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Reliability of Optimal Intervals for Pavement Strength Data Collection at the Network Level

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SYNOPSIS

In road asset management, knowledge of current condition and understanding of deterioration rates of pavement strength is essential input parameter for estimating fund allocations for maintenance and rehabilitation work. However, the cost of collecting data on road pavement strength is relatively high. In a previous pilot study, a procedure was developed for optimising longitudinal sampling intervals for collection of pavement strength data for use in network level of road asset management for the State of Queensland, Australia. The findings indicated that pavement strength data could be collected at 1000-meter intervals rather than at 200-meter intervals for a tropical region of northeast Queensland, Australia. This paper presents the results of the continuing research to assess the reliability of the usage of the 1000-metre interval pavement strength data in predicting budget estimates for road maintenance and rehabilitation at the network level.

In the reliability assessment, the 95th percentile budget estimates were compared with the budget estimates calculated from 1000-metre interval pavement strength data. The results indicated that the differences between the 95th percentile budget estimates and the budgets estimated from the 1000-metre interval pavement strength data were less than four per cent for 10-,15-, 20- and 25-year budget estimates, and were approximately 12.25 per cent for 5-year periods.

INTRODUCTION

One of the issues in road asset management is the high cost of data collection for pavement strength prediction at the network level. Pavement deflection is used as a measure of pavement strength. 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 at the network level.

Piyatrapoomi et. al. (2003) adopted the Kolmogorov-Smirnov (K-S) probability-based goodness-of-fit test method to identify optimal intervals for pavement deflection data collection for the State of Queensland. Pavement deflection data sets from a 92-kilometre segment in the State of Queensland Australia were used in their study. The 92-kilometre pavement deflection data set was obtained from a National Highway in a tropical region of north-east Queensland with wet and non-reactive soil conditions. Falling Weight Deflectometer (FWD) deflection tests were used to collect the data. The majority of the tests were performed at 200-metre spacing alternating between the inner and outer wheel paths for the 92-kilometre National Highway segment.

The results from the probability-based goodness-of-fit analysis showed that the mean, standard deviation and probability distribution of deflection data collected at 1,000-metre intervals were similar in value to the mean, standard deviation and probability distribution for data collected at 200-metre intervals. More details can be found in Piyatrapoomi and Kumar (2003a) and Piyatrapoomi et. al. (2003). The findings indicated that pavement deflection data could be collected at 1,000-metre intervals rather than at 200-metre intervals while providing similar prediction outcomes. The result from this analysis may open the door for affordable pavement deflection data collection at the network level.

A continuing research was conducted to determine the reliability of the use of the optimal pavement deflection data in predicting the maintenance and rehabilitation budget estimates at the network level. In this study, the same data set of the 92-kilometre National Highway segment was employed in assessing the budget estimates for road maintenance and rehabilitation and to assess the reliability of the usage of the optimal pavement strength data of 1000-metre intervals.

The overall variability of pavement strength was used to calculate and establish the probability distribution of budget estimates. In the reliability assessment, the 95th percentile budget estimates were chosen to compare with the budgets estimated from the pavement strength of 1000-metre intervals. The 95th percentile value is a value that is commonly selected to provide an appropriate level of confidence (Ang and Tang 1975, Billinton and Allan 1992, Kececioglu 1991, Lewis 1987). The 95th percentile budget estimates were calculated using the probability-based reliability assessment method, and were calculated for 5-, 10-, 15-, 20- and 25-year periods. This paper presents the results of the comparison between the budget estimates calculated from the optimal pavement deflection data of 1000-metre intervals and the 95th percentile budget estimates for 5-, 10-, 15-, 20- and 25-year periods.

CALCULATION OF THE 95TH PERCENTILE BUDGET ESTIMATES

In this study, the term "reliability" is defined as the degree of discrepancy between the 95th percentile budget estimates and the budget estimates calculated from the pavement strength data of 1000-metre intervals. It must be noted that only the discrepancy influenced by the pavement strength was compared. Thus, the variability of pavement strength was used in the calculation of the 95th percentile budget estimates for maintenance and rehabilitation. While other input variables remain deterministic in the budget estimates.

The probability-based method was adopted in establishing the probability distribution of budget estimates and in assessing the 95th percentile budget estimates (Piyatrapoomi and Kumar 2003b). The first step in the probability-based reliability assessment is to define a performance function which transforms input variables into output variables (Ang and Tang 1984, Billinton and Allan 1992, Lewis 1987, O'Connor 1985, Kececioglu 1991). The second step is to define the input variables and their variability. In this study, the performance function that takes the variability of pavement strength into account is given below:

$$G = f(z_1\ Y_1) \qquad (1)$$

Where z_1 is the transform function that transforms input variables into budget estimates, Y_1 is the variable that takes into account the variability of pavement strength or the so called "random" variable in reliability assessment.

The outcome of Equation (1) will be the probability distribution of budget estimates as shown in Figure 1. The budget estimates at the 95th percentile can be obtained by selecting the budget estimates at the 95% probability of occurrence from the probability distribution.

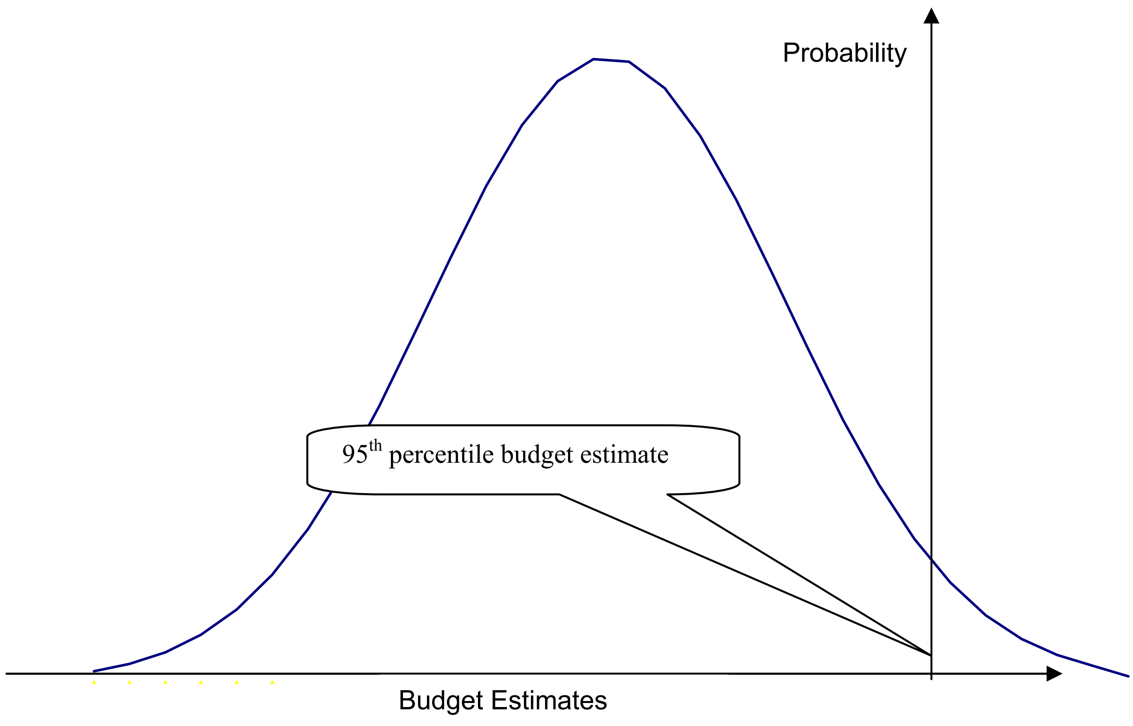

Figure 1 Probability of Budget Estimate

The calculation of Equation (1) is the subject of determining the relationship between input and output statistics (i.e. how the variability of input variables affect the variability of output variables). In this study, Latin-Hypercube sampling technique was used to assess this relationship. Latin hypercube sampling technique, as extensively studied by Iman and Conover (1980), appears to provide 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.

