Nigerian Journal of Technology (NIJOTECH)
Vol. 31, No. 3, November, 2012, pp. 321–328.

ISSN 1115-8443

MINIMUM THRESHOLDS OF MONTE CARLO CYCLES FOR NIGERIAN EMPIRICAL-MECHANISTIC PAVEMENT ANALYSIS AND DESIGN SYSTEM

A.A. Murana[a], **A.T. Olowosulu**[b], **H.S. Otuoze**[c]

Civil Engineering Department, Faculty of Engineering, Ahmadu Bello University, Zaria, Nigeria.
Emails: [a]*fatinoyi2007@yahoo.co.uk;* [b]*olowosulu@hotmail.com;* [c]*hassanotuoze@yahoo.com*

Abstract

Monte Carlo simulation has proven to be an effective means of incorporating reliability analysis into the Mechanistic-Empirical (M-E) design process for flexible pavements. Nigerian Empirical-Mechanistic Pavement Analysis and Design System procedure for Nigeria Environments has been proposed. This work aimed at providing most appropriate number of Monte Carlo simulation cycles that should be adopted for used to provide enough sufficient repeatability for damage reliability relationship in the Nigerian environments. Two selected fatigue distress models and a selected rutting distress models were evaluated for Nigerian environment. It was observed that Monte Carlo simulation cycle of 2, 500 thresholds were enough to be used to provide sufficient repeatability for damage reliability relationship and that axle weight has an overwhelming effect on the output variability as an increase in applied load was highly noticed in the reliability values.

Keywords: pavement distress, fatigue, rutting, mechanistic-empirical, Monte Carlo

1. Introduction

An M-E pavement analysis and design has been proposed for use in Nigeria [1]. 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 generation of variability of design parameters using Monte Carlo method with the aid of MATrixLABoratory.

Reliability concept was first introduced to pavement design and management by Lemer and Moavenzadeh [2], and Darter and Hudson [3]. Also, (Irick et al [4] and Uzan et al [5]) incorporate reliability concepts in the Texas flexible pavement design systems as well as in the AASHTO Design Guide [6]. Many of the parameters associated with pavement design and construction exhibit natural variability. Reliability analysis allows for a rational treatment of the variability in the design parameters. Other advantages of using reliability analysis include the calibration of new design methods, developing rational design specifications, optimizing resources, and assessing the damage and remaining life of the pavement [7].

Determining reliability requires quantifying the variability of the input values (such as layer thickness and modulus of input parameters e.g. asphalt concrete, granular base, granular sub-base and sub-grade) and then using those values to estimate the variability of the output (expected pavement life). 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 [8].

2. Nigerian Empirical Mechanistic Pavement Analysis and Design System

Nigerian Empirical Mechanistic Pavement Analysis and Design System (NEMPADS) is a framework for mechanistic-empirical pavement design for tropical climate developed by Olowosulu [1]. An advantage of this approach is the modular nature, which allows for adaptation of new development into pavement design without change to the process. 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. Each component of the design procedure is developed specifically for Nigeria environment. The material characterization, load characterization and mechanistic analysis and behaviour functions developed for overlay design procedure [9] were adopted for the new method.

3. Input Data Characterization and Reliability

3.1. 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 [7].

The pavement input parameters for this study were extracted from Region 1 of Trunk Road study of Nigeria [9]. The region (A236 route) comprises of Kano, Jigawa, Kaduna and Katsina States with layer thickness of 2.5in, 5.5in, 2.8in and 300in for Asphalt concrete, Granular base, Granular sub-base and Sub-grade respectively; and Coefficient of Variation of 5%, 8% and 15% for Asphalt concrete, Granular base and Granular sub-base respectively.

3.2. 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. 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 [9].

3.3. Traffic input

The design traffic is calculated as number of equivalent single axle load (ESAL) expected to be carried on the design lane over the design period. It is expressed in terms of 8, 200kg (80kN) Equivalent Single Axle Loads (ESAL). Ani and Isimijola [10] conclude that at low traffic intensities the behaviour of the distribution varies while at high traffic intensities they behave alike.

