Original Article

Basic Science

Evaluation of Fatigue Models for Mechanistic-Empirical Design of Flexible Pavement

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ABSTRACT [ENGLISH/ANGLAIS]

This work aimed at providing most appropriate pavement performance distress model for the prediction of pavement fatigue life for Mechanistic-Empirical Flexible Pavement Design. Nine fatigue distress models were evaluated for Nigerian environment. Simulation analysis was employed base of some reliability level to effect comparison of the selected fatigue models. 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 Minnesota fatigue distress models respectively at 60.82% and 52% show the most promising in terms of development and quick prediction for pavement reliability. It was also observed that axle weight has an overwhelming effect on the output variability as an increase in the applied load was highly noticed in the reliability value.

Keywords: Pavement distress, fatigue, mechanistic-empirical, Monte Carlo, reliability

RÉSUMÉ [FRANÇAIS/FRENCH]

Ce travail vise à fournir le plus approprié modèle détresse trottoir de performance pourla prédiction de la vie de fatigue des chaussées pour mécaniste-empirique de conception des chaussées souples. Neuf modèles de détresse fatigue ont été évaluéspour l'environnement du Nigéria. Une analyse de simulation a été employé de base d'un certain niveau de fiabilité pour effectuer la comparaison des modèles sélectionnés de la fatigue. Cycles de simulation Monte Carlo a été fixé à 2, 200 seuil pour fournir une répétabilité suffisante pour une relation de fiabilité des dommages. Les résultats de l'étude paramétrique a démontré que tant le transport et le chemin de la recherche en laboratoire et des modèles de détresse Minnesota fatigue respectivement à 60,82% et 52% montrent les plus prometteuses en termes de développement et de la prévisionrapide pour la fiabilité de la chaussée. Il a également été observé que le poids d'essieua un effet énorme sur la variabilité de la production par une augmentation de la charge appliquée a été très remarquée dans la valeur de fiabilité

Mots-clés: La détresse de la chaussée, la fatigue, mécanique-empirique, Monte Carlo, la fiabilité

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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. Among the many factors causing flexible pavement cracking are the traffic loading, sub-grade characteristics, and the environmental factors as the primary elements. As one of the important factors of M-E based pavement design, fatigue cracking has been reported as the most prevalent form of structure distress for flexible pavements in the United States [1].

Flexible pavement fatigue cracking is usually controlled by the maximum tensile stress at the bottom of the asphalt layer. A number of predictive models of fatigue cracking 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 fatigue cracking and play crucial roles in the M-E based design method. To predict fatigue cracking of flexible pavement, damage needs to be cumulated according to certain rules. The most popular rule of these rules is the Miner's law. Cumulated damage is interpreted as degree of fatigue deterioration of flexible pavement due to traffic loading [2].

MATERIALS AND METHODS

Nigerian Empirical Mechanistic Pavement Analysis and Design System (NEMPADS)

M-E methods are now used extensively in developed and developing countries. Many countries had developed the M-E method procedure based on their local conditions for use in design of new and rehabilitated pavements.

'*NEMPADS*' is a framework for mechanistic-empirical pavement design for tropical climate in Nigeria. This consists of two parts. First is 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. The second part of the design process is structural response analysis. Miner's hypothesis was used to quantify accumulating damage, in terms of rutting or fatigue, over the life span of the pavement.

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 [3]:

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

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 & 0.6)

LDF = lane distribution factor

P_t = percent trucks, and

F_{avg} = average 8, 200 kg single axle load equivalence factor from the *TRUKWT* program

Design Input Parameters to Mechanistic-Empirical modelling

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.

Poisson's ratio (υ) is the ratio of transverse strain (ε_t) to axial strain (ε_a) when a material is axially loaded. The influence of many factors on Poisson's ratio for most pavement material is generally small.

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.

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 (e.g., normal or lognormal), it is possible to work directly with equations to artificially generate the distribution. To generate a normally distributed random variable with some mean and standard deviation, two standard uniform random numbers are to be generated. These numbers are then transformed to standard normal values. The final step uses the standard normal values and transforms them to the desired normal distribution [4].

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 [5].

Transfer functions (distress models) relate 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 which relate maximum wheel load tensile strain in the hot-mix asphalt surface layer to eventual fatigue cracking [6].

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 presented in Tables 1 – 3 [7].

Standard uniform random numbers are transformed to independent standard normal values using the relationship in Equations 2 and 3.

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

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

where

$S11$ and $S12$ is a pair of statistically independent standard normal values.

