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Final Report
Assessing Risk and Variation in Maintenance and Rehabilitation Costs for Road Network

Research Project No: 2003-029-C-05

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PREFACE

This report presents a methodology, analysis process, and results in assessing risk and variation in life-cycle cost estimates for road maintenance and rehabilitation. The report is part of a CRC CI research project, 2003-029-C “Maintenance Cost Prediction for Roads”. The aim of this research project is to estimate variations in life-cycle costing for road maintenance and rehabilitation by taking into account the variability of road asset conditions.

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EXECUTIVE SUMMARY

This report presents the results of research projects conducted by The Australian Cooperative Research Centre for Construction Innovation, Queensland University of Technology, RMIT University, Queensland Government Department of Main Roads and Queensland Department of Public Works. The research projects aimed at developing a methodology for assessing variation and risk in investment in road network, including the application of the method in assessing road network performance and maintenance and rehabilitation costs for short- and long-term future investment.

The objectives of the report are:

- To present a methodology for predicting the variation and likelihood (probability) of whole-of-life outcomes for short- and long-term investments in maintenance of road works given the natural variability of asset properties affecting road asset performance;
- To demonstrate the feasibility of the method on an Australian road network.

The expected outcomes of the study include:

- Greater confidence in predicting future whole-of-life costs for short- and long-term investment in road assets;
- Greater confidence in predicting the nature of future maintenance required and return periods (time intervals) for maintenance and rehabilitation;
- Greater confidence in economic outcomes;

Road asset managers have to make their decisions to invest in maintenance and rehabilitation based on uncertainties, such as uncertainty in forecasting future road deterioration, in current and future road asset conditions, in types and number of vehicles that use the road network, in the effects that these vehicles have on the road pavement, in climatic condition, soil condition that affect the road network and so forth. They have limited information on risk of errors and degree of variation which is likely to occur as the result of these uncertainties. Attempts have been made by this research project to quantify the uncertainties of these road network related input variables in predicting the risk of errors and variation for road maintenance and rehabilitation investment. A method based on the probability risk-based concept using statistical analysis, simulation technique and categorisation of road networks has proven that the method is practical in analysing these types of complex issues.

In this method, road networks are characterised into different groups, each group possesses common characteristics. The uncertainties or variability of road related input variables are statistically quantified for each category. The combination of categorisation of road networks and the quantification of the variability of road network characteristics for each road category reduces substantially the degrees of freedom for the analysis. This combined technique provides an alternative solution to these complex problems. In this analysis method, the variability and uncertainties of road-related variables are incorporated in the network performance and investment analysis by the simulation technique. The output network performance and investment estimates will be in the form of statistical information. From the statistical information of the outputs, road asset managers can investigate risk of errors and the degree of variation in road network performance and investment estimates. They can adjust their budgets appropriately based on the amount of risk involved and the degree of variation in the predicted cost and predicted network performance.

In this study, road network performance and investment that will be assessed include:

- Whole-of-life cycle costs

- Nature of maintenance and rehabilitation activities
- Cost per kilometre
- Physical performance characteristics

Primary inter-city road networks of approximately 4,500 km are used in the analysis as a case study. Discussion of the results is given below.

Whole-of-life cycle costs

Road asset managers can use the statistical information of the output to estimate the risk of errors in predicting network performance and investment costs. They can investigate the likelihood or probability of costs of not being exceeded for a certain degree of confidence. For instance, they can investigate the mean cost estimate with a probability of occurrence of approximately 50 per cent. Or they can investigate higher levels of probability of occurrence, for instance, 90th or 95th percentile for which there is, respectively, 10 and 5 per cent probability that the cost will be exceeded. The statistical information including the mean, standard deviation and probability distributions can be used to assess levels of risk in cost estimates. Table S1 shows examples of calculated levels of risk (probability of occurrence) when it is assumed that costs are blown out by 10 and 20 per cent from the mean estimates for the 4,500 km road networks. These levels of risk assessment are calculated for a 5-year period. Decision-makers will have informed knowledge on the risk (probability) of errors in the prediction which is very helpful in preparing a realistic budget for road network maintenance and rehabilitation.

Table S1 Risk or probability of occurrence of cost blowouts

Years of Cumulative Cost Estimates	Mean Cost Estimates (A$ Million)	10% Blown out Costs (A$ Million)	Risk or (probability of occurrence) (%)	20% Blown out Costs (A$ Million)	Risk or (probability of occurrence) (%)
1st year	39.95	43.29	36.0%	47.22	29.7%
2nd year	48.61	53.47	37.4%	58.33	28.8%
3rd year	69.46	76.40	35.2%	83.34	25.6%
4th year	115.30	126.83	32.6%	138.36	20.1%
5th year	115.23	170.73	32.2%	186.30	18.7%

Nature for maintenance and rehabilitation activities

Table S2 shows typical results of time-intervals for maintenance and rehabilitation treatments for a road category. The table shows means and standard deviations of the time-intervals. In the Table, WNR-Good-Bt-Flx-(1.5k-3k) represents road category in wet non reactive soil, with pavement roughness of IRI less than 2.31, bitumen surfacing, flexible pavement and carrying traffic of AADT between 1501 and 3000 vehicles.

The first time interval is the time required for a treatment from the start of the analysis year. The start of the analysis year for this analysis is 2006. The second time interval is the return period for a major rehabilitation after the first treatment has been carried out. The percentage (%) of treatment types represents the possibility or percentage of a selected treatment that is likely to occur. There may be different possibilities of selected treatments for a road category. These different possibilities of treatment resulted from the variability of road-related input variables and the random combination of the variability represented in the analysis and random simulation. This information allows road asset managers to be aware that there are other possibilities in the treatments that can occur or can be selected. Mean and standard deviation values of the time intervals presented in the tables provide flexibility of the variation in selecting a time for treatments.

Cost per kilometre

Cost per kilometre was calculated from the whole-life cycle cost of 25-year period of each road category divided by the number of kilometres of road length within that category. Table S3 shows typical results of means and standard deviations of costs per kilometre. This information can assist road asset managers to make informed decisions in relation to investment costs and the degree of variation in the predicted costs for each road category.

Physical performance characteristic

Figure S1 shows an example of predicted mean and mean plus one standard deviation of the whole-of-life cycle performance for pavement roughness for a 25-year period of a road category in wet non reactive soil having initial roughness of less than 2.31, bitumen surfacing, flexible pavement and carrying traffic of AADT between 1500 to 3000 vehicles. In this example, the mean IRI values are less than 4 for the whole-life-cycle. The mean value represents approximately 50 per cent probability of occurrence. When we consider the IRI values of mean plus one standard deviation which represents approximately 83.33 per cent of occurrence, the maximum value of mean plus one standard deviation of most road categories are below 5 IRI. From this information, road asset managers can investigate in detail the degree of roughness variation and probability of occurrence of pavement roughness for the whole-of-life cycle of their road networks to gain more confidence in the level of service they provide to the community.

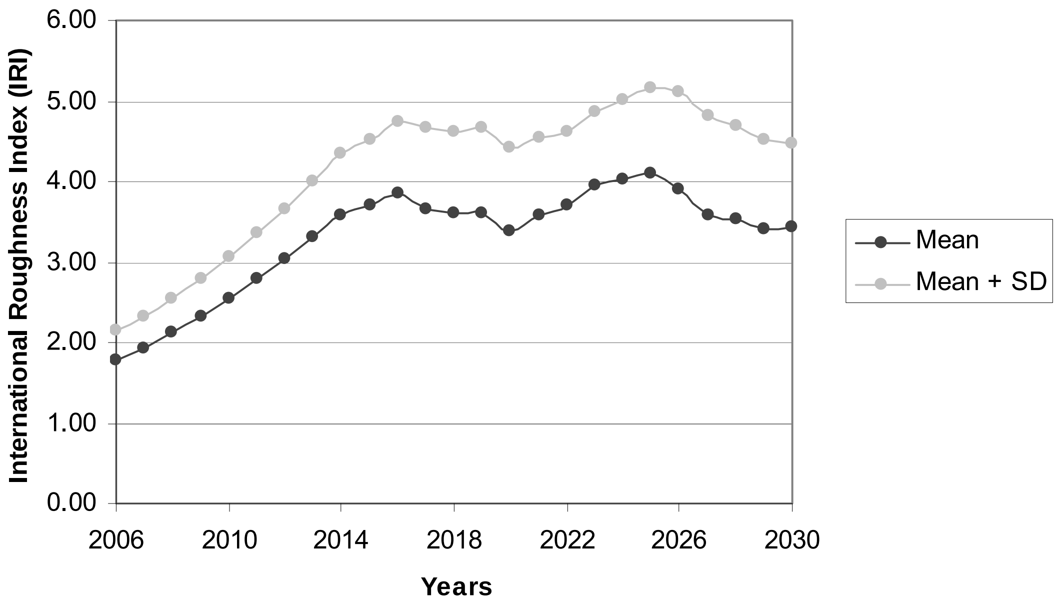

Figure S1 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for WNR-Good-Bt-Flx-(1.5k-3k) road category

Table S2 Mean and Standard Deviation Values for Time-Interval for Maintenance and Rehabilitation for Wet Non Reactive Soil

Description	1st Time Interval (Years)				2nd Time Interval (Years)			
	Mean (Years)	SD (Years)	% of Treatment	Treatment Types	Mean (Years)	SD (Years)	% of Treatment	Treatment Types
WNR-Good-Bt-Flx-(1.5k-3k)	4.3	1.2	34%	Reseal-15% Cracked	13.5	1.7	34%	Granular Overlay-5IRI& 10% Cracked
	11.1	1.9	66%	Granular Overlay-5IRI& 10% Cracked	9.4	0.4	66%	Granular Overlay-5IRI& 10% Cracked

Note: WNR-Good-Bt-Flx-(1.5k-3k) is the road category located in wet non-reactive soil areas, IRI<2.31, bitumen surfacing, flexural pavement type, 1500<AADT≤3000.
IRI is the International Roughness Index. SD is the standard deviation.

Table S3 Mean and Standard Deviation Values of Cost/Kilometre for Road Categories for Wet Non Reactive Soil

Description	Km	(Mean , SD) of Structure Number (SN)	Cost per Kilometre (Mean) A$ million	Cost per Kilometre (SD) A$ million	Coefficient of Variation
WNR-Good-Bt-Flx-(1.5k-3k)	269	(3.66, 0.92)	0.4439	0.1068	0.241
WNR-Good-Bt-Flx-(3k-5k)	181	(3.73, 1.06)	0.4701	0.1483	0.316
WNR-Good-Bt-Flx-(5k-10k)	154	(3.76, 0.97)	0.5404	0.2152	0.398

Note: WNR-Good-Bt-Flx-(1.5k-3k) is the road category located in wet non-reactive soil areas, IRI<2.31, bitumen surfacing, flexural pavement type, 1500<AADT≤3000.
WNR-Good-Bt-Flx-(3k-5k) is the road category located in wet non-reactive soil areas, IRI<2.31, bitumen surfacing, flexural pavement type, 3000<AADT≤5000.
WNR-Good-Bt-Flx-(5k-10k) is the road category located in wet non-reactive soil areas, IRI<2.31, bitumen surfacing, flexural pavement type, 5000<AADT≤10000.

1. INTRODUCTION

Realistic estimates of short- and long-term costs for maintenance and rehabilitation of road asset management should take into account the variability of the stochastic characteristics of asset conditions of road networks. The probability theory has been widely used in assessing life-cycle costs for bridge infrastructure by many researchers, such as Zayed et.al. (2002), Kong and Frangopol (2003), Liu and Frangopol (2004) and Noortwijk and Frangopol (2004). The outcomes of the analyses were the statistics of the cost estimates. The output statistical information of the cost estimates produced useful information for further analysis in selecting cost estimates with a reasonable degree of confidence (e.g. 90th or 95th percentile). However, very few studies were reported to take into account the variability of stochastic characteristics of road asset condition for road network investment analysis (Salem et. al. 2003, Zhao et. al. 2003). In the existing studies, analysts usually made assumptions about the stochastic characteristics of road network conditions and other relevant data for investment analysis.

It is evident from the review of the literature that there is very limited information relating to the methodology that uses the stochastic characteristics of asset condition and road data in assessing costs for road maintenance and rehabilitation (Piyatrapoomi and Kumar, Sept. 2004).Two research projects conducted by Queensland University of Technology, RMIT University, Queensland Government Department of Main Roads and Queensland Government Department of Public Works attempted to incorporate the natural variability of stochastic characteristics of road asset condition and other critical input variables in the investment analysis and to develop a practical method in assessing risk of errors and degree of variation in road network performance for investment. Research in the first two-year project, CRC CI 2001-010-C titled “Investment Decision Framework for Infrastructure Asset Management” aimed at developing a methodology to assess risk and variation in network performance for maintenance and rehabilitation investment of road networks.

The second project study, CRC CI 2003-029-C titled “Maintenance Cost Prediction for Roads” builds upon the knowledge developed in the CRC CI 2001-010-C project to develop a detailed investment analysis. This report presents the results of the second project conducted by the four research partners. The method was applied to assess whole-of-life-cycle network performance for primary Queensland inter-city road networks of approximately 4500 km.

1.1 Purposes of the Report

This report presents the methodology and results of a case study. The outcome of the study includes risk and variation for;

- Long-term physical performance of road networks
- Nature of maintenance and rehabilitation activities selected based on different options of assigned treatments
- Cost per kilometre
- Whole-life cycle costs

2. BACKGROUND

This section discusses the background and outcome of the previous project CRC CI 2001-010C "Investment Decision Framework for Infrastructure Asset Management. Queensland University of Technology, RMIT University, Queensland Government Department of Main Roads (QDMR) and Queensland Government Department of Public Works (QDPW) undertook this research project with the Cooperative Research Centre for Construction (CRC) for Construction Innovation since 2002. The project was completed in 2004.

2.1 Review of Previous Project

In the first project, the research team developed a procedure for assessing the stochastic characteristics of road data and a methodology for predicting risk and variation in network performance. These methods included:

- A method for optimising asset data collection;
- A method for calibrating deterioration prediction models;
- A method for assessing risk-adjusted estimates for life-cycle cost estimates.

2.1.1 A Method for Analysing Optimal Data Collection

To enable the effective management of any infrastructure asset, knowledge of current conditions and understanding of deterioration rates for critical condition variables are essential inputs for estimating fund allocations for maintenance and rehabilitation work. For road assets, pavement strength is one such critical condition parameter. However, the cost of collecting data on road pavement strength is relatively high.

In developing a data collection program for pavement strength for road asset management at the network level, it is necessary to make a decision on the method of data collection, the time interval between surveys, longitudinal sampling intervals, data parameters to collect, parameters to use in the analysis, and selection of characteristic values.

Based on the probability-based goodness-of-fit technique, the project team developed a method for optimising pavement strength data collection for network application.

In this stochastic analysis of pavement strength, pavement strength data were sampled by the Falling Weight Deflectometre (FWD) at 200 metre intervals from road networks located in three climatic and soil conditions of Queensland. These sampled data included:

- an approximate of 92 km sampled data of pavement strength of road networks in wet non-reactive soil
- 60 km sampled data of pavement strength of road networks in dry non-reactive soil, and
- 30 km sampled data of pavement strength of road networks in dry reactive soil.

The stochastic properties of road pavement strength data over these extensive lengths of road network were assessed. A brief discussion of the analysis method is discussed in Annex 1.The conclusions drawn from this study are:

- The method used would be suitable for determining optimal intervals of FWD tests for network analysis of road pavements, in a broad range of different circumstances (eg, environmental conditions, soil types, traffic loading, and pavement types).
- That the optimal spacings between alternate wheel paths for pavement deflection found are as follows:
  - 1,000m in the North Queensland National Highway segment (wet climate, non-reactive soils);
  - 700m in the south-west Queensland regional road segment (dry climate, reactive soils), and
  - 1400m in the south-west Queensland regional road segment (dry climate, non-reactive soils.
- These satisfactory results are likely to occur from network level analysis if pavement deflection testing is limited to the outer wheel path.
- Road agencies can analyse their data using this method to determine the most appropriate spacing for their networks and other road owners can readily implement these recommendations in their asset management practices.

2.1.2 A Method for Calibrating Deterioration Prediction Models

A method was developed for calibrating road performance prediction models for local condition. A model that can accurately predict the rate of road deterioration condition will enable road asset managers to better predict costs for maintaining their road infrastructure. Attempts have been made in almost every country to calibrate these deterioration prediction models to suit each country's specific conditions. The variability in road data arising from the variability in climatic condition, soil condition, materials used, user vehicles and so forth has given less confidence in using the calibrated functions when the functions do not show a strong correlation or relationship with recorded data.

The proposed method is based on the probability-based theory and Monte Carlo simulation technique. In this method, the stochastic characteristics of input variables of the deterioration prediction models were quantified by probability distributions. Monte Carlo simulation method was used to simulate the variability of the input variables of the prediction model to predict the variability of the model output. The model output is then tuned so that the predicted variability demonstrated by modelled deterioration closely replicates actual variability of measured deterioration. In this method, the degree of goodness-of-fit between the calibrated function and recorded road data is explicitly assessed and identified. Thus, this method gives a higher degree of confidence in using the calibrated models.

The method has been used to determine the calibration factors (as a case study) for HDM-4's deterioration prediction models of road pavement roughness for the state of Queensland. In theHDM-4's road pavement deterioration model used in this study, the total annual rate of change in road pavement roughness is a function of pavement strength deterioration, pavement cracking, pavement rutting, pothole and climatic condition. A brief discussion of the analysis method is presented in Annex 2.

Using the probability-based calibration method, the calibration factors for the annual rates of change in road pavement roughness were found, for the tropical region of Queensland (Bruce Highway), to be:

For the tropical region of Queensland (Bruce Highway)

Thickness	Calibration Factor (Kgp) for HDM-4 annual change in pavement roughness model
200-300 mm	0.55
300-400 mm	0.35
400-500 mm	0.25
500-600 mm	0.20

For the dry region of Queensland (Landsborough Highway)

Thickness	Calibration Factor (Kgp) for HDM-4 annual change in pavement roughness model
100-200 mm	0.78
200-300 mm	0.48
300-400 mm	0.48
400-500 mm	0.43

These calibrated factors for road deterioration prediction model for road pavement roughness provide realistic annual rates of change of road pavement roughness. Hence, the prediction of pavement performance would provide realistic estimates for road maintenance and rehabilitation costs.

2.1.3 A Methodology for Risk-Adjusted Assessment of Cost Estimates for Road Maintenance and Rehabilitation

The method for risk-adjusted assessment of cost estimates that takes into account the variability of asset data is developed. The term "risk-adjusted" in cost estimates is a cost that is adjusted according to an acceptable risk level or probability of being exceeded.

According to the risk-adjusted assessment method, the variability of asset conditions are statistically modelled and incorporated into the analysis using simulation technique. The Latin-Hypercube sampling technique, that can simulate a small number of data, is used which results in a more practical method for the analysis. A brief discussion of the analysis method is presented in Annex 3.

2.1.4 Outcome of Previous Project

As mentioned, the outcomes of the first research project (CRC CI 2001-010-C "Investment Decision Framework for Infrastructure Asset Management) include a method that can be used to identify optimal intervals for pavement strength data collection at the network level for network analysis; a method for analysing calibration factors for pavement performance models and a method for risk-adjusted assessment for cost estimates for road maintenance and rehabilitation investment. The outcome of the project led Queensland Government Department of Main Roads to allocate funding in the 2005/6 budget specifically for collecting pavement strength data collection for network application.

The pavement strength data of the network and the method developed in the previous project will be used to demonstrate the application of the method in predicting the risk (likelihood or probability) and variation of short-term and whole-of-life-cycle network performance for investments in maintenance and rehabilitation for road networks.

3. PROJECT OBJECTIVES

The objectives are:

- To develop a detailed methodology for predicting the risk (likelihood or probability) and variation for short-term and whole-of-life cycle investments in the maintenance of road works given the natural variability of asset properties affecting road asset performance;
- To demonstrate the feasibility of the method for an Australian road network.

The expected outcomes of the project include:

- Greater confidence in predicting short- and long-term investments in road assets;
- Greater confidence in predicting the nature of future maintenance required and return periods (time intervals) for maintenance and rehabilitation;
- Greater confidence in economic outcomes;
- Greater accuracy in predicting the relationships among the variability of critical input variables, such as traffic, environmental zones, roughness, etc. on predicted outcomes (i.e. roughness, costs)
- Greater confidence in assessing cost per kilometre for each road category.

4. DATA COLLECTION AND DATA ANALYSIS

Queensland government Department of Main Roads monitors road asset condition every year. These data are stored and managed by a database called "A Road Information Management System (ARIMS)". Figure 1 shows road networks in red lines where data were collected and used for this case study. For details on collecting data on road asset condition, refer to Queensland Government Department report on Guideline for road data collection (QDMR 2002). In this case study, road networks of approximately 2,295 km, 1195 km and 1408 km represented wet non-reactive soil, dry non-reactive soil and dry reactive soil, respectively. In the analysis of data, road sample data were analysed by the statistical method. Road sample data were tested for goodness-of-fit with theoretical probability distributions. Once the theoretical probability distributions that had a goodness-of-fit with the road sample data were identified, then the mean and standard deviation values were quantified.

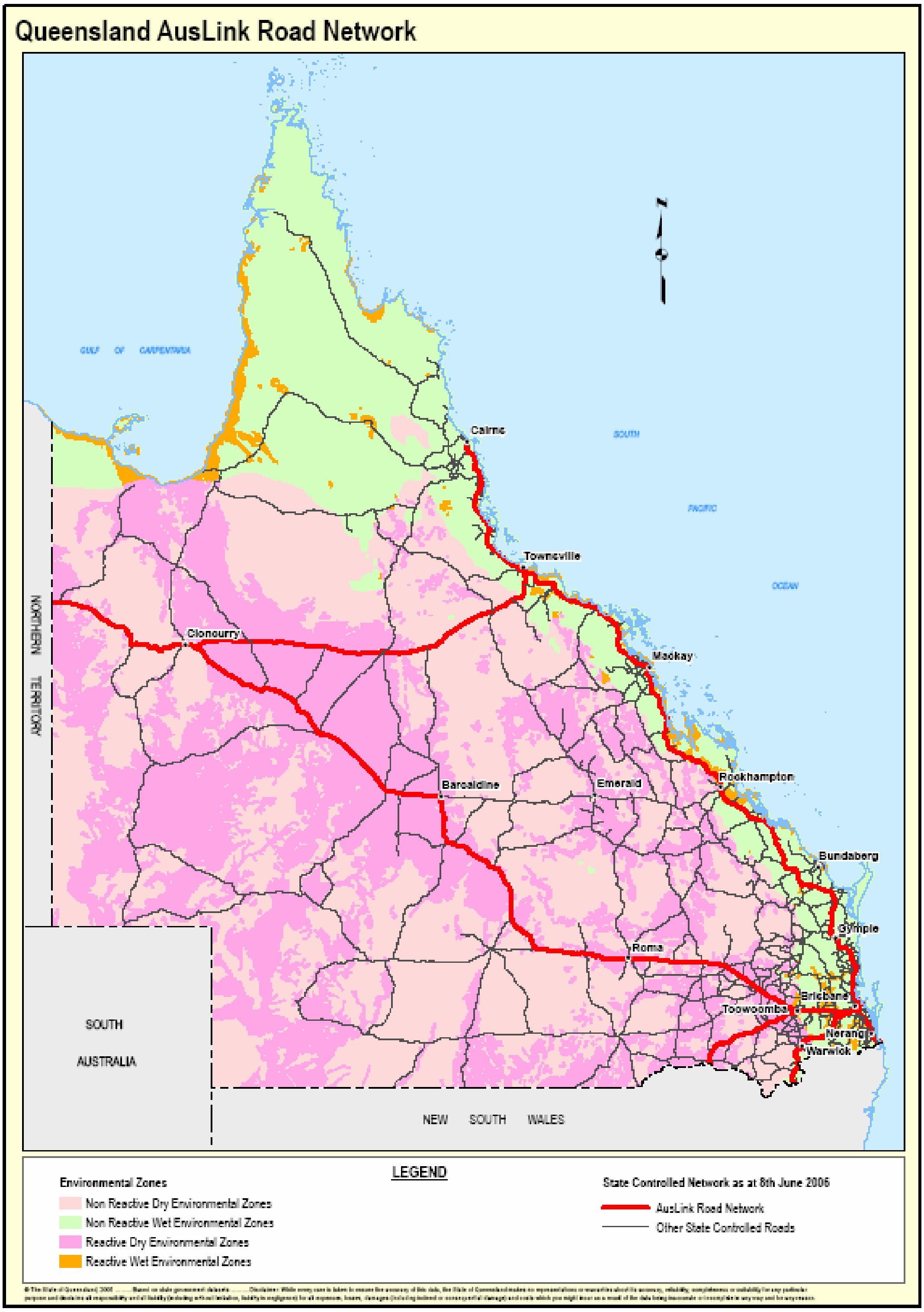

Figure 1 Road networks

5. APPLICATION

The Industry can use the developed methods to improve road asset management practice. The method for analysing optimal data collection for pavement strength can be used for designing or planning pavement strength data collection programs at the network level. The analysis method has demonstrated its benefit by saving expenditure of approximately 70 to 80 per cent in data collection costs for Queensland Government Department of Main Roads for network data collection.

Understanding future road network performance is important for managing road assets and for predicting both short- and long-term budgets. It is recognised that accuracy in allocating and budgeting funding for road asset management depends on the accuracy in predicting road network performance. The nature of the variability of road asset condition, environmental characteristics as well as the characteristics of vehicles using the networks make it difficult to predict future road network performance. Worldwide attempts have been made to calibrate road performance prediction models to reflect local condition. Using the knowledge of variability of road asset condition and the variability of relevant road data, a reliable method for calibrating road performance predicting models was developed by this research study. This method tunes the accuracy of the models by examining the relationship between actual or observed variability of road asset condition and predicted variability obtained from road performance predicting models. The calibration is conducted by adjusting the model so that the variability of actual road asset condition and the predicted variability obtained from the prediction model are similar or the same. Road agencies can reliably predict future road network performance using this technique.

Realistic cost estimates should take into account the variability of road network characteristics. Currently, the mean values of input parameters such as road asset condition, annual average daily traffic (AADT) and other input parameters are used for calculating maintenance and rehabilitation costs. The mean values represent approximately 50 per cent chance of occurrence. The variation in cost estimates arising from the nature variability of road network characteristics should be assessed. A practical method for assessing risk and variation in road network performance and investment has been developed. The method uses a simulation technique and probabilistic method in the assessment. Latin-Hypercube simulation (sampling) technique was recommended for this analysis method since it has been proven to be effective in simulating small sample sizes for the analysis. The Latin-Hypercube simulation technique allows an analysis of complex systems to be economically and viably conducted. Risk and variation in network performance and investment can be investigated using this method.

6. OUTLINE OF CURRENT PROJECT

The objective of the current project (CRC CI 2003-029-C “Maintenance Cost Prediction for Roads”) is to demonstrate the applicability of the methods developed in the first project. The method uses the variability of asset conditions, calibration factors for pavement performance models suitable for local condition and the risk-adjusted method, in predicting the likelihood (probability) of short-term and whole-of-life investments for road maintenance and rehabilitation for an Australian road network. A road network of approximately 4500 km located in three climatic and soil conditions was used as a case study.

The potential benefits of the project include:

- Road agencies can better understand expected patterns of future performance of road network and expected variability in observed performance.
- Road agencies can better understand the risk and consequences of future budget allocations for maintenance.
- Road agencies will be better informed in making a stronger case to the federal central government for a needs-based budget allocation
- These benefits will be equally applicable and useful to private sector network maintenance managers.
- Road network managers will be able to formulate strategies for data collection that are more cost effective for high cost/high value asset data.

7. METHODOLOGY FRAMEWORK FOR ASSESSING CONFIDENCE IN ROAD NETWORK PERFORMANCE

This section presents a framework of analysis for the second project (CRC CI 2003-029-C “Maintenance Cost Prediction for Roads). The aim of the analysis is to predict the likelihood (probability) of short-term and whole-of-life investments for road networks given the natural variability of asset properties affecting road asset performance. The method of the analysis is used for the network or strategic analysis. Figure 3 shows the schematic chart of the framework.

1) The first step is to identify network performance characteristics to be modelled in the analysis.

2) Identify critical input variables that significantly affect road network performance and, hence, cost estimates.

3) Categorise road networks and variability assessment. In this step the analysed road network is categorised into different categories, so that each category has common characteristics. The variability of critical input variables is assessed for each category. This step allows the possibility of incorporating the variability of road data for road networks into the analysis.

4) Establish probability distributions and statistical information (means, standard deviation and etc.) of the stochastic characteristics of the critical input variables of the road network.

5) Use Latin-Hypercube Sampling Technique to sample data from the probability distributions of the identified critical input variables.

6) Use a calculation tool to predict network performance characteristics (HDM-4 is used in this study). At this stage, it is necessary to calibrate HDM-4 prediction models to reflect observed local road asset condition.

7) Calibrate deterioration prediction models to reflect the rate of change in road pavement condition for local condition.

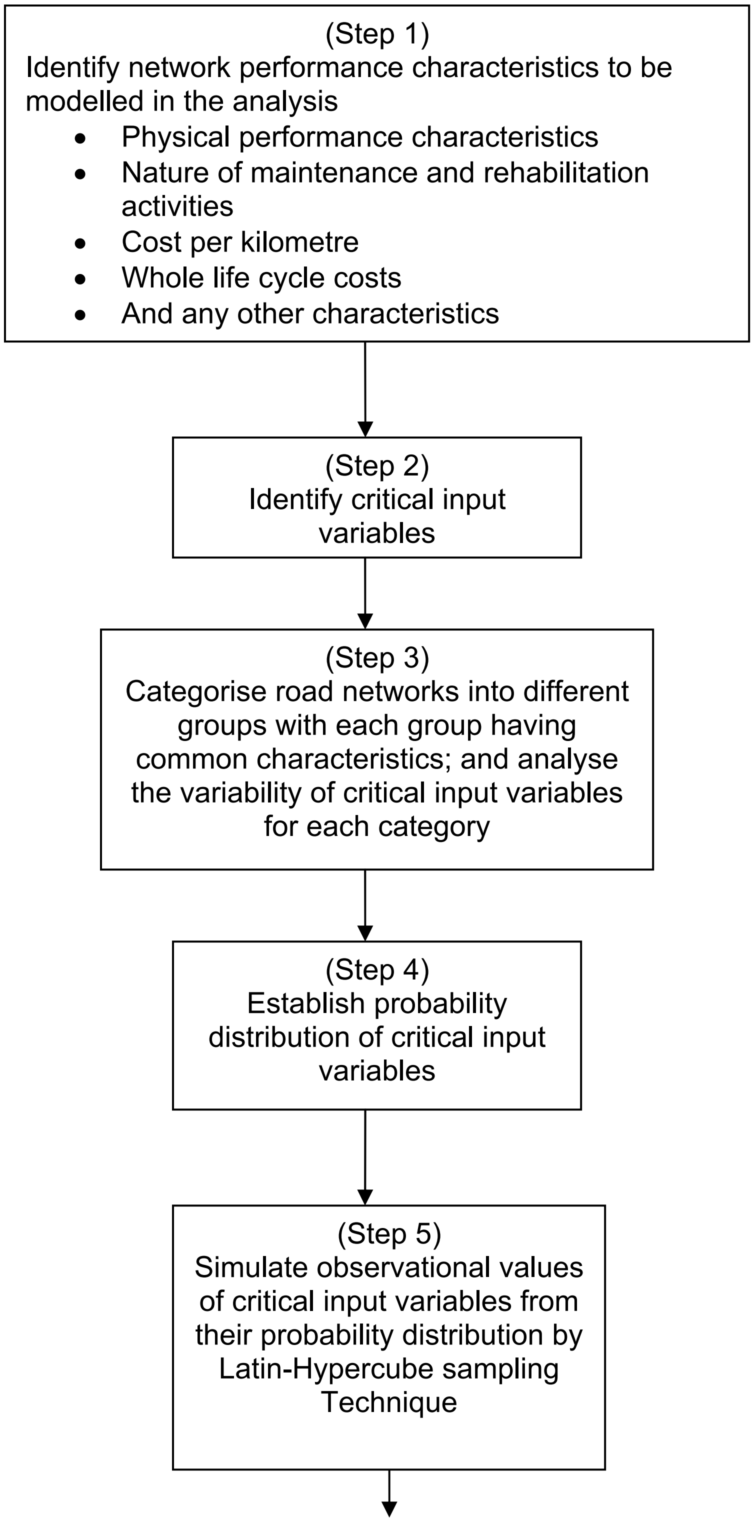

Figure 3 Flow chart for assessing variation in life-cycle costs

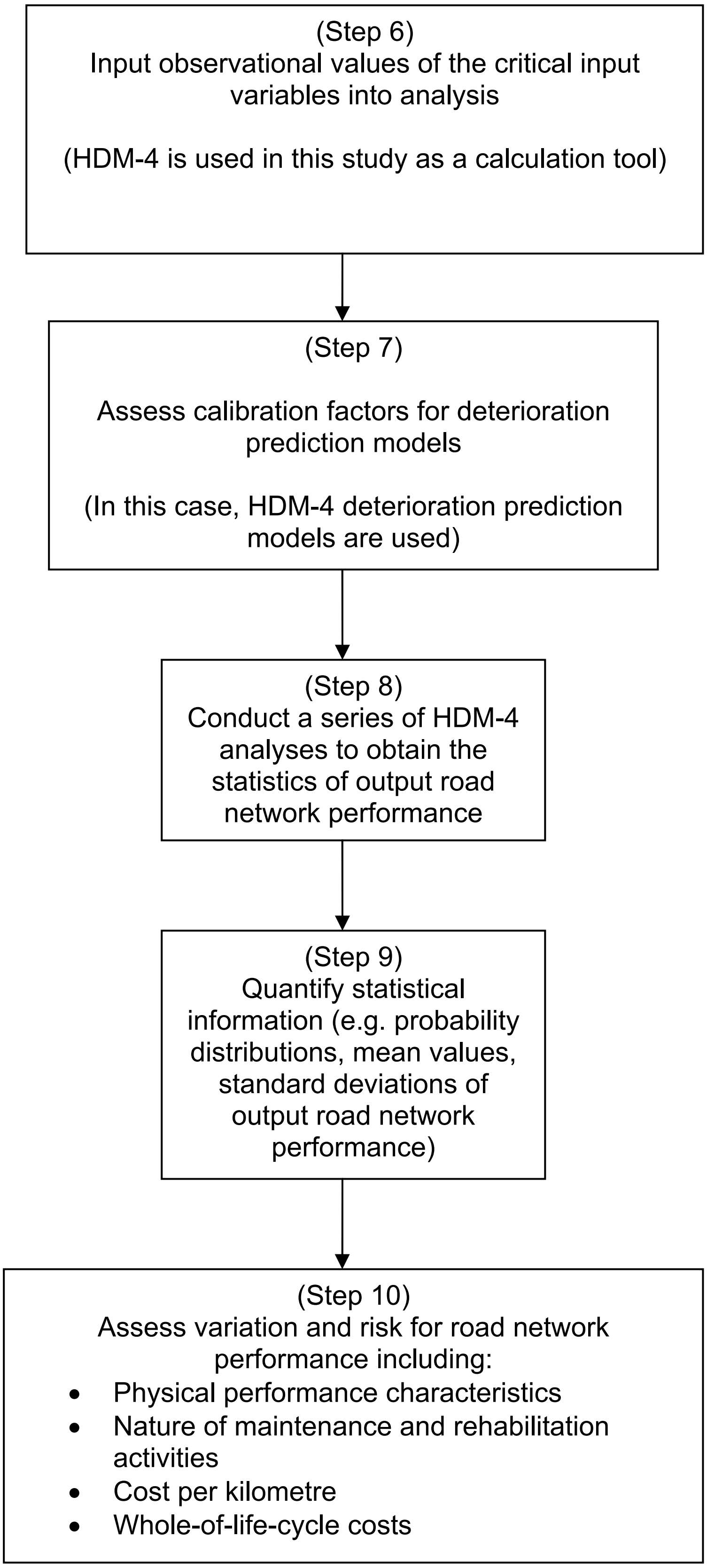

Figure 3 Flow chart for assessing variation in life-cycle costs (continued)

8) Conduct a series of HDM-4 analyses to obtain the statistics of output road network performance characteristics.