3.4. 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 [7]. The resilient modulus of all the materials (asphalt concrete, granular base, granular sub-base, and sub-grade was 900, 000psi, 90, 000psi, 45, 000psi and 26, 000psi respectively with their Coefficient of Variation of 20%, 30%, 30% and 40% respectively).

3.5. Monte Carlo methods

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 [11]. Monte-Carlo Simulation is the most common basic technique and is applicable to all probabilistic problems [12].

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 [7].

The first step requires the generation of a pair of independent standard uniform values (standard uniform random numbers), Us. These standard uniform random numbers are then transformed to independent standard normal values.

Next, thickness values can be generated for the first two layers from their respective normal distributions. For log-normally distributed modulus values, independent standard uniform values are generated in the same fashion. Finally, pairs of modulus values are generated from the standard uniform values.

3.6. 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 [1].

3.7. Transfer function

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. It acts as a chain between the pavement reactions and appeared damages in the pavements [13].

Transfer functions (distress models) relate the pavement responses determined from mechanistic models to pavement performance as measured by the type and severity of distress (rutting, cracking, roughness, and so forth) [14].

Two fatigue models are being tested for pavements in Nigeria. Claros et al [9] used a version developed by Craus et al [15] that was calibrated using data from the AASHO Road test for thin pavements and a failure criterion of thirty percent class II cracking. This model includes a modulus term for the asphalt layer in order to capture the relationship between stiffness and fatigue cracking.

The Nigerian version is as shown in equation (1).

$$N_f = 9.727 \times 10^{15} \left(\frac{\varepsilon_t}{10^{-6}}\right)^{-3.291} \left(\frac{E}{10^3}\right)^{0.854} \tag{1}$$

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.

A fatigue model developed by Finn et al [16] and similar the one developed by Craus et al [15] was also evaluated which was the version used by Olowosulu [1]. This model also includes a modulus term for the asphalt layer in order to capture the relationship between stiffness and fatigue cracking.

$$N_f = 1.219 \times 10^{16} \left(\frac{\varepsilon_t}{10^{-6}}\right)^{-3.291} \left(\frac{E}{10^3}\right)^{0.854} \tag{2}$$

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.

Equation (3) shows the rutting transfer function used in Nigerian Overlay Pavement Design. This equation was also calibrated for NEMPADS as described by Claros et al [9].

$$N_r = 1.36 \times 10^{-2} \left(\frac{1}{\varepsilon_v}\right)^{4.7036} \tag{3}$$

where N_r = Number of allowable 8, 200 kg ESAL application and ε_v = Vertical compressive strain at the top of the subgrade.

The Layer Elastic Analysis (LEA) model calculates normal stresses, strains, and deflections as well as shear stresses at any point in the pavement structure [8]. In NEMPADS [1], 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.

3.8. *Miner's hypothesis*

Central to the NEMPADS software is the calculation of lifetime pavement damage using Miner's Hypothesis [1]. In the simplest case (single load configuration and no seasonal variations in material properties), the damage over the life of the pavement can be characterized by equation (4):

$$\text{Damage} = \frac{n}{N} \tag{4}$$

where Damage = an index indicating the expected level of damage after n load applications (Damage 1 indicates pavement failure); n = applied number of loads and N = number of loads required to cause failure (based on empirical transfer functions).

3.9. *Reliability formulation*

In this work, the definition of reliability is taken as the probability that the number of allowable traffic loads exceeds the number of applied traffic loads [7].

$$R = P[N > n] \tag{5}$$

where N = number of allowable loads until either fatigue or rutting failure and n = number of load repetitions during life of pavement.

From the results of Miner's hypothesis, reliability values can be obtained using equation (6).

$$\text{Reliability} = \frac{\text{number of cycles where Damage} < 1}{\text{total number of cycles}} \tag{6}$$

4. Results

Figures 1 - 11 illustrate the effect of number of Monte Carlo simulation cycles required on different axle load application for selected Craus fatigue, Finn fatigue and rutting models. In these figures, an increased value of reliability was noticed as the number of Monte Carlo cycles increases from 1,000 to 2,000 but no noticeable difference in value of reliability for 2,200 and 2,500 Monte Carlo simulation cycles for Craus and Finn fatigue models. For the rutting model, it was noticed that no sensitive response to increase in number of Monte Carlo simulation cycles from 1,000 up to 2,000 on the value of reliability not until it recorded a sensitive response to increase in numbers of Monte Carlo cycles from 2,000 up to 2,500.

