A Probability-Based Analysis for Identifying Pavement Deflection Test Intervals for Road Data Collection

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ABSTRACT

This paper presents a probability-based method of goodness-of-fit test to determine spacing intervals for pavement deflection tests at the network level. One of the issues in road asset management is the high cost of collecting pavement deflection data at the network level. In a pilot study, Falling Weight Deflectometer Deflection tests were conducted on a 92-kilometer road length of a national highway in Queensland, Australia. The majority of the tests were performed at 200-meter spacing for both inner and outer wheel paths.

A probability-based analysis using goodness-of-fit technique showed that the mean, standard deviation and probability distribution of deflection data collected at 1000-meter intervals were similar in value to the mean, standard deviation and probability distribution for data collected at 200-meter intervals. The findings indicated that pavement deflection data could be collected at 1000-meter intervals rather than at 200-meter intervals. This could result in a substantial decrease in the cost of data collection of road pavement deflection data while still achieving similar pavement performance prediction outcomes.

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. There is currently no specified policy on the collection of pavement deflection data at the network level in the Department of Main Roads, Queensland. The Pavement Condition Data Collection Policy (2001/2002) states that the minimum survey requirements for collection of pavement strength data are project specific *(1)*. A recent study on the identification of pavement deflection test intervals for the network level was presented by Hossain et. al. in 2000 *(2)*. The principle of statistical confidence levels was used to determine how many tests were necessary to ensure that the estimate mean was within a certain limit of the actual mean. Student's t-tests were employed in their study. They reported that three tests per mile would be the minimum test interval required at the network level.

In our study, goodness-of-fit tests were used in the analysis to determine test intervals for pavement deflection data collection. The goodness-of-fit method for best fit distribution has been widely used to explain the probabilistic characteristics of a random phenomenon *(3-10)*. The goodness-of-fit tests were used in this study to establish the probability distribution, mean and standard deviation of the pavement deflection data. 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.

The first objective of the present study was to use the goodness-of-fit method to assess and identify a theoretical probability distribution that best fits the pavement deflection sample data of a 92-kilometer road length of a national highway in Queensland, Australia. The second objective was to determine an optimal interval for pavement deflection data collection. The second objective was achieved by eliminating some of the data in the original data set to create different data sets with larger spacing intervals. The goodness-of-fit method was then used to test the goodness of fit of the new sets of data and to test whether the data were well fitted with the same probability distribution and had similar means and standard deviations to those obtained from the original data set. The validity of the results obtained from the goodness-of-fit analysis was tested by comparing roadwork costs computed from the original pavement deflection data set and the reduced data set. The development of pavement management systems, such as Highway Development and Management Systems (HDM-4) *(11, 12)*, allows pavement management assessment to be conducted at the network level. In this study, roadwork costs, which include the costs of maintenance and rehabilitation, were assessed at the strategy level using HDM-4 software package. The additional future benefit arising from this study is that the probability distribution of the pavement deflection data can be used for risk and reliability assessment in investment decision-making.

GOODNESS-OF-FIT TEST METHODS

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 subjective judgment in selecting intervals for plotting the number of occurrence for each sampling value. The degree of goodness-of-fit depends on this subjective 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 subjective judgment required in the procedure is a shortcoming of the Chi-squared method for analyzing 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 *(10)*.

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 *(3, 6, 10)*. 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

$$Dn = \max \left| F(x) - S(x) \right| \qquad (1)$$

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

$$P(Dn \le Ds) = 1 - a \qquad (2)$$

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 *(3, 10)*.

FALLING WEIGHT DEFLECTOMETER PAVEMENT DEFLECTION TESTS

Pavement strength and flexibility 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 *(1, 13, 14,15)*. The condition of pavement strength is important to highway engineers for pavement management activities. The Falling Weight Deflectometer (FWD) is used as one of the primary tools around the world for rapid in situ pavement structural characterization. The FWD consists of a drop weight mounted on vertical shaft and housed in a trailer that can be towed by most conventional vehicles. 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. Figure 1 shows a typical Falling Weight Deflectometer test and a typical deflection bowl. With a known load, deflections and pavement layer thickness, layer moduli can be computed using mathematical or empirical models.

Falling Weight Deflectometer was used in the pavement deflection tests for this pilot project. The FWD testing was conducted in May 2002 on a 92-kilometer 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 categorized 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 (chip seal) surface. The applied load was 50 kN. The deflections were measured in microns.

PROBABILITY-BASED ANALYSIS OF PAVEMENT DEFLECTION DATA BY GOODNESS-OF-FIT TECHNIQUE

The steps for analyzing pavement deflection data using goodness-of-fit technique are given below:

1. The probability distributions of pavement deflection data of the inner and outer wheel paths were assessed and expressed in discrete cumulative distributions.
2. The discrete cumulative distributions of pavement deflection data of the inner and outer wheel paths were compared with different theoretical probability distribution functions. The best fit probability distribution was selected. The degree of goodness-of-fit was tested by the Kolmogorov-Smirnov (K-S) method.
3. The assessment of optimization of pavement deflection data collection intervals was conducted by eliminating the original data set to create different data sets with intervals of 400, 600, 800, 1000 and 1200 meters.
4. The reduced data sets mentioned in step 3 were assessed and described by their discrete cumulative distributions and compared with the specified theoretical cumulative distribution function given by step 2.
5. The mean and standard deviation of each data set in step 3 were calculated.
6. The theoretical probability distribution, mean and standard deviation of each data set in step 3 were compared with the probability distribution, mean and standard deviation obtained from the original data set.
7. The process of eliminating the data was stopped when the reduced data set could no longer be fitted by the specified probability distribution function.