In this study, the performance function which transforms input variables into budget estimates is very complicated. It involves establishing deterioration prediction models of road conditions; identifying current road conditions; quantifying road usage and forecasting incremental road usage in future; and optimising different budget scenarios to obtain optimal budget estimates. This complexity makes the relationships between the input and output not mathematically tractable. Highway Development and Management (HDM-4) System software package (ISOHDM 2001) was employed as the calculation tool in the analysis to determine the relationship between input and output variables and to calculate output statistics HDM-4, developed by the International Study of Highway Development and Management (ISOHDM), is a globally accepted pavement management system.

Figure 2 shows the schematic chart of the framework for the reliability assessment and details are described below;

Step 1: Establish probability distributions and statistical information (means, standard deviation and etc.) of pavement strength.
Step 2: Sample observational values from the established probability distribution of pavement strength for the analysis. The Latin Hypercube Sampling Technique was employed for the sampling procedure.
Step 3: Employ Highway Development Management System (HDM-4) in the statistical analyses to obtain output statistics (i.e. the output statistics of the budget estimates).
Step 4: Establish the probability distribution and determine the statistical information of the output budget estimates.
Step 5: Compare the 95th percentile budget estimates with the budget estimated from the pavement strength of 1000-metre intervals.

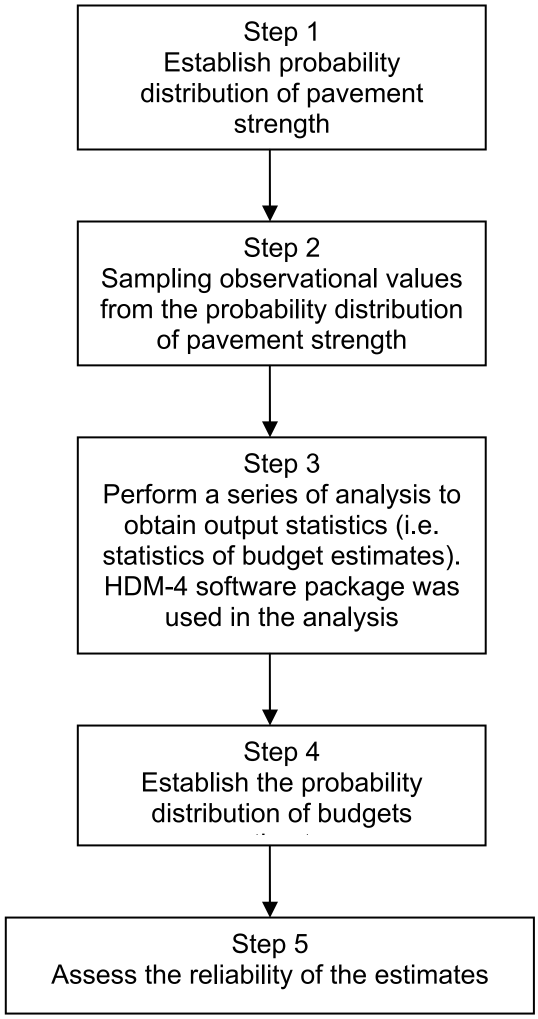

Figure 2 Flow chart of the framework for the reliability assessment

ESTABLISHING PROBABILITY DISTRIBUTION OF PAVEMENT STRENGTH DATA

Step 1 in Figure 2 is to establish the probability distribution of pavement strength. As mentioned earlier, the 92-kilometre National Highway segment in a tropical region of north-east Queensland was employed in this reliability assessment. Pavement strength and flexibility is usually determined from pavement deflection data that 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. The popular method used for pavement deflection testing is the Falling Weight Deflectometer (FWD) testing as shown in Figure 3. Additional details of the Falling Weight Deflectometer (FWD) testing can be found in Piyatrapoom and Kumar (2003a).

The FWD testing was conducted in May 2002 on a 92-kilometre section of a National Highway located in the tropical northern region of Queensland in Australia. Soil types in this area were classified as wet and non-reactive. The tests were performed at 200-meter spacing for both inner and outer wheel paths. This road section was categorised by the type of pavement, surface, subgrade, and the volume of traffic. The type of pavement was a flexible pavement. Typical sections of the national highway network in this area represented 300mm-350mm granular base with spray seal surface. The applied load was 50 kN. The deflections were measured in microns.

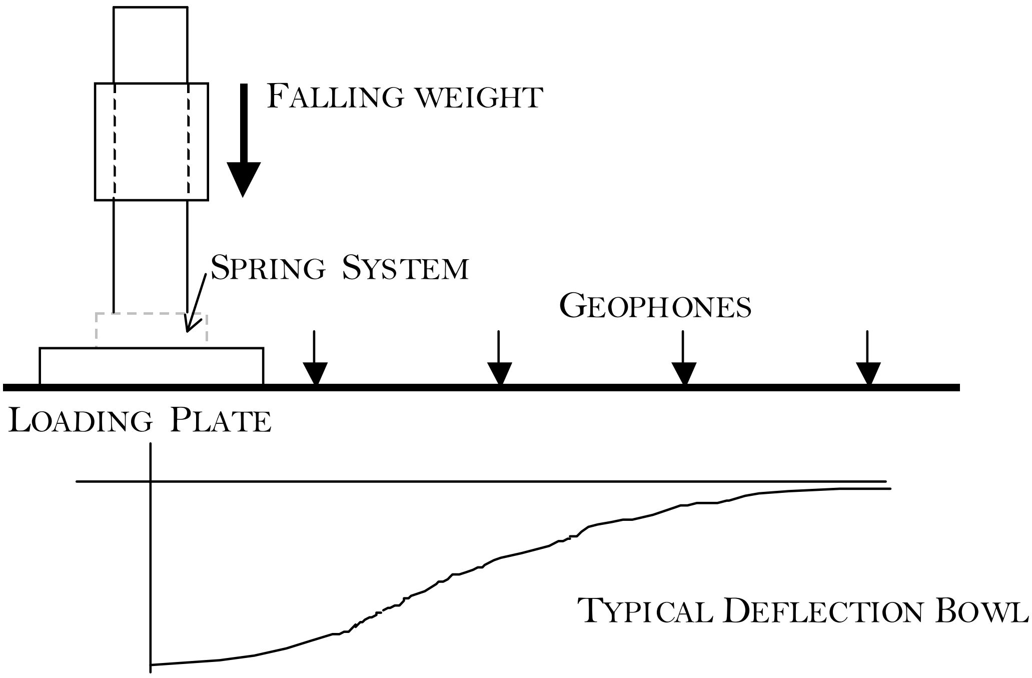

Figure 3 The Falling Weight Deflectometer (FWD) pavement deflection test and a typical deflection bowl.

As mentioned earlier, pavement deflection is a measure of pavement strength. There are numerous functions to convert pavement deflection data into pavement strength indicators. Structural Number is used globally in pavement management systems to predict structural capacity and the life of pavement structures at the network or project level. HDM-4 requires Structural Number (SN) as the input parameter for pavement strength. Various researchers have developed the relationship between pavement deflection and Structural Number (Rhode 1994, Rhode and Hartman 1996, Salt and David 2001, QDMR 2002, O'Brien 2002). In this study, Salt's formula was used for the conversion of pavement deflection into the Structural Number. Salt used the back-calculated layer moduli and the AASHTO method to develop the relationship between Structural Number and pavement deflection. Salt's formula is given below. Figure 4 shows the fitting of the cumulative distribution of Structural Number converted by using Salt's formula to the cumulative probability distribution of the pavement strength data. It shows that the two cumulative distributions are log normally distributed.

$$SN = 112(Do)^{-0.5} + 47(Do - D900)^{-0.5} - 56(Do - D1500)^{-0.5} - 0.4 \quad (2)$$

Where: *SN* is the Structural Number. *Do* is the pavement deflection under the load cell. *D900* and *D1500* are the pavement deflections at locations 900mm and 1500mm from the load cell, respectively.

