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Distress Model for Nigerian Empirical Mechanistic Pavement Analysis and Design System

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Abstract

Nigerian Empirical Mechanistic Pavement Analysis and Design System (NEMPADS), a Mechanistic-Empirical Pavement Analysis and Design procedure for Nigeria has been proposed. This work was aimed at providing most appropriate Pavement Performance distress model for the prediction of pavement fatigue and rutting life in the NEMPADS. Empirical-Mechanistic simulation analysis based on some reliability levels in comparison with existing ones was carried out. Nine fatigue distress models and 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 both the Transport and Road Research Laboratory and Indian distress models for fatigue and rutting respectively show the most promising in terms of development and quick prediction for pavement reliability with the Nigerian Empirical Mechanistic Pavement Analysis and Design System.

Keywords: Pavement Distress, Rutting, Fatigue, Mechanistic-Empirical, Monte Carlo, Reliability

Introduction

A Mechanistic-Empirical (M-E) pavement analysis and design has been proposed for use in Nigeria. M-E lends itself to characterization variability in pavement design. There is statistical variation in the input parameters. Consequently, there is variability in the calculated stresses and strains that lead to variations in the number of allowable loads. There is also variability in the number of expected loads during the design period. Finally, there is variability in regard to the transfer functions that predict pavement life. The component of concern was the pavement performance model that predicts pavement life in flexible pavement thickness design. In this study variability in number of allowable loads is considered with a view to specify performance model most suitable for Nigeria environment.

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 (Bruce, 2001).

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 and more recently for new pavement design (Olowosulu, 2005).

Nigerian Empirical Mechanistic Pavement Analysis and Design System

Nigerian Empirical Mechanistic Pavement Analysis and Design System is a framework for Mechanistic-Empirical Pavement Design for tropical climate developed by Olowosulu (Olowosulu, 2005). Part 1 consists of the development of input values, which include traffic, climate and material. Geotechnical analysis is also performed in this part to determine the strength and stiffness of the sub-grade. Part 2 of the design process is structural response analysis.

Miner's hypothesis (Miner, 1945) was used to quantify accumulating damage, in terms of rutting or fatigue, over the life span of the pavement. The expression simply adds the damage done in the particular seasons under given load configurations. When the damage exceeds unity, the pavement has been under-designed and thicknesses are increased. If the damage is much less than unity, the pavement has been over-designed and thicknesses are decreased. An optimum design is achieved when the damage is near but not exceeding unity.

Techniques for incorporating the variation of the input parameters

One of the generally accepted techniques for accommodating the variation of the input parameters in the design model is the Monte-Carlo techniques (Jooste, 1999).

The Monte-Carlo simulation technique randomly generates huge numbers of input data sets from the known distributions of the input parameters while adhering to the distribution characteristics of the individual input parameters. These input data sets serve as input to the structural analysis model and by running the structural analysis model successively using the different input data sets, a distribution of the resilient pavement response parameters is generated. The distribution of the pavement response parameter in turn serves as the input to the pavement performance model.

Reliability in Pavement Design and Analysis

The challenge of evaluating pavement performance model was handled in several phases. The first phase involved gathering information regarding the design input parameters and generating associated variability using the ideas of Monte Carlo simulation. These values formed the basis of design inputs for the mechanistic load-displacement model. The second phase required the mechanistic load-displacement model for Nigeria (NEMPADS) which uses ELYSM 5 to generate 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 third phase involved reliability formulation for (the evaluation of) the available pavement performance models.

Input Data Characterization and Reliability

Pavement layer thickness

The pavement input parameters for this study are secondary data from Claros et al., work in 1986. The layer thicknesses were taken to be normally distributed with Coefficient of Variation (COV) of 5%, 8% and 15% for asphalt concrete, granular base and granular sub-base respectively and layer thicknesses of 2.5, 5.5, 2.8, and 300 inches for asphalt concrete, granular base, granular sub-base and sub-grade (Claros, et al., 1986).

