Evaluation of M-E PDG for Rigid Pavements—Incorporating the State-of-the-Practice in Michigan

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Abstract

The adoption and implementation of the Mechanistic-Empirical Pavement Design Guide (M-E PDG) by various state highway agencies requires validation and calibration of its performance models. However, to facilitate the use of the guide, sensitivity analyses are warranted as a preliminary step. Such an analysis will identify significant input variables required for the design process. The results from the sensitivity analysis will also highlight the needs for resources required to quantify the input variables. Subsequently, the calibration of performance models will assist the state highway agencies to customize the design process to reflect local practices. This paper highlights the evaluation of the current performance models for jointed plain concrete pavements (JPCP) for the state of Michigan. The sensitivity analyses involved: (a) preliminary sensitivity—one variable at a time, (b) detailed analysis—full factorial. Both analyses reflect the local design and construction practices in Michigan. The purpose of the preliminary sensitivity investigation was to prepare a short-list of significant variables. The abbreviated variables were further refined based on engineering judgment and local practices while levels of the significant variables were selected based on the local design practices. In the detailed analysis, the full factorial multivariate analyses were conducted to highlight both main and interaction effects between input variables on rigid pavement performance. Finally, it is highlighted that the interactions among input variables play an important role while interpreting the pavement performance from the design perspective.

Introduction

Recognizing the limitations of the 1993 AASHTO design guide and the need for improvement in the pavement design process, the NCHRP project 1-37A was initiated to develop a pavement design guide for new and rehabilitated pavements based on mechanistic-empirical (M-E) approaches. The initial step in adopting the new M-E PDG by state highway agencies (SHAs) requires a comprehensive evaluation of the M-E PDG for both rigid and flexible pavements. The findings from this evaluation will determine the impact of the various inputs (material, traffic, construction and climatic) on pavement performance prediction. In addition, identifying a list of input variables, having a significant impact on pavement performance, will determine the amount

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of "new" data collection that SHAs will have to engage in. Guidance with respect to practical ranges of significant inputs will demonstrate viability and robustness of the performance models.

The M-E PDG Software was made public in 2004. Since that time many SHAs are working to explore various aspects of this new design and analysis procedure. This ongoing research effort generally involves: input variable sensitivity to determine the most important inputs, local calibration of performance models and implementation issues. Several SHAs have sponsored studies for the preliminary sensitivity analyses of M-E PDG. For example, Iowa, Indiana, California, Arkansas, Kansas, Kentucky and Texas (Galal and Chehab 2005; Guclu and Ceylan 2005; Hall and Beam 2005; Kannekanti and Harvey 2005; Khanum et al. 2005; Uzan et al. 2005) were among the lead states for such work. However, the majority of these investigations were based on theoretical basis where the impact of each input variable was assessed by varying its magnitude considering all other variables at a constant level. Such analyses are useful only in studying the effect of one variable at a time for the considered levels (magnitude) on pavement performance. On the other hand, certain input variables may interact with each other in explaining their effects on pavement performance; therefore, it is essential to consider the interaction between input variables. In addition, for the sensitivity analyses, the state-of-the-practice in a particular state must be considered for designing pavements. Incorporating the local experience will not only enhance the prospects for implementation of the M-E PDG but will also give more confidence to SHAs in adopting the state-of-the-art analysis and design procedures. This study documents a practical way of selecting variables for the M-E PDG from a SHA perspective.

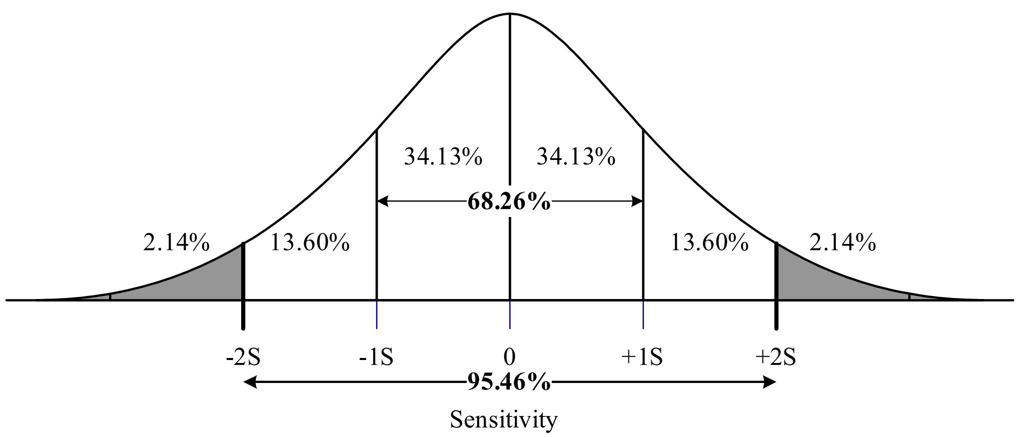
Considering the local experience for Michigan, it was necessary that various input variables reflect the state-of the-practice. Furthermore, there was a need to evaluate and verify the national calibrated performance models within these practical ranges. The objectives of this paper are to: (a) evaluate the M-E PDG rigid pavement design procedure for Michigan conditions; (b) identify the most important design variables considering the state-of-the-practice in Michigan, and; (c) highlight the interactive relationships between input variables. The accomplishment of these objectives will pave the way in the prospective implementation of this new pavement design procedure in Michigan.

Evaluation of M-E PDG for Michigan Conditions

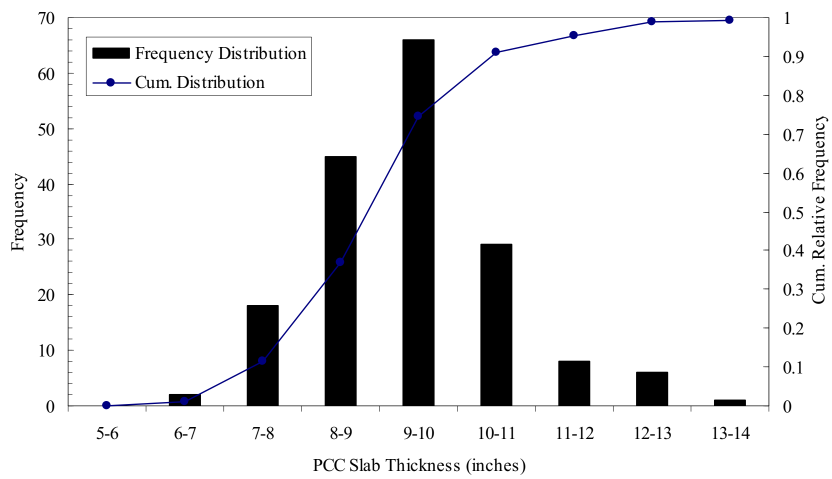
The M-E PDG requires detailed information on several input variables. In order to identify the variables which significantly affect the performance prediction, sensitivity analyses are essential. The approach used to conduct the sensitivity analysis in this research includes: (1) one variable at a time to investigate the effect of individual input variables on performance (preliminary sensitivity analyses), and (2) full factorial design matrix to investigate the interaction effects of input variables on performance (detailed sensitivity analyses). The first task involves a preliminary analysis for each input variable to eliminate the less significant variables while the second task deals with detailed analyses including interaction between sensitive variables identified by the first task. The analyses involved in the above two tasks are presented below.

Preliminary Sensitivity Analyses. For conducting preliminary sensitivity analysis, each variable was assigned different levels. These levels were decided based on the practical ranges from in-service pavements in the Long Term Pavement Performance (LTPP) data, as explained below.
Input variable ranges. A series of frequency histograms were plotted for each input variable for which the data were available in the LTPP DataPave (Release 19.0). From these histograms the

average values were identified. The distributions also provide information about “extreme” values (□ ± 2□□ for each input variable (see Figure 1a). These extreme values were used to conduct the sensitivity while the mean values for input variable distributions were used for the base design. For non-normal distributions, 25th and 75th percentile values were used instead. For example, the mean PCC slab thickness within the GPS-3 experiment is 8 to 9-inch and the extreme values are 7 and 14-inch (see Figure 1b). It should be noted that not all required input variables data were available in the LTPP database. Therefore, in those cases, the lower and upper levels of ranges provided in the M-E PDG software were used.



