Local Calibration for Fatigue Cracking Models Used in the Mechanistic-Empirical Pavement Design Guide

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ABSTRACT

This paper identified two important calibration factors for a Midwest implementation of the Mechanistic-Empirical Pavement Design Guide (MEPDG). The calibration factors are for the fatigue damage model in flexible pavements. The gathering of the data required for calibration is labor intensive because the data resides in various and incongruent data sets. Spreadsheet templates specifically designed to manage the calibration data were used to collect pavement performance data from state transportation agencies in Michigan, Ohio, and Wisconsin. Calibration factors were then derived by minimizing the differences between observed and predicted pavement performance. The pavement performance field data in Wisconsin were employed for calibration initially, and the distresses predicted with these calibration factors were compared to pavement field performance in the other states. These calibrated models in the MEPDG assure the reliable prediction of pavement distress, such as longitudinal and alligator cracks.

Key words: fatigue cracking prediction—local calibration—Mechanistic-Empirical Pavement Design Guide

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INTRODUCTION

The Mechanistic-Empirical Pavement Design Guide (MEPDG) is a new product that was developed to enhance and improve existing pavement design procedures. It will result in transitioning from the existing empirically based pavement design procedure to a mechanistic-empirically based procedure that will combine the strengths of advanced analytical modeling capacity and observed field performance. The model parameters are based on data collected from a few pavement test sites and full-scale testing facilities. These performance models are key elements in the accuracy of the design results and thus warrant detailed validation and calibration, particularly with regard to the effect of local climate and pavement structure conditions.

This paper presents the results of a regional pooling effort for the purpose of calibrating the MEPDG models for the Midwest. Regional pooling of performance data is not an easy task because it requires coordination among participating states, uniformity in data collection, similarity of database structures, and a centralized approach for data analysis and reporting. To collect the pavement data from the states in the Midwest region, a uniform database format was developed, and state highway agencies were asked to fill out the form. The collected pavement date from Michigan, Ohio and Wisconsin were applied to evaluate the calibration factors in the fatigue cracking models for the Midwest region. The collected data was fed in to the MEPDG software, and a comparison of the output from the program to actual pavement performance enabled validation and calibration.

BACKGROUND

The most widely used procedure for pavement design is the 1993 American Association of State Highway and Transportation Officials (AASHTO) Guide for Design of Pavement Structures (AASHTO 1986; AASHTO 1993). A few states use the 1986 or 1972 AASHTO guidelines. Some states have developed their own design procedures, some based on mechanistic-empirical procedures (Khanum et al. 2005). For example, the Wisconsin Department of Transportation (WisDOT) developed its own pavement design procedure based on the 1972 AASHTO Interim Guide.

The design methodologies in all versions of the AASHTO guide are based on the empirical performance equations developed using AASHO road test data from the late 1950s (Khanum et al. 2005). Those equations are based on the obsolete construction methods, materials, and loads of the 1950s. The limitations of earlier versions motivated the development of the MEPDG through NCHRP project 37-1(A).

MEPDG Procedure

The MEPDG combines empirical and mechanistic procedures. Mechanistic methods are used to predict pavement responses, and pavement performance is predicted based on performance data collected from real-world pavements. Figure 1 illustrates the design procedure in the MEPDG. The designer first considers the pavement construction (structure) and site conditions (material, traffic, climate, and existing pavement condition, in the case of rehabilitation). The designer then selects a trial design, including the number of total layers, thickness of each layer, and choice of material. From these inputs, the design procedure mechanistically calculates structural responses: stress (σ), strain (ε), and deformation (δ). From these calculated responses, damages are projected during design life and accumulated monthly by pavement performance models. The MEPDG allows the designer to calibrate pavement performance models depending on environmental factors such as traffic and climate. Well-calibrated prediction models result in reliable pavement designs and enable precise maintenance plans for state highway agencies

(Carvalho and Schwartz 2006). Local pavement performance data can be used to validate and adjust calibration factors integrated in the MEPDG. The procedure empirically relates damage over time to pavement distress and smoothness level, as chosen by the designer. The key damage features and smoothness problems are surface cracking, fracture, fatigue, rutting, and roughness. With selection of calibration and design reliability levels, the trial design is then evaluated against some predetermined failure criteria. If the trial design does not meet desired performance criteria at a predetermined level of reliability, it is modified and the evaluation process is repeated as necessary (NCHRP 2004).