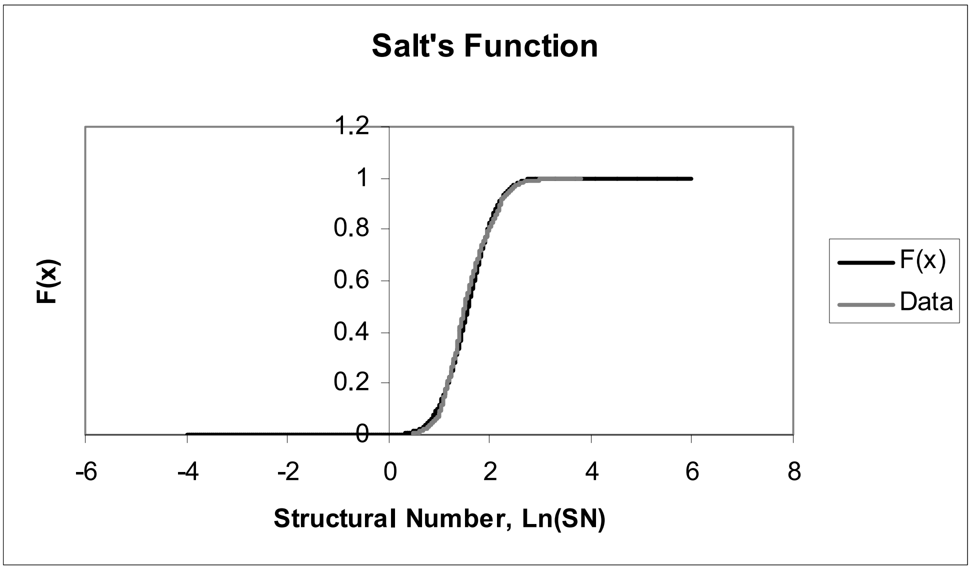

Figure 4 Cumulative distribution of Structural Number (SN) converted by Salt's formula compared with a theoretical probability distribution.

The mean, standard deviation values of the Structural Numbers for each kilometre of the 92-kilometre National highway were quantified from the tested data and are graphically presented in Figures 5 and 6. The probability distribution of pavement strength for each kilometre can be established from the mean, standard deviation of each kilometre and the probability distribution (in this case, log normal distributions). Figure 7 shows typical probability distributions of Structural Numbers of the first five kilometres of the 92-Kilometre National Highway. From Figure 7, it is worth noting that different road sections have different pavement strength characteristics. The probability distributions of the structural number for each kilometre of 92-kilometre National highway located in wet and non-reactive soil areas are shown in Appendix A.

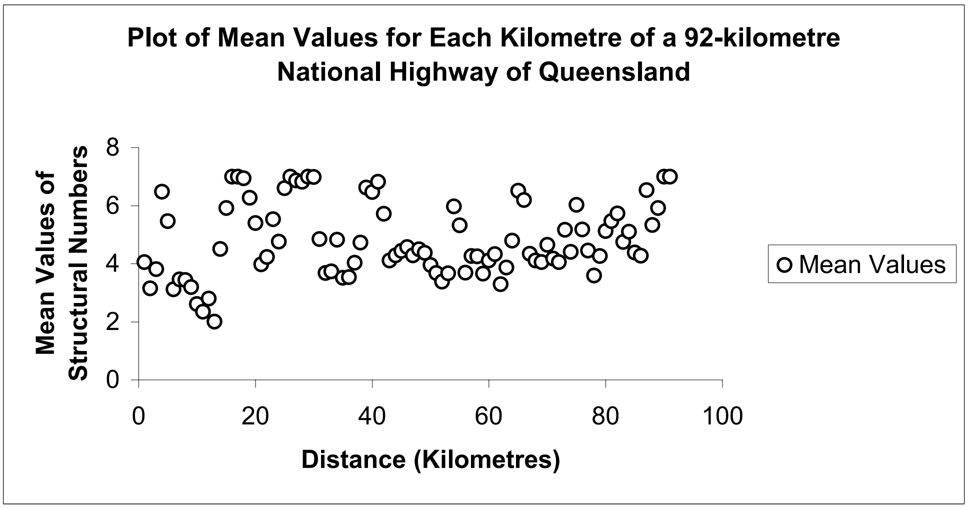

Figure 5 Mean values of each kilometre of a 92-kilometre National highway of Queensland

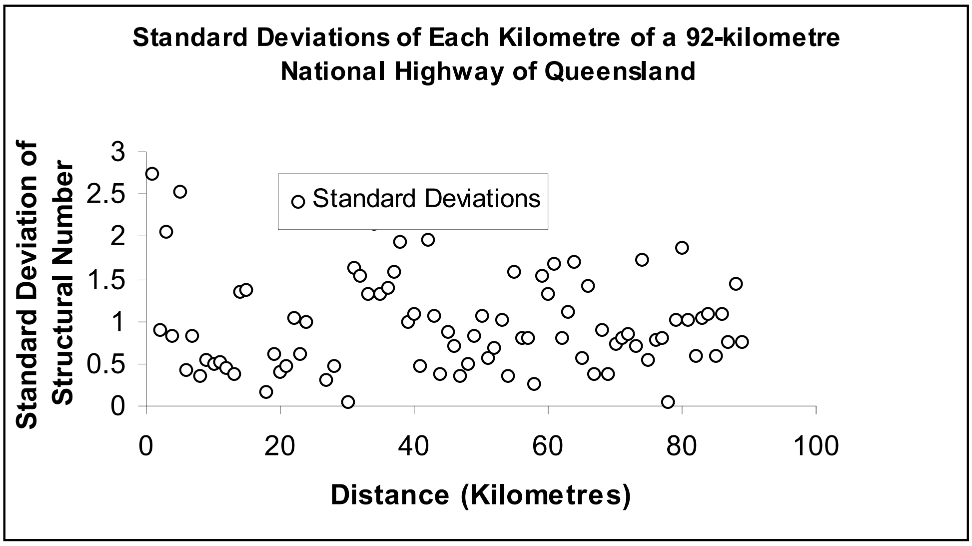

Figure 6 Standard deviations of each kilometre of a 92-kilometre National highway of Queensland

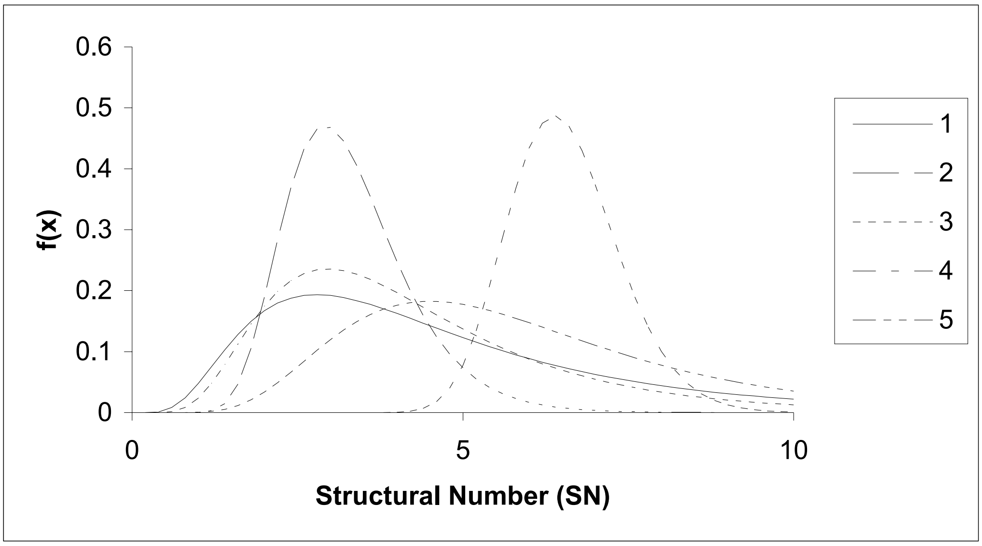

Figure 7 Typical probability distributions of Structural Numbers of the first five kilometres of the 92-Kilometre

SIMULATION OF STRUCTURAL NUMBERS FOR EACH KILOMETRE BY LATIN HYPERCUBE SAMPLING TECHNIQUE

In step 2 in Figure 2, The Latin-Hypercube sampling technique was employed in the sampling of the Structural Numbers from the probability distributions to represent the variability of pavement strength in the analysis. In the Latin Hypercube Sampling Technique, the probability of the input variable is assumed known. The probability distributions of pavement strength and their statistical information (e.g. mean and standard deviation) were quantified in the preceding section.