Layer modulus

The resilient modulus of all the materials were taken to be log-normally distributed (Timm, et al., 1999). The practical range of COV assumed by literature was adopted for each of the material. From Nigeria Overlay design procedure. The estimate of the elastic modulus of asphalt concrete from the resilient modulus test using the standard test AASHTO T-274 was taken to be 900,000 psi and based upon the synthesis of information presented by the design procedure, a practical range of modulus COV of 20%. For the Granular base and sub-base, the elastic modulus of bases and sub-bases was estimated to be 90, 000 psi and 45, 000 psi respectively with a practical range of modulus COV of 30%. Also, the sub-grade modulus obtained after adjusting the modulus for representative stresses by this procedure for the selected route was 26, 000 psi with a practical COV of 40% (Claros, et al., 1986).

Poisson's ratio

The following values (0.35, 0.20, 0.35 and 0.40) were selected as Poisson's ratios for Asphalt concrete, Granular base, Granular sub-base and Sub-grade (Cohesive soils) respectively (Claros, et al., 1986).

Monte Carlo simulation

Monte Carlo simulation is straightforward, involving nothing more than generation of random numbers and transforming these into particular distributions. Distribution of output is produced from randomly combining each of function's input variables (Harr, 1987).

When a distribution is characterized by a well-known function (e.g., normal or lognormal), it is possible to work directly with equations to artificially generate the distribution. The first step requires the generation of a pair of independent standard uniform values (standard uniform random numbers). These standard uniform random numbers are then transformed to independent standard normal values. Thickness values can be generated for the first two layers from their respective normal distributions and for the next two layers through the same process. For log-normally distributed modulus values, independent standard uniform values are generated in the same fashion (Timm, et al., 1999).

Layered-Elastic Analysis Output

In NEMPADS, 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'. The program enables the designer to generate the horizontal tensile strain at the bottom of the existing asphalt concrete layer and vertical compressive strain at the top of the sub-grade (Olowosulu, 2005).

Parametric Study with existing Pavement Distress models

Table 1 gives a collection of the existing fatigue models tested in this study. The models are nine in number and characterised by E and/or ε_t alone. Also, Table 2 represents the seven rutting distress models employed in this study. They are all characterised with the compressive strains on the sub-grade layer.

Table 1: Fatigue Distress Models

S/N	Models	Fatigue equation
1	AI model	$N_f = 0.0796(\varepsilon_t)^{-3.291}(E)^{-0.854}$
2	Shell model	$N_f = 0.0685(\varepsilon_t)^{-5.671}(E)^{-2.363}$
3	Belgian Road Research Center	$N_f = 4.92 \times 10^{-14}(\varepsilon_t)^{-4.76}$
4	UC-Berkeley Modified AI model	$N_f = 0.0636(\varepsilon_t)^{-3.291}(E)^{-0.854}$
5	Transport and Road Research Laboratory	$N_f = 1.66 \times 10^{-10}(\varepsilon_t)^{-4.32}$
6	Illinois model	$N_f = 5 \times 10^{-6}(\varepsilon_t)^{-3.0}$
7	U.S. Army model	$N_f = 478.63(\varepsilon_t)^{-5.0}(E)^{-2.66}$
8	Minnesota model	$N_f = 2.83 \times 10^{-6}(\varepsilon_t)^{-3.206}$
9	Indian model	$N_f = 0.1001(\varepsilon_t)^{-3.565}(E)^{-1.4747}$

Source: (Murana & Olowosulu, 2012)

Table 2: Rutting Distress Models

S/N	Models	Rutting equation
1	Iranian model	$N_r = 1.365 \times 10^{-9}(\varepsilon_v)^{-4.477}$
2	Indian model	$N_r = 2.56 \times 10^{-8}(\varepsilon_v)^{-4.5337}$
3	Minnesota model	$N_r = 5.5 \times 10^{15}\left(\frac{1}{\varepsilon_v \times 10^6}\right)^{-3.949}$
4	Federal Ministry of Works and Housing	$N_r = 1.66 \times 10^{-9}\left(\frac{1}{\varepsilon_v}\right)^{4.7037}$
5	Original shell model	$N_r = 2.3 \times 10^{-10}\left(\frac{1}{\varepsilon_v}\right)^{4.92}$
6	Asphalt institute	$N_r = \left(\frac{0.0105}{\varepsilon_v}\right)^{3.5714}$
7	Updated shell model	$N_r = \left(\frac{0.0105}{\varepsilon_v}\right)^{3.5714}$