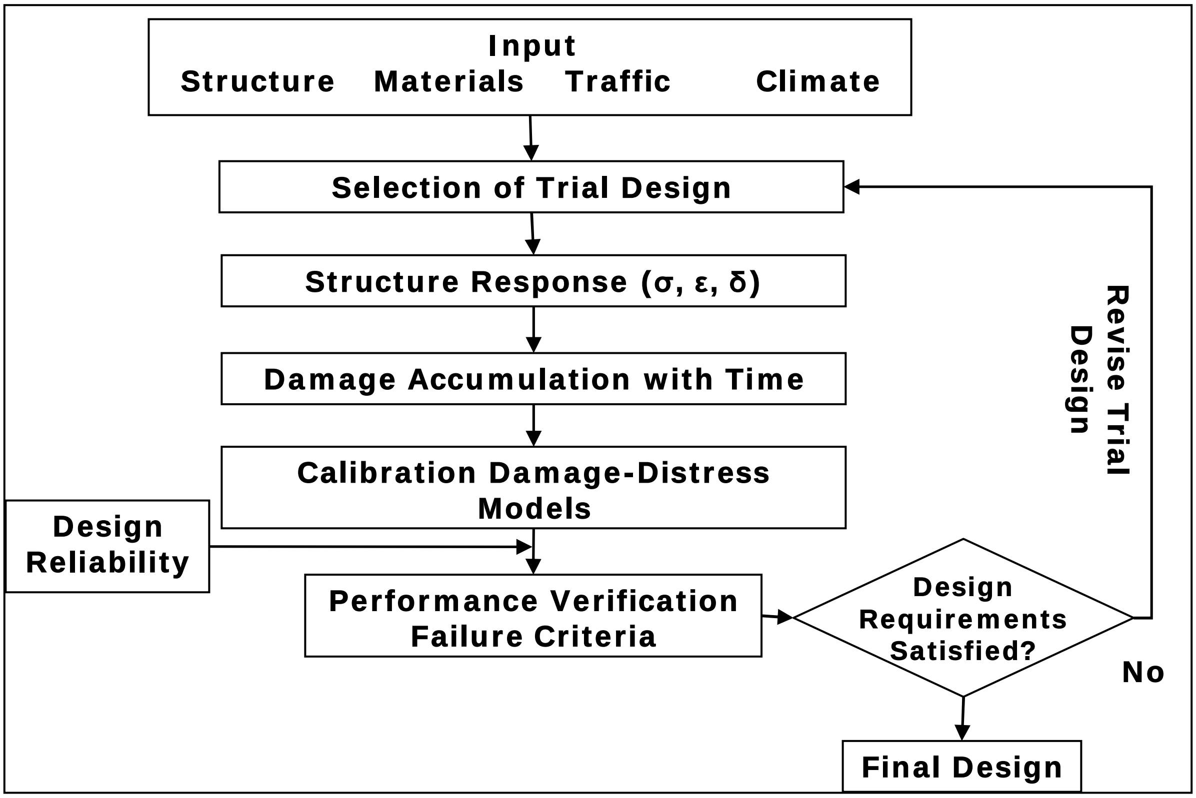


Figure 1. MEPDG procedure (NCHRP 2004)

PAVEMENT DATA COLLECTION

The pooling of pavement material, structure, and performance data from multiple states requires coordination with the participating states, a common data collection format, and similar levels of data availability. Thus, for this project, a uniform data collection format was established and delivered to the participating state agencies. The uniform format was created based on Appendix EE of the MEPDG. In considering data gathering familiarity for the participating state agencies, Microsoft Excel spreadsheets were determined to be the best format for gathering the pavement data, since they have functions that help the agencies complete the forms. The Excel file consists of five different work sheets: general project information, traffic, climate, pavement structure/material, and pavement performance. The first four sheets are for the input data required for the MEPDG program, and the last sheet, pavement performance, is for comparing output from the software to measured field data. Comparison of the output from the software to field data allowed the reviewing and adjusting, if necessary, of calibration factors in the MEPDG distress models.

Data Quality and Assumptions for Wisconsin Pavement Sections

To select sections from which to gather data in Wisconsin, WisDOT's primary pavement performance database, the Pavement Information Files, was used. When the representative sections were selected, three criteria were considered: (1) sections with severe distresses, (2) sections with no rehabilitation and no overlay, and (3) sections more than five years old. Sections with severe distresses were defined as having total rutting greater than 0.25 in., an International Roughness Index (IRI) value greater than 172 in./mile, and a Pavement Distress Index (PDI) value greater than 65. PDI is a mathematical expression for pavement condition rating that is keyed to observable surface distresses in Wisconsin. The PDI number (0 for best condition and 100 for worst) is used to summarize the level of distress and is used primarily for network-level evaluation (in WisDOT's PDI Survey Manual). Table 1 shows the specific values of criteria for selecting the sections in Wisconsin.

Table 1. Initial selection criteria in Wisconsin

Distress	Criteria value	Mark
Rutting	0.25"	Default limitation value for failure in MEPDG
IRI	172 in/mile	Default limitation value for failure in MEPDG
PDI	65	Level when WisDOT recommends maintenance on Principal Arterials

It was not an easy task to collect the available pavement information required to run MEPDG. Due to the lack of available pavement information, only nine sections were employed for flexible pavement. Table 2 lists the representatives sections with pavement performance and the required data available. The sequence number shown is the primary key in the PIF database used to identify each section.

Table 2. Wisconsin sections with significant distress in 2006 (flexible pavement)

			Pavement Performance					
Sequence #	County	High way #	Rutting (in.)	IRI (in./mi)	Alligator cracking (%)	Transverse cracking (number/sta*)	Longitudinal cracking (ft./sta*)	PDI**
23010	DANE	19	0.25-0.5	214	50-74	1-5	1-100	70
34230	PIERCE	29	0.25-0.5	234	25-49	6-10	201-300	92
98490	GRANT	80	0.25-0.5	259	25-49	6-10	1-100	83
133580	OUTAGAMIE	187	0.25-0.5	274	50-74	1-5	101-200	93
33620	SHEBOYGAN	28	0	198	50-74	0	1-100	95
34240	PIERCE	29	0.25-0.5	192	25-49	6-10	201-300	83
113040	BROWN	96	0.5-1	46	1-24	6-10	101-200	88
133510	OUTAGAMIE	187	0	227	25-49	6-10	101-200	81
136706	WAUKESHA	164	0	56	0	6-10	1-100	22

* sta: station (100ft = 0.21 mile per station on average)
** PDI: Pavement Distress Index