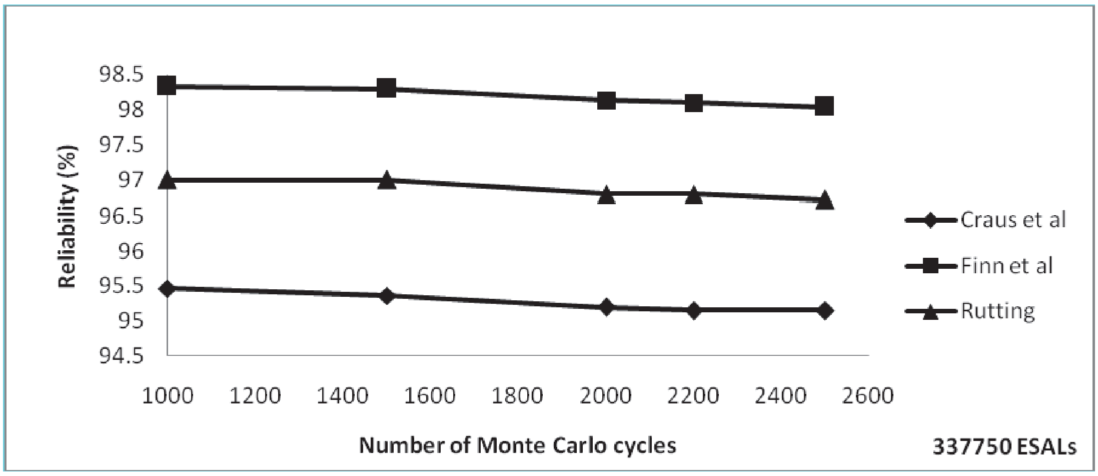

Figure 1: Reliability values for axle load of 337750 ESALs at different Monte Carlo cycles.

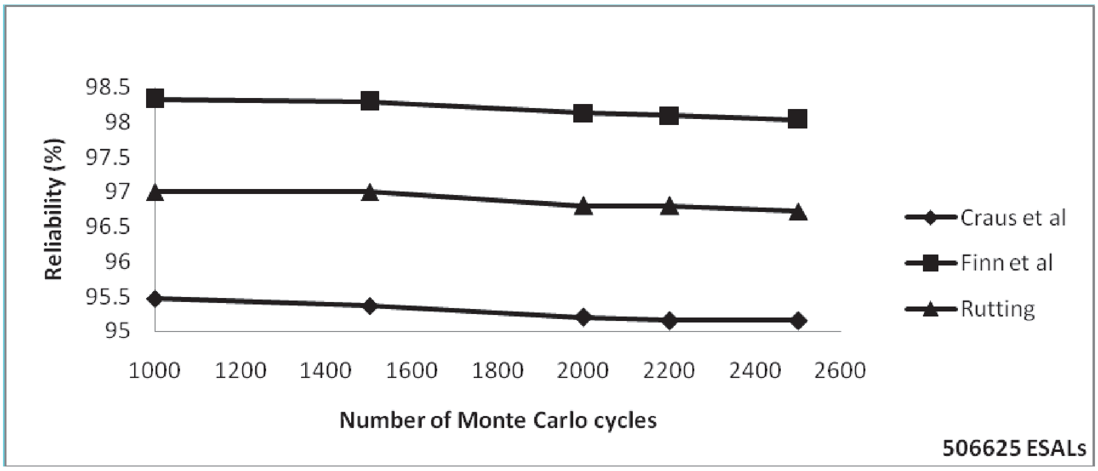

Figure 2: Reliability values for axle load of 506625 ESALs at different Monte Carlo cycles.