There were, in total, 920 data points used in this study. Figure 2 shows the discrete cumulative distributions of the outer and inner wheel paths of the pavement deflection sample data. A trial and error process was carried out to select a theoretical probability distribution that best fits the discrete cumulative distribution of the pavement deflection sample data. This was achieved by comparing the cumulative distributions of a number of possible theoretical probability distribution functions with the discrete cumulative distribution of the pavement deflection sample data. By observation, the deflection data of both wheel paths were best fitted by a log normal distribution. The next step is to test the goodness of fit of the assumed probability distribution and the probability distribution of the sample data. As mentioned previously, the basic aim of Kolmogorov-Smirnov's (K-S) goodness-of-fit test is to determine the maximum discrepancy between the cumulative distribution of the sample data set, $S(x)$, and the theoretical cumulative distribution, $F(x)$, i.e. $Dn = |F(x) - S(x)|$. The calculated maximum discrepancy value of Dn is then compared with the established critical values (Ds) at an appropriate level of significance. The maximum discrepancies between the cumulative distribution of the sample data, $S(x)$, and the theoretical cumulative distribution, $F(x)$, for the outer and inner wheel paths, were observed to be $Dn = 0.053$ and 0.059, respectively. In this study, a level of significance of 5% was adopted. For data points greater than 50, the critical value at a 5% level of significance is given by $1.36/\sqrt{n}$ *(3,10)*. For a sample size (n) of 460 of each wheel path, the critical value was $Ds = 0.063$. Since the calculated maximum discrepancy values (Dn) were less than the critical value (Ds), Kalmogorov-Smirnov's (K-S) goodness-of-fit test indicated that a log normal distribution was a good fit at a significance level of $\alpha = 5\%$, or $P(Dn \le Ds) = 1-\alpha = 95\%$. In other words, the goodness of fit was 95% for the sample data of both inner and outer wheel paths. The pavement deflection sample data of both wheel paths showed similar means, standard deviations and probability distribution. The data were plotted on a natural logarithm scale. The means and standard deviations for outer and inner wheel paths are given below.

$Ln(Do) = N(6.05, 0.805)$ for outer wheel path

$Ln(Do) = N(5.95, 0.817)$ for inner wheel path.

Do is denoted as the maximum displacement under the load cell. $Ln(Do)$ is the natural logarithm of Do.

$N(Mean, SD)$ is mean and standard deviation of normal distribution.

As mentioned earlier, the objective of this study was to identify optimized intervals for pavement deflection data collection. Optimization analysis was carried out by eliminating data from the original data set to create a new data set, which was in turn, tested to see whether the data set 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. Since the statistical means, standard deviations and the probability distributions of the original pavement deflection data sets for outer and inner wheel paths were similar in values, the pavement deflection sample data of the outer wheel path were used for the optimization analysis.

It was possible to eliminate data from the original data set to create new data sets with intervals of 400, 600, 800, 1000 meters that had minimum discrepancies in the means and standard deviation values when compared with those of the original data set. Figures 3 to 6 show the discrete cumulative distributions and the cumulative distributions of log normal distributions for the data sets of 400-, 600-, 800- and 1000-meter intervals. Table 1 shows a summary of the statistics obtained from the goodness-of-fit analysis. The results in the table indicated that the discrepancies (or errors) in the mean and standard deviation calculated from the original set of pavement deflection sample data and those obtained from the 400-meter interval data set were 1.77 per cent and 0.625 per cent, respectively. For the data set of 600-meter intervals, the discrepancies of the mean and standard deviation when compared with those of the original data set were 2.33 per cent and 0.88 per cent, respectively. The discrepancies for the data set of 800-meter intervals were 1.77 per cent and 0.62 per cent, respectively. Finally, for the 1000-meter interval data set, the discrepancies in the mean and standard deviation compared with the original data set were 2.32 per cent and 1.25 per cent, respectively.

As shown in Table 1, Kalmogorov-Smirnov's (K-S) goodness-of-fit test indicated that the maximum discrepancy values (Dn) were less than the critical values (Ds) at a 5% level of significance for the 400-, 600-, 800- and 1000-meter interval data sets. A log normal distribution was a good fit for these sets of data at a 5% level of significance.

When the original data set was eliminated to create a data set of 1200-meter intervals, it can be observed from Figure 7 that the data set of 1200-meter intervals was not well fitted by a log normal distribution. Even though the discrepancy in the mean value was 2.09 percent, which was similar in value with the means from the original data set and those from the other data sets, the discrepancy of the standard deviation was 10.88 per cent. A discrepancy of this magnitude in the standard deviation may not provide confidence for the outcome of prediction. At this point, the analysis was stopped since it was evident that a data set with an interval greater than 1000 meter would not provide consistent mean, standard deviation and probability distribution with those obtained from the original data set.