In the Latin Hypercube sampling technique, the probability distribution of the pavement strength of each kilometre is divided into small intervals with equal probabilities. Piyatrappomi (1996) found that sampling observational values of thirty data points were enough to obtain the good estimates of the means, standard deviations and probability distribution functions of output variables. To obtain better results, in this study the probability of the pavement strength was 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 Structural Number values are obtained for each kilometre. Details of the Latin Hypercube Sampling Technique can be found from the original paper (Iman and Conover, 1980).

The steps in sampling Structural Number values from the probability distributions using the Latin-Hypercube sampling technique are given below;

1) The probability distributions of the Structural Numbers of each kilometre for the 92-kilometre National Highway were established in the preceding section. There are all together 92 probability distributions for the 92-kilometre National Highway.
2) The probability distribution of each kilometre was divided into forty intervals of equal probabilities. Figure 8 shows a typical cumulative distribution of the Structural Number when the probability distribution was divided into forty equal probabilities.
3) Within the divided forty equal probabilities of each kilometre, randomly select a sampled value of the Structural Numbers from each of the 92 probability distributions by Latin Hypercube procedure described above (Iman and Conover 1980). Ninety-two Structure Numbers were obtained, each value representing the Structural Number of each kilometre. These 92 Structural Number values were used as input values for HDM-4 analysis in estimating the maintenance and rehabilitation budget.
4) At this point, there are thirty-nine intervals remaining for each kilometre to be sampled and represented in the analysis. Repeat step 3 until all forty values of data have been randomly selected for the analysis. Thus, there are now a total of forty sets of the Structural Numbers. Each set contains the Structural Numbers of the 92-kilometre National Highway.
5) Conduct forty HDM-4 analyses to obtain forty values of the output (i.e. forty values of the budget estimates).
6) Establish the mean values, standard deviation values and probability distribution of the budget estimates from the forty value outcomes.

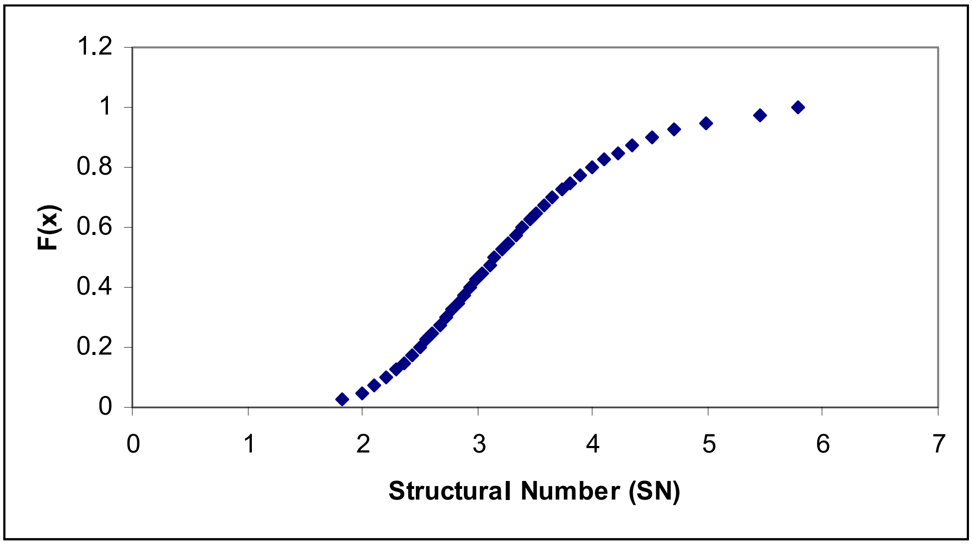

Figure 8 A typical cumulative distribution of Structural Number sampled by Latin Hypercube Sampling Technique.

ESTABLISHING PROBABILITY DISTRIBUTION OF BUDGET ESTIMATES

Step 3 in Figure 2 is to perform a series of analysis to obtain the statistical output of the budget estimates. HDM-4, developed by the International Study of Highway Development and Management (ISOHDM), a globally accepted pavement management system, was used to perform such analysis. HDM-4 is a computer software package used for planning, budgeting, monitoring and management of road systems. There are three analysis options in HDM-4. These analysis options include (1) Strategy Analysis, (2) Program Analysis and (3) Project Analysis. The Strategy Analysis Option was employed in this study.

As mentioned in the preceding section, the 92-kilometer road segment was divided into 92 sections of one kilometre in length for each section. Each kilometre section has its own pavement strength characteristic. Maintenance and rehabilitation budget estimates for 5, 10, 15, 20 and 25 year periods were calculated starting from 2003. Four classes of vehicle types were used in the analyses, including short vehicles (85 per cent), trucks (7 per cent), articulated vehicles (7 per cent) and road-trains (1 per cent). Increases in the number of vehicles were estimated at two per cent annually for all four types of vehicles.

From the forty sets of the Structure Numbers obtained by the Latin Hypercube sampling technique, forty HDM-4 analyses were undertaken to calculate the statistics of the budget estimates. From the output statistics of budget estimates, probability distributions of budget estimates were established.

Figure 9 to Figure 13 show the cumulative probability distributions of budget estimates for 5-, 10-, 15-, 20- and 25-year periods. The probability distributions of the budget estimates were shown to be normally distributed.

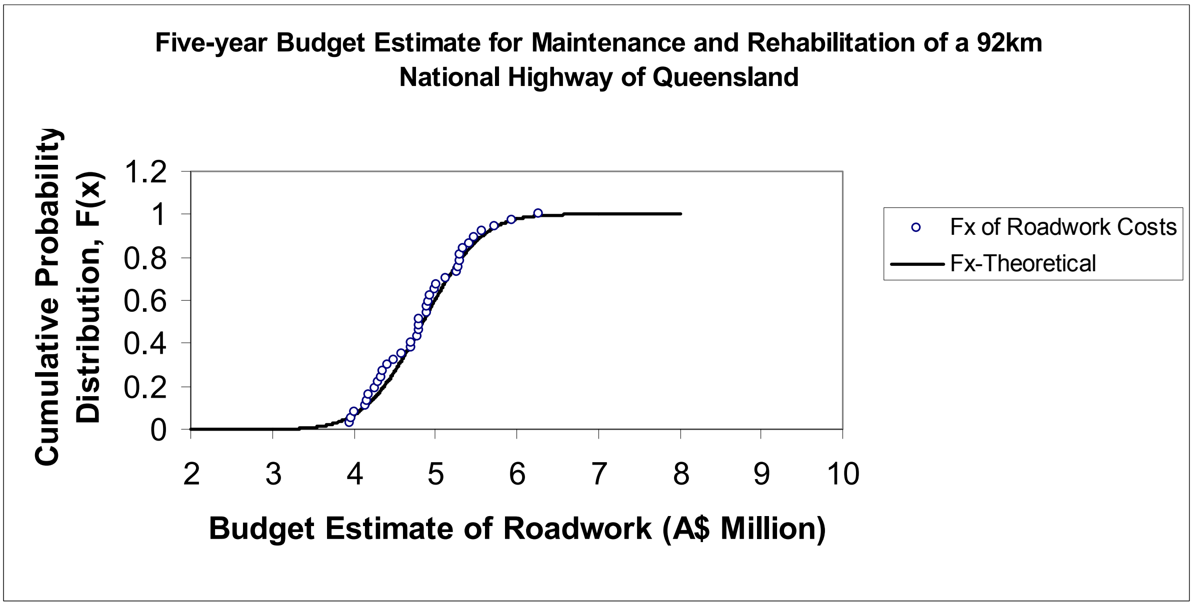

Figure 9 Cumulative distribution of budget estimate for 5-year roadwork cost of a 92-kilometre National highway of Queensland (roadwork includes maintenance and rehabilitation).

