DEVELOPMENT OF A REGIONAL PAVEMENT PERFORMANCE DATABASE FOR THE AASHTO MECHANISTIC - EMPIRICAL PAVEMENT DESIGN GUIDE:

PART 2: VALIDATIONS AND LOCAL CALIBRATION

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16. Abstract This project identified two important calibration factors for a Midwest implementation of the Mechanistic-Empirical Pavement Design Guide (M-E PDG). The calibration factors are for the fatigue damage model in flexible pavements in Wisconsin. Pavement performance data was collected from Michigan, Ohio, Iowa and Wisconsin state transportation agencies using uniform data structures as spreadsheet templates specifically designed to manage the calibration data. Spreadsheets were developed for both flexible and rigid pavements. Calibration factors were derived by minimizing differences between observed and predicted pavement performance. The gathering of data required for calibration is labor intensive because the data resides in various and incongruent data sets. Furthermore, some pavement performance observations include temporary effects of maintenance and those observations must be removed through a tedious data cleaning process. The scope of calibration factors are limited by these data impediments. For each state, the observed and predicted performances are compared for both flexible and rigid pavements. The predicted performance is computed using default and derived calibration factors. The project includes a case study design as an example for quantifying the benefits of the M-E PDG.

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EXECUTIVE SUMMARY

This project identified two important calibration factors for a Midwest implementation of the Mechanistic-Empirical Pavement Design Guide (M-E PDG). The calibration factors are for the fatigue damage model in flexible pavements in Wisconsin. Pavement performance data was collected from Michigan, Ohio, Iowa and Wisconsin state transportation agencies using uniform data structures as spreadsheet templates specifically designed to manage the calibration data. Spreadsheets were developed for both flexible and rigid pavements. Calibration factors were derived by minimizing differences between observed and predicted pavement performance. The gathering of data required for calibration is labor intensive because the data resides in various and incongruent data sets. Furthermore, some pavement performance observations include temporary effects of maintenance and those observations must be removed through a tedious data cleaning process. The scope of calibration factors are limited by these data impediments. For each state, the observed and predicted performances are compared for both flexible and rigid pavements. The predicted performance is computed using default and derived calibration factors. The project includes a case study design as an example for quantifying the benefits of the M-E PDG.

In 2004, the National Cooperative Highway Research Program (NCHRP) released version 0.7 of the Mechanistic-Empirical Pavement Design Guide. The M-E PDG is a new pavement design guide intended to enhance and improve pavement design and many state transportation agencies including Wisconsin are considering its implementation. The benefits of cost savings and improved performance have motivated state highway agencies to use the M-E PDG and focus on evaluating the calibration factors.

The performance models in the M-E PDG are key elements in the accuracy of the design results and thus warrant detailed validation and calibration. To collect the pavement information from multiple states, uniform database structures were developed: one for flexible pavement and one for rigid pavement. Four state transportation agencies agreed to provide data for the project: Michigan, Ohio, Iowa and Wisconsin. Obtaining data was far more difficult than expected due to data integration issues. Considerable efforts were spent assuring quality of the data. Due to timing of available data and funding constraints, calibration was conducted using Wisconsin's data, and then comparisons were provided with observed trends of other states.

The calibrations are achieved by minimizing differences between collected pavement performance and predicted pavement performance. Longitudinal and alligator cracks were considered for flexible pavement and faulting and transverse cracking were studied for rigid pavement. The default values in the M-E PDG were applied initially and then the calibration factors were adjusted to reduce the difference between collected and predicted pavement performance. The best fit minimizes the difference between M-E PDG prediction and observed performance. Two calibration values were recommended for the fatigue damage model in flexible pavement. Due to the limited data quantity and unreliability, calibration of distress prediction for rigid pavement could not be performed although default calibration factors were compared to the field collected distresses.

A case study analysis quantified the potential benefits of adopting the M-E PDG. The pavement design outputs of WisPAVE, a current pavement design tool used in Wisconsin, were compared to the results generated using the M-E PDG. Current maintenance plans were also evaluated by the pavement performance projection tools in the M-E PDG. The analysis estimated the potential dollar value savings resulting from the adoption of the M-E PDG.

