A FRAMEWORK FOR RISK-BASED ANALYSIS OF INVESTMENT IN MAINTENANCE AND REHABILITATION OF LARGE ROAD NETWORKS

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ABSTRACT

Budget/cost estimates for road maintenance and rehabilitation are subjected to uncertainties and variability in road asset condition and characteristics of road users. In the current method for road network investment analysis, road networks are usually divided into different groups or categories with similar characteristics. Mean values are used to represent road characteristics of each category, however the variability of asset conditions and road user characteristics is not included in the analysis. Reliable budgets/cost estimates need to include the variability and uncertainties of input parameters in the investment analysis. This paper presents a framework and a case study using probability-based method for assessing the variability and reliability for road network maintenance investment. A road network of approximately 4500 km located in the state of Queensland, Australia was used as a case study.

KEY WORDS
maintenance, rehabilitation, categorise, variation, variability, investment

INTRODUCTION

In Australia, road assets are valued at around A$140 billion. As the condition of assets deteriorates over time, close to A$ 6 billion is spent on asset maintenance and rehabilitation annually (i.e. A$ 16 million per day). Realistic estimates of short- and long-term costs for maintenance and rehabilitation of road assets should take into account the stochastic characteristics of asset conditions of road networks. The probability theory has been used in assessing risk-based costs for infrastructure assets by many researchers (Kong & Frangopol 2003, Zayed et al. 2002). However, very few studies were reported for road network analyses (Salem et al 2003) and no studies were reported to have incorporated stochastic characteristics of road data into budget/cost estimates.

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A research project titled "Maintenance Cost Prediction for Road" under the Cooperative Research Centre (CRC) for Construction Innovation has developed a method that takes into account the variability and uncertainties of road data in investment analysis (Piyatrapoomi et al. 2005). This paper presents a framework for probability risk-based investment analysis for maintenance and rehabilitation at the network level that takes into account the variability of road data in the analysis. A road network, located in the state of Queensland which comprises approximately 4500 km of road length located across three soil types and three climatic zones, was used in the analysis as a case study.

FRAMEWORK FOR INVESTMENT ANALYSIS OF LARGE ROAD NETWORKS

The concept in investment analysis that takes into account the variability of road data comprises the following tasks:

1) Identifying parameters considered to be critical in investment analysis;
2) Categorising road networks;
3) Analysing variability and uncertainties of road data for each category;
4) Incorporating the variability and uncertainties of road data into the analysis

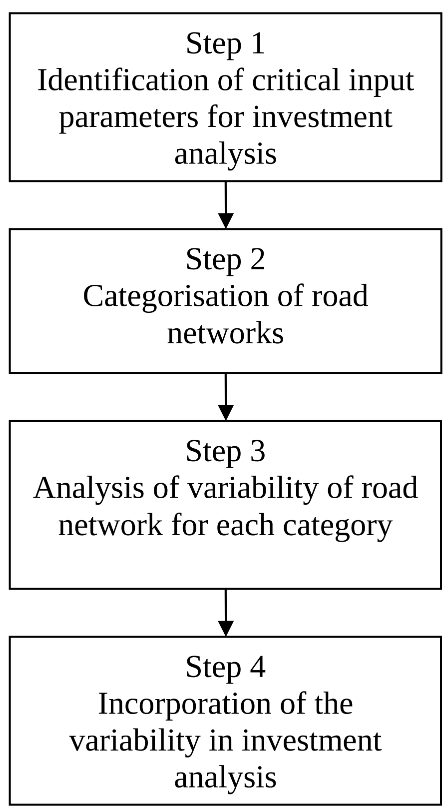

Figure 1: Framework for Analysis

The first task in the analysis method is to identify input parameters that are critical in contributing to the variation in investment estimates. The second step is to categorise road network into different groups of common characteristics and, thirdly, to assess the variability or the stochastic characteristics of the road network for each category. The last step is to incorporate the variability of road data into the investment analysis.

