Technical Paper

ISSN 1997-1400 Int. J. Pavement Res. Technol. 5(4):218-224

Parametric Evaluation of Design Input Parameters on the Mechanistic-Empirical Pavement Design Guide Predicted Performance

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Abstract: The objective of this study was to conduct a sensitivity analysis to identify the input parameters with the greatest effects on the predicted pavement performance from the Mechanistic-Empirical Pavement Design Guide (MEPDG). Three levels of analysis (low, medium, and high) with five input parameters (traffic level, hot-mix asphalt (HMA) thickness, E*, base course thickness, and subgrade type) were evaluated through a full factorial design. The main influence of each individual input parameter and the combinational interaction effects of the input parameters on the predicted distress response were quantified. It was determined that the traffic level input parameter was the main effect on all predicted pavement distresses in the MEPDG. The second main effect for international roughness index (IRI), fatigue cracking, and total pavement rutting was HMA thickness. For asphalt concrete (AC) rutting, the mixture dynamic modulus ranked second for the main effect followed by HMA thickness. For top-down cracking, it was observed that the base course thickness ranked second for the main effect followed by the HMA dynamic modulus. The influence of base thickness on top-down cracking was not expected but it may be due that the MEPDG adopted a traditional fatigue cracking model to describe this failure mechanism.

Key words: *Full factorial design; HMA; MEPDG; Pavement distresses; Sensitivity analysis.*

Introduction

Pavement structures are designed to withstand distresses caused by environmental and traffic loadings. The purpose of the American Association of State Highway and Officials (AASHO) road test constructed in 1958 "was to determine any significant relationship between the number of repetitions of specified axle loads of different magnitudes and arrangements and the performance of different thicknesses of flexible and rigid pavements" [1]. The 1993 American Association of State Highway and Transportation Officials (AASHTO) Pavement Design Guide is based on the results of the AASHO road test. The first issued design guide was in 1961 with major updates in 1972 and 1993. This semi-empirical design method has a number of limitations since it is based on performance measurements in one climatic zone, one subgrade type, two years of accelerated testing, and with the 1950s traffic loads and data analysis capabilities [1]. The 1993 AASHTO design version is still in use today in the state of Louisiana and in most of the United States of America (U.S.) [2].

While the 1993 AASHTO guide has been widely popular in the U.S., there has been an urgent need to develop a more accurate mechanistic-empirical design guide. This urgency is due to increased truck volume and loading, changes in materials, construction techniques, design features, and environmental conditions that affect pavement performance since the original AASHO road test in 1958. To address these needs, the MEPDG was developed to relate mechanistic responses to predicted pavement distresses. As part of the implementation plan for the MEDPG, it is necessary to perform model calibration and a sensitivity analysis to correlate predicted responses with local conditions. Louisiana is actively pursuing implementation of the MEPDG and currently has several active and completed projects that characterize traffic spectra, HMA mixtures, pavement distress value thresholds, and subgrade resilient moduli [3-7].

As part of the implementation plan for the state, this study conducted a full factorial analysis to assess the sensitivity of the design to the MEPDG inputs. Results of this analysis allowed the researchers to determine the main effects of the MEPDG inputs on the predicted pavement performance for flexible pavements. To this end, the main objectives of this study were as follows:

- Utilize a statistically-based full factorial analysis to determine the design factors that influence the predicted performance of flexible pavements against major distresses; and
- Identify the presence of combinational interactive effects in the design process.

Background

The MEPDG is based on mechanistic and empirical components in which the mechanistic component involves the computation and analysis of stresses, strains, and deflections due to the variations in loading and temperature, while the empirical component relates these mechanistic responses to pavement distresses utilizing empirical equations [8-9]. In addition, the MEPDG uses numerical models based on mechanistic-empirical principles to analyze input data from climate, materials, traffic, and proposed structure to estimate the damage caused by pavement distresses over the pavement's service life. These models relate pavement responses to pavement performance and were calibrated based on data obtained from the long-term pavement performance (LTPP) database [10].

