summers. With increasingly uncertain climatic factors and stretched infrastructure budgets, efficient optimisation and prioritisation of works is critical to the overall network condition.

Historically, works programs were focused on the highest priority treatments, which in some cases resulted in an overall deterioration in network condition over time, as measured by condition indicators such as roughness and seal age. Strategic, timely maintenance and rehabilitation programs are thought to be preferable to one-off major reconstruction programs such as the recently completed Transport Network Reconstruction Program (TNRP).

There was a need to review pavement management, maintenance, and rehabilitation practices to decrease exposure to damage in a cost-effective manner. In order to prove this, this project analysed the life-cycle costing implications of rain and flood events in Queensland through modelling three strategic options across a series of seven case studies.

The analysis also highlighted two critical factors in this discussion: the uncertainty surrounding future extreme climate and weather events in the face of predicted increased climate risks to Queensland and the importance of treating pavements within their target life before the start of accelerated deterioration (Beecroft & Peters 2017).

NACoE Project A34: Customer-based Levels of Service in Road Maintenance (ongoing)

In the context of road maintenance, road agencies have identified that there is a pressing need to relate Customer-based Levels of Service (CLoS) requirements related to road maintenance, to the maintenance intervention measures (roughness, rutting, cracking, potholes, etc.) used by road asset managers, or the Technical-based Levels of Service (TLoS). It is expected that some of these technical measures can be related to customer level of service as these are often not directly observed by the customer. A re-justification of existing levels of service is required to provide a defendable position to TMR in its decision to allocate funds and manage financial risks for the department and potential road user impacts, and the extent to which they are consistent with whole-of-life-cycle costing based funding priorities.

This project aims to determine the existence of relationships between CLoS and TLoS for an agreed set of road categories that will allow the determination of a customer acceptable level of TLoS.

1.3 Project Progress and Chronology

Work commenced on Stage 1 of this project in 2017–18 (Year 1) and continued to Stage 2 in 2018–19 (Year 2) with final completion of Stage 3 currently scheduled for 2019–20.

The work has required collaboration with several TMR departments during the project.

1.4 Scope and Contents of this Report

This report is aimed at providing progress on the work undertaken during the year 2018–19 (part Stage 1 and Stage 2) that is particularly focused on the development of the residual risk management tool for pavements. The structure of the report is as follows:

- Section 2 outlines the methodology adopted for this project.
- Section 3 documents the development of the Pavement Residual Risk Model (PRRM).
- Section 4 presents the results of the PRRM applied to a sample of Districts.
- Section 5 presents the conclusions from the work on the PRRM in Year 2.

Other work for the development of the residual risk approach applied to the intelligent transport systems (ITS) and structures (bridges and culverts) assets has also been underway concurrently with the residual risk for pavement assets.

2 Project Methodology

2.1 Stage 1 – Development of Residual Risk Models

Stage 1 of this project involved the development of a general framework and methodology for determining the level of risk by individual asset types associated with different condition states and operating conditions, with risk quantified in terms of both likelihood and consequence. This work built on an extension of the PRS methodology under NACoE project A26 (Martin & Hore-Lacy 2017), but used the PCI, which was calibrated for road pavements, under NACoE project A26, against the measures employed in the department's PMS, including whole-of-life-cycle–based financial and economic costs. The aim was to:

- review existing element management plan approaches and national and international practice on risk management
- extend the composition and weightings employed in the PCI to reflect the sensitivity of outcomes to changes in key input variables, with the weightings defined as a simplified distribution (with boundary conditions) relevant to each variable, and taking account of estimated time-based changes in distribution, e.g. for climate-related variables
- ensure the estimated level of risk is responsive to different treatment strategies, e.g. where 'full resilience' or 'stitch-in-time' strategies are adopted, or where funding levels are varied, including accounting for different road use (AADT and HV composition)
- assemble evidence to allow the principles of the above 'risk model' approach to be adapted and applied to two non-pavement asset elements, selected in consultation with TMR
- present the proposed prototype model (and supporting illustrations) to the MPO Steering Committee to inform the suitability of the approach and direction for Stage 2.

As part of Stage 1, four different residual risk models were investigated. This involved the Pavement Residual Risk Model (PRRM), the Intelligent Transport Systems Residual Risk Model (ITSRRM), the Structures Residual Risk Model (SRRM), and the environmental Residual Risk Model (ERRM).

2.2 Stage 2 – Trial Assessment of PRRM

Stage 2 of this project, detailed in this report, operationalised the PRRM in a trial application on the TMR road network. As mentioned, this project was based on a continuation of the methodology used for NACoE Project A26. Therefore, the trial assessment of the PRRM was completed for road segments which were field rated as part of NACoE Project A26.

The main element of this work was the development of the indicators used to assess each risk dimension. This involved an in-depth review of the data which was available from TMR for indicators which were of a quantitative nature, and an investigation for alternate methodologies for indicators which were of a more qualitative nature.

Once the indicators to be used for the assessment had been finalised, the data was combined, and presented in both a graphical and spatial format (see Section 4.1 and Section 4.2).

2.3 Stage 3 – Network-level Assessment of PRRM

Stage 3 of this project will involve applying the PRRM to the entire TMR state-controlled road network. In addition, Stage 3 will conclude with the development and dissemination of the technical documentation and resources to support the application of the PRRM for ongoing asset management. Lastly, Stage 3 will investigate avenues for further research and methodologies for the expansion of the ITSRRM and SRRM.

3 Pavement Residual Risk

Stage 1 of this project involved the initial development of the Pavement Residual Risk Model (PRRM) in Year 1 of the project.

In addition, during Stage 1, work was also progressed on the initial development of the residual risk approach applied to intelligent transport systems (ITS), structures (bridges and culverts) and the environment. The ITS and structures applications of residual risk focused on defining the risk indicators and dimensions that are relevant for these asset types. Further development of the residual risk approach applied to the environment is not planned to proceed under this project. Finalisation of these indicators and dimensions are currently underway in conjunction with TMR. These models will be further investigated as part of a proposed Stage 4 of this project.

3.1 General

This section of the report details the information used as input for the PRRM. This includes the selection of road segments, the indicators, the rating categories, and the calculation of residual risk.

Specifically, this section of the report is structured as follows:

- Road segment selection (Section 3.2)
- Environment and traffic indicators (causes) (Section 3.3)
  - Thornthwaite Moisture Index (Section 3.3.1)
  - Annual rainfall (Section 3.3.2)
  - Traffic (Section 3.3.3)
  - Terrain (Section 3.3.4)
  - Slope stability (Section 3.3.5)
- Infrastructure performance and condition indicators (Section 3.4)
  - Drainage condition index (DCI) (Section 3.4.1)
  - Pavement condition index (PCI) (Section 3.4.2)
  - Reactive soil impact (Section 3.4.3)
  - Asset safety (Section 3.4.4)
  - Regulation compliance (Section 3.4.5)
  - Priority of defects (Section 3.4.6)
  - Loss of action/function (Section 3.4.7)
- Risk dimension rating categories (Section 3.5)
  - Access vulnerability (Section 3.5.1)
  - Stakeholders and community 3.5.2)
  - Safety performance (Section 3.5.3)
  - Legislative compliance impact potential (Section 3.5.4)
  - Operations impact potential (Section 3.5.5)
- Calculation of residual risk (Section 3.6).

The PRRM is based on an analytical hierarchical process (AHP), as outlined in Figure 3.1. The AHP applied to the calculation of residual risk was adapted from RIVA, a GIS-based risk analysis tool, used in Germany to account for natural hazards (Klose 2017). In 2014, Auerbach and Herrmann (2014) outlined a risk analysis approach for adapting the road infrastructure to climate change, which formed the initial basis for the RIVA work.

Another methodology (Nicolosi, Augeri & Soccodato 2019) for allocating funding across assets is available but was not used for this project. In this case, Nicolosi et al. (2019) used a hybrid framework combination of top down/bottom-up multi-objective approaches. Typically, most asset funding allocation approaches struggle to quantify some of the factors influencing the allocations. In addition, the adoption of a risk-focused quantitative approach to allocation of funding needs a substantial database encompassing all the factors contributing to the risk.

The PRRM shown in Figure 3.1 uses a set of indicators for the causes, such as traffic and the environment and another set of indicators for the effects of risks, which are the performance and condition of the infrastructure. The indicators are aligned to different risk dimensions to estimate a residual risk at each sub-component level. Finally, the residual risks of each sub-component are combined using various pre-determined weightings to estimate an aggregated residual risk for each road segment.

The indicators for causes and effects rely on quantifiable measures that are accessible and regularly updated in the TMR database, which was the source for the indicators on each road segment. The definitions and details of these indicators are outlined in the following section.

3.2 Road Segment Selection

The road segments used for the PRRM calculation were selected based on the previous NACoE Project A26 *Incorporation of the Pavement Risk Score (PRS) into the Pavement Condition Index (PCI).* NACoE Project A26 sought to calibrate (and adjust) TMR's PRS methodology with field observations, and a whole-of-life-cycle costing methodology applied in the PMS.

Within NACoE Project A26, the pavement condition index (PCI) for samples of road segments, from differing districts across Queensland, was calculated. In addition, many of these road segments were field rated for their condition. Road segments which had the PCI calculated, and were field rated, formed the basis of the dataset.

A list of the road segments, and the associated districts, included in this project are provided in Appendix A.

3.3 Environment and Traffic Indicators

Environment and traffic indicators refer to those which are generated by environmental factors, and factors related to traffic/road usage. For this project, this included: the Thornthwaite Moisture Index (TMI) (Thornthwaite 1948), annual rainfall, annual average daily traffic, AADT, commercial/heavy vehicle traffic (%HV), terrain and slope stability. Each of these indicators are detailed in the following sections.

3.3.1 Thornthwaite Moisture Index

TMI is a reflection of the aridity or humidity of the soil and climate of an area. It is calculated by analysing the collective effects of precipitation, evapotranspiration, soil water storage, moisture deficit and runoff (Austroads 2004).

TMI can be used to classify various climate types according to the moisture index limits, which are outlined in Table 3.1. The distribution of TMI is shown in Figure 3.2.

Figure 3.1: Pavement residual risk model (PRRM)