INDENTIFICATION OF CRITICAL INPUT PARAMETERS

Most road agencies monitor road asset conditions and collect relevant road data such as those pertaining to roughness, rut depth, cracking, pothole, annual average daily traffic (AADT), pavement strength, to name a few. It must be recognized that it is not feasible to incorporate the variability of all road data in investment analysis. The first step in the analysis is to identify parameters that critically affect the variability of the predicted outcome. Piyatrapoomi et al. (2005) identified the variability that made a significant contribution to the variability of the predicted budget/cost estimates, which include (Piyatrapoomi et al. 2005):

1) rut depth,
2) annual average daily traffic
3) initial roughness
4) pavement strength.

Currently, road data on rut depth, annual average daily traffic, initial roughness can be collected at affordable costs and most road agencies have these data in their database. However, data on road pavement strength is expensive and time consuming to collect and not usually available at the network level. The probability-based method has been used by Piyatrapoomi et al. (2004) to assess optimal intervals of pavement strength data collection for network application (Piyatrapoomi et al. 2004). They hypothesized in their 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"*. Extensive pavement strength data located in three climatic and soil conditions were used in the analysis. These climatic and soil conditions included wet non-reactive soils, dry non-reactive soils and dry reactive soils. They found that pavement strength could be collected at 1000, 1400 and 700 meter intervals for network application for wet non-reactive soil, dry non-reactive soils and dry reactive soils, respectively. The outcome of the analysis shows that pavement strength could be collected at affordable costs at the network level. As a consequence, Queensland Government Department of Main Roads began allocating funding in the 2005/2006 budget for collecting pavement strength information for road network investment analysis.

CATEGORISATION OF ROAD NETWORKS

For network investment analysis, a road network is categorized into different groups of common characteristics. Categorisation criteria are based on annual average daily traffic

(AADT), pavement roughness conditions, climatic zones, soil conditions, surface types and base types. Two surface types, including bitumen and asphalt concrete, and two types of pavement bases including flexible and semi-rigid were used in the analysis. Seven levels of annual average daily traffic were used in the categorisation which included annual average daily traffic of less than 500 vehicles, 501-1500 vehicles, 1501-3000 vehicles, 3001-5000 vehicles, 5001-10000 vehicles, 10001-25000 vehicles, and greater than 25000 vehicles. Three pavement roughness conditions were used in the categorisation which included international roughness index (IRI) is less than 2.31, IRI is greater than 2.31 but less than 4.2), and IRI is greater than 4.2. Three climatic and soil conditions were used including wet non-reactive soils, dry and non-reactive soils and dry reactive soils. Table 1 summaries the categorisation criteria used in the analysis. Based on the categorising criteria, the 4500 km of road network can be grouped into sixty five categories of common characteristics (Piyatrapoomi et al. 2005).

Table 1: Criteria Used for Categorising Road Pavements

Annual Average Daily Traffic (no. of cars)	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)			Dry Reactive Soil
3001-5000				
5001-10000				
10001-25000				
>25000				

VARIABILITY ANALYSIS OF ROAD NETWORK DATA

As mentioned previously, sixty-five categories were obtained from the categorisation of the 4500 km of road network. The variability of the identified critical input parameters including rut depth, pavement roughness and annual average daily traffic (AADT) was quantified by probability distributions, means and standard deviations for each category. Figures 2, 3 and 4 show means and standard deviation values for international roughness index (IRI), rut depth and AADT, respectively. Details of the statistical analysis of these critical input parameters were presented in another publication (Piyatrapoomi et al. 2006). The probability distributions of IRI, rut depth and AADT are shown to be in good fit with Bete General, Log normal and exponential distributions, respectively. Pavement strength information is currently being tested for the network level. The collection of pavement strength data is expected to be completed by early 2006. Hence, the variability of pavement strength will be incorporated in the analysis at a later stage.

