Effect of the MEPDG Hierarchal Levels on the Predicted Performance of a Jointed Plain Concrete Pavement

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Abstract

The primary objective of this research effort is to investigate the impact of using different means of establishing each input (typical value, correlated value or measured value) on pavement design. First, a comparison was made of the design thickness obtained by using the 1993 AASHTO Design Guide with that using the Mechanistic Empirical Pavement Design Guide (MEPDG) developed under the National Cooperative Highway Research Program (NCHRP) 1-40 (ver. 1.0). It was shown that there can be a considerable difference in design thickness obtained using the 1993 AASHTO Design Guide compared to that of the MEPDG. The MEPDG was then used to determine the slab thickness while defining the input parameters using different input levels for a field test section. Finally, several parameters identified as critical inputs by other researchers based on the results of sensitivity analyses, were evaluated individually by determining the effect of different levels of input for one parameter at a time. The results of the study showed that the use of different levels of input can change the design thickness for this particular section of roadway by up to 51 mm (2 in).

Introduction

For many years, pavement designers have been using just nine inputs to determine the thickness of a rigid pavement. The new Mechanistic Empirical Pavement Design Guide (MEPDG), developed under National Cooperative Highway Research Program (NCHRP) 1-40 (ver. 1.0), requires more than fifteen inputs just to characterize the Portland cement concrete (PCC). A substantial amount of effort has been put forth in performing sensitivity analyses to identify the most critical design inputs (Gueterrez 2008; Coree et al. 2005; Kannekanti and Harvey 2005; 2006; Li et al. 2006; Schram and Abdelrahman 2006; Yut and Khazanovich 2005). By identifying the inputs having the largest effect on the design, resources can be allocated to define these inputs in a more efficient manner.

When defining the inputs for the MEPDG, there are three hierarchal input levels. The input level used is selected depending on the amount of information available to the designer and the criticality of the project. The three levels of input are as follows:

- Level 1: Inputs directly measured through laboratory or field testing.
- Level 2: Inputs estimated through correlations to available data, inputs from an agency database, or inputs derived from limited testing.

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- Level 3: Inputs estimated using typical values chosen from available sources and experience

The purpose of this research is to evaluate several of the inputs identified as critical in previous sensitivity analyses to determine if using different input levels has a significant impact on the design. The sensitivity analysis will help in identifying critical inputs for the range of design parameters used by any one agency. Once the critical inputs are determined, the next step is to determine if there is any added benefit in using a lower level input. If the Level 2 and Level 3 inputs are sufficiently accurate in estimating the Level 1 measured value then and the additional money and resources necessary to actually measure the parameter are not justified. Therefore, the significance of this research is that it helps determine the necessity of allocating additional resources that are required for Level 1 inputs.

This study first compares the design thickness predicted using the *1993 AASHTO Guide for the Design of Pavement Structures* (AASHTO 1993) to that using the MEPDG for two jointed plain concrete pavements (JPCP) constructed in Murrysville, Pennsylvania. Next, the effects of the three different levels of inputs on predicted faulting, cracking and IRI are evaluated. Finally, the effect of the three input levels for individual design parameters on predicted performance will be investigated.

Project Background

An instrumented JPCP was constructed in August 2004 along a section of U.S. Route 22 (SR22), which is located approximately 32 km (20 miles) east of Pittsburgh. The design AADTT for SR 22 was 851 trucks and the 20-year linear growth rate was 1.8 percent. This section of roadway has 3.7-m (12-ft) lanes and 4.6-m (15-ft) transverse joint spacing. The pavement structure consists of a 305-mm (12-in) PCC slab constructed on top of a 102-mm (4-in) asphalt treated permeable base (ATPB) and 127-mm (5-in) of densely graded subbase. Additionally, 610-mm (24-in) of the subgrade was cut and filled with a gap-graded soil and aggregate mixture due to poor subgrade conditions (CBR < 5). The test section contains both doweled and undoweled slabs. Some of the slabs contained 38-mm (1.5-in) epoxy-coated dowel bars every 305-mm (12-in) along the transverse joints and No. 5 epoxy-coated tie bars every 0.8 meters (2.5-ft) along the lane/shoulder and centerline joints. Other slabs did not contain dowels or tie bars (Wells et al. 2005).

The relevant PCC material properties that were measured and are needed for the analysis of the performance of the pavement using the MEPDG at all three hierarchal levels include: unit weight, Poisson's ratio, coefficient of thermal expansion, drying shrinkage, flexural strength, compressive strength and elastic modulus. Over a 100 beams and cylinders were cast during paving. These specimens were tested after 1, 3, 7, 28 and 365 days. In addition, cores pulled from the pavement were subjected to testing at ages of 28 and 365 days. The results of the early-age testing are provided in detail in the construction report (Wells et al. 2005) and the results of the one-year tests are provided in the one-year report (Asbahan et al. 2006).

Early age data collected from the static strain and pressure sensors was analyzed to determine the built-in construction gradient in the PCC slabs. Data collected from strain gages embedded at different locations and depths in the concrete slabs is analyzed for the first 42 hours after placement. The time when the concrete starts experiencing strain corresponding to changes in temperature is selected as that corresponding to the time of set of concrete. Then, data collected from static pressure cells embedded at different locations along the interface between the concrete slabs and the base layer is analyzed for the first 42 hours after placement. The time when the base layer starts experiencing uniform changes in pressure along with changes in temperature gradients within the slab is selected as that corresponding to the time of set of concrete. The results of these two methods are analyzed and compared to determine the time of set. Once the set time is determined, data from the thermocouples embedded in the concrete slabs are used to estimate the corresponding built-in construction gradient. The built-in temperature gradient was found to be 0.0067 °C/mm (0.31˚F/in) (Asbahan et al. 2006). Therefore the built-in temperature difference to be used in the MEPDG is 2 °C (3.5 ˚F).