Specific outcomes of the project include the following:

- Database structures were developed for gathering pavement data for calibration of the M-E PDG.
- Detailed pavement information was collected from four transportation state agencies for both flexible pavement and rigid pavement in the Midwest region: Michigan, Ohio, Iowa and Wisconsin.
- A set of calibration factors for the fatigue cracking model in flexible pavement were determined from Wisconsin pavement data: β_1=1.0 β_2=1.2 and β_3=1.5.
- The pavement data from other states were compared graphically to the calibrated predictions, which may help the state transportation agencies determine goodness of fit leading to appropriate calibration factors.
- A case study revealed that both maintenance and construction costs may be reduced by implementing M-E PDG.

This research project was intended to compile the regional pavement data for the M-E PDG and to evaluate calibration values for the Midwest region. Due to unexpected difficulties in obtaining data, only the fatigue cracking model for flexible pavement was calibrated only for Wisconsin pavement. For future studies, more reliable pavement data should be collected. The data collection template will enable that effort.

1. INTRODUCTION

1.1. Problem Statement

In 1996, the American Association of State Highway and Transportation Officials (AASHTO) Joint Task Force on Pavements, in cooperation with the NCHRP and FHWA, were charged with identifying the means for developing an AASHTO mechanistic-empirical pavement design procedure by the year 2002. From that meeting came NCHRP Project 1-37A, Development of the 2002 Guide for Design of New and Rehabilitated Pavement Structures. Although the target was 2002, a printed guide and version 0.7 of the software were delivered in June 2004. Still in the review stage, it represents a major improvement in pavement design. The M-E PDG includes performance prediction models that were developed based on mechanistic and empirical models. 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 report presents the results of a regional pooling effort for the purpose of calibrating the M-E PDG models. Some state highway agencies are calibrating the models based on selected sections within their state highway network. Others are leveraging data for calibration by pooling information regionally. Regional pooling of performance data is not an easy task because it requires coordination among participating states, uniformity in data collection, similarity of data base structures, and a centralized approach for data analysis and reporting.

1.2. Objectives

The main objectives of the project are threefold.

1) Sensitivity analysis of input variables to design outcomes.
2) Development of a Midwest regional pavement database for calibrating design factors in the M-E PDG.
3) Establishment of new set of field calibration factors for distress models of the design guide for both rigid and flexible pavements.

The first objective was to conduct an analysis of the M-E PDG parameters so that the pavement designer can recognize the important factors among input variables. Sensitivity analysis in this project is concentrated on the traffic and pavement material properties. The report of sensitivity analysis is documented separately in a report titled Development of Regional Pavement Performance Database: Part 1 Sensitivity Analysis.

The second objective was to develop a pavement database for calibrating the M-E PDG models for use in the Midwest region. The Wisconsin DOT, as well as other state agencies, may wish to use the calibration factors developed in this project. The research team contacted highway agencies of the states in the Midwest region including Illinois, Indiana, Iowa, Michigan, Minnesota, Ohio, and Wisconsin to collect pavement data including materials, structure and performance. Michigan, Ohio, Iowa and Wisconsin responded positively and the data for rigid and flexible pavements from these states were acquired for developing the database.

The third objective was to evaluate and then adjust, if necessary, the calibration factors of the M-E PDG models for the Midwest region. The collected data was fed in to the M-E PDG software and a comparison of output from the program to actual pavement performance enabled the validation and calibration.

1.3. Scope

This project created a database for use in calibrating the models used to predict pavement performance in the M-E PDG. The data required in this study is based on the final report of the National Cooperative Highway Research Program (NCHRP) project 1-37A. Appendix EE-1, "*INPUT DATA FOR THE CALIBRATION AND VALIDATION OF THE DESIGN GUIDE FOR NEW CONSTRUCTED FLEXIBLE PAVEMENT SECTIONS*". The analysis in this report uses M-E PDG; version 0.90 which describes additional required input parameters for calibration.