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Note: Submitted November 10, 2011; Revised March 31, 2012; Accepted April 10, 2012.

The predicted distresses for flexible pavements are cracking (longitudinal, transverse, and fatigue) and permanent deformation (rutting). The as-designed performance values are compared against threshold values, or comparisons of performance may be made using alternate designs with varying traffic, structure, and materials [8].

Sensitivity Analysis

Prior to implementation of the MEPDG, a calibration and sensitivity analysis should be conducted to address local conditions and to identify relevant factors in the design. The National Cooperative Highway Research Program (NCHRP) has an active project (NCHRP 01-47, "Sensitivity Evaluation of MEPDG Performance Prediction") that will determine the sensitivity of the predicted MEPDG performance to the variability of input parameter values for flexible and rigid pavements. In addition, a number of studies have investigated the influence of variations in axle loads and traffic inputs on the MEPDG predicted flexible pavement distresses [11-16].

Kim et al. conducted a study to evaluate the sensitivity of MEPDG to asphalt cement, traffic, and climatic input parameters for two Iowa flexible pavement designs [10]. Five MEPDG performance measures (longitudinal cracking, alligator cracking, thermal cracking, rutting, fatigue cracking, and smoothness) were evaluated by varying either a single input or two inputs at a time. It was concluded that increasing layer thickness to reduce distresses is not the only solution in the MEPDG. In addition, asphalt cement performance grade (PG) binder, volumetric properties, climate, annual average daily truck traffic (AADTT), and type of base generally influenced most of the predicted measures of performance. Mohammad et al. reported that the predicted rut depths from the MEPDG software followed the same trend found in the dynamic modulus test results at high temperatures [17]. Aguiar-Moya et al. found a considerable change in the predicted fatigue cracking performance as the layer thickness was changed within ± 3 standard deviations of the mean thickness [18].

Thyagarajan et al. reported that there has been a number of sensitivity analysis studies conducted on predicted critical distresses from the MEPDG, but these studies have two key drawbacks [19]: (a) the analysis may be project-specific, and (b) the sensitivity analysis varies input parameters one-at-a-time, which results in the inability to consider the correlations between different input variables and the combined influence of input parameters on the predicted distresses being evaluated.

Sensitivity analysis methods can be grouped into three methods [20]: (a) screening methods, (b) local sensitivity analysis, and (c) global sensitivity analysis. Screening methods generally provide no quantifiable information regarding the importance of one factor over another. However, this method usually provides a ranking of importance of input factors. The local sensitivity analysis method varies one input variable at a time while holding the remaining factors constant. The global sensitivity analysis method varies the input parameters across the entire input spectrum. It is further recognized that other sampling-based methods such as Monte Carlo and Latin hypercube sampling of the input parameters were shown to be effective in the sensitivity evaluation of the complex modulus.

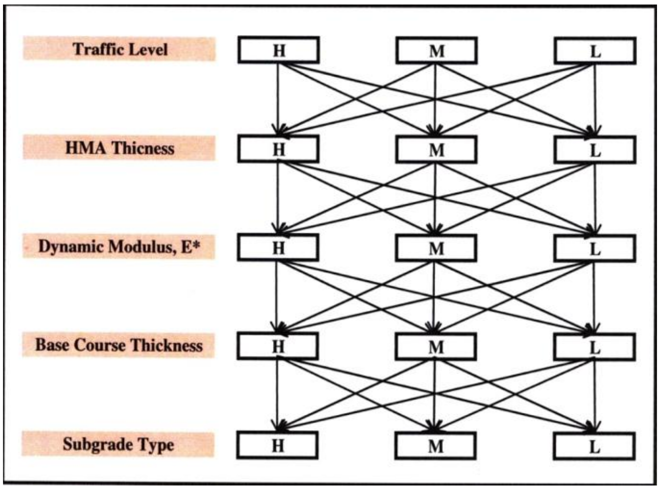


Fig. 1. General Layout of the Full Factorial Design.

