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Sensitivity Analysis of Flexible Pavement Sections Using Mechanistic-Empirical Pavement Design Guide

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Abstract: In damage analysis of flexible pavement sections, the AASHTO 2002 design guide, also called as MEPDG (Mechanistic-Empirical Pavement Design Guide), adopted a mechanistic-empirical approach. In the MEPDG, the pavement performance is computed using different input parameters that characterize pavement materials, design features and condition. However, these input parameter values are expected to differ to varying degrees and, therefore, the predicted performance may also vary to some degree depending on the input parameter values. The current study evaluated the influence of four input parameters, namely, reliability level, climate, traffic characteristics and modulus values on the performance of selected pavement sections using MEPDG software. Knowledge gained from the sensitivity analysis of different pavement sections using MEPDG is expected to be useful to pavement designers and others using MEPDG for future pavement design. Specifically, this paper focuses on the sensitivity study of flexible pavement sections at four different locations namely, Chicago in Illinois, Grand Forks in North Dakota, Oklahoma City in Oklahoma, and Houston in Texas, for addressing sensitivity towards climatic conditions. For addressing effect of reliability and traffic three levels of reliability (80%, 90%, 95%) and traffic (low, medium, high) were used, respectively, for designing flexible pavement sections. Additionally, sensitivity towards modulus of subgrade soil was evaluated by designing pavement sections containing 6% lime, 15% class C fly ash (CFA), and 15% cement kiln dust (CKD). The performance of each pavement section was monitored for 240 months (20 years) using MEPDG software by generating plots for rutting, alligator cracking, and International Roughness Index (IRI). It was found that rut predicted by MEPDG is sensitive towards climate, modulus values of chemically stabilized layer and reliability level. IRI values showed sensitiveness toward only reliability and traffic level. Alligator cracking showed sensitiveness toward climate with unexpected trend, modulus of chemically stabilized layer, reliability and traffic level.

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***Key words**: International roughness index; Mechanistic-Empirical; Reliability; Resilient modulus; Sensitivity; Traffic.*

Introduction

The basis of AASHTO 1993 flexible pavement design method was a landmark pavement performance test (AASHO Road Tests) conducted in the late 1950s near Ottawa, Illinois, at a cost of $27 million (1960 dollars) [1]. This experiment consisting of 288 flexible pavements generated substantial database of pavement performance observations, which formed the basis for the pavement design methodology adopted by AASHTO.

The limited nature of the AASHO Road Test in terms of loading pattern, environmental conditions and unrealistic assumptions forced pavement engineers to look beyond existing empirical-based design and move towards the mechanistic-empirical (M-E) design procedure. The research and development in the structural design of pavements over the past fifty years have focused on a shift from empirical design equations to a more powerful and adaptive design scheme. The M-E design has been developed to utilize the mechanical properties of the pavement structure along with information on traffic, climate, and observed performance, to more accurately model the pavement structure and predict its life. Although M-E design still relies on observed performance and empirical relationships, it is a much more robust system that can easily incorporate new materials, different traffic distributions, and changing conditions [2-3].

Although there are several existing M-E pavement design approaches developed by various organizations, the AASHTO 2002 MEPDG developed under NCHRP 1-37A has brought international attention to M-E design. The M-E design and analysis process integrates the environmental conditions and material properties of the HMA layer and underlying layers into the pavement structure. The responses of pavement structure to load (i.e., stresses and strains) are mechanistically calculated based on material properties, environmental conditions, and traffic characteristics. Thermal and moisture distributions are mechanistically determined using the Enhanced Integrated Climatic Model (EICM). These responses are then used as inputs in empirically derived distress models (or transfer functions), translating them into damage, and accumulating the damage into distresses (e.g., rutting, alligator cracking, thermal cracking and roughness) that are responsible for reduced pavement performance over time [3-4].

The MEPDG provides methodologies for the analysis and performance prediction of different types of flexible and rigid pavements [5-6]. The performance predicted by these methodologies depends on the values of input parameters that characterize pavement materials, layers, design features, and condition. However, these input parameter values are expected to differ to varying degrees and, therefore, the predicted performance

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may also vary to some degree depending on the input parameter values.