The scope of this research focuses on asphalt and concrete pavements. The data from Michigan, Ohio, Iowa and Wisconsin contribute to the database. The research sources depend on each state's pavement database. The research team developed a uniform data template and the states that agreed to cooperate in the project were asked to complete the database depending on data availability.

For Wisconsin, various pavement databases were reviewed and evaluated. They included as-built plans for pavement profiles, pavement material information, and the Pavement Information Files (PIF) for pavement performance.

1.4. Organization of the Report

This report is organized into several chapters:

Chapter 2. Background and Literature Review – This chapter reviews previous studies about the M-E PDG procedure and possible benefits of its application.
Chapter 3. Development of Database Format – This chapter presents the development of a database format for collecting pavement data for calibration.
Chapter 4. Data Source and Collection – This chapter characterizes the data collected from state DOTs in the Midwest region.
Chapter 5. Calibration of Prediction Models – This chapter presents the methodology and results of the calibration process as well as a new set of field calibration factors for the M-E PDG distress models.
Chapter 6. **Benefits of Using the M-E PDG** – This chapter provides an example to illustrate the quantified benefits of applying the M-E PDG.
Chapter 7. Conclusions and Recommendations – This chapter summarizes the findings and offers suggestions for implementing the M-E PDG in the Midwest region.
Appendices – Include the database structures and the output from the M-E PDG. Comparisons of pavement performance data to output from the M-E PDG are also shown.

2. BACKGROUND and LITERATURE REVIEW

2.1. Introduction

The most widely used procedure for pavement design is the 1993 AASHTO Guide for Design of Pavement Structures, (AASHTO 1986; AASHTO 1993). A few states apply the 1986 or 1972 AASHTO guidelines. Some states have developed their own design procedures, some based on mechanistic-empirical procedures (Khanum et al. 2005). The Wisconsin Department of Transportation (WisDOT) has developed their 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). Thus, it is almost impossible to apply new pavement material like PG-binder to the old pavement design method. The limitations of earlier versions forced development of a new design guide, based on mechanistic principals.

The National Cooperative Highway Research Program (NCHRP) Project 1-37A, which developed a mechanistic-based software program and design guide, was initially released in 2004. Several other interim versions have since been released. AASHTO has not yet adopted these procedures. In this chapter, the M-E PDG is reviewed briefly, including design procedure. Moreover, potential advantages and benefits comparing to the current design method will be presented.

2.2. M-E PDG Procedure

The M-E PDG is intended to enhance and improve pavement design procedures. It represents a transition from existing empirical procedures to a mechanistic-empirical based procedure that combines the strengths of advanced analytical modeling and observed field performance. 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 M-E PDG.

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 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 calculated responses, damages are projected during design life and accumulated monthly. The procedure empirically relates damage over time to pavement distress and smoothness level chosen by the designer. The key damage features and smoothness are surface cracking, fracture, fatigue, rutting and roughness. Table 1 lists the eligible predicted distresses from the M-E PDG for both flexible and rigid pavements. For example, roughness can be excluded for pavement design, depending on the designer's decision.

