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RELIABILITY ANALYSIS OF PAVEMENT PERFORMANCE PREDICTION

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Abstrak

Prediksi kinerja perkerasan dapat difasilitasi dengan menggunakan model yang sesuai yang dikembangkan dengan menganalisa data historis atau data yang dikumpulkan dari percobaan perecepatan fasilitas perkerasan. Akan tetapi, dimungkinkan adanya kesalahan sistematis atau kesalahan acak dalam sekumpulan data dan juga mungkin data yang tidak lengkap atau tidak mewakili kondisi keseluruhan sepertinya terjadi dilapangan. Hasilnya, prediksi yang dihasilkan oleh model tidak sepenuhnya akurat dan termasuk ketidakpastiann. Oleh karena itu, idealnya perilaku pemodelan kinerja perkerasan jangka panjang harus menyertakan tahapan yang menyertakan ketidakpastiann data dan mengguantifikasikannya. Tulisan ini menyajikan suatu metodologi yaitu pertama mendefinikan reliabilitas dari prediksi kinerja perkerasan dan hubungan risiko menggunakan pendekatan probabilitas. Kemudian memperlihatkan bagaimana reliabilitas dalam prediksi kinerja perkerasan dapat diestimasi dengan mempertimbangkan variasi dalam parameter (seperti kekuatan perkerasan, kumulatif beban gandar standard dan ketidakrataan permukaan perkerasan awal) yang membentuk model kinerja. Suatu kerangka kerja disajikan yaitu menggunakan simulasi Monte Carlo untuk mengevaluasi pengaruh variasi parameter model pada kumulatif beban gandar standar yang diperbolehkan. Analisa memperlihatkan bahwa variasi data mempunyai pengaruhs yang signifikan terhadap reliabilitas prediksi kinerja perkerasan.

Kata kunci: analisa realibilitas, kinerja perkerasan, system mnajemen perkerasan.

Abstract

The prediction of road pavement performance may be facilitated by appropriate models developed by analyzing sets of historical data or data collected from accelerated pavement testing facilities. However, there may be systematic or random errors in these data sets and also the data sets may not be complete or represent the full range of conditions likely to occur in the field. As a result the predictions made by the models may not be fully accurate and include a degree of uncertainty. Therefore, ideally the behavioral modeling of long-term pavement performance should include a procedure for taking into account the uncertainty in the data and quantify it accordingly. This paper presents such a methodology that first defines the reliability of pavement performance predictions and its associated risk using a probabilistic approach. It then demonstrates how the reliability of pavement performance predictions can be estimated by considering the variability of the parameters (such as pavement strength, cumulative equivalent standard axle load and initial pavement roughness) that make up the performance model. A framework is presented that uses the Monte Carlo simulation to evaluate the effect of the model parameters variability on the allowable cumulative equivalent standard axle load applications. The analysis demonstrates that data variability has a significant influence on the reliability of pavement performance prediction.

Keywords: *pavement management system, Reliability analysis.*

1. INTRODUCTION

The prediction of pavement performance may be achieved by the development of appropriate deterministic models and the most popular method used for this is that of regression analysis [1]. However such conventional deterministic methods do not consider the variability in the model parameters which produces uncertainty in the performance predictions [2]. To address this, a probabilistic approach may be followed and the variability inherent in the performance predictions may be thus quantified. Statistics may be used to cater for the variability in three major items that affect the prediction outcomes which are the model form, the model parameters and the model coefficients. This paper focuses on the variability in the model parameters and deals with reliability using a statistical analysis method based on the assumption that a probability distribution exists in the model parameters.