As-built plans were the major source for obtaining pavement profile, such as number of layers and material properties, and PIF provided WisDOT with the pavement performance history. After obtaining as-built plans, however, the research team discovered that resurfacing had been done, and overlays had been applied, to some of the sections. An irregularity in the distress measures was also recognized. Occasionally, distress quantities appeared to increase then drop back down without explanation. After discussion with WisDOT's pavement design experts, two explanations were possible: First, minor maintenance may have been applied. Minor maintenance activities are not considered restoration or reconstruction that can be designed by the MEPDG. Such operations usually focus on the ride quality, rather than structural improvement. The distresses thus seem to disappear for awhile, but they rise a few years later. Second, the irregularity may be due to human factors when distresses are observed. Prior to 1999, the pavement performance data (except IRI) was collected manually by pavement crews in each region and then sent to the central office. This, by itself, induces variability. In 1999, WisDOT purchased new equipment to collect both IRI and pavement distress data. Both the use of new equipment and the removal of regional variability caused adjustments to the PIF data. Thus, it was decided that only the data collected after 2000 were to be applied for calibration study.

Michigan and Ohio Pavement Sections

The pavement database structures were delivered to the states as Excel spreadsheet files, and the state agencies were asked to complete the spreadsheets for at least five flexible pavement sections. Michigan and Ohio delivered five sections for flexible pavement. Even though the states made efforts to provide the pavement data, critical obstacles were encountered in conducting the calibration. Required data items for running MEPDG were missing, and some of the data collected by the state transportation agencies were not applicable to MEPDG. For these missing data, the default values in MEPDG were used.

The pavement performance data from Michigan and Ohio show trends in irregularities similar to those observed in Wisconsin. Most of the representative sections were constructed in the late 1980s and early 1990s. It is not likely these sections have been rehabilitated. Given the unresolved irregularities in the Ohio and Michigan data, Wisconsin's data was used for calibration. After determining calibration values with Wisconsin's data, the field data from Ohio and Michigan were compared to the prediction models using default calibration values in the MEPDG and to the prediction models using calibration values for Wisconsin data. The comparisons will show whether other states best fit the Wisconsin or default model. The comparison will also show the deviations between actual field data and the prediction models.

CALIBRATION OF THE FATIGUE CRACKING MODEL

The calibration factors in the MEPDG prediction models can be determined by analyzing corresponding field performance data. The calibration factors are adjustable and known to depend upon conditions such as climate, loads, and pavement structure. Climatic and material sources vary regionally, and thus there is some logic to calibrating the models on a regional basis. The calibrations are done by comparing the collected pavement performance with the predicted pavement performance. The default values in the MEPDG were applied initially, and then the calibration factors were adjusted to reduce the difference between collected/observed and predicted pavement performance. The best fit minimizes the difference between MEPDG prediction and observed performance.

Calibration of the fatigue cracking model in the MEPDG was conducted based on the model presented in Appendix II-1 of the MEPDG (NCHRP 2004) and in a Transportation Research Board conference paper by El-Basyouny and Witczak (2005). Accordingly, fatigue cracking prediction is based on the cumulative damage concept. The damage is calculated as the ratio of cumulative predicted load repetitions from traffic to the allowable number of load repetitions. The damage for fatigue cracking is expressed as a percentage. Theoretically, fatigue cracking occurs when accumulated damage is 100%. The equation for calculating the damage for fatigue cracking is as follows:

$$D=\sum_{i=1}^{T}\frac{n_i}{N_i} \qquad (1)$$

where

D = Damage
T = total number of periods
n_i = actual traffic for periods i
N_i = allowable failure repetitions under conditions prevailing in period i

The general mathematical form for the number of load repetitions is also shown in the MEPDG. The form of the model is a function of the tensile strains at a given location and the modulus of the asphalt layer (El-Basyouny and Witczak 2005; NCHRP 2004).

$$N_f = \beta_{f1} k_1 (\varepsilon_t)^{-\beta_{f2} k_2} (E)^{-\beta_{f3} k_3} \tag{2}$$

where

N_f = Number of repetitions to fatigue cracking
ε_t = Tensile strain at the critical location
E = Stiffness of the material (psi)
$\beta_{f1}, \beta_{f2}, \beta_{f3}$ = calibration parameters.
k_1, k_2, k_3 = material constants from laboratory testing

Here, β_{f1} , β_{f2} , β_{f3} are the calibration parameters to be determined. According to the literature, β_{f1} is assumed to be 1 unless the asphalt concrete layer thickness is less than 3 in. In this study, because the total thickness of the asphalt layer is more than 3 in., β_{f1} is assumed to be 1 for all sections. As recommended in the literature, the calibration should be done by running the software for combinations of calibration factors β_{f2} , β_{f3} Following the MEPDG, three values of β_{f2} and three values of β_{f3} were applied for calibration. Hence, total runs were nine times per section. The runs were conducted for values of 0.8, 1.0, and 1.2 for the calibration factor on the strain (β_{f2}) and values of 0.8, 1.5, and 2.5 for the modulus calibration factor (β_{f3}) for the MS-1 model (NCHRP 2004). Table 3 lists the possible combinations of calibration values.

Table 3. All combinations of calibration values for fatigue cracking model

Number	β_{f2}	β_{f3}
1	0.8	0.8
2		1.5
3		2.5
4	1.0	0.8
5		1.5
6		2.5
7	1.2	0.8
8		1.5
9		2.5

Comparison of predicted to actual percent damage in the pavement should deliver the appropriate calibration values. However, field data on percent damage is not available. State highway agencies monitor fatigue damage through visible distresses in the pavement, such as longitudinal and alligator cracks. Thus, fatigue calibration values must be related to those visual distresses.