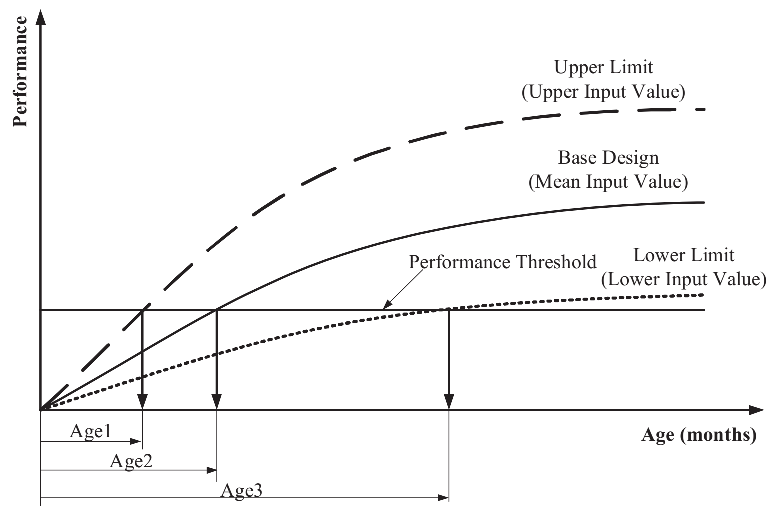
(a) Extreme values for normal distribution



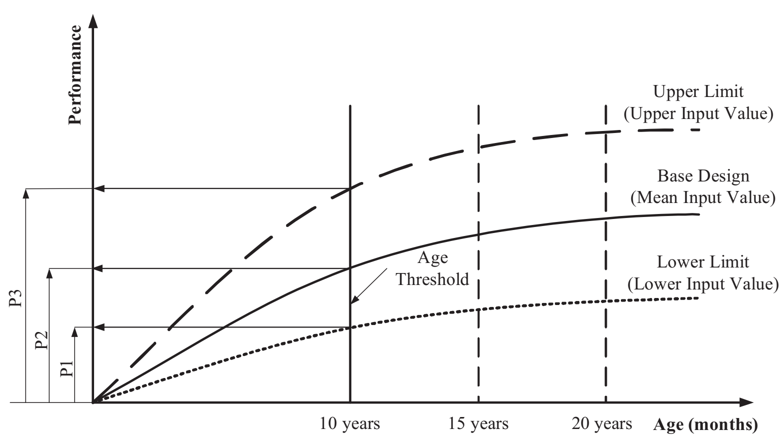
(b) Example of slab thickness distribution

Figure 1 Ranges for sensitivity of input variable

Practical significance of input variables. To determine the significance of input variables, rather than using subjective criteria based on visual inspection, a more practical approach based on performance thresholds was adopted in this study. Two methods can be used to determine the significant effects: (a) performance threshold, and (b) age threshold. For performance threshold, acceptable failure criteria can be employed for various performance measures. Figure 2 (a) shows the ages corresponding to a given performance threshold for the input level of a variable. From these ages significance (statistical and practical) can be determined. For example, if the difference in ages is more than 5 years, one can consider this variable as having a significant effect. On the other hand if the difference is less than 5 years, one can assume less significant effect. For the age threshold, the performance for each variable input level can be determined based on age as shown in Figure 2 (b). In this research age threshold criteria were used. The difference in performances at a particular age (10, 15 or 20 years) were compared to the common characteristics (normal-poor) of pavement performance (Khazanovich et al. 1998; Rauhut et al. 1999).



(a) Performance Threshold



(b) Age Threshold

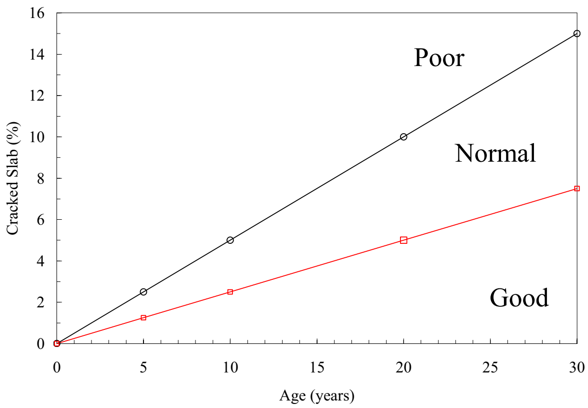
Figure 2 Illustration of input variables effects on pavement performance

Performance thresholds. In this investigation, performance criteria developed by the Federal Highway Administration (FHWA), based on age threshold were modified to reflect MDOT practice and were used to determine the practical significance of an effect on cracking, faulting and IRI. The FHWA performance criteria between normal-poor were extracted for different performance measures (see Table 1). The normal-poor performance threshold was used to assess the practical significance of an effect, as shown in Figure 3.

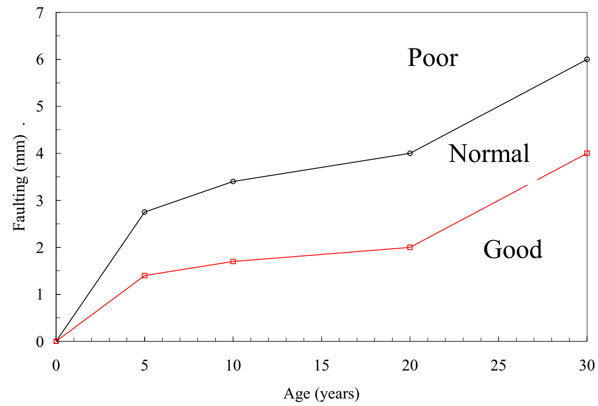
Table 1 Rigid pavement performance criteria at different ages

Performance Measure	Criteria	Pavement Age (years)				
		0	*5*	*10*	*20*	*30*
Cracking (% Slab Cracked)	Good-Normal	0	1.25	2.5	5	7.5
	Normal-Poor	0	2.5	5	10	15
	□	*0*	*1.25*	*2.5*	*5*	*7.5*
	Increase/year		0.5	0.5	0.5	0.5
	Weighted Avg. (Increase/year)	0.5				
Faulting (mm)	Good-Normal	0	1.4	1.7	2	4
	Normal-Poor	0	2.75	3.4	4	6
	□	*0*	*1.35*	*1.7*	*2*	*2*
	Increase/year		0.55	0.13	0.06	0.2
	Weighted Avg. (Increase/year)	0.2				
IRI (m/km)	Good-Normal	0.7	0.9	1.2	1.9	2.2
	Normal-Poor	1.2	1.75	2.1	3	3.45
	□	*0.5*	*0.85*	*0.9*	*1.1*	*1.25*
	Increase/year		0.11	0.07	0.09	0.045
	Weighted Avg. (Increase/year)	0.075				

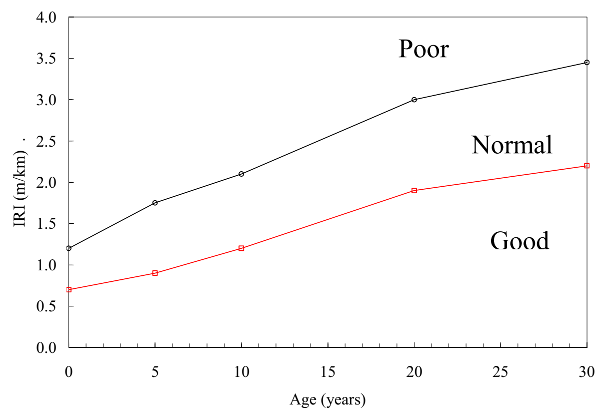
Variable identification. Based on the preliminary sensitivity results, a list of 25 sensitive (practically significant) input variables (characterizing environment, traffic, and pavement materials, etc) was established as listed in Table 2. It should be noted that these variables were identified by the preliminary sensitivity by considering three levels for each variable as mentioned before. This list does not reflect the state-of-the-practice in Michigan and is entirely based on the theoretical results (predicted performance by M-E PDG). Certain variables can not be determined at the design stage; for example, it is not clear for the design engineer to identify permanent curl/wrap effective temperature difference and surface shortwave absorptivity for a particular site. However, these input variables significantly affect the predicted pavement performance. Consequently, these variables were not considered and their default values in M-E PDG were adopted in further analysis. Perhaps there is a need to quantify these variables by adopting some testing protocols in the future.