Consequently, the primary objective of the study presented here is to conduct sensitivity analysis of flexible pavement sections towards four input parameters, namely, climate, reliability, traffic, and modulus. A total of four different locations namely, Chicago in Illinois, Grand Forks in North Dakota, Oklahoma City in Oklahoma, and Houston in Texas, for addressing sensitivity towards climatic conditions. For addressing effect of reliability and traffic three levels of reliability (80%, 90%, 95%) and traffic (low, moderate, high) were used, respectively, for designing flexible pavement sections. Additionally, sensitivity towards modulus of subgrade soil was evaluated by designing pavement sections containing 6% lime, 15% class C fly ash (CFA), and 15% cement kiln dust (CKD). The performance of each pavement section was monitored for 240 months (20 years) using MEPDG software by generating plots for rutting, alligator cracking, and International Roughness Index (IRI).

Review of Previous Studies

Carvalho and Schwartz [6] compared flexible pavement designs and performance between the empirical 1993 AASHTO pavement design guide and the mechanistic-empirical NCHRP project 1-37A methodologies. But particular emphasize is devoted to compare the influence of traffic and reliability levels on designs. Traffic load plays an important role in pavement design and this response is influenced by factors such as stress state, temperature, moisture, time, and loading rate. The mechanistic component is the theoretical determination of pavement responses such as stresses, strains and deflections due to loading and environmental influences. The first difference reported is that AASHTO 1993 guide underestimates amount of pavement distress. Secondly, AASHTO 1993 includes reliability as one of the input parameters, which has the highest impact on the final pavement structural design. After many researches it has been concluded that the NCHRP project 1-37A method is more robust than the AASHTO 1993 empirical approach. One of the main reasons for this difference could be that as the NCHRP project 1-37A methodologies has been calibrated against a wider range of pavement conditions than AASHTO 1993 guide.

In a similar study by Guclu [7] emphasized on evaluating and comparing the relative sensitivity of input parameters needed for the design of jointed plain concrete pavements (JPCPs) and continuously reinforced concrete pavements (CRCPs) in Iowa using the different versions of MEPDG software (Versions 0.7, 0.9, and 1.0). A lot of research has been carried out on MEPDG software and it concludes that MEPDG requires over 100 input parameters to model traffic, environment, materials, and pavement performance to predict pavement distress over the design life of the pavement.

A sensitivity analysis study by Ceylan and Coree [8] evaluated 20 input parameters varying them one at a time, by using 50% reliability. As part of their study, a limited study on 2-way interactions among the inputs was also carried out by varying two inputs at a time, but no input parameter was found to be sensitive to all the performance measures. The criteria that has been used to determine the sensitivity level of the input parameters in rigid pavements was applied to flexible pavement input parameters.

However, one study by Masad [9] on the granular base sensitivity indicates that the base modulus and thickness have a significant influence on the IRI and longitudinal cracking. The effect of these properties on alligator cracking is approximately half of that on longitudinal cracking. The study also includes the granular base material properties.

A recent study by Orobio and Zaniewski [10] on the sensitivity analysis of MEPDG to material properties was studied in a flexible pavement structure and the results were used to investigate the effect of different combination of material properties in the different layers of the pavement structure using MEPDG. This study revealed that a suitable combination of material properties in the different layers of a pavement structure leads to a better predicted pavement performance from MEPDG.

Design Parameters

Following are the specific design inputs used in this study for designing a pavement using MEPDG software.

General Information

This includes information regarding expected pavement design life, base/subgrade construction month, pavement construction month, traffic opening month and pavement design type. In this study, flexible pavement was designed for 240 months (20 years).

Site Project Identification

Project site is identified using project location, project ID, section ID and functional class of the pavement. The location of the project is provided in the form of latitude, longitude and height above sea level. This defines the climatic condition which is extracted from available database of nearly 800 weather stations throughout the United States, which allows the user to select a given station or to generate virtual weather stations for a project site under design from a climatic data file.