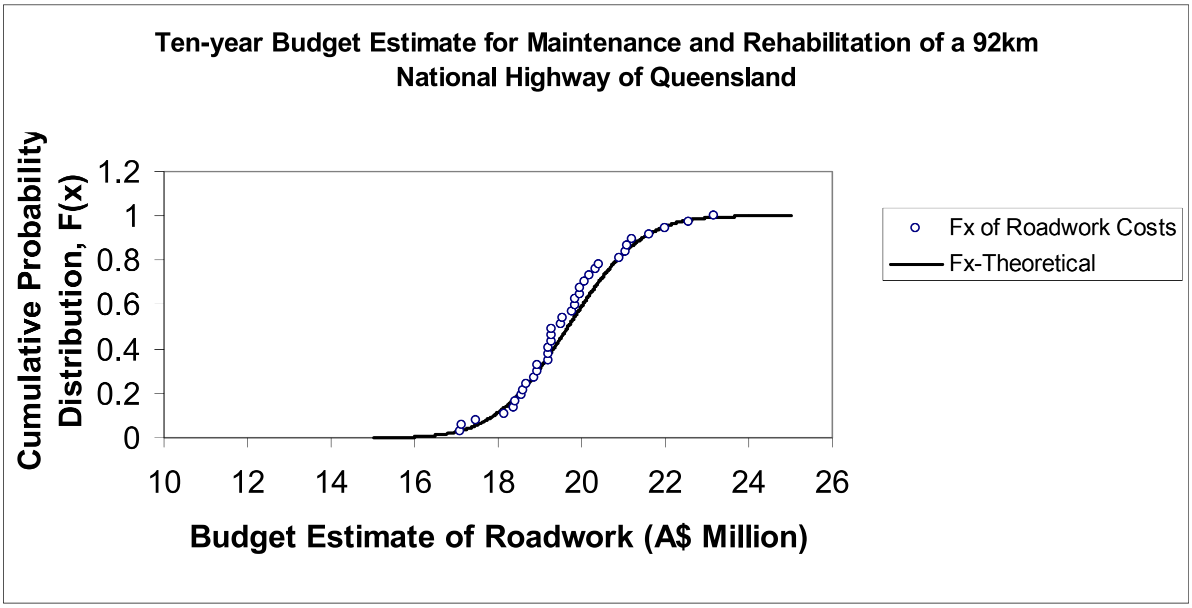

Figure 10 Cumulative distribution of budget estimate for 10-year roadwork cost of a 92-kilometre National highway of Queensland (roadwork includes maintenance and rehabilitation).

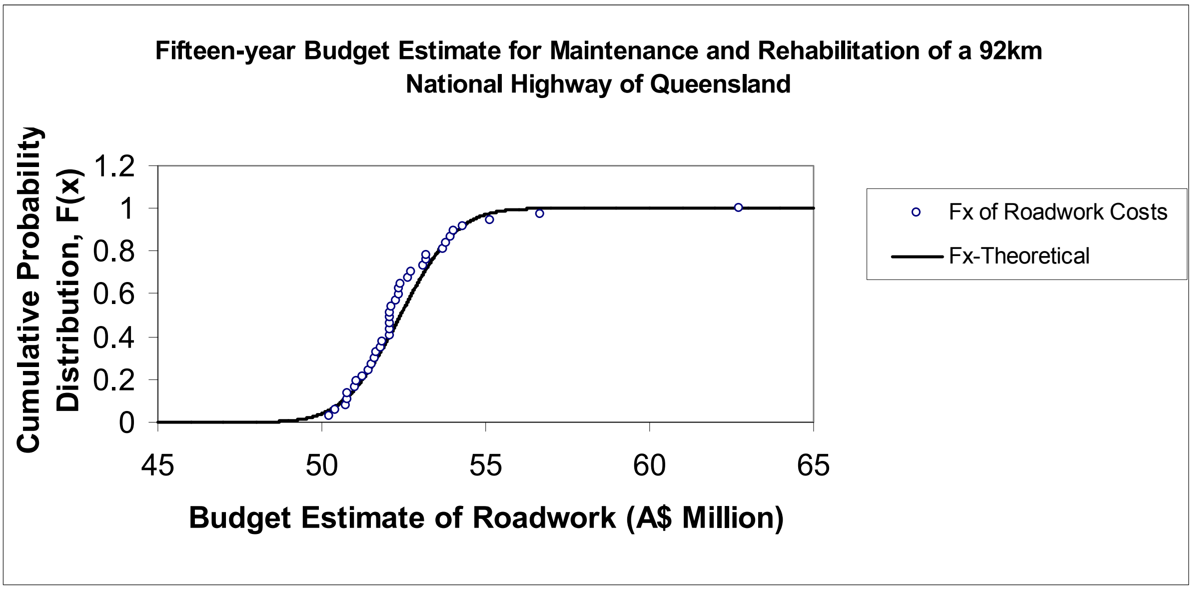

Figure 11 Cumulative distribution of budget estimate for 15-year roadwork cost of a 92-kilometre National highway of Queensland (roadwork includes maintenance and rehabilitation).

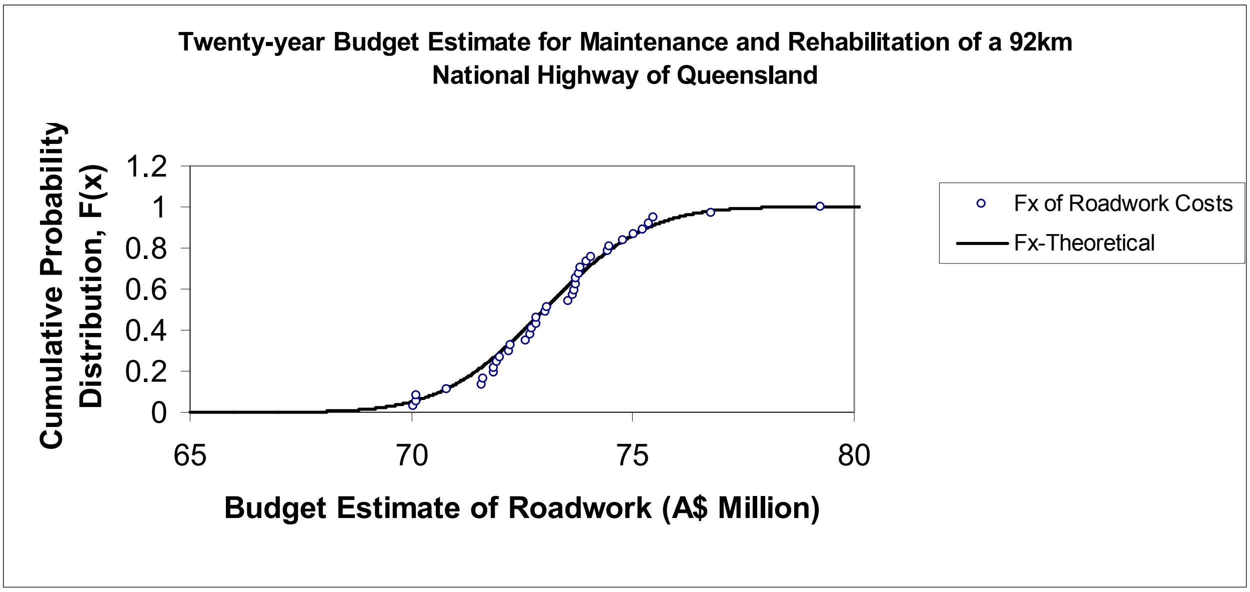

Figure 12 Cumulative distribution of budget estimate for 20-year roadwork cost of a 92-kilometre National highway of Queensland (roadwork includes maintenance and rehabilitation).