(a) Percent slab cracked



(b) Joint or crack faulting



(c) Roughness in terms of IRI

Figure 3 Adopted performance criteria for JPCP

Several other similar M-E PDG evaluation studies (Ceylan et al. 2006; Guclu and Ceylan 2005; Hall and Beam 2005; Kannekanti and Harvey 2005; Kannekanti and Harvey 2006) have identified the same input variables (see Table 2) based on their important effects on the rigid pavement predicted performance. However, the impact of each variable may vary for a particular performance measure (i.e., cracking, faulting and roughness).

The state-of-the-practice in Michigan based on the observed pavement performance highlights the need to use a uniform joint spacing in all the new JPCP pavements. Therefore, the joint spacing is typically fixed between 14 to 16 feet depending on the PCC slab thickness. While higher joint spacing (up to 16 feet) is adopted for a thicker slab (up to 14 inches), the dowel diameter also depends on PCC slab thickness. Higher dowel diameter (1.5 inches) is used for a thicker PCC slab. Typical geology of aggregates in Michigan needs to be considered for allocating a coefficient of thermal expansion (CTE) for concrete pavements. Also, typical soil support in terms of subgrade moduli were also adopted in this analysis. The effects of adopting the state-of-the-practice in Michigan on the detailed evaluation of the M-E PDG are described in the next section.

Table 2 List of sensitive input variables from preliminary sensitivity—JPCP

Category		Input variable	Levels
Traffic		AADTT	Low, Medium and High
		Axle Load Spectra	Low, Medium and High
		Monthly Adjustment Factors	Low, Medium and High
		Hourly Adjustment Factors	Low, Medium and High
Design		Permanent Curl/Warp Effective Temperature Difference	-10
		Joint Spacing (ft)	10, 15 and 25
		Edge Support	Tied, Asphalt and Widened
		Dowel Diameter (in)	1, 1.25 and 1.5
		Dowel Spacing (in)	10, 12 and 15
Surface Properties		Surface Shortwave Absorptivity	0.85
Materials	PCC	PCC Slab Thickness	7, 9 and 14
		CTE (per ^oF)	4×10^{-6}, 5.5×10^{-6} and 7×10^{-6}
		Thermal Conductivity (BTU/hr-ft-^oF)	0.2, 1.25 and 2
		PCC Zero-stress Temperature (^oF)	70, 98 and 125
		fc' (Compressive Strength, psi)	3000, 5000 and 8000
		MOR (Modulus of Rupture, psi)	450, 750 and 1200
		Elastic Modulus (psi)	2×10^6, 4×10^6 and 6×10^6
	Base/Subbase	Base Type	Granular Base and Asphalt Treated
		Base Thickness (in)	2, 6 and 10
		Passing # 200	0, 8 and 15
		Plasticity Index	0, 3 and 6
	Subgrade	Soil Type	A-7-6, A-4 and A-1-a
		Passing # 200	30, 60 and 90
		Plasticity Index	0, 5 and 10
Environmental		Different Climatic Regions	Extreme and Moderate

Note: Excluding two variables—Permanent curl/warp effective temperature difference and surface shortwave absorptivity, there are remaining 23 variables in the above list to be considered for further analysis.

Detailed Sensitivity Analyses. For a full factorial design, a complete test of 23 variables, each at three levels, requires $3^{23} = 9.4 \times 10^{10}$ tests (runs) which is impractical given the time and financial constraints. Therefore, it was decided to reduce the number of variables (based on engineering judgment and MDOT practice) and their levels to decrease the number of runs within an achievable practical limit. This was accomplished by adopting the following strategies:

1. Conducting separate satellite sensitivity studies for certain important variables such as traffic.
2. Considering the variables that can be controlled at the design stage, such as joint spacing, edge support and slab thickness. It is important to note that as some variables such as subgrade type and traffic are site dependent, the designer may not have a choice to vary them; however, design variables can be selected to fulfill the requirements for a particular site.
3. Adopting only surrogate variables. For example, the compressive strength, *fc'*, is correlated with flexural strength, hence only the flexural strength was considered in the analysis.

Based on the above strategies and further discussions with MDOT engineers regarding their state-of-practice for rigid pavements, the input variables were further reduced. For example, in practice, the dowel diameter and spacing are generally not varied. Table 3 shows the final input variables along with their levels for detailed sensitivity analysis. The factorial consists of six variables at two levels and the environment has three levels. This combination results in a full factorial with 192 runs ($2^6 \times 3$). The key objective for the detailed sensitivity by employing a full factorial design was to establish the statistical and the practical significance of main and interactive effects among input variables. The statistical significance was established from the results of analysis of variance (ANOVA), i.e., a *p-value* of less than 0.05 (a confidence level of 95%) while the practical significance was established by comparing the mean differences between the levels of input variables and comparing them with the threshold for a particular distress at a given age (see Table 1). A brief discussion of these results is presented next.

Discussion of results for detailed sensitivity analyses. Table 4 summarizes the runs required within each cell of the full-factorial matrix. These runs were executed to capture pavement performance curves (cracking, faulting and IRI). Once all the desired runs were completed, a database was prepared to study the input variables effects on various distresses. Using this database detailed statistical analyses were conducted for each rigid pavement predicted performance measure. The distress magnitudes at 5, 10, 20 and 30 years were used to conduct Analysis of Variance (ANOVA). In this analysis, all main effects and all possible two-way interactions were considered between seven variables.

In the detailed analyses, the descriptive statistics such as mean performance for each input variable were summarized initially. However, as the differences in the means might not ascertain a significant difference, essentially due to uncertainty (variability) associated with the means. Statistical analyses using ANOVA were performed for all performance measures.

To investigate the average effects of all input variables on cracking, time series data were plotted for different input variable levels. For example, Figure 4 presents the effects of input variables on percent slab cracked. It is evident from Figure 4 (a), that the effect of slab thickness, as expected, is very significant on cracking. Rigid pavements with thin slab thickness showed more cracking than those with thick slabs. Also, this effect is more pronounced over a longer life of a pavement.