The analysis of reliability analysis was first used by Lemer et al. (1971)[3] and was later developed by Moavenzadeh et al., (1977)[4] and George et al., (1982)[5]. It was used to overcome the inadequacy in the safety factors used to cater for the uncertainty of the predictions and received considerable attention as a way of predicting pavement performance. It was then incorporated in the 1993 AASHTO guide and its further developments. Common methods used to address reliability are sensitivity analysis (Fernando et al., 1988; Wang et al.,1995)[6] [7], the Monte Carlo (MC) simulation, the first-order approximation (FOA) method, also known as the mean value first-order second moment (MVFOSM), and the first order reliability method (FORM) also known as the advance first-order second moment (AFOSM) method. Further details on these techniques may be found elsewhere [8]. However their practical applications include that of Darter et al., (1972) who introduced the FOA method to a comprehensive pavement design and analysis system [9]. Kenis, et al., (1998) implemented the same method to observe the effects of uncertainty in the calculation of the present serviceability index [10] and Veeraragavan, et al., (2001) followed a similar approach for crack growth models.[11]. As an alternative to the FOA method, Barenberg, et al., (1976) have used the MC method to obtain a pattern of pavement responses from a variety of pavements types and loading conditions[12]. The MC method has been also used to determine transition probability matrices that describe progression of deterioration [13]. Easa, et al. (1996) used the FORM to predict the failure probability of low temperature and thermal fatigue cracking models [14]. Similarly, Chua, et al. (1994) used the same method to determine transition probability matrices for pavement deterioration [15].

This study used the Monte Carlo simulation whereby the variability in the model parameters is simulated in terms of statistical distributions of the data concerned and in conjunction with an appropriate prediction model the pavement performance is obtained, which also follows a particular distribution. Then a system performance function calculates the probability of pavement failure and the allowable traffic expressed in cumulative equivalent standard axle loads is determined.

2. METHOD

For the analysis of reliability reported hereinafter, a pavement performance model was developed using data from flexible pavement sections stored in an existing road management system database. The performance model predicts pavement roughness as a function of cumulative equivalent standard axle loads, pavement strength expressed by its structural number and initial pavement roughness. The performance model was as follows Equation (1).

$$IRI_p = \exp\left(0.262 + 0.062\, Ln(IRI_0) + 0.827\left(\frac{1}{SNC}\right) + 0.522\, CESA\right) \quad (1)$$

Where:

IRI_p is the predicted pavement surface roughness, IRI_0 is the initial pavement surface roughness, SNC is the pavement strength, $CESA$ is the cumulative equivalent standard axle loads. Further information on the development of this relationship may be found elsewhere [8].

To model reliability a function describing the performance of a component of interest is needed [16]. In the case of predicting pavement performance this component may be pavement roughness as an overall index of performance. However pavement performance depends on layer material properties, the environment, traffic loading, and is also associated with the specific definition of failure adopted by the highway authority concerned [17]. Failure in this sense occurs when roughness exceeds the limiting or terminal level defined. In this study a terminal pavement roughness of 8.0 m/km was selected [18].

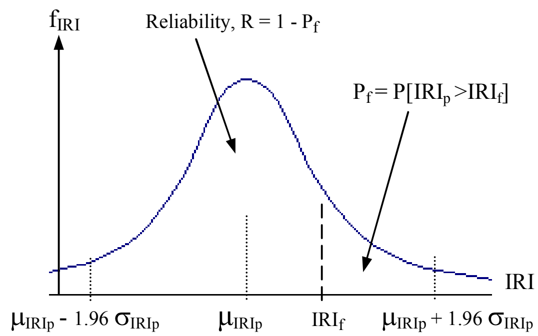

Figure 1. Normal distribution model of the pavement roughness predicted

The reliability of a pavement section, may be defined as the probability that the pavement roughness, IRI_p, predicted at any traffic level will be less than the pavement roughness at failure, IRI_f. Figure 1 illustrates a normal distribution of the predicted pavement roughness. The predicted pavement roughness is assumed to be normally distributed described by the statistical properties of a mean μ_{IRIp} and a standard deviation σ_{IRIp}.

The estimated probability of failure, P_f, associated with roughness, IRI_f, may be computed using the Monte Carlo simulation method. The success in predicting pavement failure may be estimated by the following equation:

$$Z = IRI_p - IRI_f \quad (2)$$

Theoretically, Equation (2) can always be obtained from knowledge of the joint distribution of the random model parameters of Equation 1. However, in general, the solution from Equation (2) is very complicated, due to the joint probability density functions, which are hardly known. One possible way to obtain an approximate solution is to use the MC method [19]. If this is done, Equation (2) may be estimated as follows [20]:

$$P_f = \frac{the\ number\ of\ trials\ with\ Z \geq 0}{total\ number\ of\ trials} \quad (3)$$