MEPDG Versus 1993 AASHTO Design Guide Thickness Designs

A comparison was made between the design thickness determined for S.R. 22 using the MEPDG and the 1993 AASHTO Design Guide. The design thickness for the doweled and undoweled slabs was determined using the MEPDG and Level 1 inputs (or the highest level input available) and the 1993 AASHTO Design Guide. The design thickness using the 1993 Guide and standard PennDOT inputs, as defined in *Pub. 242 Pavement Policy Manual*, (PennDOT 2007) was 250 mm (10 in) for the doweled slabs and 305 mm (12 in) for undoweled slabs. A design thickness of 280 mm (11 in) was determined for the undoweled slabs and 203 mm (7 in) for the doweled slabs using the MEPDG. A design thickness of 230 mm (8 in) was obtained for the restrained slab and 254 mm (10 in) for the unrestrained slab when the 1993 Guide was used along with the actual measured material properties. Based on the MEPDG, the service life of the 305-mm (12-in) doweled slabs is 45 years and is 17 years for the 305-mm (12-in) undoweled slabs at a reliability of 95 percent. Therefore, the design thickness determined using the 1993 Guide is 25 mm (1 in) thicker than the MEPDG design thickness for the restrained slab and 25 mm (1 in) thinner for the unrestrained slabs.

Table 1. Design thickness obtained for S.R.-22 using the 1993 Guide and the MEPDG.

Design Methodology	[illegible]	Doweled, mm (in)
MEPDG (ver. 1.0)	[illegible]	203 (7)
1993 Guide (Stan. PennDOT Inputs)	[illegible]	250 (10)
1993 Guide (Measured Inputs)	254 (10)	230 (8)

There are significant differences in the design thicknesses between the two procedures; however, there are also significant differences between the design methods. While the 1993 Guide is an empirical design method based on the AASHO Road Test, the MEPDG is more versatile and considers empirical-mechanistic principles. The implications of these dissimilarities on the design thickness must be acknowledged when comparing the two methods.

Effect of the Hierarchal Levels on Pavement Performance Prediction

The effects of using different hierarchal input levels (Level 1, 2, or 3) on predicting the performance of SR 22 was evaluated next. The analysis evaluates the predicted faulting, cracking, and IRI throughout the 20-year design period for both doweled and undoweled slabs. Table provides a summary of the critical design inputs for SR 22 at the three hierarchal input levels. If an input was unavailable at a particular level then the input was defined using the next highest level for which that input could be defined. For example, if Level 1 data was not available, then Level 2 data would be used. A complete list of all design inputs and a description of how each was determined can be found in the reference 8 (McCracken et al. 2008).

Table 2. Design inputs for SR 22.

Design Input			**Level 3 (Typical Value)**
Built-in Temp. Difference, °C (°F)			-6 (-10)
Poisson's Ratio			0.18
Coefficient of Thermal Expansion, /°C (/°F)			3.0×10^{-6} (5.4×10^{-6})
Unit Weight, kg/m^3 (lb/ft^3)			2403 (150)
Shrinkage, microstrain			711
[1]PCC Stiffness/Strength (28-day), MPa (psi)	E = 25,500 (3.7×10^6)	f'_c = 39 (5,690)	f'_c = 40 (5,868)

[1] E = elastic modulus; f'_c = compressive strength

Doweled Pavement The effects of using the three hierarchal levels on the performance prediction for the doweled slabs throughout the 20-year design life is evaluated first. This analysis was performed using a design thickness of 178 mm (7 in). All results represent a level of reliability of 50 and 95 percent.

As Figure 1 shows, there is little variation in the amount of pavement faulting between the three hierarchal levels of input. This is largely due to the fact that the primary mode of failure for the doweled slabs is cracking. The 38-mm (1.5-in) dowel bars provide good load transfer and therefore, limit the amount of faulting at all three hierarchal levels. Both 50 and 95 percent levels of reliability are provided for each performance prediction graph.

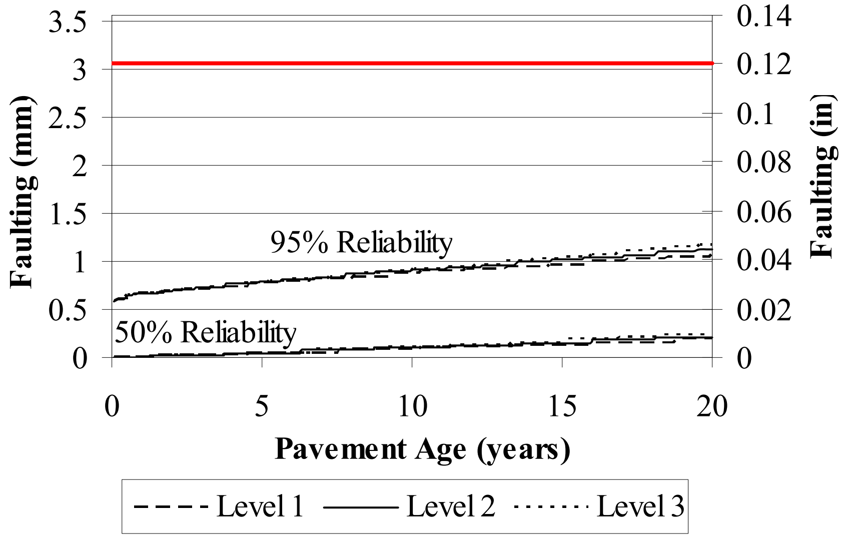

Figure 1. Faulting of the doweled slabs throughout the design life.

Figure 2 presents the variation in slab cracking throughout the design life for the three hierarchal levels. As the figure shows, the predicted performance for the doweled slabs is acceptable throughout the design life, at all three levels, due to the strength and stiffness of the pavement structure. At the end of the 20-year design life, the Level 1 analysis predicted 4 percent cracked slabs, Level 2 predicted 4 percent, and Level 3 predicted 0 percent at 50 percent reliability. For this case, using higher level inputs produces a less conservative design, although the differences are not significant.

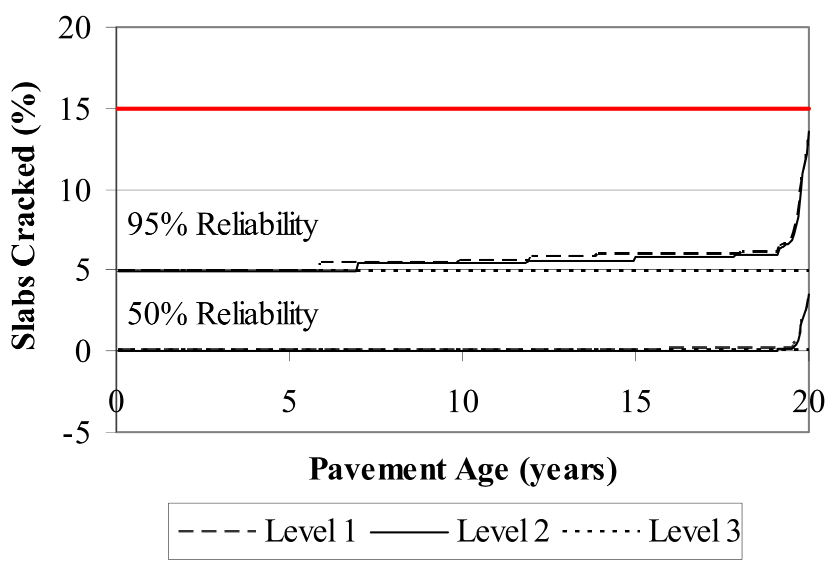

Figure 2. Percent cracking in the doweled slabs throughout the design life.