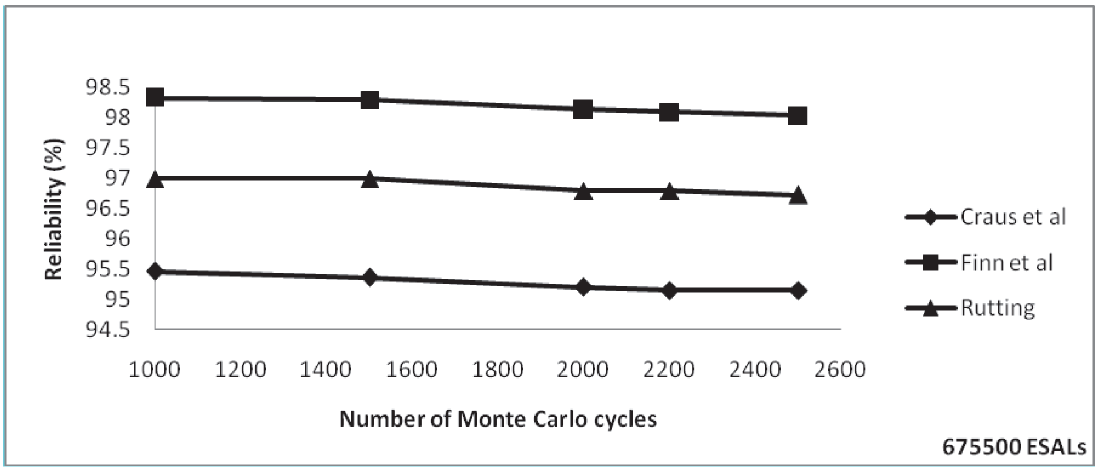

Figure 3: Reliability values for axle load of 675500 ESALs at different Monte Carlo cycles.

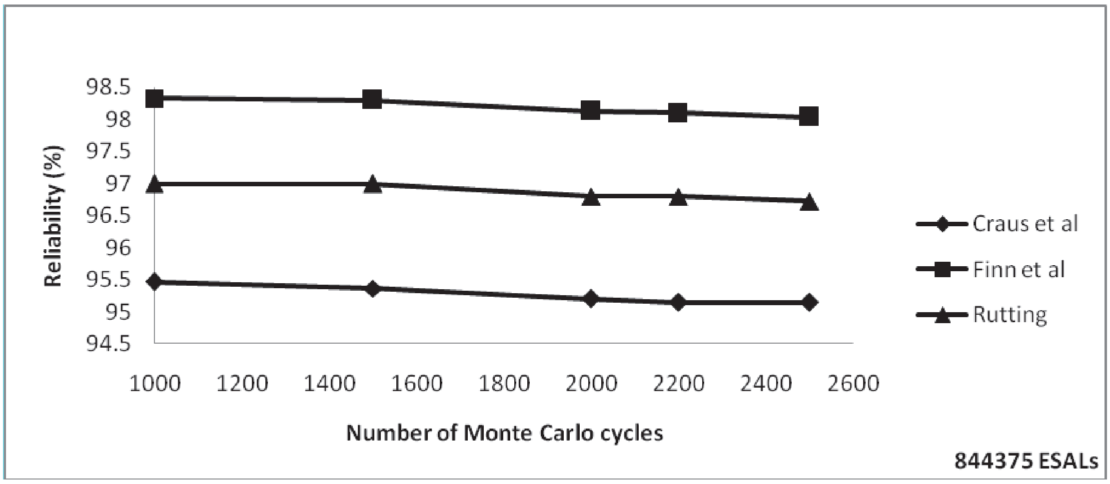

Figure 4: Reliability values for axle load of 844375 ESALs at different Monte Carlo cycles.