9) Quantify the statistical information (e.g. probability distribution, mean, standard deviation, etc) of the output road network performance characteristics.

10) Investigate the degrees of variation for the established probability distributions of the output road network performance characteristics.

7.1 Step1: Identify road network performance

The first step is to identify network performance characteristics to be modelled in the analysis. Road network performance outcomes to be investigated in this study include:

- Physical performance of road network
- Nature of maintenance and rehabilitation activities
- Estimated cost per kilometre
- Whole-of-life-cycle costs

7.2 Step2: Identify critical input variables

An important step in the analysis is to identify critical input variables. It may not be feasible to incorporate the variability of all input variables in the analysis. To explore the possibility of incorporating the variability of input variables that are critical for road deterioration prediction, a case study was conducted to identify such variables. HDM-4 roughness deterioration model was used in the analysis. The HDM-4 roughness deterioration model is a function of pavement strength, traffic loading, cracking, rut depth and initial roughness of the analysis year. The HDM-4 roughness deterioration model is given below:

$$\Delta RI = Kgp\ (\Delta RIs + \Delta RIc + \Delta RIr + \Delta RIt) + m\ Kgm\ RIa \qquad (1)$$

$$\Delta RIs = a_0 \exp(mKgmAGE3)(1 + SNPK_b)^{-5} YE4$$

$$\Delta RI_c = a_0 \Delta ACRA$$

$$\Delta RI_r = a_0 \Delta RDS$$

$$\Delta RI_e = mK_{gm} RI_a$$

Where;

Kgp	=	calibration factor, Default value = 1.0
ΔRI	=	total annual rate of change in roughness
ΔRIs	=	annual change in roughness resulting from pavement strength deterioration due to vehicles
ΔRIc	=	annual change in roughness due to cracking
ΔRIr	=	annual change in roughness due to rutting
ΔRIt	=	annual change in roughness due to pothole
ΔRIe	=	annual change in roughness due to climatic condition
a_0	=	constants for roughness due to pavement strength, cracking and rut depth
m	=	environmental coefficient

Kgm	=	calibration factor for environmental coefficient
AGE3	=	pavement age since last overlay or reconstruction
$SNPK_b$	=	adjusted structural number of pavement due to cracking
YE4	=	annual number of equivalent standard axles (millions/lane)
ΔACRA	=	change in area of total cracking during the analysis year (% of total carriageway area)
ΔRDS	=	change due to rutting during the analysis year (m/km)
RIa	=	initial roughness of the analysis year

Road data of 1688 km national highway located in the tropical northeast of Queensland, Australia, was used in the analysis. The probability distributions and statistical information of pavement strength, pavement age (AGE3), annual equivalent standard axles (YE4), percentage (%) of cracking of total carriage way, standard deviation of rut depth and initial roughness were quantified. An extensive analysis using probabilistic method was conducted to determine the relationships between the annual rate of change in road pavement roughness and annual equivalent standard axles (YE4), pavement ages (AGE3) and pavement thickness. The analysis of these data showed a strong relationship between the annual rate of change in road pavement roughness and pavement thickness. Tables A1 to A6 in Appendix A show the results of the statistical analysis of the road condition parameters for different pavement thicknesses.

The effect of an input variable on the annual change in roughness is assessed by assigning the probability distribution values of the input variable in Equation 1, while other variables remain constant. Monte Carlo simulation technique was used to simulate sample data from the input probability distribution. The statistics of the annual change in roughness were calculated. The effect of input parameters on the output annual rate of change was measured by the coefficient of variation (Cov). The coefficient of variation (Cov) is the standard deviation divided by the mean *(σ/μ).*

The same process was repeated to investigate the effects of the other variables on the annual change in road pavement roughness. The values of the parameters a_0 and *m* for Equation 1 are given in Table 1. The calibration factors *Kgp* and *Kgm* used default values of 1.00. Tables 2 to 7 show comparisons between the coefficients of variation (Cov) of the input parameters and of the predicted annual rate of change in road roughness.

Table 1 Default values of *m* and a_0 for pavement strength, cracking and rut depth

Parameters	Values used
A_0 for pavement strength	134
a_0 for cracking	0.0066
a_0 for rut depth	0.088
m	0.025

Table 2 Comparison between the coefficient of variation (Cov) of the input pavement strength (*$SNPK_b$*) and of the output annual change in roughness

Parameters	200-300mm Cov	300-400 mm Cov	400-500 mm Cov	500-600mm Cov
$SNPK_b$	0.308	0.376	0.175	0.175
(*ΔRI)*	0.594	1.00	0.289	0.368

Note: Cov = Coefficient of Variation (Standard deviation divided by the mean)

Table 3 Comparison between the coefficient of variation (Cov) of the input standard deviation of rut depth and of the output annual change in roughness

Parameters	200-300mm Cov	300-400 mm Cov	400-500 mm Cov	500-600mm Cov
SD of rut depth	1.686	1.971	1.205	1.589
(*ΔRI)*	0.727	0.784	0.472	0.585

Note: Cov = Coefficient of Variation (Standard deviation divided by the mean)

Table 4 Comparison between the coefficient of variation (Cov) of the input annual equivalent standard axles (YE4) and of the output annual change in roughness

Parameters	200-300mm Cov	300-400 mm Cov	400-500 mm Cov	500-600mm Cov
YE4	0.285	0.522	0.662	0.505
(*ΔRI)*	0.065	0.153	0.216	0.194

Note: Cov = Coefficient of Variation (Standard deviation divided by the mean)

Table 5 Comparison between the coefficient of variation (Cov) of the input initial roughness and of the output annual change in roughness

Parameters	200-300mm Cov	300-400 mm Cov	400-500 mm Cov	500-600mm Cov
Initial IRI	0.228	0.335	0.276	0.252
(*ΔRI)*	0.131	0.100	0.074	0.053

Note: Cov = Coefficient of Variation (Standard deviation divided by the mean)

Table 6 Comparison between the coefficient of variation (Cov) of the input pavement age (*AGE3*) and of the output annual change in roughness

Parameters	200-300mm Cov	300-400 mm Cov	400-500 mm Cov	500-600mm Cov
AGE3	0.688	0.746	0.859	0.333
(*ΔRI)*	0.0195	0.031	0.043	0.019

Note: Cov = Coefficient of Variation (Standard deviation divided by the mean)

Table 7 Comparison between the coefficient of variation (Cov) of the input % of cracking of the total carriageway and of the output annual change in roughness

Parameters	200-300mm Cov	300-400 mm Cov	400-500 mm Cov	500-600mm Cov
% of cracking	0.847	0.919	0.793	0.567
(*ΔRI)*	0.005	0.009	0.008	0.006

Note: Cov = Coefficient of Variation (Standard deviation divided by the mean)

Discussion

Table 2 shows that the coefficient of variation (Cov) values of the output annual changes in roughness were greater than those of input pavement strength, while the Cov values of the output annual rate of change in roughness shown in the other tables (Tables 3 to 7) were smaller than the coefficients of variation of input parameters. These results indicated that among the variability of the input parameters, pavement strength had significantly influenced the variability of annual change in roughness since the variability of the output is greater than the variability of the input pavement strength.

Table 3 shows the comparison between the Cov values of standard deviation of rut depth and the Cov values of annual change in roughness. The Cov values of the output annual change in roughness were high (i.e. 0.727, 0.784, 0.472 and 0.585) which resulted from the Cov values of input standard deviation of the rut depth of 1.686, 1.971, 1.205 and 1.589, respectively. In this case, the Cov values of the output annual change in roughness decrease when compared with the Cov values of the input rut depth. The values of the coefficients of variation of rut depth are considered significant because they are high in values. The variability of rut depth will be taken into account in the risk and variation analysis.

Table 4 shows the comparison between the Cov values of the annual equivalent of standard axles (YE4) and of annual change in roughness. The Cov values of the output annual change in roughness are shown to be less than 0.20, however, they are considered moderately significant. The variability of YE4 will be taken into account in the risk and variation analysis.

Table 5 shows that the Cov values of output annual change in roughness did not substantially decrease when compared with the Cov values of initial roughness which indicated that the variability of output annual change in roughness can be influenced by the variability of the initial roughness. The variability of initial roughness will be taken into account in the risk and variation analysis.

Table 6 shows that even though the Cov values of pavement ages (AGE3) are high (i.e. 0.333 to 0.859), but the Cov values of output annual change in roughness are insignificant (i.e. 0.019 to 0.043). The variability of AGE3 is considered insignificant and will not be incorporated in the analysis.

Similarly, the Cov values of input percentage of cracking are high in value (i.e. 0.567 to 0.919) but the Cov values of the output annual change in roughness are very low (i.e. 0.005 to 0.009) which are considered insignificant. The variability of percentage of cracking will not be considered in the analysis.

In the analysis of critical input variables, only the effects of the variability of input variables on the variability of annual change in roughness were investigated. The variability of the identified input variables are considered to have relationship with the variability of output road network performance which will be investigated in the case study. If the variability of other input variables were considered to have a significant influence on the variability of predicted outcomes, these variables could be subjected to further investigation.

The variability of unit costs can have a significant influence on the variability of the output network investment costs, however, the variability of unit costs is not considered at this stage since the variability of unit costs is not available. The variability of unit costs can be incorporated in the future when knowledge of the variability of unit costs for road maintenance and rehabilitation are gathered from organisations involved and statistically modelled.

7.3 Step3: Categorise road networks

The next step in risk and variation analysis for road network investment is to categorise the road network into different groups, with each group possessing common characteristics and conditions, and to quantify the variability of the input critical input variables. Road characteristics may include pavement types, surface types, locations of the roads and so forth. Road asset condition may include road pavement strength, pavement roughness, rutting of pavement surface, cracking, potholes and so on. Factors that affect road asset condition may include road vehicles, climatic condition, soil condition, etc.

In this study, the categorisation criteria of road network are based on annual average daily traffic, pavement roughness conditions, climatic zones, soil conditions, surface types and base types.

Two surface types including bitumen and asphalt concrete were used. Three types of pavement bases including flexible, semi-rigid and full-depth asphalt were used. Seven levels of annual average daily traffic (AADT) were used including annual average daily traffic of less than 500, 501-1500, 1501-3000, 3001-5000, 5001-10000, 10001-25000, and greater than 25000. Three pavement roughness conditions were used including the international roughness index (IRI) with values less than 2.3; IRI values greater than 2.31 but less than 4.2; and IRI values greater than 4.2.

Four climatic and soil conditions were used including wet non-reactive soils, dry and non-reactive soils, wet reactive soils and dry reactive soils. Figure 4(a) shows climatic and soil conditions classified by Queensland Department of Main Roads for road asset management purposes. In the figure, green (G) represents wet non-reactive soils, blue (B) represents dry reactive soils, while red (R) represents dry non-reactive soils, yellow represents wet reactive soil. In figure 4(b), red indicates the road networks to be analysed in this study. Table 8 summaries the categorisation criteria used in the analysis.

For simplicity in identifying road categories, generic identifications were developed. Descriptions of the generic identifications are described as follows:

For soil and Climatic conditions
WNR = wet non-reactive soil
DR = Dry reactive soil
DNR = Dry non-reactive soil
For pavement roughness conditions
Poor = IRI > 4.2
Fair = 2.31 < IRI < 4.2
Good = IRI <2.31
Note: IRI refers to International Roughness Index
For Pavement Surface Types
AC = Asphalt concrete surfacing
Bt = Bitumen surfacing
For Pavement Types
Flx = Flexible pavement
SR = Semi rigid
FDA = Full depth asphalt
For Annual Average Daily Traffic (AADT)
< 0.5k = AADT less than 500
0.5k-1.5k = AADT between 501-1500

1.5k-3k = AADT between 1501-3000
3k-5k = AADT between 3001-5000
5k-10k = AADT between 5001-10000
10k-25k = AADT between 10001-25000
> 25k = AADT greater than 25000

Road Category Identification

Identification of a road category may be written as follows:
'WNR-Good-Bt-Flx-(1.5k-3k)' which refers to road category located in wet non-reactive soil, IRI < 2.31, bitumen surfacing, flexible pavement type, ADDT between 1501-3000, respectively.

The road network of approximately 4500 km was categorised according to the criteria given in Table 8. Sixty five categories were obtained from the categorisation. It must be noted that only the categories whose data were available were obtained. Tables B1, B2 and B3 in Appendix B give categories in the 4500 km road network.

In the 'Description' column of Tables B1 to B3, 'WNR', 'DR' and 'DNR' stand for wet, wet non-reactive soil, dry reactive soil and dry non-reactive soil, respectively. 'Good' means roughness of IRI value is less than 2.31. 'Fair' is where IRI value is greater than 2.31 but less than 4.2, while 'Poor' is where IRI value is greater than 4.2. 'Bt' stands for bitumen surfacing while 'AC' stands for asphalt concrete. 'Flx' means flexible pavement, SR refers to semi-rigid pavement. The terms '0.5k, 1.5k, 3k, 5k, 10k, 25k' refer to annual average daily traffic (measured by the number of vehicles) of 500, 1500, 3000, 5000, 10000 and 25000, respectively.

Table 8 Criteria used for categorising road pavements

Annual Average Daily Traffic	Pavement Roughness (IRI)	Surface Types	Base Types	Climatic and Soil Types
< 500	(IRI<2.31)	Bitumen	Flexible	Wet Non-reactive soil
501-1500	(2.31<IRI>4.2)	Asphalt concrete (AC)	Semi Rigid	Dry Non-reactive soil
1501-3000	(IRI>4.2)		Full Depth Asphalt	Dry Reactive soil
3001-5000				
5001-10000				
10001-25000				
>25000				

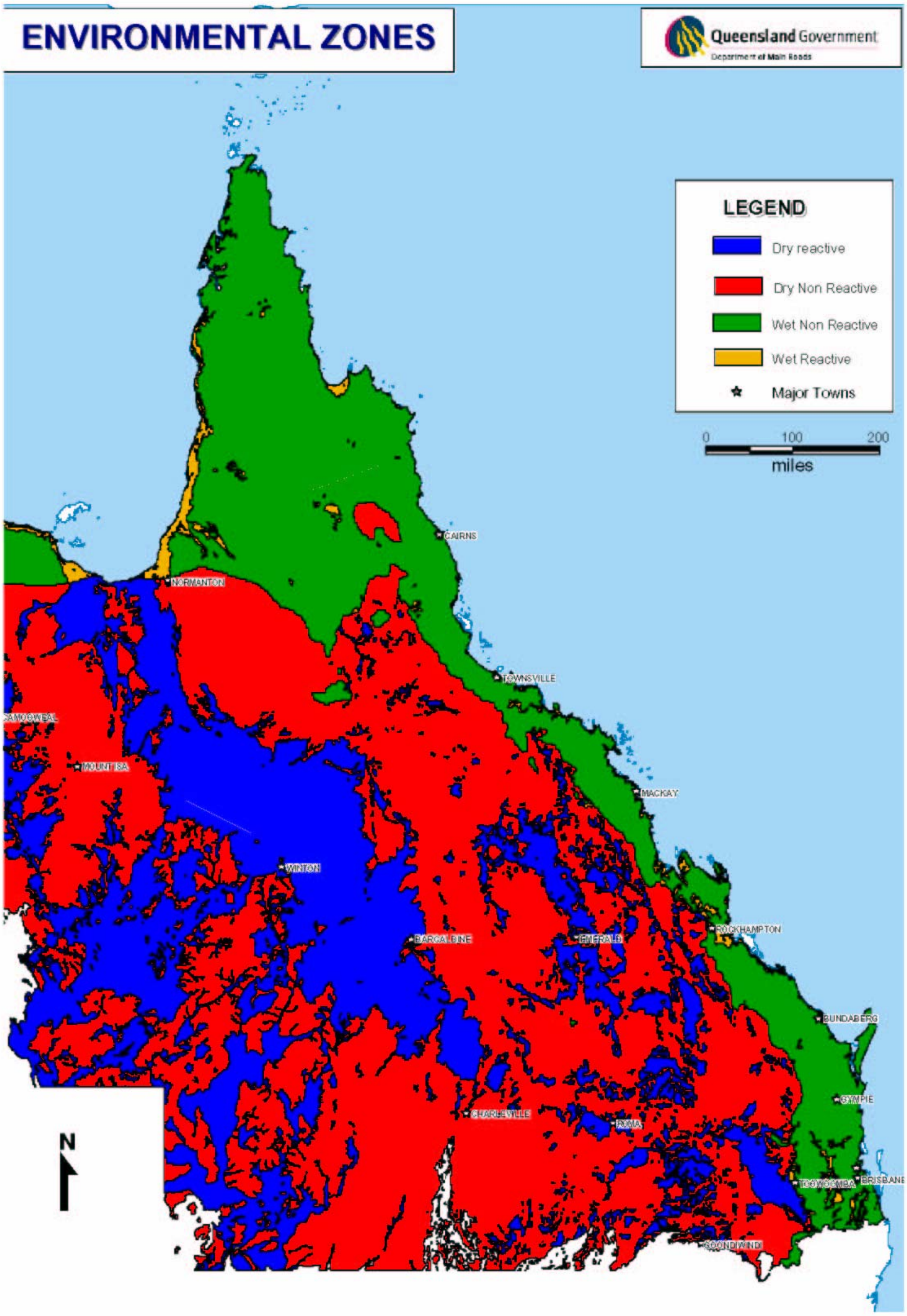

Figure 4 Climatic zones and soil conditions

Discussion

For road network analysis, categorisation technique has been used for grouping road networks into different categories based on common characteristics in the road networks. The categorisation technique can substantially reduce the degrees of freedom of the road network to a manageable size for the analysis, and allows the variability of a large network to be analysed without losing detailed information on its variability.

In this study, there are three hundred and seventy eight overall categories resulting from the categorisation criteria which are based on seven types of annual average daily traffic, three types of pavement types, two types of surface types, three roughness conditions, three climatic and soil conditions. From road data of the 4,500 km road network, sixty-five categories can be grouped based on the given categorisation criteria.

The next stage in the analysis is to assess the degree of variability of the critical input variables that were identified in the preceding section for each category. The categorisation technique and the statistical method provides the opportunity to take into account the observed variability of road input data in risk and variation analysis for road network investment analysis.

7.4 Step4: Establish probability distributions of critical input variables

Previous sections discussed critical input variables and categorisation of road networks. In this section, the variability of critical input variables for each category is statistically quantified. The critical input variables that were identified in Section 5 include pavement strength, rut depth, annual equivalent standard axle loads and initial roughness. From the categorisation of road network, there are sixty-five categories for the 4,500 km road network.

The next step in the analysis is to establish the probability distributions of the stochastic characteristics of these critical input variables. The 4,500 km road network data were extracted from Queensland Government Department of Main Roads database, and the statistical information of the critical input variables for each category was quantified.

7.4.1 Probability distributions of roughness

This section presents the variability of the critical input variable expressed in terms of statistical information for pavement roughness. Tables C1 – C3 in Appendix C present probability distributions, means and standard deviation values of pavement roughness for the identified sixty five road categories.

Discussion

The variability of the critical variables is measured by the coefficient of variation which is the standard deviation divided by the mean and is summarised below.

For wet non-reactive soil
The coefficients of variation (Cov) for pavement roughness are between 0.13 and 0.34.

For dry reactive soil
The coefficients of variation (Cov) for pavement roughness are between 0.15 and 0.56.

For dry and non-reactive soil
The coefficients of variation (Cov) for pavement roughness are between 0.14 and 0.61.

It can be observed that the coefficients of variation of roughness are similar for road categories located in the three climatic and soil conditions. This can be a result of the coefficients of variation varying within the identified ranges of pavement roughness (i.e. IRI<2.31, 2.31≤IRI≥4.2 and IRI >4.2). The majority of probability distributions of the sixty-five categories were found to have good fit with beta general distributions. The second best good-fit distribution was found to be log logistic distributions. Logistic, Pearson and Log Normal distributions were also found to have goodness-of-fit with the data for some categories.

In conclusion, beta general distribution and log normal distribution can be used for modelling the probability distributions of pavement roughness.

7.4.2 Probability distributions of rut depth

This section presents the variability of rut depth. Tables D1 – D3 in Appendix D present probability distributions, means and standard deviation values of average rut depth for sixty five categories.

Discussion

The variability of the critical input variables for average rut depth is summarised below.

For wet non-reactive soil
The coefficients of variation (Cov) for rut depth are between 0.31 and 0.70

For dry reactive soil
The coefficients of variation (Cov) for rut depth are between 0.35 and 0.96

For dry and non-reactive soil
The coefficients of variation (Cov) for rut depth are between 0.33 and 0.61

The coefficients of variation of rut depth varied between 0.31 and 0.70 for wet non-reactive soil, between 0.35 and 0.96, and 0.33 and 0.61 for dry reactive and dry non-reactive soils, respectively. The variability of rut depth represents the observed variability for each road category because rut depth was not one of the categorised criteria.

For average rut depth, the most common probability distributions that have goodness-of-fit with the data were found to be log normal and gamma distributions. Both probability distributions can be used to model the variability of average rut depth.

7.4.3 Probability distributions of AADT

This section presents the variability of annual average daily traffic (AADT). Tables E1 – E3 in Appendix E present probability distributions, means and standard deviation values of AADT for the sixty five road categories.

Discussion

The variability of the critical input variable AADT is summarised below.

For wet non-reactive soil
The coefficients of variation (Cov) fo AADT are between 0.13 and 0.48

For dry reactive soil
The coefficients of variation (Cov) fo AADT are between 0.12 and 0.41

For dry and non-reactive soil
The coefficients of variation (Cov) fo AADT are between 0.02 and 0.32

Since, the annual average daily traffic (AADT) is one of the categorised criteria, the coefficients of variation varied within the categorised ranges (i.e. AADT < 500, 500≤AADT≤1500, 1500<AADT≥3000, 3000<AADT≥5000, 5000<AADT≥10000, 10000<AADT≥25000, AADT>25000). In this case, one observation that can be made is that the coefficients of variation are smaller in values for the road categories located in dry and reactive soil than those located in wet non-reactive and dry reactive respectively.

For annual average daily traffic, the data did not have a good fit with any probability distributions. This may be due to the fact that the annual average daily traffic data were collected at certain locations, and in some cases via weigh in motion (WIM) at other locations. Thus, the data were dictated by locations of collection. However, the data showed some trend in goodness-of-fit with triangular and exponential distributions.

Triangular or exponential distribution can be used for modelling the probability distribution of average daily traffic (AADT). When a probability distribution, such as triangular or exponential distribution is chosen for modelling AADT, it should be further investigated whether triangular or exponential distribution has a better goodness-of-fit to the analysed AADT data.

7.4.4 Probability distributions of pavement strength

Pavement strength was identified as one of the critical input variables. Pavement strength is quantified by Structural Number (SN). Structural Number is used globally in pavement management systems to predict structural capacity and the life of pavement structure at the network or project level (Rhode 1994, Rhode and Hartman 1996, Salt and David 2001, O'Brien 2002).

Structural numbers are usually determined from pavement deflection data which are obtained when the pavement is subjected to a "standard" load. Pavement deflection data can be converted into pavement strength by using a number of available functions (O'Brien 2002, Rhode 1996, Rhode 1994, Salt and David 2001, Evdorides 1999). In this study, the Falling Weight Deflectometer (FWD) deflection tests were used to collect pavement strength data.

According to this test method, the FWD equipment applies impulse loading to a circular plate in contact with the pavement surface. When the pavement surface is subjected to the load, the pavement yields, and a deflection bowl is created. Surface deflections at various distances from the centre of loading are measured through a series of geophone sensors at fixed distances from the load and stored in a data file. Details of the Falling Weight Deflectometer (FWD) can be found in O'Brien (2002).

Pavement deflections can be transformed into structural numbers by many recommended functions (Rhode 1996, Rhode 1994, Salt and David 2001, Evdorides 1999). Robert's function was tested with a large data set of a wide range of New Zealand unbound granular pavements. Many functions were used and it was found that Robert's function yielded a reasonably close relationship to $r^2 > 0.9$ (Salt and Stevens 2004).

In this study, Robert's function was used to calculate the structural number from the deflection data collected by FWD tests. Robert's function is given below;

$$SNP = 12.992 - 4.167 Log(D_o) + 0.936 Log(D_{900}) \quad (2)$$

Where;

SN	=	the Structural Number
Do	=	pavement deflection under load cell
D900	=	pavement deflections at locations 900mm from the load cell

The Falling Weight Deflectometre (FWD) tests were carried out to collect deflection data for road network that had been analysed. The intervals for the tests were used based on the results suggested in the previous project (CRC CI 2001-029-C "Investment Decision Framework for Infrastructure Asset Management"). These results were briefly discussed in Section 2.1. However, it was decided in this study that FWD tests would be conducted at 400-meter intervals for the analysed network.

After the pavement deflection data were collected using the FWD tests and the structural numbers were calculated from the FWD deflection data using Robert's function, the probability distribution, mean and standard deviation of the structural number for each category were quantified. Tables G1 to G3 in Appendix G provide the means, standard deviation values and probability distribution of the structural number for the sixty-five categories.

The statistics of structural numbers for the sixty-five categories mostly had a goodness of fit with log normal distributions. A few groups of the structural number data were in good fit with normal and log-logistic distributions. Log normal distribution can be used for modelling the probability distribution of the structural number.

Discussion

Pavement strength of road network is expressed by numerical values of structural number (SN). Pavement strength was not one of the categorised criteria, thus statistical information of the structural numbers represents the observed variability of pavement strength of the road categories located in the three climatic and soil conditions. Mean values and coefficients of variation (Cov) of the structural numbers (SN) are summarised for three climatic and soil conditions below.

For wet non-reactive soil
Means of the structural number (SN) are between 3.4 and 5.95 for wet non-reactive soil.
The coefficients of variation (Cov) for structural number are between 0.15 and 0.37. The road category of WNR-Fair-Bt-SR-(1.5k-3k) has a much greater value (0.78) of the coefficient of variation than the values of most of the other categories located in wet non- reactive soil.

For dry reactive soil
Means of the structural number (SN) are between 2.07 and 3.53 for dry reactive soil. The coefficients of variation (Cov) for structural number are between 0.15 and 0.33. The road category of DR-Good-AC-Flx-(3k -5k) has a much greater value (0.53) of the coefficient of variation than the values of most of the other categories located in dry reactive soil.

For dry and non-reactive soil
Means of the structural number (SN) are between 2.7 and 3.95 for dry non-reactive soil
The coefficients of variation (Cov) for structural number are between 0.17 and 0.39.

It can be observed that the road categories located in wet non-reactive soil have the highest values of structural numbers (i.e. 3.4 to 5.95) when compared with those of the other two climatic and soil conditions. The differences in values indicate that pavement strength of the road categories in the wet non-reactive soil is stronger than that of the road categories located in the other two climatic and soil condition. Road networks located in wet non-reactive soil are located along the northeast coast of Queensland which carry more vehicles than the road networks located in the other two areas. This can explain why the pavement strength of road networks located in wet non-reactive soil have been designed to be relatively stronger than that of the other two climatic and soil conditions.

The structural numbers of the road categories located in dry reactive soils have the lowest values which reflect the lowest pavement strength. Most of these road networks are located in remote areas which carry a smaller number of vehicles per day when compared with the road networks located in the wet non-reactive soil. Furthermore, since these road networks are located in the soil type that is reactive to moisture, this condition may result in relatively lower pavement strength.

The pavement strength of road categories located in dry non-reactive soil is ranked second. Most of these road networks are located in remote areas and carry a smaller number of vehicles per day. These road networks have supporting soil that is not expansive and reactive to moisture which can explain why the pavement strength of these road networks are stronger than the pavement strength of road networks located in dry reactive soil.

Since the structural number was not one of the categorised criteria, the variability of the structural numbers represents the variability of the observed variability of the pavement strength. The variability is measured by the coefficient of variation (Cov). It can be observed that the coefficients of variation of the road categories located in the three climatic and soil conditions are similar in value (i.e. 0.15-0.37, 0.15-0.33, 0.17-0.39 for wet non reactive soil, dry reactive soil and dry non reactive soil, respectively). However, there are two categories where the coefficients of variation are much higher than the coefficients of variation of other road categories. These two categories include WNR-Fair-Bt-SR-(1.5k-3k and DR-Good-AC-Flx-(3k -5k) where the coefficients of variation are 0.78 and 0.53, respectively. This is subject to further investigation.

In modelling the probability distribution of the structural number, log normal distribution can be used since the majority of the structural numbers are in good fit with log normal distributions.

7.5 Step5: Simulate sample data of critical input variables

As mentioned, input variables that have been identified as critical for assessing risk and variation in network performance include:

1. Pavement strength (quantified by the structural number (SN))
2. Annual change in rut depth (expressed in terms of standard deviation rut depth)
3. Traffic loading (expressed in terms of annual equivalent standard axle loads)
4. Initial roughness (IRI)

Unit costs are expected to contribute a great deal to the risk and variation in cost estimates. However, the effect of the unit costs in the risk and variation has not yet been investigated at this stage. Only the variability of the engineering aspects of road asset data is incorporated in the analysis. Once the variability of the unit costs has been established, the variability of the unit costs can be incorporated at a later stage. The probability distributions, mean values and standard deviations of these four critical variables for each road category have been quantified in Section 7. Sample values of these critical input variables are simulated by Latin-Hypercube sampling technique.

In the Latin-Hypercube sampling technique, the probability distributions of the structural numbers, annual change in standard deviation rut depth, annual equivalent standard axle loads, initial roughness and unit costs are divided into N intervals with equal probability.

According to the Latin-Hypercube sampling technique, the probability distributions of the critical input variables are identified for each road category. One sample is randomly selected to represent the sampled value of each interval.

Piyatrapoomi (1996) found that sampling observational values of thirty data points were enough to obtain good estimates of the means, standard deviations and probability distribution functions of output variables. To obtain better results, in this study the probability distributions of the critical input variables were divided into forty intervals, each interval having 2.5 per cent probability of occurrence. One value of each interval is randomly selected to be the observed value of each interval, so that forty sampled values are obtained for each category. Details of the Latin Hypercube Sampling Technique can be found from the original paper (Iman and Conover, 1980).

Forty values were sampled from the probability distribution of one critical parameter to represent its variability for each road category. The procedure of the Latin-Hypercube sampling technique for such analysis is given below:

1. The probability distribution of each critical parameter is divided into intervals of equal probabilities. In this study, each interval has a probability of 2.5 per cent change of occurrence. Thus, the probability of each critical input variable for each category is divided into forty intervals of equal probability.