$U11$ and $U12$ is independent standard uniform values

Thickness values can be generated for the first two layers from their respective normal distributions. Therefore, a pair of random numbers from a normal distribution ($N(\mu,\sigma)$) may be obtained by:

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

$$H2 = [M2 + (D1 \times S12)] \quad 5$$

where

$H1$ & $H2$ is a pair of random thicknesses for layer 1 & 2

$M1$ & $M2$ are mean values for layer thickness 1 & 2

$D1$ & $D2$ are standard deviation values for layer thickness 1 & 2

Equations 2 through 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, equations 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 $Y = ln(E)$, equations 6 and 7 can be used to calculate the standard deviation and mean of the transformed variable, respectively.

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

$$M1 = logM - D1^2/2 \quad 7$$

where,

$D1$ = standard deviation of the transformed variable

$M1$ = mean of the transformed variable

Finally, equations 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. 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*'. 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.

Table 4 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.

It was observed that equations for Minnesota, Illinois, Transport and Road Research Laboratory, Belgian Road Research Centre models considered a conservative estimation of the fatigue life in pavement in that modulus term for the asphalt layer has an exponent of zero. Also, the equations for Asphalt Institute, Shell, University of California at Berkeley, United States Army and Indian models include a modulus term for the asphalt layer in order to capture the relationship between stiffness and fatigue cracking.

Miner's Hypothesis

Central to the NEMPADS software is the calculation of lifetime pavement damage using Miner's Hypothesis[3]. The damage over the life of the pavement can be characterized by equation 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 = number of loads required to cause failure

Reliability Formulation

From the results of Miner's hypothesis, reliability values can be obtained using equation 11.

$$Reliability = 100 \times \frac{number\ of\ cycles\ where\ Damage < 1}{total\ number\ of\ cycles} \quad 11$$

RESULTS

Figure 1 shows the relationship between reliability and Equivalent Single Axle Load for the nine fatigue models using Monte Carlo simulation runs of 1, 000 cycles. University of California at Berkeley, Asphalt Institute, Shell, Belgian Road Research Center, Indian, U.S. Army, Illinois, Minnesota and Transport and Road Research Laboratory pavement performance models for fatigue has an reliability values of 13.4%, 19.6%, 44%, 0.3%, 0.2%, 12.7%, 4.7%, 50.9% and 60.2% respectively at an axle load application of 8.3×10^6 *ESALs*.

Table 1: This table shows the Coefficient of Variation and thickness of Pavement Layer Thickness for the materials used in this study

Material	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	-

Source [7]

Table 2: This table shows the Coefficient of Variation and modulus of Pavement Layer for the materials used in this study

Material	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%

Source [7]

Table 3: This table shows the Poisson's ratio for the materials used in this study

Material	Poisson's ratio
Asphalt concrete	0.35
Granular base	0.20
Granular sub-base	0.35
Granular sub-grade	0.4

Source [7]

Figure 2 shows the relationship between reliability and Equivalent Single Axle Load for the nine fatigue models using Monte Carlo simulation runs of 1, 500 cycles. University of California at Berkeley, Asphalt Institute, Shell, Belgian Road Research Center, Indian, U.S. Army, Illinois, Minnesota and Transport and Road Research Laboratory pavement performance models for fatigue has an reliability values of 14%, 19.9%, 44.5%, 0.5%, 0.2%, 13.3%, 5.3%, 52.5% and 61.5% respectively at an axle load application of 8.3×10^6 *ESALs*.

Figure 3 shows the relationship between reliability and Equivalent Single Axle Load for the nine fatigue models using Monte Carlo simulation runs of 2, 000 cycles. University of California at Berkeley, Asphalt Institute, Shell, Belgian Road Research Center, Indian, U.S. Army, Illinois, Minnesota and Transport and Road Research Laboratory pavement performance models for fatigue has an reliability values of 14.2%, 19.9%, 44.1%, 0.7%, 0.15%, 13.5%, 5.65%, 52.2% and 61.3% respectively at an axle load application of 8.3×10^6 *ESALs*.