Calibration of the Longitudinal Fatigue Cracking Model

The damage transfer function used in the MEPDG for longitudinal (surface-down) fatigue cracking is in the form shown as follows.

$$F.C. = \left(\frac{1000}{1 + e^{C_1 - C_2 * LogD}} \right) * (10.56) \qquad (3)$$

where

$F.C.$ = fatigue cracking (ft/mile)
D = Damage in percentage
C_1, C_2 = regression coefficients

In the MEPDG, the regression coefficients, C_1 and C_2, were evaluated using a Microsoft Solver numerical with more than 100 sections nationwide, and the default values of each C (C_1=7.0, C_2=3.5) were decided to be used for this study. Damage in percentage, D, can be calculated by the fatigue cracking model. All combinations of calibration values were applied to discover the best ones. Nine runs for each section were conducted, and the outputs were evaluated by the sum of squares (SS) for each plot. SS is defined as follows:

$$Sum\ of\ Square\,(SS) = \sum_{i=1}^{n} (Output\ from\, ME\ PDG - Observed\ Field\ Value\ in\ PIF)^2 \qquad (4)$$

where n = number of data points.

Nine trials for each section resulted in two sets of betas, one for each section, that minimized the SS values for longitudinal cracking (β_{f1}=1.0 β_{f2} =0.8 β_{f3}=0.8 and β_{f1}=1.0 β_{f2} =1.2 β_{f3}=1.5). Figure 2 and Figure 3 are the plots of the output from the MEPDG for various combinations of the calibration factors. The numbers in parentheses are beta values β_{f1}, β_{f2}, and β_{f3}, respectively. The default beta values are (1.0, 1.0, 1.0). For reference, “PIF” denotes the field-observed pavement performance.

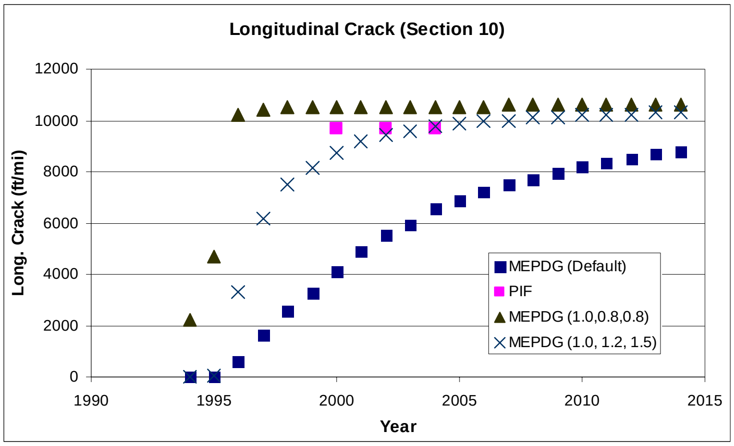


Figure 2. Predicted longitudinal cracking in Wisconsin Section 10 for various calibration values

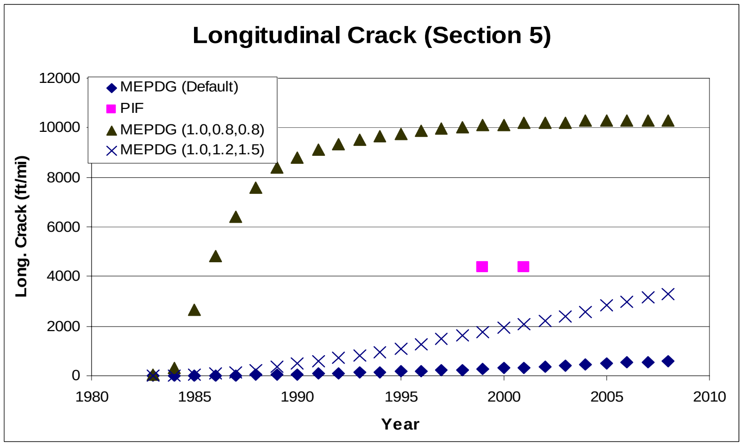


Figure 3. Predicted longitudinal cracking in Wisconsin Section 5 for various calibration values

SS values for three beta sets, including default values, were calculated and compared. The results indicate that a prediction model with β_{f1}=1.0, β_{f2}=1.2, and β_{f3} =1.5 has the smallest SS value and is thus the best fit. To investigate further, the possible combinations of calibration factors were applied for all sections. Figure 4 though 6 show plot comparisons of actual pavement performance versus predicted pavement performance for each calibration set. Ideally, if there is no difference between actual and predicted performance, the data points should fall on the 45 degree line (y=x in graphs). From the figures, the plot in which β_{f2}=1.2 and β_{f3} =1.5 shows the best fit for longitudinal cracking, which is consistent with the SS analysis.

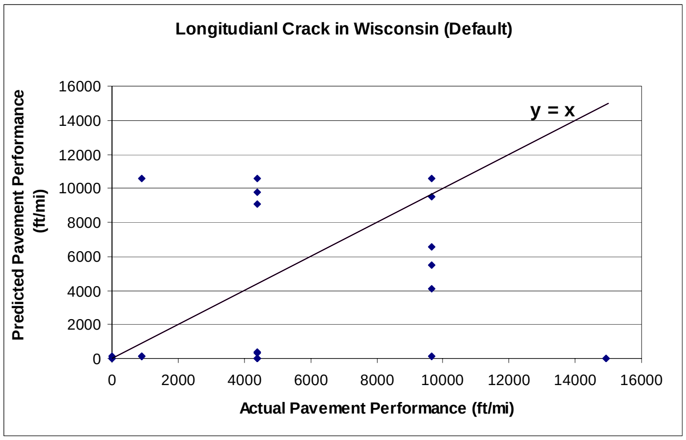


Figure 4. Longitudinal cracking comparison plot for Wisconsin (default)