Analysis Parameters

Analysis parameters are defined initial IRI and performance criteria. The typical initial IRI values range between 789 to 1579 mm/km (i.e., 50 to 100 in/mile). For our selected flexible pavement design the initial IRI value is 1026 mm/km (65 in/mile) and the terminal IRI value is 2715 mm/km (172 in/mile). The MEPDG software version 1.1 supports five different criteria namely asphalt concrete (AC) surface down cracking (longitudinal cracking), AC bottom up cracking (fatigue or alligator cracking), AC thermal cracking, fatigue cracking in chemically stabilized layer, permanent deformation. In this study, a total of three reliability levels namely, 80%, 90%, and 95% for functional classification of collector, principal arterials, and interstate, respectively, were used in accordance with AASHTO (2004). Table 1 shows the fixed input requirements of general information, site project identification and analysis parameter.

Traffic

The basic required information is Annual Average Daily Truck

Table 1. General Information.

Fixed Input Parameter	Standard Value
General Information	
Design Life (Years)	20
Type of Design	Flexible Pavement
Analysis Parameters	
Initial IRI	1026 mm/km (65 in/mi)
Terminal IRI (in/mi)	2715 mm/km (172 in/mi)
Asphalt Concrete Bottom up Cracking (%)	25
Permanent Deformation-Total Pavement	19 mm (.75 in)

Table 2. Traffic Input Parameters

Traffic General			
Initial Two-way AADTT	341	150	900
Two-way Annual Average Daily Traffic (AADT)	11378	5000	30000
Percent of Heavy Vehicle (Class-4 or Higher)	3		
Number of Lanes in Design Direction	2		
Percent of Trucks in Design Direction (%)	50		
Percent of Trucks in Design Lanes (%)	80		
Operational Speed	96 kmph (60 mph)		
Traffic Volume Adjustment Factors			
Hourly Traffic Distribution	Default		
Traffic Growth Factor	Compound Growth Rate of 1.5%		
Axle Load Distribution Factor	Default		
General Traffic Inputs			
Mean Wheel Location	457 mm (18 in)		
Design Lane Width	3.7 m (12 ft)		
Axle Configuration			
Average Axle Width	2.6 m (8.5 ft)		
Dual Tire Spacing	305 mm (12 in)		
Axle Spacing-Tandem, Tridem, Quad Axle	51.6, 49.2, 49.2		
Wheel Base			
Average Axle Spacing	12, 15, 18		
Percent of Trucks (%)	33, 33, 34		

Traffic (AADTT) for base year, directional distribution factor and lane distribution factor and operational speed of vehicles are presented in Table 2. The traffic volume adjustment is comprised of monthly adjustment factors, vehicle class distribution, hourly truck traffic distribution and traffic growth factors.

Material properties

The subgrade layer properties are incorporated in terms of resilient modulus values from laboratory [11]. All material properties are presented in Table 3.

Table 3. Input Parameters for Structure.

Structure				
HMA Design	NCHRP 1-37A Viscosity Based Model			
Layer	Type	Material	Thickness	Interface
1	Asphalt Concrete	Asphalt Concrete	5.0	1
2	Chemically Stabilized	Lime Stabilized	6.0	1
3	Subgrade	CL	12.0	1
4	Subgrade	CL	Semi-infinite	n/a

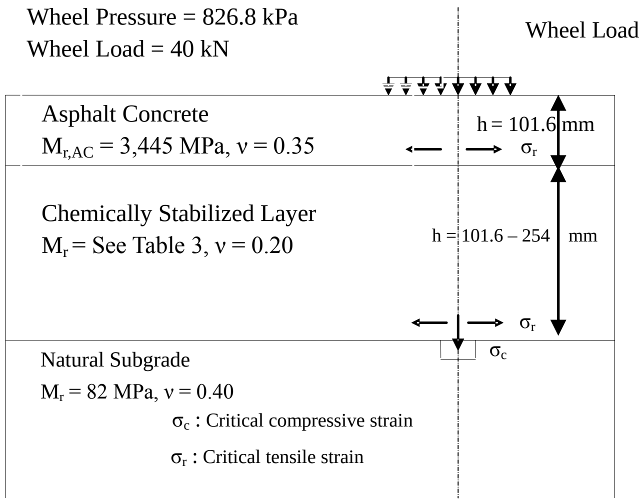

Fig. 1. Pavement Configuration with Stabilized Subgrade Layer.