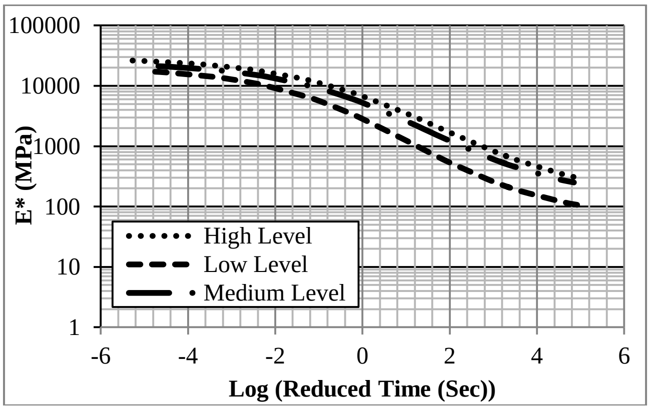


Fig. 2. Dynamic Modulus Master Curves.

Statistically Based Factorial Design

A full factorial design is used to determine the effects of two or more factors on the response variable (in this case, pavement performance against major distresses) as well as the influence of interactions between factors on the response variable. The use of a statistically based factorial design method allows the variation of more than one input parameter at a time according to the factorial design. While a full factorial design may be used to assess high order interactions, a system is usually dominated by the main effects and the low-order (two-way) interactions. The influence of higher order interactions such as three-factor interactions is very rare [21].

Factorial Design

The developed factorial design consisted of three levels of analysis (low, medium, and high) with five input factors, see Fig. 1. The combination of varying three levels of analysis with five input factors resulted in a full factorial design of 35 = 243 MEPDG analysis runs. The levels of analysis were based on actual measured data for the MEPDG model inputs. The pavement structures evaluated in this study were a three-layer system consisting of HMA, base course, and subgrade. The measured data included: (a) dynamic modulus values (Fig. 2), asphalt binder properties, and HMA mixture properties that were obtained for three typical

Table 1. Levels and Factors Descriptions.

Factor Description	Factor ID	Low Level	Medium Level	High Level
Traffic Level (Two-Way AADTT)	x_1	816	1,992	14,554
HMA Thickness mm (inches)	x_2	50.8 (2.0)	101.6 (4.0)	203.2 (8.0)
Dynamic Modulus, E*	x_3	Low E* Values	Medium E* Values	High E* Values
Base Course Thickness mm (inches)	x_4	152.4 (6.0)	304.8 (12.0)	457.2 (18.0)
Subgrade Type	x_5	A-4 Clayey-Silt	A-6 Clay	A-3Sand
Subgrade Resilient Modulus, M_r MPa (ksi)[1]		51.9 (7.5)	71.7 (10.4)	168.9 (24.5)

[1]Adopted from [22]

Table 2. SAS Fractional Factorial Design Output.

Run Number	Input Parameters					Run ID
	x_1	x_2	x_3	x_4	x_5	
1	-1	-1	-1	-1	-1	R_1
2	-1	-1	-1	0	1	R_2
3	-1	-1	-1	1	0	R_3
4	-1	-1	0	-1	1	R_4
…	…	…	…	…	…	…
…	…	…	…	…	…	…
242	1	1	1	0	1	R_{242}
243	1	1	1	1	0	R_{243}

mixtures used in Louisiana [17]; (b) the unbound granular base course, subgrade material (clay, clayey-silt, and sand), and resilient modulus properties were obtained from Mohammad et al. [22], Table 1; and (c) the traffic spectra and truck distribution was reported by Ishak and Shin from measurements in Louisiana [7]. The climatic data input used for MEPDG analysis was for Baton Rouge, Louisiana as defined in the MEPDG model. Table 1 presents the three levels of analysis for each input factor evaluated in this study.