Source: (Murana & Olowosulu, 2012)

where N_f = Number of allowable 8200 kg ESAL applications,
ε_t = Horizontal tensile strain at the bottom of the asphalt layer, and
E = dynamic modulus of the asphalt concrete in PSI.
N_r = Number of allowable 8, 200 kg ESAL application.
ε_v = Vertical compressive strain at the top of the subgrade

Analysis of Result

The performance of the selected pavement structure was evaluated using Monte Carlo simulations. Figures 1 and 2 illustrate the effects of each input parameter's variability on output variability in terms of each of the pavement performance model studied at cycles ranging of 2, 200 cycles.

Pavement Performance (Fatigue) Models

Figure 1 illustrates the effect of each input parameter's variability on output variability in terms of each of the model for fatigue studied at 2, 200 Monte Carlo simulation cycles. At an axle load application of (1 – 2 $\times 10^6$ ESALs), the U.S. Army, Belgian Road Research Centre and Indian models for fatigue has a low reliability values. For an axle load application of 4×10^6 ESALs, the remaining models for fatigue both have low reliability values. Finally, at an axle load application of 8.3×10^6 ESALs, the Minnesota and Transport and Road Research Laboratory models for fatigue has a better reliability values.

Pavement Performance (Rutting) Models

Figure 2 illustrates the effect of each input parameter's variability on output variability in terms of each of the model for rutting studied at 2, 200 Monte Carlo simulation cycles. At an axle load application ranging from 1×10^6 ESALs to 1.5×10^6 ESALs, the Minnesota and Asphalt Institute models for rutting have low reliability values. Also, Iran model has low reliability value for Monte Carlo simulation of 2, 200 cycles at an axle load application ranging from 2×10^6 ESALs to 8.3×10^6 ESALs while the remaining models for rutting has high reliability values. The Indian model gives higher reliability value (93 %) at an axle load application of 8.3×10^6 ESALs.