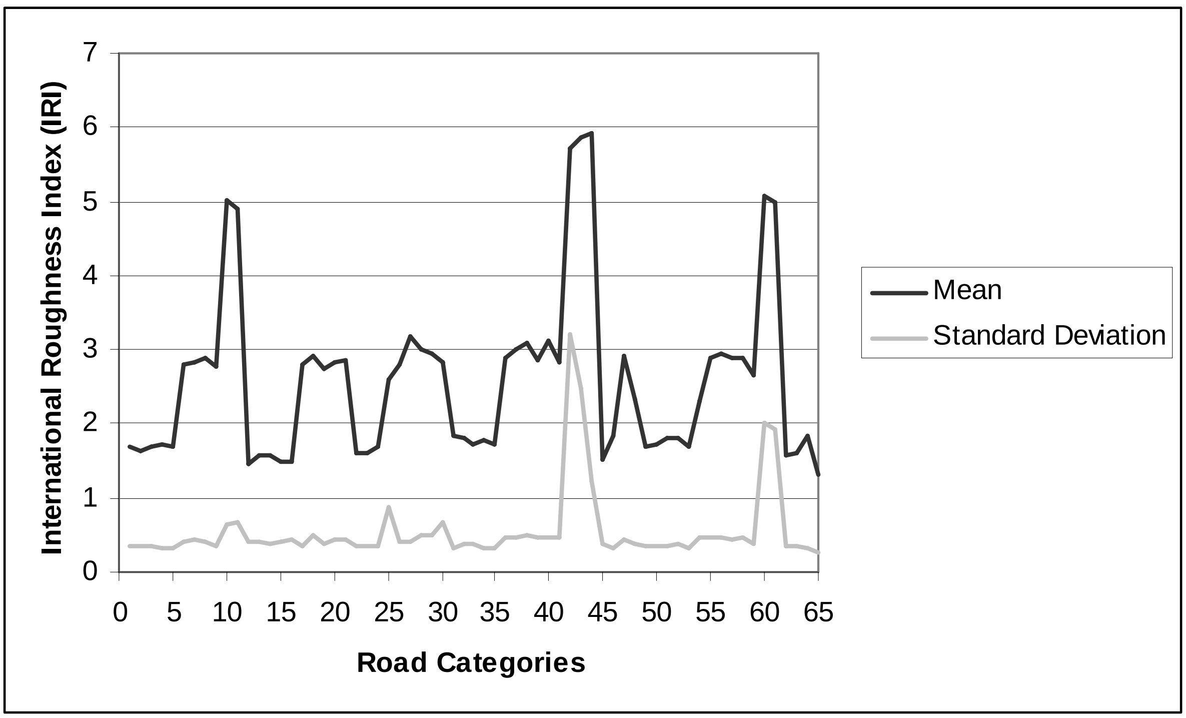

Figure 2: Mean and Standard Deviation of International Roughness Index (IRI) for Sixty-Five Road Categories