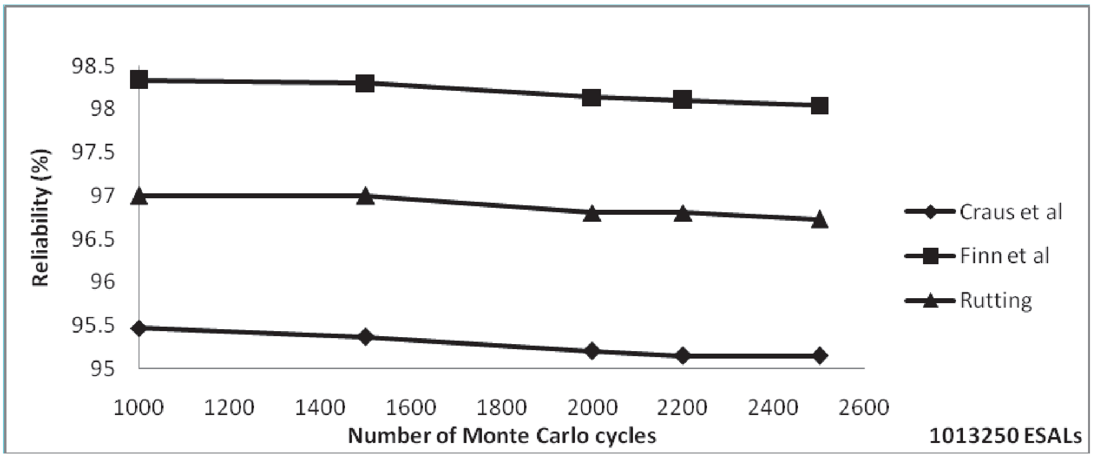

Figure 5: Reliability values for axle load of 1013250 ESALs at different Monte Carlo cycles.

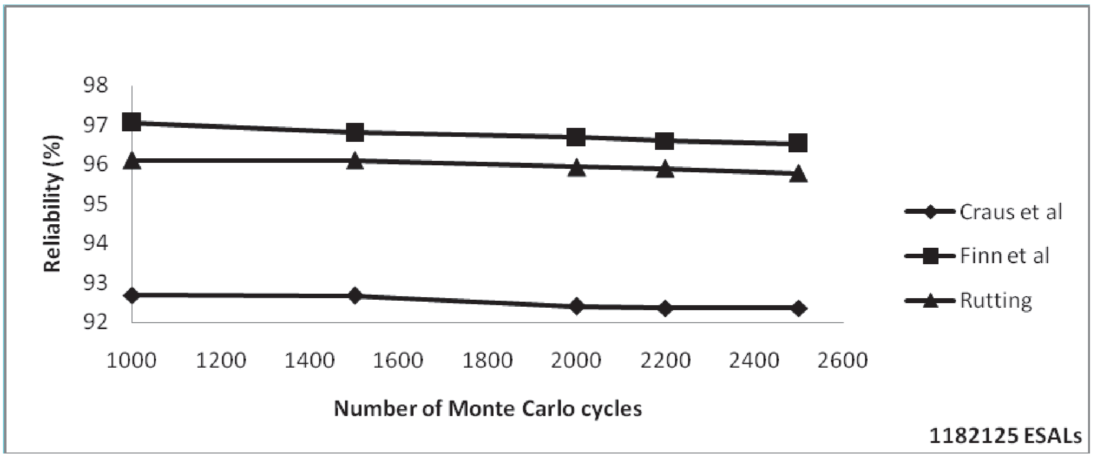

Figure 6: Reliability values for axle load of 1182125 ESALs at different Monte Carlo cycles.