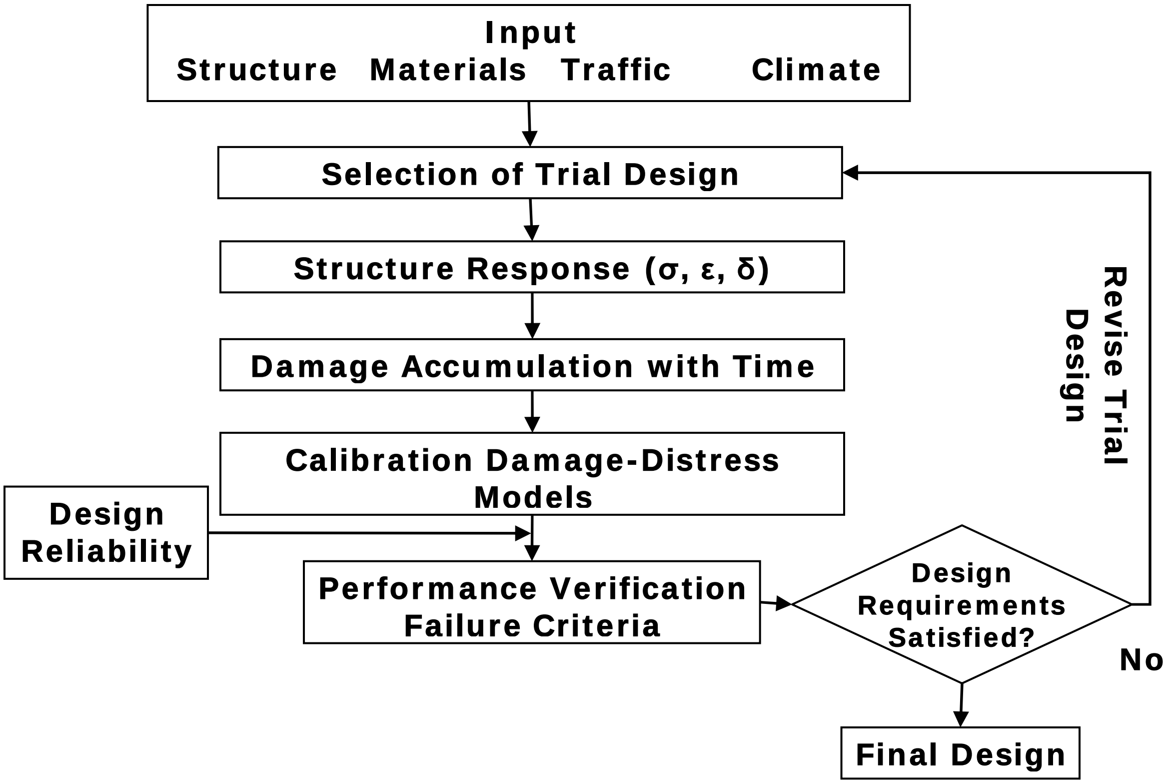


Figure 1 M-E PDG Procedure (NCHRP 2004)

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).

Table 1 Predicted Distresses in the M-E PDG

Flexible Pavement	Rigid Pavement
• International Roughness Index (IRI) • Surface Down Cracking • Bottom Up Cracking • Thermal Fracture • Chemically Stabilized Layer Fatigue Fracture • Rutting for Asphalt Layer only • Rutting for Total Layers	• International Roughness Index (IRI) • Transverse Cracking • Mean Joint Faulting • CRCP Punchouts (not activated in Version 0.90)

2.3. Features of the M-E PDG

The M-E PDG offers several important advances over current design methods. These are summarized below.

Reliable Prediction of Pavement Performance

The outstanding advantage of using the M-E PDG is reliable monthly predictions of pavement performance. Seven distresses for flexible pavement and four distresses for rigid pavement can be projected within design life. The projected distresses are evaluated against predetermined failure criteria. Moreover, projected pavement performance can assist state highway agencies in establishing maintenance or rehabilitation plans. The M-E PDG can help ensure that major rehabilitation activities incur costs at optimal time during the design life. A reduction of even 1% in maintenance and rehabilitation frequencies will lead to significant long-term savings (Coree 2005). Reliable predictions can assure when pavement maintenance should be applied as well as what kinds of maintenance techniques are necessary.

Reduced Errors from Mechanistic and Empirical Techniques for Pavement Design

As mentioned previously, most of the previous and current design methodologies are based on the AASHTO Road Test performed at late 1950s. Observations are used to establish the relationship between design input parameters and pavement performance. Current pavement design procedures cannot quantify impacts of new traffic conditions, new materials, and new construction procedures. The mechanistic design approach, based on the theories of mechanics, can accurately predict the responses of the pavement material. However, some critics caution that material behavior assumptions (such as linearly elastic material) are incompatible with real world observations (Carvalho and Schwartz 2006). The M-E PDG uses mechanics to determine pavement responses theoretically and then pavement responses are related to the pavement performance by documented empirical procedures.