2. Randomly select one sample value from each of the divided probabilities. One value represents the sampled value of the divided probability. The same process is repeated for the remaining divided probabilities to obtain forty values representing the overall sampled values of the probability distribution. By using the Latin-Hypercube sampling technique, the overall variability of a probability distribution can be represented, in this case, by forty sample data to represent the variability of each critical input variable for each road category.

3. Randomly select one value from the forty sampled data for each critical input variable. Therefore, there are four sampled values representing four critical input variables for each category. The sample process is repeated for the remaining sampled data of the critical input variables. Hence, there are forty sets of the critical input variables. The variability of each critical input variable is represented by each set of data using the random sampling process.

4. The same process is repeated for the other categories of the road network to be considered in the analysis.

5. There are forty data sets of the critical input variables. The variability of all critical input variables is randomly selected and represented in these forty input data sets.

Discussion

In analysing a complex system, the Latin-hypercube sampling is more appropriate than the well-known Monte Carlo simulation since the Latin-hypercube sampling is a simulation technique that can be used for assessing the relationship of the variability of input to output variables by using small sampled data sizes. The Latin-hypercube sampling technique can substantially reduce the analysis tasks which would, otherwise, not be economical or viable using the Monte Carlo simulation. Since the Latin-hypercube sampling technique has been popular in recent years for assessing quantitative risk, the technique has been incorporated in commercial risk analysis softwares, such as @Risk software. In this study, the Latin-hypercube sampling technique which is available in the @Risk software was used for simulating the observational values of critical input variables for the analysis.

7.6 Step6: Input observational values of critical input variables for analysis

The objective in assessing risk and variation in future network performance and cost estimates for investment is to better understand and gain more confidence in the degree of the variability of future network performance and cost estimates which occurs as the result of the variability of critical input variables (such as the variability of pavement roughness, of pavement strength, of annual average daily traffic, etc.).

Step six is to model road network for network performance analysis and input observational values of the critical input variables for the network performance and investment analysis. The assessment of the relationship between the variability of road input variables and the variability of future network performance and cost estimates can be extremely complicated. During the last decade, systematic analyses of road network performance and road investment have dramatically improved and, through experience, have further developed. Hence, the analysis methodologies have evolved and analysis tools have been developed. One such tool is Highway Development and Management System (HDM-4). In this study HDM-4 was used as a calculation tool. The combination of the HDM-4 software tool and the probability-based method can assist us in assessing risk and variability in future network performance and investment costs.

As mentioned previously, Latin-Hypercube sampling technique was used to simulate the variability of input variables for the analysis. Highway Development and Management (HDM-4) System software was used for calculating network performance and investment costs for maintenance and rehabilitation. The variability of the future network performance and investment costs was obtained by running a series of HDM-4 analysis. Each run of the HDM-4 represents the randomness in the variability of the critical input variables

HDM-4, developed by the International Study of Highway Development and Management (ISOHDM), is a globally accepted pavement management system. It is a computer software package used for planning, budgeting, monitoring and management of road systems. There are three analysis options in HDM-4, which include: (1) Strategy Analysis, (2) Program Analysis and (3) Project Analysis. The Strategy Analysis Option was employed in this study in assessing the effects of the variability of pavement strength on estimates of maintenance and rehabilitation budgets.

In modelling road networks for HDM-4 analysis, as mentioned earlier the 4500 km of the road networks is divided into different categories each having common characteristics. Then, the probability distributions, mean values and standard deviations of the critical input variables were identified for each category. The Latin-hypercube sampling technique was used to simulate observational values of the variability of the critical input variables for the analysis.

In modelling the road network for HDM-4 analysis, the categories that the annual average daily traffic are greater than 25000 vehicles were excluded from the analysis since the road network modelling used in this study does not support the analysis for multiple lane road networks. Small road sections of less than one kilometre were also excluded from this analysis.

Discussion

The combination of probability-based method, categorisation technique, Latin-hypercube sampling technique and High Development and Management System (HDM-4) has made it possible to investigate risk and variation in network performance and investment costs. The methodology in assessing risk and variation presented in this report is practical and generic for such investigation. It can be used to analyse complex problems in infrastructure engineering.

7.7 Step7: Calibrate deterioration prediction models

The method for calibrating road performance models was developed in an earlier project "Investment Decision Framework for Infrastructure Asset Management. It is essential in the analysis to calibrate road performance prediction models to reflect observed change in road performance deterioration. Two case studies were conducted to assess the calibration factors of annual change in roughness for HDM-4 models in the previous study. Road data of 1688 kilometres of a National Highway (Bruce Highway) located in the tropical Northeast region of Queensland were used in the analysis. Road data of 1034 kilometre from Landsborough Highway located in central Queensland were used in the second analysis. Details of the analysis were given in CRC CI Report 2001-010-C/009 “Assessment of Calibration Factors for Road Deterioration Models”. The calibration factors for annual change in roughness found in that study were used in the analysis. Tables 9 and 10 show the calibration factors for annual change in pavement roughness for wet and dry regions to be used in this study.

Table 9 Wet tropical region of Queensland

Thickness	Calibration Factor (Kgp)
200-300 mm	0.55
300-400 mm	0.35
400-500 mm	0.25
500-600 mm	0.20

Table 10 Dry region of Queensland

Thickness	Calibration Factor (Kgp)
100-200 mm	0.78
200-300 mm	0.48
300-400 mm	0.48
400-500 mm	0.43

Discussion

The calibration factors in tables 9 and 10 are presented for different pavement thicknesses. It was observed that annual rates of change in road pavement roughness decrease when pavement thicknesses increase. The annual change in pavement roughness was also assessed against annual average daily traffic (AADT) and pavement ages. The results did not show clear trends in annual changes of road pavement roughness when analysed against AADT and pavement ages. Thus, calibration factors for annual changes in road pavement roughness were categorised and grouped by the pavement thickness. Calibration factors for other deterioration prediction models will be subjected to further investigation. Calibration factors for other deterioration prediction models used default values of 1.0.

7.8 Step8: Conduct a series of analysis

A series of forty HDM-4 analyses was conducted. For each run of HDM-4 analysis, the results of road network investments were optimised for the best net present values when compared with base-case alternatives. Each HDM-4 run represents the results in the random nature of the identified degree of variability of the critical input variables. There are forty output files obtained from the series of forty HDM-4 analyses which represent possible results of the random combination of the variability of the critical input variables. The next step is to assess the statistical information or the likelihood of the output network performance and investment costs and degrees of variation of the prediction.

7.9 Step9 and 10: Analyse outputs and investigate risk and variation in road network performance

This section presents the statistical results for road network performance and maintenance and rehabilitation in investment analysis. Statistical information and probability distribution of the network performance and investment costs were quantified. Network performance and investment costs of interest in this study include:

- Time intervals for maintenance and rehabilitation for each road category
- Whole-of-life roughness performance
- Cost per kilometre for maintenance and rehabilitation for each category
- Whole-of-life costing for the whole road network

7.9.1 Time-intervals for maintenance and rehabilitation

This section presents the statistical outputs of time-intervals for maintenance and rehabilitation. The variability in the time-intervals for maintenance and rehabilitation were quantified and presented in terms of the mean and standard deviation values. The time-intervals for maintenance and rehabilitation were analysed for each road category. Details relating to maintenance and rehabilitation treatment choices and intervention criteria used to invoke which treatment choice are given below:

For AADT<1500
Reconstruction after 8 IRI
Granular overlay for roughness greater than 5IRI and total damage of area <= 15%
Slurry seal for rut depth > 30 mm
Reseal for total damaged cracks >= 20%
Pothole patching for pothole > 10 no./km
Crack sealing for wide structural cracking >= 10%

For 1500<AADT>5000
Reconstruction after 7 IRI
Granular overlay for roughness greater than 6IRI and total damage of area <= 10%
Slurry seal for rut depth > 30 mm
Reseal for total damaged cracks >= 15%
Pothole patching for pothole > 10 no./km
Crack sealing for wide structural cracking >= 8%

For 5000<AADT>10000
Reconstruction after 6.5 IRI

Granular overlay for roughness greater than 5IRI and total damage of area <= 10%
Slurry seal for rut depth > 20 mm
Reseal for total damaged cracks >= 10%
Pothole patching for pothole > 10 no./km
Crack sealing for wide structural cracking >= 5%

For AADT>10000
Reconstruction after 6 IRI
AC50 for >= 3IRI and total damage of area <=10% damaged
Pothole patching for pothole > 10 no./km
Crack sealing for wide structural cracking >= 5%

For 1500<AADT>5000 (Asphalt Concrete)
Reconstruction after 7 IRI
AC50 for >= 4IRI and total damage of area <=10% damaged
Pothole patching for pothole > 10 no./km
Crack sealing for wide structural cracking >= 8%

For 5000<AADT>10000 (Asphalt Concrete)
Reconstruction after 6.5 IRI
AC50 for >= 3.5IRI and total damage of area <=10% damaged
Pothole patching for pothole > 10 no./km
Crack sealing for wide structural cracking >= 5%

Discussion

Tables H1 to H3 in Appendix H show the mean and standard deviation values of time-intervals for road categories in wet non-reactive soil, dry reactive soil and dry non-reactive soil, respectively. In the tables, the first time interval is the year for the selected treatment of maintenance and rehabilitation that need to be conducted after the start of the analysis year. For this analysis the start of the analysis year is 2006. The second time interval is a selected time interval for major maintenance or rehabilitation. The percentage (%) of treatment types represents a possibility or percentage of a selected treatment that is likely to occur. There may be different possibilities of selected treatments for a road category. These different possibilities of treatment resulted from the variability of critical input variables and the random combination of the variability represented in the analysis and random simulation. This information allows road asset managers to be aware that there are other possibilities in the maintenance and rehabilitation choices that can occur or can be selected. This standard deviation information provides flexibility in time variation of the selected treatment choices.

The mean and standard deviation values of time-intervals for road maintenance and rehabilitation for each road category could be used as a guide for establishing standard rules for maintenance and rehabilitation work.

7.9.2 Cost per kilometre for maintenance and rehabilitation

This section presents statistical information (i.e. mean and standard deviation) of costs per kilometre for maintenance and rehabilitation of road network. The whole-life cycle costs of the forty output files from the forty HDM-4 analyses were used in assessing the statistical mean and standard deviation of cost per kilometre for each road category. The whole-life cycle cost of 25-year period of each road category was divided by the number of kilometres of road length within that category. The means and standard deviations of cost per kilometre were then quantified.

Discussion

Tables J1 to J3 in Appendix J present the statistical mean, standard deviation and coefficient of variation values of costs per kilometre for the analysed road categories. The information relating to the kilometre in the tables represents the road length in that category. Cost per kilometre was calculated from the calculated whole-of-life cycle cost of 25-year period divided by the length of that category. There are consistencies in the costs per kilometre for low and high volumes of annual average daily traffic (AADT), and in most cases for the three climatic and soil conditions. For low traffic volume, costs per kilometre were calculated to be lower than costs per kilometre for high traffic volume. However, there are smaller discrepancies in some categories. However, the discrepancies are not shown to be of significant values. For instance, cost per kilometre for the road category of WNR-Good-AC-Flx-(3k-5k) was calculated to be approximately A$ 70,000 higher than that of WNR-Good-AC-Flx-(5k-10k) for a 25-year period of maintenance and rehabilitation. These discrepancies may arise from many factors such as differences in initial pavement strength. In this case, the Structural number (SN) of the WNR-Good-AC-Flx-(3k-5k) is smaller than the SN of WNR-Good-AC-Flx-(5k-10k). Further investigation may be required.

7.9.3 Whole-of-life-cycle roughness condition

This section presents an analysis of whole-of-life pavement roughness condition for the analysed road categories. Annual changes in international roughness indices (IRI) were calculated for the whole-life-cycle of 25-year period for each road category. The statistical mean, standard deviation of IRI were quantified for each year. The curves of mean of standard deviation of IRI for the whole-of-life of 25-year period were obtained for each category.

Discussion

Figures in Appendix K, L, and M show the whole-life-cycle of the international roughness index (IRI) for each road category for wet non-reactive soil, dry reactive soil and dry non-reactive soil, respectively. The figures show the mean and mean plus one standard deviation of pavement roughness for a whole-of-life of 25-year period. It must be noted that the variation in IRI values observed in the figures in Appendix K, L, and M reflect the effect of the combined variability of the critical input variables of pavement strength, rut depth, annual average daily traffic and initial roughness.

For most categories, the maximum mean values of IRI are less than 4 IRI for the 25-year whole-life-cycle. It represents approximately 50 per cent probability of occurrence. When we consider the IRI values of mean plus one standard deviation which represents approximately 83.33 per cent of occurrence, the maximum value of mean plus one standard deviation of most of road categories are below 5 IRI. In some categories, the maximum value of mean plus one standard deviation are greater than 6 IRI. Road asset managers can investigate in detail the variation and probability of occurrence of pavement roughness for the whole-of-life cycle for each road category. Detailed investigation of the variation in pavement roughness provides greater confidence for road asset managers in investment decision-making in providing road service at acceptable levels of risk.

7.2.4 Whole-of-life cycle costs

Whole-of-life cycle costs and variations for a 25-year period were investigated. The mean values and coefficients of variation were investigated for annual costs. Figures 10 and 11 show annual mean costs and the coefficients of variation for the 25-year period. The coefficients of variation of the annual cost estimates are different and very high in values. The mean values of annual cost estimates and the coefficients of variation may not be appropriate for assessing risk and variation for whole-of-life cycle costs. This is due to the fact that major maintenance and rehabilitation may occur in adjacent years resulting in double counts of the variability of the analysis outputs. The period for assessing the variability of cost estimates should be cumulative and longer than one year to allow for the variability of maintenance and rehabilitation that occurs in adjacent years to be included the variation estimates. Thus, it is better to investigate risk and variation based on the cumulative whole-of-life-cycle costs than that based on annual costs. Figures 12 to 14 show mean costs, cost variations of one standard deviation and coefficients of variation of cumulative whole-of-life cycle costs.

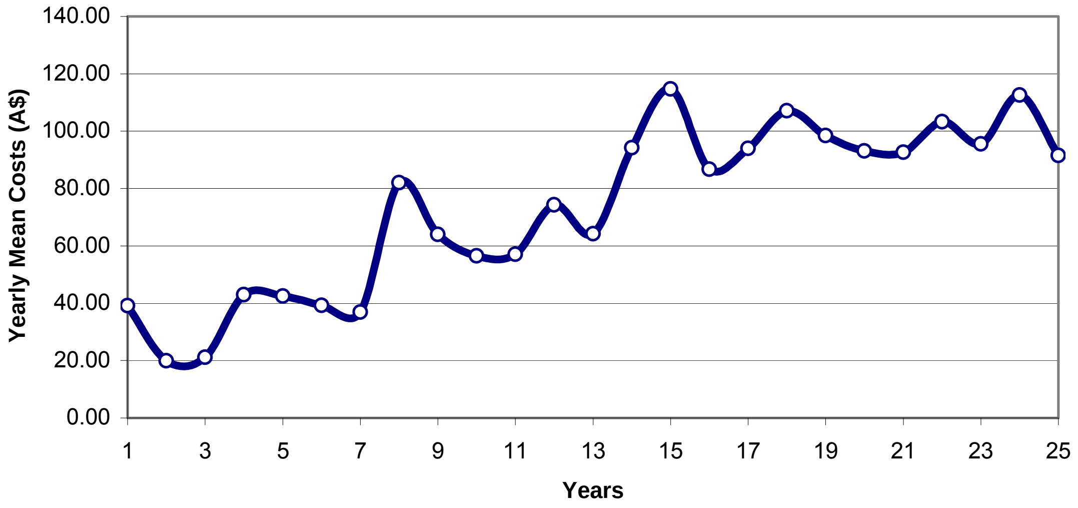

Figure 10 Mean estimates of annual budgets/costs for road maintenance and rehabilitation for a whole life cycle of 25 years for 4,500 km road network.

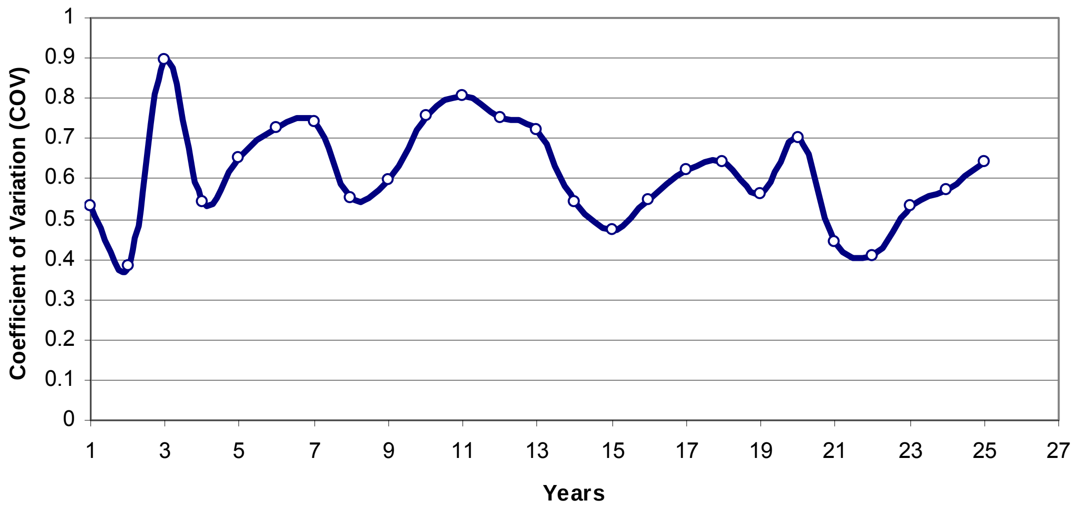

Figure 11 Standard deviations of annual cost estimates for road maintenance and rehabilitation for a whole life cycle of 25 years for 4,500 km road network.

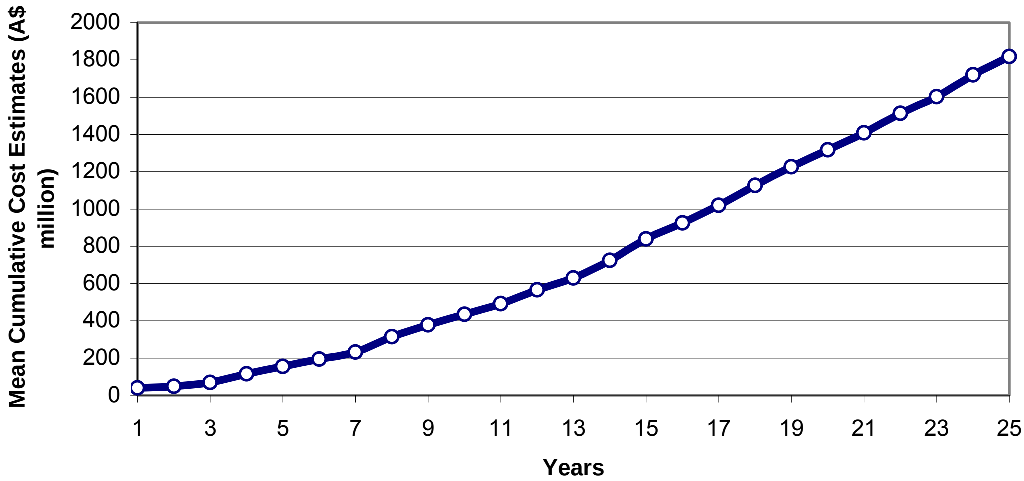

Figure 12 Mean estimates of cumulative budgets/costs for road maintenance and rehabilitation for a whole life cycle of 25 years for 4,500 km road network.

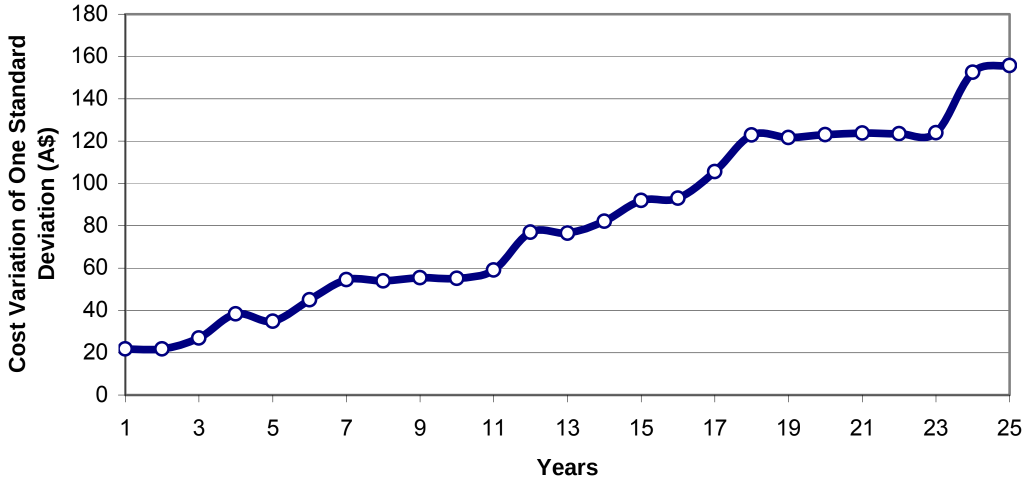

Figure 13 Standard deviations of cumulative cost estimates for road maintenance and rehabilitation for a whole life cycle of 25 years for 4,500 km road network.

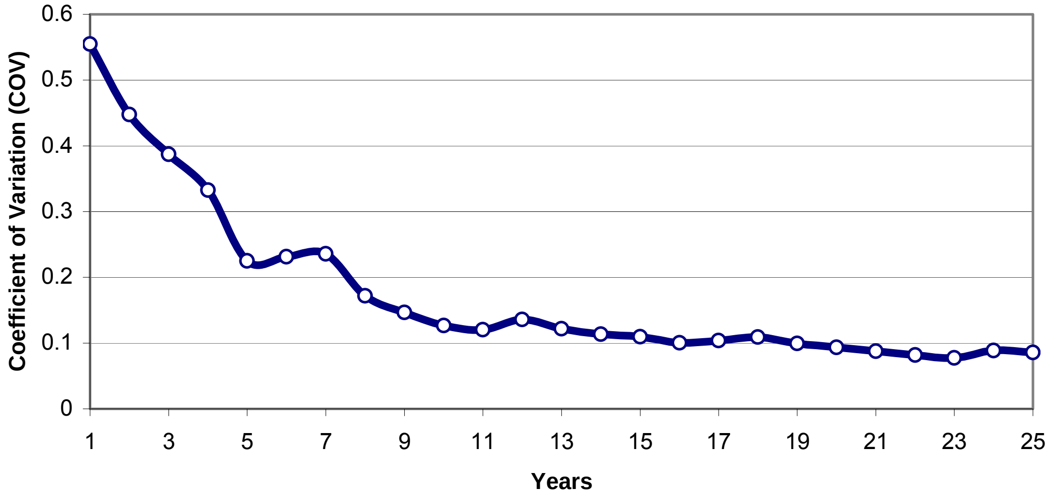

Figure 14 Coefficients of variation of cumulative cost estimates for road maintenance and rehabilitation for a whole life cycle of 25 years for 4,500 km road network.

The total mean costs for the network investment for the next 25-year period would be approximately A$1.8 billion. It is noted that the estimated cost had not yet been discounted. Cost variation of one standard deviation shown in Figure 13 indicated sudden increases in the calculated standard deviation values. This characteristic indicated that there are possibilities of major maintenance and rehabilitation or major spending occurring in those years. It is observed that these are between 3 and 5 years for sudden increases in the standard deviation values.

Figure 14 shows the degrees of variation in cost estimates expressed in terms of coefficients of variation for a 25-year period. The coefficients of variation in cost estimates decreased as time passed. This is due to the fact that when costs and cost variations were cumulated along the years, the increase in cost variation is relatively less than the increase in the cumulative cost. Higher values of the coefficients of variation in the cumulative costs for early years of the analysis resulted from the variability of the critical input variables. When maintenance and rehabilitation treatments have been conducted, the road asset condition regains the condition as specified in the treatment choices and criteria for treatment. Thus, the variability of the road asset condition after providing treatments would be less than the initial variability of the input variables. However, maintenance and rehabilitation treatment for large road networks may not be conducted in accordance with maintenance and rehabilitation plans. The actual variability of road asset condition of the network may be different from the variability of the analysed results. If the road networks cannot be maintained according to the plan, the effect of the variability of network condition on risk and variation of the predicted network performance should be invested at an appropriate time. Three to five years would be appropriate time intervals to reinvestigate the effect of the variability of the critical input variables on the variation of the network performance.

The statistical information including the mean cost estimates, standard deviation and probability distributions can be used to assess levels of risk in cost estimates. Table 11 shows the calculation of levels of risk (probability of occurrence) when it is assumed that costs were blown out by 10 and 20 per cent from the mean estimates. These levels of risk assessment were calculated for a 5-year period. Reliable periods for assessing levels of risk in cost estimates would be 3 to 5 years since maintenance and rehabilitation could be provided according to the plans for short-time periods.

Table 11 Risk or probability of occurrence of cost blowouts

Years of Cumulative Cost Estimates	Mean Cost Estimates (A$ Million)	10% Blown out Costs (A$ Million)	Risk or (probability of occurrence) (%)	20% Blown out Costs (A$ Million)	Risk or (probability of occurrence) (%)
1st year	39.95	43.29	36.0%	47.22	29.7%
2nd year	48.61	53.47	37.4%	58.33	28.8%
3rd year	69.46	76.40	35.2%	83.34	25.6%
4th year	115.30	126.83	32.6%	138.36	20.1%
5th year	115.23	170.73	32.2%	186.30	18.7%

8. KEY FINDINGS AND DISCUSSION

Risk and variation in predicting road network performance arise from many sources of uncertainties and variability, such as the variability in road asset condition, environment, soil condition and so forth. In this study, the variability of pavement strength, rut depth, annual average daily traffic (AADT) and initial roughness were identified as critical input variables. A 10-step methodology for assessing risk and variation in road network performance has been developed.

The proposed 10-step methodology is practical and generic for assessing risk of errors and predicting variation of an outcome for any complex system. The methodology combines the concepts of probability-based analysis, categorisation technique and simulation technique. The combination of categorisation of road networks and the probability-based method allows the variability of the road network to be analysed at manageable sizes. The application of the simulation technique using Latin-Hypercube sampling technique allows the overall variability of critical input variables to be sampled in small sample sizes for the analysis. Thus, the methodology is practical and generic and can be used to assess risk and variation for other applications. The findings for each step of the methodology are summarised below.

Step1: Identify Road Network Performance

The first step is to identify road network performance to be modelled in the analysis. In this study, risk and variation in road network performance to be analysed includes:

- Time intervals for maintenance and rehabilitation
- Cost per kilometre
- Whole-of-life pavement roughness performance
- Whole-of-life cost

Assessing risk of errors and predicted variation of time-intervals for maintenance and rehabilitation is to identify periods for major maintenance and rehabilitation and their degrees of flexibility in conducting such maintenance and rehabilitation work.

Cost per kilometre and its variation were calculated for each road category. Road asset managers will be able predict costs for maintenance and rehabilitation for each road category. They also can investigate the degree of risk of errors and predicted variation in the cost estimates.

Whole-of-life pavement roughness and its variation were calculated for each category for a 25-year period. This information allows road asset managers to investigate levels of confidence in predicting roughness levels for the specified whole-of-life of the road network.

Information relating to whole-of-life-cycle costs and their variation allows road asset managers to investigate the likelihood or probability of costs of not being exceeded for a certain degree of confidence. They can also conduct sensitivity analysis to investigate the probability of occurrence when a budget is assigned.

Step2: Identify critical input variables for risk and variation analysis

It must be recognised that it would not be possible to incorporate the variability of all input variables into the analysis. The critical input variables were identified by comparing the coefficients of variation of input variables and of output variables. The coefficient of variation is the standard deviation divided by the mean. The coefficient of variation of the output variable that is high in value resulting from the variability of input variables were considered critical. Based on an analysis of road networks of approximately 1688 km, the results of the analysis indicated that the variability of pavement strength, pavement roughness, annual equivalent of standard deviation and rut depth is critical for the prediction of risk and variation of the predicted road network performance.

Step3: Categorise road networks

The objective of the categorisation of road networks is to group together the characteristics of road networks that have similar or common characteristics. The variability of road characteristics in each category is quantified and accounted for in risk and variation analysis. In this study, the road networks to be analysed were categorised based on five criteria namely:

1. Annual average daily traffic (AADT)
2. Pavement roughness
3. Surface types
4. Base types,
5. Climatic and soil conditions

The variability of road characteristics observed in the recorded data was modelled by the statistical method. The combination of categorisation technique and the statistical analysis method allows us to incorporate the observed variability in road asset data in network performance analysis. The combination of the categorisation and statistical analysis reduces substantially the degrees of freedom for the analysis.

Step 4: Establish probability distributions of the critical input variables

Road authorities have to monitor and collect road asset condition data at the network level to support their network investment for maintenance and rehabilitation. Data collection is high in cost, some data are even more expensive to collect at the network level – one of those is pavement strength. Road agencies do not usually monitor pavement strength at the network level, Pavement strength is usually monitored by the Falling Weight Deflectometre (FWD). It is time consuming as well as high in cost. An analysis for optimising longitudinal test intervals for pavement strength was developed by the project team. The results indicated that road agencies could reduce strength test sampling rates by 75 to 80 per cent compared to current practice without losing statistical relevance for network applications. Based on the optimising analysis for data collection, the stochastic characteristic of pavement strength could be made available at the network level at affordable costs. The variability of the critical input variables including pavement strength, pavement roughness, AADT and rut depth could be statistically quantified by means, standard deviation values and probability distribution for each category.

Step 5: Use Latin-Hypercube Sampling Technique for data sampling

The variability of critical input variables was incorporated in the risk and variation analysis by using Latin-Hypercube sampling technique. The technique was chosen for this application since it can simulate relatively smaller sample sizes to represent the variability of critical input variables for the analysis. The Latin-Hypercube sampling technique has made this complex problem become the practical solution.

Step 6: Input sampled data of the critical input variables for statistical analysis.

In this step, the variability of the identified critical input variables was simulated using the Latin-Hypercube sampling technique and incorporated in a series of network performance analysis. The outcome of the analysis is the statistics of road network performance.

Step 7: Calibrate network performance models to suit local network performance

Performance prediction models are needed for calibration to reflect local network performance. A method was developed by the research team by adjusting the predicted variability of deterioration rates to replicate the actual variability of road asset condition. Historical data of road asset condition of 1688 km and 1034 of National Highways located in the tropical Northeast region of Queensland and

Central Queensland respectively were used in the analysis. The results of the analysis are encouraging.

Step 8: Conduct a series of HDM-4 analyses to obtain the statistics of the output road network performance. The use of HDM-4 as a calculation tool has also made this complex problem become a practical solution. In this step, a series of forty HDM-4 analyses were conducted to obtain the statistics of network performance and investment costs.

Step 9: Quantify the statistical information (e.g. probability distribution, mean, standard deviation, etc) of the output road network performance characteristics.

The statistics of network performance were quantified by the statistical information (e.g. mean, standard deviation, etc.) in this step. The network performance of interest includes:

- Time intervals for maintenance and rehabilitation
- Cost per kilometre
- Whole-of-life pavement roughness performance
- Whole-of-life cost

The network performance outputs were predicted based on specified maintenance and rehabilitation treatment choices and intervention criteria. The statistical information including mean, standard deviation and coefficients of variation values of the identified network performance for each road category were quantified.

Step 10: Investigate the degrees of variation for the established probability distributions of the output road network performance characteristics

Mean time-intervals for maintenance and rehabilitation and their variation expressed by one standard deviation values were presented for each road category. The outcomes of time-intervals could be used as standard time-intervals for road maintenance and rehabilitation. The standard deviation values of the time-intervals allow flexibility in conducting road maintenance and rehabilitation. Road asset managers could make informed decisions in relation to time-intervals for road work and have greater flexibility in making such decisions.

Mean and one standard deviation costs per kilometre were assessed for each road category. This information allows confidence and flexibility in selecting costs for maintenance and rehabilitation. The degree of variation in the cost estimates can be investigated from the standard deviation values. A level of confidence in the cost estimates can be selected. For instance the mean cost estimate represents approximately 50 per cent probability of occurrence, a cost estimate of mean plus one standard deviation has approximately 83.33 per cent of occurrence. Road asset managers could select cost estimates of other values with the confidence level that they are comfortable with. This information assists road asset managers in assessing confidence level and flexibility in selecting maintenance and rehabilitation costs.

The mean and mean plus one standard deviation values of road pavement roughness for whole-of-life cycle provide the statistical information of the network performance for the whole-life period. The mean values represent the average pavement roughness. There is approximately 16.67 per cent probability that pavement roughness will be greater than the mean plus one standard deviation values. Road asset managers can assess a level of pavement roughness against the level of probability of occurrence. Road asset managers will be able to make informed decisions on an appropriate pavement roughness threshold and level of confidence.

Whole-of-life cycle costs and their variations provide cost profiles for long-term investment. The variation of the cost profiles provides information on the flexibility and degrees of confidence in selecting an investment cost. Road asset managers can investigate varying levels of risk associated with costs that are greater than the budget. For instance, they can investigate a probability of occurrence for a cost that blows out from a budget by 10 or 20 per cent.