Methodology

The main objective of the factorial design was to determine which input parameters have the greatest effect on pavement performance against the main distresses using the least amount of runs. The Statistical Analysis Software (SAS) PROC FACTEX feature was utilized to develop the full factorial design. Table 2 shows a sample of the factorial design output obtained from SAS. In this table, the low level is designated by -1, the medium level is designated by 0, and the high level is designated by 1. The definition of the factors x_1, x_2, x_3, x_4, and x_5 is given in Table 1. The input parameters were used in the MEPDG software in accordance with the design matrix obtained from SAS. As part of the input parameters, simulations were based on a 20-year design life, a 4 percent growth rate, and performance criteria evaluated at 90 percent reliability. An analysis from the MEPDG results was then performed to determine the main effects of the input parameters on pavement performance against the main distresses.

The influence of the input parameters (traffic level, HMA thickness, dynamic modulus, base thickness, and subgrade modulus) on pavement performance was quantified. The main effect of a given factor x_i is a measure of the change in response due to a change in an individual factor. The main effect for each factor was determined based on the following equation:

$$e_i = \frac{\sum_{i=1}^{n} d_{ik} R_{in}}{n} \tag{1}$$

where,
e_i = main effect for factor i = 1, 2, 3, 4, and 5;
n = number of design runs (n = 243);
R = response from each run; and
d_{ik} = ± sign for factor k in run i.

For example, to calculate the main effect, e_4, for input parameter x_4, the following equation was used:

$$e_4 = \frac{(-1)R_1 + (0)R_2 + (1)R_3 + (-1)R_4 + \cdots + (-0)R_{242} + (1)R_{243}}{243} \tag{2}$$

The interactions between the five input parameters were also quantified because the effect of factor xi could depend in some way on the level of another factor x_j. This is called a two-way interaction effect and is denoted by e_{jk}.

The two-way interaction effects were determined based on the following equation:

$$e_{jk} = \frac{\sum_{i=1}^{n} (d_{ij})(d_{ik})(R_{in})}{n} \tag{3}$$

where,
e_{jk} = two-way interaction effect for factor jk;
n = number of design runs (n = 243);
R = response for each run;
d_{ij} = ± sign for factor j in run i; and
d_{ik} = ± sign for factor k in run i.

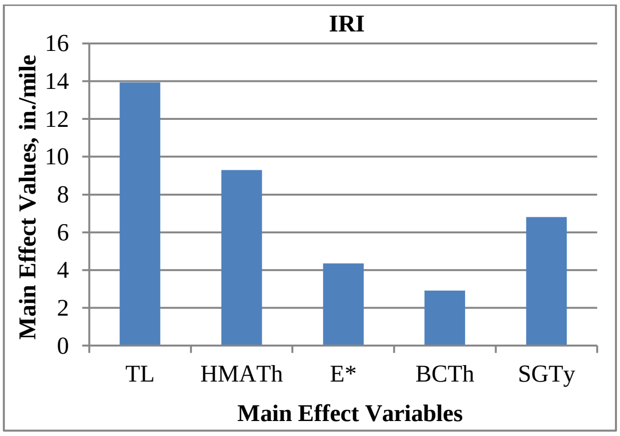
For example, to calculate the two-way interaction between factor x_3 and x_4, the following equation was used:

$$e_{34} = \frac{(1)R_1 + (0)R_2 + (-1)R_3 + (0)R_4 + \cdots + (0)R_{242} + (1)R_{243}}{243} \tag{4}$$

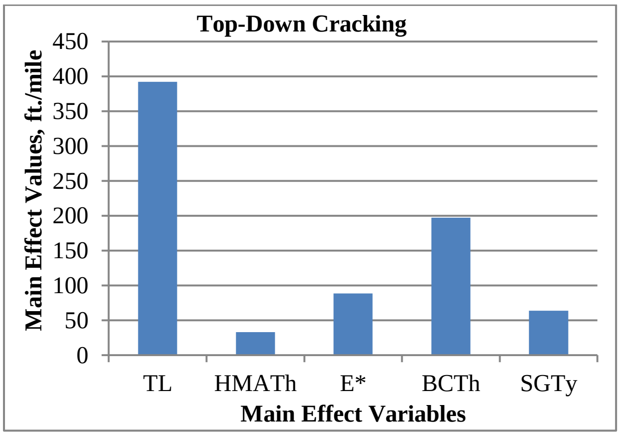
The sign for each response was obtained by multiplying the level designations from Table 2 for the two factors for which the interaction was calculated [23].