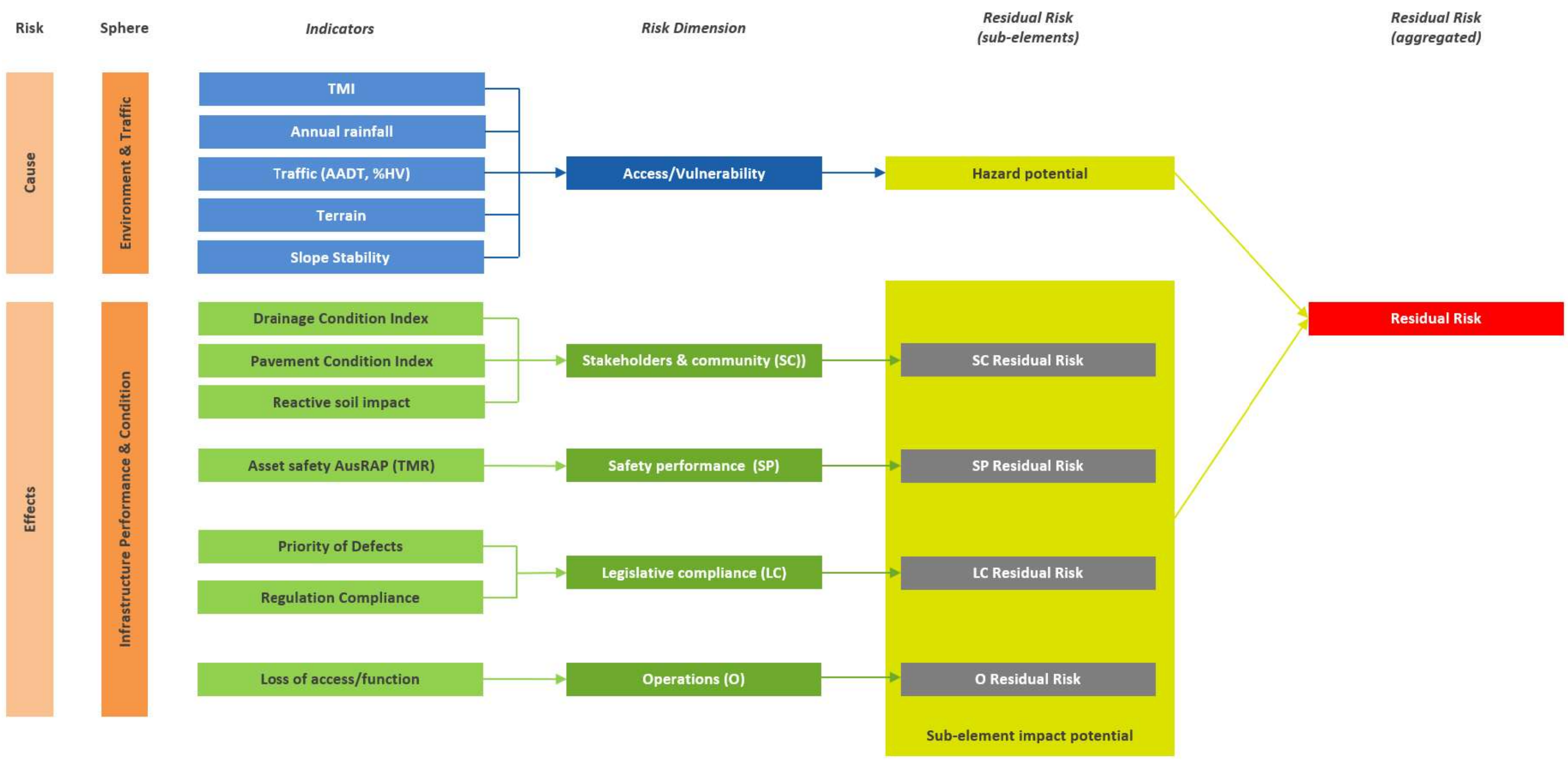
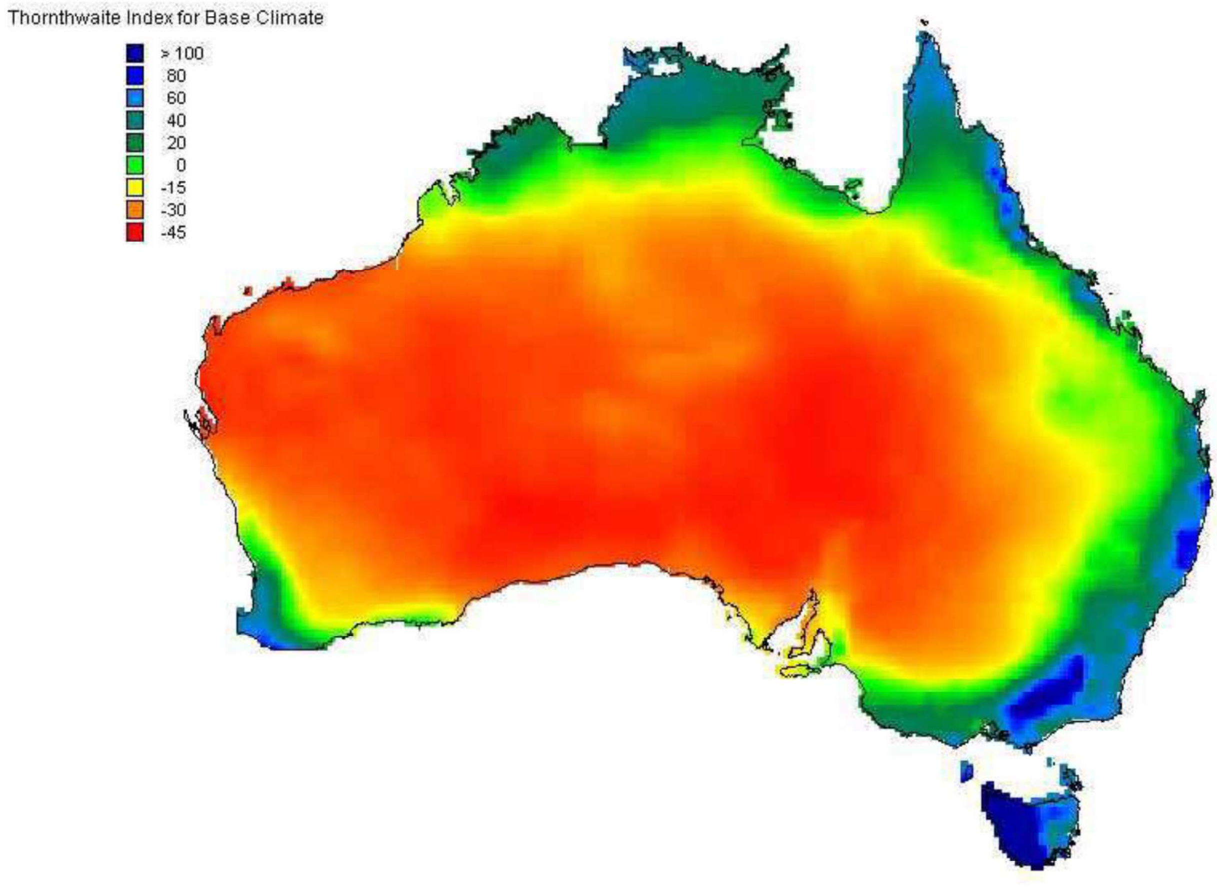


Table 3.1: Thornthwaite's climate type classifications

Thornthwaite climate type		Thornthwaite Moisture Index
Grid type	Unit	Range
A	Perhumid	> 100
B4	Humid	80 to 100
B3	Humid	60 to 80
B2	Humid	40 to 60
B1	Humid	20 to 40
C2	Moist subhumid	0 to 20
C1	Dry subhumid	−20 to 0
D	Semi-arid	−40 to −20
E	Arid	−60 to −40

Source: Thornthwaite (1948).

Figure 3.2: Thornthwaite Moisture Index for Australia in 2000



Source: Austroads (2004).

Data on the TMI for each of the locations assessed as part of this project was obtained from the A26 dataset, which as mentioned, was used as the basis for the road list in this project.

3.3.2 Annual Rainfall

The annual rainfall indicator is defined as the long-term average annual rainfall for a location. The long-term average annual rainfall for each location was calculated by averaging the annual rainfall of the most recent 30-year period, 1988–2018.

The annual rainfall for each road segment location was generated using data from the Bureau of Meteorology (BOM). Based on the chainages of the road segments, the nearest town was identified. This town was entered into the BOM's search engine to locate the closest weather station. Relevant towns, and associated weather station characteristics were recorded. Weather stations were selected based on their proximity to the town, and the amount of data available. Ideally, weather stations with 30 years of rainfall data were selected.

3.3.3 Traffic (AADT/%HV)

The impact of traffic on residual risk was calculated for two separate indicators, AADT and %HV for traffic using the road. Both these indicators were obtained from the data provided by TMR. The data used was relevant for 2018.

3.3.4 Terrain

The terrain indicator refers to the physical features of the land across which the road traverses. TMR defines terrain into three categories, level, rolling and mountainous. The terrain category associated with each of the road segment locations was provided by TMR.

3.3.5 Slope Stability

The slope stability indicator refers to the stability of the batter and cutting slopes along the road. The batter and cutting slopes are the uniform side slope of the road batter and cutting, which is distinct from grade, and is expressed as a ratio of the horizontal distance to vertical slope height (Austroads 2015). The stability of the batter and cutting slope is important as it contributes to the structural resilience of the road pavement, including shoulders. The batter and cutting slopes contribute to the ability of the road to shed water by providing a stable base for its table drains to drain runoff from rain and flood events.

Slope stability is measured by TMR with an assessed risk level (ARL). This ARL value is a number from 1 to 5 with 5 being a stable slope, and 1 being an unstable slope. Data on the stability of slopes was provided by TMR. This data included the ARL, the slope type, the slope height, the slope angle, location information and whether or not the slope has a management plan.

3.4 Infrastructure Performance and Condition Indicators

Infrastructure performance and condition indicators refer to the elements of the asset itself which effect the level of service it provides. In this project, this includes the following indicators that were used to build the risk dimensions:

- drainage condition index (DCI)
- the pavement condition index (PCI)
- impact of reactive soils
- AusRAP asset safety rating
- priority of defects, set by TMR's corporate priorities in the Routine Maintenance Guidelines (TMR 2017)
- regulation and compliance
- loss of access which would occur due to closure of the asset.

3.4.1 Drainage Condition Index

Drainage refers to the natural or artificial means of intercepting and removing surface or sub-surface water usually by gravity (Austroads 2015). DCI in this context refers to the portion (percentage, %) that drainage culverts are blocked with detritus reducing the effectiveness of the culvert. The DCI was originally developed by Austroads (2011) and was revised to an indicator that can be assessed on ARRB expert opinion, using the soil type information provided by TMR.

Soil group data was provided by TMR, based on 2014 survey results. There were 62 different soil types included in the data. These were grouped into categories and assigned assumed blocking percentages based on Table 3.2.

Table 3.2: Soil grouping and assumed DCI

Soil type	Assumed Drainage Condition Index (DCI)
Sandy or loamy	0% blocked
TC* soils	1–10% blocked
Non-cracking clays	11–25% blocked
Cracking clays/expansive	26–50% blocked
Waterlogged/silt	> 50% blocked
Note: *Tertiary colluvial.	

3.4.2 Pavement Condition Index

PCI is calculated based on various individual condition indices (CI). The PCI is an aggregate of these individual CIs, based on the concept of a 'weighted maximum', i.e. instead of using an average of the CIs, the maximum (worst) dominates the overall index (COST 2008). The current composition of the CIs to calculate the PCI used by TMR is outlined in Table 3.3.

Table 3.3: Composition of the TMR PCI

Attribute (CI)	Description
NAASRA Roughness (NRM)	Counts per km with separate limits defined by traffic level and speed zone
Rutting	Mean rut depth (mm), with separate limits defined by traffic level, climate, and speed zone
Cracking	Area (%) of all cracking
Remaining useful life (RUL)	RUL of the road pavement in years
Surface age	Age of the latest surfacing in years
Skid deficiency	% less than investigatory skid resistance

Source: Martin and Hore-Lacy (2017).

In order to express the overall condition of an asset in terms of a PCI, the above condition indices are aggregated (Martin & Hore-Lacy 2017). The estimation of the RUL attribute is detailed in Appendix B.3. The RUL is based on the traffic speed deflectometer (TSD) measurements of maximum pavement deflection (Martin & Hore-Lacy 2017).

> Engineering decisions are usually made based on the worst condition, e.g., a structurally very weak, but a perfectly smooth road would have an average (say 2.5) pavement condition index. Treatments, however, would be decided based on the worst condition, in this case the structural weakness. The proposed PCI is shaped by the engineering decision-making approach, consequently it gives greatest weight to the worst condition, whilst the other condition indices are also accounted for as minor adjustments.

The PCI is calculated by applying Equation 1, as follows:

$$PCI = MAX(w_i \times Index_i) + p(\frac{SUM(w_i \times Index_i) - MAX(w_i \times Index_i)}{\sum(w_i) - Avg(w_i)}) \quad 1$$

where

PCI = pavement condition index

w_i = weight for individual condition criteria, including cracking, roughness, rutting and surface age

$Index_i$ = index value for individual condition criteria, including cracking, roughness, rutting and surface age

p = condition factor (the current value is 0.1)

It should be noted that the weights (w_i) must be relatively close to 1 to avoid significant distortion of the index.

As mentioned, the PCI was calculated for many road segments as part of NACoE Project A26. These segments were also field rated as part of that project.

3.4.3 Reactive Soil Impact

The reactive soil impact indicator refers to the effects of the environmental zone through which the road traverses. Reactive soils are based on the type of soil they are composed of which can cause them to swell when wet and shrink when dry, i.e. they are reactive to water. TMR classifies their soils into four environment zones, including: dry reactive, wet reactive, dry non-reactive and wet non-reactive.

3.4.4 Asset Safety – AusRAP

The AusRAP indicator is from the Australian Road Assessment Program. AusRAP provides safety ratings for roads, where roads are assigned a score from one star (least safe) to five stars (most safe). In this context AusRAP is a useful indicator for the safety risk dimension.