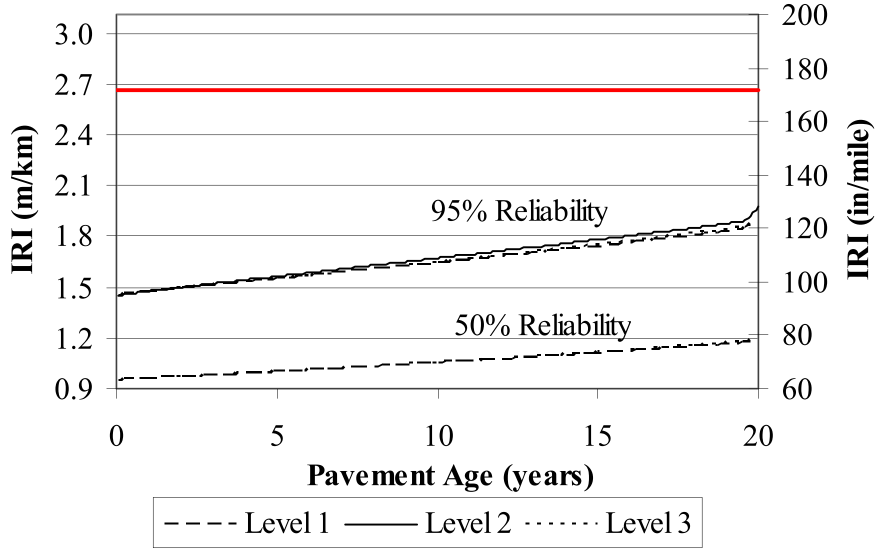

Figure **3** presents the variation in the roughness of the pavement surface throughout the design life for the three hierarchal levels. The performance trend of the predicted IRI is similar to the predicted slab cracking since only a minor amount of faulting is predicted.

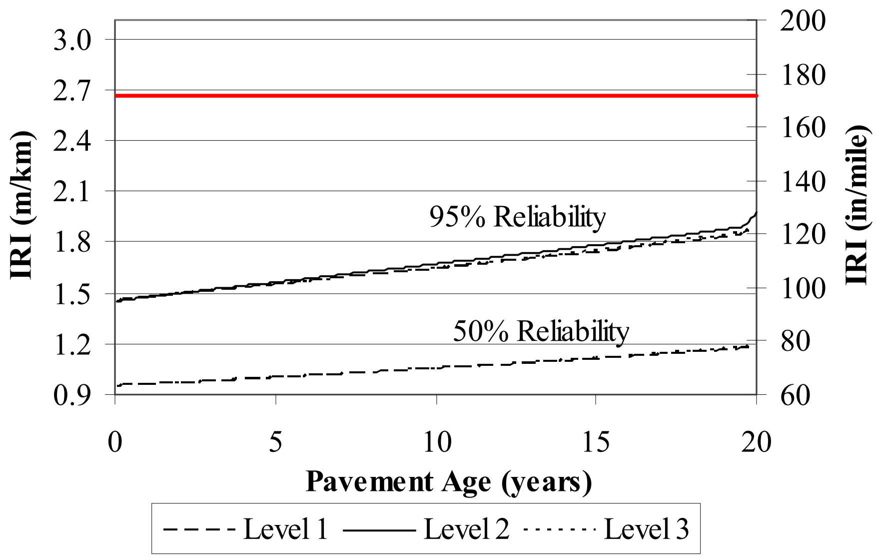

Figure 3. IRI for the doweled slabs throughout the design life.

Undoweled Pavement This section presents the results of the performance of the undoweled slabs throughout the 20-year design life using the three hierarchal levels. This analysis was performed using a design thickness of 330 mm (13 in) and the inputs previously reported at each hierarchal level. As Figure 4 shows, there is no variation in the amount of pavement cracking between the three hierarchal levels since the primary mode of failure for the undoweled slabs is faulting. The thickness of the slab had to be increased substantially to limit the amount of faulting to an acceptable level since this is only an indirect means of limiting faulting.

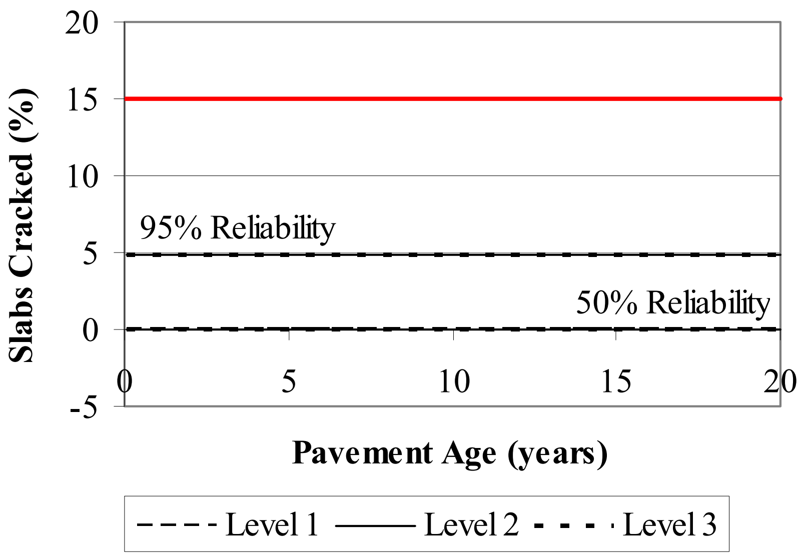

Figure 4. Percent cracking in the undoweled slabs throughout the design life.