Figure 8 shows a comparison between the data sets collected at 200-meter intervals and at 1000-meter intervals. The results from this study were then tested for validity by calculating roadwork costs using Highway

Development and Management Systems (HDM4) software package. In this test of validity, roadwork cost using pavement deflection data from the original data set of 200-meter intervals was compared with roadwork cost using pavement deflection data of 1000-meter intervals.

TEST OF VALIDITY OF GOODNESS-OF-FIT ANALYSIS

The results from the preceding section suggested that pavement deflection data could be collected at 1000-meter intervals rather than at 200-meter intervals. In this section, a test of validity using roadwork costs is presented. The roadwork costs include the costs of maintenance and rehabilitation. In the present study, Highway Development and Management (HDM-4) System software package was employed in the analysis. HDM-4, developed by the International Study of Highway Development and Management (ISOHDM), is a globally accepted pavement management system. 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 in assessing the validity of the results presented in the preceding section. Roadwork costs were calculated for comparison using the original pavement deflection data set collected at 200-meter intervals and at 1000-meter intervals.

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 (*13, 14, 15, 16*). Figure 9 shows the cumulative distributions of Structural Number converted from pavement deflection data by different functions. The Functions recommended by Rolt, Salt and Jameson *(1, 13, 15)* provided similar cumulative distributions of Structural Number. 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 (*15*). Salt's formula is given below. Figure 10 shows the cumulative distribution of Structural Number converted by using Salt's formula.

$$SN = 112(Do)^{-0.5} + 47(Do - D900)^{-0.5} - 56(Do - D1500)^{-0.5} - 0.4 \qquad (3)$$

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

For the analysis, the 92-kilometer road segment is divided into 92 sections of 1000-meter in length for each section. Each 1000-meter section has its own pavement strength characteristic. Two sets of Structural Number were prepared as input data for HDM-4 analyses. In the first set, every data point of the 1000-meter interval data set was assigned to each of the 92 road sections. In the second set, the original data were used. The mean values of pavement deflection data collected at 200-meter intervals were calculated for each 1000-meter length and the mean value was assigned to each of the 92 road sectors. A period of 25 years of roadwork was used in this analysis 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.

Figure 11 shows a comparison of roadwork costs between the 200-meter interval data set and the 1000-meter interval data set. The total roadwork cost calculated from the 200-meter interval data set was US$69.8 million and US$69.9 million for the 1000-meter interval data set. The roadwork cost calculated from the 1000-meter interval data set was approximately 0.22 per cent greater than the total roadwork cost calculated from the original 200-meter interval data set. Figure 12 shows an estimate of cost in pavement deflection data collection for the state controlled road of Queensland, if pavement deflection data were collected at 1000-meter intervals rather than at 200-meter intervals.

CONCLUSIONS

1. An analysis method for determining the minimum data collection interval for pavement deflection testing is presented in this paper.
2. The means and standard deviations of the pavement deflection sample data sets collected at 200-meter intervals and at 1000-meter intervals were similar in values. This indicated that pavement deflection data could be collected at every 1000-meter interval to achieve similar pavement strength prediction outcomes.
3. In this study, a test of validity of the results indicated a 0.22 per cent difference in roadwork costs when the 200-meter interval and 1000-meter interval pavement deflection data were used in the analysis for comparison.
4. The results from the study indicated that road uniformity can result in greater intervals for data collection while yielding similar performance prediction.

5. It should be noted that these results were calculated for a particular pavement type and therefore, analysis need to be conducted for different pavement and subgrade types.
6. The probability distribution and statistical information developed in this study can be used for the assessment of risk and reliability for investment decision-making.

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TABLE 1 Summary Statistics for Goodness-of-Fit Test Analysis

Interval meters	*n*	*Ln(Do) =N(Mean, SD)*	*% Error Mean*	*% Error SD*	*Dn*	*Ds*	a	*P(Dn=Ds)*
200*(o)*	460	Ln(Do)=N(6.05, 0.805)	*	*	0.053	0.063	5%	95%
200*(i)*	460	Ln(Do)=N(5.95, 0.817)	*	*	0.059	0.063	5%	95%
400	230	Ln(Do)=N(5.945,0.800)	1.77	0.625	0.0603	0.089	5%	95%
600	154	Ln(Do)=N(5.912,0.798)	2.33	0.88	0.0907	0.109	5%	95%
800	115	Ln(Do)=N(5.945, 0.810)	1.77	0.62	0.0608	0.127	5%	95%
1000	92	Ln(Do)=N(5.913, 0.795)	2.32	1.25	0.0508	0.141	5%	95%
1200	77	Ln(Do)=N(5.926, 0.726)	2.09	10.88	0.156	0.154	5%	95%