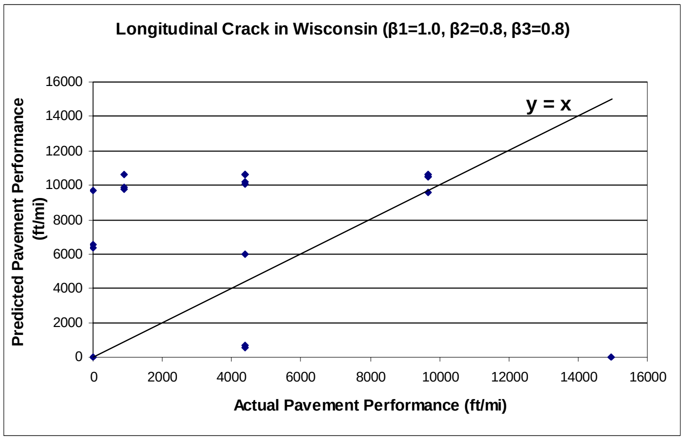


Figure 5. Longitudinal cracking comparison plot for Wisconsin (β_{f1}=1.0, β_{f2}=0.8, β_{f3} =0.8)

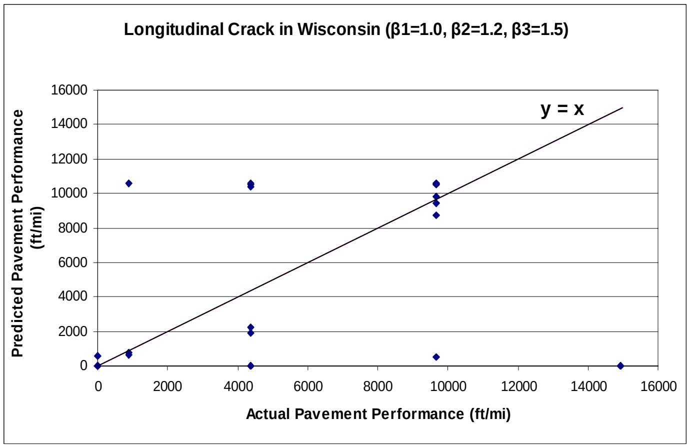


Figure 6. Longitudinal cracking comparison plot for Wisconsin (β_{f1}=1.0, β_{f2}=1.2, β_{f3} =1.5)

Calibration of Alligator Fatigue Cracking Model

The fatigue cracking-damage transfer function used in the calibration of the alligator (bottom-up) cracking is presented in the MEPDG as follows:

$$F.C.=\left(\frac{6000}{1+e^{C_1-C_2*LogD}}\right)*\left(\frac{1}{60}\right) \tag{5}$$

where

$F.C. =$ fatigue cracking (% of lane area)
$D =$ Damage in percentage
$C_1, C_2 =$ regression coefficients

Similar to longitudinal cracking, the default values, C_1 and C_2, are used in this calibration. Damage in percentage, D, depends on the fatigue cracking model. To find the calibration values for alligator cracking, nine runs were conducted for each section. Comparing the outputs from the MEPDG for various calibration factors determines the β_{f2} and β_{f3} with the least SS of errors. Two sets of betas (β_{f1}=1.0 β_{f2} =0.8, β_{f3}=0.8, and β_{f1}=1.0, β_{f2} =1.2, β_{f3}=1.5) for Section 10 and three sets of betas (β_{f1}=1.0, β_{f2} =0.8, β_{f3}=0.8; β_{f1}=1.0, β_{f2} =1.2, β_{f3}=1.5; and β_{f1}=1.0, β_{f2} =1.0, β_{f3}=1.5) for Section 5 have a high chance of reducing the SS values for alligator cracking. Figures 7 and 8 show the plots of the output from the MEPDG after changing the calibration values. Again, the output with default calibration values is also shown in the figures. The number by “MEPDG” represents the beta values (β_{f1}, β_{f2}, and β_{f3}), and “PIF” denotes the collected pavement performance data in the figures.

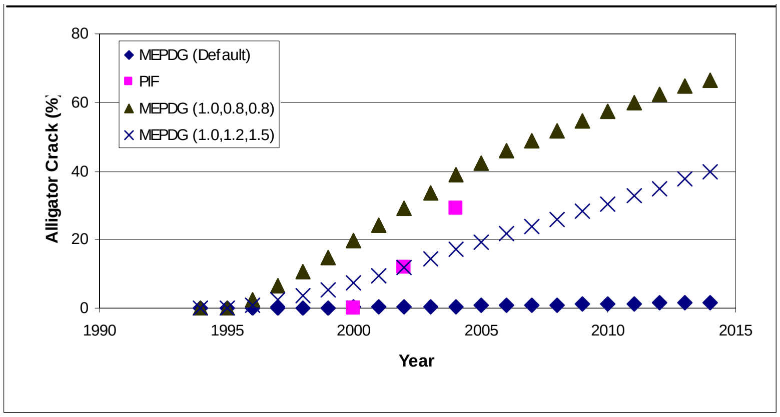


Figure 7. Alligator cracking in Section 10 in Wisconsin by various calibration values