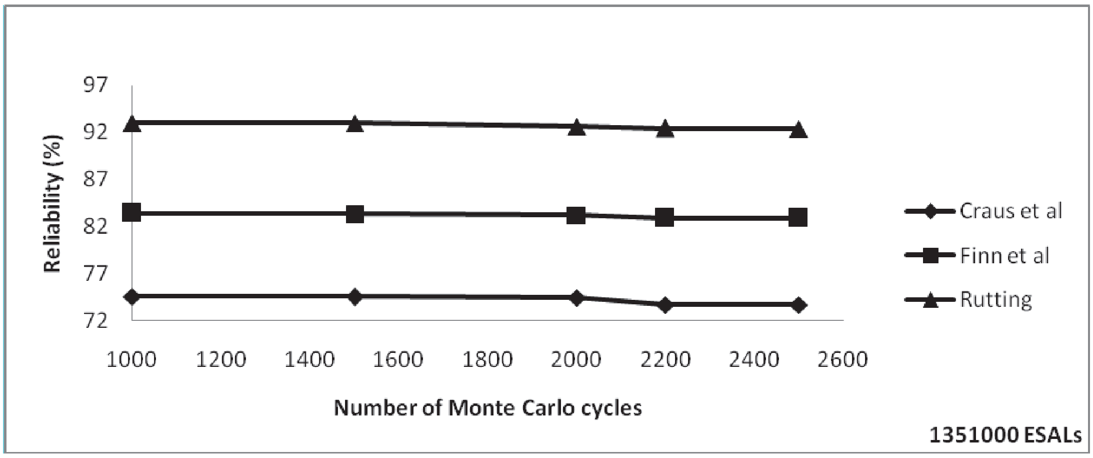

Figure 7: Reliability values for axle load of 1351000 ESALs at different Monte Carlo cycles.

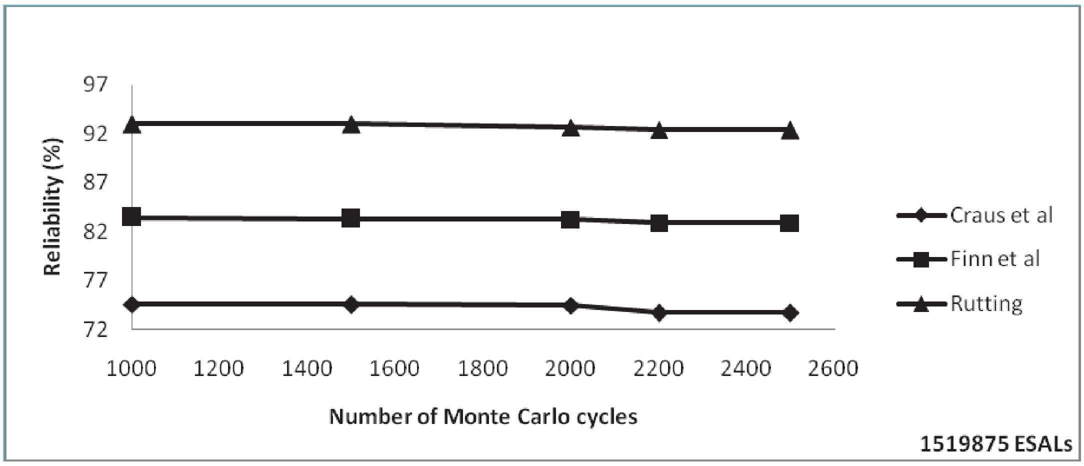

Figure 8: Reliability values for axle load of 1519875 ESALs at different Monte Carlo cycles.

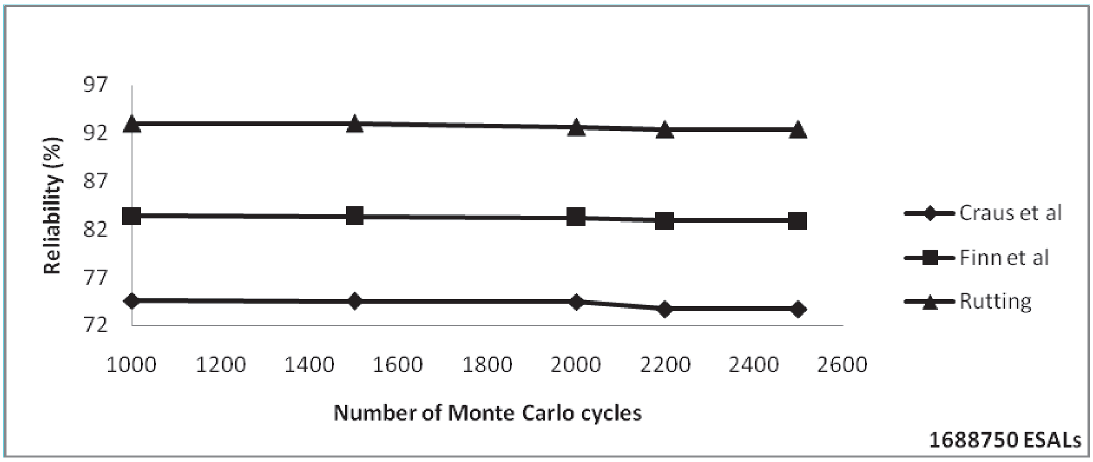

Figure 9: Reliability values for axle load of 1688750 ESALs at different Monte Carlo cycles.