AusRAP uses four complementary methods – or protocols – for assessing the safety of roads: risk mapping, performance tracking, star ratings and safer roads investment plans (SRIPs). Risk maps use detailed crash data to illustrate the actual number of deaths and injuries on a road network. Performance tracking enables the use of star ratings and risk maps to track road safety performance and establish policy positions. Star ratings provide a simple and objective measure of the level of safety provided by the road design. SRIPs draw on proven road improvement options to generate affordable and economically sound infrastructure options for saving lives (Australian Automobile Association (AAA) 2013).

The AusRAP star rating for the road segments, used as input for this project, was used as the indicator for safety.

3.4.5 Regulation Compliance

The regulation compliance indicator has been defined broadly as being the compliance of the road to the roughness intervention levels defined by TMR. Road segments were categorised by the percentage to which the road is either compliant with the 'desirable' roughness intervention level or whether it exceeds the roughness intervention level. Table 3.10 is a summary of TMR's roughness intervention levels based on the AADT.

Table 3.4: TMR roughness intervention limits

AADT range	NAASRA roughness
< 500	130
< 500 & < 1 000	110
>=1,000 & <10 000	95
>=10 000	80

3.4.6 Priority of Defects

Priority of defects refers to the corporate priorities assigned by TMR to each of the defects recorded on a road segment. There are six categories of corporate priorities that are summarised in Table 3.5. These corporate priority ratings were grouped together to generate the residual risk ratings.

Table 3.5: TMR corporate priority defects categories

Corporate priority	Description
Priority 1 – Hazard	Defects where the likelihood of harm occurring is greater than a safety defect determined by the hazardous defect identification procedure
Priority 2 – Ordered works	Work undertaken in accordance with the Principal's order and directions
Priority 3 – Safety	Defects that are an issue of safety
Priority 4 – Legislative	Defects that are required to be repaired by legislation
Priority 5 – Preventative	Defects that if treated will reduce the asset's rate of deterioration
Priority 6 – Appearance/Usability	Defects that are a nuisance or unsightly

Source: TMR (2017).

3.4.7 Loss of Access/Function

Originally two indicators, the loss of access and loss of function contributed to the operations risk dimension and refer to an event in which the entirety of the road segment is not functional, and therefore cannot provide access. This indicator was generated by calculating the percentage increase in the distance required to be travelled if a road is closed.

This category is based on the number of alternate routes available to travel to a destination, if a road is closed. This is a high-level assessment, using a route application such as Google maps. Table 3.6 shows the basis for establishing the ratings for loss of access/function. These percentage increases in distance travelled can be coarsened to reflect the reality of the increases in distances travelled in Queensland.

Table 3.6: Ratings for loss of access/function

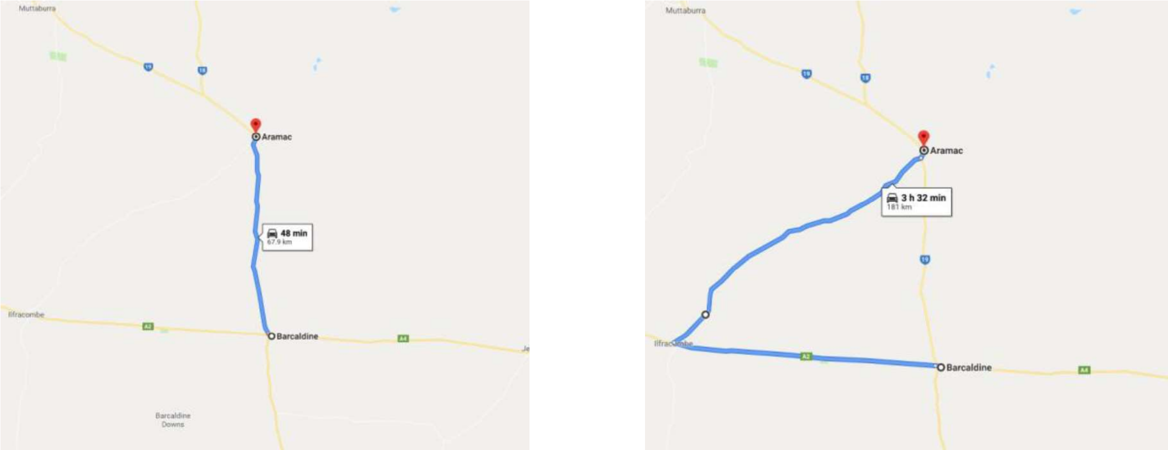
Ratings	Loss of access/function
1	< 5% increase in distance travelled
2	5–10% increase in distance travelled
3	10–20% increase in distance travelled
4	> 20% increase in distance travelled
5	No alternate route

This approach to the ratings was applied to Road 573 as shown in Table 3.7 and Figure 3.3. As can be seen from Table 3.7, this category does not apply a different rating to each road segement, rather, it assumes the whole road segemnt has been closed so the same redirected route option is applied.

Table 3.7: Example calculation of loss of access/function indicator for Road 573

Road section ID	Dist start	Dist end	Run no.	Traffic (AADT)	Road length	Alternate route length	Percentage increase in distance travelled	Rating
573	9.7	9.8	4693	180	67.9 km	181 km	166.57%	4
573	9.8	9.9	4693	180	67.9 km	181 km	166.57%	4
573	9.9	10	4693	180	67.9 km	181 km	166.57%	4
573	10	10.1	4693	180	67.9 km	181 km	166.57%	4
573	45.6	45.7	4693	180	67.9 km	181 km	166.57%	4
573	45.7	45.8	4693	180	67.9 km	181 km	166.57%	4
573	45.8	45.9	4693	180	67.9 km	181 km	166.57%	4
573	45.9	46	4693	180	67.9 km	181 km	166.57%	4

Figure 3.3: Example calculation of loss of access/function indicator for Road 573



(a) Road 573 Direct Route (b) Road 573 Alternate Route

Source: Google Maps (2019), 'Barcaldine', map data, Google, California, USA.

3.5 Risk Dimension Rating Categories

3.5.1 Access Vulnerability

The access vulnerability dimension refers to the extent to which a road is susceptible to, or unable to cope with, the adverse effects of the environment and traffic. The indicators included in this category are the TMI, annual rainfall, traffic, terrain and slope stability.

The TMI and the annual rainfall represent the impacts of climatic events on the road infrastructure. These affect access as extreme weather events commonly cause road closures due to damage, and associated repairs. Further, the retention of water in the environment, caused by rainfall, can lead to network disruption due to flooding. Similarly, the slope stability is of importance regarding access, as unstable slopes can cause road closures.

Traffic contributes to access vulnerability as, with increasing traffic comes increasing road congestion, and higher road congestion reduces the accessibility service that a road can provide. In addition, traffic increases the wear on the road.

Terrain contributes to access vulnerability as roads on a level terrain provide a higher level of access service than those on a mountainous terrain. This is because roads on a mountainous terrain are more likely to be affected by rainfall, land subsidence, etc. As noted above, slope stability can impact on access to close the road with unstable slope material covering the road. Lastly, the combination of terrain and slope stability leads to the risk of landslides, which affects the availability of road for users.

The rating categories for indicators in the access vulnerability risk dimension category are outlined in Table 3.8. Each of these elements has been weighted to a value of one. Based on likelihood, the risk of flooding would rate more highly than the risk of landslides. Further, the risk of these environmental hazards is more likely than a loss of access based on damage to the road.

Table 3.8: Rating categories for the indicators that affect asset vulnerability

Indicators	Category/Rating					Weight
	V Low (1)	Low (2)	Fair (3)	High (4)	V High (5)	
TMI	−50 to −25	−24.9 to 0	0.1 to 30	30.1 to 60	60.1 to 100	0.25
Annual rainfall (mm)	< 250	251–500	501–800	801–1500	> 1 500	0.25
Traffic (AADT)	< 250	251–1 000	1 001–10 000	10 001–15 000	> 15 000	0.05
Traffic (%HV)	< 25	25–100	101–300	301–1 000	> 1 000	0.12

Indicators	Category/Rating					Weight
	V Low (1)	Low (2)	Fair (3)	High (4)	V High (5)	
Terrain class	Level	–	Rolling	–	Mountainous	0.17
Slope stability (ARL rating)	Inert (ARL = 5)	Stable (ARL = 4)	Mod. Stable (ARL = 3)	Mod. Unstable (ARL = 2)	Very unstable (ARL = 1)	0.17

3.5.2 Stakeholders and Community

The stakeholders and community dimension connects the pavement's performance and condition to the road users and general community. Pavement performance and condition should be assessed in response to road use and the pavement's interaction with the environment.

The PCI indicator accounts for several factors including roughness, rutting, cracking, RUL, surface age, and skid deficiency. Several of these elements are heavily influenced by environmental factors. For example, if the soils below the road do not drain properly, then the road is more susceptible to cracking. Further, these indicators can greatly affect the economic viability of a pavement, as they can lead to high maintenance costs in returning the pavement to its expected level of service.

The DCI measure assesses the ability of the sub-surface soils to deal with water. This, in turn, is the ability of the soils to cope with the environmental conditions of the area, and therefore, refers to the environmental sustainability of the asset.

As described, the impact of reactive soils refers to the shrinkage and expansion of soils in wet and dry environments, respectively. Similarly, this is an environmental impact and, therefore, contributes to the environmental sustainability of the asset.

The rating categories for indicators in the stakeholders and community risk dimension category are outlined in Table 3.9. Each of these elements has been weighted to a value of one. The risk factors here are based on the condition of the road, the PCI, and the amount of water that the road is exposed to due to the functionality of the drainage, measured by the DCI. A road in poor condition is susceptible to an increased rate of deterioration that is proportional to the amount of water in the immediate environment (i.e. if a road is cracked and subject to minor flooding, the subgrade is more likely to be damaged).

The DCI and the reactivity of the soils contribute equally to the risk of expansion in the soil. If the soils are reactive and drainage is poor, these factors will amplify one another. Conversely, the impact of poor drainage is reduced if the soils are non-reactive. The impact of these factors on this risk dimension are dependent on one another, and thus share equal contribution to the risk.

Table 3.9: Rating categories for the indicators that affect stakeholder & community

Indicators	Category/Rating					Weight
	V Low (1)	Low (2)	Fair (3)	High (4)	V High (5)	
Drainage condition index (DCI)	V Good (0% blocked +ve slope)	Good (1–10% blocked)	Fair (11–25% blocked)	Poor (26–50% blocked)	V Poor (> 50% blocked −ve slope)	0.25
Pavement condition index (PCI)	V Good (PCI = 0–1)	Good (PCI = 1.001–2)	Fair (PCI = 2.001–3)	Poor (PCI = 3.001–4)	V Poor (PCI = 4.001–10)	0.5
Reactive soil impact	Non-reactive dry	–	Non-reactive wet	Reactive dry	Reactive wet	0.25

3.5.3 Safety Performance

The safety performance dimension of an asset refers to the ability of the asset to provide public safety and minimise harm to the environment. As the environment is covered by the access vulnerability dimension, this dimension mainly refers to public safety for this project.

As mentioned, the AusRAP indicator can provide safety ratings for roads, where roads are assigned a score from one star (least safe) to five stars (most safe). As AusRAP generates a safety rating for the road, based on several indicators, this covers most of the issues which need to be considered in this dimension. Table 3.10 provides the rating for the indicators for the safety performance dimension.

Table 3.10: Rating categories for the indicators that affect safety performance

Indicators	Category/Rating					Weight
	V Low (1)	Low (2)	Fair (3)	High (4)	V High (5)	
Safety (AUSRAP)	V Good (AusRAP = 4–5)	Good (AusRAP = 3–3.9)	Fair (AusRAP = 2–2.9)	Poor (AusRAP = 1–1.9)	V Poor (AusRAP = 0–0.9)	1

3.5.4 Legislative Compliance – Impact Potential

The legislative compliance dimension refers to the level to which an asset conforms to the regulations outlined by the TMR standards and specifications. Differing from access vulnerability, stakeholders and community, and safety performance, this dimension is quite qualitative in nature. Table 3.4 shows the roughness intervention limits used to determine compliance to roughness conditions. In addition, this category includes the priority of defects, as specified by TMR's corporate priorities in routine maintenance.