Design Sections

A schematic diagram of a pavement section showing all properties used is presented in Fig. 1. In this study, a total of ten sections (S1 through S10) were designed as presented in Table 4. Sections S1 through S4 were used for addressing sensitivity of MEPDG towards climate. The sensitivity of MEPDG towards modulus, reliability, and traffic was addressed using section S5-S6, S7-S8, and S9-S10, respectively. Section S1 was used in analyses as control section for comparison purpose.

Presentation and Discussion of Results

The result section has been divided into four parts, which explains the influence of climate, modulus, reliability and traffic.

Influence of Climate

As noted earlier (Table 3), four locations with wide variation in climatic conditions were selected for analysis as represented by sections S1 through S4 in Table 4. The rutting performance predicted by MEPDG software is presented in Fig. 2. It is evident from Fig. 2 that MEPDG predicted highest rutting for Houston, TX followed by Oklahoma City, OK, Chicago, IL and Grand Forks, ND. For example, the final predicted rutting values at the end of 240 months is 0.4186 in and 0.3717 in for Houston, TX and Grand Forks, ND, respectively. This is an expected trend of rutting as rut value increases with increase in temperature [12]. The average summer

Table 4. Test Sections.

Parameters	Test Sections									
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Climate	Chicago, IL	Grand Forks, ND	Oklahoma City, OK	Houston, TX	Chicago, IL	Chicago, IL	Chicago, IL	Chicago, IL	Chicago, IL	Chicago , IL
Stabilizer	6% Lime	6% Lime	6% Lime	6% Lime	15% CFA	15% CKD	6% Lime	6% Lime	6% Lime	6% Lime
Modulus (Mr) (MPa)	715	715	715	715	951	1575	715	715	715	715
Reliability	90	90	90	90	90	90	80	95	90	90
Traffic	341	341	341	341	341	341	341	341	150	900

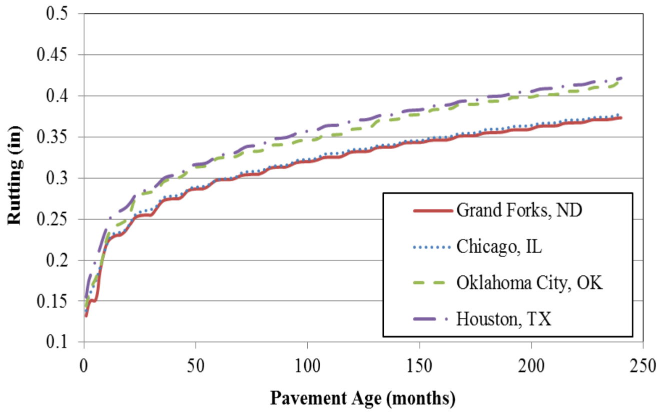

Fig. 2. Effect of Climate on Rutting.

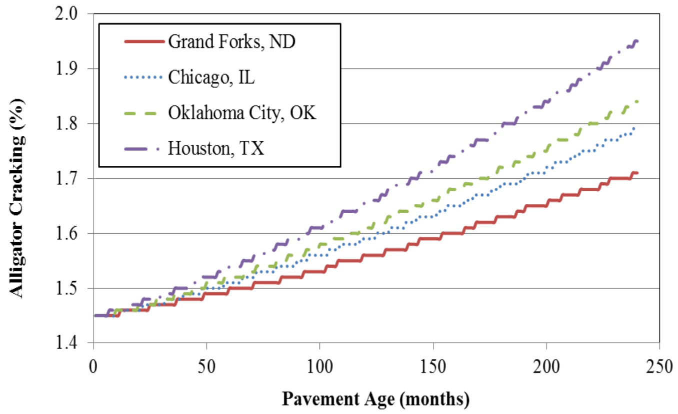

Fig. 3. Effect of Climate on Alligator Cracking.

temperature in Houston, TX, Oklahoma City, OK, Chicago, IL and Grand Forks, ND are 93.7°F, 85°F, 81.5°F and 81°F, respectively.