9. CONCLUSIONS

This report presented a ten-step framework for assessing risk and variation in whole-of-life cycle road network performance for maintenance and rehabilitation investment of road networks. Queensland Inter-city road networks of approximately 4,500 km were used as a case study. The outcomes of the study included:

- Greater confidence in predicting future whole-of-life costs for short- and long-term investment in road assets;
- Greater confidence in predicting the nature of future maintenance required and return periods (time intervals) for maintenance and rehabilitation;
- Greater confidence in economic outcomes;
- Greater accuracy in predicting the relationships among the variability of critical input variables, such as traffic, environmental zones, roughness, etc. on predicted outcomes (i.e. roughness, costs)
- Greater confidence in assessing cost per kilometre for each road category.

The case study has achieved the following:

- Identified critical inputs that influence the reliability of road investment model outputs.
- Incorporated stochastic properties of critical model inputs for chosen road networks into the investment analysis process.
- Improved and applied a methodology for calibrating road investment models that make use of the variability input properties. A calibrated model reliably predicts the variability of the roughness model outputs when compared with the network variability of actual roughness of the chosen network.
- Analysed and demonstrated the variability of predicted network performance (both physical and financial performance) for a chosen primary inter-city road network in Queensland, The Queensland National Land Transport Network.

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Author Biography

Noppadol Piyatrapoomi obtained his Ph.D. degree from the University of Melbourne. He has practiced as a civil and structural design engineer for ten years before he joined RMIT University Melbourne, Australia in 2002. His research interests include the application of risk and reliability in decision-making for infrastructure asset management; assessment of public risk perception on engineering investments; risk and reliability assessment of structure; seismic risk and reliability assessment of structure; the application of an evolutionary method for data analysis. He developed an evolutionary method of data analysis during his Ph.D. study. This method can be used to refine existing functions and develop new formulas by using probability, statistical, and risk assessment theories in the analysis. The method provides a more fine-grained analysis and yields more accurate results and better fitness of data than commonly used methods, such as regression or correlation analyses.

Annex 1: Analysis method for optimising pavement strength data collection

Current methods for pavement strength data collection require test instruments to travel very slowly or to stop while loading the pavement and measuring surface deflections (a proxy for strength). These processes are time consuming, can cause traffic delays, and may prejudice safety. As a result, many road agencies do not collect data on pavement strength for network level purposes. Pavement strength data are usually collected at 100m or 200m intervals for project purposes.

The objective of this technique is to identify optimal intervals for pavement deflection data collection for network application. It is hypothesized in the analysis that *"if the statistical characteristics (i.e. mean, standard deviation and probability distribution) of data sets were quantifiable, and if different sets of data possessed similar means, standard deviations and probability distributions, these data sets would produce similar prediction outcomes"*. Optimisation analysis was carried out by eliminating data from the original data set to create a new data set, which were in turn, tested to see whether they had similar mean, standard deviation and probability distribution to those found in the original data set. If the new data set possessed similar mean, standard deviations and probability distribution, the new data set would provide similar prediction outcomes.

The goodness-of-fit method for best-fit distributions is used to test the probabilistic characteristics for data sets. The basic procedure of the goodness-of-fit method involves a comparison between the probability distribution of observational data and an assumed theoretical distribution function. If the discrepancy is larger than what is normally expected from a given sample data size, the theoretical model is rejected.

Two popular methods used for goodness-of-fit-tests are the Chi-squared and the Kolmogorov-Smirnov (K-S) test methods. In the Chi-squared method, the basic procedure involves a comparison between an observed histogram (or frequency distribution diagram) of sample data and an assumed theoretical probability density function. The Chi-squared method requires judgment in selecting intervals for plotting the number of occurrence for each sampling value. The degree of goodness-of-fit depends on this judgment of selected intervals. For general engineering data, this may require a trial and error process to select an appropriate interval for the best-fit distribution, but the result may not be accurate. The judgment required in the procedure is a shortcoming of the Chi-squared method for analysing engineering data.

The Kolmogorov-Smirnov (K-S) method involves a comparison between the cumulative distribution of sample data and the cumulative distribution of an assumed theoretical probability distribution function. This method is simpler to use than the Chi-squared test method and can yield better results using a smaller number of data points (Piyatrapoomi 1996).

In the Kolmogorov-Smirnov (K-S) method, the cumulative distribution of sample data is simply obtained by ranking the data. Then the cumulative frequency of occurrence is calculated for each ranked data. The result can be plotted in a graphical form. The cumulative distribution of a theoretical probability distribution function can be determined by the integral of its probability density function. The theoretical cumulative distribution is then compared with the cumulative distribution of the sample data. Additional details of the Kolmogorov-Smirnov (K-S) method can be found in most statistics and reliability theory texts (Ang and Tang 1975, Kececioglu 1991, O'Conner 1985). Using this method, all possible theoretical probability distributions can simply be compared with the cumulative distribution of the sample data. The best-fit distribution can be observed from the comparison. Then the test of goodness-of-fit can be evaluated as follows

$$Dn = \max \left| F(x) - S(x) \right| \qquad \text{(AN1.1)}$$

Where: *F(x)* is the proposed theoretical cumulative distribution function, *S(x)* is the discrete cumulative distribution of sample data, *Dn* is the absolute value of *F(x)-S(x).*

The Kolomogorov-Smirnov (K-S) method compares the observed maximum difference of Eq. 1 with the established critical value *Ds* which is defined by

$$P(Dn \leq Ds) = 1 - \alpha \qquad \text{(AN1.2)}$$

Where: α is the level of significance. For different critical values *(Ds)*, the values of α can be obtained from tabulated K-S critical values in standard statistics or reliability theory texts (Ang and Tang 1975, O'Conner 1985).

Pavement deflection data sets from a 92km segment located in wet non-reactive soil, a 28.7km segment located in dry reactive soil and a 60km segment in dry reactive soil were assessed as case studies. The majority of the tests were performed at 200-meter spacing between inner and outer wheel paths for the 92-kilometre road segment. The tests were performed at 100-meter spacing for the 28.7-kilometre segment and the tests were performed at 200-meter spacing for both inner and outer wheel paths for the 60km dry non-reactive soil.

The outcome of the analysis indicated that the optimal spacings between FWD tests in alternate wheel paths for pavement deflection are:

- 1,000m for wet climate, non-reactive soils, and
- 700m for dry climate, reactive soils
- 1200m for dry climate, non-reactive soils

The benefits accrued from this analysis include;

- a potential 75% savings on pavement strength data collection costs, or increase data collection length by four times when compared with current pavement data collection costs.
- The method is generic and could be used for analysing optimal data collection for other types of physical infrastructure.

Annex 2: Method for calibrating pavement performance models

This annex presents a method using probability-based theory in assessing the calibration factors for road deterioration prediction models. In road asset management, assessing network performance for budgeting road maintenance and rehabilitation programmes is important for any road authority. A model that can accurately predict the rate of road deterioration condition will enable road asset managers to predict the correct budget for maintaining road infrastructure. Attempts have been made in almost every country to calibrate the deterioration prediction models to suit each country's specific conditions. The variability in road data arising from the variability in climatic condition, soil condition, user vehicles and so forth has given less confidence in using the calibrated functions when the functions do not show a strong correlation or relationship with recorded data. The deterministic regression or correlation analysis has normally been used for this calibration purpose.

This method is based on the probability-based method and Monte Carlo simulation technique. In this method, the degree of goodness-of-fit between the calibrated function and recorded road data can be explicitly assessed and identified. Thus, this method gives a higher degree of confidence in using the calibrated models.

An example of the analysis is given below. One of such deterioration models for predicting the rate of change in road pavement roughness suggested by The International Study of Highway Development and Management (ISOHDM 2001) is given below:

$$\Delta RI = Kgp\,(\Delta RIs + \Delta RIc + \Delta RIr + \Delta RIt) + Kgm \times m \times RI \qquad \text{(AN2.1)}$$

Where;

Kgp	=	calibration factor, Default value = 1.0
Kgm	=	calibration factor for environmental condition
ΔRI	=	total annual rate of change in road pavement roughness
ΔRIs	=	change in roughness resulting from pavement strength deterioration due to vehicles
ΔRIc	=	change in roughness due to cracking
ΔRIr	=	change in roughness due to rutting
ΔRIt	=	change in roughness due to pothole

The last term in the right hand side of the equation takes into account environmental condition.

Where;

Kgm	=	calibration factor for environmental condition
m	=	a constant taking into account environmental effects
RI	=	road pavement roughness at the start of the analysis year

Figure AN2.1 illustrates the cumulative probability of annual rates of deterioration in road pavement roughness for a three-year period (i.e. 2000-01, 2001-02, and 2002-03). According to this method, the input variables in Equation AN2.1 are expressed in terms of the probability distribution. The rate of change (ΔRI) in Equation AN2.1 will result in a probability distribution.

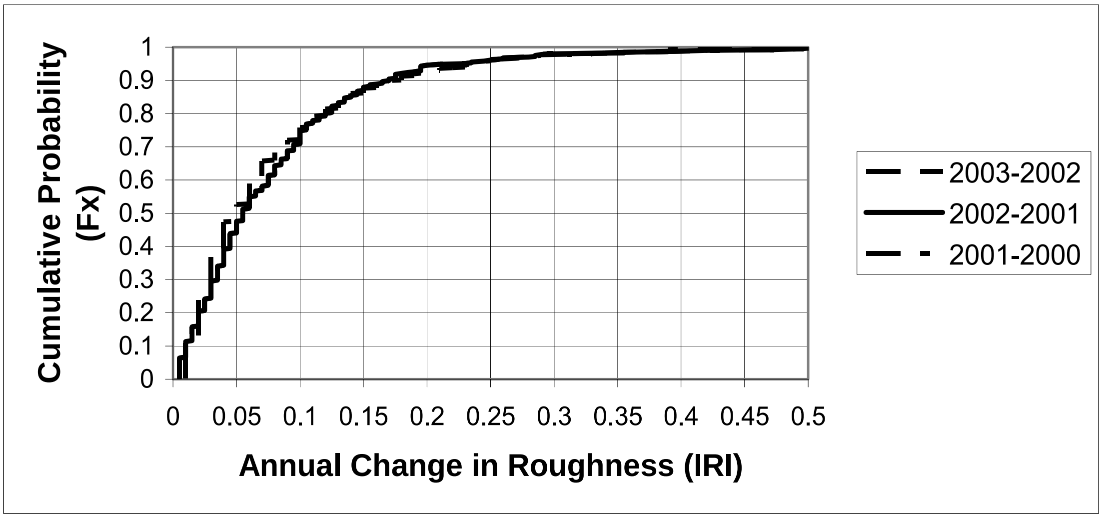

Figure AN2.1 The cumulative probability distribution of annual rate of change in road pavement roughness between the years, 2000-01, 2001-02 and 2002-03

In the calibration, the probability distribution of the rate of change obtained from Equation AN2.1 and the actual rate of change obtained from the recorded data are compared while the calibration factors are adjusted so that the two cumulative probability distributions achieve best fit.

Figure AN.2.1 illustrates the result of a comparison between the cumulative probability distributions of the actual rate of change of road pavement roughness and the rate of change of road pavement roughness obtained from Equation AN.2.1. The calibration factors (Kgm) can be used in giving different percentiles that reflect the actual variability of the recorded data. The method yields calibrated models that closely replicate the actual variability in road network condition.

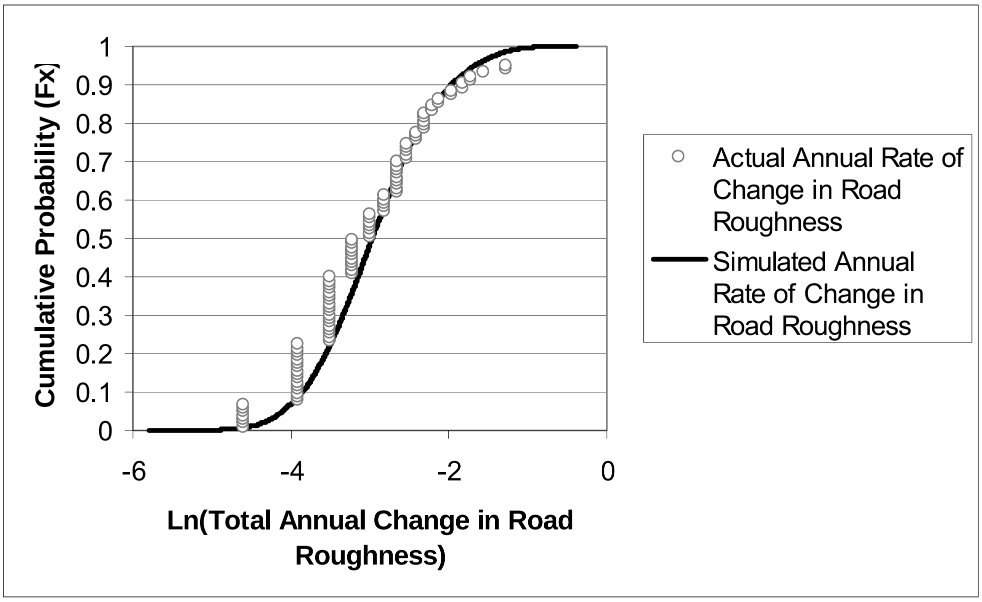

Figure AN2.2 Comparison between the cumulative probability distributions of actual and simulated annual change in roughness for pavement thickness

Annex 3: Method for assessing risk and variation in road network performance

Currently, road asset managers need to make their decisions with limited information on risk and variation in network investment. The risk of errors and variation of maintenance and rehabilitation investment budgets is one of the key factors affecting investment decision-making and, thereby, the allocation of funds. Risk of errors in investment estimates may result from the variability in the prediction of pavement performance, variability in costs of material, variability in costs of constructions, variability in road users as well as in climatic condition and etc.

The aim of the proposed method is to incorporate the variability of the stochastic characteristics of road asset conditions and other critical input parameters along the road network into the assessment of life-cycle network performance and investment costs.

The first step in this method is to define a performance function which transforms input variables into network performance and maintenance and rehabilitation investment costs. A performance function for budget estimates for road maintenance and rehabilitation may be written as:

$$G = \frac{1}{(1+r)^t} \sum_1^t \sum_1^n f\left(Z_1 Y_{1,n,t}, Z_2 Y_{2,n,t}, \ldots, Z_m Y_{m,n,t}\right) \qquad \text{(AN3.1)}$$

Where G is the total budget expressed in terms of probability distribution. m is the number of critical input variables, the variability of which is considered in the analysis. $Y_{1,n,t}$, $Y_{2,n,t}$, …, $Y_{m,n,t}$ are random variables of input variables with known probabilities of section n in year t. Z_1, Z_2, …, Z_n are random transform functions representing model errors in prediction. n is the number of road sections used in the analysis. t is the total year used for the life-cycle budget estimates. r is the discount rate.

The calculation of Equation AN3.1 is the subject of determining the relationship between input statistics and output statistics (i.e. how the variability of input variables affects the variability of output variables). The calculation of the probability of Equation AN3.1 becomes difficult since the transform function is highly complicated. It involves establishing deterioration prediction models of road conditions; quantifying road usage and forecasting the incremental road usage into the future; and optimising different budget scenarios to obtain optimal budget estimates.

To this end, a simulation method is desirable for assessing the statistical relationship between the input and output variables. A simplified sampling technique such as the Monte Carlo Simulation technique (Gary an Travers, 1987) may require a larger number of data to be sampled to represent the overall variability of an input variable in the analysis. The Latin hypercube sampling technique, as extensively studied by Iman and Conover (1980), provides satisfactory results for using small samples of input variables so that good estimates of the means, standard deviations and probability distribution functions of the output variables can be obtained.

The outcome of the analysis will be probability distributions of network performance parameters (e.g. physical performance of road network, nature of maintenance and rehabilitation activities, estimated cost per kilometre, whole-of-life-cycle costs and etc.)

The risk is defined as the probability of network performance that is greater than specified thresholds. The risk can be adjusted in terms of the level of confidence, for example the estimated budget that will be within the 95% probability of confidence.

Pr = P(Estimated network performance > Specified network performance threshold (AN3.2)

The reliability of network performance will be less than a specified network threshold can be written as;

$\Re = 1 - Pr$ (AN3.3)

The probability for estimated network performance can be schematically illustrated in Figure AN3.1.

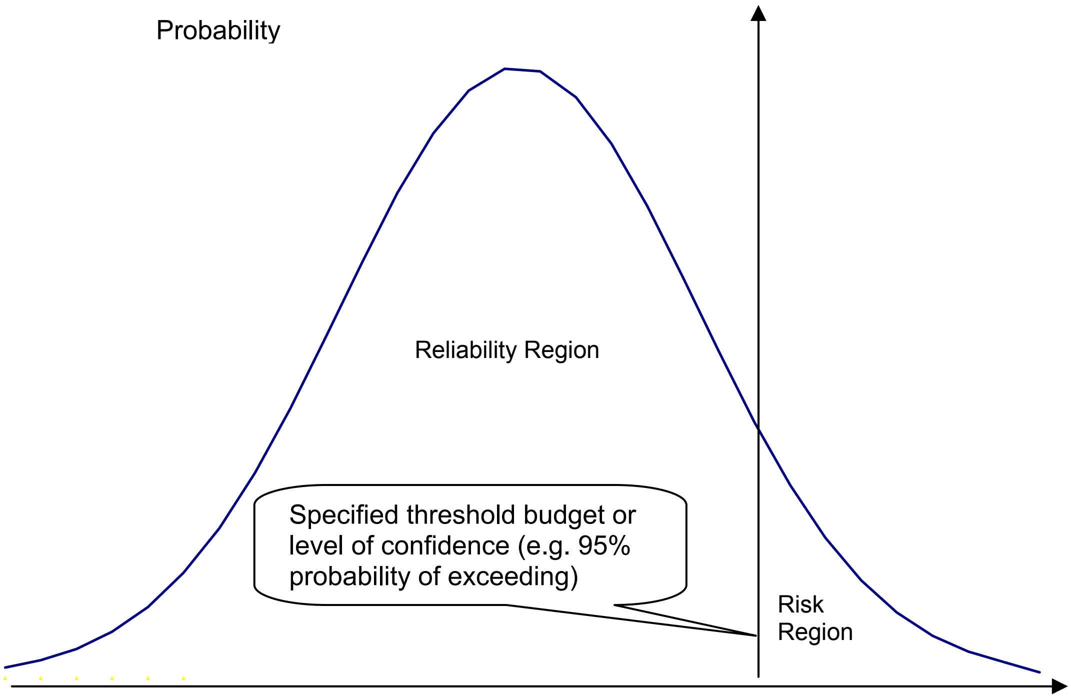

Figure AN3.1 Probability of Network Performance (e.g. Budget/Cost Estimate)

Appendix A

Table A1 Means, standard deviations and the probability distributions of pavement age (*AGE3*) for pavement thicknesses of 200-300 mm, 300-400 mm, 400-500 mm and 500-600 mm.

Thickness	Parameter	Mean	Standard Deviation	Probability Distribution
200-300 mm	*AGE3*	5.48 (years)	3.77 (years)	Log-normal
300-400 mm	*AGE3*	5.04 (years)	3.76 (years)	Log-normal
400-500 mm	*AGE3*	5.03 (years)	4.32 (years)	Log-normal
500-600 mm	*AGE3*	6.04 (years)	2.01 (years)	Log-normal

Table A2 Means, standard deviations and the probability distributions of annual equivalent of standard axle load (*YE4*) for pavement thickness of 200-300 mm, 300-400 mm, 400-500 mm and 500-600 mm.

Thickness	Parameter	Mean	Standard Deviation	Probability Distribution
200-300 mm	*YE4*	0.48 (million/lane)	0.137 (million/lane)	Log-normal
300-400 mm	*YE4*	0.69 (million/lane)	0.36 (million/lane)	Log-normal
400-500 mm	*YE4*	0.74 (million/lane)	0.49 (million/lane)	Log-normal
500-600 mm	*YE4*	0.99 (million/lane)	0.50 (million/lane)	Log-normal

Table A3 Means, standard deviations and the probability distributions of modified structural number ($SNPK_b$)for pavement thickness of 200-300 mm, 300-400 mm, 400-500 mm and 500-600 mm

Thickness	Parameter	Mean	Standard Deviation	Probability Distribution
200-300 mm	$SNPK_b$	3.73	1.17	Log-normal
300-400 mm	$SNPK_b$	3.70	1.39	Log-normal
400-500 mm	$SNPK_b$	3.64	0.64	Log-normal
500-600 mm	$SNPK_b$	3.64	0.64	Log-normal

Table A4 Means, standard deviations and probability distributions of percentage of cracking per carriage way for pavement thickness of 200-300 mm, 300-400 mm, 400-500 mm and 500-600 mm

Thickness	Parameter	Mean	Standard Deviation	Probability Distribution
200-300 mm	*% of crack*	0.157	0.113	Log-normal
300-400 mm	*% of crack*	0.235	0.216	Log-normal
400-500 mm	*% of crack*	0.276	0.219	Log-normal
500-600 mm	*% of crack*	0.326	0.185	Log-normal

Table A5 Means, standard deviations and probability distributions of standard deviation rut depth for pavement thickness of 200-300 mm, 300-400 mm, 400-500 mm and 500-600 mm

Thickness	Parameter	Mean (mm)	Standard Deviation (mm)	Probability Distribution
200-300 mm	*SD of rut depth*	0.64	1.08	Log-normal
300-400 mm	*SD of rut depth*	0.70	1.38	Log-normal
400-500 mm	*SD of rut depth*	0.73	0.88	Log-normal
500-600 mm	*SD of rut depth*	0.78	1.24	Log-normal

Table A6 Means, standard deviations and probability distributions of roughness (*IRI*) at the start of the analysis year for pavement thickness of 200-300 mm, 300-400 mm, 400-500 mm and 500-600 mm

Thickness	Parameter	Mean (IRI)	Standard Deviation (IRI)	Probability Distribution
200-300 mm	*Initial IRI*	1.84	0.47	Log-normal
300-400 mm	*Initial IRI*	1.85	0.62	Log-normal
400-500 mm	*Initial IRI*	1.70	0.47	Log-normal
500-600 mm	*Initial IRI*	1.74	0.44	Log-normal

Appendix B
Table B1 Road Categories for Wet Non-Reactive Soil

No	ID	Description	Climatic Zone	Surface Type	Pavement Type	Roughness IRI	AADT
1	G1	WNR-Good-Bt-Flx-(1.5k-3k)	Wet Non Reactive	Bitumen	Flexible	< 2.31	1501-3000
2	G2	WNR-Good-Bt-Flx-(3k-5k)	Wet Non Reactive	Bitumen	Flexible	< 2.31	3001-5000
3	G3	WNR-Good-Bt-Flx-(5k-10k)	Wet Non Reactive	Bitumen	Flexible	< 2.31	5001-10000
4	G4	WNR-Good-Bt-Flx-(10k-25k)	Wet Non Reactive	Bitumen	Flexible	< 2.31	10001-25000
5	G5	WNR-Good-Bt-Flx-(>25k)	Wet Non Reactive	Bitumen	Flexible	< 2.31	>25000
6	G6	WNR-Fair-Bt-Flx-(1.5k-3k)	Wet Non Reactive	Bitumen	Flexible	2.31-4.2	1501-3000
7	G7	WNR-Fair-Bt-Flx-(3k-5k)	Wet Non Reactive	Bitumen	Flexible	2.31-4.2	3001-5000
8	G8	WNR-Fair-Bt-Flx-(5k-10k)	Wet Non Reactive	Bitumen	Flexible	2.31-4.2	5001-10000
9	G9	WNR-Fair-Bt-Flx-(10k-25k)	Wet Non Reactive	Bitumen	Flexible	2.31-4.2	10001-25000
10	G10	WNR-Poor-Bt-Flx-(1.5k-3k)	Wet Non Reactive	Bitumen	Flexible	>4.2	1501-3000

Table B1 Road Categories for Wet Non-Reactive Soil /Continued

No	ID	Description	Climatic Zone	Surface Type	Pavement Type	Roughness IRI	AADT
11	G11	WNR-Poor-Bt-Flx-(3k-5k)	Wet Non Reactive	Bitumen	Flexible	>4.2	3001-5000
12	G12	WNR-Good-AC- Flx -(1.5k-3k)	Wet Non Reactive	AC	Flexible	< 2.31	1501-3000
13	G13	WNR-Good-AC-Flx-(3k-5k)	Wet Non Reactive	AC	Flexible	< 2.31	3001-5000
14	G14	WNR-Good-AC-Flx-(5k-10k)	Wet Non Reactive	AC	Flexible	< 2.31	5001-10000
15	G15	WNR-Good-AC-Flx-(10k-25k)	Wet Non Reactive	AC	Flexible	< 2.31	10001-25000
16	G16	WNR-Good-AC-Flx-(>25k)	Wet Non Reactive	AC	Flexible	< 2.31	>25000
17	G17	WNR-Fair-AC-Flx-(1.5k-3k)	Wet Non Reactive	AC	Flexible	2.31-4.2	1501-3000
18	G18	WNR-Fair-AC-Flx-(3k-5k)	Wet Non Reactive	AC	Flexible	2.31-4.2	3001-5000
19	G19	WNR-Fair-AC-Flx-(5k-10k)	Wet Non Reactive	AC	Flexible	2.31-4.2	5001-10000
20	G20	WNR-Fair-AC-Flx-(10k-25k)	Wet Non Reactive	AC	Flexible	2.31-4.2	10001-25000

Table B1 Road Categories for Wet Non-Reactive Soil /Continued

No	ID	Description	Climatic Zone	Surface Type	Pavement Type	Roughness IRI	AADT
21	G21	WNR-Fair-AC-Flx-(>25k)	Wet Non Reactive	AC	Flexible	2.31-4.2	>25000
22	G22	WNR-Good-Bt-SR-(1.5k-3k)	Wet Non Reactive	Bitumen	Semi Rigid	< 2.31	1501-3000
23	G23	WNR-Good-Bt-SR-(3k-5k)	Wet Non Reactive	Bitumen	Semi Rigid	< 2.31	3001-5000
24	G24	WNR-Good-Bt-SR-(5k-10k)	Wet Non Reactive	Bitumen	Semi Rigid	< 2.31	5001-10000
25	G25	WNR-Fair-Bt-SR-(1.5k-3k)	Wet Non Reactive	Bitumen	Semi Rigid	2.31-4.2	1501-3000
26	G26	WNR-Fair-Bt-SR-(3k-5k)	Wet Non Reactive	Bitumen	Semi Rigid	2.31-4.2	3001-5000
27	G27	WNR-Fair-Bt-SR-(5k-10k)	Wet Non Reactive	Bitumen	Semi Rigid	2.31-4.2	5001-10000
28	G28	WNR-Fair-Bt-SR-(10k-25k)	Wet Non Reactive	AC	Flexible	2.31-4.2	10001-25000
29	G29	WNR-Fair-AC-SR-(10k-25k)	Wet Non Reactive	AC	Flexible	2.31-4.2	10001-25000
30	G30	WNR-Fair-AC-SR-(>25k)	Wet Non Reactive	AC	Flexible	2.31-4.2	>25000

Table B2 Road Categories for Dry Reactive Soil

No	ID	Description	Climatic Zone	Surface Type	Pavement Type	Roughness IRI	AADT
31	B1	DR-Good-Bt-Flx-(<0.5k)	Dry Reactive	Bitumen	Flexible	< 2.31	<500
32	B2	DR-Good-Bt-Flx-(1.5k-3k)	Dry Reactive	Bitumen	Flexible	< 2.31	1501-3000
33	B3	DR-Good-Bt-Flx-(3k-5k)	Dry Reactive	Bitumen	Flexible	< 2.31	3001-5000
34	B4	DR-Good-Bt-Flx-(5k -10k)	Dry Reactive	Bitumen	Flexible	< 2.31	5001-10000
35	B5	DR-Good-Bt-Flx-(10k-25k)	Dry Reactive	Bitumen	Flexible	< 2.31	10001-25000
36	B6	DR-Fair-Bt-Flx-(<0.5k)	Dry Reactive	Bitumen	Flexible	2.31-4.2	<500
37	B7	DR-Fair-Bt-Flx-(0.5k-1.5k)	Dry Reactive	Bitumen	Flexible	2.31-4.2	501-1500
38	B8	DR-Fair-Bt-Flx-(1.5k-3k)	Dry Reactive	Bitumen	Flexible	2.31-4.2	1501-3000
39	B9	DR-Fair-Bt-Flx-(3k-5)	Dry Reactive	Bitumen	Flexible	2.31-4.2	3001-5000
40	B10	DR-Fair-Bt-Flx-(5k-10k)	Dry Reactive	Bitumen	Flexible	2.31-4.2	5001-10000

Table B2 Road Categories for Wet Non-Reactive Soil /Continued

No	ID	Description	Climatic Zone	Surface Type	Pavement Type	Roughness IRI	AADT
41	B11	DR-Fair-Bt-Flx-(10k-25k)	Dry Reactive	Bitumen	Flexible	2.31-4.2	10001-25000
42	B12	DR-Poor-Bt-Flx-(<0.5k)	Dry Reactive	Bitumen	Flexible	>4.2	<500
43	B13	DR-Poor-Bt-Flx-(0.5k-1.5k)	Dry Reactive	Bitumen	Flexible	>4.2	501-1500
44	B14	DR-Poor-Bt-Flx-(1.5k-3k)	Dry Reactive	Bitumen	Flexible	>4.2	1501-3000
45	B15	DR-Good-AC-Flx-(3k -5k)	Dry Reactive	AC	Flexible	< 2.31	3001-5000
46	B16	DR-Good-Bt-SR-(<0.5k)	Dry Reactive	Bitumen	Semi Rigid	< 2.31	<500
47	B17	DR-Fair-Bt-SR-(<0.5k)	Dry Reactive	Bitumen	Semi Rigid	2.31-4.2	<500

Table B3 Road Categories for Dry Non-Reactive Soil

No	ID	Description	Climatic Zone	Surface Type	Pavement Type	Roughness IRI	AADT
48	R1	DNR-Good-Bt-Flx-(<0.5k)	Dry Non Reactive	Bitumen	Flexible	< 2.31	<500
49	R2	DNR-Good-Bt-Flx-(0.5k-1.5k)	Dry Non Reactive	Bitumen	Flexible	< 2.31	501-1500
50	R3	DNR-Good-Bt-Flx-(1.5k-3k)	Dry Non Reactive	Bitumen	Flexible	< 2.31	1501-3000
51	R4	DNR-Good-Bt-Flx-(3k-5k)	Dry Non Reactive	Bitumen	Flexible	< 2.31	3001-5000
52	R5	DNR-Good-Bt-Flx-(5k -10k)	Dry Non Reactive	Bitumen	Flexible	< 2.31	5001-10000
53	R6	DNR-Good-Bt-Flx-(10k-25k)	Dry Non Reactive	Bitumen	Flexible	< 2.31	10001-25000
54	R7	DNR-Fair-Bt-Flx-(<0.5k)	Dry Non Reactive	Bitumen	Flexible	2.31-4.2	<500
55	R8	DNR-Fair-Bt-Flx-(0.5k-1.5k)	Dry Non Reactive	Bitumen	Flexible	2.31-4.2	501-1500
56	R9	DNR-Fair-Bt-Flx-(1.5k-3k)	Dry Non Reactive	Bitumen	Flexible	2.31-4.2	1501-3000
57	R10	DNR-Fair-Bt-Flx-(3k-5k)	Dry Non Reactive	Bitumen	Flexible	2.31-4.2	3001-5000

Table B3 Road Categories for Dry Non-Reactive Soil /Continued

No	ID	Description	Climatic Zone	Surface Type	Pavement Type	Roughness IRI	AADT
58	R11	DNR-Fair-Bt-Flx-(5k-10k)	Dry Non Reactive	Bitumen	Flexible	2.31-4.2	5001-10000
59	R12	DNR-Fair-Bt-Flx-(10k-25k)	Dry Non Reactive	Bitumen	Flexible	2.31-4.2	10001-25000
60	R13	DNR-Poor-Bt-Flx-(<0.5k)	Dry Non Reactive	Bitumen	Flexible	>4.2	<500
61	R14	DNR-Poor-Bt-Flx-(0.5k-1.5k)	Dry Non Reactive	Bitumen	Flexible	>4.2	501-1500
62	R15	DNR-Good-AC-Flx-(0.5k-1.5k)	Dry Non Reactive	AC	Flexible	<2.31	501-1500
63	R16	DNR-Good-AC-Flx-(1.5k-3k)	Dry Non Reactive	AC	Flexible	<2.31	1501-3000
64	R17	DNR-Fair-AC-Flx-(0.5k-1.5k)	Dry Non Reactive	AC	Flexible	2.31-4.2	501-1500
65	R18	DNR-Good-Bt-SR-(0.5k -1.5k)	Dry Non Reactive	Bitumen	Semi Rigid	< 2.31	501-1500

Appendix C

Table C1 Probability Distributions, Means and Standard Deviation Values of Road Categories for Wet Non-Reactive Soil