Table 3.11 provides the ratings for the indicators for the legislative compliance dimension. Each of these elements has been weighted to a value of one. Both of these indicators are related to the condition of the road, and as they represent deterioration or damage in the pavement, they were weighted equally.

Table 3.11: Rating categories for the indicators that affect legislative compliance

Indicators	Category/Rating					Weight
	V Low (1)	Low (2)	Fair (3)	High (4)	V High (5)	
Roughness compliance (% meeting NAASRA roughness limit)	100% compliant	> 90% compliant	90–80% compliant	80–70% compliant	< 70% compliant	0.5
Priority of defects	No recorded defects	Assigned corporate priority of 6 (appearance/ usability)	Assigned corporate priority of 4 or 5 (legislative or preventative)	Assigned corporate priority of 2 or 3 (ordered works or safety)	Assigned corporate priority of 1 (hazard)	0.5

3.5.5 Operations – Impact Potential

The operations impact potential dimension refers to the indicators that will affect the asset's ability to operate to a normal functional standard. Differing from access vulnerability, stakeholders and community, and safety performance, the loss of access/function indicator can be quantified as noted in Section 3.4.7. Table 3.12 provides the ratings for the indicator for the Operations dimension.

Table 3.12: Rating categories for the indicator that affect operations

Indicator	Category/Rating					Weight
	V Low (1)	Low (2)	Fair (3)	High (4)	V High (5)	
Loss of access/function	< 5% increase in distance travelled	5–10% increase in distance travelled	10–20% increase in distance travelled	> 20% increase in distance travelled	No alternative access route	1

3.6 Calculation of Residual Risk

As detailed above, there are five risk dimensions associated with the PRRM which include:

- access/vulnerability of the road asset due to hazards
- the impact of hazards on stakeholders and the community
- the impact of hazards on the safety performance of the asset
- the impact of hazards on the legislative compliance of the asset
- the impact of hazards on the operations of the asset.

Each of these is weighted prior to being included in the calculation. The weightings are outlined in Table 3.13. The potential for hazards involved with the indicators as part of the access and vulnerability risk dimension are the most prevalent, as these indicate whether the road is useable. Further, usability is also greatly impacted by the impact potential of the operations of the road. Therefore, these two categories have been given the second highest weightings. Safety performance has been given the highest weighting, as road fatalities have the greatest social impact. Roads need to be safe for road users to travel on, and therefore this is a high priority in estimating residual risk. The remaining categories are comprised of indicators which are aspects of physical factors affecting the road. These are aspects which can be managed as part of routine maintenance. Therefore, these have been weighted lower.

Table 3.13: Combination of rating categories

Risk dimension	Index weight[1]	Indices	Variable name
Access/vulnerability	$w_1 = 0.25$	Hazard potential	AV
Stakeholders and the community	$w_2 = 0.09$	Impact potential	SC
Safety performance	$w_3 = 0.33$	Impact potential	SP
Legislative compliance	$w_4 = 0.08$	Impact potential	LC
Operations	$w_5 = 0.25$	Impact potential	O
Note: 1. Weighting is an initial assessment.			

The PRRM results are calculated by summing the index weights multiplied by each risk dimension, as shown in Equation 2, which can have a minimum value of 1 and a maximum value of 5.

$$Pavement\ Residual\ Risk = w_1 * \mathrm{AV} + w_2 * \mathrm{SC} + w_3 * \mathrm{SP} + w_4 * \mathrm{LC} + w_5 * \mathrm{O} \quad (2)$$

3.7 Other Considerations in the Residual Risk

The residual risk is a combination of many elements which are generally considered by road asset managers, as they cause major network disruption issues which affect the sustainability of an asset. Many of the indicators which have been discussed as part of the development of this project, are those which are influenced by the information which has been included.

A key concern for road asset managers is the exposure to legal redress caused by management practices. This is something which has been included in the PRRM as part of the priority of defects indicator. As mentioned, within TMR's Routine Maintenance Guidelines, there is a provision for the classing of defects into corporate priorities. Defects which are classed as a priority of 4, are defects that are required to be repaired by legislation.

A further concern is that defects which are unrepaired will not meet the technical levels of service set in place by TMR, or the customer-based levels of service which are expected by the road user. Currently within the NACoE Program, Project A34 *Customer-based Levels of Service in Road Maintenance*, is seeking to address these inconsistencies. Once A34 is complete, TMR will have the ability to use the relationships identified to build a levels of service framework, which could be used in conjunction with the residual risk framework.

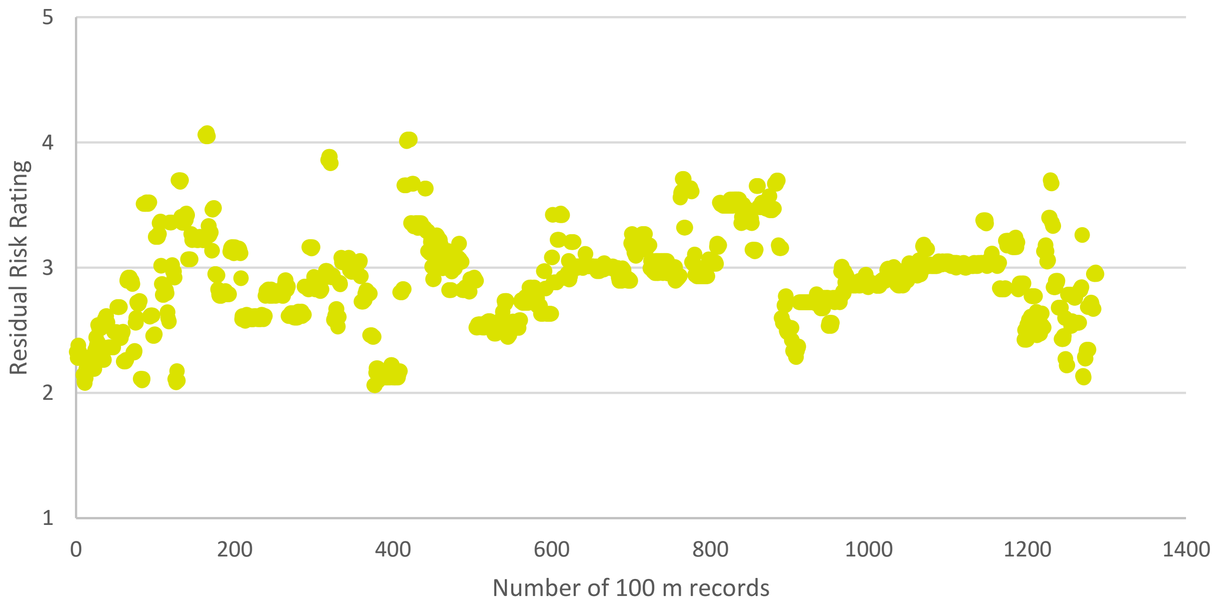
4 Presentation of Preliminary Results of PRRM

This section details the PRR score estimates based on the TMR road segment data set used for NACoE A26 (Martin & Hore-Lacy 2017). The PRR score as defined in Section 3.1, was estimated using the indicators described in Section 3.3 and Section 3.4, which were used to calculate the risk dimensions described in Section 3.5. As noted, there are some indicators which required further evaluation and replacement due to the challenges with obtaining the data as outlined in Section 3.7.

4.1 Pavement Residual Risk Results

Figure 4.1 provides an overview of the weighted PRR score rating estimates for the A26 dataset that was field rated. This graph presents the number of 100 m road sections which have been assessed, which fall into each residual risk category. As can be seen from the graph most of the residual risk values fall between 2 and 4.

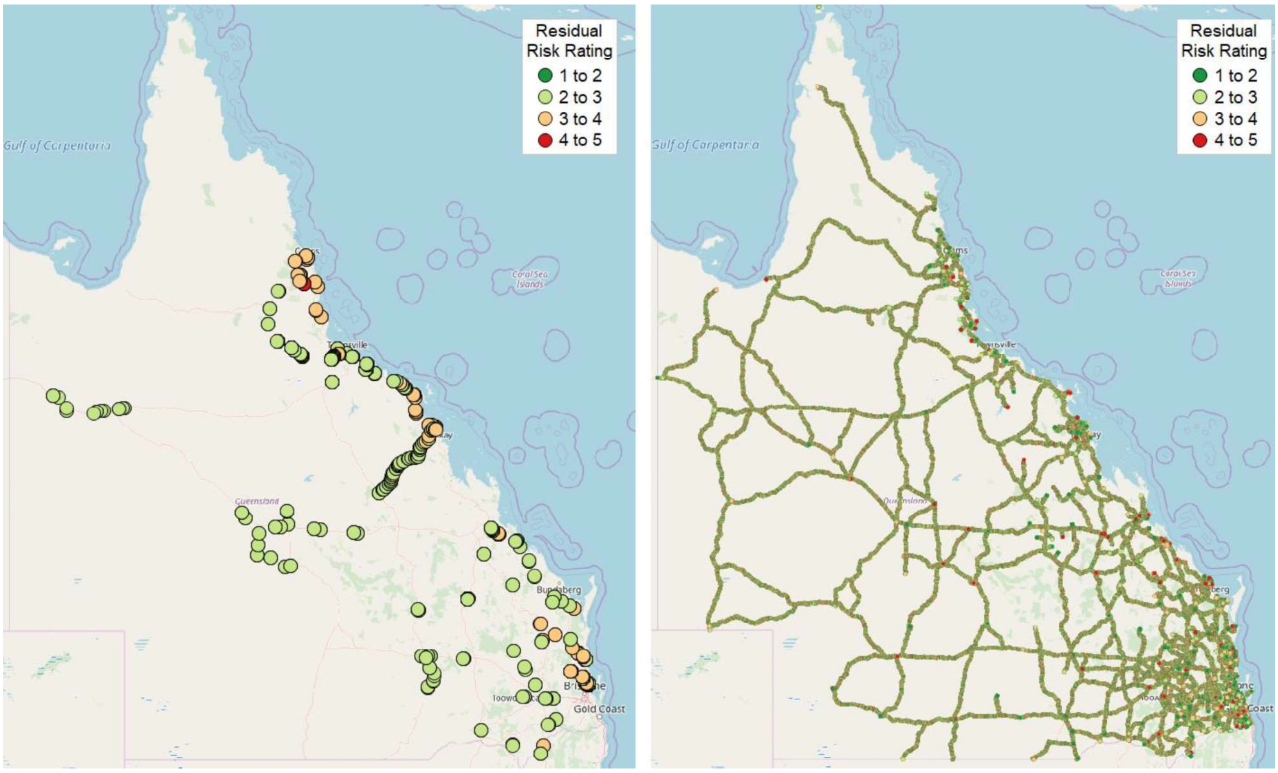
Figure 4.1: Pavement residual risk model weighted results



4.2 Visual Representation of PRRM Results

Figure 4.2 provides a visual map representation of the PRR score estimates from the analysis, based on the weighted PRR score estimates to display the full range. Due to the ‘scattered’ and limited nature of the dataset, the results were difficult to present visually as shown in Figure 4.2(a). Figure 4.2(b) has been ‘filled-in’ with the sampled PRR score estimates. This expansion was undertaken for demonstration purposes only.

Figure 4.2: Map of Queensland showing the location of the residual risk sites with coloured risk ratings



(a) Results in dataset

(b) Results repeated to fill out entire network

Source: TMR (n.d.)

4.3 Comparison of Results between Districts

The mean weighted PRR scores were estimated for each district. Another assessment of overall residual risk, such as an advanced maximum, could be used. As can be seen in Table 4.1, the average conceals much of the variation in the residual risk data. For example, it will hide the road segments with a very high residual risk value, if the majority of the other road segments are low.

Table 4.1: Mean residual risk by district

District	Mean weighted residual risk
Central West District	2.36
Darling Downs District	2.84
Far North District	2.94
Fitzroy District	2.64
Mackay Whitsunday District	2.92
Metropolitan District	3.01
North Coast District	3.23
North West District	2.48
Northern District	2.93
South West District	2.58
Wide Bay Burnett District	2.75

Therefore, histograms were generated for each district to show the distribution of the PRR scores (weighted residual risk) and are shown in Figure 4.3 to Figure 4.13. These histograms show the number of 100 m segments which fall into each of the residual risk categories (1 to 5) for each district.