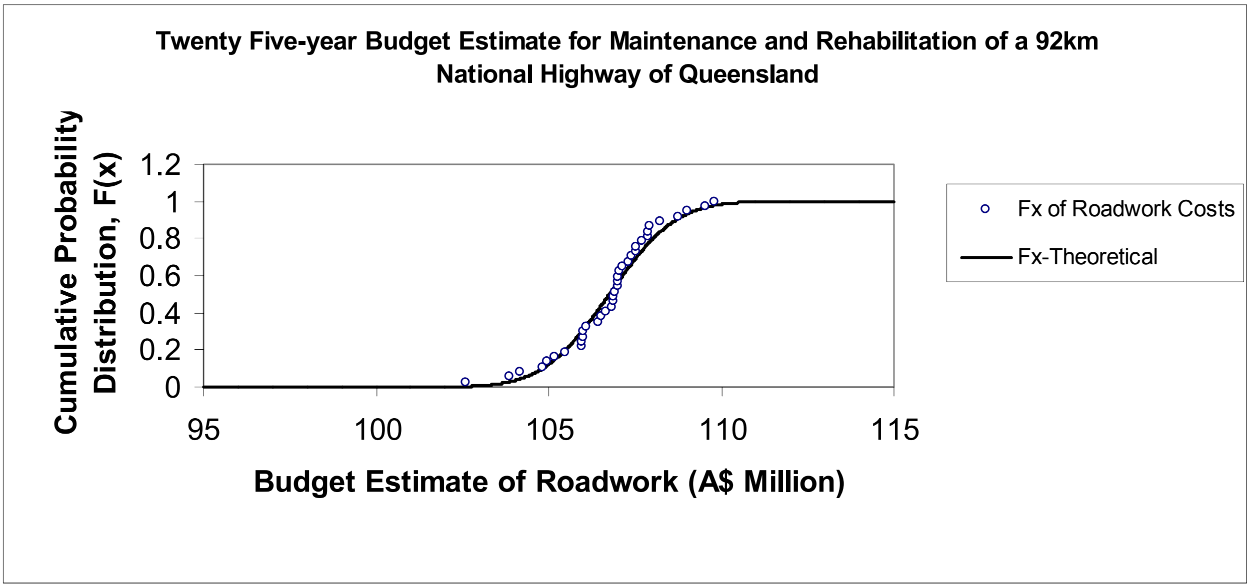

Figure 13 Cumulative distribution of budget estimate for 25-year roadwork cost of a 92-kilometre National highway of Queensland (roadwork includes maintenance and rehabilitation).

ANALYSIS OF THE RESULTS

The 95th percentile can be obtained from the probability distributions of 5-, 10-, 15-, 20- and 25-year budget estimates. The 95th percentile budget estimates are obtained from the probability by selecting the budget estimates having the 95% probability of occurrence. The 95th percentile budget estimates are graphically shown in Figure 14.

An additional HDM-4 analysis was undertaken to calculate the budget estimates for 5-, 10, 15, 20- and 25-year periods using the optimal pavement deflection data of 1000-metre intervals. Every data point of the optimal 1000-meter interval data set obtained from the original optimisation analysis (Piyatrapoomi et. al 2003) was assigned to each of the 92 road sections. Figure 15 shows the budget estimates calculated from the optimal pavement deflection data of 1000-metre intervals for 5-, 10-, 15-, 20- and 25-year periods.

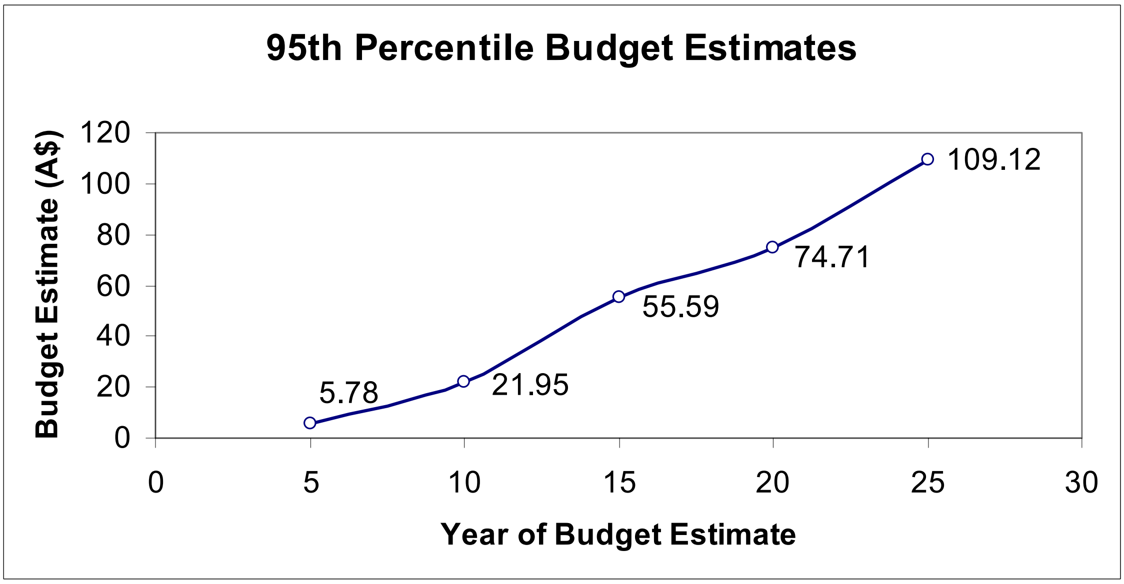

Figure 14 The 95th percentile maintenance and rehabilitation budget estimates for 5-, 10-, 15-, 20-, 25-year periods for a 92-kilometre National highway of Queensland.

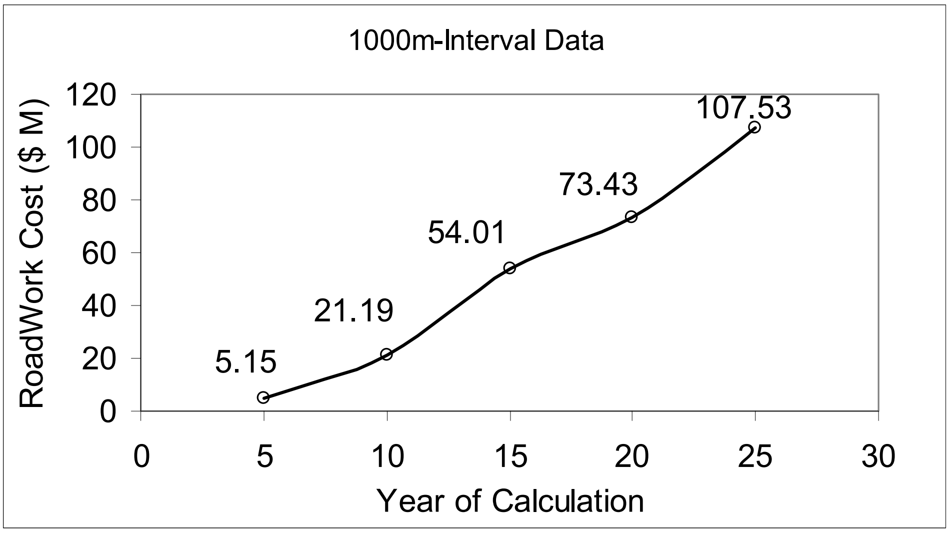

Figure 15 Budget estimates calculated from the optimal pavement deflection data of 1000-metre intervals for 5-, 10-, 15-, 20- and 25-year periods.

Figure 16 shows the differences in percentage between the budget estimates at the 95th percentile and the budget estimates calculated from the optimal pavement deflection data of 1000-metre intervals. The differences between the 95th percentile budget estimates and the budget estimates calculated from the optimal data of 1000-metre intervals are calculated to be 12.23, 3.58, 2.85, 1.74 and 1.47, per cent for 5- and 10-, 15-, 20- and 25-year periods, respectively.

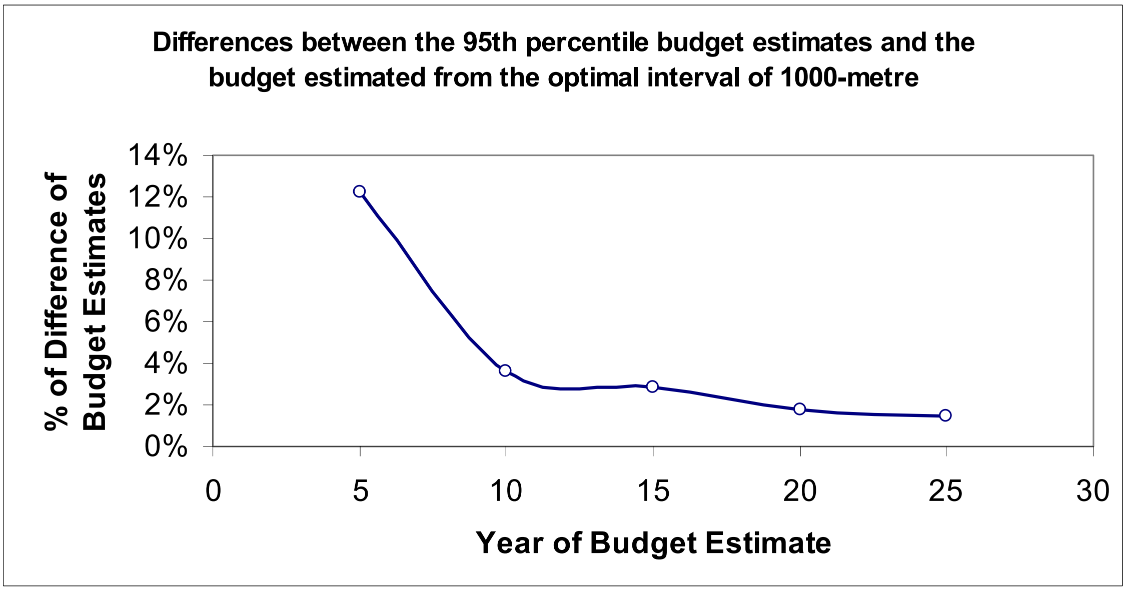

Figure 16 Percentage differences between mean budget estimates and the 95th percentile budget estimates for 5-, 10-, 15-, 20- and 25-year periods