** = original data sets*
n = number of pavement deflection data
(o) = outer wheel path
(i) = inner wheel path
a = level of significance
Dn = maximum discrepancy between cumulative distribution of sample data and cumulative distribution of a theoretical probability distribution
Ds = tabulated K-S critical values, for a level significance of 5% and when n >50, Ds= 1.36/vn
Do = the maximum displacement under the load cell.
P(Dn = Ds) = Probability that Dn will be equal or less than Ds, P(Dn=Ds)=1- a
Ln(Do) = the natural logarithm of Do
N(Mean, SD) = Mean and standard deviation of normal distribution

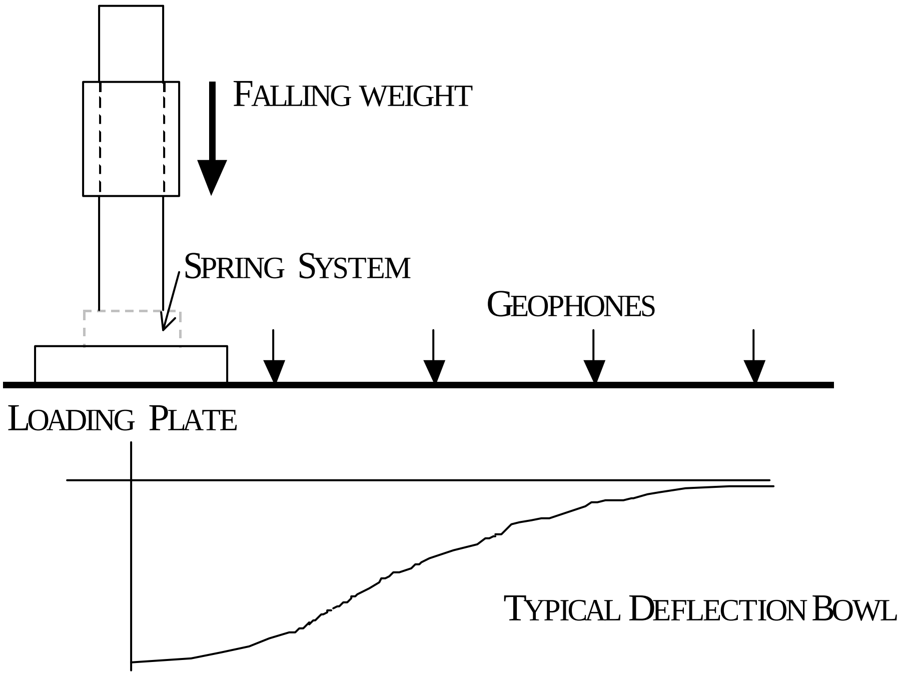

FIGURE 1 The Falling Weight Deflectometer (FWD) pavement deflection test and a typical deflection bowl.

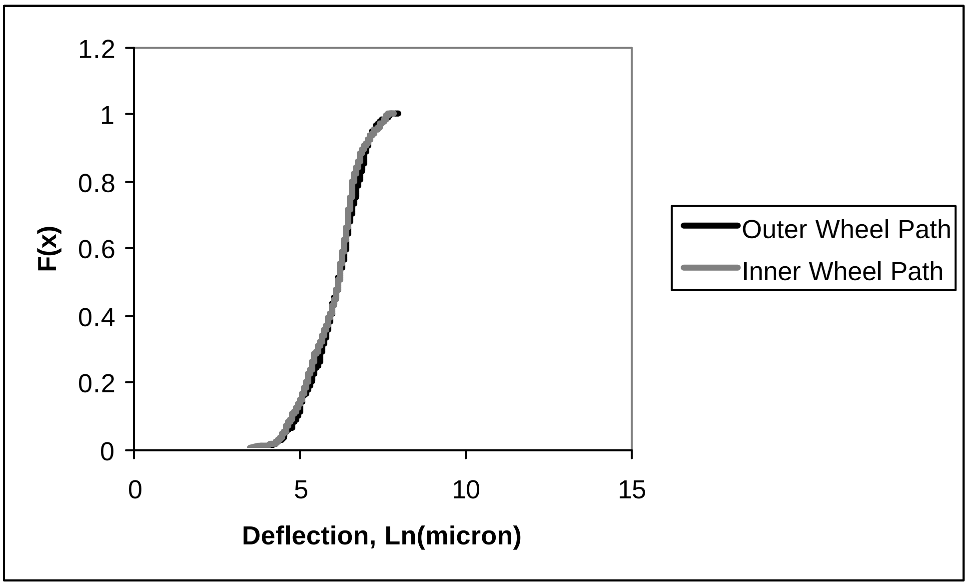

FIGURE 2 Cumulative distribution of pavement deflection sample data for outer wheel path and inner wheel path.