Table 3 Final variable list for JPCP incorporating Michigan state-of-the-practice

<table>
<tr><th colspan="2">Category</th><th>Surrogate Variable</th><th>Levels</th><th>Remarks</th></tr>
<tr><td colspan="2" rowspan="2">Design</td><td>Edge Support</td><td>12 ft tied shoulder
versus
14 ft asphalt shoulder</td><td>2 Levels[4]</td></tr>
<tr><td>PCC Slab Thickness</td><td>9 inches
(Joint Spacing = 14 ft)
(Dowel Diameter = 1.25 in)
(Dowel Spacing = 12 in)
versus
14 inches
(Joint Spacing = 16 ft)
(Dowel Diameter = 1.5 in)
(Dowel Spacing = 12 in)</td><td>2 Levels[5]</td></tr>
<tr><td rowspan="4">Materials</td><td rowspan="2">PCC</td><td>CTE (per ^{o}F)</td><td>4×10^{-6}
versus
6.5×10^{-6}</td><td>2 Levels[6]</td></tr>
<tr><td>MOR
(Modulus of Rupture, psi)</td><td>450
versus
900</td><td>2 Levels[7]</td></tr>
<tr><td>Base/Subbase</td><td>Base Type</td><td>Granular Base
versus
Asphalt Treated</td><td>2 Levels[8]</td></tr>
<tr><td>Subgrade</td><td>Soil Type</td><td>A-7-6 (fine)
versus
A-1-a (Coarse)</td><td>2 Levels[9]</td></tr>
<tr><td colspan="2">Environmental</td><td>Different Climatic Regions</td><td>Lansing
Pellston
Detroit</td><td>3 Levels[10]</td></tr>
</table>

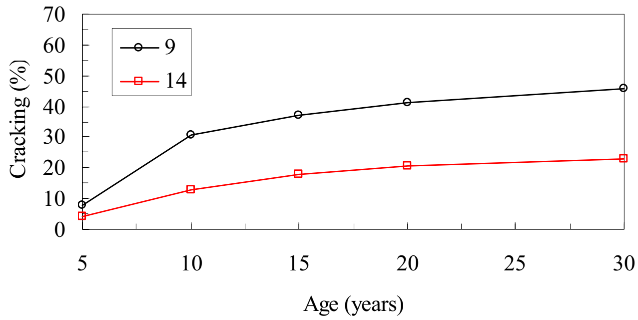
[4] Edge support is dependent lane width and shoulder type (MDOT practice)
[5] Slab thickness is tied with joint spacing, dowel diameter and dowel spacing (MDOT practice)
[6] Based on aggregate types
[7] *fc'* and *E* is correlated with *MOR*
[8] Asphalt treated base is permeable asphalt treated base
[9] Change strength and material properties according to soil type
[10] Represents three different climatic regions within Michigan

Table 4 Matrix for JPCP sensitivity analyses

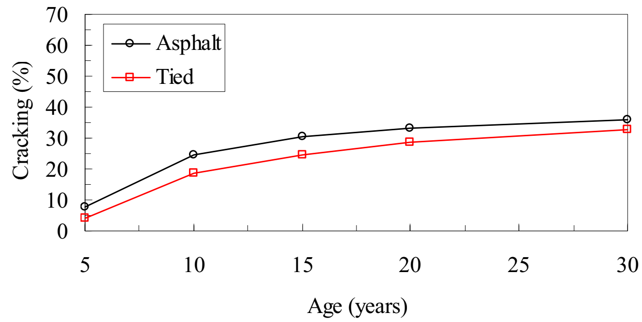
Slab Thickness	Edge Support	Base Type	CTE	MOR	Soil Type/Climate						Total
					Coarse			Fine			
					Detroit	Lansing	Pellston	Detroit	Lansing	Pellston	
9	Asphalt	DGAB	4	450	1	2	3	4	5	6	6
				900	7	8	9	10	11	12	6
			6.5	450	13	14	15	16	17	18	6
				900	19	20	21	22	23	24	6
		PATB	4	450	25	26	27	28	29	30	6
				900	31	32	33	34	35	36	6
			6.5	450	37	38	39	40	41	42	6
				900	43	44	45	46	47	48	6
	Tied	DGAB	4	450	49	50	51	52	53	54	6
				900	55	56	57	58	59	60	6
			6.5	450	61	62	63	64	65	66	6
				900	67	68	69	70	71	72	6
		PATB	4	450	73	74	75	76	77	78	6
				900	79	80	81	82	83	84	6
			6.5	450	85	86	87	88	89	90	6
				900	91	92	93	94	95	96	6
Total					32	32	32	32	32	32	192

Note: The above table presents the half factorial. The same number of runs was repeated for 14 inch slab thickness.

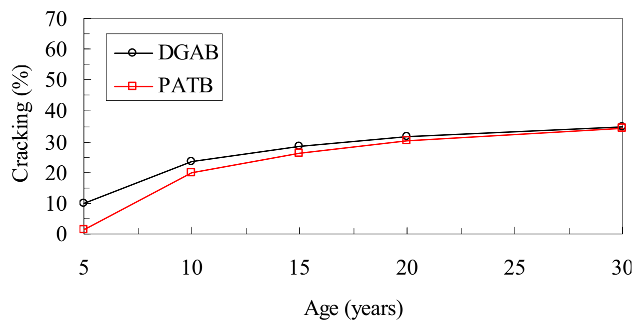
In general, rigid pavements with asphalt shoulders (untied) showed more cracking than those with tied shoulders, as shown by Figure 4 (b). The effect of edge support is not as significant as slab thickness. The results of the predicted cracking show that at early age, rigid pavements with permeable asphalt treated base (PATB) performed marginally better than those with dense graded aggregate base (DGAB). However, over the long-term the effect of base type diminishes for cracking, see Figure 4(c). The pavements with higher coefficient of thermal expansion (CTE) showed much more cracking than those with a lower CTE value. This effect is very significant and is consistent throughout the life span as presented in Figure 4 (d). Similarly, the effect of modulus of rupture (MOR) on cracking seems to be the most significant. Pavements slabs having a higher MOR exhibited little or no cracking as compared to those with lower MOR, which showed a very high level of cracking; see Figure 4 (e). The effect of subgrade type is fairly insignificant as shown by Figure 4 (f). Three locations were selected to investigate the effect of climate on pavement performance in Michigan. Figure 4 (g) shows that on average, the local climate variations seem to have only a slight effect on cracking. Rigid pavements located in Pellston exhibited higher amount of cracking than those located in Detroit and Lansing areas. The effect of location seems to be consistent throughout the pavement life. Figure 5 presents the average climatic properties (temperature, rainfall, and number of freeze/thaw cycles) for three locations considered with the state of Michigan. It can be observed that higher cracking potential is associated with locations having higher freeze index and number of freeze/thaw cycles.



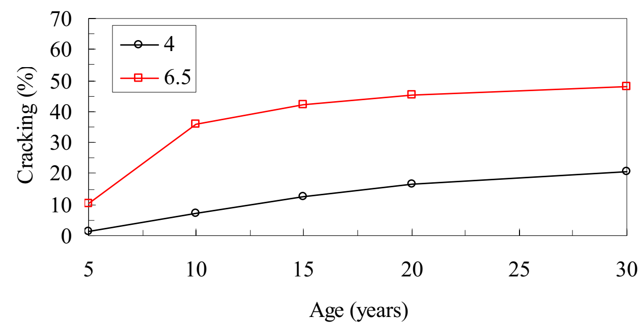
(a) Effect of *slab thickness* on cracking



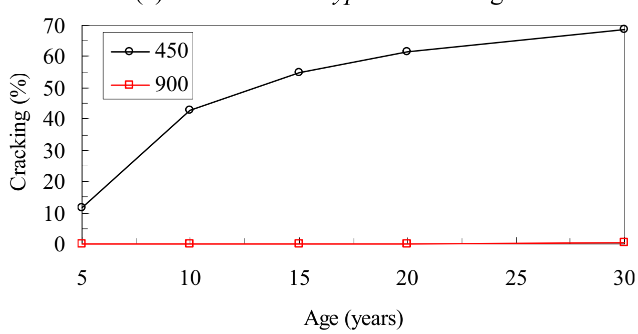
(b) Effect of *edge support* on cracking