Results and Analysis

The MEPDG software was used to predict pavement performance against the major distresses (IRI, top-down cracking, fatigue cracking, AC rutting only, and total rutting) for the 243 cases evaluated in the factorial design. A summary of the main effects and the two-factor (two-way) interaction effects of the input parameters on the MEPDG predicted pavement distresses are provided in the following sections for the three levels and five factors evaluated in this study.



(a)



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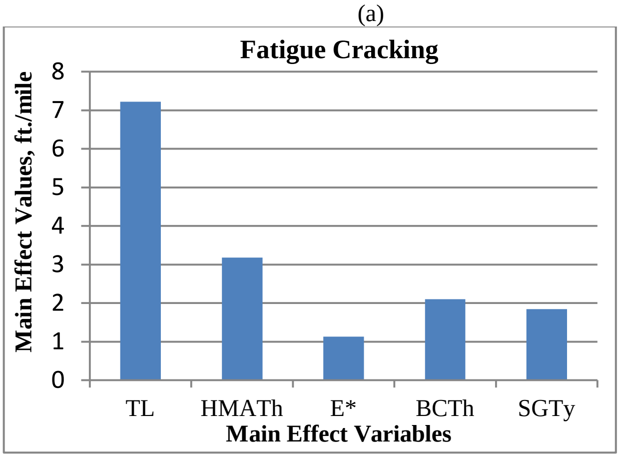

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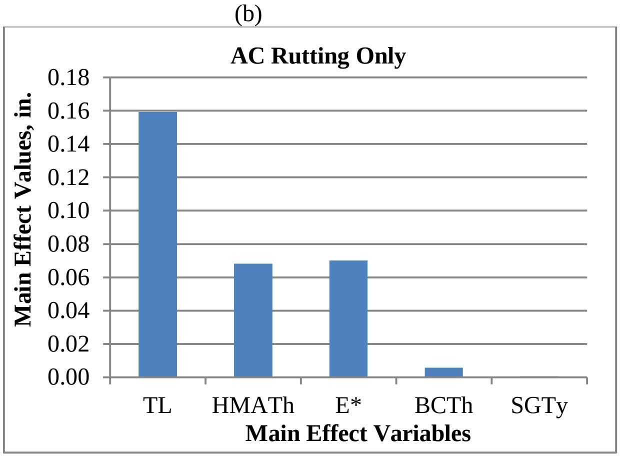

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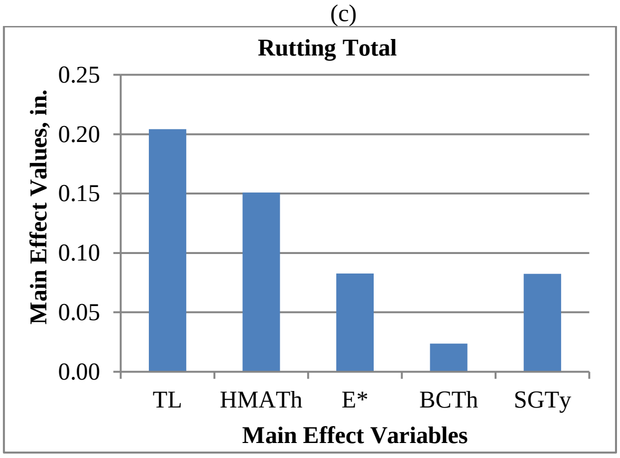

(e)

- TL: Traffic level,
- HMATh: HMA thickness,
- E*: Dynamic Modulus, E*,
- BCTh: Crushed limestone base course thickness, and
- SGTy: Sub-grade type.