Figure 4.3: Histogram of PRR for Central West District

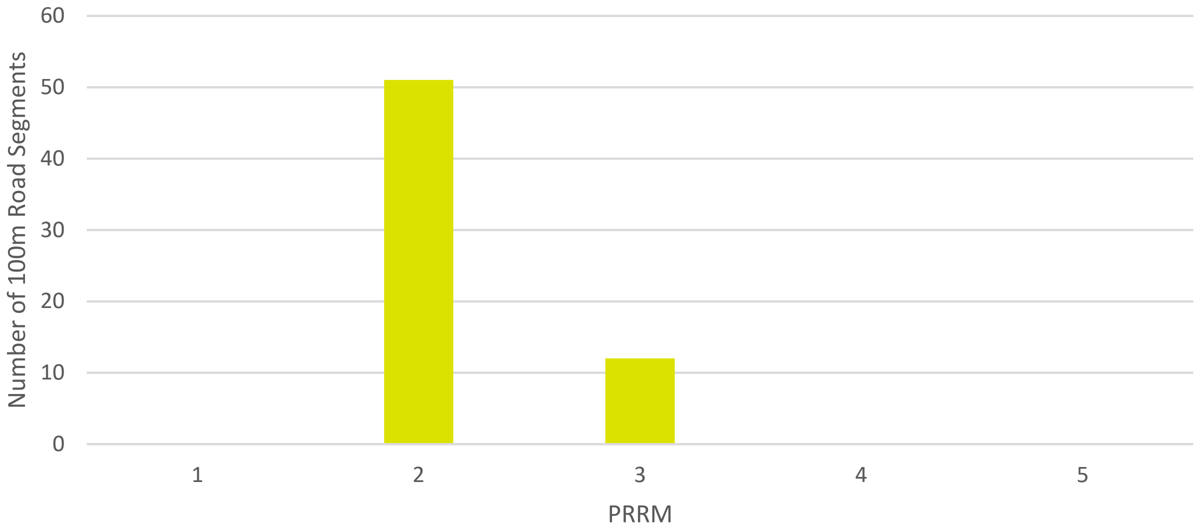


Figure 4.4: Histogram of PRR for Darling Downs District

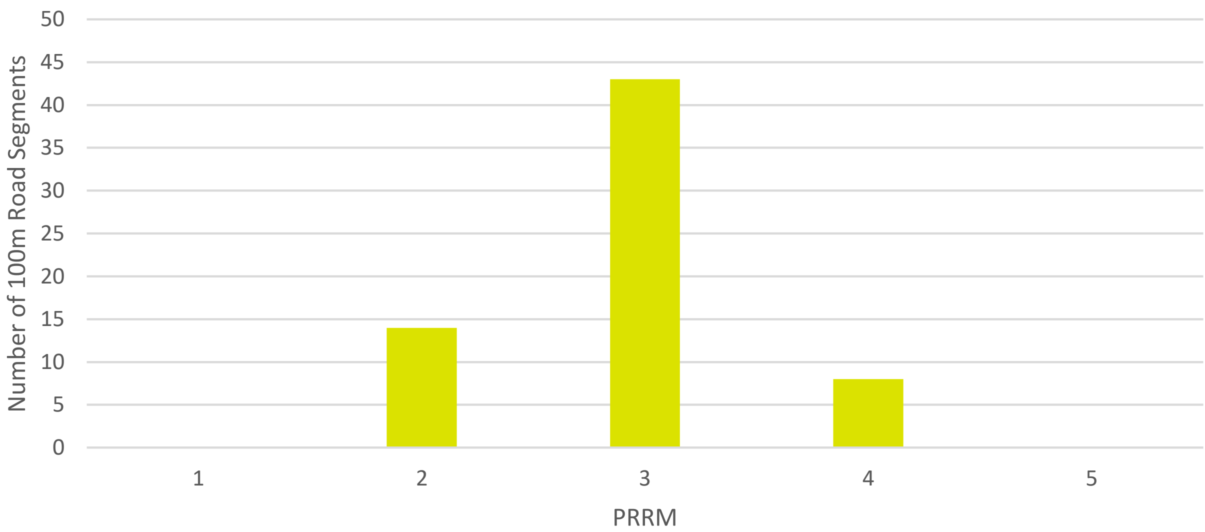


Figure 4.5: Histogram of PRR for Far North District

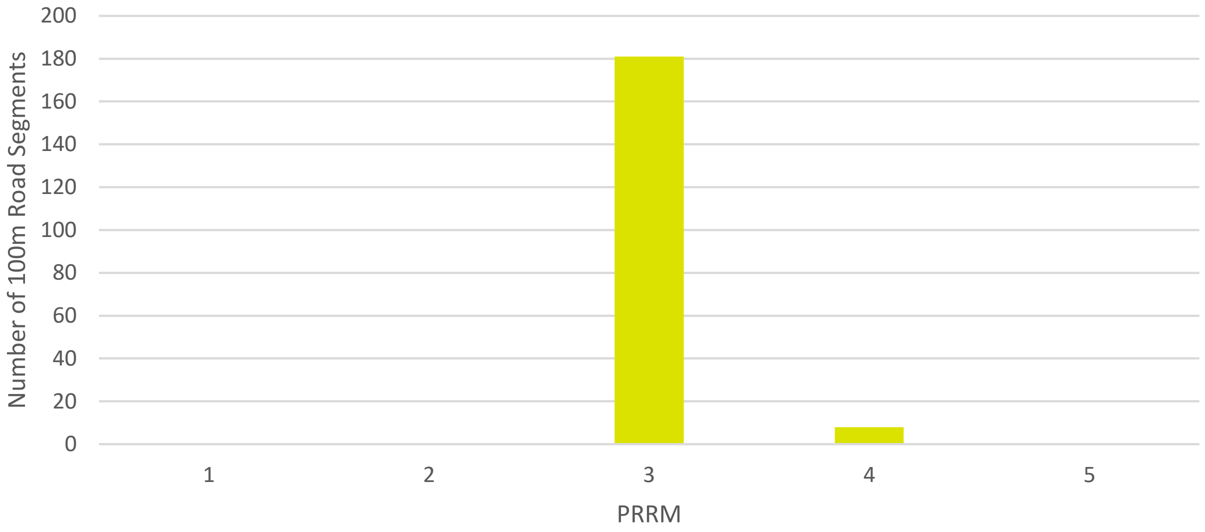


Figure 4.6: Histogram of PRR for Fitzroy District

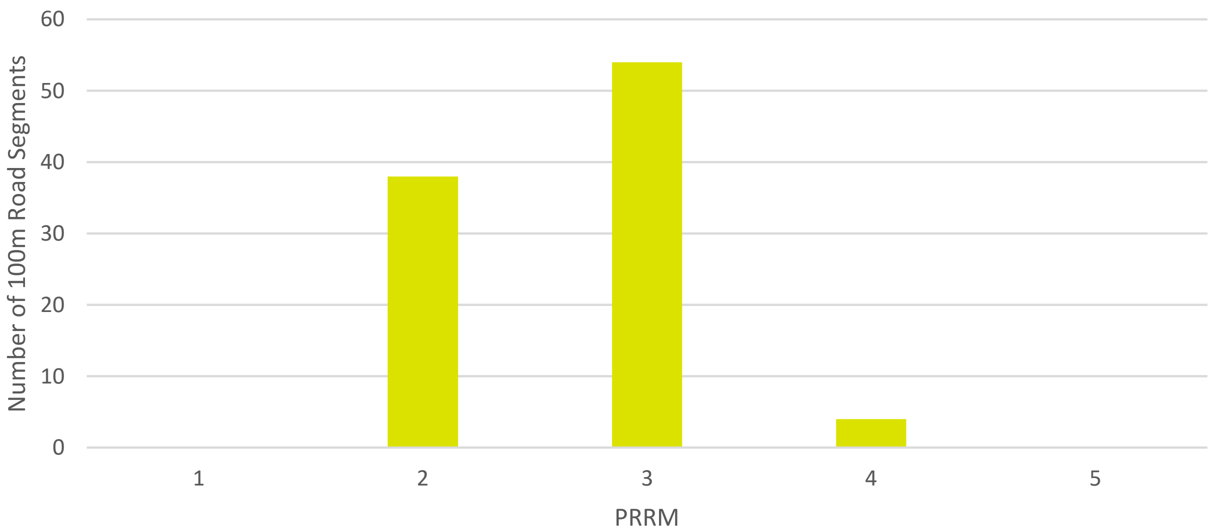


Figure 4.7: Histogram of PRR for Mackay Whitsunday District

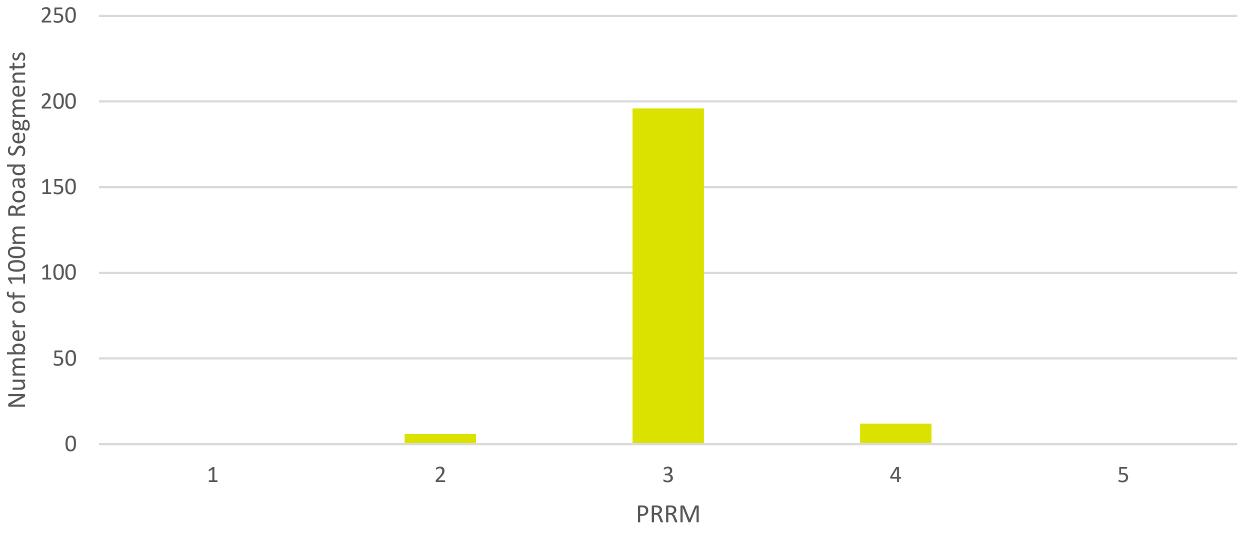


Figure 4.8: Histogram of PRR for Metropolitan District

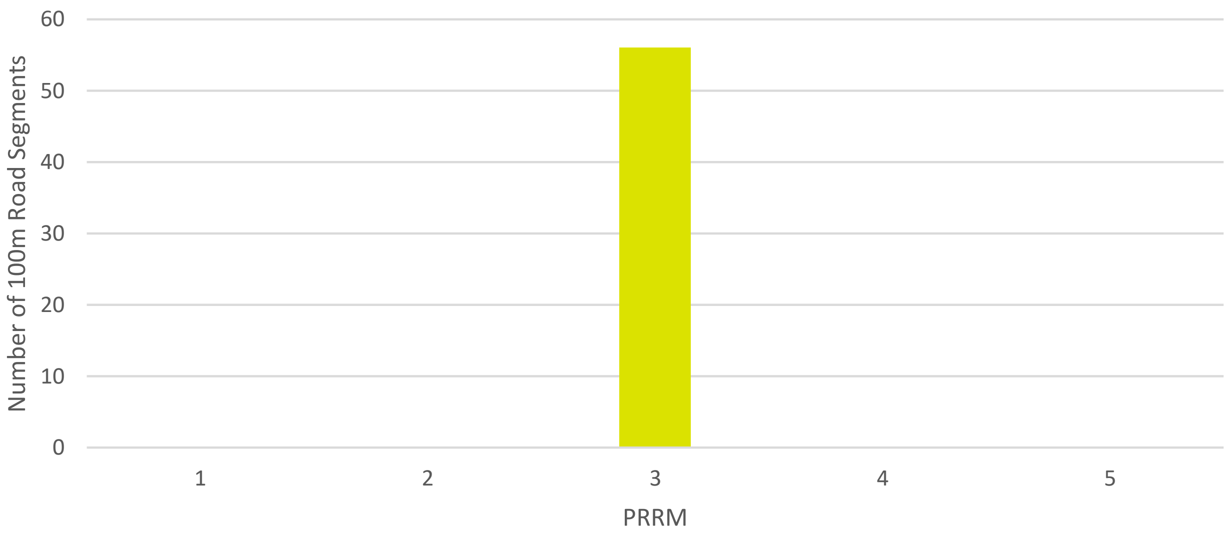


Figure 4.9: Histogram of PRR for North Coast District

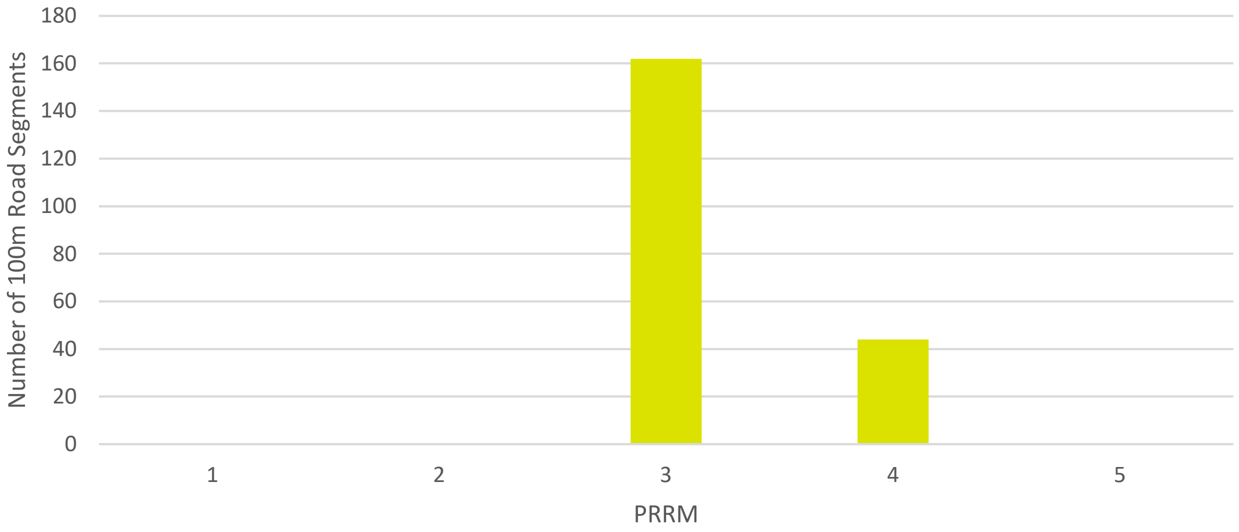


Figure 4.10: Histogram of PRR for Northern District

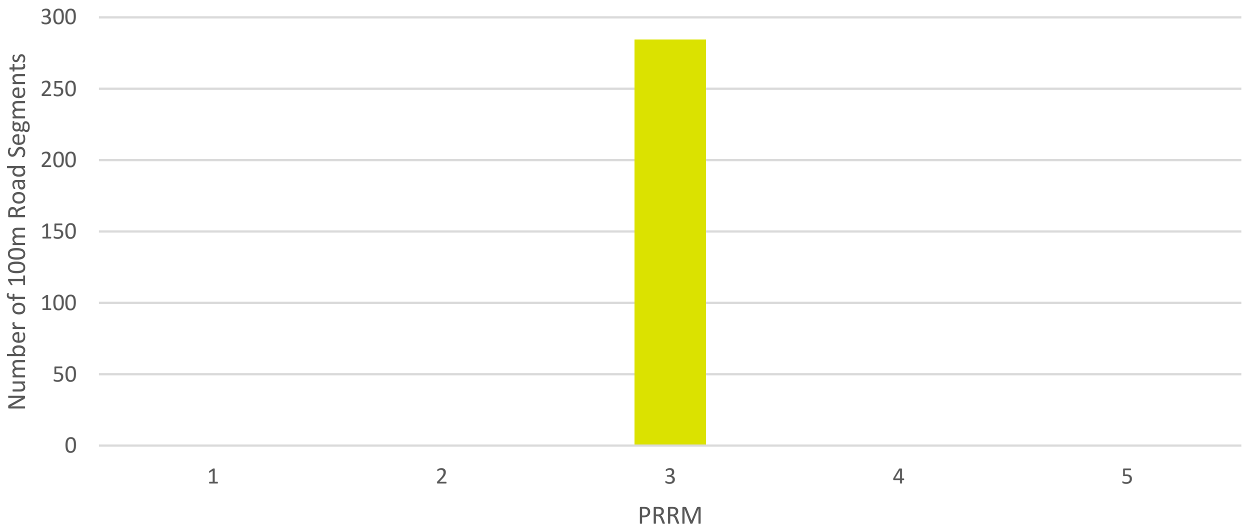


Figure 4.11: Histogram of PRR for North West District