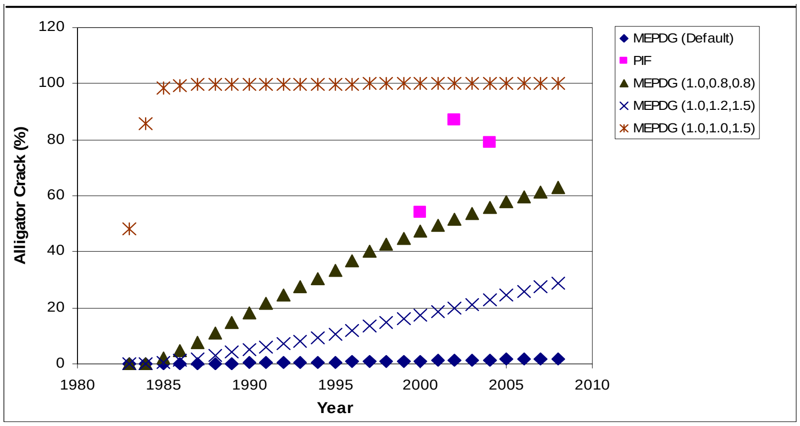


Figure 8. Alligator cracking in Section 5 in Wisconsin by various calibration values

The prediction model with $\beta_{f2}=1.2$ and $\beta_{f3}=1.5$ shows the smallest SS values for Section 10 and $\beta_{f2}=0.8$ and $\beta_{f3}=0.8$ for Section 5. Two sets of calibration values ($\beta_{f2}=0.8$, $\beta_{f3}=0.8$ and $\beta_{f2}=1.2$, $\beta_{f3}=1.5$) were applied to other sections. Comparison graphs were plotted showing actual pavement performance vs. predicted pavement performance. Ideally, if there is no difference between actual performance data and predicted performance data, the points should be on the perfect 45 degree line. The comparison plots with default calibration factors ($\beta_{f2}=1.0$ and $\beta_{f3}=1.0$) and the best fit calibration factors ($\beta_{f2}=0.8$, $\beta_{f3}=0.8$ and $\beta_{f2}=1.2$, $\beta_{f3}=1.5$) are shown in Figures 9 to 11.

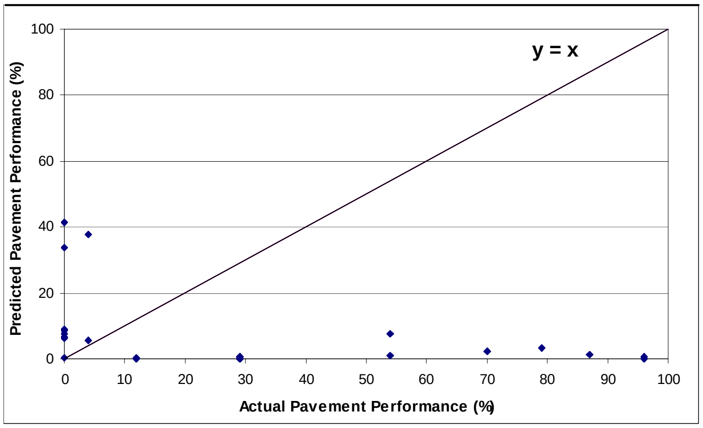


Figure 9. Alligator cracking comparison plot in Wisconsin (default)

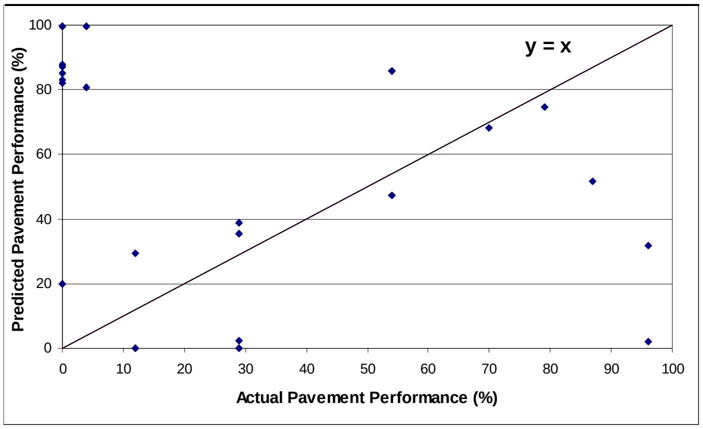


Figure 10. Alligator cracking comparison plot in Wisconsin (β_{f1}=1.0, β_{f2}=0.8, β_{f3} =0.8)

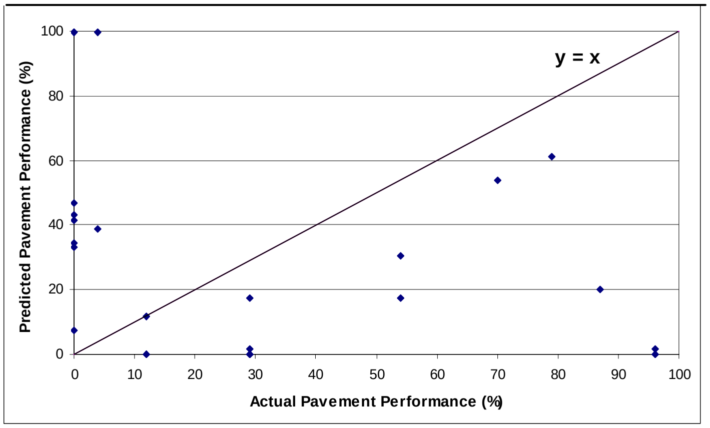


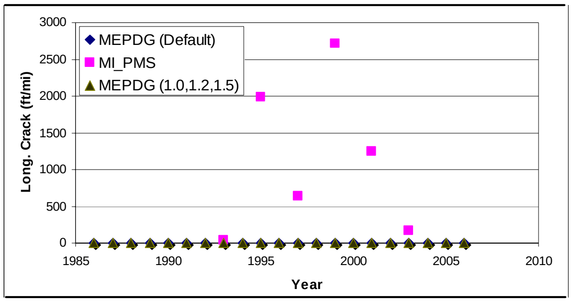
Figure 11 Alligator cracking comparison plot in Wisconsin (β_{f1}=1.0, β_{f2}=1.2, β_{f3} =1.5)