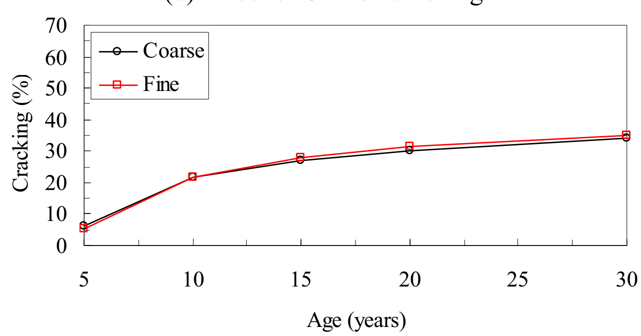
(c) Effect of *base type* on cracking



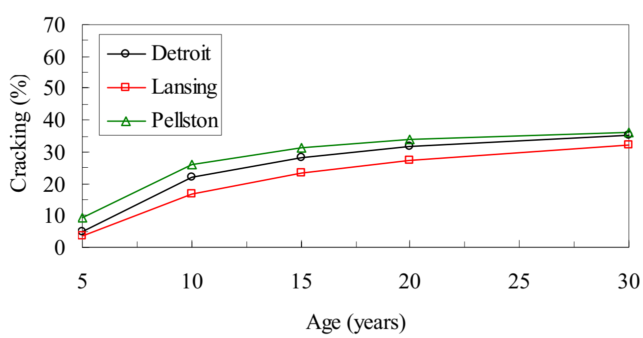
(d) Effect of *CTE* on cracking



(e) Effect of *MOR* on cracking

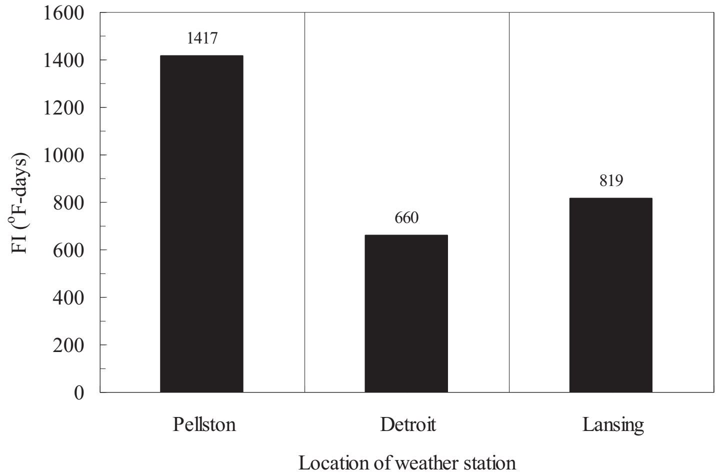


(f) Effect of *subgrade type* on cracking

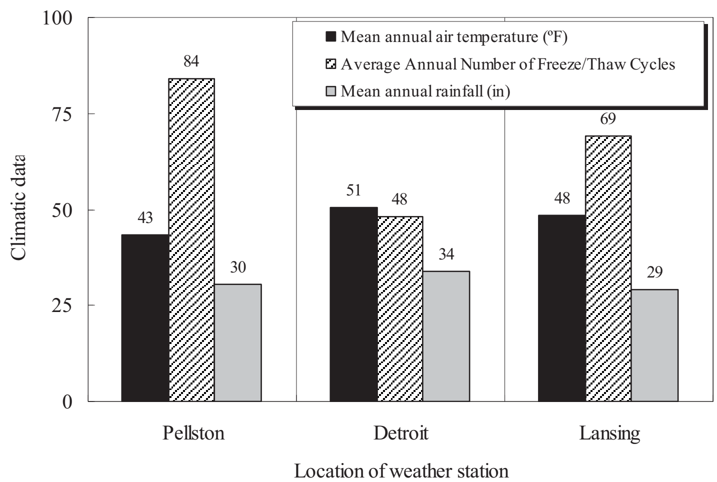


(g) Effect of *climate* on cracking

Figure 4 Main effects of input variables on JPCP cracking



(a) Average Freezing index by location



(b) Mean annual air temperature, number of F/T cycles
and average precipitation by location

Figure 5 Summary of climatic properties by location within Michigan

It should be noted that the above discussion of the results is based on the average performance. The main objectives of the statistical analyses are to: (a) obtain the real main effects with some level of confidence, (b) explore the interactive effects between various input variables, and (c) provide guidance with respect to input selection. Typically, a full-factorial experiment design such as the one considered in this study can be analyzed using the fixed-effect models employing analysis of variance (ANOVA). This type of statistical analyses can help in identifying the main and the interactive effects between variables. However, if certain variables interact with each other, their main effect should not be considered while making a conclusion. Therefore, the conclusion in this case should be based on cell means rather than marginal means (Haider et al. 2007b).

The summary results, at 30 years, from ANOVA are given in Table 5. As an example, the results for transverse cracking for statistically and practically significant interactions between variables are presented below.

Table 5 also shows the significant interaction effects between input variables on various performance measures. The interactions between CTE and slab thickness, MOR and slab thickness, and CTE and MOR were found to be statistically significant (*p-value* < 0.05). Table 6 shows the summary of cell means for these interactions, which can be used to explain the practical significance of these effects. The following findings can be drawn from these results:

CTE by Slab Thickness: This interaction shows that for a lower level of CTE, slab thickness has a significant effect on cracking. This effect is of both practical and statistical significance. On the other hand, for higher level of CTE, the slab thickness did not show a very significant difference in cracking. From the design perspective, the results of this interactive effect imply that if the CTE for a concrete is higher, increasing slab thickness will not help in achieving improved cracking performance.

MOR by Slab Thickness: This interaction demonstrates that the effect of slab thickness on cracking is more prominent for lower MOR than for higher MOR concrete. This means that for cracking, change in thickness is more important for lower MOR values in designing rigid pavements. These effects are of both statistical and practical significance.

CTE by MOR: The interaction between CTE and MOR was found to be the most important for rigid pavements. These effects are of both statistical and practical significance. The combination of higher CTE with lower MOR is drastic for cracking. This also means that higher flexural strength of concrete can compensate for a higher CTE value.

The results for faulting and IRI are summarized in Table 5. It should be noted that only significant interactions from both practical and statistical stand points are highlighted in these results.

Satellite Sensitivity Analyses. As mentioned above, to achieve analysis efficiency and adopt local practice, the detailed sensitivity evaluation was executed based on variables mentioned in Table 3. Two separate analyses were conducted as satellite studies; these evaluations included:

a) Studying the effect of CTE, slab thickness and joint spacing on pavement performance
b) Determining the impact of traffic inputs on pavement performance.

The results of analyses from these two evaluations are presented briefly in the following sections.

Effect of CTE, slab thickness and joint spacing on JPCP performance. Considering CTE and PCC slab thickness interactions, the effect of joint spacing on performance is hidden due to MDOT practice of tying joint spacing with the PCC slab thickness. Therefore, it was decided to initiate separate satellite sensitivity by considering three levels of joint spacing (12-, 16- and 20-feet). This sensitivity analysis will determine the importance of these three variables on the rigid pavement performance and interactions between them (if any). While the results of the sensitivity are purely an academic exercise, the practical aspects of the results will be useful in providing guidance to the designer. At present MDOT uses DARWIN software (based on

AASHTO 1993 Pavement Design Guide); however, the old AASHTO design procedure does not completely account for concrete material properties, for example CTE.

Table 5 Summary of results for statistical and practical significance

Transverse cracking (% slab cracked)

Variable	Main effect	Interaction effect						
		Slab thickness	Edge support	CTE	MOR	Base type	Subgrade soil type	Climate
Slab thickness	*S*	-		**S**	**S**			
Edge support			-					
CTE	*S*	**S**		-	**S**			
MOR	*S*	**S**		**S**	-			
Base type						-		
Subgrade soil type							-	
Climate								-

Joint faulting (mm)

Variable	Main effect	Interaction effect						
		Slab thickness	Edge support	CTE	MOR	Base type	Subgrade soil type	Climate
Slab thickness	*S*	-		**S**	**S**	S	S	S
Edge support	*S*		-	S		S	S	
CTE	*S*	**S**	S	-			**S**	**S**
MOR	*S*	**S**			-		S	
Base type	*S*	S	S			-		
Subgrade soil type	*S*	S	S	**S**	S		-	
Climate	*S*	S		**S**				-

Roughness, IRI (in/mile)

Variable	Main effect	Interaction effect						
		Slab thickness	Edge support	CTE	MOR	Base type	Subgrade soil type	Climate
Slab thickness	*S*	-		**S**				
Edge support			-					
CTE	*S*	**S**		-			**S**	
MOR	*S*				-			
Base type	*S*					-		
Subgrade soil type	*S*			**S**			-	**S**
Climate	*S*						**S**	-

Note: *S* implies statistical significance of main effects
S implies statistical significance of interaction effects
S and **S** imply both statistical and practical significance of main and interactive effects, respectively.