Ability to Calibrate Performance Prediction for Specific Locations

The M-E PDG 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). Calibration factors affect pavement prediction. Local pavement performance data can be used to validate and adjustment of calibration factors integrated in M-E PDG.

Capability to Design for All Stages of Pavement Life Cycle

Unlike a design method such as AASHTO 1993, the M-E PDG includes procedures for the analysis and design of new pavements, restoration, and overlays for flexible and rigid pavement. Table 2 shows the scope of design that can be facilitated using the M-E PDG.

Table 2 Scope of Design Applications for the M-E PDG (Applied Research Associates 2006)

Design Type	Pavement Type	Description
New Design	Flexible	Asphalt concrete surface layer with base, subbase, subgrade and bedrock (optional) layers
	Jointed Plain Concrete (JPCP)	PCC surface layer with base, subgrade and bedrock (optional) layers. Slabs are jointed and may or may not contain dowels
	Continuously Reinforced Concrete	PCC surface layer longitudinally reinforced with base, subgrade, and bedrock (optional) layers
Restoration	Jointed Plain Concrete	Same as JPCP

Design Type	Pavement Type	Description
	(JPCP)	
Rehabilitation	AC Overlay	• AC over AC • AC over JPCP • AC over CRCP • AC over fractured JPCP • AC over fractured CRCP
	PCC Overlay	• Bonded PCC over CRCP • Bonded PCC over JPCP • Unbonded JPCP over JPCP • Unbonded JPCP over CRCP • Unbonded CRCP over CRCP • Unbonded CRCP over JPCP • JPCP over AC • CRCP over AC

Customized Design for State Highway Agencies

The M-E PDG allows transportation agencies to customize a pavement design for specific needs, including local climate, material types and their availability, subgrade, ground water conditions, and performance criteria.

Hierarchical Pavement Design Procedure for Various Input Quality Levels

Detailed input data is required in the M-E PDG procedure, especially traffic, climatic conditions, and material properties. The procedure employs a hierarchical concept in which the designer can choose different input quality levels, depending on information resources available and the importance of the project (Carvalho and Schwartz 2006). In general, three levels of inputs are provided:

- Level 1: The “First class” or advanced procedure provides for the highest practically achievable level of reliability but requires site-specific data collection and/or testing.
- Level 2: The inputs for routine design are typically user-selected, possibly from an agency database. The data can be derived from a less than optimal testing program or can be estimated empirically.
- Level 3: The lowest class of the design procedure may be used when there are minimal consequences of early failure. Inputs typically are user-selected default values or average values for the region.

A mix of input levels may be used for a given pavement design project. Level 1 traffic data can be used with Level 3 subgrade resilient modulus data and Level 2 asphalt material inputs. It is important to know that the computational algorithms for damage are the same, no matter the input level.

Safe and Economical Design by Multiple Pavement Performance Criteria

The 1993 AASHTO Guide designs pavements by considering only a single performance criterion, Pavement Serviceability Index (PSI), while the M-E PDG considers multiple performance criteria. Seven distresses for flexible pavement and four distresses for rigid pavement can be evaluated as performance criteria (see Table 1) depending upon the desired characteristics of the specific pavement design. Furthermore, the M-E PDG allows the specification of design limits for each criterion. For example, the designer can determine the limit of permanent deformation as 0.25 inches, and then projected deformation is evaluated against 0.25 inches at the end of a predetermined design life.

2.4. Summary

Most state highway agencies use the 1993 AASHTO design guide, some use the 1986 or 1972 AASHTO guidelines, while others have developed their own guidelines and procedures. These guidelines are not applicable to new design materials and cannot cover many design situations. Thus, many state highway agencies, including Wisconsin, are considering the implementation of the M-E PDG. The M-E PDG can predict seven pavement distresses for flexible pavement and four distresses for rigid pavement during the design life. Furthermore, agencies can calibrate the coefficients in the M-E PDG formulas such that projections are customized for location conditions. These benefits have motivated state highway agencies to implement the M-E PDG and focus on evaluating the calibration factors.