Figure 5 presents the variation in the amount of faulting between the three hierarchal levels. At the end of the 20-year design life, the Level 1 analysis predicted 1 mm (0.06 in) of faulting, Level 2 predicted 1 mm (0.06 in) and Level 3 predicted 2 mm (0.07 in) at 5 percent reliability. Similar to the faulting prediction for the doweled slabs, the Level 2 and 3 analyses predict a larger amount of distress. At a reliability of 95 percent, the design thickness would need to be increased by 13 mm (0.5 in) to maintain performance within the specified faulting criteria for the 20-year analysis. This trend was also experienced in the pavement roughness predicted for the undoweled slabs, as shown in Figure 6. Figure 5 also shows that the pavement is predicted to fail just before the end of its intended design life of 20 years when using Level 3 inputs, while this design would be sufficient if Level 1 or 2 inputs were used to design the slab.

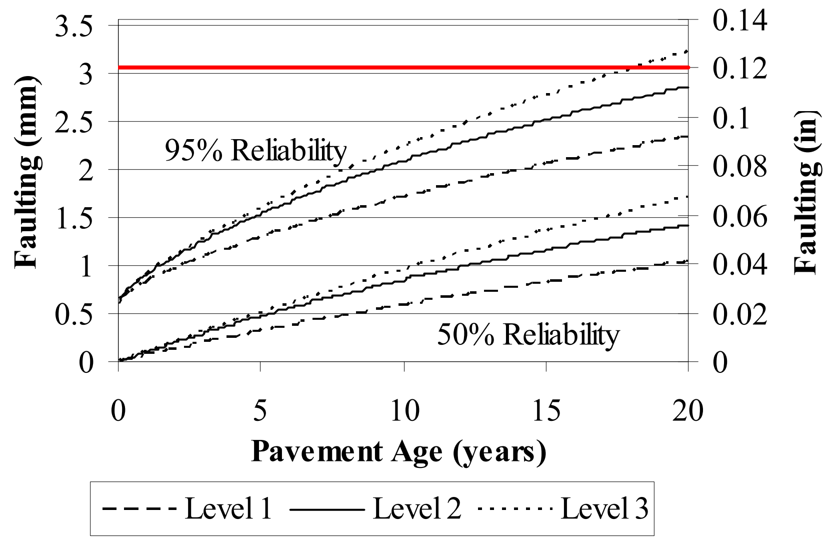

Figure 5. Faulting of the undoweled slabs throughout the design life.

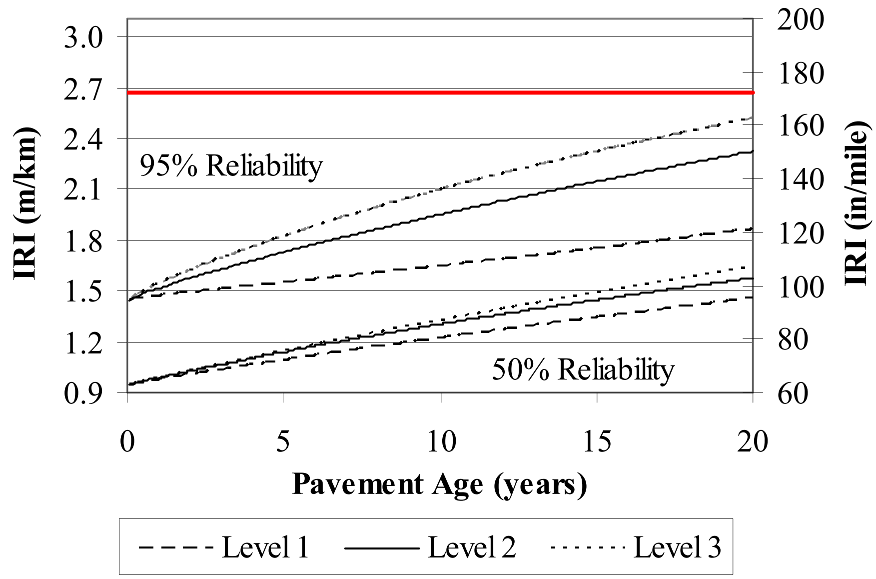

Figure 6. IRI for the undoweled slabs throughout the design life.

Effect of Changing Hierarchal Level of Individual Inputs on Predicted Performance

The following sub-sections present the performance prediction for the doweled and undoweled slabs on SR 22 as the hierarchal level of individual design parameters are varied. All parameters will be evaluated at a reliability of 50 and 95 percent. The following parameters will be investigated due to their significance in predicting pavement damage through the faulting and cracking models of the MEPDG:

- Traffic (Level 2 and 3)
- Climate (varying weather stations)
- PCC Strength (Level 1, 2, and 3)
- PCC Coefficient of Thermal Expansion (Level 1, 2, and 3)
- Subgrade Resilient Modulus (Level 2 and 3)

In each analysis, each individual design parameter is varied between the hierarchal Levels (1, 2, and 3). All other inputs are defined using the lowest level of hierarchal data available. The performance of the doweled slabs will be evaluated based the percent slabs cracked, while the performance of the undoweled slabs will be based on the faulting since these are the primary modes of failure for each pavement section.

Traffic The effect of the hierarchal level of the traffic inputs on pavement performance was evaluated using Level 2 and 3 data available for SR 22. Level 1 characterization was not performed because site specific WIM data was not available. Therefore, in both analyses (Level 2 and 3) national averages of axle load distributions were used. In the Level 2 analysis, the monthly adjustment factors, vehicle class distribution, and hourly distribution were determined for SR 22. For the Level 3 analysis, national averages of these parameters, determined from various Long Term Pavement Performance (LTPP) sites, were used.

Figure 7 presents the predicted percent cracking for the doweled slabs throughout the 20-year design life at 50 and 95 percent reliability. There is a significant difference between the predicted cracking when traffic is varied between Levels 2 and 3. At a reliability of 50 percent, the Level 2 analysis predicted approximately 4 percent of the slabs would crack while the Level 3 analysis predicted approximately 12 percent. Therefore, the Level 3 analysis predicted three times more damage then the Level 2 analysis indicating a more conservative design. The design thickness using Level 3 traffic data would be 13-mm (0.5-in) thicker based on a reliability of 95 percent.