Table 4: This table shows the available fatigue distress models used to predicts pavement performance

S/No	Models	Fatigue equation (N_f)
1	AI model [8]	$0.0796(\varepsilon_t)^{-3.291}(E)^{-0.854}$
2	Shell model [9, 10]	$0.0685(\varepsilon_t)^{-5.671}(E)^{-2.363}$
3	Belgian Road Research Center [11]	$4.92\times10^{-14}(\varepsilon_t)^{-4.76}$
4	UC-Berkeley Modified AI model [12]	$0.0636(\varepsilon_t)^{-3.291}(E)^{-0.854}$
5	Transport and Road Research Laboratory [7]	$1.66\times10^{-10}(\varepsilon_t)^{-4.32}$
6	Illinois model [6]	$5\times10^{-6}(\varepsilon_t)^{-3.0}$
7	U.S. Army model	$478.63(\varepsilon_t)^{-5.0}(E)^{-2.66}$
8	Minnesota model [13]	$2.83\times10^{-6}(\varepsilon_t)^{-3.206}$
9	Indian model [14]	$0.1001(\varepsilon_t)^{-3.565}(E)^{-1.4747}$

Figure 4 shows the relationship between reliability and Equivalent Single Axle Load for the nine fatigue models using Monte Carlo simulation runs of 2, 200 cycles. University of California at Berkeley, Asphalt Institute, Shell, Belgian Road Research Center, Indian, U.S. Army, Illinois, Minnesota and Transport and Road Research Laboratory pavement performance models for fatigue has an reliability values of 13.7%, 19.6%, 43.8%, 0.64%, 0.14%, 13.1%, 5.55%, 52.0% and 60.8% respectively at an axle load application of 8.3×10^6 *ESALs*.

DISCUSSION

Observing figures 1 to 4, an increased in reliability values was noticed (from 60.2% to 60.82%) for Transport and Road Research Laboratory pavement performance model and (50.9% to 52%) for Minnesota pavement performance model as the number of Monte Carlo simulation cycles increases from 1, 000 to 2, 200. Also, Minnesota, University of California at Berkeley, Transport and Road Research Laboratory, Asphalt Institute, Shell, Illinois pavement performance models for fatigue has an average reliability values of 60% at an axle load application of 2×10^6 *ESALs* while that of U.S. Army, Belgian Road Research Center and Indian pavement performance models for fatigue produce a low reliability values. At an axle load application of 4×10^6 *ESALs*, Minnesota, Transport and Road Research Laboratory, Shell and Asphalt Institute pavement performance models for fatigue both have reliability values of 86.55%, 84.36%, 66.82% and 52% respectively while the University of California at Berkeley, U.S. Army and Illinois pavement performance models for fatigue both have a very low reliability values of 39.64%, 27.55% and 22.95% respectively. Finally, at an axle load application of 8.3×10^6 *ESALs*, both Minnesota and Transport and Road Research Laboratory pavement performance models for fatigue has reliability value of 52% and 60.8% respectively. This implies that the Transport and Road Research Laboratory and Minnesota pavement performance models for fatigue equations proof to 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'. Both models (i.e. Transport and Road Research Laboratory and Minnesota) are not that sensitive to increase in axle load application compared to other models for all levels of number of Monte Carlo simulation studied.

Figure 1: This figure shows graph of reliability vs ESALs using fatigue models, 1000 cycles