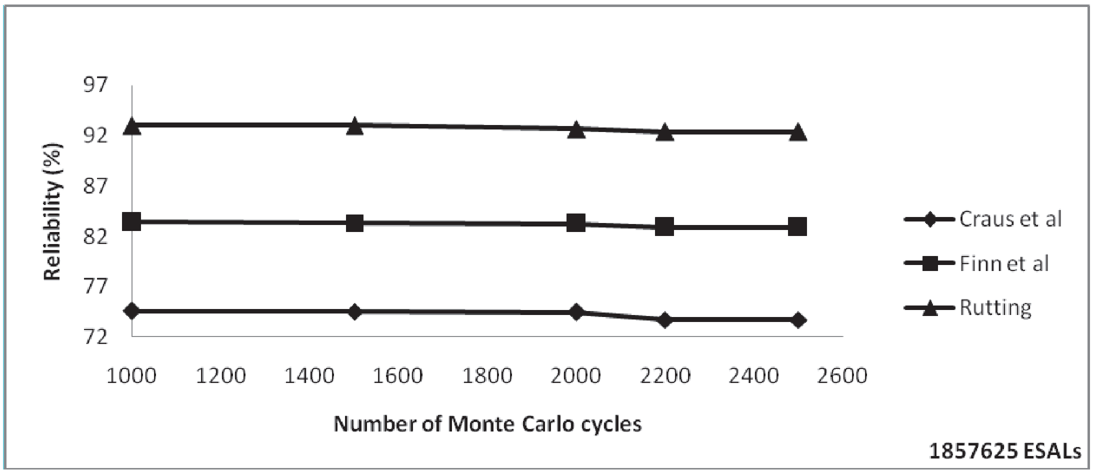

Figure 10: Reliability values for axle load of 1857625 ESALs at different Monte Carlo cycles.

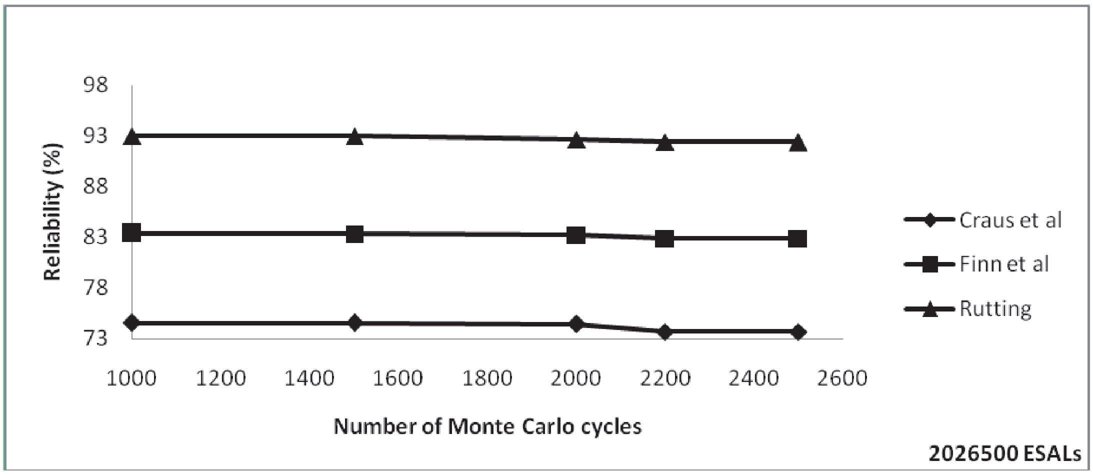

Figure 11: Reliability values for axle load of 2026500 ESALs at different Monte Carlo cycles.