Similarly, the percent alligator cracking and IRI performance is also predicted by MEPDG software, as presented in Figs. 3 and 4, respectively. It can be noted from Fig. 3 that MEPDG has shown highest cracking in Houston, TX followed by Oklahoma City, OK, Chicago, IL and Grand Forks, ND, which is quite unexpected trend because cracking is higher at the cold climatic temperature as compared to the hot temperature; the average climatic temperature at Grand Forks, ND is much lesser then average temperature of Houston, TX. The IRI values of sections S1, S2, S3 and S4 showed no significant difference (Fig. 4). For example, the percent difference between final IRI value at the end of 240 months for Houston, TX and Grand Forks, ND is approximately 3.5%.

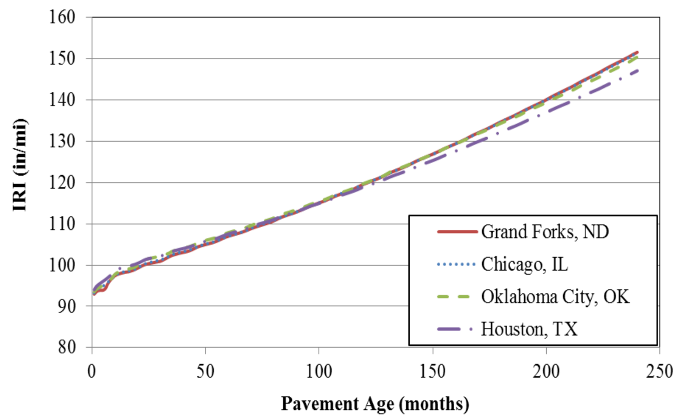

Fig. 4. Effect of Climate on IRI.

Influence of Modulus

As noted earlier, three resilient modulus values were selected to observe the effect of modulus on the flexible pavement design (sections S1, S5 and S6). The rutting, alligator cracking and IRI performance predicted by MEPDG are presented in Figs. 5, 6 and 7 respectively. It is evident from Fig. 5 that the rutting is highest for 15% CFA followed by 6% lime and 15% CKD. For example, the final predicted rut value at the end of 240 months is 0.3737 in, 0.3804 in and 0.3451 in for 6% lime, 15% CFA, and 15% CKD, respectively. This is an expected trend of rutting as modulus value is highest for 15% CKD followed by 6% lime and 15% CFA. It can be noted from Fig. 6 that MEPDG has shown highest alligator cracking for 15% CFA followed by 6% lime and 15% CKD. The IRI values of sections S1, S5, and S6 showed no significant difference.

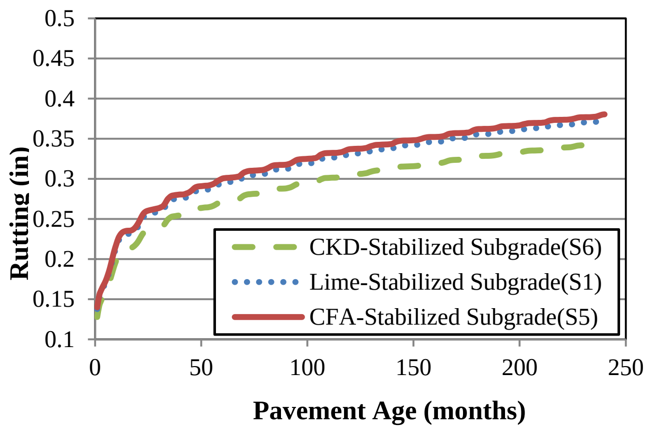

Fig. 5. Effect of Stabilized Subgrade Modulus on Rutting.