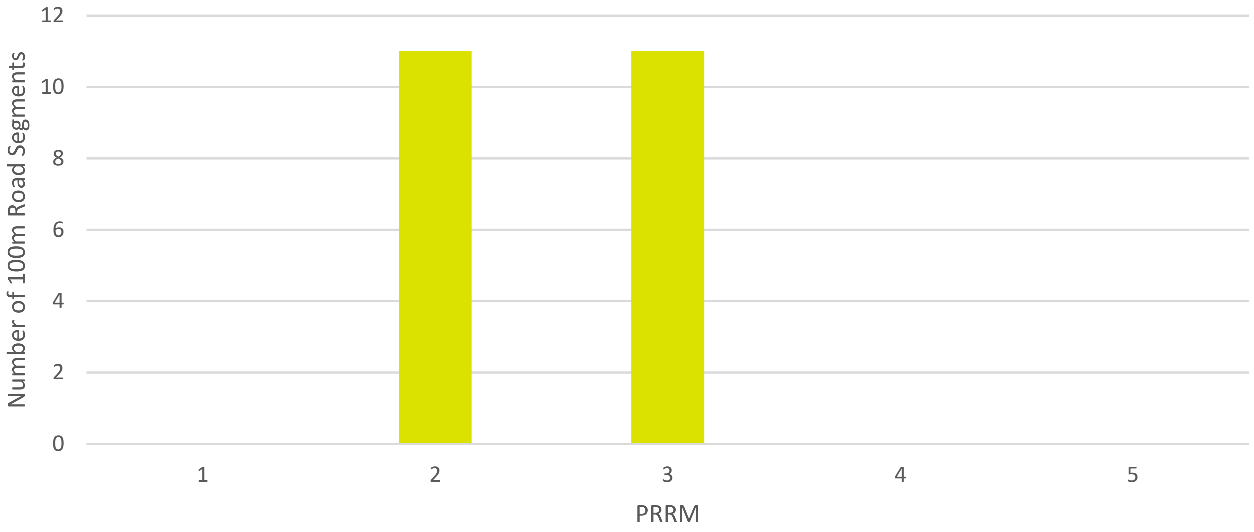


Figure 4.12: Histogram of PRR for South West District

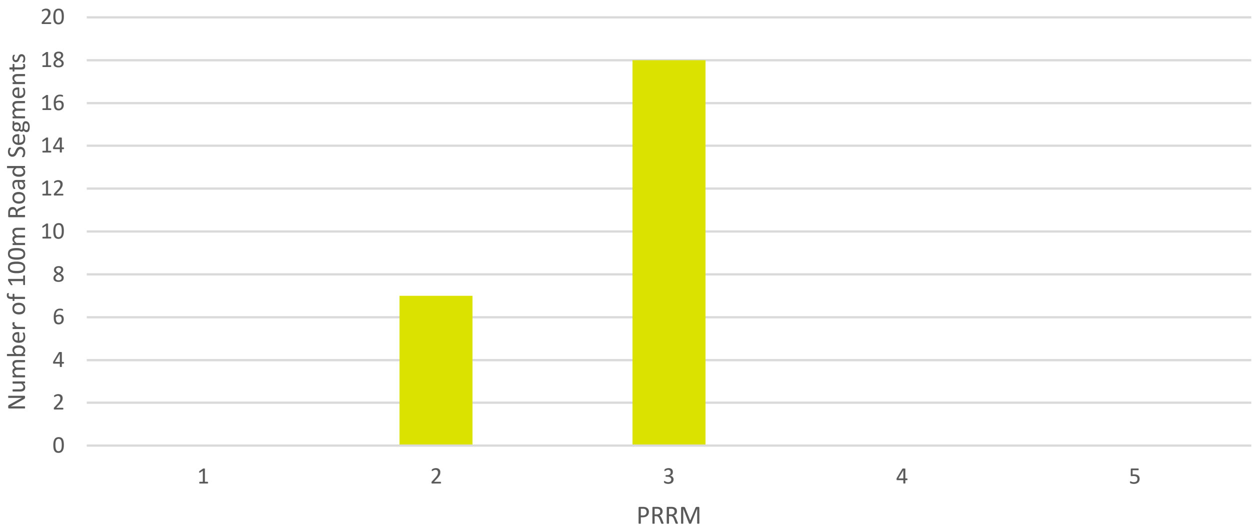
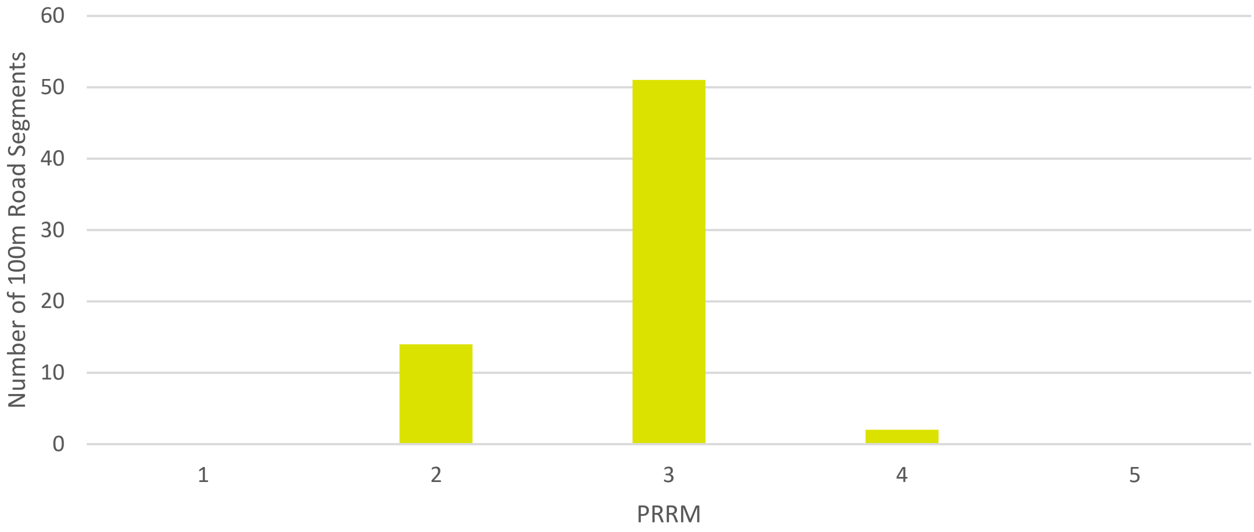


Figure 4.13: Histogram of PRR for Wide Bay Burnett District



5 Conclusions

5.1 Summary

The development of an analytical hierarchical process (AHP) as the basis of an approach for objectively estimating values of residual risk applied to road segments shows promising potential for the allocation of annual asset management program funding. The approach outlined in this report shows the potential to estimate values on the relative residual risks associated with road segments located in different geographical and geological areas subject to differences in traffic and environmental impacts. Critically, the approach relies on an extensive and well-maintained database from the road agency.