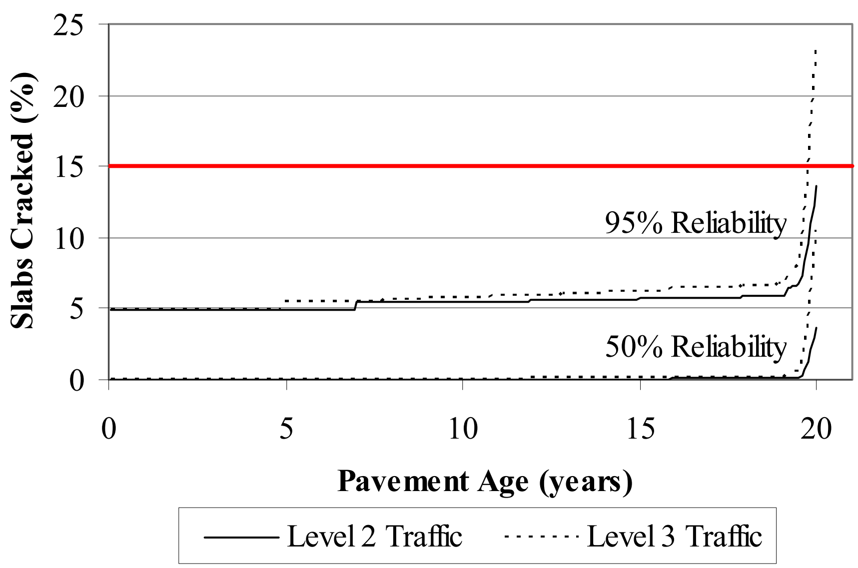

Figure 7. Percent cracking in the doweled slabs while varying the hierarchal level of the traffic inputs.

Figure 8 presents the variation in the predicted pavement faulting of the undoweled slabs when the traffic inputs are varied between hierarchal Levels 2 and 3. At the end of the 20-year design life, Level 2 predicted 1.0-mm (0.04-in) of faulting and Level 3 predicted 1.7-mm (0.07–in) at 50 percent reliability. As shown below, at 95 percent reliability the Level 3 performance only meets the design criteria for 17 years. Therefore the design thickness using Level 3 traffic data, would need to be increased by 13-mm (0.5-in) to meet the 20-year design criteria.

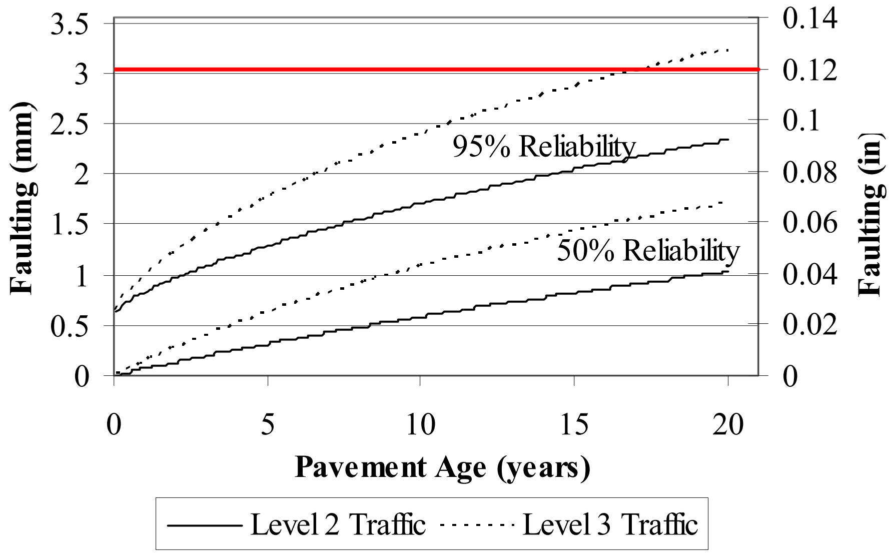

Figure 8. Predicted faulting in the undoweled slabs while varying the hierarchal level of the traffic inputs.

Climate The effect of climatic data on the predicted performance was evaluated using climatic data from different weather stations. The predicted performance of the pavement when the climatic data was collected from the onsite weather station was compared to performance predictions based on climatic data collected from the two weather stations closest to the site. The locations of the selected weather stations are presented in Table 1. The table also includes the proximity of the weather stations to the site and the number of months of available data for each station.

Table 1. Weather stations used in the climatic analysis.

	Latitude (degrees)	**Longitude (degrees)**	**Elevation, m (ft)**	**Distance from site, km (miles)**	**Available data (months)**
Murrysville (onsite)	40.43 N	79.66 W	285 (935)	--	32
Pittsburgh International Airport (PIT)	40.30 N	80.14 W	358 (1175)	31.1 (19.3)	116
Allegheny County Airport (AGC)	40.21 N	79.55 W	390 (1281)	41.4 (25.7)	85

Figure 9 presents the predicted percent cracking for the doweled slabs throughout the 20-year design life. There is a significant difference between the predicted cracking even though the proximity of the three weather stations is within a 48-km (30-mile) radius. The Murrysville (onsite) weather station and Allegheny County Airport (AGC) weather station predicted 4 percent of the slabs would crack while the Pittsburgh International Airport weather station predicted less than 1 percent at 50 percent reliability. Therefore, the onsite and AGC weather stations are predicting approximately slightly more damage than the Pittsburgh (PIT) weather station. These two weather stations have substantially less data than the Pittsburgh weather station, which is most likely contributing to the difference between the predicted performances. This difference in not sufficiently significant that it would affect the overall design thickness.

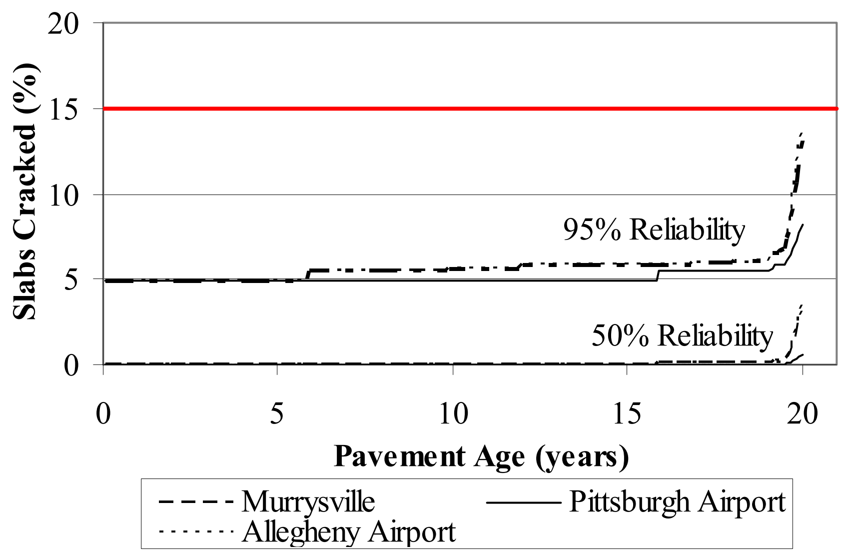

Figure 9. Percent cracking in the doweled slabs while varying the source of climatic data used in the design.