ID	Description	Roughness (IRI)		
		Mean	SD	Probability Distribution
G1	WNR-Good-Bt-Flx-(1.5k-3k)	1.69	0.35	Beta General
G2	WNR-Good-Bt-Flx-(3k-5k)	1.63	0.35	Beta General
G3	WNR-Good-Bt-Flx-(5k-10k)	1.70	0.35	Beta General
G4	WNR-Good-Bt-Flx-(10k-25k)	1.73	0.32	Beta General
G5	WNR-Good-Bt-Flx-(>25k)	1.69	0.31	Logistic
G6	WNR-Fair-Bt-Flx-(1.5k-3k)	2.80	0.41	Beta General
G7	WNR-Fair-Bt-Flx-(3k-5k)	2.84	0.44	Beta General
G8	WNR-Fair-Bt-Flx-(5k-10k)	2.89	0.41	Beta General
G9	WNR-Fair-Bt-Flx-(10k-25k)	2.76	0.35	Lognormal
G10	WNR-Poor-Bt-Flx-(1.5k-3k)	5.02	0.63	Pearson5
G11	WNR-Poor-Bt-Flx-(3k-5k)	4.89	0.67	Pearson5
G12	WNR-Good-AC- Flx -(1.5k-3k)	1.46	0.42	Beta General
G13	WNR-Good-AC-Flx-(3k-5k)	1.58	0.42	Beta General
G14	WNR-Good-AC-Flx-(5k-10k)	1.58	0.39	Beta General
G15	WNR-Good-AC-Flx-(10k-25k)	1.48	0.41	Beta General
G16	WNR-Good-AC-Flx-(>25k)	1.48	0.43	Beta General
G17	WNR-Fair-AC-Flx(1.5k-3k)	2.81	0.36	Beta General
G18	WNR-Fair-AC-Flx(3k-5k)	2.92	0.50	Beta General
G19	WNR-Fair-AC-Flx-(5k-10k)	2.75	0.37	Beta General
G20	WNR-Fair-AC-Flx-(10k-25k)	2.83	0.45	Beta General

Table C1 Probability Distributions, Means and Standard Deviation Values of Road Categories for Wet Non-Reactive Soil /Continued

ID	Description	Roughness (IRI)		
		Mean	SD	Probability Distribution
G21	WNR-Fair-AC-Flx-(>25k)	2.87	0.43	Beta General
G22	WNR-Good-Bt-SR-(1.5k-3k)	1.60	0.34	Log Logistic
G23	WNR-Good-Bt-SR-(3k-5k)	1.61	0.34	Log Logistic
G24	WNR-Good-Bt-SR-(5k-10k)	1.69	0.36	Log Logistic
G25	WNR-Fair-Bt-SR-(1.5k-3k)	2.60	0.88	Log Logistic
G26	WNR-Fair-Bt-SR-(3k-5k)	2.79	0.40	Beta General
G27	WNR-Fair-Bt-SR-(5k-10k)	3.18	0.41	Log Logistic
G28	WNR-Fair-Bt-SR-(10k-25k)	3.00	0.49	Log Logistic
G29	WNR-Fair-AC-SR-(10k-25k)	2.96	0.51	Log Logistic
G30	WNR-Fair-AC-SR-(>25k)	2.82	0.66	Log Logistic

Table C2 Probability Distributions, Means and Standard Deviation Values of Road Categories for Dry Reactive Soil

ID	Description	Roughness (IRI)		
		Mean	SD	Probability Distribution
B1	DR-Good-Bt-Flx-(<0.5k)	1.85	0.31	Beta General
B2	DR-Good-Bt-Flx-(1.5k-3k)	1.82	0.39	Beta General
B3	DR-Good-Bt-Flx-(3k-5k)	1.71	0.37	Beta General
B4	DR-Good-Bt-Flx-(5k -10k)	1.79	0.32	Beta General
B5	DR-Good-Bt-Flx-(10k-25k)	1.73	0.33	Beta General
B6	DR-Fair-Bt-Flx-(<0.5k)	2.88	0.46	InvGauss
B7	DR-Fair-Bt-Flx-(0.5k-1.5k)	2.99	0.47	Beta General
B8	DR-Fair-Bt-Flx-(1.5k-3k)	3.08	0.51	Beta General
B9	DR-Fair-Bt-Flx-(3k-5)	2.85	0.46	Beta General
B10	DR-Fair-Bt-Flx-(5k-10k)	3.12	0.47	Uniform
B11	DR-Fair-Bt-Flx-(10k-25k)	2.83	0.48	Log Normal
B12	DR-Poor-Bt-Flx-(<0.5k)	5.73	3.22	Pearson5
B13	DR-Poor-Bt-Flx-(0.5k-1.5k)	5.86	2.47	Pearson5
B14	DR-Poor-Bt-Flx-(1.5k-3k)	5.93	1.23	Pearson5
B15	DR-Good-AC-Flx-(3k -5k)	1.52	0.39	Beta General
B16	DR-Good-Bt-SR-(<0.5k)	1.83	0.33	Beta General
B17	DR-Fair-Bt-SR-(<0.5k)	2.91	0.45	Beta General

Table C3 Probability Distributions, Means and Standard Deviation Values of Road Categories for Dry Non-Reactive Soil

ID	Description	Roughness (IRI)		
		Mean	SD	Probability Distribution
R1	DNR-Good-Bt-Flx-(<0.5k)	2.32	0.39	Beta General
R2	DNR-Good-Bt-Flx-(0.5k-1.5k)	1.70	0.35	Beta General
R3	DNR-Good-Bt-Flx-(1.5k-3k)	1.72	0.36	Beta General
R4	DNR-Good-Bt-Flx-(3k-5k)	1.82	0.34	Beta General
R5	DNR-Good-Bt-Flx-(5k -10k)	1.80	0.37	Beta General
R6	DNR-Good-Bt-Flx-(10k-25k)	1.70	0.31	Beta General
R7	DNR-Fair-Bt-Flx-(<0.5k)	2.30	0.48	Beta General
R8	DNR-Fair-Bt-Flx-(0.5k-1.5k)	2.90	0.46	Beta General
R9	DNR-Fair-Bt-Flx-(1.5k-3k)	2.96	0.47	Beta General
R10	DNR-Fair-Bt-Flx-(3k-5k)	2.89	0.43	Beta General
R11	DNR-Fair-Bt-Flx-(5k-10k)	2.90	0.46	Beta General
R12	DNR-Fair-Bt-Flx-(10k-25k)	2.64	0.37	Log Normal
R13	DNR-Poor-Bt-Flx-(<0.5k)	5.07	2.0	Log Normal
R14	DNR-Poor-Bt-Flx-(0.5k-1.5k)	4.98	1.92	Log Normal
R15	DNR-Good-AC-Flx-(0.5k-1.5k)	1.57	0.36	Log Normal
R16	DNR-Good-AC-Flx-(1.5k-3k)	1.60	0.34	Log Normal
R17	DNR-Fair-AC-Flx-(0.5k-1.5k)	1.83	0.33	Normal
R18	DNR-Good-Bt-SR-(0.5k -1.5k)	1.32	0.27	Log Logistic

Appendix D

Table D1 Probability Distributions, Means and Standard Deviation Values of Road Categories for Wet Non-Reactive Soil

ID	Description	Rut Depth (mm)		
		Mean	SD	Probability Distribution
G1	WNR-Good-Bt-Flx-(1.5k-3k)	5.09	2.84	Gamma
G2	WNR-Good-Bt-Flx-(3k-5k)	5.18	2.77	Gamma
G3	WNR-Good-Bt-Flx-(5k-10k)	4.73	2.27	Log Normal
G4	WNR-Good-Bt-Flx-(10k-25k)	4.32	3.03	Log Normal
G5	WNR-Good-Bt-Flx-(>25k)	4.19	1.93	Normal
G6	WNR-Fair-Bt-Flx-(1.5k-3k)	5.80	2.91	Gamma
G7	WNR-Fair-Bt-Flx-(3k-5k)	5.59	3.02	Log Normal
G8	WNR-Fair-Bt-Flx-(5k-10k)	5.25	2.20	Log Normal
G9	WNR-Fair-Bt-Flx-(10k-25k)	5.39	2.88	Log Normal
G10	WNR-Poor-Bt-Flx-(1.5k-3k)	3.67	1.39	Log Normal
G11	WNR-Poor-Bt-Flx-(3k-5k)	8.53	7.46	Log Logistic
G12	WNR-Good-AC- Flx -(1.5k-3k)	3.95	1.92	Log Normal
G13	WNR-Good-AC-Flx-(3k-5k)	4.30	2.32	Log Normal
G14	WNR-Good-AC-Flx-(5k-10k)	3.55	2.33	Log Normal
G15	WNR-Good-AC-Flx-(10k-25k)	3.98	2.21	Gamma
G16	WNR-Good-AC-Flx-(>25k)	4.12	2.75	Log Normal
G17	WNR-Fair-AC-Flx(1.5k-3k)	4.34	1.76	Log Normal
G18	WNR-Fair-AC-Flx(3k-5k)	5.84	3.53	Log Normal
G19	WNR-Fair-AC-Flx-(5k-10k)	4.92	2.62	Log Normal
G20	WNR-Fair-AC-Flx-(10k-25k)	5.41	2.91	InvGauss

Table D1 Probability Distributions, Means and Standard Deviation Values of Road Categories for Wet Non-Reactive Soil /Continued

ID	Description	Rut Depth (mm)		
		Mean	SD	Probability Distribution
G21	WNR-Fair-AC-Flx-(>25k)	5.21	2.39	Log Normal
G22	WNR-Good-Bt-SR-(1.5k-3k)	3.80	2.04	Gamma
G23	WNR-Good-Bt-SR-(3k-5k)	3.83	1.84	Log Normal
G24	WNR-Good-Bt-SR-(5k-10k)	5.08	3.39	Log Normal
G25	WNR-Fair-Bt-SR-(1.5k-3k)	4.14	2.59	Log Normal
G26	WNR-Fair-Bt-SR-(3k-5k)	4.77	2.19	Log Normal
G27	WNR-Fair-Bt-SR-(5k-10k)	6.83	2.99	Log Logistic
G28	WNR-Fair-Bt-SR-(10k-25k)	3.34	1.06	Normal
G29	WNR-Fair-AC-SR-(10k-25k)	4.17	2.54	Log Normal
G30	WNR-Fair-AC-SR-(>25k)	4.51	1.56	Log Normal

Table D2 Probability Distributions, Means and Standard Deviation Values of Road Categories for Dry Reactive Soil

ID	Description	Rut Depth (mm)		
		Mean	SD	Probability Distribution
B1	DR-Good-Bt-Flx-(<0.5k)	5.30	3.21	Gamma
B2	DR-Good-Bt-Flx-(1.5k-3k)	5.27	3.32	Log Normal
B3	DR-Good-Bt-Flx-(3k-5k)	4.83	4.67	Log Normal
B4	DR-Good-Bt-Flx-(5k -10k)	3.90	2.15	Log Normal
B5	DR-Good-Bt-Flx-(10k-25k)	5.09	4.36	Log Normal
B6	DR-Fair-Bt-Flx-(<0.5k)	6.25	3.15	Log Normal
B7	DR-Fair-Bt-Flx-(0.5k-1.5k)	5.42	2.75	Log Normal
B8	DR-Fair-Bt-Flx-(1.5k-3k)	6.44	4.12	Log Normal
B9	DR-Fair-Bt-Flx-(3k-5)	5.47	2.76	Log Normal
B10	DR-Fair-Bt-Flx-(5k-10k)	4.18	2.59	Log Normal
B11	DR-Fair-Bt-Flx-(10k-25k)	4.62	1.92	InvGauss
B12	DR-Poor-Bt-Flx-(<0.5k)	6.43	3.03	Log Normal
B13	DR-Poor-Bt-Flx-(0.5k-1.5k)	6.37	3.30	Log Normal
B14	DR-Poor-Bt-Flx-(1.5k-3k)	6.9	3.7	Log Normal
B15	DR-Good-AC-Flx-(3k -5k)	5.18	1.79	Log Logistic
B16	DR-Good-Bt-SR-(<0.5k)	4.37	1.82	Log Normal
B17	DR-Fair-Bt-SR-(<0.5k)	5.12	2.35	Log Normal

Table D3 Probability Distributions, Means and Standard Deviation Values of Road Categories for Dry Non-Reactive Soil

ID	Description	Rut Depth (mm)		
		Mean	SD	Probability Distribution
R1	DNR-Good-Bt-Flx-(<0.5k)	4.52	1.97	Log Normal
R2	DNR-Good-Bt-Flx-(0.5k-1.5k)	4.54	2.37	Log Normal
R3	DNR-Good-Bt-Flx-(1.5k-3k)	4.20	2.29	Log Normal
R4	DNR-Good-Bt-Flx-(3k-5k)	4.24	2.61	Log Normal
R5	DNR-Good-Bt-Flx-(5k -10k)	3.43	1.72	Log Normal
R6	DNR-Good-Bt-Flx-(10k-25k)	4.60	1.53	Normal
R7	DNR-Fair-Bt-Flx-(<0.5k)	6.14	3.06	Log Normal
R8	DNR-Fair-Bt-Flx-(0.5k-1.5k)	5.88	2.74	Log Normal
R9	DNR-Fair-Bt-Flx-(1.5k-3k)	5.53	2.75	Log Normal
R10	DNR-Fair-Bt-Flx-(3k-5k)	4.55	2.46	Log Normal
R11	DNR-Fair-Bt-Flx-(5k-10k)	4.35	1.33	Log Normal
R12	DNR-Fair-Bt-Flx-(10k-25k)	5.40	1.29	Log Normal
R13	DNR-Poor-Bt-Flx-(<0.5k)	6.91	4.0	Log Normal
R14	DNR-Poor-Bt-Flx-(0.5k-1.5k)	6.13	2.98	Log Normal
R15	DNR-Good-AC-Flx-(0.5k-1.5k)	6.04	1.67	Normal
R16	DNR-Good-AC-Flx-(1.5k-3k)	2.47	0.97	Log Normal
R17	DNR-Fair-AC-Flx-(0.5k-1.5k)	4.01	1.34	Log Normal
R18	DNR-Good-Bt-SR-(0.5k -1.5k)	3.48	1.54	Log Normal

Appendix E

Table E1 Probability Distributions, Means and Standard Deviation Values of Road Categories for Wet Non-Reactive Soil

ID	Description	AADT		
		Mean	SD	Probability Distribution
G1	WNR-Good-Bt-Flx-(1.5k-3k)	2502	345	Triangular
G2	WNR-Good-Bt-Flx-(3k-5k)	3978	650	Logistic
G3	WNR-Good-Bt-Flx-(5k-10k)	6680	1140	Triangular
G4	WNR-Good-Bt-Flx-(10k-25k)	14877	2930	Triangular
G5	WNR-Good-Bt-Flx-(>25k)	32181	2847	Triangular
G6	WNR-Fair-Bt-Flx-(1.5k-3k)	2492	351	Triangular
G7	WNR-Fair-Bt-Flx-(3k-5k)	4042	538	Logistic
G8	WNR-Fair-Bt-Flx-(5k-10k)	6845	1123	Triangular
G9	WNR-Fair-Bt-Flx-(10k-25k)	16413	3198	Triangular
G10	WNR-Poor-Bt-Flx-(1.5k-3k)	2529	325	Triangular
G11	WNR-Poor-Bt-Flx-(3k-5k)	3728	525	Log Normal
G12	WNR-Good-AC- Flx -(1.5k-3k)	2702	266	Normal
G13	WNR-Good-AC-Flx-(3k-5k)	4097	441	Triangular
G14	WNR-Good-AC-Flx-(5k-10k)	6831	1179	Triangular
G15	WNR-Good-AC-Flx-(10k-25k)	15942	3050	Triangular
G16	WNR-Good-AC-Flx-(>25k)	52880	18438	Triangular
G17	WNR-Fair-AC-Flx(1.5k-3k)	2430	351	Triangular
G18	WNR-Fair-AC-Flx(3k-5k)	4047	501	Triangular
G19	WNR-Fair-AC-Flx-(5k-10k)	7052	1336	Triangular
G20	WNR-Fair-AC-Flx-(10k-25k)	16166	3147	Triangular

Table E1 Probability Distributions, Means and Standard Deviation Values of Road Categories for Wet Non-Reactive Soil /Continued

ID	Description	AADT		
		Mean	SD	Probability Distribution
G21	WNR-Fair-AC-Flx-(>25k)	54606	20896	Triangular
G22	WNR-Good-Bt-SR-(1.5k-3k)	1840	-	-
G23	WNR-Good-Bt-SR-(3k-5k)	4204	409	Triangular
G24	WNR-Good-Bt-SR-(5k-10k)	6635	1041	Triangular
G25	WNR-Fair-Bt-SR-(1.5k-3k)	2786	-	-
G26	WNR-Fair-Bt-SR-(3k-5k)	4250	377	Triangular
G27	WNR-Fair-Bt-SR-(5k-10k)	6457	915	Triangular
G28	WNR-Fair-Bt-SR-(10k-25k)	22200	-	-
G29	WNR-Fair-AC-SR-(10k-25k)	18852	3873	Triangular
G30	WNR-Fair-AC-SR-(>25k)	53915	25895	Exponential

Table E2 Probability Distributions, Means and Standard Deviation Values of Road Categories for Dry Reactive Soil

ID	Description	AADT		
		Mean	SD	Probability Distribution
B1	DR-Good-Bt-Flx-(<0.5k)	320	133	Exponential
B2	DR-Good-Bt-Flx-(1.5k-3k)	821	226	Triangular
B3	DR-Good-Bt-Flx-(3k-5k)	3666	-	-
B4	DR-Good-Bt-Flx-(5k -10k)	5914	-	-
B5	DR-Good-Bt-Flx-(10k-25k)	10035	-	-
B6	DR-Fair-Bt-Flx-(<0.5k)	306	72	Triangular
B7	DR-Fair-Bt-Flx-(0.5k-1.5k)	823	228	Triangular
B8	DR-Fair-Bt-Flx-(1.5k-3k)	1853	240	Triangular
B9	DR-Fair-Bt-Flx-(3k-5)	3666	-	-
B10	DR-Fair-Bt-Flx-(5k-10k)	6164	822	Exponential
B11	DR-Fair-Bt-Flx-(10k-25k)	10035	-	-
B12	DR-Poor-Bt-Flx-(<0.5k)	300	60	Triangular
B13	DR-Poor-Bt-Flx-(0.5k-1.5k)	847	245	Triangular
B14	DR-Poor-Bt-Flx-(1.5k-3k)	1889	206	Triangular
B15	DR-Good-AC-Flx-(3k -5k)	3749	-	-
B16	DR-Good-Bt-SR-(<0.5k)	360	83	Exponential
B17	DR-Fair-Bt-SR-(<0.5k)	314	37	Exponential

Table E3 Probability Distributions, Means and Standard Deviation Values of Road Categories for Dry Non-Reactive Soil

ID	Description	AADT		
		Mean	SD	Probability Distribution
R1	DNR-Good-Bt-Flx-(<0.5k)	322	52	Triangular
R2	DNR-Good-Bt-Flx-(0.5k-1.5k)	970	244	Normal
R3	DNR-Good-Bt-Flx-(1.5k-3k)	1990	337	Exponential
R4	DNR-Good-Bt-Flx-(3k-5k)	3420	386	Exponential
R5	DNR-Good-Bt-Flx-(5k -10k)	6154	424	Exponential
R6	DNR-Good-Bt-Flx-(10k-25k)	10035	-	-
R7	DNR-Fair-Bt-Flx-(<0.5k)	311	54	Triangular
R8	DNR-Fair-Bt-Flx-(0.5k-1.5k)	953	210	Triangular
R9	DNR-Fair-Bt-Flx-(1.5k-3k)	1940	428	Exponential
R10	DNR-Fair-Bt-Flx-(3k-5k)	3300	267	Exponential
R11	DNR-Fair-Bt-Flx-(5k-10k)	6063	152	Exponential
R12	DNR-Fair-Bt-Flx-(10k-25k)	10035	-	-
R13	DNR-Poor-Bt-Flx-(<0.5k)	299	64	Exponential
R14	DNR-Poor-Bt-Flx-(0.5k-1.5k)	960	205	Triangular
R15	DNR-Good-AC-Flx-(0.5k-1.5k)	795	159	Triangular
R16	DNR-Good-AC-Flx-(1.5k-3k)	2211	345	Triangular
R17	DNR-Fair-AC-Flx-(0.5k-1.5k)	720	233	Exponential
R18	DNR-Good-Bt-SR-(0.5k -1.5k)	940	-	-

Appendix G

Table G1 Probability Distributions, Means and Standard Deviation Values of Structural number (SN) for Road Categories in Wet Non-Reactive Soil

ID	Description	Pavement Strength (SN)		
		Mean	SD	Probability Distribution
G1	WNR-Good-Bt-Flx-(1.5k-3k)	3.66	0.92	Log normal
G2	WNR-Good-Bt-Flx-(3k-5k)	3.73	1.06	Log normal
G3	WNR-Good-Bt-Flx-(5k-10k)	3.76	0.97	Log normal
G4	WNR-Good-Bt-Flx-(10k-25k)	3.72	1.19	Log normal
G5	WNR-Good-Bt-Flx-(>25k)	4.47	0.69	Log normal
G6	WNR-Fair-Bt-Flx-(1.5k-3k)	3.51	0.91	Log normal
G7	WNR-Fair-Bt-Flx-(3k-5k)	4.09	1.22	Log normal
G8	WNR-Fair-Bt-Flx-(5k-10k)	3.61	1.06	Log normal
G9	WNR-Fair-Bt-Flx-(10k-25k)	3.73	1.32	Log normal
G10	WNR-Poor-Bt-Flx-(1.5k-3k)	3.40	-	Log normal
G11	WNR-Poor-Bt-Flx-(3k-5k)	4.33	1.12	Log normal
G12	WNR-Good-AC- Flx -(1.5k-3k)	3.57	0.76	Normal
G13	WNR-Good-AC-Flx-(3k-5k)	3.63	0.71	Log normal
G14	WNR-Good-AC-Flx-(5k-10k)	3.89	1.04	Log normal
G15	WNR-Good-AC-Flx-(10k-25k)	3.68	1.08	Log normal
G16	WNR-Good-AC-Flx-(>25k)	4.51	1.04	Log normal
G17	WNR-Fair-AC-Flx(1.5k-3k)	3.47	1.28	Log normal
G18	WNR-Fair-AC-Flx(3k-5k)	3.57	1.08	Normal
G19	WNR-Fair-AC-Flx-(5k-10k)	3.92	0.99	Log normal
G20	WNR-Fair-AC-Flx-(10k-25k)	3.49	1.07	Log normal

Table G1 Probability Distributions, Means and Standard Deviation Values of SN for Road Categories in Wet Non-Reactive Soil/Continued

ID	Description	Pavement Strength (SN)		
		Mean	SD	Probability Distribution
G21	WNR-Fair-AC-Flx-(>25k)	5.12	0.74	Log normal
G22	WNR-Good-Bt-SR-(1.5k-3k)	3.53	1.68	Log normal
G23	WNR-Good-Bt-SR-(3k-5k)	4.31	1.25	Log normal
G24	WNR-Good-Bt-SR-(5k-10k)	4.51	1.30	Normal
G25	WNR-Fair-Bt-SR-(1.5k-3k)	3.73	2.92	Log logistic
G26	WNR-Fair-Bt-SR-(3k-5k)	4.37	1.15	Beta General
G27	WNR-Fair-Bt-SR-(5k-10k)	4.32	1.32	Normal
G28	WNR-Fair-Bt-SR-(10k-25k)	3.28	0.76	Log normal
G29	WNR-Fair-AC-SR-(10k-25k)	5.61	0.863	Log normal
G30	WNR-Fair-AC-SR-(>25k)	5.95	-	

Table G2 Probability Distributions, Means and Standard Deviation Values of SN for Road Categories in Dry Reactive Soil

ID	Description	Pavement Strength (SN)		
		Mean	SD	Probability Distribution
B1	DR-Good-Bt-Flx-(<0.5k)	2.56	0.85	Log normal
B2	DR-Good-Bt-Flx-(1.5k-3k)	2.98	0.66	Log normal
B3	DR-Good-Bt-Flx-(3k-5k)	2.73	0.69	Log logistic
B4	DR-Good-Bt-Flx-(5k -10k)	3.2	-	
B5	DR-Good-Bt-Flx-(10k-25k)	2.91	0.46	Log normal
B6	DR-Fair-Bt-Flx-(<0.5k)	2.51	0.82	Log normal
B7	DR-Fair-Bt-Flx-(0.5k-1.5k)	2.08	0.65	Log normal
B8	DR-Fair-Bt-Flx-(1.5k-3k)	3.14	0.72	Log normal
B9	DR-Fair-Bt-Flx-(3k-5)	2.07	0.66	Log normal
B10	DR-Fair-Bt-Flx-(5k-10k)	3.02	0.70	Log normal
B11	DR-Fair-Bt-Flx-(10k-25k)	2.71	0.66	Log normal
B12	DR-Poor-Bt-Flx-(<0.5k)	2.53	0.49	Normal
B13	DR-Poor-Bt-Flx-(0.5k-1.5k)	2.97	0.45	Log normal
B14	DR-Poor-Bt-Flx-(1.5k-3k)	3.08	0.65	Log normal
B15	DR-Good-AC-Flx-(3k -5k)	3.35	1.78	Log normal
B16	DR-Good-Bt-SR-(<0.5k)	3.10	0.83	Log normal
B17	DR-Fair-Bt-SR-(<0.5k)	3.53	1.05	Log normal

Table G3 Probability Distributions, Means and Standard Deviation Values of Structural number (SN) for Road Categories in Dry Non-Reactive Soil

ID	Description	Pavement Strength (SN)		
		Mean	SD	Probability Distribution
R1	DNR-Good-Bt-Flx-(<0.5k)	3.39	0.86	Log normal
R2	DNR-Good-Bt-Flx-(0.5k-1.5k)	2.80	0.83	Log normal
R3	DNR-Good-Bt-Flx-(1.5k-3k)	3.39	0.77	Log normal
R4	DNR-Good-Bt-Flx-(3k-5k)	3.00	0.52	Log normal
R5	DNR-Good-Bt-Flx-(5k -10k)	3.6	-	
R6	DNR-Good-Bt-Flx-(10k-25k)	3.19	0.95	Log normal
R7	DNR-Fair-Bt-Flx-(<0.5k)	3.17	0.76	Log normal
R8	DNR-Fair-Bt-Flx-(0.5k-1.5k)	2.83	0.78	Beta general
R9	DNR-Fair-Bt-Flx-(1.5k-3k)	3.14	0.70	Log normal
R10	DNR-Fair-Bt-Flx-(3k-5k)	3.10	1.21	Log normal
R11	DNR-Fair-Bt-Flx-(5k-10k)	3.41	-	
R12	DNR-Fair-Bt-Flx-(10k-25k)	3.07	0.74	Log normal
R13	DNR-Poor-Bt-Flx-(<0.5k)	2.85	0.59	Normal
R14	DNR-Poor-Bt-Flx-(0.5k-1.5k)	2.71	0.75	Log normal
R15	DNR-Good-AC-Flx-(0.5k-1.5k)	3.47	1.24	Normal
R16	DNR-Good-AC-Flx-(1.5k-3k)	3.38	0.63	Normal
R17	DNR-Fair-AC-Flx-(0.5k-1.5k)	2.86	0.63	Log normal
R18	DNR-Good-Bt-SR-(0.5k -1.5k)	3.95	-	

Appendix H

Table H1 Mean and Standard Deviation Values for Time-Interval for Maintenance and Rehabilitation for Wet Non-Reactive Soil

Description	Last Surfacing	1st Time Interval (Years)				2nd Time Interval (Years)			
		Mean (Years)	SD (Years)	% of Treatment	Treatment Types	Mean (Years)	SD (Years)	% of Treatment	Treatment Types
WNR-Good-Bt-Flx-(1.5k-3k)	11	4.3	1.2	34%	Reseal-15% Cracked	13.5	1.7	34%	Granular Overlay-5IRI& 10% Cracked
		11.1	1.9	66%	Granular Overlay-5IRI& 10% Cracked	9.4	0.4	66%	Granular Overlay-5IRI& 10% Cracked
WNR-Good-Bt-Flx-(3k-5k)	12	3.1	0.4	100%	Reseal-15% Cracked	9.9	1.0	73%	Reseal-15% Cracked
						13.2	2.7	37%	Granular Overlay-5IRI& 10% Cracked
WNR-Good-Bt-Flx-(5k-10k)	12	2.4	1.1	16%	Reseal-15% Cracked	12.6	1.1	16%	Reseal-15% Cracked
		2.2	0.3	84%	Reseal-15% Cracked	10.6	3.1	84%	Granular Overlay-5IRI& 10% Cracked
WNR-Good-Bt-Flx-(10k-25k)	11	3	-	97%	Cracking Sealing-5%WC	6.3	2.9	97%	Reconstruction-6IRI
		3	-	3%	AC50-3IRI and 10% Damaged	3.0	-	3%	AC50-3IRI and 10% Damaged
WNR-Fair-Bt-Flx-(1.5k-3k)	11	7.1	1.9	100%	Reseal-15% Cracked	9.4	0.4		Granular Overlay-5IRI& 10% Cracked

Table H1 Mean and Standard Deviation Values for Time-Interval for Maintenance and Rehabilitation for Wet Non-Reactive Soil/Continue.

Description	Last Surfacing	1st Time Interval (Years)				2nd Time Interval (Years)			
		Mean (Years)	SD (Years)	% of Treatment	Treatment Types	Mean (Years)	SD (Years)	% of Treatment	Treatment Types
WNR-Fair-Bt-Flx-(5k-10k)	13	3.6	0.8	100%	Reseal-15% Cracked	12.9	2.4		Granular Overlay-5IRI& 10% Cracked
WNR-Fair-Bt-Flx-(10k-25k)	16	0.0 3.0	- -	42% 58%	AC50-3IRI and 10% Damaged Cracking Sealing-5%WC	4.0 6.4	- 2.0	42% 58%	AC50-3IRI and 10% Damaged Reconstruction-6IRI
WNR-Good-AC-Flx-(1.5k-3k)	12	5.0 9.0	0.2 0.8	86% 14%	Reseal-15% Cracked Granular Overlay-5IRI& 10% Cracked	10.4 9.0	4.5 -	86% 14%	Granular Overlay-5IRI& 10% Cracked Granular Overlay-5IRI& 10% Cracked
WNR-Good-AC-Flx-(3k-5k	12	5.0	-	100%	Cracking Sealing-8%	9.8	2.6	100%	Reconstruction-7IRI
WNR-Good-AC-Flx-(10k-25k)	14	5.0 2.8	0.5 0.4	97% 3%	Cracking Sealing-5%WC AC50-3IRI and 10% Damaged	7.4 5.5	2.8 1.0	89% 11%	Reconstruction-6IRI AC50-3IRI and 10% Damaged

Table H1 Mean and Standard Deviation Values for Time-Interval for Maintenance and Rehabilitation Treatment for Wet Non-Reactive Soil/Continue.

Description	Last Surfacing	1st Time Interval (Years)				2nd Time Interval (Years)			
		Mean (Years)	SD (Years)	% of Treatment	Treatment Types	Mean (Years)	SD (Years)	% of Treatment	Treatment Types
WNR-Good-AC-Flx-(10k-25k)	14	5.0	0.5	97%	Cracking Sealing-5%WC	7.4	2.8	89%	Reconstruction-6IRI
		2.8	0.4	3%	AC50-3IRI and 10% Damaged	5.5	1.0	11%	AC50-3IRI and 10% Damaged
WNR-Fair-AC-Flx-(1.5k-3k)	11	7.8	2.1	100%	Granular Overlay-5IRI& 10% Cracked	9.3	0.6	100%	Granular Overlay-5IRI& 10% Cracked
WNR-Fair-AC-Flx-(3k-5k)	13	1.8	1.3	46%	AC50-4IRI and 10% Damaged	17.2	2.7	46%	Reconstruction-7IRI
		5.0	-	54%	Cracking Sealing-8%	8.0	1.3	54%	Reconstruction-7IRI
WNR-Fair-AC-Flx-(5k-10k)	13	2.1	1.1	57%	AC50-3.5IRI and 10% Damaged	9.1	0.5	57%	AC50-3IRI and 10% Damaged
		4.9	0.9	43%	Cracking Sealing-5%WC	8.6	3.2	43%	Reconstruction-6.5IRI
WNR-Fair-AC-Flx-(10k-25k)	13	0.7	1.1	100%	AC50-3IRI and 10% Damaged	6.8	0.5	100%	AC50-3IRI and 10% Damaged

Table H1 Mean and Standard Deviation Values for Time-Interval for Maintenance and Rehabilitation Treatment for Wet Non-Reactive Soil/Continue.

Description	Last Surfacing	1st Time Interval (Years)				2nd Time Interval (Years)			
		Mean (Years)	SD (Years)	% of Treatment	Treatment Types	Mean (Years)	SD (Years)	% of Treatment	Treatment Types
WNR-Good-Bt-SR-(1.5k-3k)	10	6.6	1.8	29%	Reseal-15% Cracked	15.2	1.2	29%	Granular Overlay-5IRI& 10% Cracked
		10.7	3.0	71%	Granular Overlay-5IRI& 10% Cracked	10.1	0.9	71%	Granular Overlay-5IRI& 10% Cracked
WNR-Good-Bt-SR-(3k-5k)	10	4.9	1.5	100%	Reseal-15% Cracked	13.4	2.1	100%	Reconstruction-7IRI
WNR-Good-Bt-SR-(5k-10k)	11	5.0	1.1	58%	Reseal-10% Cracked	12.8	1.1	58%	Reseal-10% Cracked
		3.1	1.2	42%	Reseal-10% Cracked	10.5	2.8	42%	Granular Overlay-5IRI& 10% Cracked
WNR-Fair-Bt-SR-(1.5k-3k)	9	8.3	1.9	100%	Granular Overlay-5IRI& 10% Cracked	9.2	0.2	100%	Granular Overlay-5IRI& 10% Cracked
WNR-Fair-Bt-SR-(5k-10k)	14	5.0	-	89%	Cracking Sealing-5%WC	8.5	2.3	89%	Reconstruction-7.5IRI
		3.3	1.0	11%	Reseal-10% Cracked	12.0	2.4	11%	Granular Overlay-5IRI& 10% Cracked

Table H1 Mean and Standard Deviation Values for Time-Interval for Maintenance and Rehabilitation Treatment for Wet Non-Reactive Soil/Continue.