Estimates of the pavement residual risk were using the PRRM for road segments that were field rated under NACoE Project A26 (Martin & Hore-Lacy 2017) for the districts from which they were sampled. The preliminary results were weighted to show a range of representative values across the indicators and risk dimensions. These results have been presented both graphically and spatially.

5.2 Challenges

There have been several challenges noted in collating the data required to quantitatively assess all the indicators requested as part of this project. Several of the issues were overcome through the assistance of the Road Asset Data team, and other members of TMR staff who were able to assist in acquiring and managing the required datasets.

However, several of the indicators requested were not specific types of data which TMR records, as these indicators were more qualitative in nature. The issue with these categories is that these tend to be flow-on effects from other impacts, which are already included as indicators. Therefore, there is the potential to double-up on datasets. It was determined that these indicators would be excluded from the PRRM.

5.3 Next Steps

Residual risk estimates can be made either for a sample of road segments, as was done in this report, or a complete road network of defined road segments provided sufficient and accurate data is available for all risk dimensions. Stage 3 of this project will comprise an assessment of the entire TMR state road network. The outcomes of estimating the PRR scores for the whole of TMR's arterial road network will be documented in a summary report. The final stages of this project will include a fully documented report, including a spreadsheet calculator, which will enable TMR to apply the residual risk approach routinely to the TMR road network.

5.4 Recommendations for Further Research

This project is currently planned to finish after Stage 3. Consequently, it is recommended that the residual risk models for ITSRRM and SRRM be undertaken as further research in part of Stage 4 of this project to estimate residual risks for ITS and structures assets, respectively. These two models would be assessed using a similar AHP methodology to what was used for developing the PRRM.

Figure 5.1 and Figure 5.2 outline the proposed approach to estimating the residual risk using the ITSRRM and SRRM models, respectively.

Figure 5.1: Intelligent transport systems (ITS) residual risk model (ITSRRM)

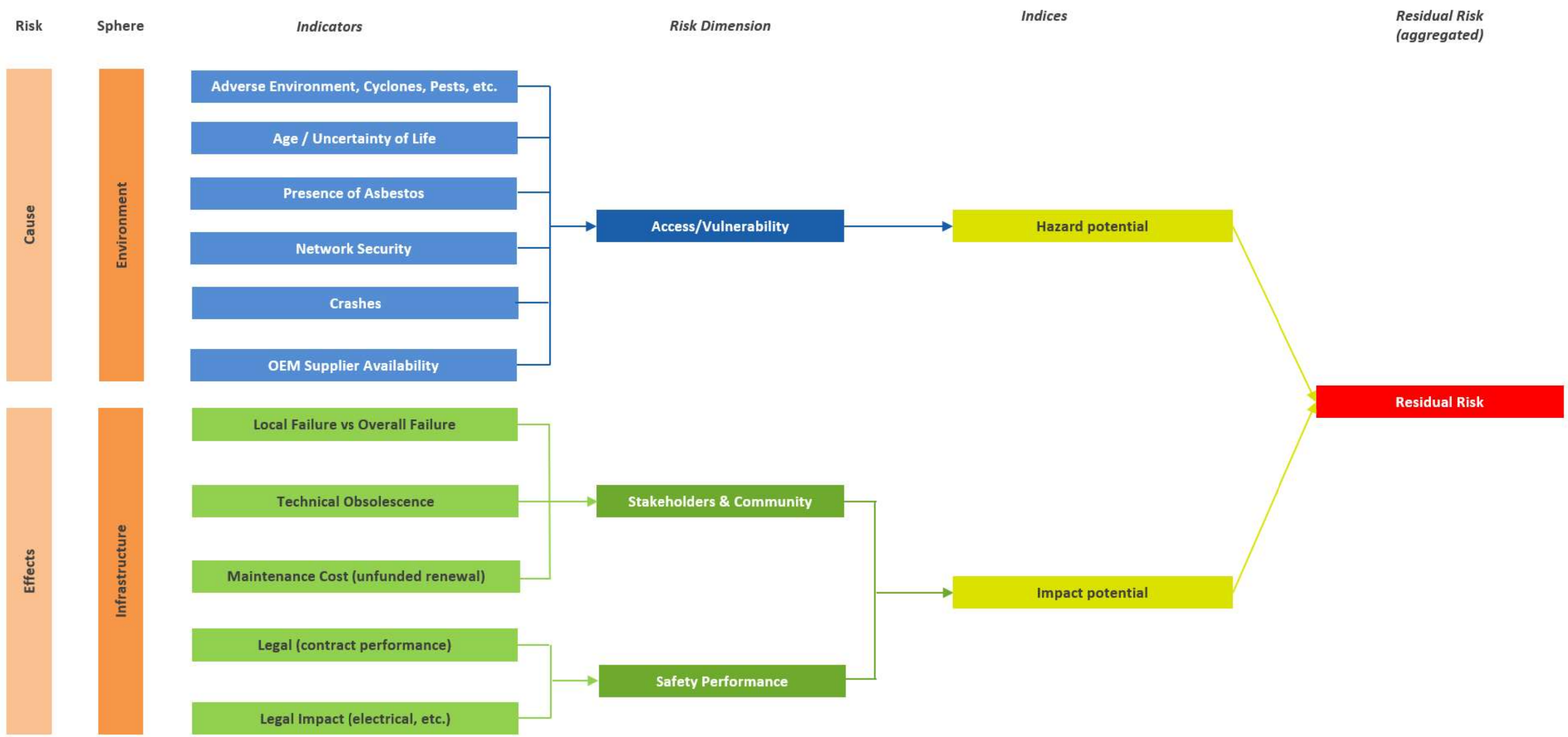
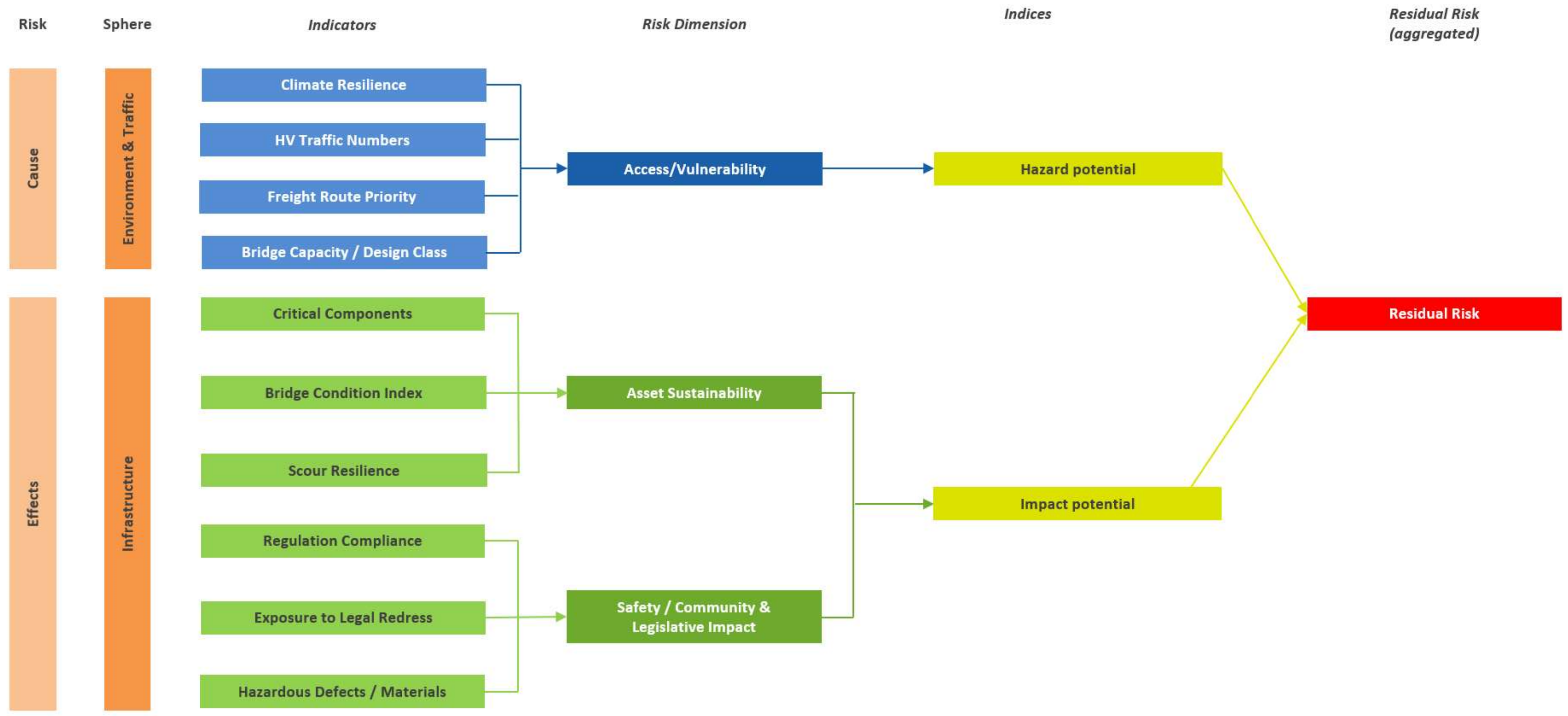


Figure 5.2: Structures residual risk model (SRRM)



References

Australian Automobile Association 2013, *Australian Road Assessment Program (AusRAP) star rating of Australia's national; network of highways*, AAA, Canberra, ACT.

Auerbach, M & Herrmann, C 2014, 'Adaptation of the road infrastructure to climate change', *Transport research arena proceedings*, Paris, France, 10 pp.

Austroads 2004, *Impact of climate change on road infrastructure*, AP-R243-04, Austroads, Sydney, NSW.

Austroads 2008, *Technical basis of the Austroads design procedures for flexible overlays on flexible pavements*, AP-T99-08, Austroads, Sydney, NSW.

Austroads 2011, *Network performance indicators – next generation*, AP-T176-11, Austroads, Sydney, NSW.

Austroads 2015, *Austroads glossary of terms*, AP-C87-15, Austroads, Sydney, NSW.

Beecroft, A & Peters, E 2017, *Accounting for life-cycle costing implications and network performance risks of rain and flood events (2013/14 – 2015/16),* project A4, National Asset Centre of Excellence (NACoE), Brisbane, Qld.

Brown, LC 2002, *Statistics for environmental engineers*, 2nd edn, CRC Press, Boca Raton, FL, USA.

COST 2008, *The way forward for pavement performance indicators across Europe*, action 354, COST (European Cooperation in the field of Scientific and Technical Research), Austrian Transportation Research Association, Vienna, Austria.

Deighton Associates Limited 2014, *Deighton's Total Infrastructure Management System,* (dTIMS), software, version 9, Deighton Associates Limited, Canada.

IPWEA 2015, *International Infrastructure Maintenance Manual*, (IIMM), 5th edn, Institute of Public Works Engineering Australia, Sydney, NSW.

Kadar, P & Sen, R 2016*, Incorporating uncertainty in PMS modelling - phase 1 (year 1 – 2013/14 and year 2 – 2014/15)*, project A5, National Asset Centre of Excellence (NACoE), Brisbane, Qld.

Klose, M 2017, 'Resilience and assessment of climate risk: experiences from road infrastructure in Germany', *paper presented at the PIARC workshop on International Climate Change Adaptation Framework for Road Infrastructure, Cuba, Technical Committee 1.4, PIARC, France*.

Lee, J 2016, 'Benefit of traffic speed deflectometer data in pavement analysis', contract report 010554, prepared for Queensland Department of Transport and Main Roads, ARRB Group, Vermont South, Vic.

Martin, T & Hore-Lacy, W 2017, *Incorporation of the pavement risk score into the pavement condition index*, project A26, National Asset Centre of Excellence (NACoE), Brisbane, Qld.

Nicolosi, V, Augeri, MG & Soccodato, 2019, 'Multi-objective approaches to cross-asset resource allocation in transportation asset management', *Routes/Roads,* no. 381, pp. 37-44.