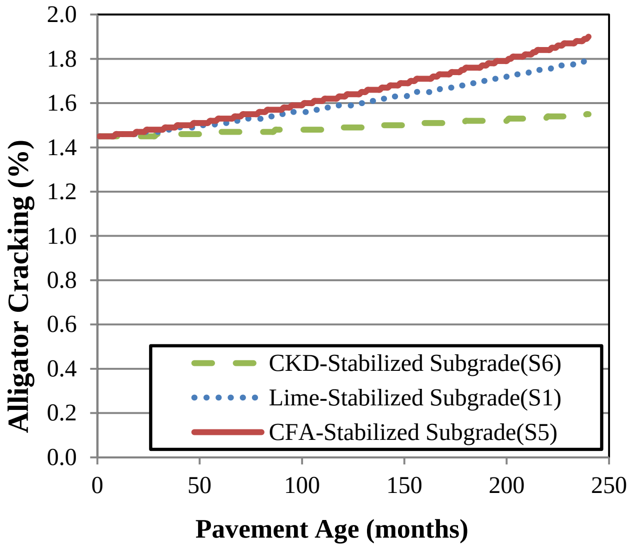

Fig. 6. Effect of Stabilized Subgrade Modulus on Alligator Cracking.

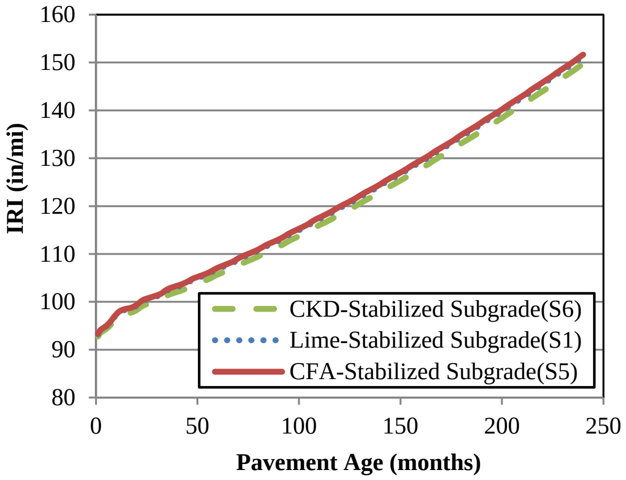

Fig. 7. Effect of Stabilized Subgrade Modulus on IRI.

For example, the percent difference between final IRI value at the end of 240 months for 6% lime and 15% CKD is approximately 1%.

Influence of Reliability

Three different reliability levels of 80%, 90% and 95% were considered for this study by designing sections S1, S7 and S8, respectively (Table 4). The effect of reliability level on pavement rutting, alligator cracking and IRI are graphically presented in Figs. 8, 9 and 10, respectively. It is evident from Fig. 8 that rutting value increases with reliability level, as expected. For example, an increase in reliability from 80 to 95% increased rutting value by approximately 15% (from 0.34 in. to 0.40 in.) at the end of design life, i.e., 240 months. On the other hand, alligator cracking showed comparatively more sensitiveness towards change in reliability level. For example, an increase in reliability level from 80% to 95% increased amount of alligator cracking by approximately 69% (from 1.3% to 2.2%) after 240 months. The IRI results also showed sensitiveness toward reliability level. For example, change in

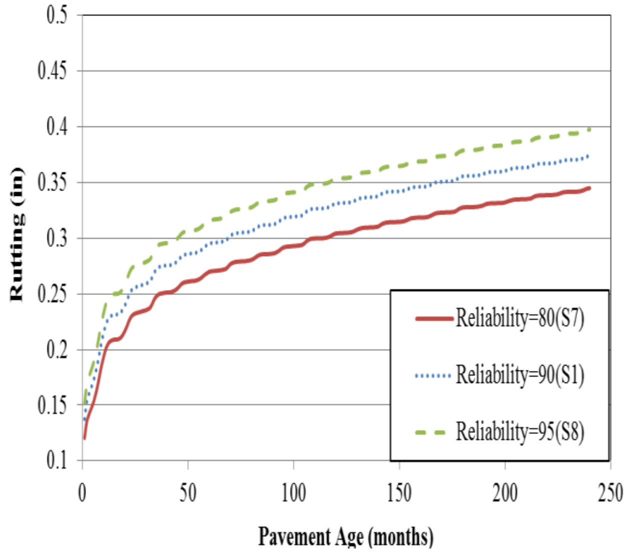

Fig. 8. Effect of Reliability on Rutting.