Description	Last Surfacing	1st Time Interval (Years)				2nd Time Interval (Years)			
		Mean (Years)	SD (Years)	% of Treatment	Treatment Types	Mean (Years)	SD (Years)	% of Treatment	Treatment Types
WNR-Fair-Bt-SR-(10k-25k)	11	3.0	-	39%	Cracking Sealing-5%WC	6.4	0.7	39%	Reconstruction-6IRI
		0.0	-	61%	AC50-3IRI and 10% Damaged	4.4	0.4	61%	AC50-3IRI and 10% Damaged
WNR-Fair-AC-SR-(10k-25k)	12	0.5	0.9	100%	AC50-3IRI and 10% Damaged	7.0	0.2	100%	AC50-3IRI and 10% Damaged

Table H2 Mean and Standard Deviation Values for Time-Interval for Maintenance and Rehabilitation Treatment for Dry Reactive Soil

Description	Last Surfacing	1st Time Interval (Years)				2nd Time Interval (Years)			
		Mean (Years)	SD (Years)	% of Treatment	Treatment Types	Mean (Years)	SD (Years)	% of Treatment	Treatment Types
DR-Good-Bt-Flx-(<0.5k)	11	7.5	1.1	100%	Reseal-15% Cracked	10.6	1.5	100%	Reseal- 15% Cracked
DR-Good-Bt-Flx-(1.5k-3k)	12	3.5	0.8	100%	Reseal-15% Cracked	12.8 20.6	1.5 1.3	72% 28%	Reseal-15% Cracked Reseal-15% Cracked-Twice
DR-Good-Bt-Flx-(3k-5k)	14	3.1	0.4	100%	Reseal-15% Cracked	9.9 13.2	1.0 2.7	73% 37%	Reseal-15% Cracked Granular Overlay-5IRI& 10% Cracked
DR-Good-Bt-Flx-(5k-10k)	12	2.1	0.4	100%	Reseal-10% Cracked	10.0	-	100%	Reseal-10% Cracked
DR-Fair-Bt-Flx-(<0.5k)	11	7.1	1.3	100%	Reseal-20% Cracked	11.8	2.6	83%	Reseal-20% Cracked
DR-Fair-Bt-Flx-(1.5k-3k)	11	4.2	1.2	100%	Reseal-15% Cracked	13.7	4.5	100%	Granular Overlay-5IRI& 10% Cracked

Table H2 Mean and Standard Deviation Values for Time-Interval for Maintenance and Rehabilitation Treatment for Dry Reactive Soil/Continue.

Description	Last Surfacing	1st Time Interval (Years)				2nd Time Interval (Years)			
		Mean (Years)	SD (Years)	% of Treatment	Treatment Types	Mean (Years)	SD (Years)	% of Treatment	Treatment Types
DR-Fair-Bt-Flx-(3k-5k)	11	3.0 6.9	0.2 2.5	41% 59%	Reseal-15% Cracked Granular Overlay-5IRI& 10% Cracked	10.0 7.0	1.0 -	41% 59%	Granular Overlay-5IRI& 10% Cracked Reseal-15% Cracked
DR-Fair-Bt-Flx-(5k-10k)	20	2.0	0.4	100%	Reseal-15% Cracked	13.2	3.8	100%	Granular Overlay-5IRI& 10% Cracked
DR-Good-Bt-SR-(<0.5k)	9	9.6	0.9	100%	Reseal-20% Cracked	10.3	1.0	100%	Reseal-20% Cracked
DR-Fair-Bt-SR-(<0.5k)	10	9.1	0.9	100%	Reseal-20% Cracked	10.9	1.0	100%	Reseal-20% Cracked

Table H3 Mean and Standard Deviation Values for Time-Interval for Maintenance and Rehabilitation Treatment for Dry Non-Reactive Soil

Description	Last Surfacing	1st Time Interval (Years)				2nd Time Interval (Years)			
		Mean (Years)	SD (Years)	% of Treatment	Treatment Types	Mean (Years)	SD (Years)	% of Treatment	Treatment Types
DNR-Good-Bt-Flx-(<0.5k)	12	7.0	0.8	100%	Reseal-20% Cracked	12.4	3.0	100%	Reseal- 20% Cracked
DNR-Good-Bt-Flx-(1.5k-3k)	14	4.1	1.2	100%	Reseal-20% Cracked	10.6	1.8	100%	Reseal-15% Cracked
DNR-Good-Bt-Flx-(3k-5k)	10	2.9	0.7	57%	Reseal-15% Cracked	13.8	0.8	57%	Reseal-15% Cracked
		3.0	-	43%	Reseal-15% Cracked	13.9	0.6	43%	Reseal-15% Cracked
DNR-Fair-Bt-Flx-(<0.5k)	12	7.1	0.6	100%	Reseal-20% Cracked	11.8	2.9	60%	Reseal-20% Cracked
						12.8	3.3	40%	Granular Overlay-5IRI& 10% Cracked
DNR-Fair-Bt-Flx-(1.5k-3k)	12	4.6	1.2	100%	Reseal-20% Cracked	11.1	1.9	53%	Reseal-20% Cracked
						14.6	3.5	47%	Granular Overlay-5IRI& 10% Cracked

Table H3 Mean and Standard Deviation Values for Time-Interval for Maintenance and Rehabilitation Treatment for Dry Non-Reactive Soil/Continue.

Description	Last Surfacing	1st Time Interval (Years)				2nd Time Interval (Years)			
		Mean (Years)	SD (Years)	% of Treatment	Treatment Types	Mean (Years)	SD (Years)	% of Treatment	Treatment Types
DNR-Fair-Bt-Flx-(3k-5k)	11	4.2 8.9	1.2 2.2	53% 47%	Reseal-15% Cracked Granular Overlay-5IRI& 10% Cracked	14.0 14.6	2.2 0.6	53% 47%	Granular Overlay-5IRI& 10% Cracked Granular Overlay-5IRI& 10% Cracked
DNR-Fair-Bt-Flx-(5k-10k)	9	3.6	0.8	100%	Reseal-15% Cracked	12.9	2.4	100%	Granular Overlay-5IRI& 10% Cracked
DNR-Good-AC-Flx-(0.5k-1.5k)	10	5.1	0.5	100%	Reseal-20% Cracked	6.9	1.1	100%	Reseal-20% Cracked
DNR-Good-AC-Flx-(1.5k-3k)	10	4.8	0.9	100%	Reseal-15% Cracked	14	1.6	100%	Reseal-15% Cracked-Twice
DNR-Fair-AC-Flx-(0.5k-1.5k)	10	5.1	0.5	100%	Reseal-20% Cracked	6.9	0.7		Reseal-20% Cracked
DNR-Good-Bt-SR-(0.5k-1.5k)	10	3.0	0.2	100%	Reseal-20% Cracked	11.7	1.4	100%	Granular Overlay-5IRI& 10% Cracked

Appendix J

Table J1 Mean and Standard Deviation Values of Cost/Kilometre for Road Categories in Wet Non-Reactive Soil

Description	Km	(Mean , SD) of Structural number (SN)	Cost per Kilometre (Mean) A$ million	Cost per Kilometre (SD) A$ million	Coefficient of Variation
WNR-Good-Bt-Flx-(1.5k-3k)	269	(3.66, 0.92)	0.4439	0.1068	0.241
WNR-Good-Bt-Flx-(3k-5k)	181	(3.73, 1.06)	0.4701	0.1483	0.316
WNR-Good-Bt-Flx-(5k-10k)	154	(3.76, 0.97)	0.5404	0.2152	0.398
WNR-Good-Bt-Flx-(10k-25k)	11	(3.72, 1.19)	0.9624	0.1339	0.139
WNR-Fair-Bt-Flx-(1.5k-3k)	303	(3.51, 0.91)	0.6063	0.2060	0.343
WNR-Fair-Bt-Flx-(5k-10k)	118	(3.61, 1.06)	0.7044	0.3139	0.446
WNR-Fair-Bt-Flx-(10k-25k)	32	(3.73, 1.32)	1.0782	0.1509	0.140

Table J1 Mean and Standard Deviation Values of Cost/Kilometre for Road Categories in Wet Non-Reactive Soil/Continued.

Description	Km	(Mean , SD) of Structural number (SN)	Cost per Kilometre (Mean) A$ million	Cost per Kilometre (SD) A$ million	Coefficient of Variation
WNR-Good-AC-Flx-(1.5k-3k)	16	(3.57, 0.76)	0.4929	0.1798	0.365
WNR-Good-AC-Flx-(3k-5k	31	(3.63, 0.71)	0.8266	0.1238	0.150
WNR-Good-AC-Flx-(5k-10k)	77	(3.89, 1.04)	0.7565	0.2947	0.398
WNR-Good-AC-Flx-(10k-25k)	72	(3.68, 1.08)	0.9431	0.1727	0.183
WNR-Fair-AC-Flx-(1.5k-3k)	12	(3.47, 1.28)	0.6057	0.104	0.171
WNR-Fair-AC-Flx-(3k-5k)	32	(3.57, 1.08)	0.7671	0.1213	0.158
WNR-Fair-AC-Flx-(5k-10k)	77	(3.92, 0.99)	0.9128	0.1546	0.169
WNR-Fair-AC-Flx-(10k-25k)	134	(3.49, 1.07)	0.7689	0.0860	0.111

Table J1 Mean and Standard Deviation Values of Cost/Kilometre for Road Categories in Wet Non-Reactive Soil/Continued.

Description	Km	(Mean , SD) of Structural number (SN)	Cost per Kilometre (Mean) A$ million	Cost per Kilometre (SD) A$ million	Coefficient of Variation
WNR-Good-Bt-SR-(1.5k-3k)	7	(3.53, 1.68)	0.5261	0.1921	0.365
WNR-Good-Bt-SR-(5k-10k)	11	(4.51, 1.30)	0.5404	0.2152	0.398
WNR-Fair-Bt-SR-(1.5k-3k)	27	(3.73, 2.92)	0.5303	0.0.714	0.135
WNR-Fair-Bt-SR-(3k -5k)	33	(4.37, 1.15)	0.7902	0.2792	0.353
WNR-Fair-Bt-SR-(5k-10k)	15	(4.32, 1.32)	0.6504	0.1416	0.218
WNR-Fair-Bt-SR-(10k-25k)	4	(3.28, 0.76)	1.2532	0.0869	0.071
WNR-Fair-AC-SR-(10k-25k)	84	(5.61, 0.86)	0.7882	0.1620	0.206

Table J2 Mean and Standard Deviation Values of Cost/Kilometre for Road Categories in Dry Reactive Soil

Description	Km	(Mean , SD) of Structural number (SN)	Cost per Kilometre (Mean) A$ million	Cost per Kilometre (SD) A$ million	Coefficient of Variation
DR-Good-Bt-Flx-(<0.5k)	406	(2.56, 0.85)	0.0592	0.0087	0.146
DR-Good-Bt-Flx-(1.5k-3k)	59	(2.98, 0.66)	0.0589	0.0404	0.686
DR-Good-Bt-Flx-(3k-5k)	48	(2.73, 0.69)	0.2026	0.1104	0.546
DR-Good-Bt-Flx-(5k-10k)	2	(3.2, -)	0.1704	0.0741	0.435
DR-Fair-Bt-Flx-(<0.5k)	689	(2.51, 0.82)	0.1098	0.1329	1.036
DR-Fair-Bt-Flx-(1.5k-3k)	89	(3.14, 0.72)	0.1378	0.0841	0.610
DR-Fair-Bt-Flx-(3k-5k)	43	(2.07, 0.66)	0.3352	0.1140	0.340
DR-Fair-Bt-Flx-(5k-10k)	7	(3.02, 0.70)	0.2626	0.1121	0.427
DR-Good-Bt-SR-(<0.5k)	12	(3.10, 0.83)	0.0629	0.0027	0.215
DR-Fair-Bt-SR-(<0.5k)	44	(3.53, 1.05)	0.1058	0.0743	0.942

Table J3 Mean and Standard Deviation Values of Cost/Kilometre for Road Categories in Dry Non-Reactive Soil

Description	Km	(Mean , SD) of Structural number (SN)	Cost per Kilometre (Mean) A$ million	Cost per Kilometre (SD) A$ million	Coefficient of Variation
DNR-Good-Bt-Flx-(<0.5k)	140	(3.39, 0.86)	0.0611	0.0026	0.018
DNR-Good-Bt-Flx-(1.5k-3k)	97	(3.39, 0.77)	0.1162	0.0884	0.762
DNR-Fair-Bt-Flx-(<0.5k)	299	(3.17, 0.76)	0.1674	0.1005	0.600
DNR-Fair-Bt-Flx-(1.5k-3k)	114	(3.14, 0.70)	0.3149	0.0764	0.243
DNR-Fair-Bt-Flx-(3k-5k)	16	(3.10, 1.21)	0.3322	0.1256	0.378
DNR-Fair-Bt-Flx-(5k-10k)	6	(3.41, -)	0.2655	0.1007	0.380
DNR-Good-AC-Flx-(0.5k-1.5k)	4	(3.47, 1.24)	0.09543	0.0472	0.494
DNR-Good-AC-Flx-(1.5k-3k)	6	(3.38, 0.63)	0.1813	0.1299	0.559
DNR-Fair-AC-Flx-(0.5k-1.5k)	5	(2.86, 0.63)	0.1330	0.0806	0.606
DNR-Good-Bt-SR-(0.5k-1.5k)	10	(3.95, -)	0.8312	0.2268	0.273

Appendix K

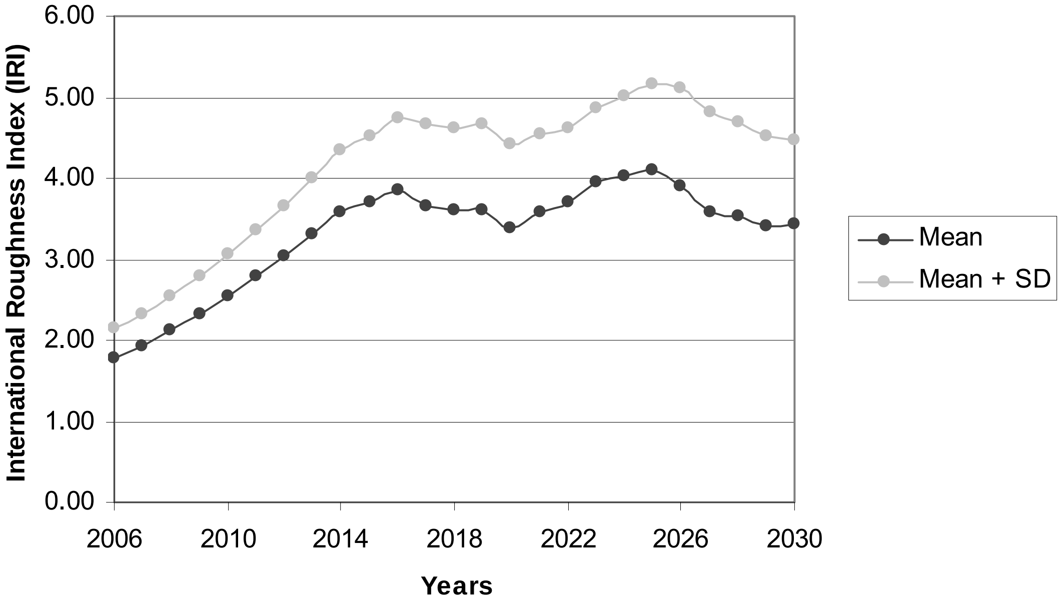

Figure K1 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of WNR-Good-Bt-Flx-(1.5k-3k)

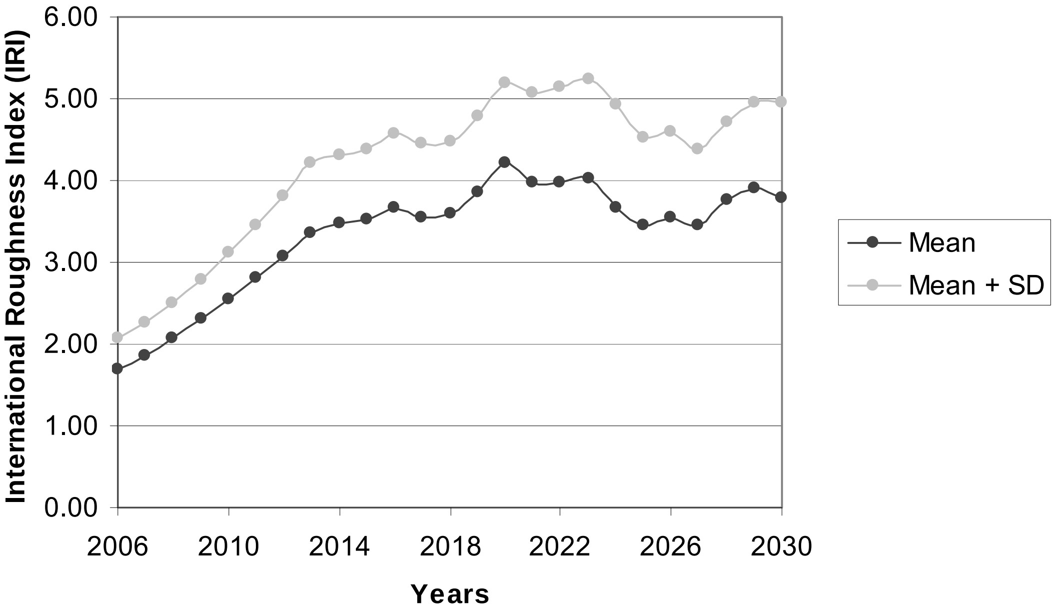

Figure K2 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of WNR-Good-Bt-Flx-(3k-5k)

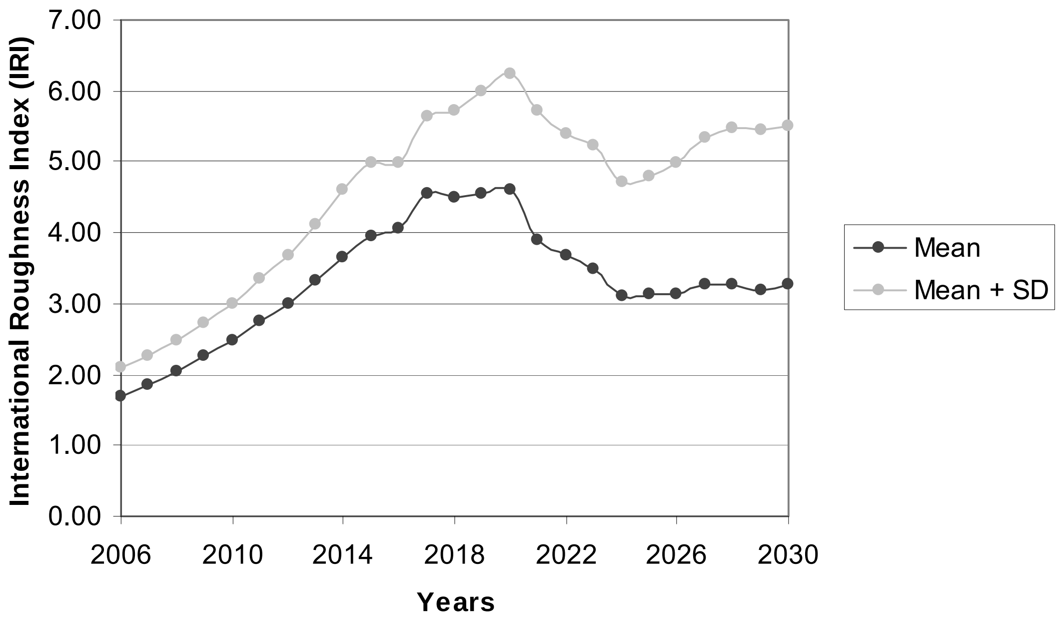

Figure K3 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of WNR-Good-Bt-Flx-(5k-10k)

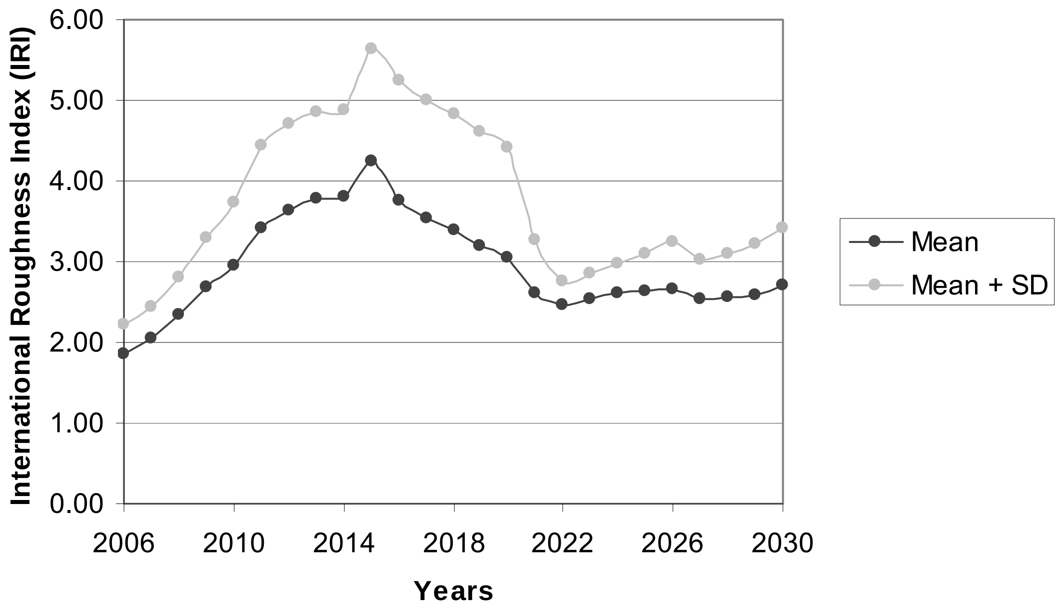

Figure K4 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of WNR-Good-Bt-Flx-(10k-25k)

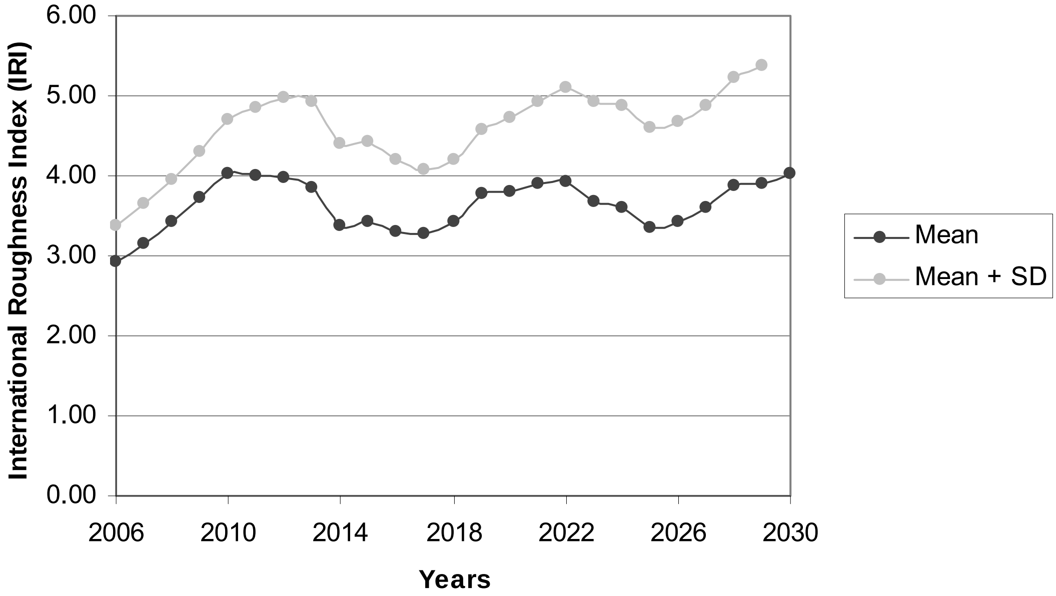

Figure K5 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of WNR-Fair-Bt-Flx-(1.5k-3k)

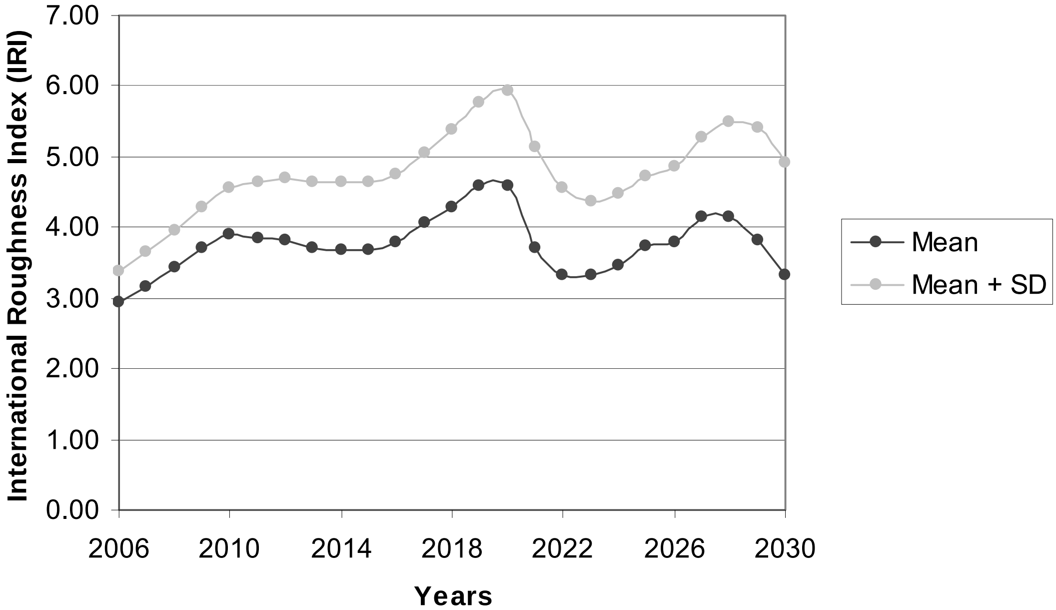

Figure K6 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of WNR-Fair-Bt-Flx-(5k-10k)

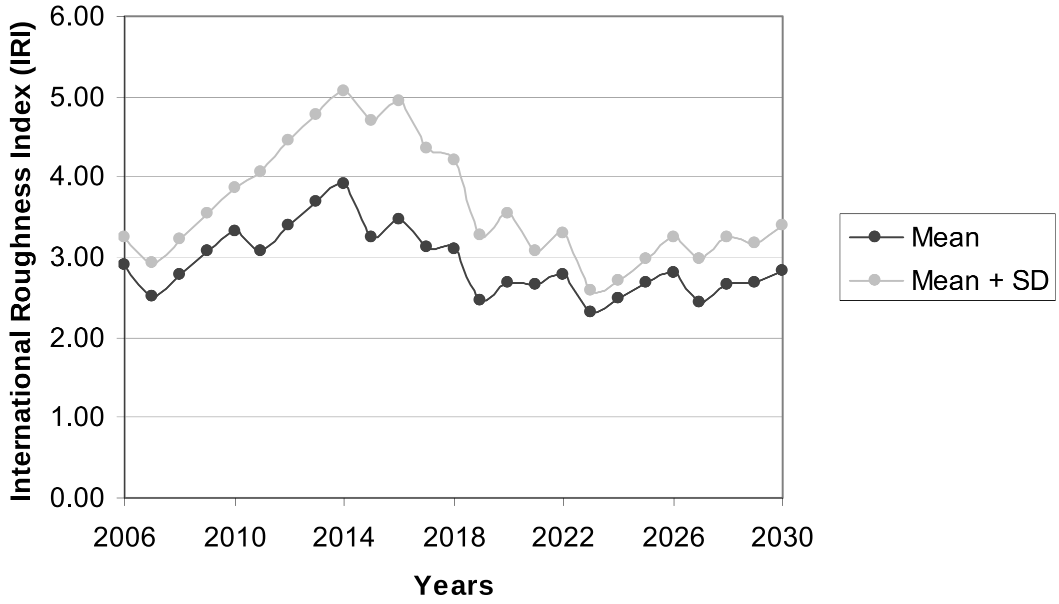

Figure K7 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of WNR-Fair-Bt-Flx-(10k-25k)

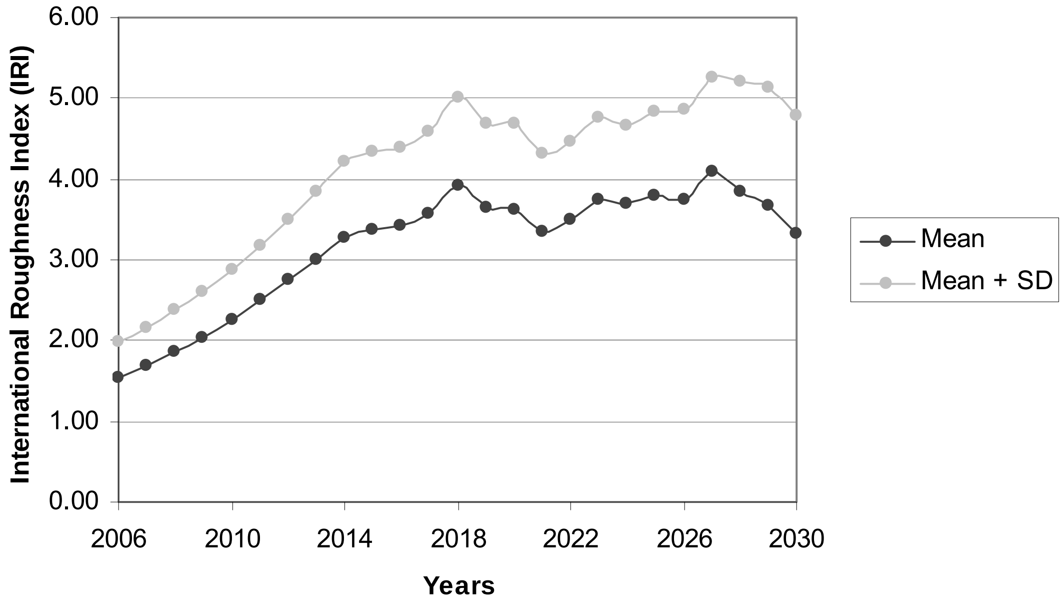

Figure K8 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of WNR-Good-AC-Flx-(1.5k-3k)

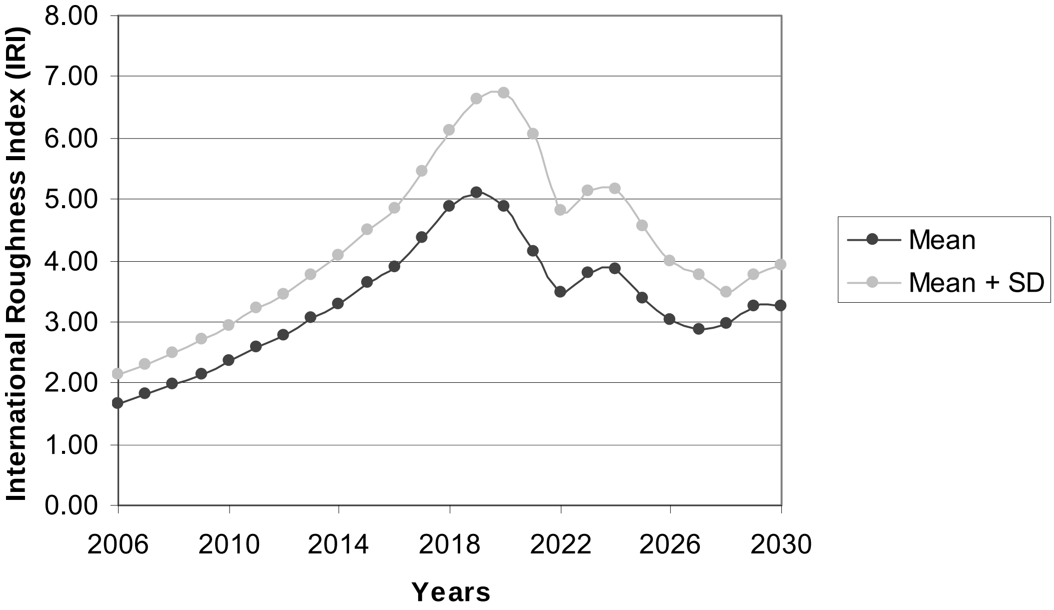

Figure K9 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of WNR-Good-AC-Flx-(3k-5k)