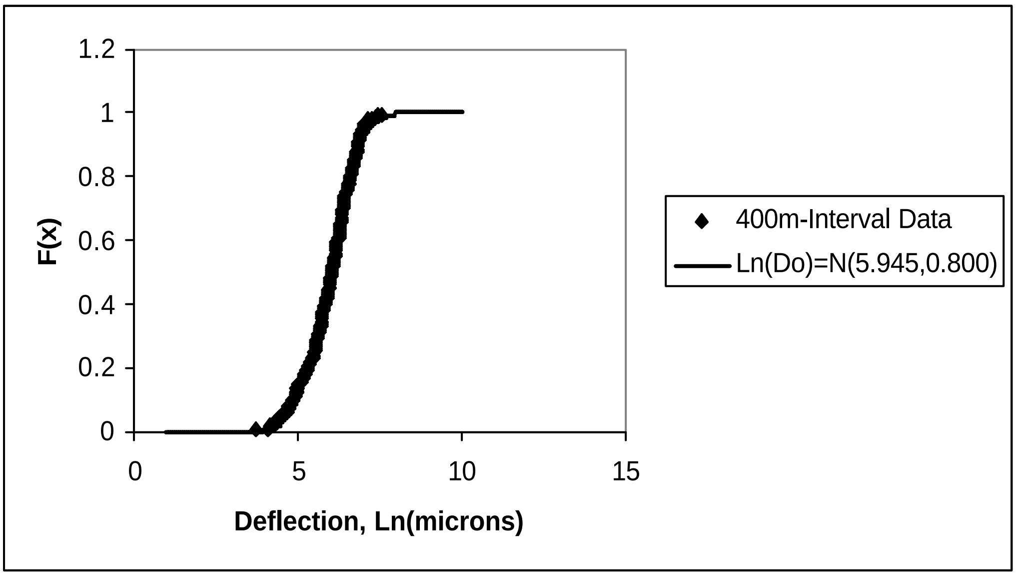

FIGURE 3 Cumulative distribution of deflection data set for 400-meter interval.

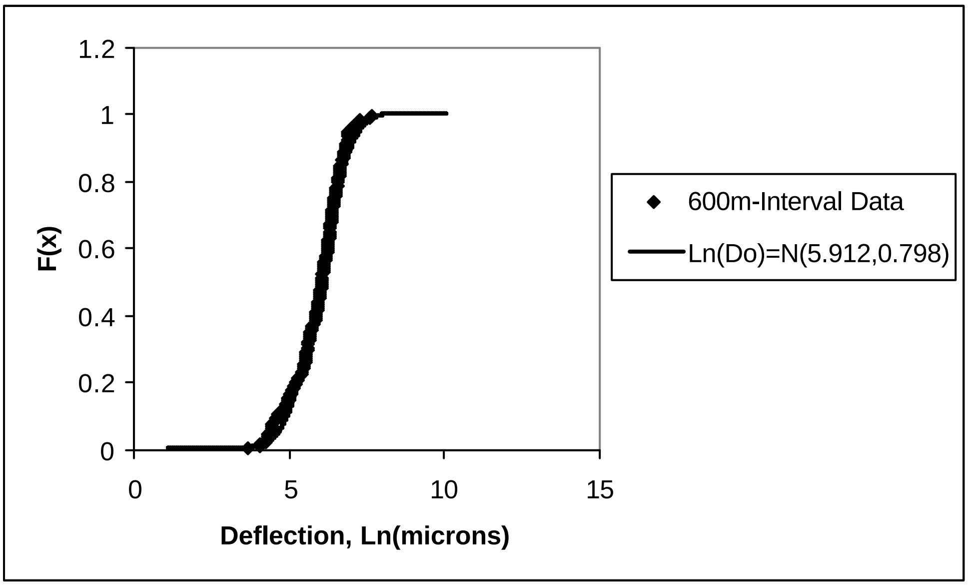

FIGURE 4 Cumulative distribution of deflection data set for 600-meter interval.

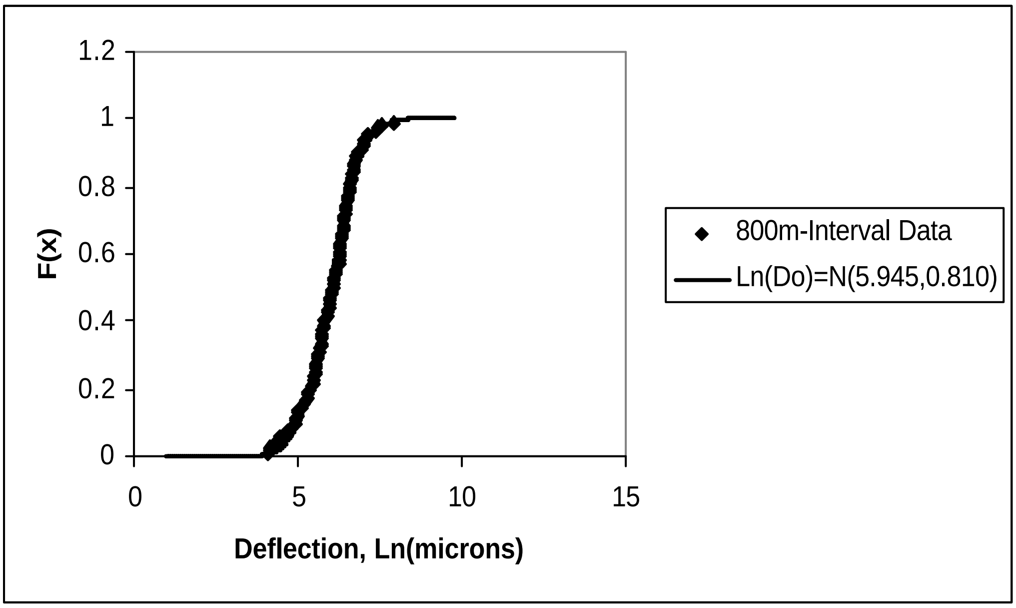

FIGURE 5 Cumulative distribution of deflection data set for 800-meter interval.