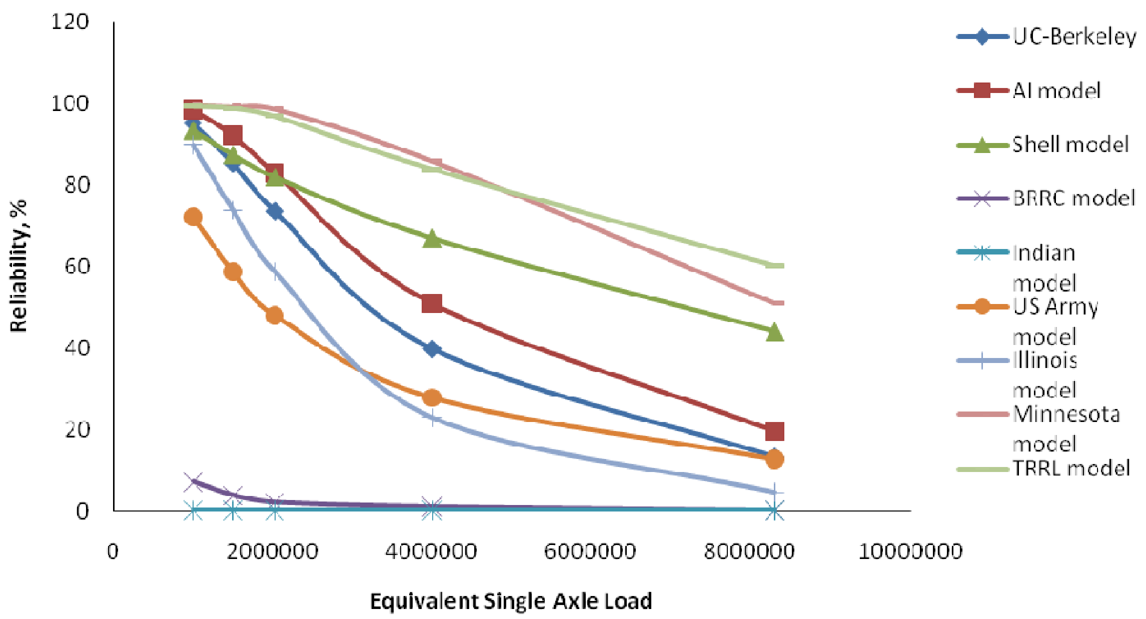


Figure 2: This figure shows graph of reliability vs ESALs using fatigue models, 1500 cycles

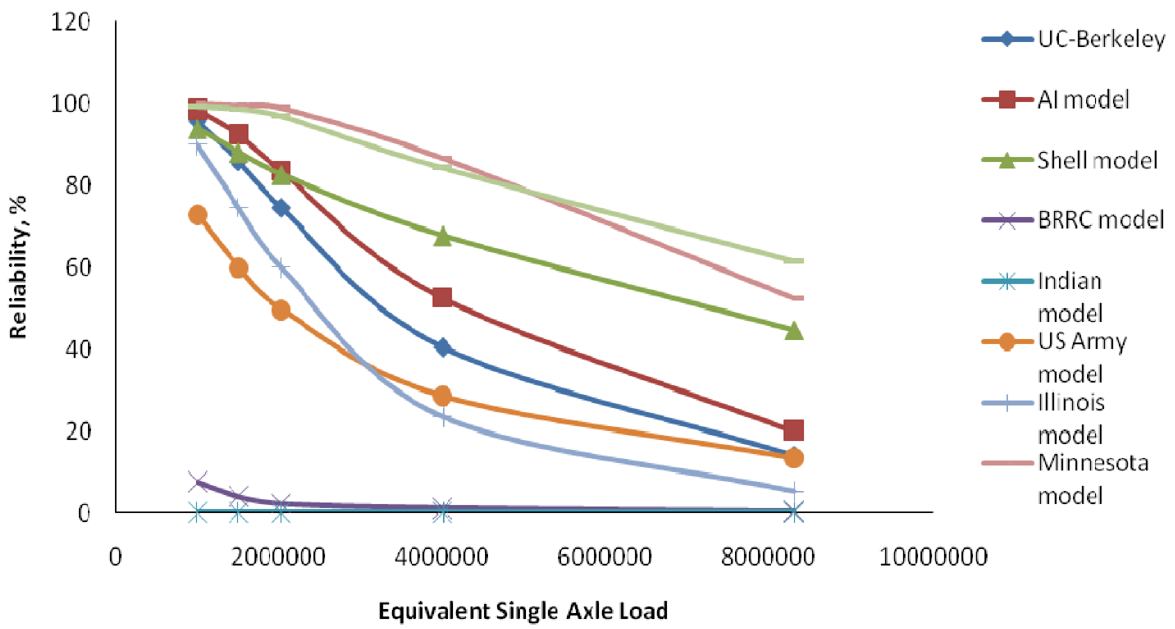


Figure 3: This figure shows graph of reliability vs ESALs using fatigue models, 2000 cycles