3. DEVELOPMENT of DATABASE FORMAT

3.1. Introduction

One of the objectives of this project was to collect pavement data from other states for calibrating the M-E PDG program. Because the intention was to use data from multiple states a uniform data collection format was established. This chapter explains the database format and presents the details of the database structure.

The uniform format was created based on Appendix EE of the M-E PDG. Several meetings were held with WisDOT pavement experts to develop the pavement database structure and collect the information from other states. Considering familiarity, Excel sheets were determined to be the best format for gathering the pavement data. The research team developed two Excel files, one for flexible pavements, and the other for rigid pavements. Each file consists of five different work sheets: general project information, traffic, climate, pavement structure/material and pavement performance. The first four sheets are for input data required for the M-E PDG 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 and field data allowed the research team to review and adjust, if necessary, calibration factors in the M-E PDG distress models.

Data for one section in Wisconsin was included as an example for other states to follow. Moreover, the sheets were designed with defined colors and explanations. The following scheme of colors was used:

- Required (Blue): These items are required for executing the program. Cells in this color had to be filled in. For some cells, agencies could use a drop down list for selection.
- Software Default Available (Yellow): The default values were taken from information integrated in the M-E PDG software. Cells could be filled in if the values were known by an agency (and were different from default values).
- Requested, not required (Red): The information was important for establishing the calibration database for the project but not required to run the software.

3.2. Project Inputs

The project input area covers general information that identifies the project. This sheet included pavement design life, traffic opening year, section ID, and initial value of International Roughness Index (IRI). Table 3 shows the spreadsheet for Project Information.

In the project input parameters, three inputs were required for executing the software - two construction month/year dates (only one is required for PCC) and the traffic opening month/year. These dates are the starting point for predicting distresses. The distresses are propagated depending on material characteristics and climatic data.

Table 3 Project Input Parameters (Flexible Pavement)

ME Field	Type of Input	
	Requirement	Software Default Value
Section ID	Required	
Design Life (years)	Software default available	20
Base/Subgrade Construction Year/Month	Required	
Pavement Construction Year/Month	Required	
Traffic Opening Year/Month	Required	
Initial IRI (in/mi)	Software default available	63
Project Location: State	Requested, not required	
Project Location: County	Requested, not required	
Project Location: City	Requested, not required	
Software default available:	This is the default value in the software. Please use actual value, if different from default.	
Required:	These items are required for running the program, cells in this color should be filled in.	
Requested, not required:	Needed for establishing database of this project.	

There are default values for design life and initial IRI (20 years for design life and 63 in/mi for IRI). The pavement distresses are predicted based on these values If an agency uses values other than the defaults, they should have been entered.

Project location information was used if provided, but was not required to run the software. If a contributing state agency provided the name of the climate station (see section 3.4 Climate Input), then the EICM file for that station was used.

3.3. Traffic Inputs

There are many required traffic inputs because traffic loadings are the main cause of pavement distress. In this sheet, traffic refers to basic traffic information, traffic volume adjustments factors, axle load distribution factors and general traffic inputs. Basic traffic information includes 2-way Average Annual Daily Truck Traffic (AADTT), number of lanes, percent of trucks and operational speed. There are three options for traffic growth rate: no growth, linear growth, and compound growth. Traffic volume adjustment factors are used for distributing the traffic monthly, hourly, and by vehicle class. Axle load distribution factors are indexed for load distribution by axle types such as single and tandem. Default values are available in the software. General traffic inputs are common traffic information such as mean wheel location, traffic wander, standard deviation, and tire pressure. Again, default values are available in the software. Table 4 displays a sample of traffic input parameters for flexible pavement. The table for rigid pavements is included in the accompanying CD.