Fig. 3. Summary of the Main Effects Analysis.

Summary of the Main Effects Analysis

Fig. 3 presents the main effects of the five input variables on the MEPDG predicted distresses of IRI, top-down cracking, fatigue cracking, AC rutting, and total pavement rutting. It was observed that the traffic level input variable was the main effect for all MEPDG predicted distresses. Although the traffic level was found to be the main effect, the designer has no control over traffic volume and evaluation of the other variables will identify the controllable inputs with the greatest influence on the predicted pavement distresses. Fig. 3(a) shows the main effects for the IRI predicted distress. In this figure, it is observed that the HMA thickness has the second main effect on IRI, followed by the subgrade strength.

Fig. 3(b) illustrates the main effects for top-down cracking. It is shown in this figure that the base course thickness has the second main effect on top-down cracking, followed by the HMA dynamic modulus. This observation was unexpected since this type of cracking is related to high tensile stresses at the top of the pavement surface. Therefore, one would hypothesize that HMA properties would have a significant effect on top-down cracking in lieu of base course thickness. This unexpected result may due that the MEPDG adopted a traditional fatigue model for predicting top-down cracking. Roque et al. reported that top-down cracking cannot be described by traditional fatigue models that are used to explain bottom-up fatigue cracking, which initiates at the bottom of the HMA layer [24].

Fig. 3(c) illustrates the main effects for fatigue cracking. This figure illustrates that HMA thickness has the second main effect on fatigue cracking followed by base course thickness, and subgrade type. Fig. 3(d) shows the main effects on AC rutting. It was observed that both E* and HMA thickness had an influential effect on AC rutting. These results agree with previous findings in the literature [17]. The main effect on the predicted total pavement rutting is illustrated in Fig. 3(e). Fig. 3(e) shows that HMA thickness followed by E* and subgrade type had an influence on total pavement rutting.

Table 3 presents the ranking of the main effects for the five input factors on the MEPDG predicted pavement distress responses. It is shown that the traffic level input variable is ranked first for all MEPDG predicted distresses. With the exception of top-down cracking, input parameters related to the top HMA layer appear influential on the predicted pavement performance. For the top-down cracking distress response, it was shown that the base course thickness is ranked second, the HMA dynamic modulus is third, and the HMA thickness is ranked last. This was not expected because the top-down cracking phenomenon should be highly correlated to the top layer and its ability to resist high stresses at the surface.

Table 3. Ranking of Main Effects on Predicted Pavement Distresses

Factor / Distress	TL	HMATh	E*	BCTh	SGTy
IRI	1	2	4	5	3
Top-Down Cracking	1	5	3	2	4
Fatigue Cracking	1	2	5	3	4
AC Rutting Only	1	3	2	4	5
Rutting Total	1	2	3	5	4

TL: Traffic level; HMATh: HMA thickness; E*: Dynamic Modulus, BCTh: Crushed limestone base course thickness; SGTy: Subgrade type.

Summary of the Two-Way Interaction Effects Analysis

Table 4 shows the combinational two-way interaction effects for the five input factors on the MEPDG predicted pavement distress responses. For the IRI predicted pavement response, it was observed that the combinational interaction of the traffic level and HMA thickness input parameters was ranked first, followed by traffic level and E*, and then base course thickness and subgrade type, respectively. For the top-down cracking, it was observed that the traffic level and base course thickness input variables had a combined two-way interaction that may influence top-down cracking pavement performance. This interaction was then followed by base course thickness and subgrade type and then traffic level and subgrade type, respectively. As previously discussed, the combined influence of these input parameters was not expected and may need to be addressed in future versions of the design guide.