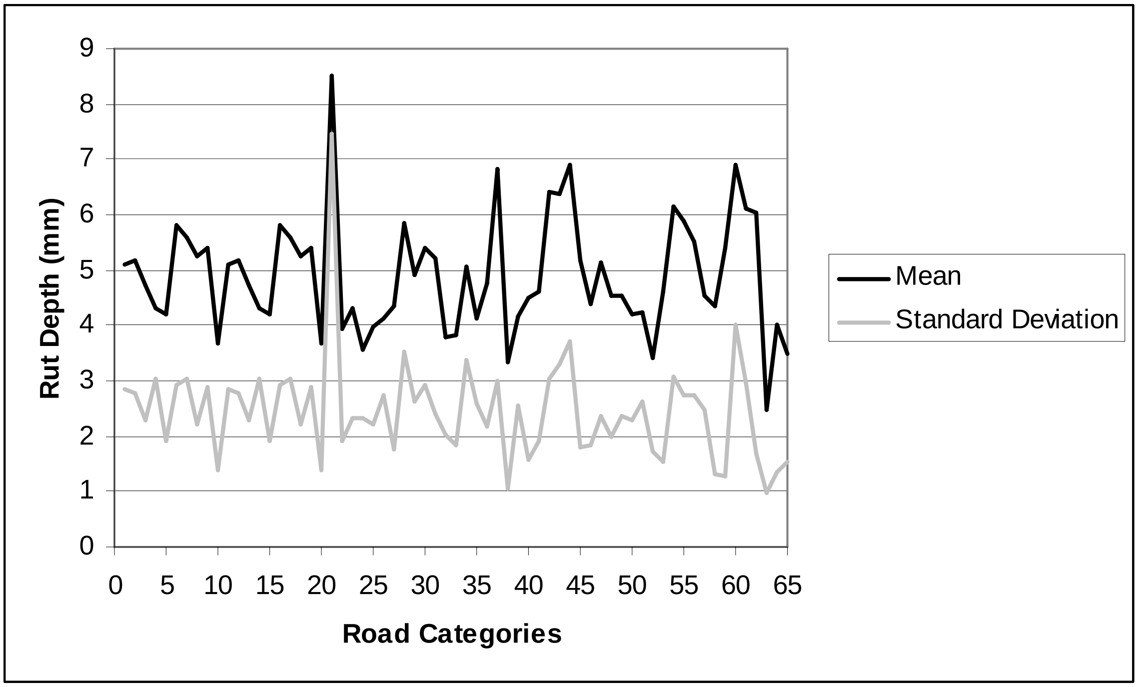

Figure 3: Mean and Standard Deviation of Rut Depth (mm) for Sixty-Five Road Categories

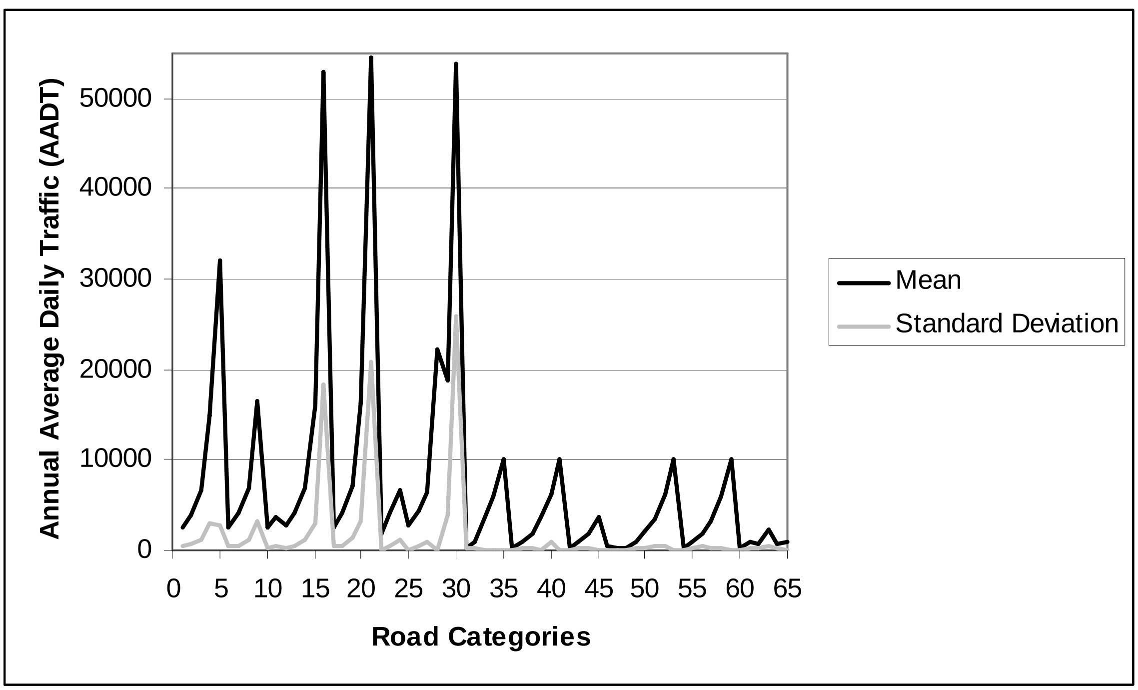

Figure 4: Mean and Standard Deviation of Annual Average Daily Traffic (AADT) for Sixty-Five Road Categories