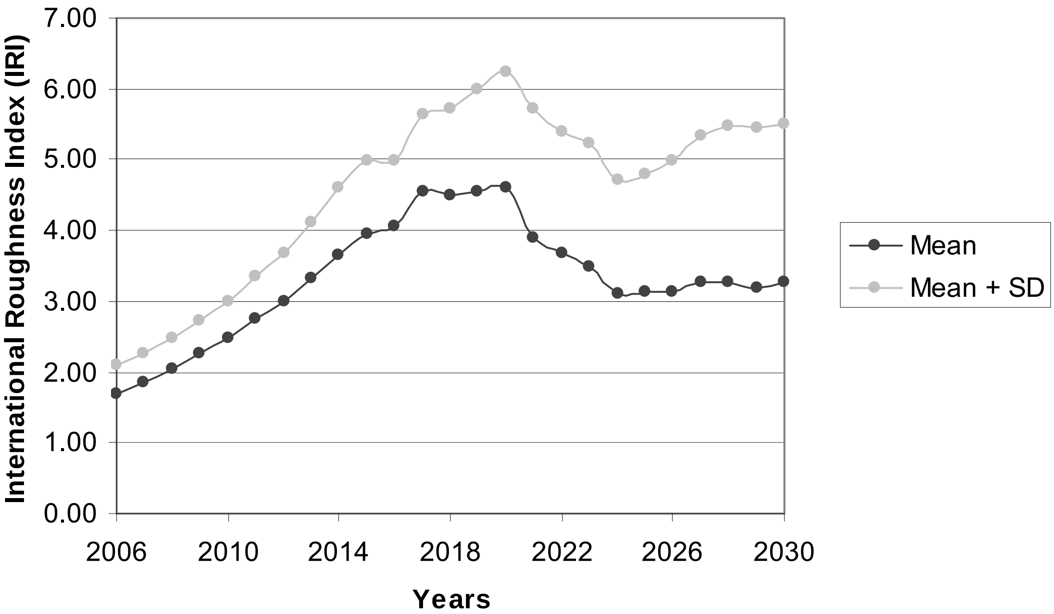

Figure K10 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of WNR-Good-AC-Flx-(5k-10k)

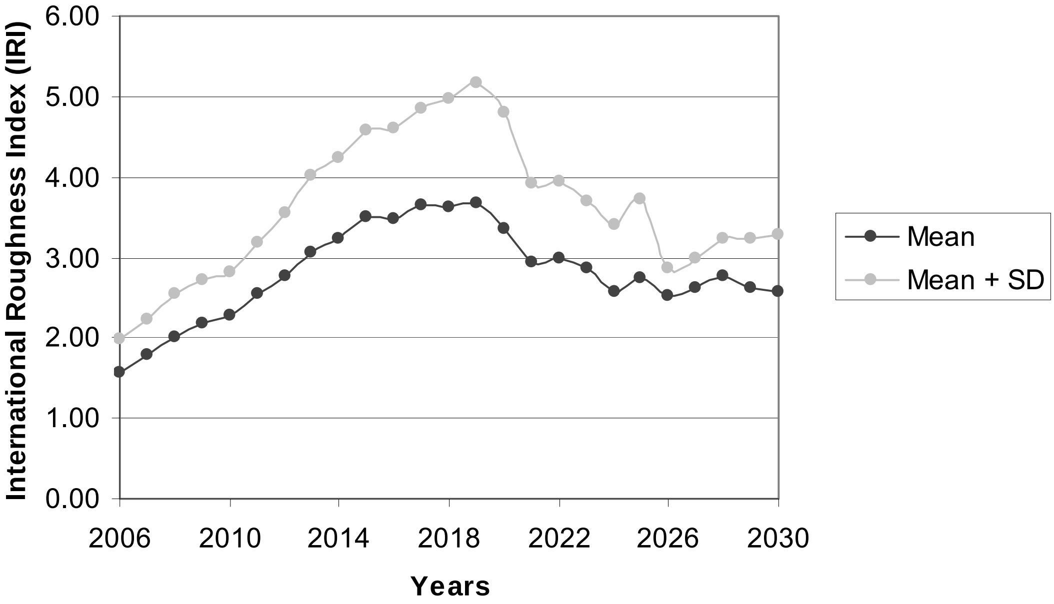

Figure K11 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of WNR-Good-AC-Flx-(10k-25k)

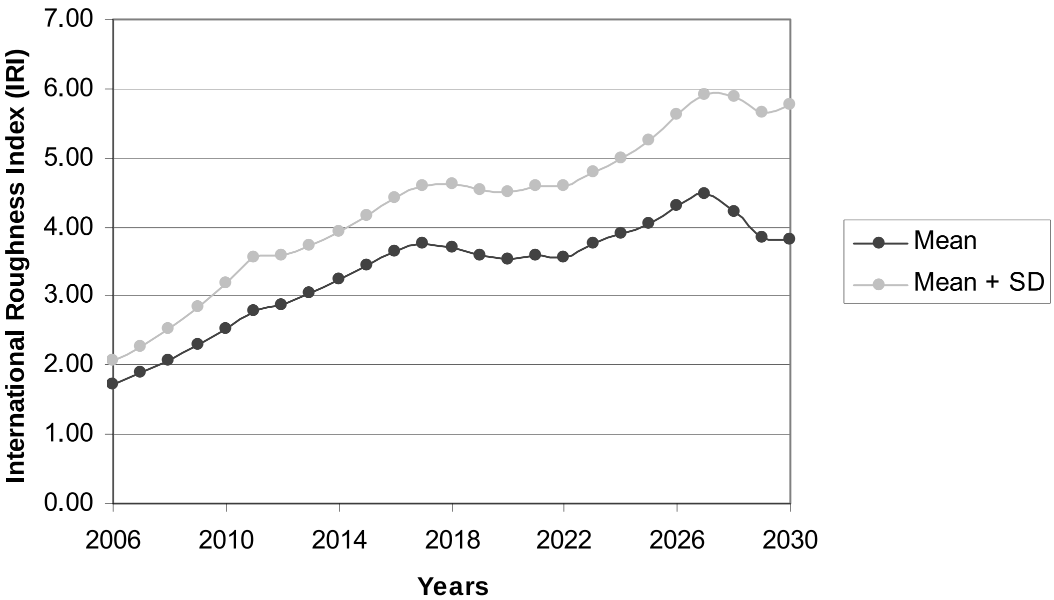

Figure K12 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of WNR-Fair-AC-Flx-(1.5k-3k)

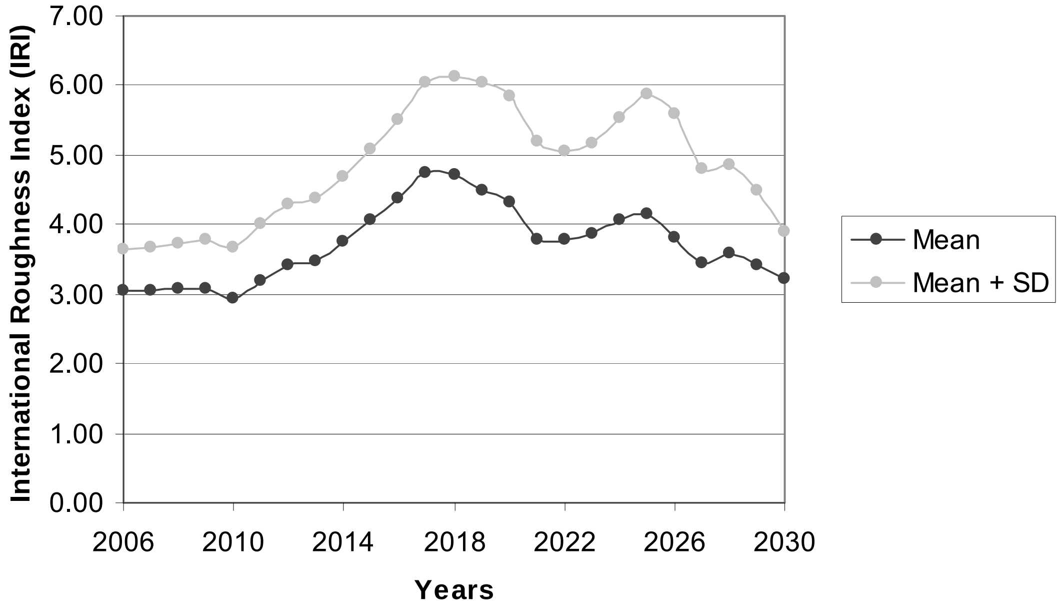

Figure K13 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of WNR-Fair-AC-Flx-(3k-5k)

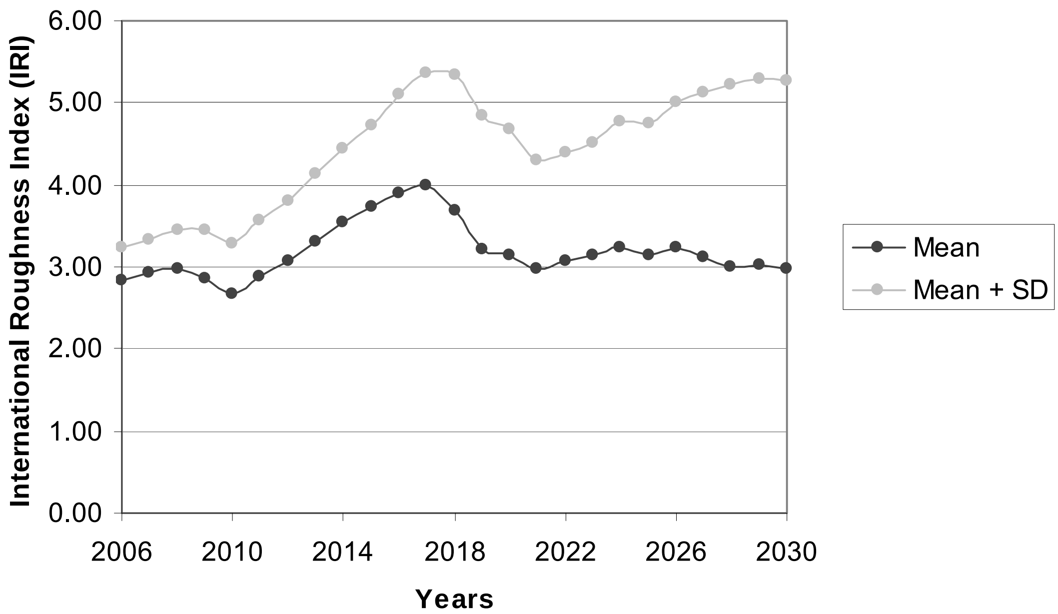

Figure K14 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of WNR-Fair-AC-Flx-(5k-10k)

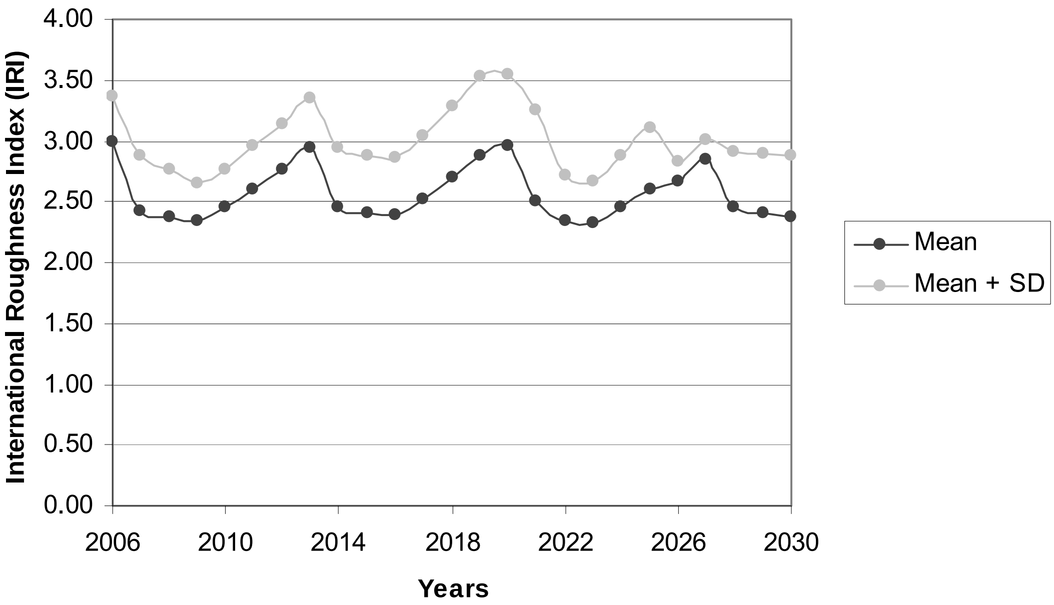

Figure K15 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of WNR-Fair-AC-Flx-(10k-25k)

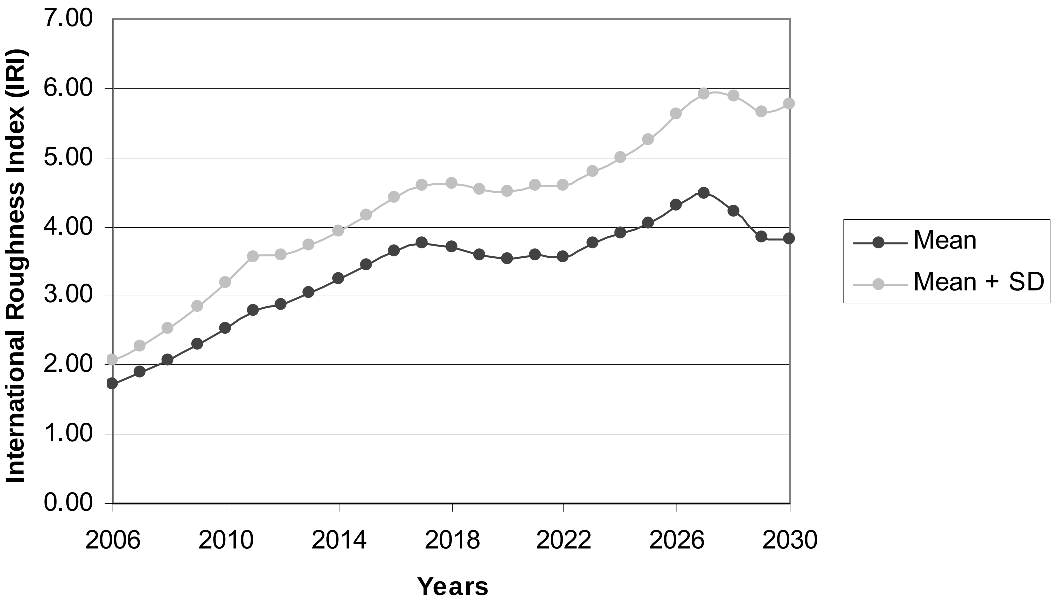

Figure K16 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of WNR-Good-Bt-SR-(1.5k-3k)

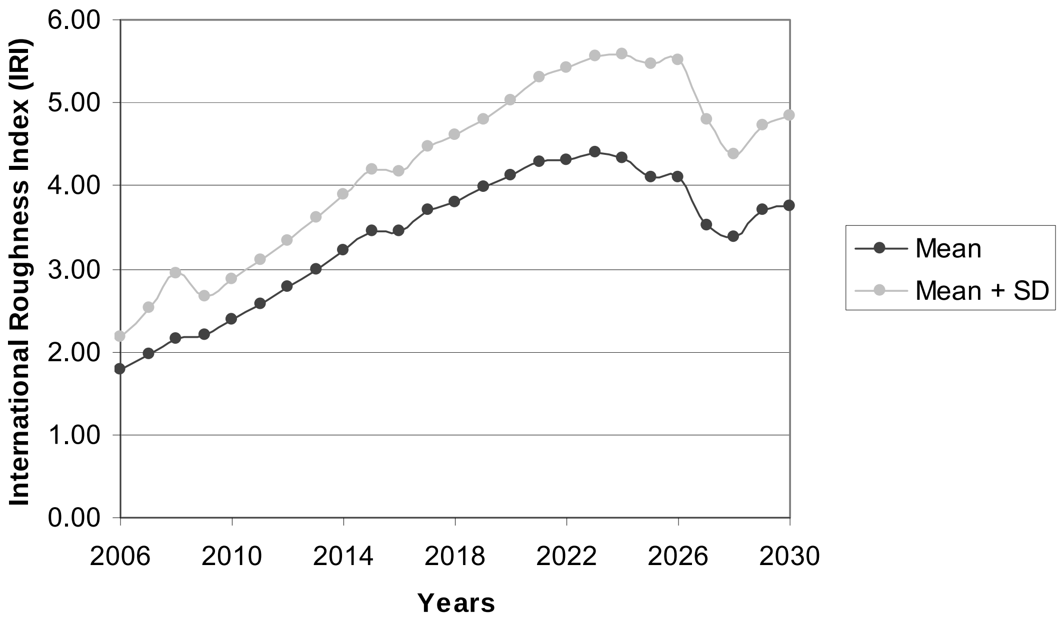

Figure K17 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of WNR-Good-Bt-SR-(5k-10k)

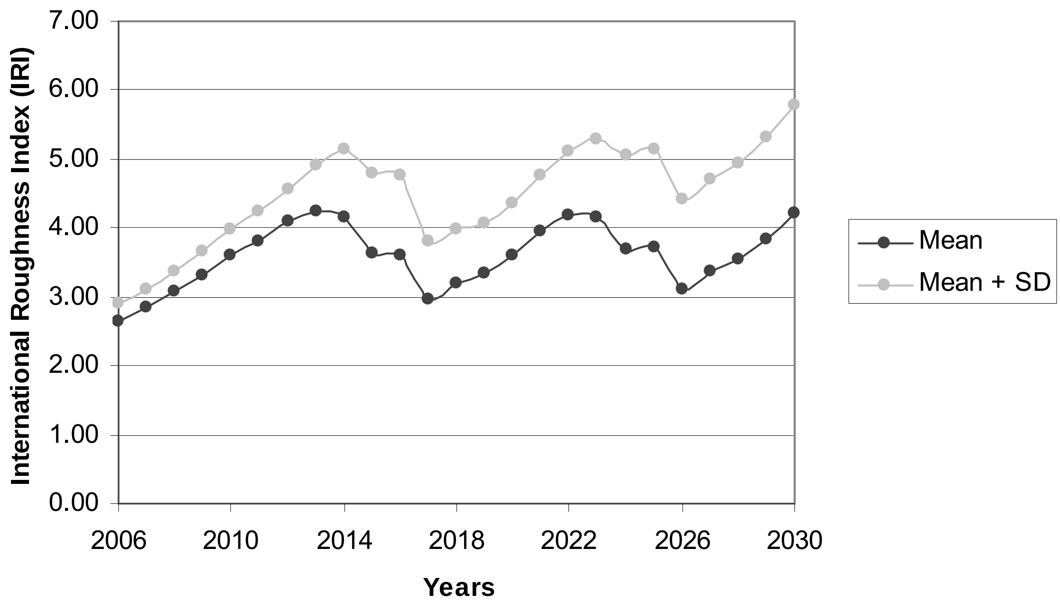

Figure K18 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of WNR-Fair-Bt-SR-(1.5k-3k)

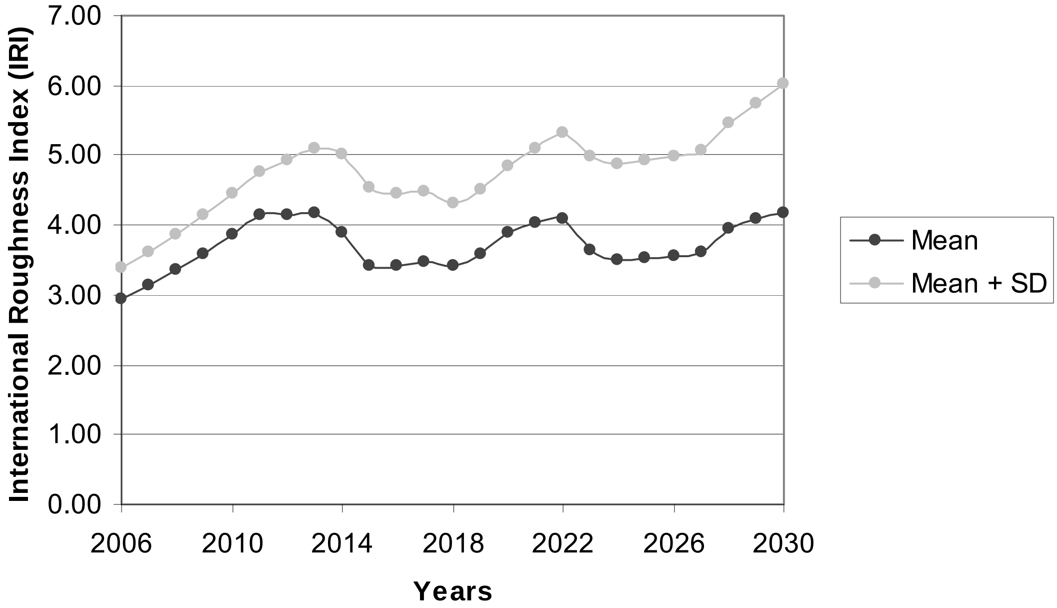

Figure K19 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of WNR-Fair-Bt-SR-(3k -5k)

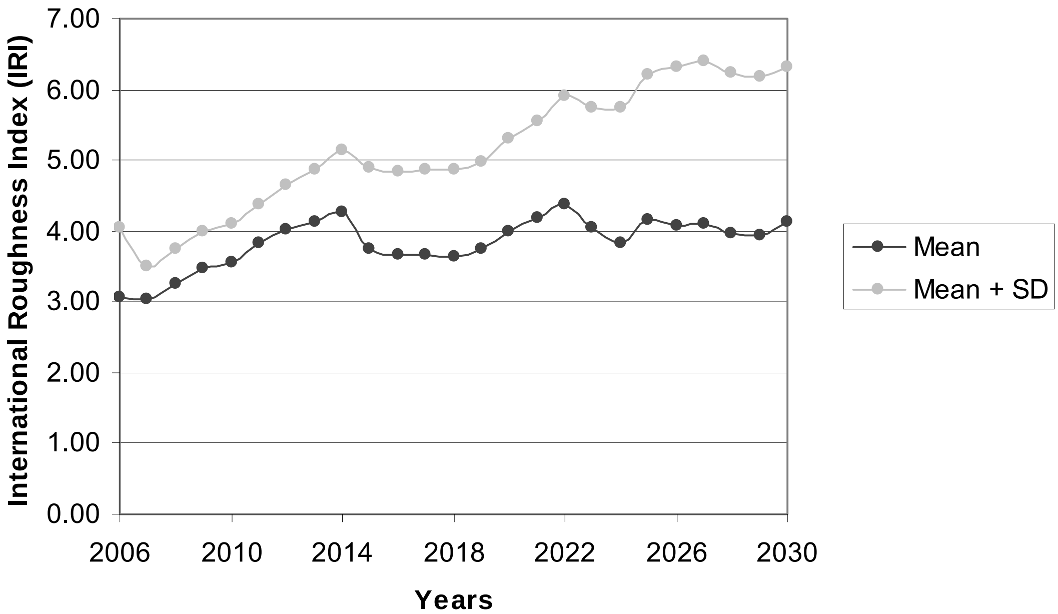

Figure K20 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of WNR-Fair-Bt-SR-(5k-10k)

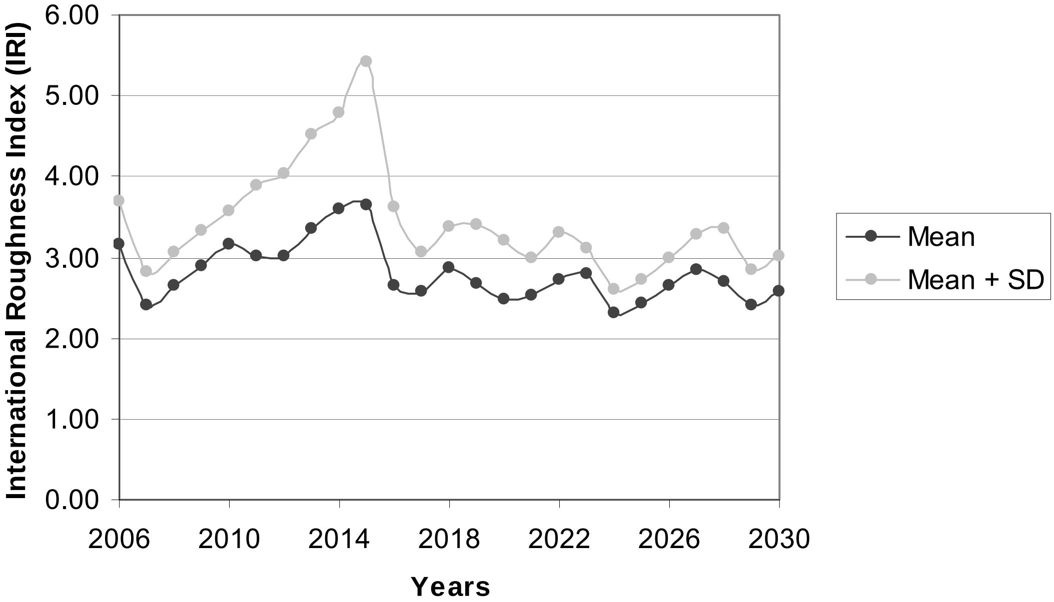

Figure K21 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of WNR-Fair-Bt-SR-(10k-25k)

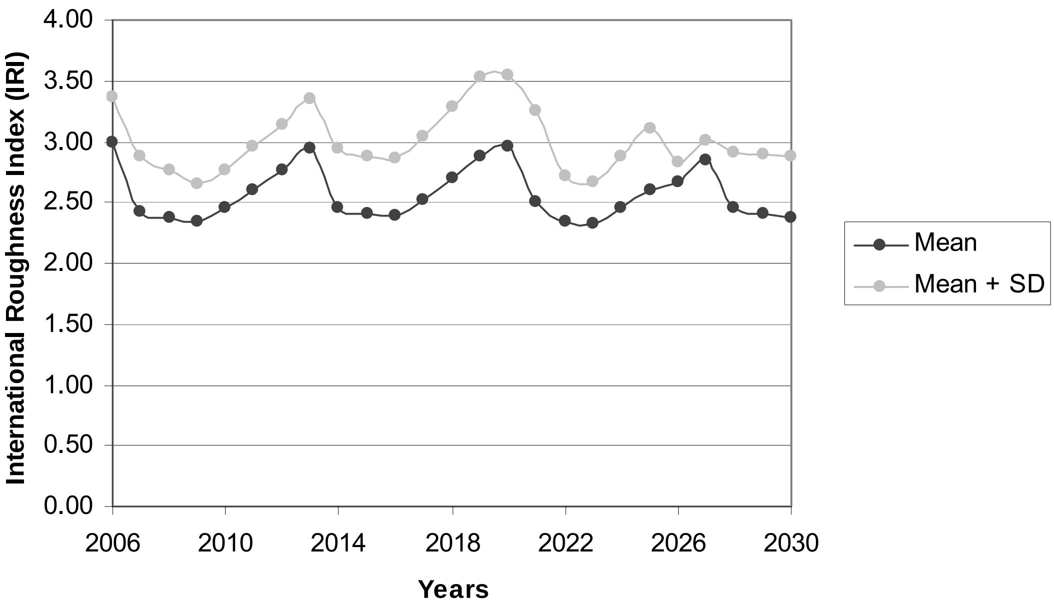

Figure K22 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of WNR-Fair-AC-SR-(10k-25k)

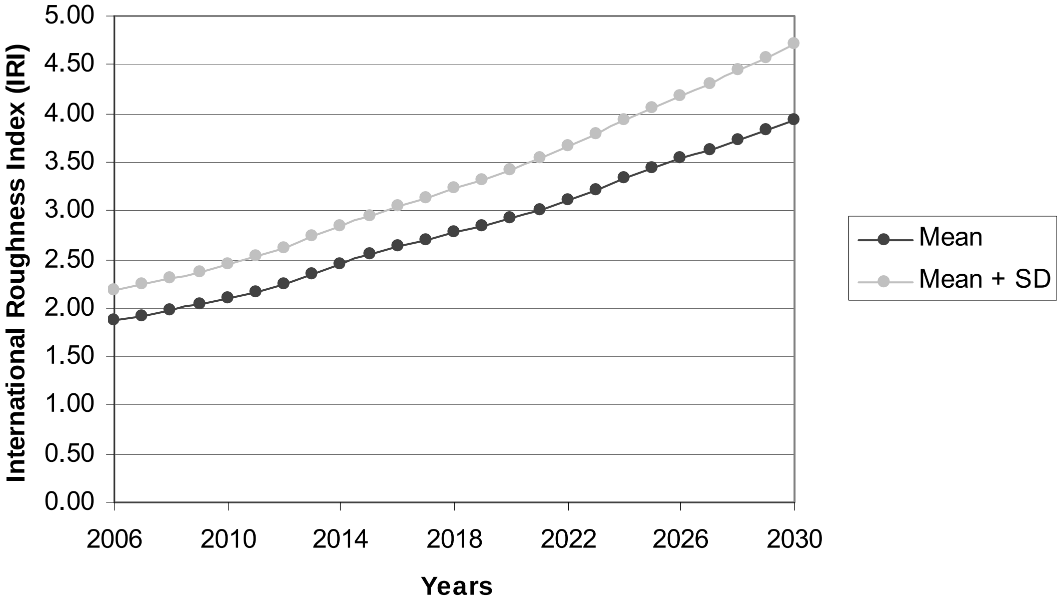

Figure K23 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of DR-Good-Bt-Flx-(<0.5k)

Appendix L

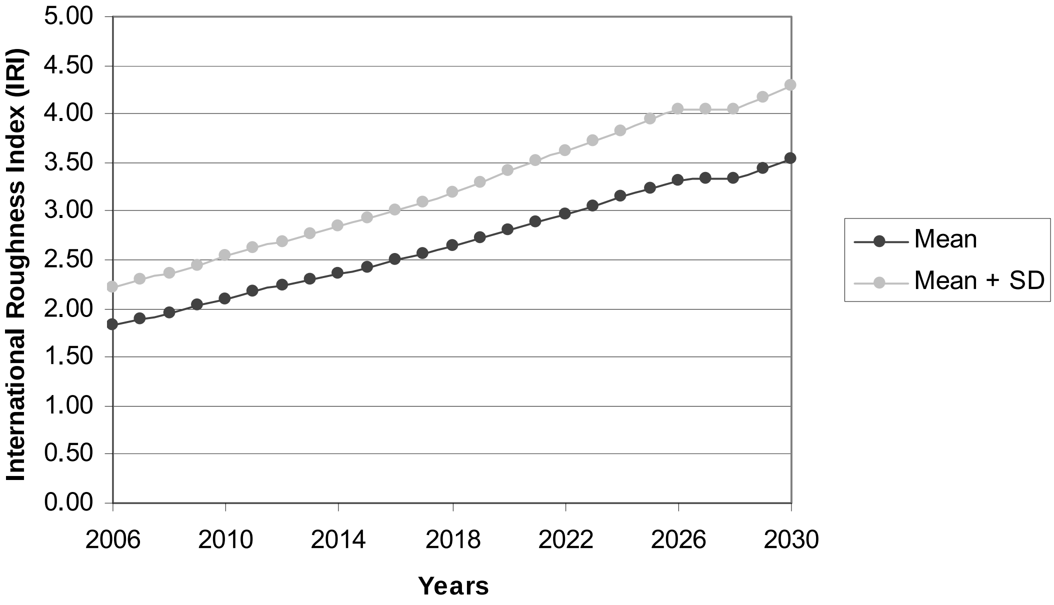

Figure L1 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of DR-Good-Bt-Flx-(1.5k-3k)

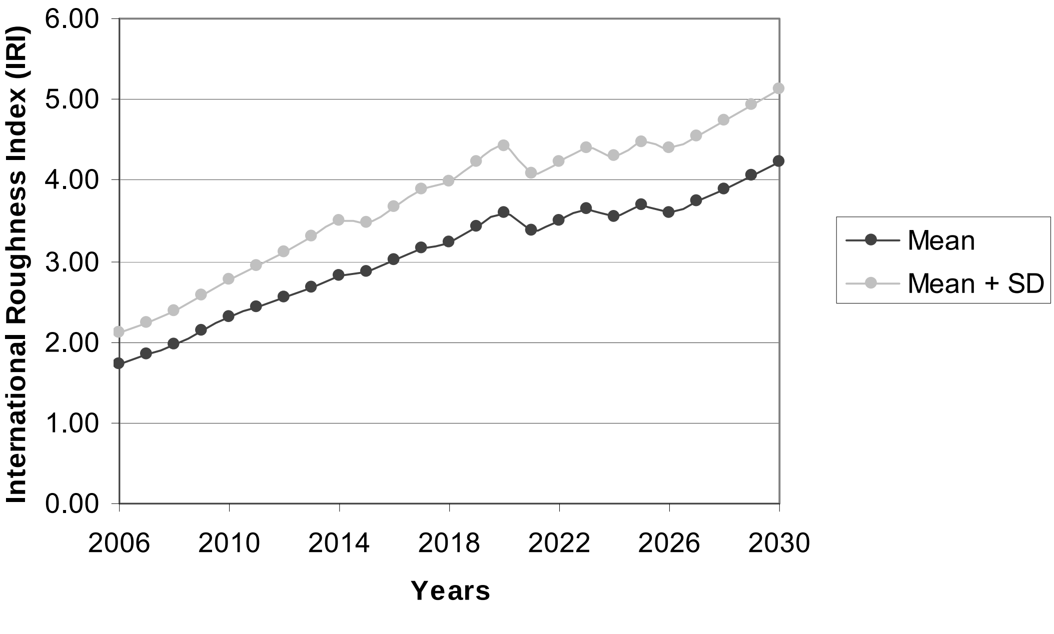

Figure L2 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of DR-Good-Bt-Flx-(3k-5k)