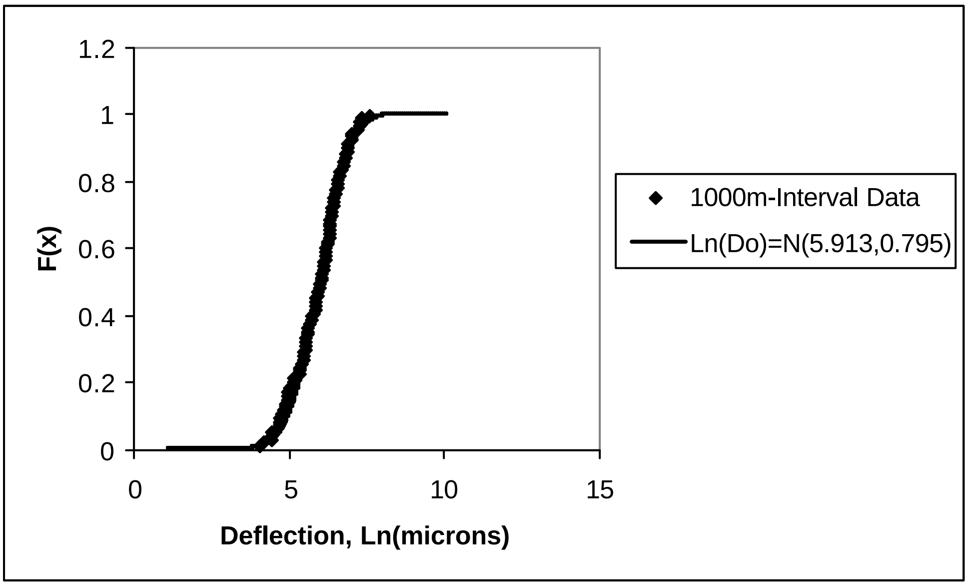

FIGURE 6 Cumulative distribution of deflection data set for 1000-meter interval.

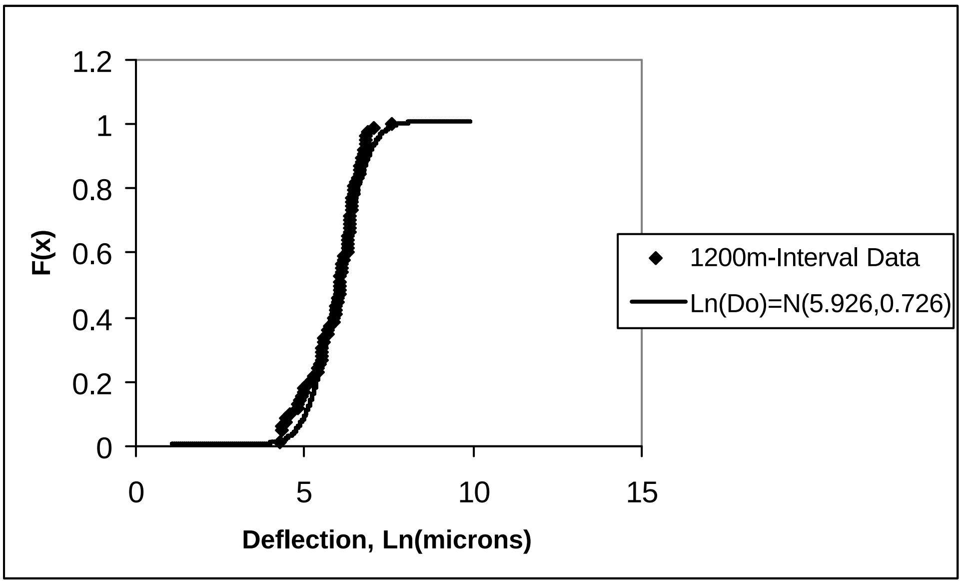

FIGURE 7 Cumulative distribution of deflection data set for 1200-meter interval.