ASSESSMENT OF VARIATION IN BUDGET/COST ESTIMATES

To incorporate the variability of road data in investment analysis, Latin-hypercube sampling technique was used to simulate the variability of critical input parameters described in the preceding section for the analysis. Using the Latin-hypercube sampling technique, sample values of international roughness index (IRI), rut depths and AADT were obtained from the probability distributions described in the previous section to represent the variability of these critical input parameters in the analysis. The variability of pavement strength will be incorporated at later stage. Latin hypercube sampling technique, as extensively studied by Iman and Conover (1980), provides a satisfactory method for selecting small samples of input variables so that good estimates of the means, standard deviations and probability distribution functions of the output variable can be obtained. The outcome of investment analysis will be a probability distribution of investment budget/cost for maintenance and rehabilitation. Highway Development and Management (HDM-4) System software package (ISOHDM 2001) was employed as the calculation tool for calculating budget/cost estimates. HDM-4, developed by the International Study of Highway Development and Management (ISOHDM), is a globally accepted pavement management system. In this study, forty samples were simulated from the probability distribution of each critical input parameter. Piyatrapoomi (1996) suggested that thirty data points simulated from a probability distribution using the Latin-hypercube sampling technique was good enough to represent their statistical information. In this study, forty data points were sampled for each input parameter for increased accuracy in the analysis. Forty HDM-4 data input files were created and a series of HDM-4 analyses was carried out to calculate forty output values of budget/cost estimates. Means, standard deviations, probability distributions and other statistical parameters were quantified from the forty values of budget/cost estimates. Details of the analysis using Latin-hypercube sampling technique and HDM-4 for investment analysis are given in Piyatrapoomi et al. (2004).

There are numerous outputs generated from HDM-4 analysis (for example, economic analysis summary, road work summary by section and year, pavement condition summary, etc.). For the illustration of risk-based investment analysis for road network, budget/cost estimates and variation in the estimates for a life-cycle of a 25-year period were calculated for the 4500 km road network. Figure 5 shows mean cumulative costs for road pavement investment for a 25-year life-cycle period beginning from 2006. The mean of total cost estimates was calculated to be approximately A$ 1.8 billion. The variation estimates were taken as one standard deviation above the mean values. Figure 6 shows the variation in cost estimates of one standard deviation. The variation in cost estimates for the first five years was calculated to be approximately A$20 million. The variation in cost estimates for the year 2030 was calculated to be approximately A$137 million. Decision-makers can take the mean estimates in their budget/cost predictions, however they need to be aware that there are certain variations in the prediction due to the variability of asset conditions and AADT. The increment in AADT was assumed to be 2 per cent annually. Alternatively, decision-makers could adjust budget/cost estimates based on the probability of occurrence or levels of confidence with which they feel most comfortable (e.g. 50^{th}, 75^{th}, 85^{th} or 95^{th} percentile).