From which the reliability is given by:

$$R = 1.0 - P_f \quad (4)$$

The overall standard deviation of the predictions which account for the variability of all model parameters may be defined as [21]:

$$\sigma_Z = \sqrt{\left[\frac{\partial Z}{\partial IRI_0}\right]^2 \sigma_{iRI}^2 + \left[\frac{\partial Z}{\partial SNC}\right]^2 \sigma_{snc}^2 + \left[\frac{\partial Z}{\partial CESA}\right]^2 \sigma_{CESA}^2} \quad (5)$$

where, σ_Z is the overall standard deviation of the predictions, while $\sigma_{IRI}, \sigma_{SNC}$ and σ_{CESA} are the standard deviation of the random model parameters initial pavement roughness, pavement strength and cumulative equivalent standard axle load respectively.

To be successful the pavement model should consider the distribution of all its parameters. For these the following may be examined.

a) It has been suggested that traffic loading may be modelled as a random parameter with a Poisson distribution [22]. However others including Darter et al. (1972)[9], Kher et al. (1976)[23], Moavenzadeh (1976) and Haas et al. (1994)[2] assumed that the traffic loading is log normally distributed. Chua et al. (1994)[15] and George et al. (1982) assumed a shifted exponential distribution and other researchers have stated that traffic loading is normally distributed with a mean and variance estimated directly from field observation [22].
b) Darter et al. (1976)[24] and Kher et al (1976)[23] found that the distribution of flexural strength for a pavement concrete is normally distributed. Another study (George et al., 1982)[5] suggested that pavement strength follows a log-normal distribution which is in agreement with Chua et al. (1994) who argued that as the subgrade strength and the pavement thickness are log normally distributed, the pavement strength is also log normally distributed.
c) The initial pavement condition has previously been assumed to follow a normal distribution without very much data to support the assumption. Holsen et al. (1976)[25] and Kenis et al. (1998)[10] have tested this assumption in terms of the initial serviceability index and the pavement's initial structural integrity. As a result of these tests it was found that the initial pavement condition may be assumed to follow a normal distribution.

From the above it may be considered reasonable to assume that all of the model parameters of Equation 1 may follow a normal distribution and this assumption was used in this study.

3. ANALYSIS AND RESULTS

Having selected an appropriate pavement performance model and investigated the distribution of its variables (i.e. road data) the Monte Carlo simulation was used to generate artificial data sets that were used for any subsequent analysis. The data sets produced had characteristics (mean and standard deviation) similar to those of the existing data. These are given in Table 1. In addition, three levels of variability low, medium and high were considered (options a, b and c) and expressed by the coefficient of variation (COV). The subsequent analysis sought to determine the degree of reliability of pavement performance predictions and the allowable cumulative equivalent standard axle load applications at 50%, 60%, 80% and 95% degrees of reliability. The resulting values from the Monte Carlo simulations are presented in Table 2.

Table 1. Variation of the mean of the model parameters

Model Parameter	IRI_0 (m/km)	SNC	CESA (msa)
(a)Low variability case			
Mean	1.700	3.000	3.900
Stdev	0.170	0.300	0.195
Coef var	10.000	10.000	5.000
(b) Medium variability case			
Mean	1.700	3.000	3.900
Stdev	0.340	0.600	0.390
Coef var	20.000	20.000	10.000
(c) High variability case			
Mean	1.700	3.000	3.900
Stdev	0.510	0.900	0.780
Coef var	30.000	30.000	20.000

Table 2: Reliability of pavement failure for low, medium and high variability cases

Variability of model parameter	Degree of reliability (%)	σ_Z	CESA (msa)
Low	95.000	0.261	3.936
	80.000	0.291	4.112
	60.000	0.317	4.247
	50.000	0.330	4.313
Medium	95.000	0.584	3.562
	80.000	0.723	3.904
	60.000	0.856	4.173
	50.000	0.923	4.294
High	95.000	0.905	3.289
	80.000	1.207	3.750
	60.000	1.513	4.111
	50.000	1.681	4.280

As may be seen in Table 2, the allowable cumulative standard axle load applications are higher when a lower degree of reliability is considered, which would imply a less conservative approach to predicting pavement performance. In addition high reliability indices σ_Z (implying poor reliability) are found for high levels of variability, while lower reliability indices are found for medium and low variabilities. The predictions of pavement performance with low reliability may entail major maintenance problems as the pavement performance prediction may not be reliable.