Table 4 Sample of Traffic Input Parameters (Flexible Pavement)

ME Field	Type of Input	
	Requirement	Software Default Value
Section ID (automatically copied from General Info sheet)	Required	
BASIC TRAFFIC INFORMATION		
Initial 2-way AADTT	Required	
Number of Lanes in Design Direction	Required	
% of Trucks in Design Direction	Required	
% of Trucks in Design Lane	Required	
Operational Speed (mph)	Required	
Traffic Volume Adjustments Factors		

ME Field	Type of Input	
	Requirement	**Software Default Value**
Monthly Adjustment Factors		
Load/Monthly Adjustment Factors*	Software default available	All traffic volumes are assumed to be same in all months. Input "Use Default".
Vehicle Class Distribution*		
Type of Highway	Required	
AADTT Distribution by Vehicle Class (If not available, Type of Highway will be used to define default distribution)		
Class 4	Software default available	Depends on Type of Hwy - Info in MEPDG
Class 5	Software default available	Depends on Type of Hwy - Info in MEPDG
Class 6	Software default available	Depends on Type of Hwy - Info in MEPDG
Class 7	Software default available	Depends on Type of Hwy - Info in MEPDG
Class 8	Software default available	Depends on Type of Hwy - Info in MEPDG
Class 9	Software default available	Depends on Type of Hwy - Info in MEPDG
Class 10	Software default available	Depends on Type of Hwy - Info in MEPDG
Class 11	Software default available	Depends on Type of Hwy - Info in MEPDG
Class 12	Software default available	Depends on Type of Hwy - Info in MEPDG
Class 13	Software default available	Depends on Type of Hwy - Info in MEPDG
Hourly Truck Traffic*		
Hourly Truck Traffic Distribution by Period	Software default available	Depends on Type of Hwy - Info in MEPDG
Traffic Growth Factors		
Default Growth Function	Required	
Default Growth Rate	Required	
Axle Load Distribution Factors		
Axle Load Distribution*	Software default available	
General Traffic Inputs		
Lateral Traffic Wander		
Mean Wheel Location (in)	Software default available	18
Traffic Wander Standard Deviation (in)	Software default available	10
Design lane width (ft)	Software default available	12
Number Axles/Truck*	Software default available	In MEPDG Software
Axle Configuration		
Average axle width (edge-to-edge outside dimension) (ft)	Software default available	8.5
Dual tire spacing (in)	Software default available	12
Tire Pressure (single tire) (psi)	Software default available	120
Tire Pressure (double tire) (psi)	Software default available	120
Tandem axle spacing (in)	Software default available	51.6
Tridem axle spacing (in)	Software default available	49.2
Quad axle spacing (in)	Software default available	49.2
Wheelbase		
Average axle spacing (short, medium, long) (ft)	Software default available	12,15,18
Percent of truck (short, medium, long) (%)	Software default available	33.0, 33.0, 34.0
Software default available:	This is the default value in the software. Please use actual value, if different from default.	
Required:	These items are required for running the program, cells in this color should be filled in.	
Please use dropdown lists to make selection		
*If you have Level 1 data, submit the data in the format used by the MEPDG		

Some required input variables such as type of highway can be selected from a "drop down" list. For example, there are five types of roadways: Principle Arterial, Minor Arterial, Major Collector, Minor Collector, and Local Street. The type can be selected from the "drop down list" in the Excel spreadsheet.

3.4. Climate Inputs

Climate condition also affects pavements. For example, the stiffness of a soil varies depending on environmental conditions such as the depth of ground water and seasonal temperatures. The climate input spreadsheet includes latitude, longitude, elevation and the groundwater table depth. Climate data can be downloaded from the Transportation Research Board (TRB) web site, (http://www.trb.org/mepdg/climatic_state.htm, accessed in Feb. 2007). Table 5 shows the spreadsheet for climate input parameters.

Table 5 Climate Input Parameters (Flexible Pavement)

ME Field	Type of Input	
	Requirement	**Software Default Value**
Section ID (automatically copied from General Info sheet)	Required	
Latitude (degrees, minutes)	Software default available	M-E PDG will estimate based on city/county*
Longitude (degrees, minutes)	Software default available	M-E PDG will estimate based on city/county*
Elevation (ft)	Software default available	M-E PDG will estimate based on city/county*
Groundwater Table Depth (seasonal if possible) (ft)	Required	
Software default available:	This is the default value in the software. Please use actual value, if different from default.	
Required:	These items are required for running the program, cells in this color should be filled in.	