Queensland Department of Transport and Main Roads 2017, *Routine maintenance guidelines*, TMR, Brisbane, Qld.

Thornthwaite, CW 1948, 'An approach toward rational classification of climate', *Geographical Review*, vol. 38, no. 1, pp. 55-94.

Appendix A Road List

Table A.1 details the roads which were included in the analysis for this study. As mentioned, this road list is based on the roads which were analysed as part of NACoE Project A26. Some roads from the A26 road list were removed due to lack of available data in the indicator categories required for this study.

Table A.1: TMR state-controlled roads included in study, sorted by district

Districts	Road name	Road section ID	PRR score
Central West District	Barcaldine – Aramac Road	573	2.28–2.38
	Isisford – Ilfracombe Road	715	2.08–2.29
	Isisford – Blackall Road	716	2.19–2.54
	Landsborough Highway (Barcaldine – Longreach)	13E	2.26–2.61
	Landsborough Highway (Longreach – Winton)	13F	2.36–2.36
	Capricorn Highway (Emerald – Alpha)	16C	2.49–2.69
	Capricorn Highway (Alpha – Barcaldine)	16D	2.25–2.49
Darling Downs District	Gatton – Helidon Road	314	2.87–2.92
	Toowoomba– Cecil Plains Road	324	2.32–2.6
	Oakey – Cooyah Road	417	2.71–2.74
	Chinchilla – Wondai Road	426	2.1–2.11
	Malanda-Atherton Road	645	3.51–3.52
	Cunningham Highway (Ipswich – Warwick)	17B	2.46–2.62
	Warrego Highway (Ipswich – Toowoomba)	18A	3.02–3.37
	Warrego Highway	18D	2.55–2.87
	New England Highway (Warwick – Wallangarra)	22C	2.92–3.36
	Leichhardt Highway (Miles – Goondiwindi)	26C	2.09–2.17
Far North District	Bruce Highway (Ingham – Innisfail)	10N	3.36–3.7
	Bruce Highway (Innisfail – Cairns)	10P	3.07–3.07
	Captain Cook Highway	20A	3.22–3.27
	Palmerston Highway	21A	3.22–4.08
	Kennedy Highway (Cairns – Mareeba)	32A	3.26–3.33
	Kennedy Highway (Mareeba – Ravenshoe)	32B	3.14–3.48
	Kennedy Highway (Mt Garnet – The Lynd)	32D	2.94–2.95
	Charters Towers – Lynd	98C	2.58–3.17
	Kennedy Developmental Road	99A	2.93–2.98
Fitzroy District	Millaa-Malanda Road	641	3.84–3.89
	Bruce Highway (Gin Gin – Benaraby)	10D	2.53–2.94
	Bruce Highway (Benaraby – Rockhampton)	10E	2.73–3.08
	Carnarvon Highway	24E	2.45–2.77
	Leichhardt Highway (Westwood – Taroom)	26A	2.06–2.83
Mackay Whitsunday District	Bruce Highway (Mackay – Proserpine)	10H	3.12–4.02
	Bruce Highway (Proserpine – Bowen)	10J	2.82–3.26
	Bruce Highway (Bowen – Ayr)	10K	2.81–3.19
	Peak Downs Highway (Clermont – Nebo)	33A	2.45–2.84
	Peak Downs Highway (Nebo – Mackay)	33B	2.63–3.43
Metropolitan District	Brighton Redcliffe Road	122	2.97–3.11

Districts	Road name	Road section ID	PRR score
North Coast District	Redcliffe Road	120	2.9–3.27
	Maroochydore Road	136	2.9–3.06
	Eumundi Kenilworth	484	3.32–3.71
	Bruce Highway	10A	2.93–3.55
	D'aguilar Highway	40A	3.13–3.7
	D'aguilar Highway	41B	3.13–3.7
North West District	Flinders Highway	14E	2.56–2.9
	Barkly Highway	15A	2.29–2.52
	Barkly Highway	15B	2.29–2.52
Northern District	Ayr – Dalbeg	545	2.68–2.79
	Ross River Road	612	2.54–2.76
	Ayr – Townsville	10L	2.8–3.01
	Townsville – Ingham	10M	2.97–3.01
	Flinders Highway	14A	2.56–2.9
	Hervey Range Road	83A	2.83–3.38
South West District	Inglewood – Texas Road	231	2.43–2.5
	Warrego Highway	18E	2.55–2.87
	Carnarvon Highway	24B	2.45–2.77
	Carnarvon Highway	24C	2.45–2.77
Wide Bay Burnett District	Maryborough – Hervey Bay Road	163	3.13–3.18
	Murgon – Gayndah Road	439	3.05–3.4
	Gympie – Brooloo Road	483	3.33–3.7
	Bruce Highway (Gympie – Maryborough)	10B	2.85–2.9
	Bruce Highway (Maryborough – Gin Gin)	10C	2.43–2.68
	Isis Highway (Bundaberg – Childers)	19A	2.22–2.6
	Isis Highway (Childers – Biggenden)	19B	2.79–2.79
	Burnett Highway (Gayndah – Monto)	41C	2.54–2.57
	Burnett Highway (Biloela – Mt. Morgan)	41E	2.56–2.76
	Wide Bay Highway	44A	2.82–3.26
	Bunya Highway (Dalby – Kingaroy)	45A	2.12–2.29
	Bunya Highway (Kingaroy – Goomeri)	45B	2.33–2.69
	Dawson Highway (Gladstone – Biloela)	46A	2.67–2.96

Appendix B Pavement Condition Index

This appendix provides information on the Pavement Condition Index (PCI). This information is extracted from NACoE Project A26 *Incorporation of the Pavement Risk Score into the Pavement Condition Index* (Martin & Hore-Lacy 2017).

B.1 Description and Application

The need for representing the overall condition of an asset in a succinct and effective manner has always been recognised from the early days of asset management. The overall condition was widely used in management and technical reports as well as for supporting funding requests.

The PCI described here represents a formulation of a general descriptor of the asset condition based on the combination of local experience and the European Cooperation in Science and Technology (COST) Action 354 (COST 2008).

The condition of an asset may be described by many parameters. These can be physical measures or index (typically rated) values. To compare or aggregate the various parameters, they must be on the same scale, which is best achieved by normalising or formulating index values. To distinguish the normalised index parameters from measured parameters, they are referred to as condition indices (CI).

The CI offers several advantages, such as:

- It is easily understandable by non-expert stakeholders: a simple scale or even a 'star rating' conveys the condition clearly without demanding any subject knowledge.
- The index value can be converted back to a physical measure, so the content remains accessible for technical requirements.
- The index value expresses the desired and actual level of service (LOS); hence it is a vehicle for measuring performance.

In a pavement management system (PMS) the CI can be used for setting intervention trigger levels and can have a direct impact on treatment selection. This is the most direct way to link agency policies to work program development. At the same time, the budget necessary to achieve the desired LOS can be easily determined.

The combined index (in this case the PCI) can be used as an optimisation target, e.g. to deliver the best overall condition with the available budget.

The following Section is a summary of the key steps in the development and implementation of the PCI incorporated within the Deighton's Total Infrastructure Management System (dTIMS) (Deighton Associates Limited 2014) established for the Queensland Department of Transport and Main Roads (TMR) in South East Queensland.

The scale adopted is consistent with the International Infrastructure Maintenance Manual (IIMM) (IPWEA 2015), and the overall approach is also consistent with the review of network performance indicators for Austroads (2011), where both individual and combined performance indicators are considered.

B.2 Formulation of a Condition Index

Definition: Condition index (CI): one property (e.g. roughness) expressed as an index number on a fixed scale.

A CI is calculated by converting the measured parameter to an index value. There are several ways to transform a measured value from one scale to another. For estimating the CI, a series of linear transformations was selected to reflect the value judgement of both the asset manager and the asset owner.

Performance indicators may be formed by using measured or rated parameters, and ought to meet the following requirements:

- All condition indicators should be on the same scale; the identical scale assists in interpreting and communicating the condition.
- All condition indicators should go in the same direction, e.g. the maximum representing the worst and the minimum representing the best condition.
- A CI should express a value judgement suitable for the given circumstances and parameters, e.g. what is 'good' in one instance may only be 'fair' under different conditions.
- A CI should have a direct link from top management level to operational level, i.e. it must exercise real control over performance. If the outcome of an operation (e.g. maintenance work) cannot be controlled or influenced by a CI, the CI is ineffective as a management tool.

The selected scale of the CI and PCI for the South East Queensland dTIMS is 1–5, where 5 represents a very poor condition and 1 represents a very good condition.

B.3 Remaining Useful Life (RUL) Input into PCI Estimation

B.3.1 Deflection, D_0, And Traffic Load Capacity, CAP, Relationship (RL3)

The following traffic capacity relationships (Equation A1 to Equation A5) using D_0 and D_{200} (from iPAVe measurements) were extracted from Austroads (2008) for asphaltic (AC) and granular (GN) pavement bases. It should be noted that these capacity relationships were for the design of granular and asphaltic overlays on in-service pavements.

$$CAP_{AC} = [\,3.1077 / (D_0 - D_{200})\,]^{4.415} \quad \text{for } WMAPT \leq 25 \qquad \text{A1}$$

$$CAP_{AC} = [\,2.6898 / (D_0 - D_{200})\,]^{5.105} \quad \text{for } WMAPT > 25 \qquad \text{A2}$$

$$CAP_{GN} = 10^{(3.666 - D_{0\,95})/0.422} \quad \text{for } D_{0\,95} \geq 1.134 \qquad \text{A3}$$

$$CAP_{GN} = [\,91.2 / (D_{0\,95} - 0.731)\,]^{1/0.3924} \quad \text{for } 0.8 \leq D_{0\,95} \leq 1.134 \qquad \text{A4}$$

$$CAP_{GN} = 100{,}000{,}000 \quad \text{for } D_{0\,95} \leq 0.8 \qquad \text{A5}$$

where

WMAPT	=	weighted mean annual pavement temperature (˚C)
D_0	=	iPAVe (TSD) maximum deflection (mm)
$D_{0\,95}$	=	95^{th} percentile of maximum estimated iPAVe deflection, D_0 (mm)
D_{200}	=	estimated mean iPAVe deflection 200 mm from the maximum iPAVe deflection (mm)

For granular pavements, the iPAVe D_0 was converted to an FWD D_0 via the following relationship in Equation A6 (Lee 2016) as Equations A3, A4 and A5 are based on FWD deflections:

$$D_{0\text{-}FWD} = 0.9 \times D_{0\text{-}iPave} + 13.8 \qquad \text{A6}$$

The 95th percentile of the maximum deflection, D_0, can be estimated via the coefficient of variation, COV, for the Austroads long-term pavement performance (LTPP) and long-term pavement performance maintenance (LTPPM) sites which was found to be 40%. The 95th percentile of a cumulative distribution, in this case the D_0 distribution, is as follows in Equations A7 and A8 (Brown 2002):

$$D_{0\,95} = 1.645 \times \sigma + \mu \qquad \text{A7}$$

$$D_{0\,95} = 1.658 \times \mu \qquad \text{A8}$$

where

COV = σ / μ

σ = standard deviation of the deflection, D_0, distribution for each 100 m segment

= COV $\times$ μ

μ = mean of the deflection, D_0, distribution for each 100 m segment

Remaining life, RL3, in terms of years, using a known annual traffic loading, $MESA_{annual}$ was estimated as per Equation A9 using the appropriate capacity estimate (CAP_{AC}, CAP_{GN}).

$$RL3 = CAP / MESA_{annual} \qquad \text{A9}$$

where

MESA = millions of equivalent standard axles per lane per year

Table B.1 is a preliminary assessment of the pavement risk score (PRS) and pavement condition index (PCI) ratings against the remaining life estimates. This will need to be reviewed in the light of forthcoming work on residual risk. Note that the remaining life in Table B.1 is expressed in terms of service life which is more relevant than the design life.

Table B.1: Initial assessment of PCI ratings for remaining life (RL) estimates

PCI rating	Expected RL (years)
1	Full service life1 (20–60)
2	75% service life (15–45)
3	50% service life (10–30)
4	25% service life (5–15)
5	< 5

Note: Service life is usually greater than the design life (up to a factor of 2).