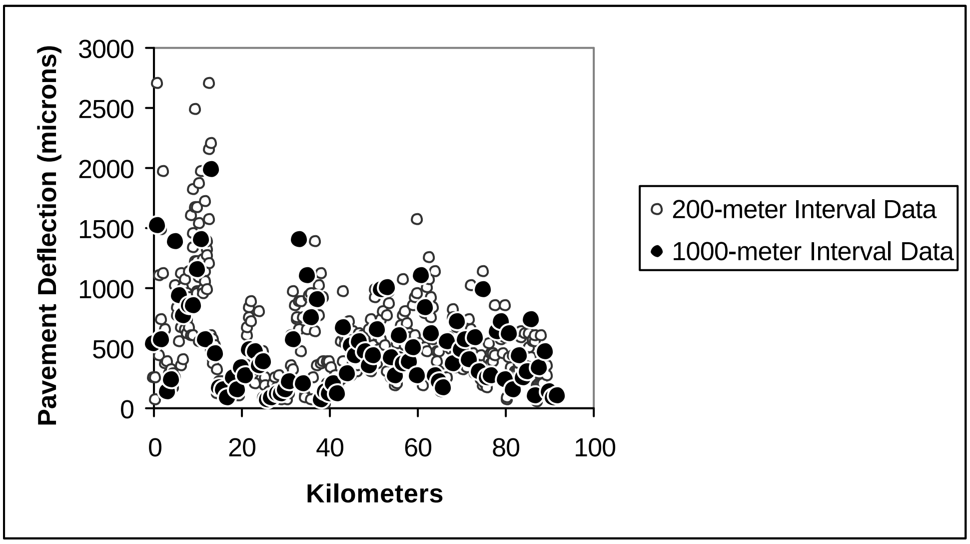

FIGURE 8 Comparison of 200-meter interval data and 1000-meter interval data.

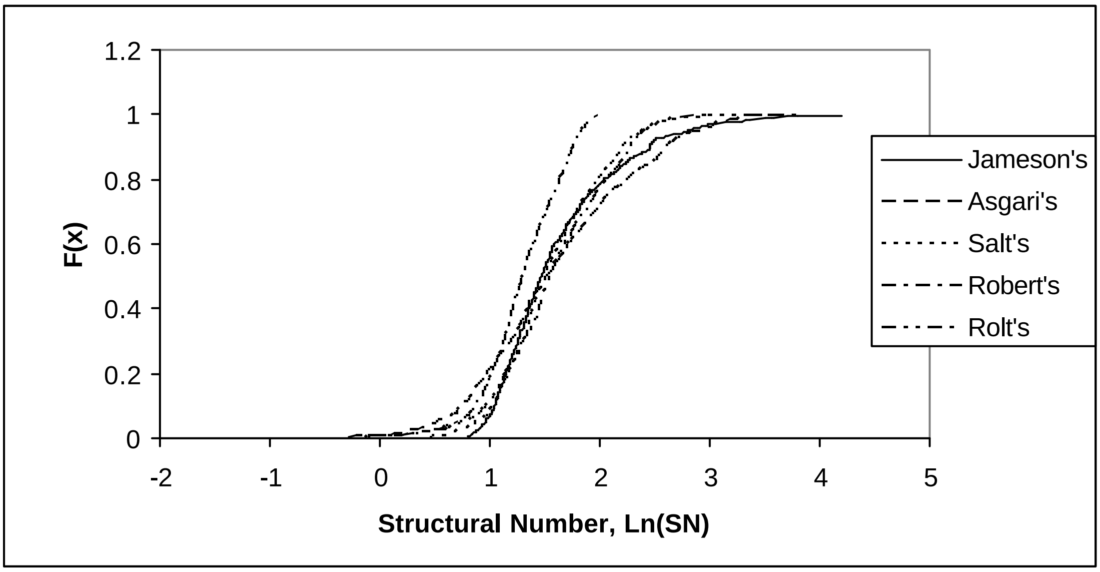

FIGURE 9 Cumulative distributions of Structural Number (SN) converted from pavement deflection data.

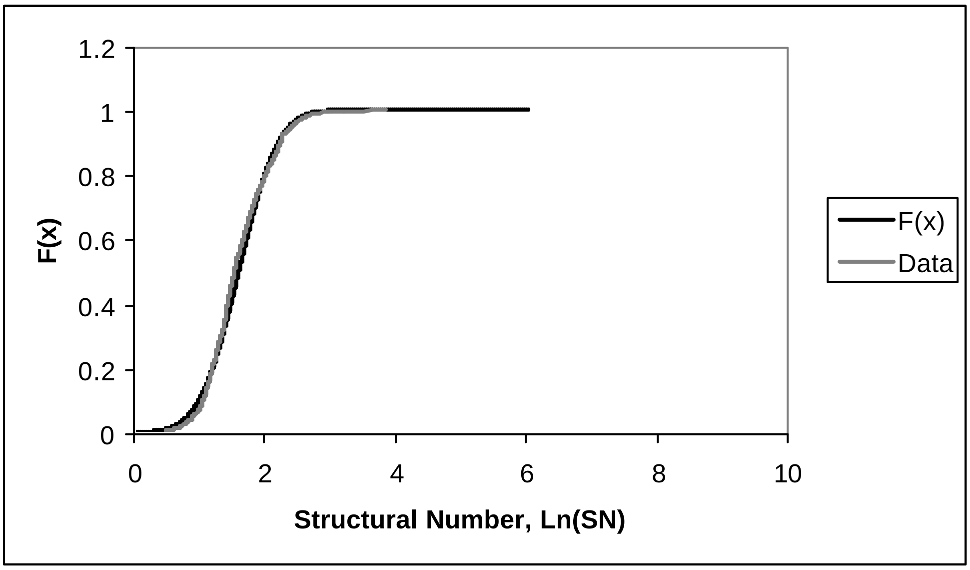

FIGURE 10 Cumulative distribution of Structural Number (SN) converted by Salt's formula. F(x) is the cumulative distribution of a log normal distribution.

