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Evaluation of Rutting Models Using Reliability for Mechanistic-Empirical Design of Flexible Pavement

Abdulfatai Adinoyi Murana and Adekunle Taiwo Olowosulu
Department of Civil Engineering, Ahmadu Bello University, Kaduna State, Zaria, Nigeria

Abstract: Monte Carlo simulation has proven to be an effective means of incorporating reliability analysis into the M-E design process for flexible pavements. This research aimed at providing most appropriate Pavement Performance Distress Model for the prediction of pavement rutting life for pavement analysis and design in Nigeria. Mechanistic-Empirical simulation analysis based on some reliability levels in comparison with existing ones was carried out. Seven rutting distress models were evaluated for Nigerian environment. Monte Carlo simulation cycles was set at 2,200 threshold to provide sufficient repeatability for a damage reliability relationship. The results from the parametric study demonstrated that the Indian Rutting Distress Model shows the highest promise in terms of development and quick prediction for pavement reliability with the Nigerian environment.

Key words: Pavement distress, rutting, mechanistic-empirical, Monte Carlo, reliability, Nigeria

INTRODUCTION

The Mechanistic-Empirical (M-E) based method of pavement design is based on the mechanics of materials which relates input such as wheel loads to output such as pavement response. The response is then used to predict pavement distress (Huang, 1993). Flexible pavement rutting distress is usually controlled by the maximum tensile stress at the top of the sub-grade layer. A number of predictive models of rutting distress which relate the number of load repetitions to a certain response of pavement structures have been developed over the past three decades to characterize traffic load induced rutting distress. It plays crucial roles in the M-E based design method (Sun *et al.*, 2003).

The role of reliability in pavement design is to quantify the probability that a pavement structure will perform as intended for the duration of its design life. Many of the parameters associated with pavement design and construction exhibit natural variability. Therefore in order for a thickness design methodology to be complete, there must be an accounting of variability within the process. Reliability analysis allows for a rational treatment of the variability in the design parameters (Timm *et al.*, 1999).

Mechanistic-Empirical (M-E) design procedures typically use a numerical method (layered-elastic analysis or finite element) to simulate the pavement structure and its response to traffic loads (Chadbourn, 2001). Mechanistic-Empirical (M-E) Methods are now used extensively in developed and developing countries. In Nigeria, the method has been used to develop an Overlay Design Procedure for Nigerian conditions (Claros *et al.*, 1986) and more recently for new pavement design (Olowosulu, 2005). This research aimed at evaluating the effectiveness (appropriateness) of the available flexible pavement rutting distress models with the Nigerian M-E analytical and design system in terms of predicted life and reliability for repeated concepts. This is achieving with following objectives:

- To generate the basic performance models of rutting for a typical pavement structure within the Nigerian M-E Design System
- To evaluate the available pavement performance models in respect of rutting distress
- To generate variability of design parameters using Monte Carlo Method with the aid of Matlab
- Select the most appropriate performance model (rutting distress) for Empirical-mechanistic modelling with the Nigerian M-E Design System

Nigerian Empirical Mechanistic Pavement Analysis and Design System (NEMPADS): NEMPADS is a framework for mechanistic-empirical pavement design for tropical climate developed by Olowosulu (2005). It consists of two parts. Development of input values which include traffic, climate and material as one part and structural response

Corresponding Author: Abdulfatai Adinoyi Murana, Department of Civil Engineering, Ahmadu Bello University, Kaduna State, Zaria, Nigeria

analysis the second part. Miner (1945)'s hypothesis was used to quantify accumulating damage in terms of rutting or fatigue over the life span of the pavement.

Design input parameters to mechanistic-empirical modelling

Layer modulus: The resilient Modulus (M_R) is a measure of the elastic property of a soil recognizing certain non-linear characteristics. It is the stiffness of a material that may be defined in the strictness sense as the slope of the stress-strain curve that results when either load or displacement are applied to the material in its elastic range. Layer modulus variability can be described by a lognormal distribution (Timm *et al*., 1999). Resilient modulus can be used in a mechanistic analysis using multi-layer elastic systems for prediction of cracking, rutting, etc. (Claros *et al*., 1986).