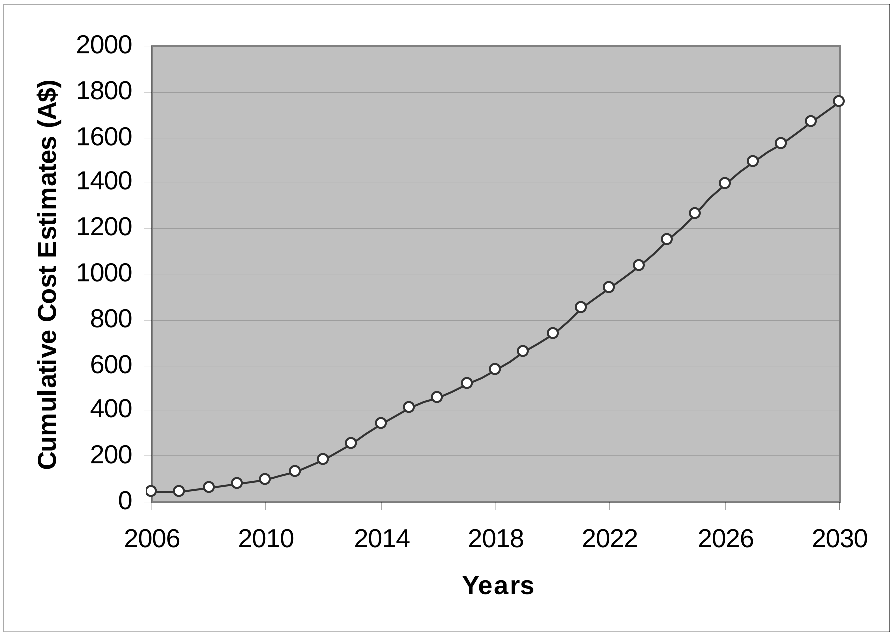

Figure 5: Mean cumulative costs for maintaining road pavement for a road network of 4500 km for a 25-year life-cycle period beginning in 2006

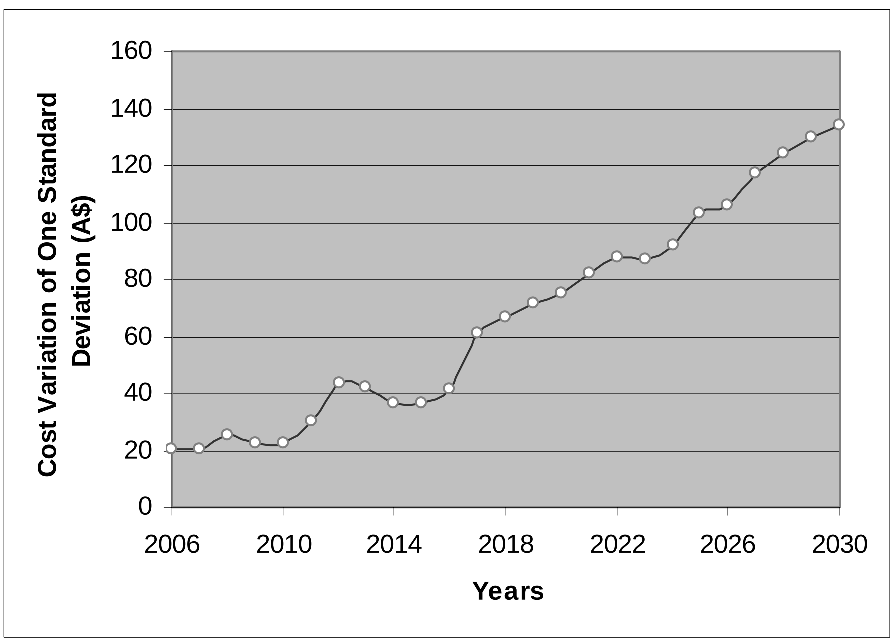

Figure 6: Variation in Cost Estimates of One Standard Deviation

CONCLUSIONS

This paper presented a framework for a probability risk-based method to analyse road network pavement management investment. Budget/cost estimates for a life-cycle period of 25 years for 4500 km road network were presented as a case study. The method allows us to understand the effect of the variability of road data on the variation in budget/cost estimates and the degree of uncertainty in budgeting for investment. The framework for the analysis includes identifying critical input parameters, categorizing road networks into different groups of common characteristics, quantifying the variability of the critical input parameters for each category, assessing the variability of budget/cost estimates due to the variability of the critical input parameters. The outcome of the analysis is probability distributions of investment estimates. Decision-makers can assess the means and the variations in the budget/cost estimates. They can also assess different risk levels in budget/cost estimates. Risk arises from the possibility that a forecast budget/cost estimate may prove to be wrong. Decision-makers can use different percentile budget estimates for assessing their level of confidence. Road agencies may choose a budget based on a percentile level with which they are comfortable (for instance, 95th percentile) and monitor costs against the chosen percentile estimate. They can adjust the percentile and adopt a suitable percentile estimate when they monitor costs for other projects. This investment analysis is a systematic approach to forecast budget/cost estimates, which considers the uncertainties and variability in road data and uses cost feedback to compare with the initial percentile selected for budget estimates.

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