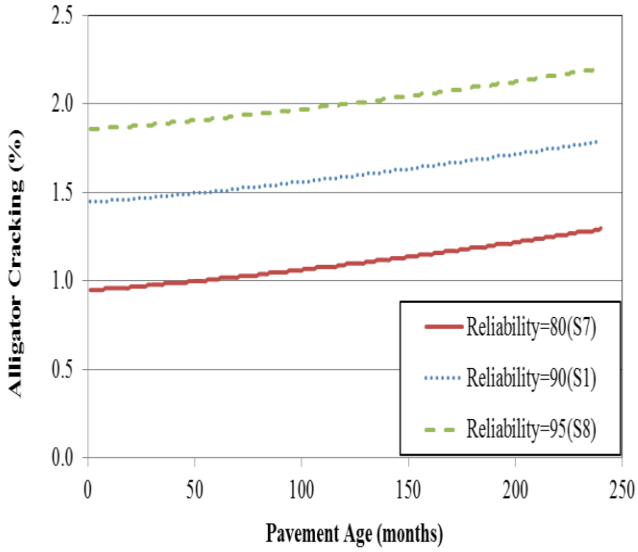

Fig. 9. Effect of Reliability on Alligator Cracking.

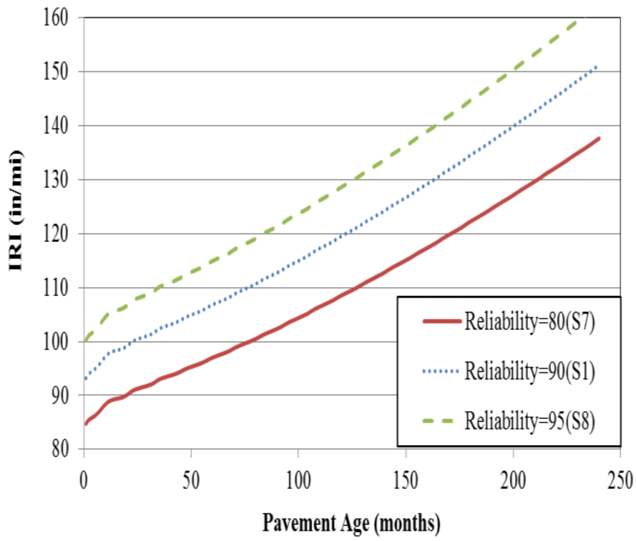

Fig. 10. Effect of Reliability on IRI.

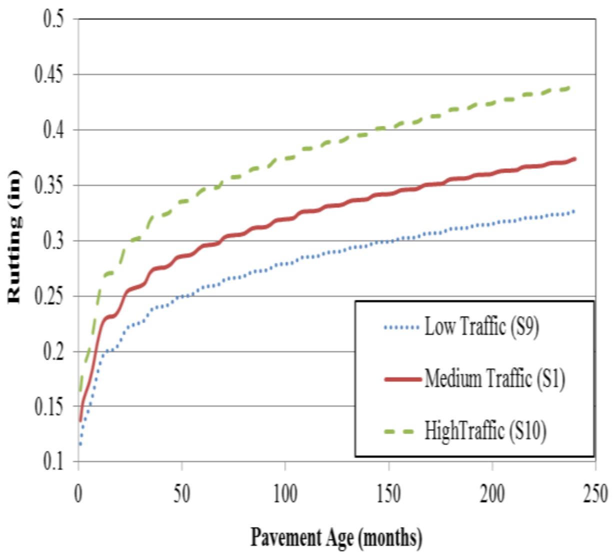

Fig. 11. Effect of Traffic on Rutting.