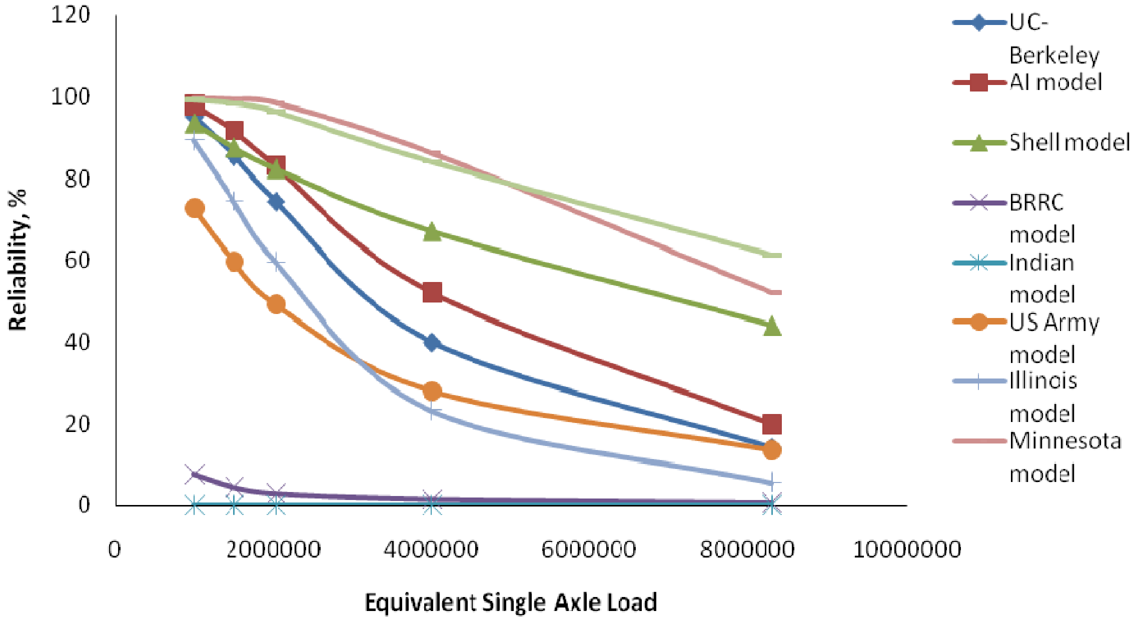
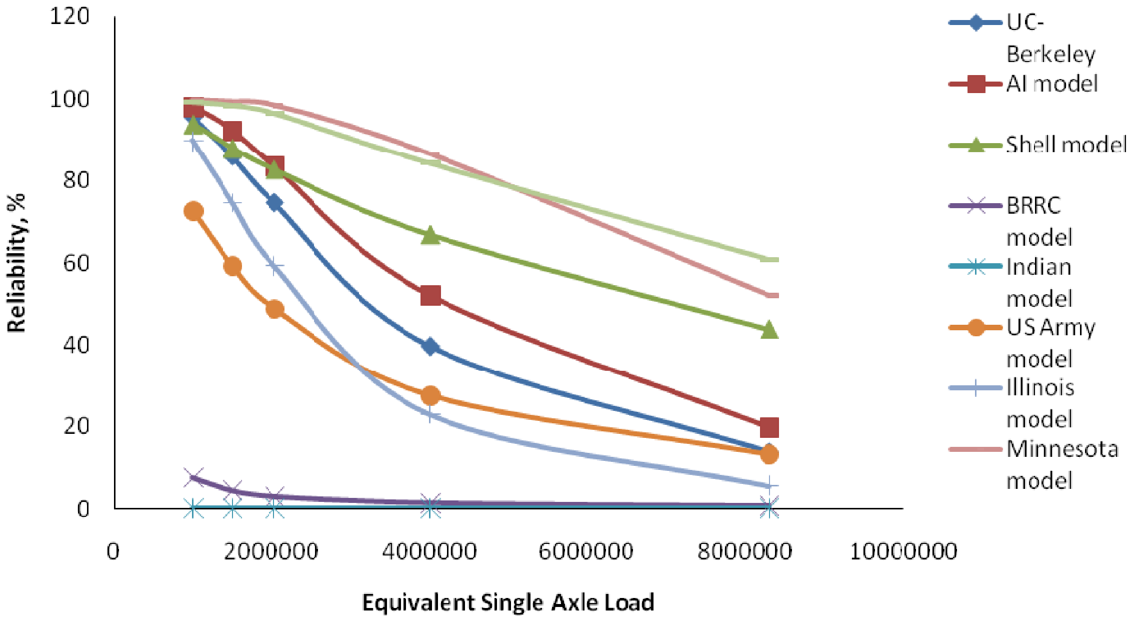


Figure 4: This figure shows graph of reliability vs ESALs using fatigue models, 2200 cycles



Also, Transport and Road Research Laboratory model pavement performance model for fatigue's equation gives better reliability value (60.8 %) at higher values of axle load application than that of Minnesota pavement performance model for fatigue's equation for Monte Carlo simulation cycles of 2, 200.

CONCLUSION

Considering high level of reliability and conservation, it can be concluded that both equations for fatigue (i.e. Transport and Road Research Laboratory and Minnesota) result in best fit for the damage reliability relationship in terms of reliability values as a result of increase in axle load application and therefore a good predictor for 'NEMPADS' fatigue. This affirms the conservative estimation of the fatigue life in pavement.

Also, axle weight has an overwhelming effect on the output variability in terms of fatigue and 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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CONFLICT OF INTEREST

Nil