Table 6 Interaction effects of input variables on cracking

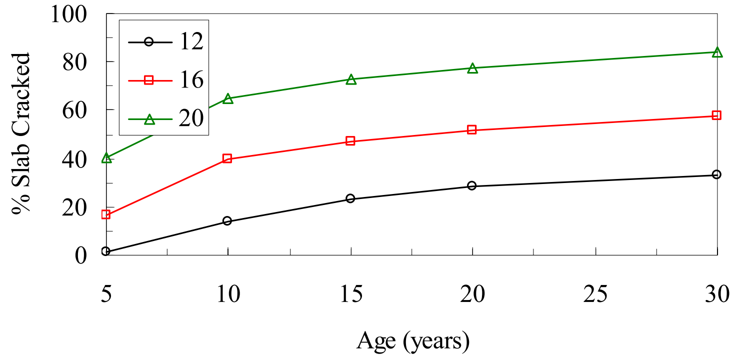
Input Variables		Levels1	Levels2	Mean % Slabs Cracked				Mean Differences			
1	2			5 years	10 years	20 years	30 years	$\square_{5}$	$\square_{10}$	$\square_{20}$	$\square_{30}$
CTE	Slab Thickness	4	9	2.66	14.30	32.66	41.45	2.56	14.20	32.54	41.24
			14	0.10	0.10	0.12	0.21				
		6.5	9	12.54	46.58	50.00	50.35	4.52	21.33	9.30	4.46
			14	8.02	25.25	40.70	45.89				
MOR	Slab Thickness	450	9	15.10	60.79	82.49	91.39	7.08	35.53	41.76	45.39
			14	8.02	25.25	40.72	46.00				
		900	9	0.10	0.10	0.18	0.41	0.00	0.00	0.08	0.31
			14	0.10	0.10	0.10	0.10				
CTE	MOR	4	450	2.66	14.30	32.68	41.57	2.56	14.20	32.58	41.47
			900	0.10	0.10	0.10	0.10				
		6.5	450	20.46	71.74	90.53	95.83	20.36	71.64	90.35	95.41
			900	0.10	0.10	0.18	0.41				

Therefore, this new design procedure will help the designer to incorporate the actual material properties, thus providing a better guidance of the expected pavement performance at the design stage. Three levels were considered for each variable as follows:

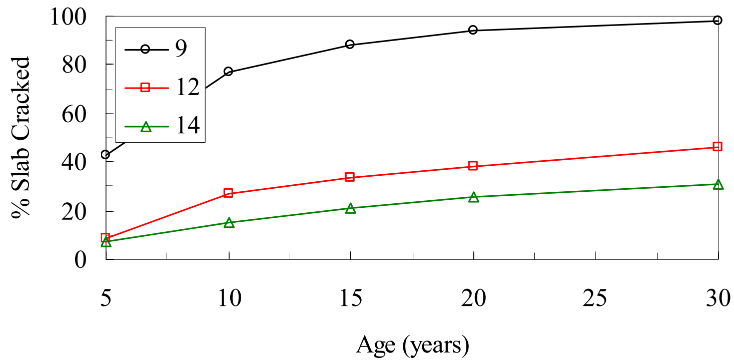
- Joint spacing (12-, 16- and 20-feet)
- CTE (4, 5 and 6.5 in/in/^{o}F)
- PCC slab thickness (9-, 12- and 14-inch)

Also to investigate the descriptive or average effects of all input variables on cracking, time series averages were plotted for input variables levels. Figure 6 presents the input variables effects on percent slab cracked. These effects are summarized below:

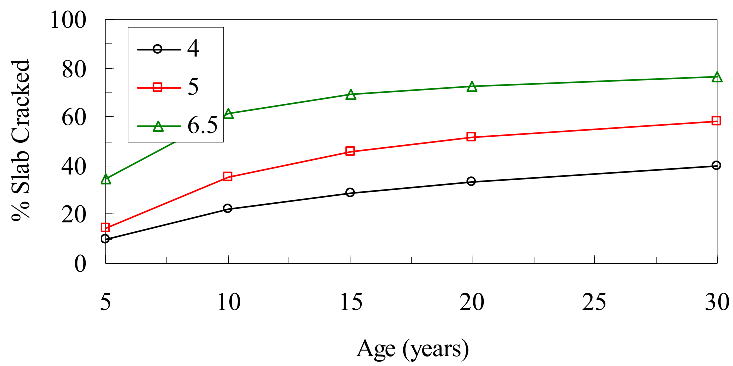
Rigid pavements with longer joint spacing showed higher cracking than those with shorter joint spacing, as shown by Figure 6(a). This effect of joint spacing is very significant and is consistent over pavement age. Figure 6(b) shows the percent slab cracked for 9-, 12- and 14-inches thick slabs. It is evident, that the effect of slab thickness is very significant on cracking. Rigid pavements with thin slab thickness showed higher levels of cracking than those with thick slabs. Also, the results show that this effect is more pronounced over a longer life of a pavement. A significant effect of CTE was observed for cracking. The pavements with higher CTE showed much higher cracking than those with a lower CTE value. This effect is consistent throughout the life span of a rigid pavement as presented in Figure 6(c).



(a) Effect of joint spacing



(b) Effect of slab thickness



(c) Effect of CTE

Figure 6 Effect of input variables on cracking performance of JPCP

It should be noted that the above discussion of the results is simply based on the average performance over time. Therefore, detailed statistical analyses were executed to ascertain the real main and interactive effects between input variables on the predicted cracking of rigid pavements. As an example, these effects are only presented for transverse cracking.

Main Effects. The results in Table 7 confirm that input variables; PCC slab thickness, CTE and joint spacing have a statistically significant effect on the cracking performance. The mean values for all variables are presented in Table 8. The interpretation of these effects is presented below:

The joint spacing has a significant effect on the cracking performance. Concrete pavements having a longer joint spacing have exhibited more cracking as compared to those having shorter joint spacing. This effect is also of practical significance. Rigid pavements with thicker PCC slabs out perform those with thinner PCC slab thickness. The practical significance of this effect can be assessed using criteria mentioned in Table 1 and comparing difference in the cracking performance between 9- and 14-inch slab thicknesses. Applying this criteria, one can easily identify that the effect of slab thickness on cracking is practically significant as well. Pavement concrete having a higher CTE value has shown higher amount of cracking than those which have a lower CTE value. This effect is also of practical significance.

Interaction Effects. Table 7 also shows the significant interactions between input variables. The interaction between joint spacing and slab thickness was found to be statistically significant (*p-value* < 0.05). Table 9 shows the summary of cell means, which can be used to explain these effects. While results were summarized above for the significant main effects, if certain variables are interacting with each other, their main effect should not be considered while making a conclusion. Following findings can be drawn from these results:

The significant interaction between joint spacing and slab thickness shows that for thicker slabs, joint spacing has a significant effect on cracking. This effect is of both practical and statistical significance. On the other hand, for thinner slabs, the joint spacing did not show a significant difference in cracking performance. This is because thinner slabs are prone to cracking irrespective of joint spacing at the later ages. Joint spacing has a very significant effect for thinner slabs at early ages (see Figure 7). From the design perspective, the results of this interactive effect imply that if the joint spacing for a concrete slab is larger, increasing slab thickness will help in achieving improved cracking performance to a certain extent.