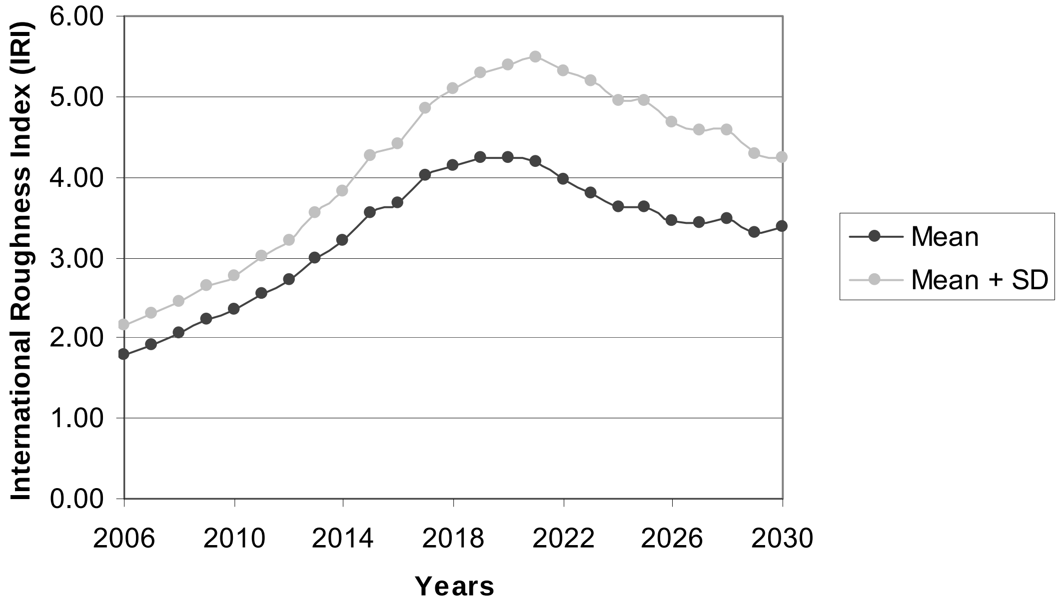

Figure L3 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of DR-Good-Bt-Flx-(5k-10k)

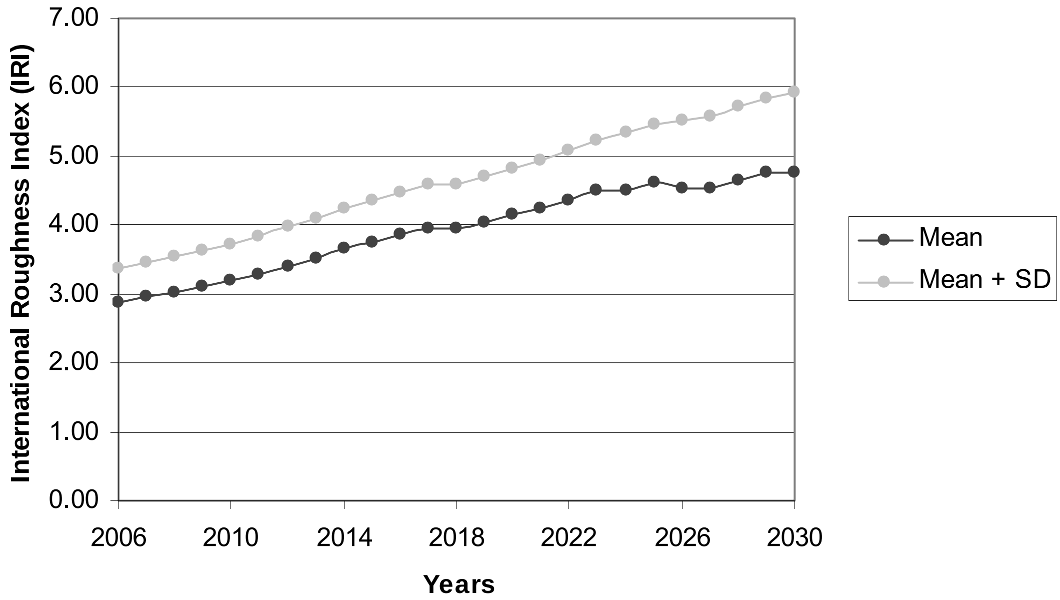

Figure L4 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of DR-Fair-Bt-Flx-(<0.5k)

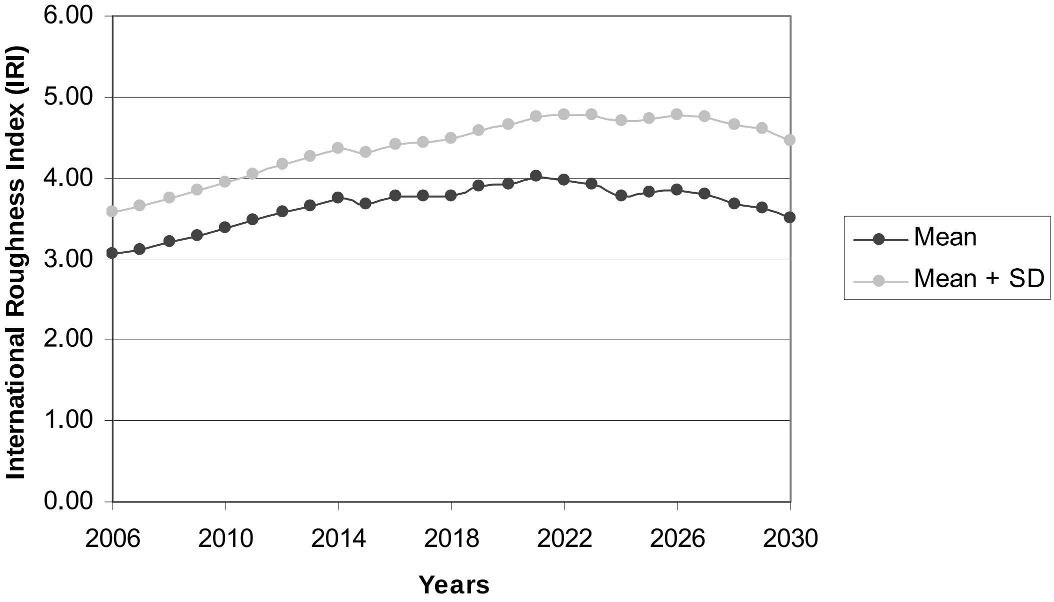

Figure L5 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of DR-Fair-Bt-Flx-(1.5k-3k)

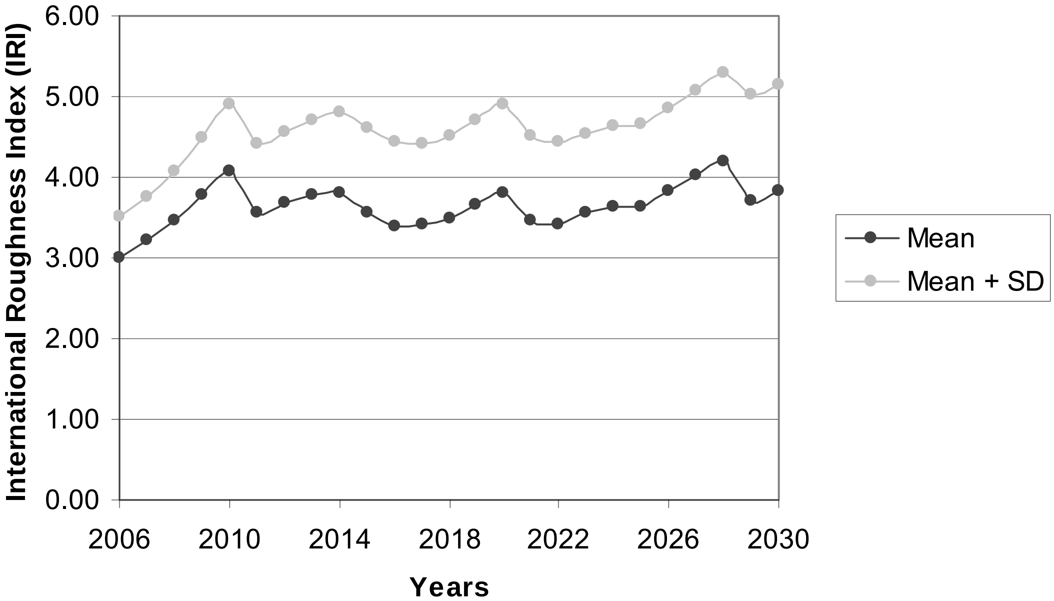

Figure L6 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of DR-Fair-Bt-Flx-(3k-5k)

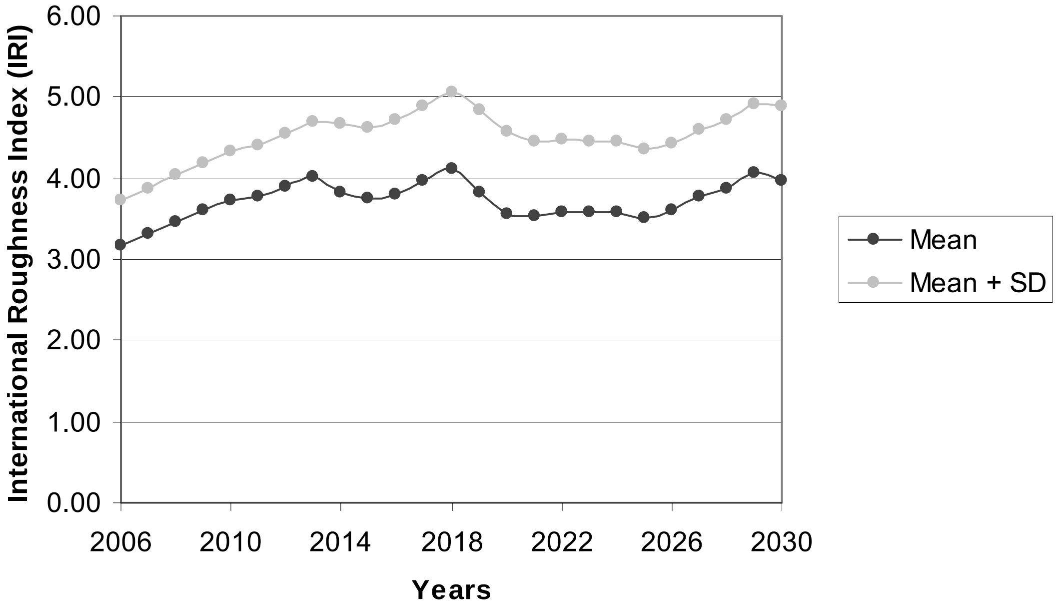

Figure L7 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of DR-Fair-Bt-Flx-(5k-10k)

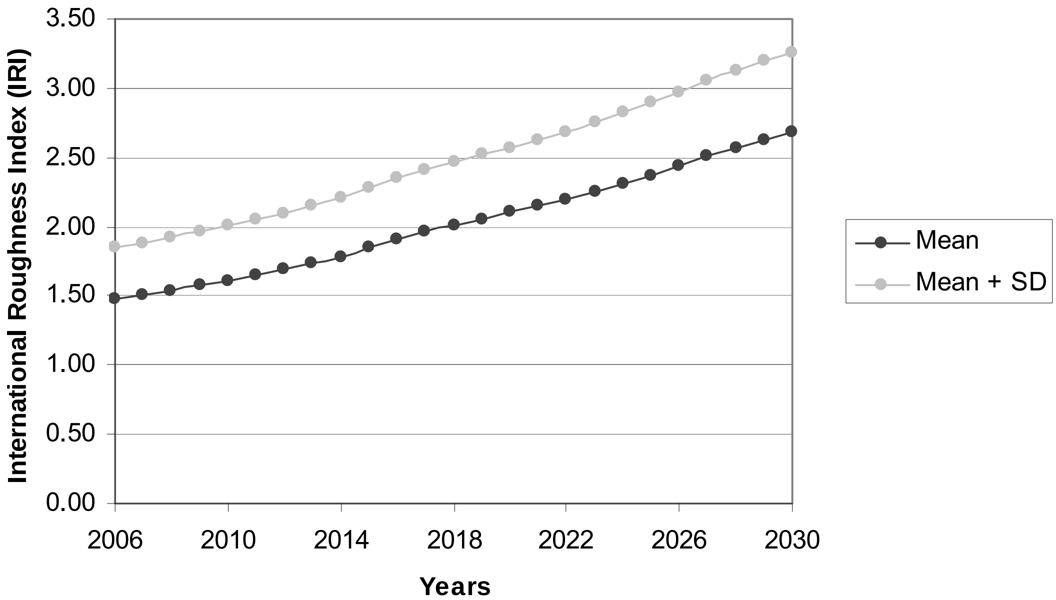

Figure L8 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of DR-Good-Bt-SR-(<0.5k)

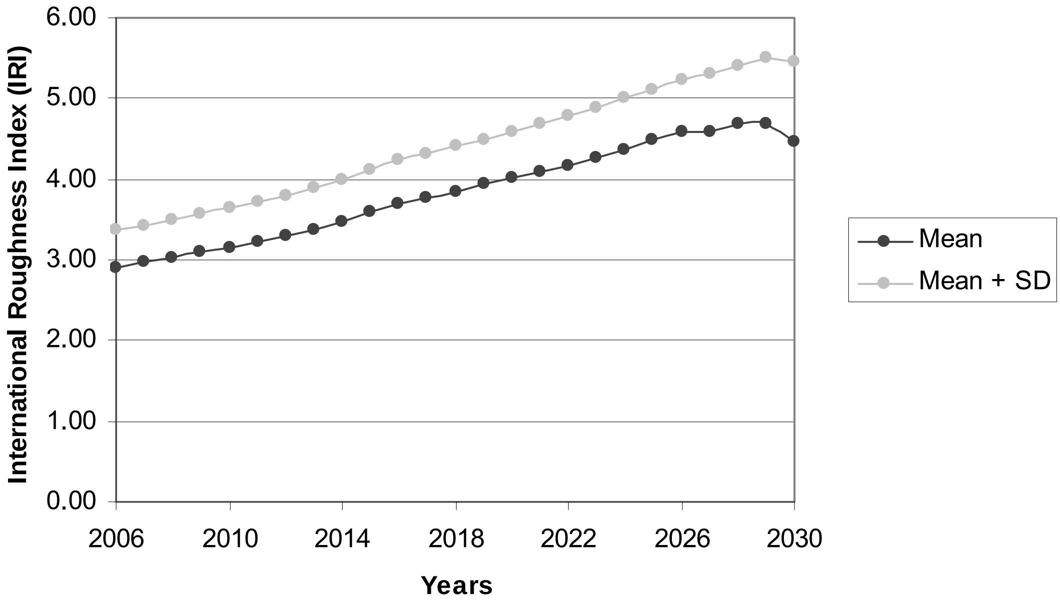

Figure L9 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of DR-Fair-Bt-SR-(<0.5k)

Appendix M

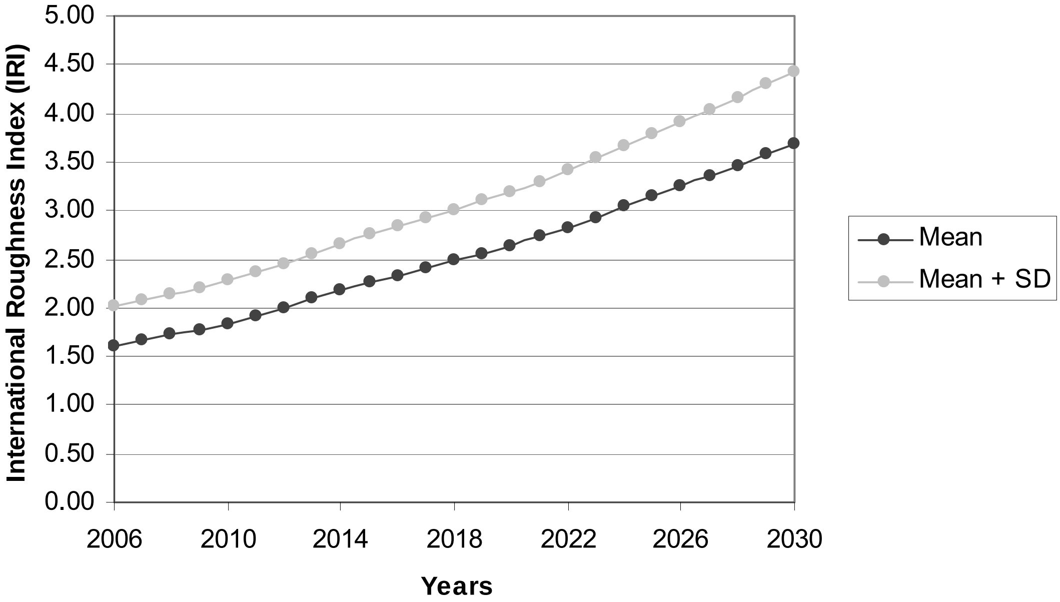

Figure M1 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of DNR-Good-Bt-Flx-(<0.5k)

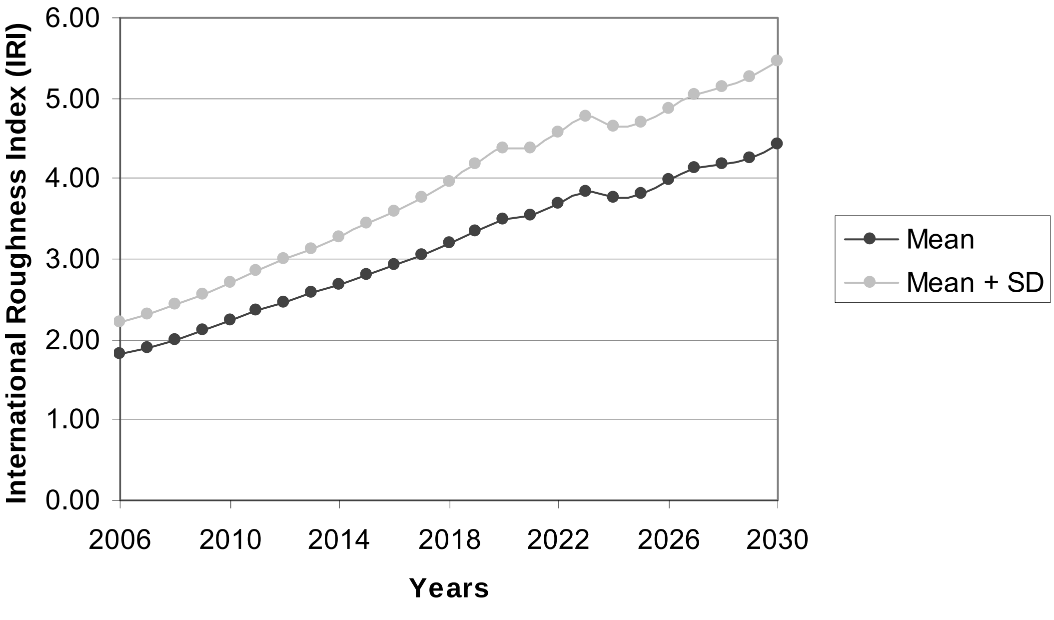

Figure M2 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of DNR-Good-Bt-Flx-(1.5k-3k)

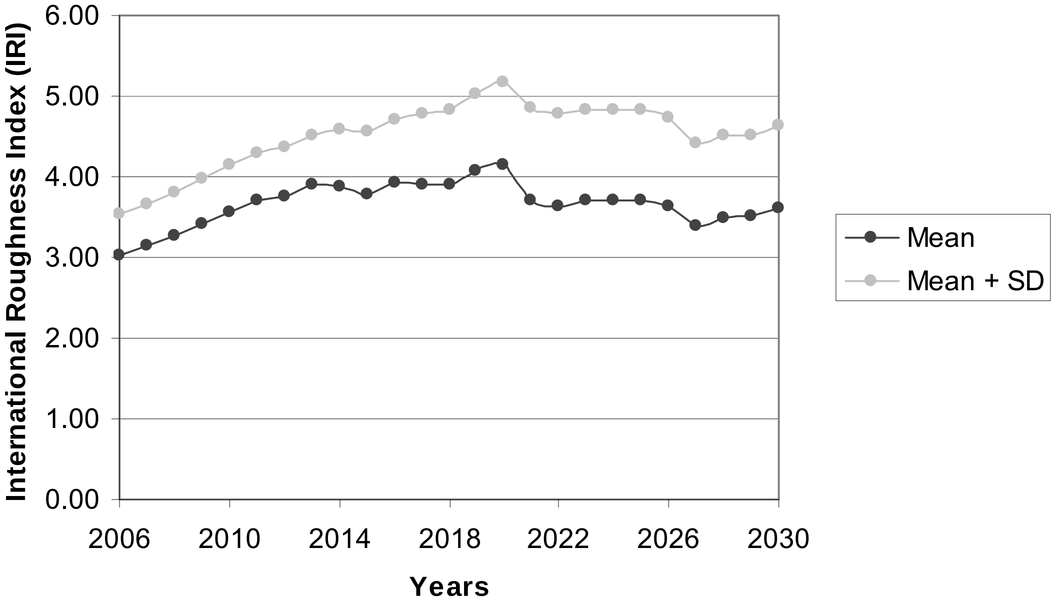

Figure M3 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of DNR-Fair-Bt-Flx-(1.5k-3k)

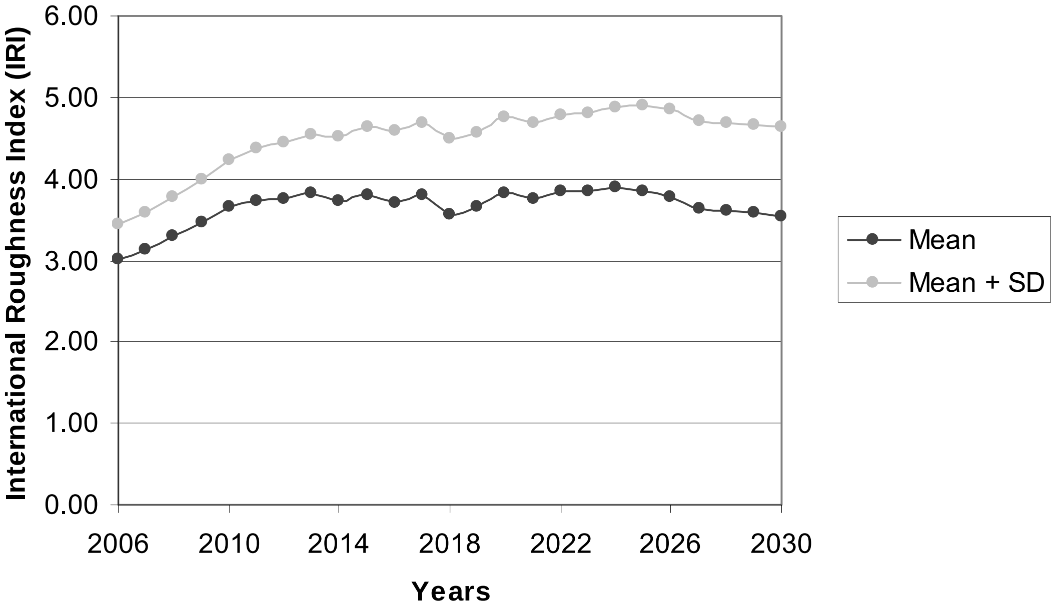

Figure M4 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of DNR-Fair-Bt-Flx-(3k-5k)

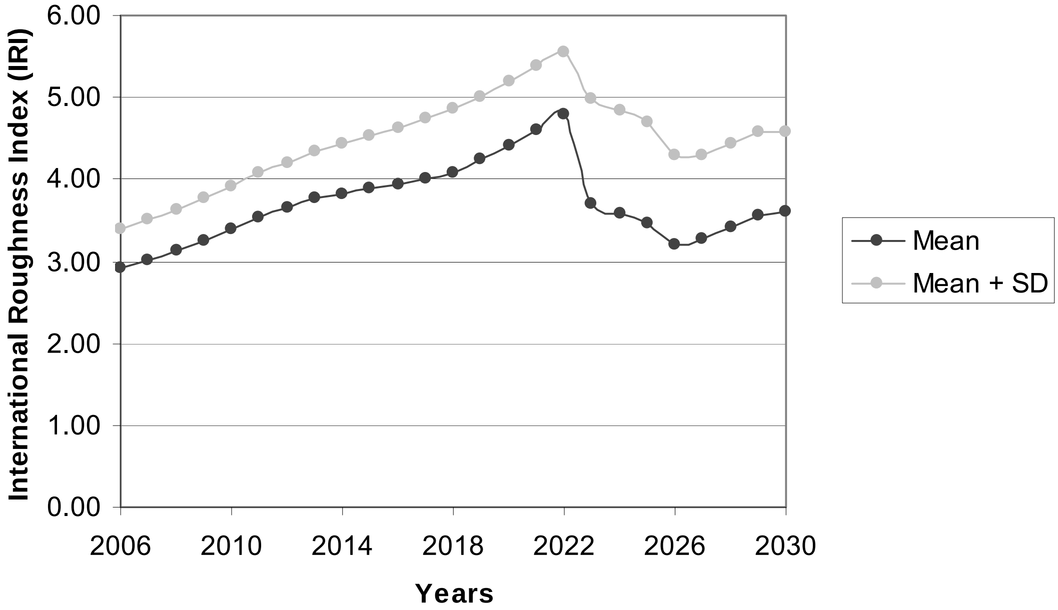

Figure M5 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of DNR-Fair-Bt-Flx-(5k-10k)

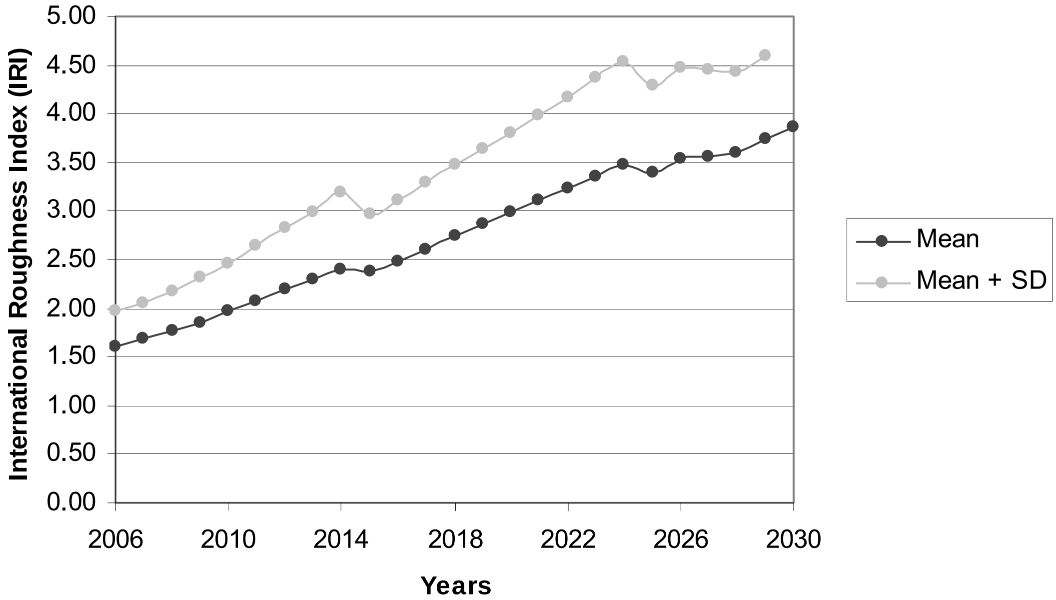

Figure M6 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of DNR-Good-AC-Flx-(0.5k-1.5k)

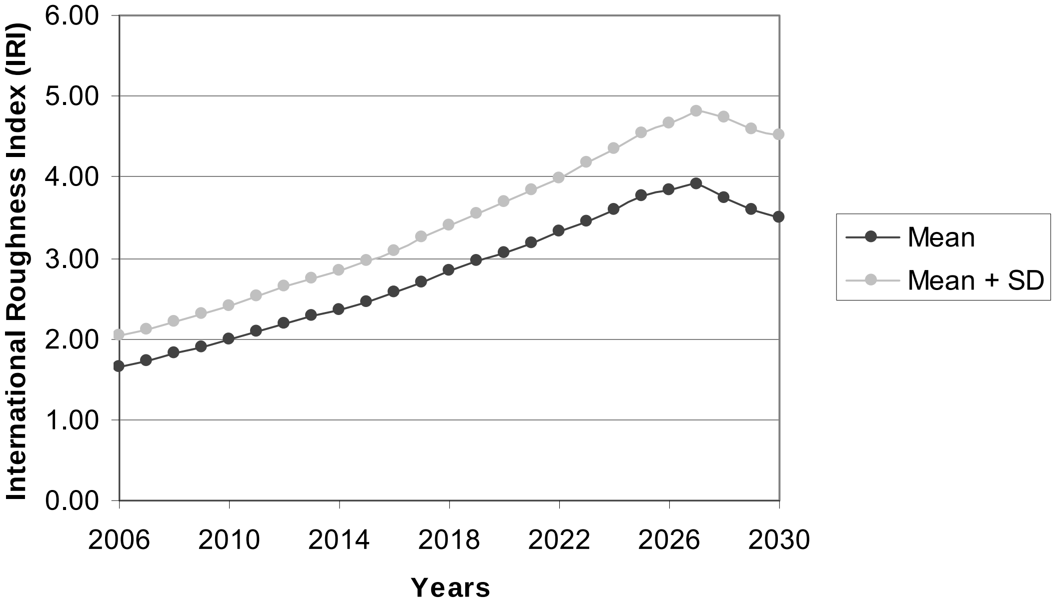

Figure M7 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of DNR-Good-AC-Flx-(1.5k-3k)

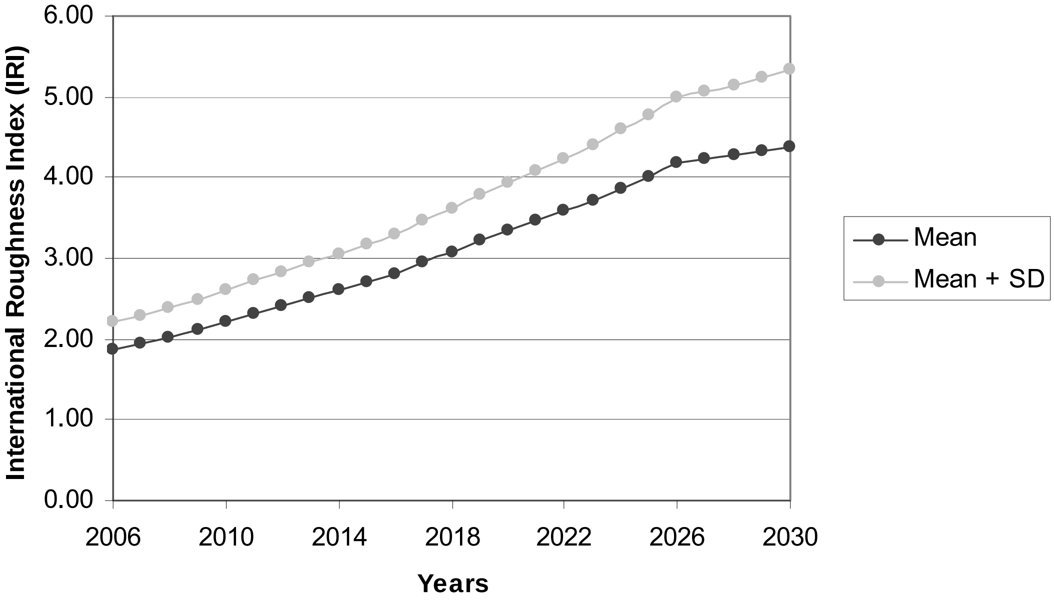

Figure M8 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of DNR-Fair-AC-Flx-(0.5k-1.5k)

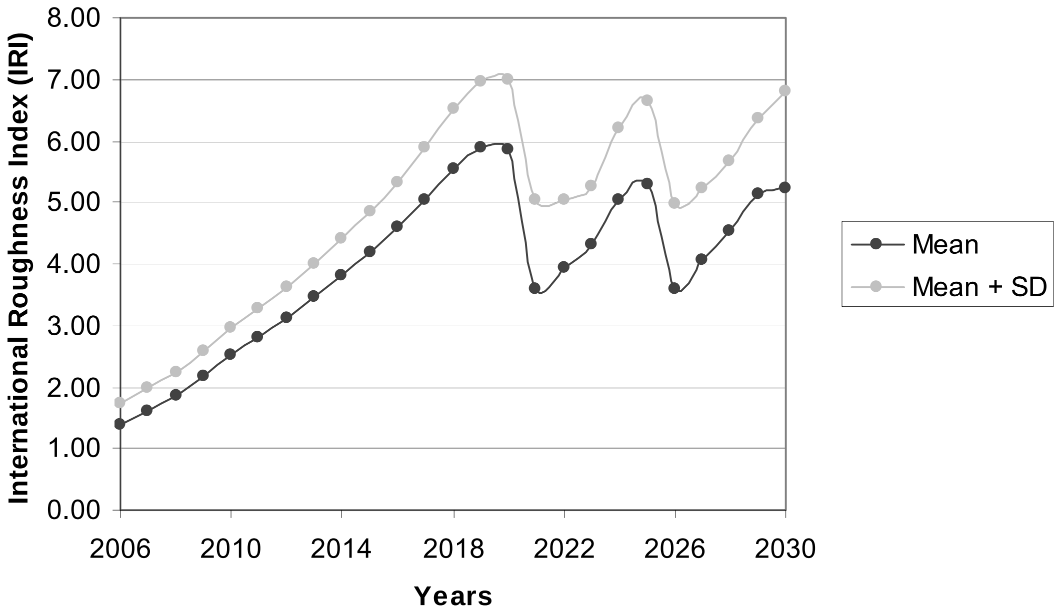

Figure M9 Mean and mean plus one standard deviation for pavement roughness for a whole life cycle of 25 years for road category of DNR-Good-Bt-SR-(0.5k-1.5k)

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