Further to this Figure 2 shows degrees of reliability of pavement performance predictions as a function of the variability of initial pavement roughness, pavement strength and traffic loading. Such plots may be used to estimate the percentage of roads likely to fail if the variability of the data used to predict pavement performance is known. In the case reported herein for example at traffic levels of 4.00 msa the reliability may be 93.4%, 75.3% and 65.7% for the various levels of data variability. In engineering terms this means that 6.6%, 24.7% and 34.3% of pavements may perform unsatisfactorily if the data variability is low, medium and high respectively.

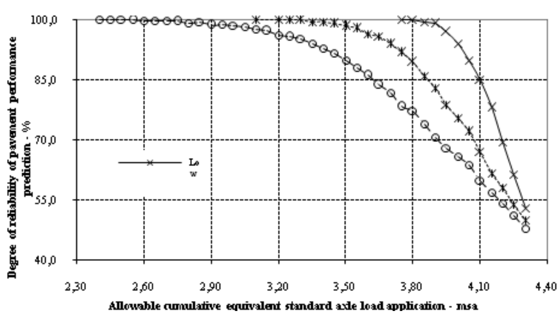

Figure 2: Degree of reliability of pavement performance prediction.

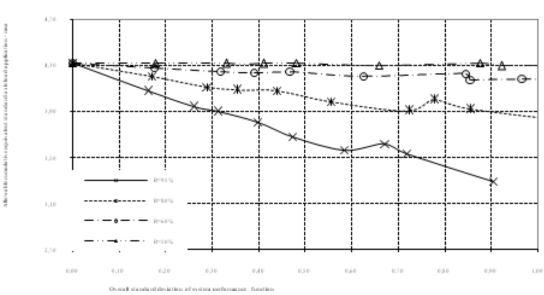

Figure 3: Allowable axle load applications at selected degrees of reliability.

An alternative presentation of the results is shown in Figure 3 where the allowable traffic loads are associated with selected degrees of reliability. From Figure 3 it may be observed that the computed allowable load applications decrease rapidly at high levels of reliability as the overall variability of predictions increases. For example, for a desired degree of reliability of pavement performance prediction of 95%, the allowable load application should be decreased from about 4.074 msa to less than 3.562 msa, if the overall standard deviation of prediction increases from 0.162 to 0.584. However for lower levels of reliability the effect of data variability is lower and sometimes insignificant. With regard to the overall standard deviation of predictions, it may be seen that it causes the allowable load applications to increase and if its value decreases toward zero the allowable load applications will be closer to the deterministic result.

4. CONCLUSIONS

In conventional deterministic approaches, the performance predictions may be unsatisfactory unless the models used are subjected to suitable calibration. However even in this case the models do not give an indication of the uncertainty included in the prediction. A statistical analysis for assessing the reliability of predictions has been presented that shows how the variation in the model dependent parameters (pavement data) may be considered in the prediction by examining their distributions. The variation was modelled by means of the Monte Carlo method that can generate sets of these data items with the same statistical properties with those found in data sets collected from field testing. The analysis is based on the assumption that the input parameters of the performance model follow a normal distribution. It should be appreciated that this assumption may not always be satisfactory. However the methodology followed could be altered to accommodate other statistical distributions such as log-normal.

With regard to the performance model itself it could be stated that it may consider data types different from those used in this paper. The selection of the most appropriate data types should be based on a realistic assessment of the availability of data both in terms of network coverage and time series (i.e. historical data). In practice such data sets may not always be available and in all cases the reliability of these data should be questioned.

To this end, the methodology presented herein provides the means to quantify the effects of data variability and subsequently its impact on pavement management. However further assessment of the reliability of the predictions is required which may be achieved by comparing the predictions from the model used with those from an independent model such as HDM-4. Other analysis systems such as those used for data mining may also be utilised. In addition the approach presented in this paper could be further validated by comparing its results with those from other methods such those of the first order approximation and the first order reliability. Finally it is understood that the process presented herein is primarily suitable for specialist highway engineers but there is a need that the concepts of reliability, risk and their quantification are better understood and more widely used.

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