Similarly, for faulting performance, the interactions between all the input variables (joint spacing by slab thickness and slab thickness by CTE) were found to be of statistical significance (*p-value* < 0.05). Due to low predicted values of faulting, the effects can be statistically significant for very low mean differences between various levels of input variables. However, practical significance may help explain some of these effects. The interaction between joint spacing and slab thickness demonstrates that the effect of slab thickness on faulting is more prominent for longer joint spacing. This means that for faulting, change in slab thickness is more important for longer joint spacing when designing rigid pavements.

The significant interaction (CTE by slab thickness) shows that for a larger CTE, slab thickness has a significant effect on faulting. This effect is of both practical and statistical significance. On the other hand, for lower CTE, the slab thickness did not show a very significant difference in faulting performance. The results of this interactive effect imply that if the CTE for a concrete is higher, increasing slab thickness will help in achieving better faulting performance. Finally, no significant interaction between CTE, slab thickness and joint spacing was found in the case of IRI.

Effect of traffic on JPCP performance. Traffic is one of the key factors influencing performance of JPC Pavements. The new M-E PDG uses each axle load distribution to describe traffic loads while classification and count data are also required to represent load repetitions. The latter data are used to calculate hourly, monthly, vehicle class distributions and growth factors. Recognizing the resources that are needed to collect detailed traffic data to accurately characterize future traffic for design, a hierarchical approach has been adopted in the M-E PDG for developing the traffic inputs. It defines three broad levels of traffic data input (Levels 1 through 3) based on the amount of traffic data available. However, it will be more appropriate to develop Levels 2 and 3 traffic inputs to better characterize the traffic within jurisdiction of a state highway agency rather than using default recommended values, which are based on national average (Khanum et al. 2006). This study evaluated the development of these important traffic inputs and their effects on performance of JPCP in Michigan. TrafLoad software (NCHRP Project 1-39 2005) was used to analyze traffic data from twelve (12) weigh stations. Based on the traffic characteristics, these twelve sites were categorized into three traffic levels, low, medium and high. Four sites were allocated to each traffic level and a representative input for traffic loadings and counts were developed within each level. In addition, a satellite sensitivity analysis was conducted to quantify the effects of traffic inputs on various performance measures (Haider et al. 2007a).

Table 7 ANOVA results for cracking

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	181.085[a]	18	10.060	8.866	.002
Intercept	188.512	1	188.512	166.134	.000
Joint spacing	52.918	2	26.459	23.318	.000
Slab thickness	59.076	2	29.538	26.031	.000
CTE	23.675	2	11.838	10.433	.006
Joint spacing * Slab thickness	26.985	4	6.746	5.945	.016
Joint spacing * CTE	6.564	4	1.641	1.446	.304
Slab thickness * CTE	11.867	4	2.967	2.615	.115
Error	9.078	8	1.135		
Total	378.675	27			
Corrected Total	190.163	26			

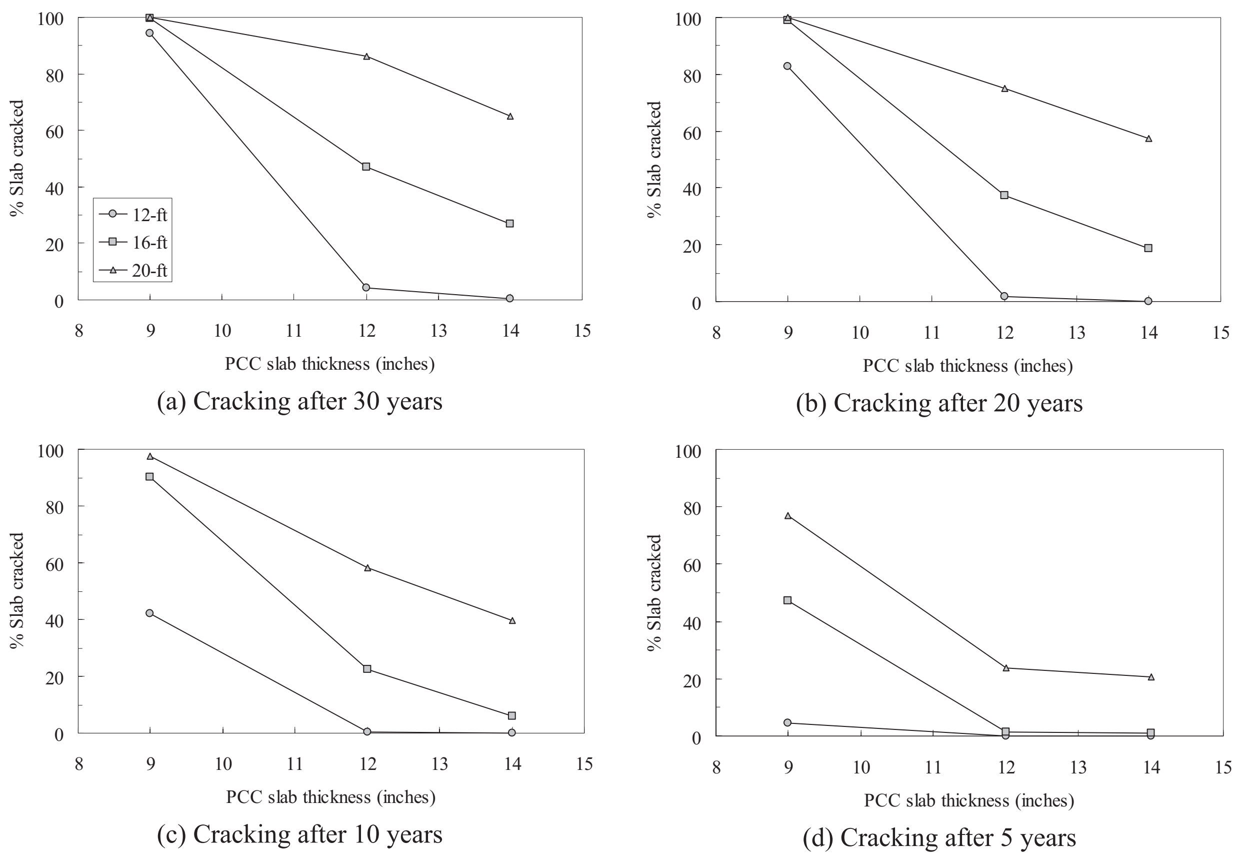
a R Squared = .952 (Adjusted R Squared = .845)

Table 8 Main effect of input variables on cracking

Input Variable	Level	Mean % Slabs Cracked				Mean Differences			
		5 years	10 years	20 years	30 years	$\square_{5}$	$\square_{10}$	$\square_{20}$	$\square_{30}$
Joint Spacing (ft)	12	1.62	14.22	28.23	33.07	38.93	50.97	49.28	50.78
	16	16.56	39.57	51.61	57.80				
	20	40.56	65.19	77.51	83.84				
Slab Thickness (inch)	9	42.94	76.72	93.87	98.08	-35.66	-61.53	-68.40	-67.31
	12	8.50	27.07	38.02	45.87				
	14	7.29	15.19	25.47	30.77				
CTE (in/in/^{o}F)	4	9.74	22.16	33.07	39.66	25.02	39.10	39.49	37.00
	5	14.22	35.57	51.73	58.40				
	6.5	34.77	61.26	72.56	76.66				

Table 9 Interaction effect of input variables on cracking

Input Variables 1	Input Variables 2	Level 1	Level 2	Mean % Slabs Cracked 5 years	10 years	20 years	30 years
Joint Spacing	Slab Thickness	12	9	4.67	42.27	82.87	94.47
			12	0.10	0.30	1.67	4.40
			14	0.10	0.10	0.17	0.33
		16	9	47.13	90.23	98.83	99.77
			12	1.50	22.60	37.30	46.83
			14	1.03	5.87	18.70	26.80
		20	9	77.03	97.67	99.90	100.00
			12	23.90	58.30	75.10	86.37
			14	20.73	39.60	57.53	65.17



(a) Cracking after 30 years

(b) Cracking after 20 years

(c) Cracking after 10 years

(d) Cracking after 5 years

Figure 7 Effects of interaction (joint spacing by slab thickness) on cracking with age

MDOT traffic data. Traffic data from twelve weigh-in-motion (WIM) stations was provided by Michigan Department of Transportation (MDOT). These WIM stations were selected to represent three different traffic levels (low, medium and high) in Michigan. Each traffic level contains four different locations distributed among various highway classes (M, US and Interstate roads). These twelve locations include a diversified traffic demand within the state of

Michigan and cover several counties on the state highways representing low, medium and high traffic, as shown in Table 10.