Poisson's ratio: Poisson's ratio (υ) is the ratio of transverse strain (ε_t) to axial strain (ε_a) when a material is axially loaded. Yoder and Witczak (1975) indicated that the influence of many factors on Poisson's ratio for most pavement material is generally small.

Pavement layer thickness: The purpose of M-E flexible pavement design is to determine the thickness of each pavement layer to withstand the traffic and environmental conditions during the design period. Ideally, the design thickness would be a deterministic parameter but construction inherently causes layer thickness to be variable. It can be described by a normal distribution (Timm *et al*., 1999).

Traffic input: Traffic data are required in the M-E pavement design procedure. It is expressed in terms of 8,200 kg (80 kN) Equivalent Single Axle Loads (ESALs). The design traffic is calculated as number of ESALs expected to be carried on the design lane over the design period. It is given by:

$$n = Q_f \,(DDF)\,(LDF)\,(P_t)\,(F_{avg}) \quad (1)$$

Where:

- n = Number of cumulative ESALs to be carried by critical lane over design period
- Q_f = Total number of estimated future vehicles during the design period in both directions
- DDF = Directional Distribution Factor (between 0.4 and 0.6)
- LDF = Lane Distribution Factor
- P_t = Percent trucks
- F_{avg} = Average 8,200 kg single axle load equivalence factor from the TRUKWT Program (Olowosulu, 2005)

Transfer functions: The empirical component of M-E design is pavement life equation known as a transfer function. Transfer function use pavement responses calculated by the mechanistic model and predict the life of pavement in terms of fatigue cracking or rutting (Ameri and Khavandi, 2009).

It relates the pavement responses determined from mechanistic models to pavement performance as measured by the type and severity of distress. In current M-E design procedures for flexible pavements, one of the primary transfer functions is that it relates wheel load compressive stress (or strain) at the top of the sub-grade layer to rutting at the surface (Thompson and Nauman, 1993).

Reliability in pavement design and analysis

Input data characterization and reliability: The Nigerian overlay design methodology research served as a primary source of data for the material properties and pavement geometry as shown in Table 1-3.

Monte Carlo simulation: Distribution of output is produced from randomly combining each of function's input variables. When a distribution is characterized by a well-known function (normal or lognormal), it is possible to study directly with equations to artificially generate the distribution (Timm *et al*., 1999). According to Chadbourn (2001), standard uniform random numbers are transformed to independent standard normal values using the relationship in Eq. 2 and 3:

$$S11 = \sqrt{\left(-2\times \log U11\times \sin\left(2\times \pi\times U12\right)\right)} \quad (2)$$

Table 1: COV and thickness of pavement layer thickness (Claros *et al*., 1986)

Materials	Layer thickness (in)	Coefficient of variation (%)
Asphalt concrete	2.5	5
Granular base	5.5	8
Granular sub-base	2.8	15
Granular sub-grade	300.0	-

Table 2: COV and modulus of pavement layer (Claros *et al*., 1986)

Materials	Layer modulus (psi)	Coefficient of variation (%)
Asphalt concrete	900,000	20
Granular base	90,000	30
Granular sub-base	45,000	30
Granular sub-grade	26,000	40

Table 3: Poisson's ratio for the materials (Claros *et al*., 1986)

Materials	Poisson's ratio
Asphalt concrete	0.35
Granular base	0.20
Granular sub-base	0.35
Granular sub-grade	0.40

Table 4: Rutting distress models

Models	Rutting equation	Sources
Iranian Model	$N_r = 1.365\times10^{-9}(\varepsilon_v)^{-4.477}$	Khavandi (2008)
Indian Model	$N_r = 2.56\times10^{-8}(\varepsilon_v)^{-4.5337}$	Das and Pandey (1999)
Minnesota Model	$N_r = 5.5\times10^{15}(\frac{1}{\varepsilon_v\times10^6})^{-3.949}$	Timm *et al.* (1999)
Federal Ministry of Works and Housing	$N_r = 1.66\times10^{-9}(\frac{1}{\varepsilon_v})^{-4.7037}$	Claros *et al.* (1986)
Original Shell Model	$N_r = 2.3\times10^{-10}(\frac{1}{\varepsilon_v})^{4.92}$	Claros *et al.* (1986)
Asphalt Institute	$N_r = (\frac{0.0105}{\varepsilon_v})^{3.5714}$	Asphalt Institute (2001)
Updated Shell Model	$N_r = (\frac{0.0105}{\varepsilon_v})^{3.5714}$	Claessen and Ditmarsh (1977)

$$S12 = \sqrt{(-2\times\log U11\times\cos(2\times\pi\times U12))} \quad (3)$$

Where:

S11 and S12 = A pair of statistically independent standard normal values
U11 and U12 = Independent standard uniform values

Thickness values can be generated for the 1st 2 layers from their respective normal distributions. Therefore, a pair of random numbers from a normal distribution (N(μ, σ)) may be obtained by:

$$H1 = [(M1 + (D1 \times S11))] \quad (4)$$

$$H2 = [(M\,1 + (D1 \times S12))] \quad (5)$$

Where:

H1 and H2 = A pair of random thicknesses for layer 1 and 2
M1 and M2 = Mean values for layer thickness 1 and 2
D1 and D2 = Standard deviation values for layer thickness 1 and 2

Equation 2 through Eq. 5 can then be used to generate pairs of thickness values for layers 3 and 4. For log-normally distributed modulus values, independent standard uniform values are generated in the same fashion. Then, Eq. 2 and 3 can again be used to generate statistically independent standard normal values S11 and S12. For a lognormal variable E and transformed variable Y = ln (E). Equation 6 and 7 can be used to calculate the standard deviation and mean of the transformed variable, respectively:

$$D1 = \sqrt{\log(CV^2+1)} \quad (6)$$

$$M1 = \log M - \frac{D1^2}{2} \quad (7)$$

Where:

D1 = Standard deviation of the transformed variable
M1 = Mean of the transformed variable

Finally, Eq. 8 and 9 can then be used to generate pairs of modulus values:

$$E11 = e^{(M1+(D1\times S11))} \quad (8)$$

$$E12 = e^{(M1+(D1\times S12))} \quad (9)$$

where, E11 and E12 are two log-normally distributed modulus values for the layer.

Layered-elastic analysis output: The Layered-elastic Analysis Model calculates normal stresses, strains and deflections as well as shear stresses at any point in the pavement structure (Chadbourn, 2001). In NEMPADS (Olowosulu, 2005), critical strains are used to determine damage and reliability. The critical strains are the tensile strain at the bottom of the asphalt layer and the compressive strain at the top of the sub-grade. The various values obtained from Monte Carlo simulation were incorporated into the existing computer program, NEMPADS. It generates the horizontal tensile strain at the bottom of the existing asphalt concrete layer and vertical compressive strain at the top of the sub-grade. The seven rutting distress models employed in the study are shown in Table 4 which are all characterised with the compressive strains on the sub-grade layer.

Miner's hypothesis: Central to the NEMPADS software is the calculation of lifetime pavement damage using Miner's hypothesis (Olowosulu, 2005). The damage over the life of the pavement can be characterized by Eq. 10:

$$Damage = \frac{n}{N} \quad (10)$$

Where:

Damage = An index indicating the expected level of damage after n load applications

n = Applied number of loads

N = No. of loads required to cause failure

Reliability formulation: Reliability is the probability that the number of allowable traffic loads exceeds the number of applied traffic loads (Timm *et al*., 1999). From the results of Miner's hypothesis, reliability values can be obtained using Eq. 11:

$$\text{Reliability} = 100 \times \frac{\text{No. of cycles where damage} < 1}{\text{Total No. of cycles}} \quad (11)$$

RESULTS AND DISCUSSION

From Fig. 1-4, Iran, Indian, Federal Ministry of Studies and Housing, Original Shell and Updated Shell Pavement Performance Models for rutting has an average reliability values of 89% while the Minnesota and Asphalt Institute Pavement Performance Models for rutting which has a low reliability values for Monte Carlo simulation of 2,200 cycles at an axle load application of (range 1-1.5×10^6 ESALs).

At an axle load application of (range 2-8.3×10^6 ESALs), Iran pavement performance model for rutting has a reliability value of 42.5% at same threshold of Monte Carlo simulation. The Indian Pavement Performance Model for rutting has the highest reliability value of 93% at an axle load application of 8.3×10^6 ESALs for the same threshold of Monte Carlo simulation.