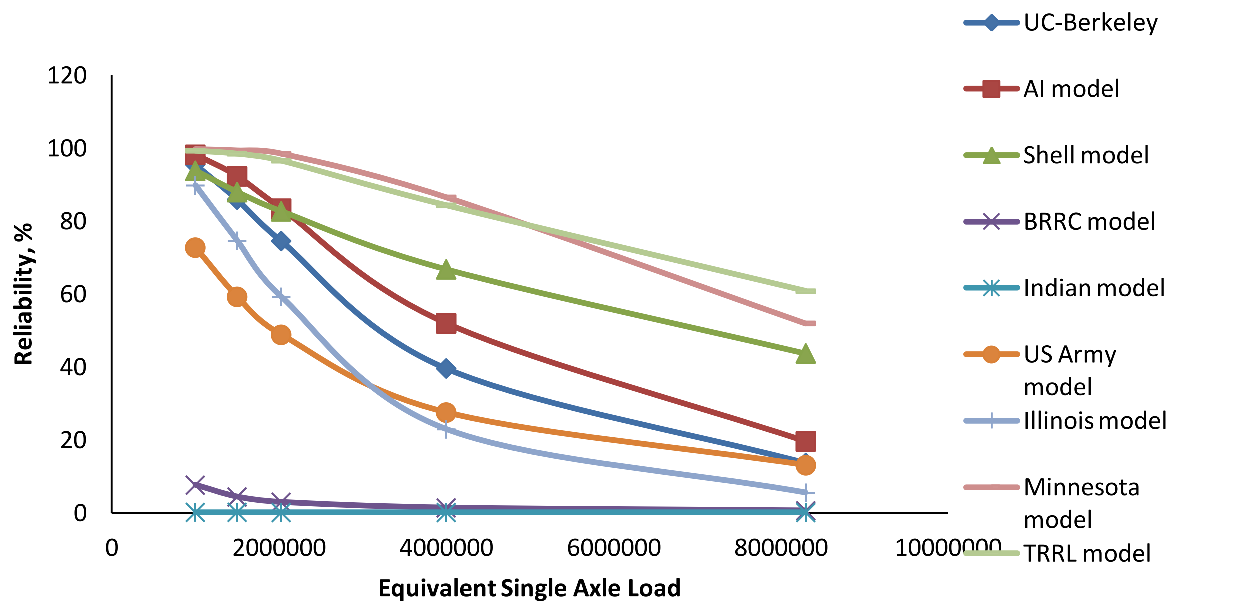

Figure 1: Graph of Reliability Vs ESALs using fatigue models

2200 cycles

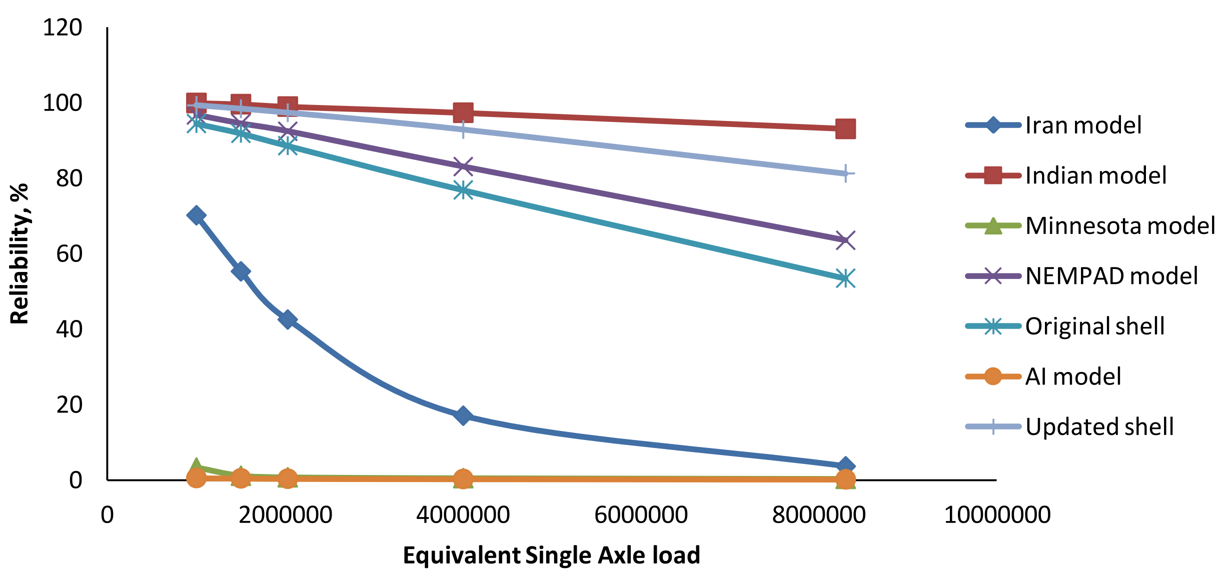

Figure 2: Graph of reliability Vs ESALs using rutting models

2, 200 cycles

Discussion

Using simulation techniques, the reliability of a selected pavement structure has been studied. The Transport and Road Research Laboratory and Minnesota models for fatigue equations result in best fit for the damage reliability relationship in terms of reliability values as a result of increase in axle load application for 'NEMPADS'.

For the rutting models equations, both Indian, Federal Ministry of Works and Housing, Original shell and updated shell are all good predictor for 'NEMPADS' when considering high level of reliability but the Indian model equation gives higher reliability value at higher axle load application which shows its equation can be use as a predictor for 'NEMPADS' pavement performance model for rutting.

Conclusions

- Transport and Road Research Laboratory pavement performance model for fatigue's equation is a good predictor for 'NEMPADS' fatigue when considering high level of reliability and conservation
- The Indian equation should be used as a predictor for 'NEMPADS' pavement performance model for rutting for the facts that the environmental conditions of Nigeria is similar to that of Indian.

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