5. Conclusions

Using Monte Carlo simulation techniques, the reliability of a selected pavement structure has been studied. The following conclusions were drawn:

- Axle weight has an overwhelming effect on the output variability in terms of fatigue and rutting.
- 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 in Nigerian environment is 2,000 cycles.

References

1. Olowosulu, A.T. A Framework for Mechanistic-Empirical Pavement Design for Tropical Climate. *Journal of Civil Engineering*, Vol. 5, No. 1, 2005, pp 44-51.
2. Lemer, A. C., and Moavenzadeh, F. Reliability of highway Pavements. *Highway Research Record 362*, Highway Research Board, Washington, D.C., 1971, pp 1-8.
3. Darter, M. I., and Hudson, W.R. *Probabilistic Design Concepts Applied to Flexible Pavement System Design: Report 123-18*, Centre for Transportation Research, and University of Texas at Austin, 1973.
4. Irick, P. E., Seeds, S. B., and Diaz, M. A. *Characteristics of Load Equivalence Relationships Associated with Pavement Distress and Performance*, Executive Summary, Trucking Research Institute, Alexandria, Va, 1991.
5. Uzan, J., Zollinger, D. G., and Lytton, R. L. *The Texas flexible pavement systems (TFPS) Mechanistic-Empirical Model* FHWA/TX-91/455-1, Texas Transportation Institute, College Station, Tex, 1990.
6. American Association of State Highway and Transportation Officials (AASHTO). *Guide for Design of Pavement Structures.* Washington, DC, 1993.
7. Timm, D.H., Newcomb, D.E., Birgisson, B., and Galambos, T.V. *Incorporation of Reliability into the Minnesota Mechanistic-Empirical Pavement Design Method.* Final Report, MN/RC-1999-35, Minnesota Department of Transportation, 1999.
8. Bruce A.C. *Development of a Quick Reliability Method for Mechanistic-Empirical Asphalt PavementDesign.* Minnesota Department of Transportation, 1400 Gervais Ave. Maplewood, MN, 2001.
9. Claros, G., Carmicheal, R.F., and Harvey, J. *Development of Pavement Evaluation Unit and Rehabilitation Procedure for Overlay Design Method*, Vol. 2, Overlay Design Manual, Texas Research and Development Foundation for the Nigeria Federal Ministry of Works and Housing, Lagos, 1986.
10. Ani, C. I. and Isimijola, S. O. Effect of Data Traffic Patterns on Qos Parameters. *Nigerian Journal of Technology*, Vol. 28 No.2, 2009, pp 23 – 28.
11. Jooste F J. The influence of variability on routine pavement design. Paper presented at the *7th Conference on Asphalt Pavements for Southern Africa*, 1999.
12. Abejide, O. S. Appraisal and Reliability of Variable Engagement Model Prediction For Fibre Reinforced Concrete. *Nigerian Journal of Technology*, Vol. 27 No.2, 2008, pp 78 – 92.
13. Ameri M. and Khavandi A. Development of Mechanistic-Empirical Flexible Pavement Design in Iran. *Journal of Applied Sciences*, Vol. 9, Number 2, 2009, pp 354-359.
14. Thompson, M. R., and Nauman D. Rutting Rate Analyses of the AASHO Road Test Flexible Pavements. *Transportation Research Record* 1384, TRB, National Research Council, Washington, D.C., 1993, pp. 36–48.
15. Craus, J., Yuce, R., and Monismith, C. L. Fatigue behaviour of thin asphalt concrete layers in flexible pavement structures. *Proc. Assoc. of Asphalt Paving Technologists*, Association of Asphalt PavingTechnologists, 53, 1984, 559–582.
16. Finn, F., Saraf, C., Kulkarni, R., Nair, K., Smith, W., and Abdullah, A. The uses of distress prediction subsystems for the design of pavement structures. *Proc., 4th Int. Conf. on Structural Design of Asphalt Pavements*, Ann Arbor, Mich., International Society for Asphalt Pavements (ISAP), Lexington, Ky., 1, 1977, 3–38.