Figure 10 shows a similar trend in the undoweled slabs of SR 22, with faulting varying approximately 17 percent between the three weather stations. The lowest amount of faulting was achieved when data from the PIT weather station and the use of data from the onsite and AGC weather stations show more faulting, although the difference between each prediction was insignificant. The use of the different climatic sources did not affect the design thickness for either the doweled or undoweled slabs. However, this was not the case when earlier versions of the MEPDG were used and the data in the climatic database was limited. The use of these different weather stations did have an effect on the design thickness in earlier versions of the MEPDG.

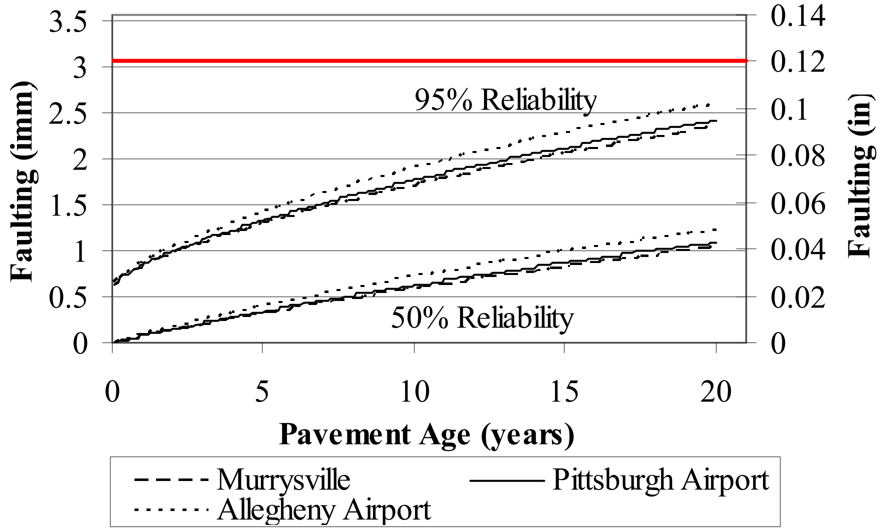

Figure 10. Faulting in the undoweled slabs while varying the source of climatic data used in the design.

PCC Strength The effect of the hierarchal level used to define the PCC strength on pavement performance is now evaluated. Figure 11 presents the predicted percent cracking of the doweled slabs throughout the 20-year design life at 50 and 95 percent reliability. At 50 percent reliability, the use of Level 1 and Level 2 data resulted in 3 percent of the slabs cracking and Level 3 resulted in 1 percent of the slabs cracking. The difference between the results predicted when using Level 1 or Level 2 data and using Level 3 data becomes more significant when the level of reliability is increased.

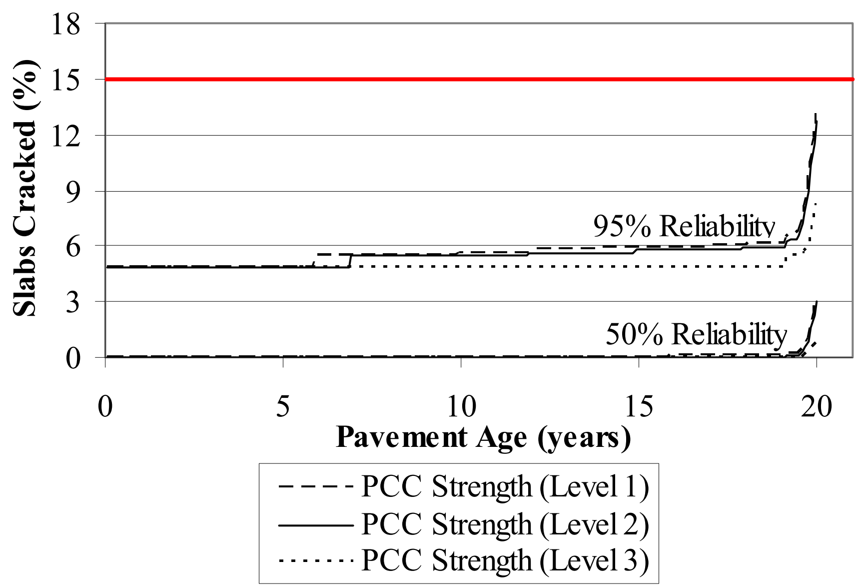

Figure 11. Percent cracking in the doweled slabs while varying the hierarchal level of PCC strength input.

As Figure 12 demonstrates, the predicted faulting of the undoweled slabs increased as the hierarchal level decreased. However, the use of different Levels of input for the PCC strength did not affect the design thickness for either the doweled or undoweled slabs.

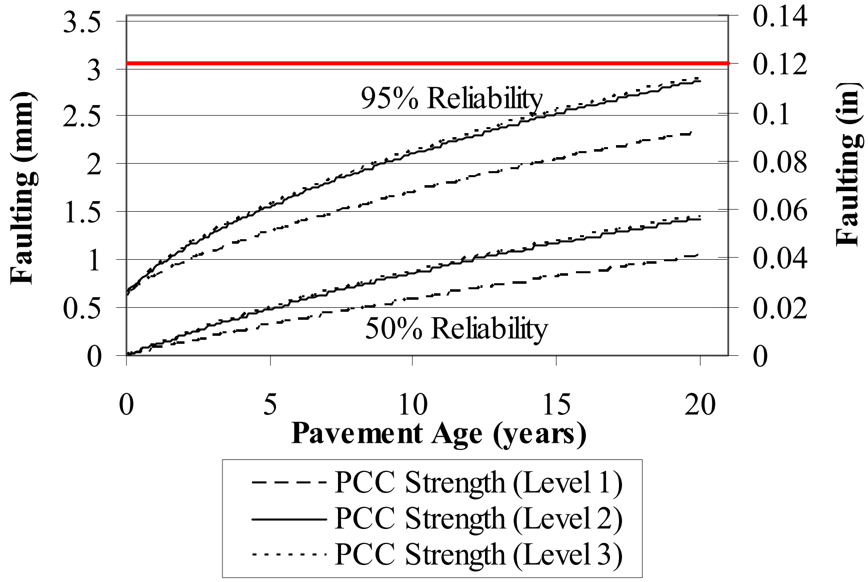

Figure 12. Faulting in the undoweled slabs while varying the hierarchal level of PCC strength input.