CONCLUSION

The reliability assessment presented in this paper indicated that pavement deflection data can be collected at 1000-metre intervals for wet and non reactive soil in the Northern tropical region of Queensland in Australia. The result showed that the differences between budget estimates calculated from the pavement deflection data of 1000-metre intervals are 12.25 per cent and are less than 4 per cent when compared with the 95th percentile budget estimates for 5-, 10-, 15-, 25- and 25-year periods, respectively. The results in this reliability assessment provide considerable confidence for highway investment decision and can open the door for affordable pavement deflection data at the network level. Considerable savings or more pavement deflection data covering greater areas can be obtained. As the result of this study a decision making on the pavement strength data collection at larger intervals can be made with greater confidence.

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APPENDIX A: PROBABILITY DISTRIBUTIONS OF THE STRUCTURAL NUMBERS FOR EACH KILOMETRE OF 92-KILOMETRE NATIONAL HIGHWAY LOCATED IN WET AND NON-REACTIVE SOIL

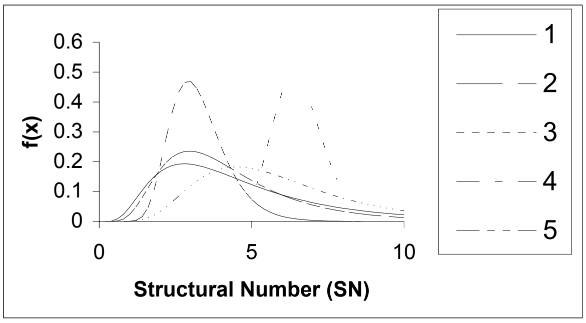


Figure A1 Probability distribution of Structural Number for kilometres of 1 to 5

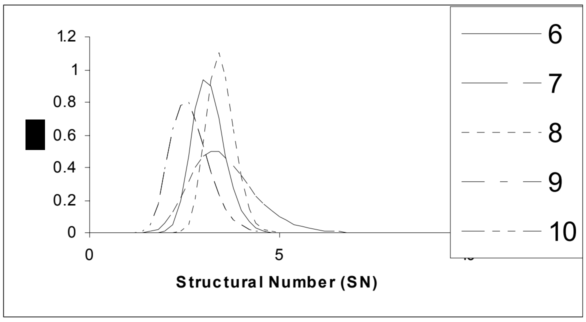


Figure A2 Probability distribution of Structural Number for kilometres of 6-10

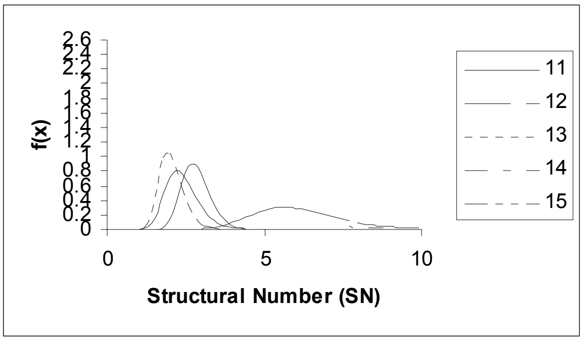


Figure A3 Probability distribution of Structural Number for kilometres of 11 to 15

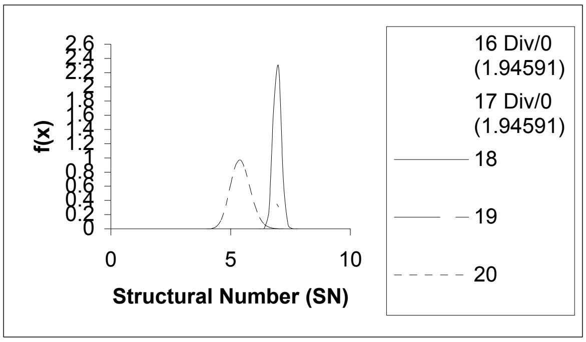


Figure A4 Probability distribution of Structural Number for kilometres of 16-20

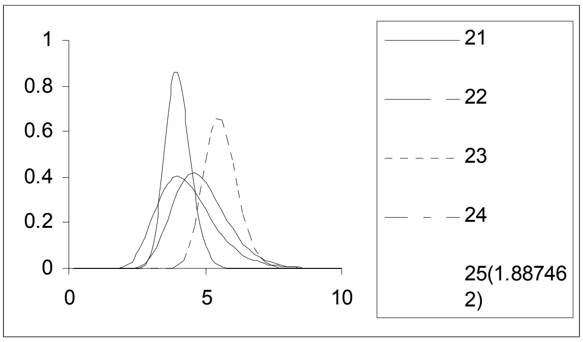


Figure A5 Probability distribution of Structural Number for kilometres of 21 to 25

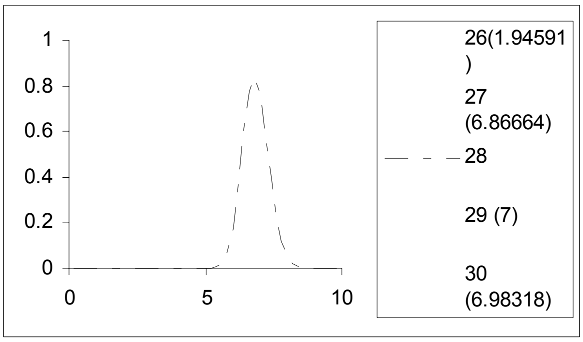


Figure A6 Probability distribution of Structural Number for kilometres of 26-30

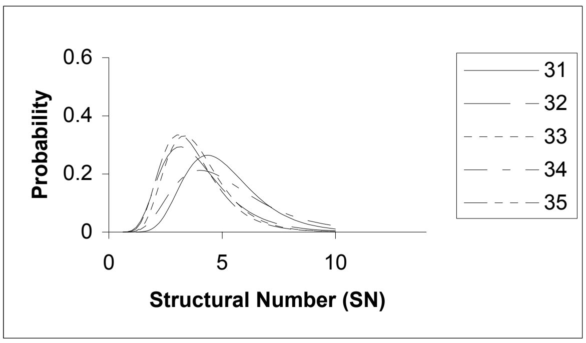


Figure A7 Probability distribution of Structural Number for kilometres of 31 to 35

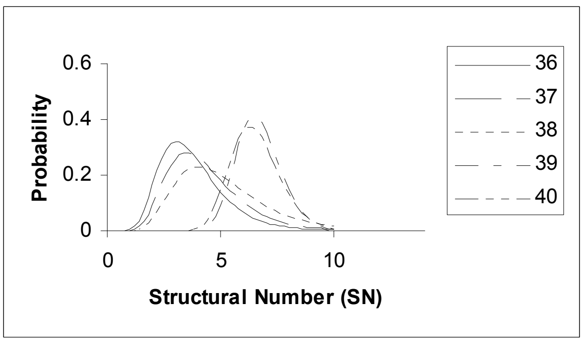
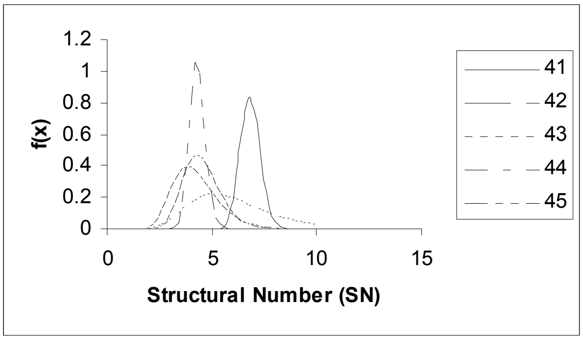