Figure 1-4 show the effects of each input parameter's variability on output variability in terms of each of the pavement performance model studied at different cycles. The results from the parametric study shows that Iran, Indian, Federal Ministry of Works and Housing, Original Shell and Updated Shell Pavement Performance Models for rutting gives a high reliability values for Monte Carlo simulation of 2,200 cycles at an axle load application ranging from 1-1.5×10^6 ESALs than that of Minnesota and Asphalt Institute Pavement Performance Models for rutting which has lower reliability values. The Indian Pavement Performance Model for rutting gives higher reliability value at an axle load application of 8.3×10^6 ESALs for Monte Carlo simulation cycles of 2,200.

It can be concluded both Indian, Federal Ministry of Works and Housing, Original Shell and Updated Shell Pavement Performance Models for rutting equations are all good predictor for NEMPADS when considering high level of reliability and conservation.

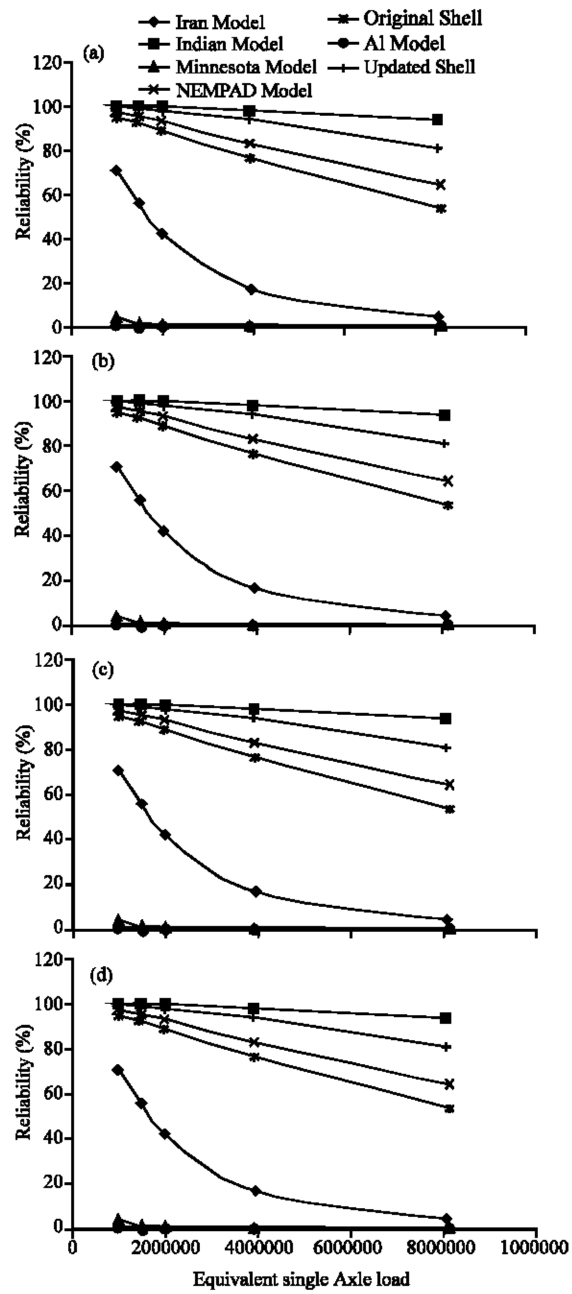

Fig. 1: Graph of reliability vs. ESALS using rutting models; a) 1,000 cycles; b) 1,500 cycles; c) 2,000 cycles; d) 2,200 cycles

CONCLUSION

For the reasons that the environmental conditions of Nigeria is similar to that of Indian, the Indian Model for rutting equation gives higher reliability value at an axle load application of 8.3×10^6 ESALs and its reliability values are not that reasonably sensitive to increase in axle load application compared to other models for all levels of number of Monte Carlo simulation studied, it can be recommended that the Indian pavement performance model for rutting equation is a good predictor for NEMPADS when considering high level of reliability and conservation. The minimum number of Monte Carlo simulation cycles that should be used for most practical design scenarios to provide enough sufficient repeatability for damage reliability relationship is 2,000 cycles.

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