PCC Coefficient of Thermal Expansion Figure 13 and Figure 14 present the predicted performance of the doweled and undoweled slabs as the hierarchal level of the PCC coefficient of thermal expansion (CTE) is varied. At a reliability of 50 percent, the predicted percent cracking for the doweled slab varies considerably as the hierarchal level is changed. The Level 1 analysis predicted that 4 percent of the slabs would crack while the Level 2 and Level 3 analyses predicted 16 percent and 2 percent, respectively. The Level 2 input predicted more distress because the value, which was estimated using the coefficient of thermal expansion of the paste and aggregate and their volumes in the concrete mixture, was larger than the other two values. See table 2. The design thickness would need to be increased by 13 mm (0.5 in) if a Level 2 input was used. The Level 3 input resulted in less distress because the typical value used in the analysis was less than the actual measured value.

The predicted faulting for the undoweled slabs also varied significantly as the hierarchal level of the PCC CTE varied. The Level 2 analysis, which had the largest CTE, predicted the most faulting and only meets the design criteria for 13 years at a reliability of 95 percent. Therefore, the design thickness would need to be increased by 51 mm (2 in) if a Level 2 data was used.

The results of this analysis stress the importance of obtaining a representative value for the PCC CTE when designing a rigid pavement. The CTE has a wide range of possible values for some aggregates and historically, this parameter has not been well documented by agencies for concrete paving mixtures. Therefore, it would be of benefit to better characterize the CTE for paving mixtures typically used by an agency.

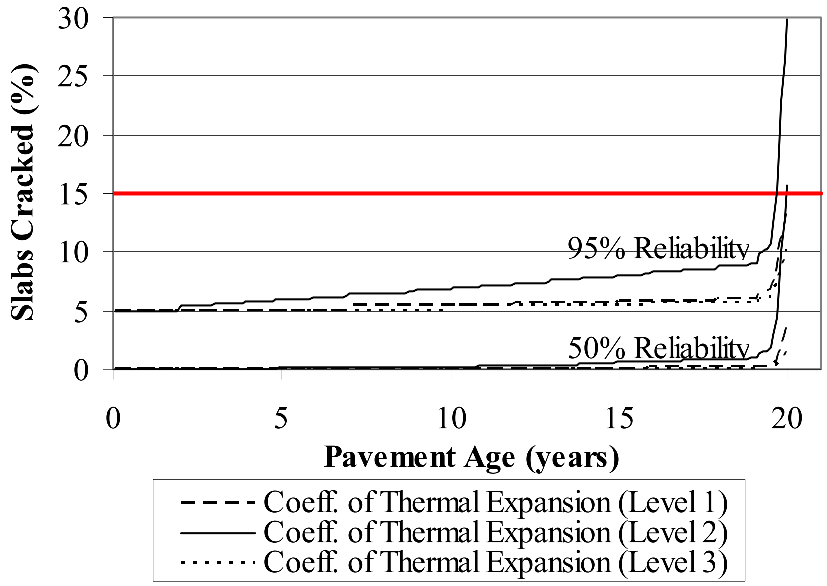

Figure 13. Percent cracking in the doweled slabs as a result of varying the hierarchal level of the PCC coefficient of thermal expansion.

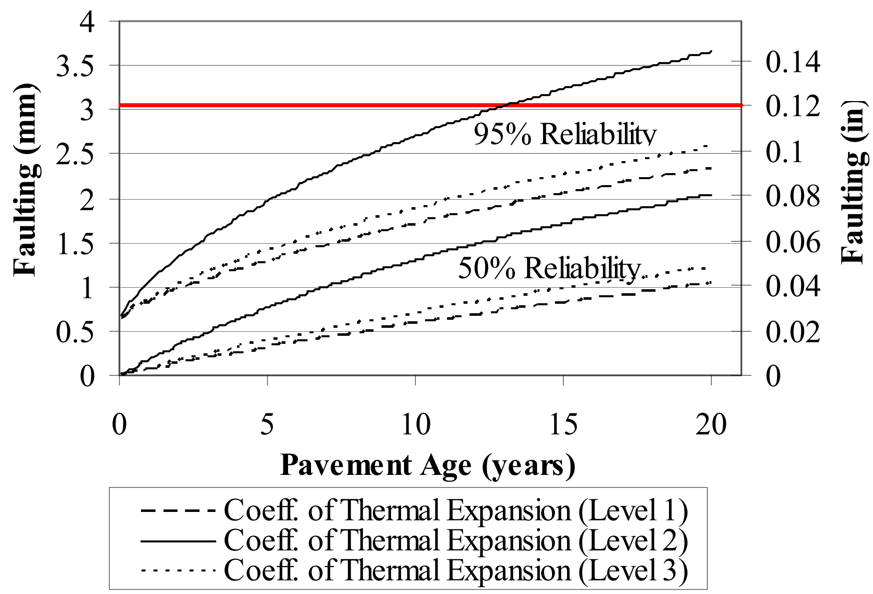

Figure 14. Predicted faulting in the undoweled slabs as a result of varying the hierarchal level of the PCC coefficient of thermal expansion.

Subgrade Resilient Modulus Figure 15 and Figure 16 present the predicted performance of the doweled and undoweled slabs as the hierarchal level of the subgrade resilient modulus input is varied. The use of Level 2 data produced a resilient modulus of 61 MPa (4500 psi), which was determined based on CBR data. The Level 3 input, which is based on the MEPDG recommended value determined using the LTPP data, produced a resilient modulus of 97 MPa (14,000 psi). Although the resilient modulus value changed drastically between the hierarchal levels, the predicted performance did not. At 50 percent reliability, the Level 2 analysis predicted that 3 percent of the slabs would crack while the Level 3 analyses predicted 4 percent. This trend was also experienced in the predicted faulting for the undoweled slabs, as shown in Figure 16. This difference in predicted slab cracking and faulting can be considered negligible therefore; the hierarchal level of the subgrade resilient modulus does not significantly affect performance for this pavement considered.