The data provided by the MDOT in ASCII format (according to FHWA requirements) were analyzed using TrafLoad Software (NCHRP Project 1-39 2005) to determine the necessary traffic-related inputs for M-E PDG Software. Two types of data were used to generate these traffic-related input data: (a) Card 4, for vehicle classification, and (b) Card 7, for axle load spectra. The results of these analyses only show the traffic in the design lane in one direction. The direction of traffic, at each location, used for the analyses was recommended by MDOT.

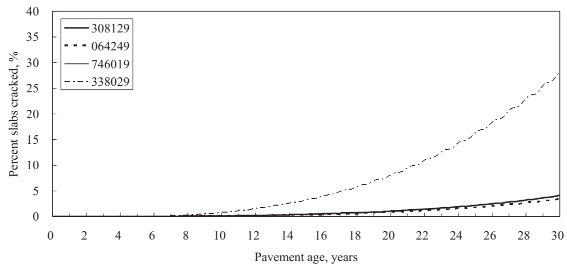
Table 10 Details of MDOT traffic data

County	Traffic Level	Site ID	Site Description	AADTT	Vehicle Class Scheme	Duration
Hillsdale	Low	308129	US-12	444	FHWA	Jan , 2005 to Dec, 2005
Arenac		064249	US-23	404		Oct, 2005 to Sep, 2006
Sanilac		746019	M-46	147		Oct, 2005 to Sep, 2006
Ingham		338029	US-127	806		Oct, 2005 to Sep, 2006
Ionia	Medium	345299	I-96	1,984	FHWA	Jan , 2005 to Dec, 2005
Clair		776369	I-69	1,784		Oct, 2005 to Sep, 2006
Ottawa		705059	I-196	1,539		Oct, 2005 to Sep, 2006
Kent		419759	M-6	1,964		Oct, 2005 to Sep, 2006
Jackson	High	387029	I-94	3,945	FHWA	Jan , 2005 to Dec, 2005
Brach		127269	I-69	3,244		Oct, 2005 to Sep, 2006
Monroe		588729	US-23	3,501		Oct, 2005 to Sep, 2006
Oakland		638209	I-96	2,629		Oct, 2005 to Sep, 2006

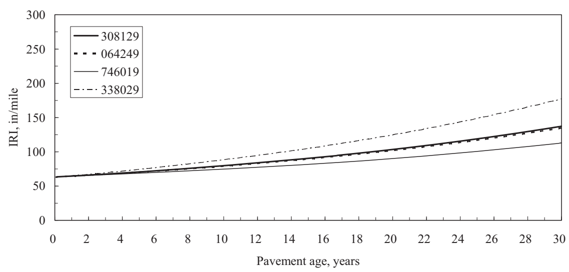
In order to determine the effects of traffic levels on various rigid pavement performance measures, the M-E PDG software (NCHRP Project 1-37A 2004) was used to analyze each site according to its traffic characteristics. All other variables were kept constant in this analysis except traffic. Therefore, the effects on performance are mainly due to traffic-related inputs. Figure 8(a, b and c) shows the effect of traffic on pavement performance within low traffic levels, as an example. These results can be used to assess the effect of traffic within each level. Also, to study the effect of traffic on pavement performance among the levels, a representative performance for each traffic level was selected for faulting, cracking, and roughness as shown in Figures 8(d, e and f). The results show that traffic levels (low, medium and high) significantly affect the rigid pavement performance. Also within a traffic level, due to variations in truck volumes and loadings, the predicted performance can vary considerably. However, the assessment of these effects within the same or among traffic level needs engineering judgment and practical considerations.

This implies that the default traffic values (respective truck traffic classification, TTC) in M-E PDG may not be representative for the actual traffic of a particular site. Therefore, traffic data plays a key role in the new design process using M-E PDG.

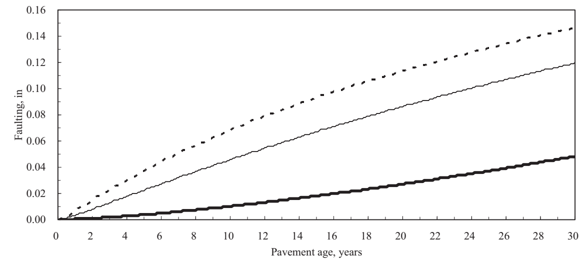
(a) Faulting – Low traffic



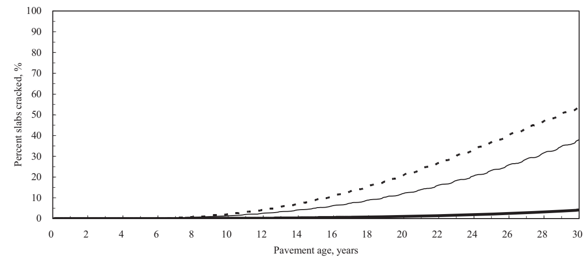
(b) Cracking – Low traffic



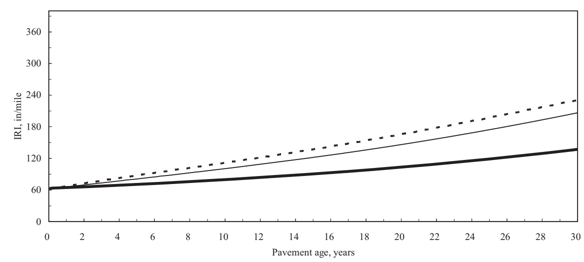
(c) Roughness – Low traffic



(d) Faulting – All traffic levels



(e) Cracking – All traffic levels



(f) Roughness – All traffic levels

Figure 8 Effect of traffic levels on JPCP pavement performance

Conclusions

The paper highlights the important steps for conducting M-E PDG sensitivity analyses. A preliminary sensitivity, considering one variable at a time, was used to determine the most important input variables affecting JPCP performance. In order to customize the use of the software to the local needs, it is essential to consider the state-of-the-practice and local experience in such analyses to reduce the number of input variables and their levels. The results showed that effect of PCC slab thickness and edge support on performance were significant among design variables while CTE, MOR, base type and subgrade played an important role among material-related properties. In addition, to effectively capture the interaction effects between variables a full factorial experiment was designed and analyzed. Statistical analyses results identified significant main and interactions effects of input variables. It was found that slab thickness interacts significantly with material properties—CTE and MOR, for cracking in JPCP. From the design perspective, increasing slab thickness for a higher CTE or a higher MOR may not help in achieving better cracking performance. On the other hand, increasing slab thickness for a lower CTE and a lower MOR may improve cracking performance. A lower MOR and a higher CTE combination is drastic for JPCP cracking. For faulting, the material properties—CTE and MOR interact significantly with site factors—subgrade soil type and climate. For roughness, the interactions — slab thickness by CTE and climate by subgrade soil types, play a significant role.

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