From these three figures, it is difficult to determine which set is the best. Clearly, the plot with default values is the worst. But the plots in Figure 10 and Figure 11 were spread out. Thus, it can be said that both of the calibration sets can be applied to alligator cracking in Wisconsin. However, one is not allowed to input different calibration factors for longitudinal cracks and alligator cracks in the MEPDG. Thus, the proper calibration values for fatigue cracking were concluded: β_{f2}=1.2 and β_{f3} =1.5.

Calibration Fit for Michigan and Ohio

The calibration values were determined only from Wisconsin data. Due to time and budget limitations, calibration factors for Michigan and Ohio could not be determined. Instead, this section presents comparisons of the following calibration methods for both states: predicted performance using the MEPDG, predicted performance using Wisconsin's calibrated model, and observed pavement field performance. Because only two calibration values were determined using Wisconsin fatigue data, only two distresses are presented: longitudinal cracking and alligator cracking.

The calibrated MEPDG model predicted longitudinal cracking poorly for Michigan. Figure 12 and Figure 13 compare the outputs of longitudinal cracking from the MEPDG and field-collected pavement performance data. Both plots show that neither of the two predictions from the MEPDG is accurate. As is especially evident in Figure 13, the prediction using the default values is better than that using the calibrated values.



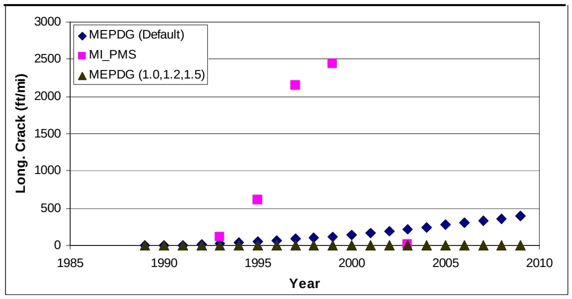
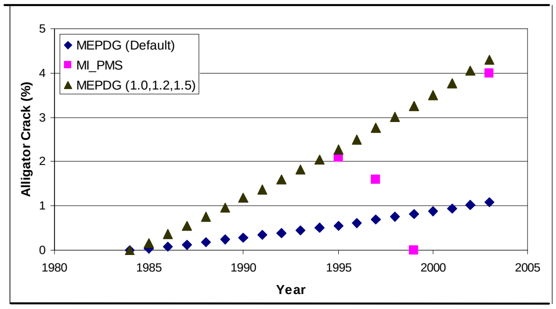


Figure 12. Longitudinal cracking in Section 2 in Michigan

Figure 13. Longitudinal cracking in Section 5 in Michigan

Unlike with longitudinal cracking, the calibrated MEPDG model predicted alligator cracking well for Michigan. Figure 14 shows that the calibrated prediction model can reduce minimize the difference between the prediction and the field-collected data. Figure 15 suggests that the prediction using the default calibration model is better than that obtained using the calibrated values. However, if the deterioration rate of field data is considered, a prediction using calibrated values may match field data better than a prediction obtained using default values.



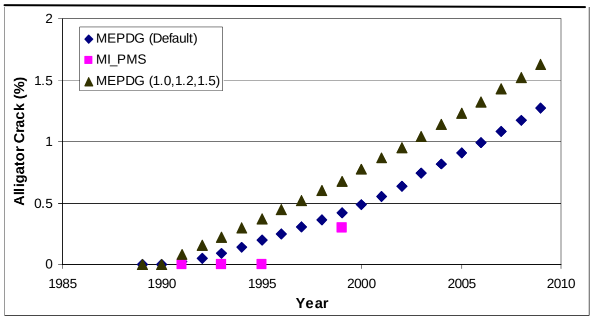
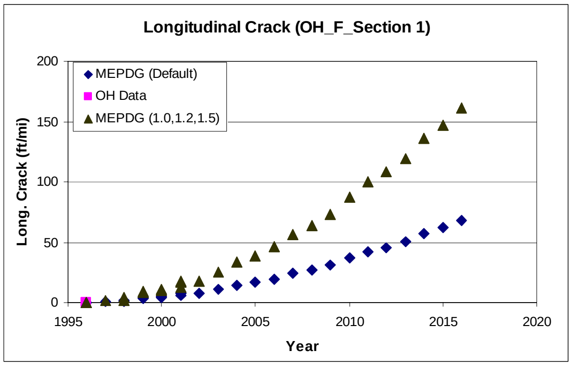


Figure 14. Alligator cracking in Section 1 in Michigan

Figure 15. Alligator cracking in Section 5 in Michigan

The collected field data from Ohio does not seem suitable for calibration. As can be seen in Figure 16 and Figure 17, the collected longitudinal data stay at "0" or rise quickly and reach 6,000 ft./mi. in only a couple of years. Thus, it is difficult to judge whether calibrated prediction is good for longitudinal cracking in Ohio.