Figure A8 Probability distribution of Structural Number for kilometres of 36-40



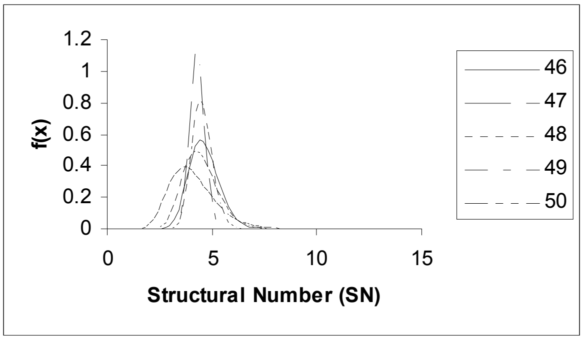
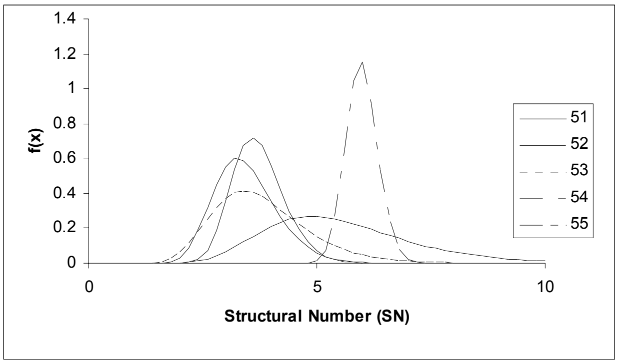


Figure A9 Probability distribution of Structural Number for kilometres of 41 to 45

Figure A10 Probability distribution of Structural Number for kilometres of 46-50



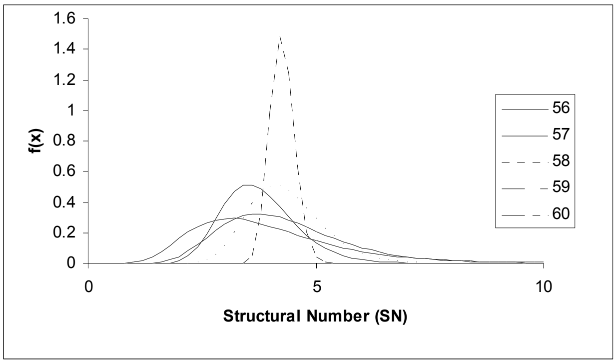
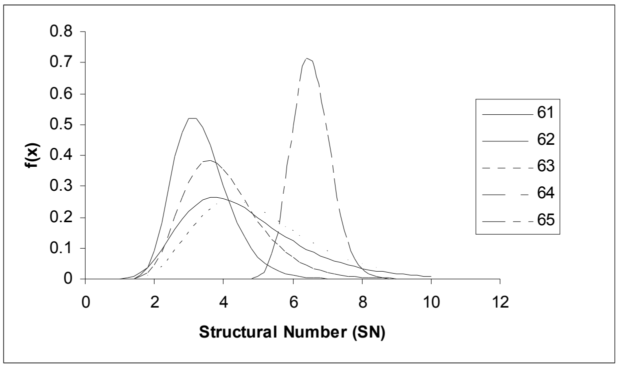


Figure A10 Probability distribution of Structural Number for kilometres of 51 to 55

Figure A11 Probability distribution of Structural Number for kilometres of 56-70



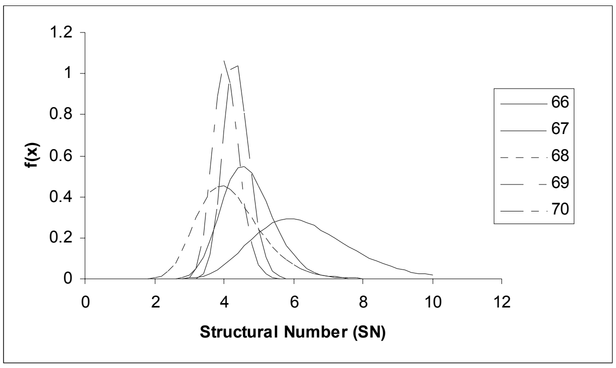
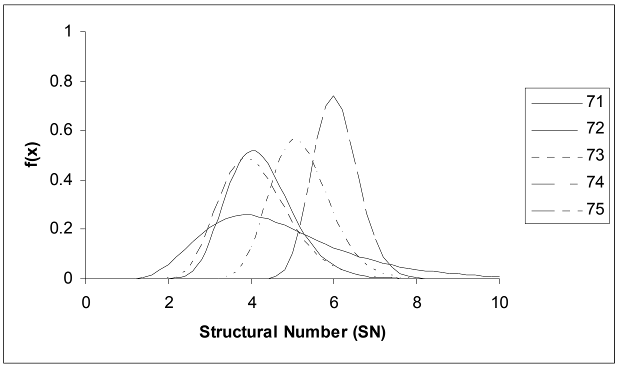


Figure A11 Probability distribution of Structural Number for kilometres of 61 to 65

Figure A12 Probability distribution of Structural Number for kilometres of 66-70



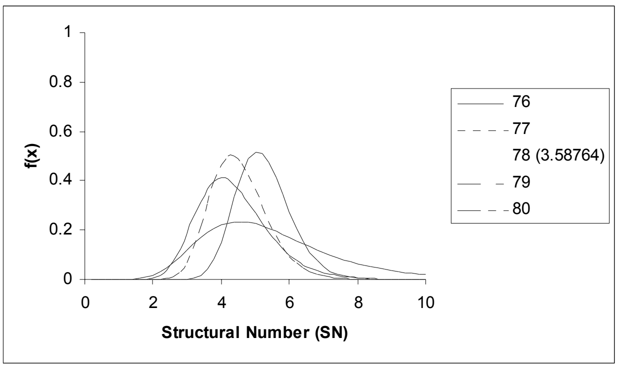


Figure A12 Probability distribution of Structural Number for kilometres of 71 to 75

Figure A13 Probability distribution of Structural Number for kilometres of 76-80

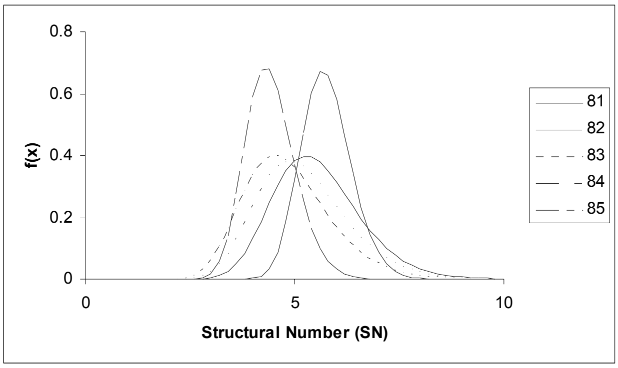


Figure A13 Probability distribution of Structural Number for kilometres of 81 to 85

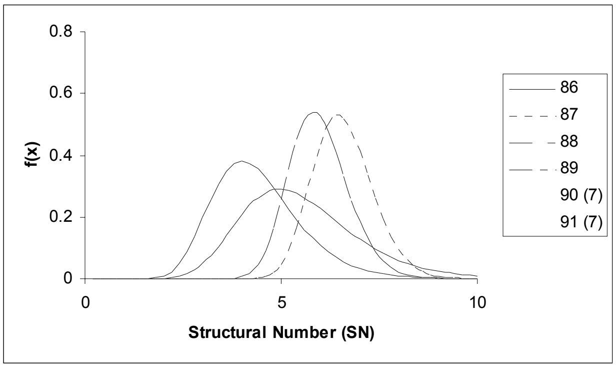


Figure A14 Probability distribution of Structural Number for kilometres of 86-91