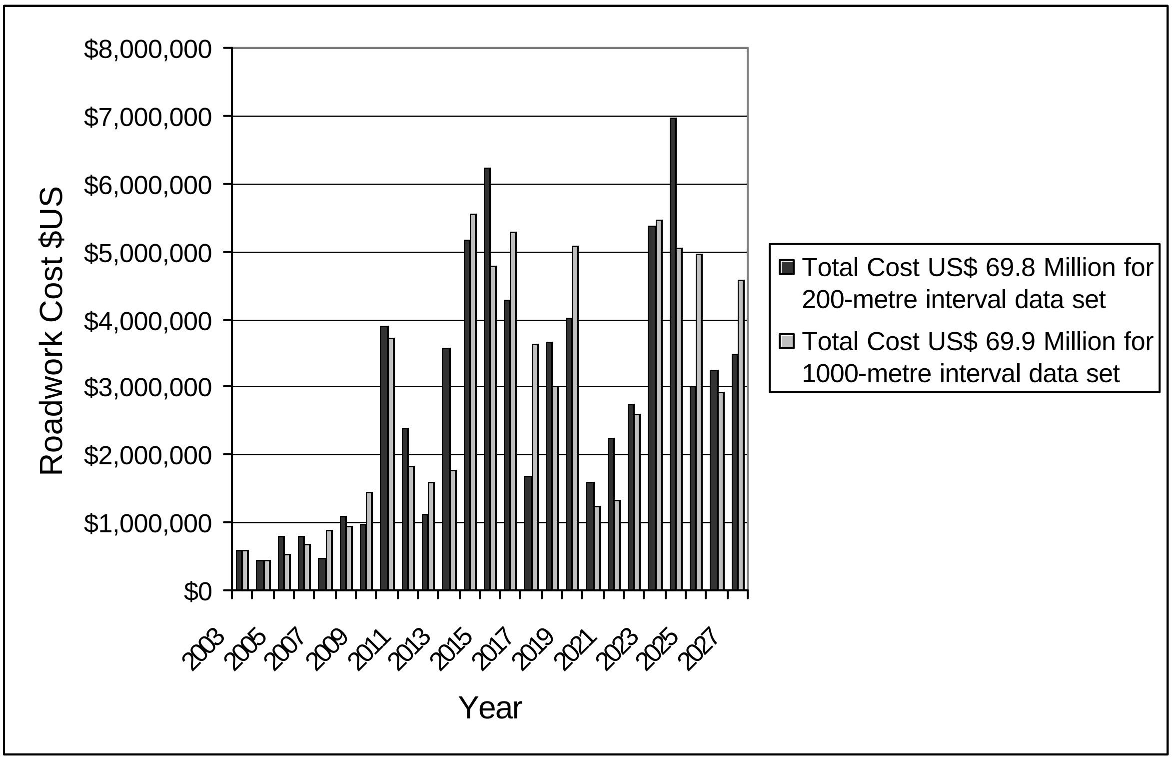

FIGURE 11 Comparison of roadwork costs between the roadwork cost calculated from the 200-meter interval pavement deflection data set and the 1000-meter pavement deflection data set for 25-year period.

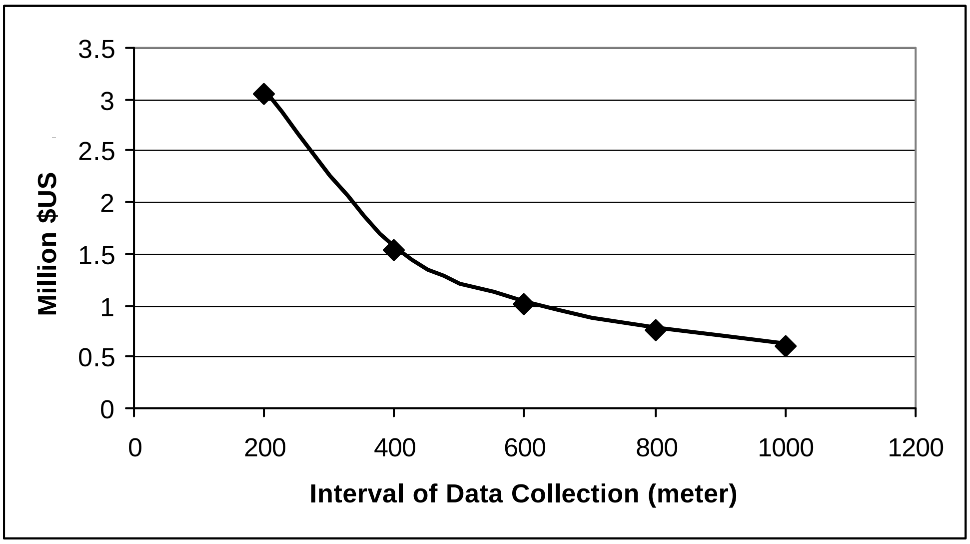

FIGURE 12 Estimated costs of pavement deflection data collection for the state controlled road of Queensland for different data collection intervals for 34000 km.