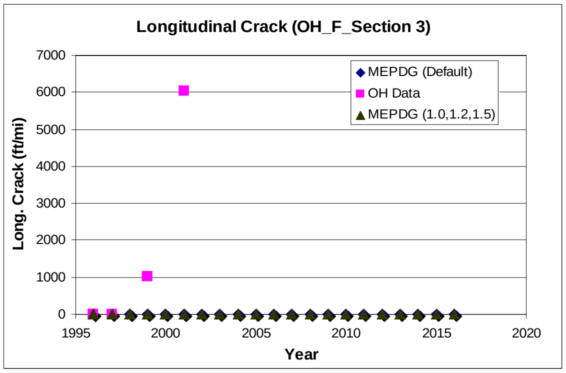


Figure 16. Longitudinal cracking in Section 1 in Ohio

Figure 17. Longitudinal cracking in Section 3 in Ohio

The collected pavement performance data is inadequate for alligator cracking. Because the pavement has deteriorated too quickly, neither of two models could predict alligator cracking well for Ohio. Figure 18 illustrates that alligator cracks increase 0% to 6% in five years, which is an increase 20 times greater than that observed in the Michigan data (Figure 15). Thus, it is difficult to predict alligator cracking using Ohio with default or calibrated values.

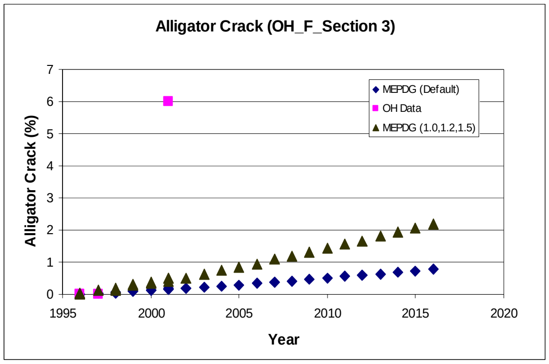


Figure 18. Alligator cracking in Section 3 in Ohio

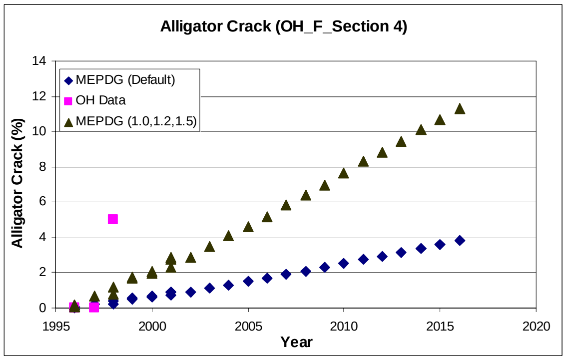


Figure 19. Alligator cracking in Section 4 in Ohio

CONCLUSIONS AND RECOMMENATIONS

This paper has presented the results of an effort to calibrate the MEPDG models. Pavement data from three state transportation agencies in the Midwest region, Michigan, Ohio, and Wisconsin, were collected using a uniform template to serve as input variables in the MEPDG. Data collection was tremendously laborious, causing delays in getting data. Due to time limitations, the data from Michigan and Ohio could not be included in the calibration analysis. A comparison of the pavement distresses predicted using the MEPDG models to the distresses observed in collected pavement field performance data has determined the recommended calibration values for Wisconsin. The distresses predicted with these calibrated factors were compared to field pavement performance data from Michigan and Ohio. Table 4 summarizes the default and recommended calibration factors for the distress models in the MEPDG.

The final goal of calibrating pavement performance prediction is to implement the MEPDG in the regional state transportation agencies. Thus, agency personnel, as well as pavement design consultants, need to be educated and trained in the new pavement design guide. A training program should be established, and MEPDG should be implemented correctly.

Table 4. Calibration factors for prediction models in the MEPDG

Type	Parameter	Formula	Calibration factor	Default value	Recommended calibrated values
Flexible pavement	Fatigue	$N_f = \beta_{f1} k_1 (\varepsilon_t)^{-\beta_{f2} k_2} (E)^{-\beta_{f3} k_3}$	β_{f1}	1.0	1.0
			β_{f2}	1.0	1.2
			β_{f2}	1.0	1.5
	Longitudinal cracking	$F.C. = \left(\frac{1000}{1 + e^{C_1 - C_2 * LogD}} \right) * (10.56)$	C_1	7.0	Default
			C_2	3.5	Default
	Alligator cracking	$F.C. = \left(\frac{6000}{1 + e^{C_1 - C_2 * LogD}} \right) * \left(\frac{1}{60} \right)$	C_1	1.0	Default
			C_2	1.0	Default

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REFERENCES

AASHTO. 1986. Guide for Design of Pavement Structures. Washington, DC: American Association of State Highway and Transportation Officials.

AASHTO. 1993. Guide for Design of Pavement Structures. Washington, DC: American Association of State Highway and Transportation Officials.

Carvalho, R. and C. Schwartz. 2006. Comparison of Flexible Pavement Designs: AASHTO Empirical vs. NCHRP 1-37A Mechanistic-Empirical. *Transportation Research Record*, 1947, 167–174.

El-Basyouny, M.M. and M. Witczak. 2005. Development of the Fatigue Cracking Models for the 2002 Design Guide. Paper presented at the Annual Meeting of the Transportation Research Board, Washington, DC.

Khanum, T., Hossain, M., Romanoschi, S. A., and Barezinsky, R. 2005. Concrete Pavement Design in Kansas Following the Mechanistic-Empirical Pavement Design Guide. Paper presented at the Mid-Continent Transportation Research Symposium, Ames, Iowa.

NCHRP. 2004. Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures, Project 37-1A. Washington DC: National Cooperative Highway Research Program, Transportation Research Board, National Research Council.