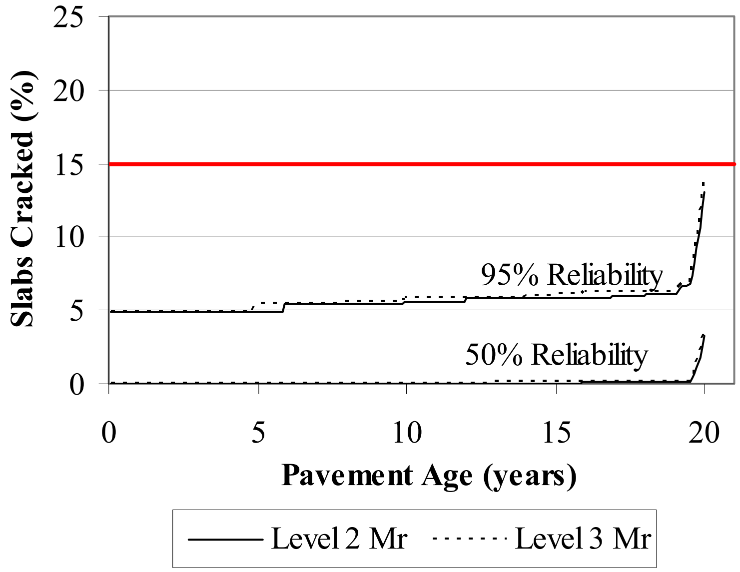

Figure 15. Percent cracking in the doweled slabs as a result of varying the hierarchal level of the subgrade resilient modulus.

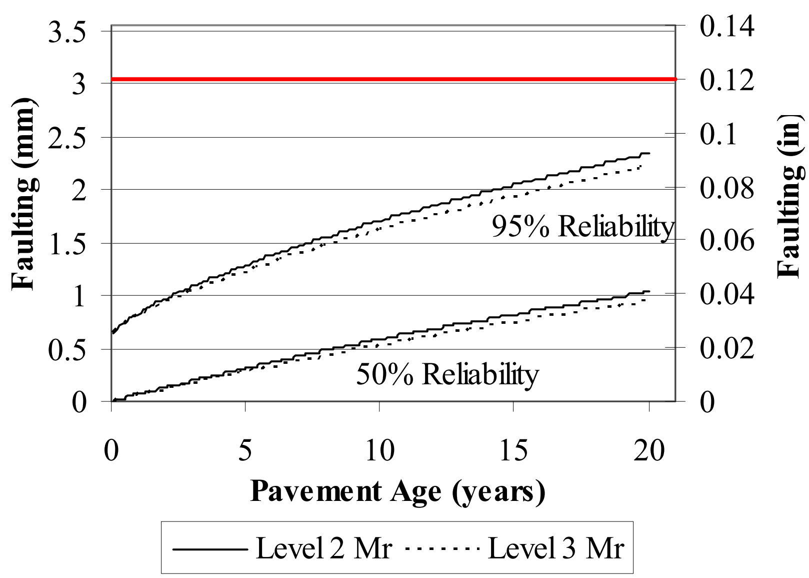

Figure 16. Predicted faulting in the undoweled slabs as a result of varying the hierarchal level of the subgrade resilient modulus.

Summary and Conclusions

The new MEPDG provides a versatile tool for the design of pavement structures using mechanistic-empirical principles. Based on the MEPDG, the doweled pavement on SR 22 will provide an acceptable level of service for 45 years and the undoweled pavement for 17 years. The design thickness determined using the 1993 Guide is 25 mm (1 in) thicker than the MEPDG design thickness for the restrained slab and 25 mm (1 in) thinner for the unrestrained slabs.

Next, the effect of using all Level 1 inputs versus all Level 2 or Level 3 inputs was compared. The results of the analysis of the hierarchal input levels showed that the doweled slabs would have the same design thickness regardless of the level of inputs used. However, the thickness of the undoweled slabs would have to be increased a 0.5 in if all Level 3 data was used.

The results of changing the hierarchal level of an individual design input provided insight into the sensitivity of traffic, climate, PCC strength, PCC CTE and subgrade resilient modulus on predicting pavement performance. Table 3 shows the effects of using different hierarchal levels to define an input. The ratio of the distress (percent slabs cracked or inches of faulting) predicted for Level 1 and Level 2 normalized by dividing it by the distress predicted using Level 3 data. The table shows using different hierarchal levels to define the thermal coefficient of expansion had the largest effect with the PCC modulus of rupture having the second largest. Defining the inputs using different hierarchal levels has a substantially larger effect on predicting cracking compared to the prediction of faulting for the pavement sections considered.

Table 3. Ratio of predicted performance (cracking/faulting) based on a Level *x* input with respect to a Level 3 input.

Input	**Cracking**			**Faulting**		
	L1/L3		*L3/L3*	*L1/L3*		*L3/L3*
Traffic	N/A		1	N/A		1
PCC thermal coefficient	2.25		1	0.85		1
PCC mod. of rupture	4		1	0.72		1
Subgrade resilient modulus	N/A		1	N/A		1
Weather Station Location	*On-site/ PIT*		*PIT/ PIT*	*On-site/ PIT*		*PIT/ PIT*
Climate	0.85	0.90	1	0.89	0.17	1

L1 = Level 1; L2 = Level 2; L3 = Level 3

A more clear view of the influence of using different hierarchal levels to define an input can be seen by looking at the effects of changing the input on the design thickness. Characterizing traffic through Level 3 data resulted in a slab 13 mm (0.5 in) thicker than Level 2 data for both the doweled and undoweled slabs. The use of Level 2 data for the PCC CTE resulted in a slab that is 51mm (2 in) thicker than the design thickness determined using Level 1 or Level 3 data for the undoweled slabs. The Level 2 PCC CTE input also required an increase in slab thickness for the doweled slabs. Varying the input levels used in defining the PCC strength and subgrade resilient modulus did not impact the design thickness nor did the use of different climatic weather stations. This study shows that using different hierarchal levels for the critical inputs can have an effect on the design thickness.

This study has shown the importance of accurately defining each design input, especially when those inputs are know to have a significant influence on the performance of rigid pavements. It has also shown that the use a climatic database that has insufficient data can also effect the performance prediction provided by the MEPDG. It is unreasonable to expect that an agency can always provide Level 1 inputs for the vast number of inputs required when using the MEPDG. Fortunately, this is not necessary. It is important to know what the effects of using different means of establishing each input (typical value, correlated value or measured value) will have on the resulting design thickness.

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