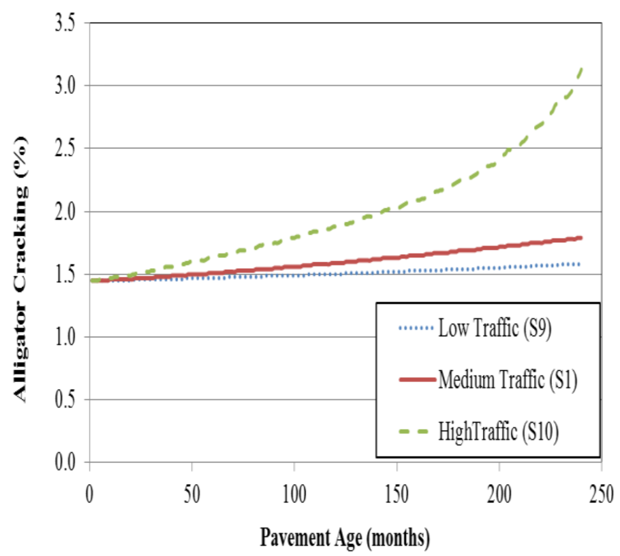

Fig. 12. Effect of Traffic on Alligator Cracking.

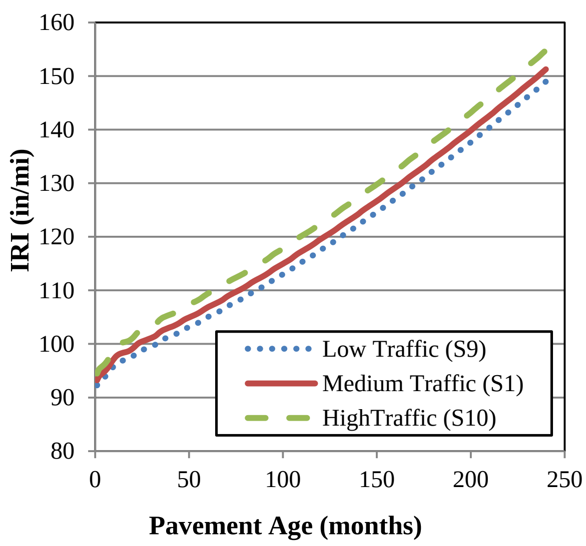

Fig. 13. Effect of Traffic on IRI.

reliability level from 80% to 95% increased IRI values by 18% (from 137 in./mi. to 163 in./mi.) at the end of design period.

Influence of Traffic

As discussed earlier, three different types of input parameters (section S1, S9 and S10) were used for evaluating the sensitivity of MEPDG towards traffic. The influence of traffic on pavement performance in terms of rutting, alligator cracking and IRI values are presented in Figs. 11, 12 and 13, respectively. It is evident from Fig. 11 that rutting value increases with increase in traffic level, as expected. For example, an increase in traffic from low to high level increased rutting value by approximately 63% (from 0.27 in. to 0.44 in.) at the end of design life, i.e., 240 months. On the other hand, alligator cracking showed comparatively less sensitiveness towards change in traffic level. For example, an increase in traffic from low to high level increased amount of alligator cracking from 1.6% to 3.2% after 240 months.

Summary and Conclusions

The influence of four input parameters, namely, climate, modulus values, reliability and traffic level on the performance of selected pavement sections using MEPDG. The performance was evaluated by predicting rutting, percent alligator cracking and IRI. A total of four regions namely, Houston, TX, Oklahoma City, OK, Chicago, IL, and Grand Forks, ND having wide variation in climate were selected. It was found that rut values predicted by MEPDG are sensitive towards climate as rut values increases with increase in temperature. The highest and least amount of percent alligator cracking was found in Houston, TX and Grand Forks, ND which was unexpected trend. However, IRI values showed no significant sensitiveness to climate. The sensitivity towards modulus of subgrade soil was evaluated by designing pavement sections containing 6% lime, 15% class C fly ash (CFA), and 15% cement kiln dust (CKD). The rut values and percent alligator cracking were found highest for 15% CFA followed by 6% lime and 15% CKD. The IRI values showed no significant difference toward modulus of subgrade soil. Both rutting, cracking and IRI showed sensitiveness toward reliability and traffic level. However, cracking was more sensitive towards reliability level and rutting was more sensitive towards traffic level.

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