For fatigue cracking, the traffic level and HMA thickness had the major two-way interaction effect on this distress. This two-way interaction was followed by both traffic level and base course thickness and traffic level and subgrade, which also had a combined effect on fatigue cracking. For AC rutting, the two-way interaction between HMA dynamic modulus and traffic level had the main combined effect followed by traffic level and HMA thickness and HMA thickness and base thickness. This trend was anticipated as both traffic level and HMA properties are expected to control the pavement performance against AC rutting. For total pavement rutting, traffic level and HMA thickness had the greatest combined influence on this distress type. It was also observed that traffic level and base course thickness followed by traffic level and subgrade type had a combined effect on total pavement rutting.

Conclusions

A sensitivity analysis study was conducted to assist the designer in identifying the input parameters with the greatest effects on the

Table 4. Ranking of Predicted Distresses Combinational Interaction Effects.

Factor / Distress	TL/ HMATh	TL/E*	TL/ BCTh	TL/ SGTy	HMATh/ E*	HMATh /BCTh	HMATh/ SGTy	E*/ BCTh	E*/ SGTy	BCTh/ SGTy
IRI	1	2	4	5	10	7	6	8	9	3
Top-Down Cracking	6	3	1	4	8	9	10	5	7	2
Fatigue Cracking	1	6	2	3	8	5	7	9	10	4
AC Rutting Only	2	1	8	10	5	3	4	9	6	7
Rutting Total	1	8	3	2	4	5	6	10	9	7

- TL/HMATh: Traffic level & HMA thickness,
- TL/E*: Traffic level & Dynamic Modulus, E*,
- TL/BCTh: Traffic level & Crushed limestone base course thickness,
- TL/SGTy: Traffic level & Subgrade type,
- HMATh/E*: HMA thickness & Dynamic Modulus, E*,
- HMATh/BCTh: HMA thickness & Crushed limestone base course thickness,
- HMATh/SGTy: HMA thickness & Subgrade type,
- E*/BCTh: Dynamic Modulus, E* & Crushed limestone base course thickness,
- E*/SGTy: Dynamic Modulus, E* & Subgrade type, and
- BCTh/SGTy: Crushed limestone base course thickness & Subgrade type.

A sensitivity analysis study was conducted to assist the designer in identifying the input parameters with the greatest effects on the predicted pavement performance from the MEPDG. Three levels of analysis (low, medium, and high) with five input parameters (traffic level, HMA thickness, E*, base course thickness, and subgrade type) were evaluated through a full factorial design. The main influence of each individual input parameter and the combinational interaction effects of the input parameters on the predicted distress response were determined. The following conclusions are drawn based on the results of this study:

- Traffic level ranked first for the main effect on all predicted pavement distresses.
- For IRI, HMA thickness ranked second on the main effect followed by subgrade strength. The combinational two-way interaction on IRI indicated traffic level and HMA thickness input parameters ranked first, followed by traffic level and E*, and then base course thickness and subgrade type, respectively.
- For fatigue cracking, HMA thickness ranked second for the main effect followed by base thickness. The combinational two-way interaction effect was traffic level and HMA thickness, followed by traffic level and base course thickness, and then traffic level and subgrade type.
- For total pavement rutting, HMA thickness ranked second for the main effect followed by the dynamic modulus. The combinational interaction analysis indicated that traffic level and HMA thickness ranked first, followed by traffic level and subgrade type, and then traffic level and base course thickness, respectively.
- For AC rutting, dynamic modulus, E*, ranked second for the main effect followed by the HMA thickness. It was observed that the traffic level and E* combinational interaction ranked first, followed by the traffic level and HMA thickness interaction.
- For top-down cracking, it was observed that the base course thickness ranked second for the main effect followed by HMA dynamic modulus. The combinational interaction effect of the traffic level and base course thickness ranked first, followed by the base course thickness and subgrade type. These observations were not expected, but it may be explained by the fact that the MEPDG adopted a traditional fatigue cracking model to evaluate the top-down cracking distress.

Acknowledgements

The authors would like to acknowledge Farshad Hashemian and Ahmed Abdel-Khalek who provided valuable assistance with this study.

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