3.5. Structure/Material Inputs

Structure and material inputs are important factors in the calculation of pavement distresses. The spreadsheet collects characteristics of each layer including material type, thickness of the layer, material properties, and sieve analysis of the materials. The more specific the inputs, the more accurate the output. However, it can be difficult to obtain specific information about selected pavement sections. Thus, many input variables may be left as default values. The required input variables are material type, thickness of each layer, and minimum level of material testing data. “Drop down lists” allowed the state transportation agencies to select a value from the list. Table 6 shows the Pavement Structure/Material Input Parameters for flexible pavement. The list of parameters for rigid pavement is included in the CD.

Table 6 Structure/Material Input Parameters (Flexible Pavement)

ME Field	Type of Input	
	Requirement	**Software Default Value**
Section ID (automatically copied from General Info sheet)	Required	
Drainage and Surface Properties		
Surface Shortwave Absorptivity	Software default available	0.85
Layers (Individual Layer Strength Properties)*		
Layer (Asphalt Concrete)		
Asphalt Material Properties**		
Layer thickness (in)	Required	
Asphalt Mix: Aggregate Gradation		
Cumulative % retained on 3/4-inch sieve	Required	
Cumulative % retained on 3/8-inch sieve	Required	
Cumulative % retained on #4 sieve	Required	
% Passing #200	Required	
Asphalt Binder		
if Superpave Binding Grading		
High Temp (K)	Required	
Low Temp (K)	Required	
if Conventional Viscosity Grade		
Viscosity Grade	Required	
if Conventional Penetration Grade		
Penetration Grade	Required	
Asphalt General		
General		
Reference Temperature (F)	Software default available	70
Volumetric Properties As Built		
Effective Binder Content (%)	Software default available	11
Air Void (%)	Software default available	8.5
Total Unit Weight (pcf)	Software default available	148
Volumetric Properties As Built		
Poisson's Ratio (or predictive model to calculate p-ratio, a, b)	Software default available	0.35 (a=-1.63, b=3.84e-6)
Thermal Properties		
Thermal Conductivity of Asphalt (BTU/hr-ft-F)	Software default available	0.67
Heat Capacity of Asphalt (BTU/lb-F)	Software default available	0.23
Thermal Cracking		
Average Tensile Strength at 14F (psi)	Software default available	Depends on material type
Creep Test Duration (sec)	Software default available	100
Creep Compliance (1/psi) per loading time**	Software default available	Depends on material type
Mixture VMA (%)	Software default available	Depends on material type
Aggregate Coefficient of Thermal Contraction	Software default available	5.00E+06
Layer (Chemically Stabilized Base)		
General Properties		

ME Field	Type of Input	
	Requirement	Software Default Value
Material Type	Required	
Layer thickness (in)	Required	
Unit Weight (pcf)	Software default available	Depends on material type
Poisson's Ratio	Software default available	Depends on material type
Strength Properties		
Elastic/Resilient Modulus (psi)	Software default available	2000000
Minimum Elastic/Resilient Modulus (psi)	Software default available	100000
Modulus of Rupture (psi)	Software default available	650
Thermal Properties		
Thermal Conductivity (BTU/hr-ft-F)	Software default available	1.25
Heat Capacity (BTU/lb-F)	Software default available	0.28
Layer (Granular Base)		
Unbounded Material (type)	Required	
Thickness (in)	Required	
Strength Properties*		
Poisson's Ratio	Software default available	0.35
Coefficient of Lateral Pressure (Ko)	Software default available	0.5
Material Modulus Type	Required	
Material Modulus Value	Required	
Integrated Climate Model (ICM)		
Gradation (Percent Passing)		
0.001 mm	Software default available	Depends on material type
0.002 mm	Software default available	Depends on material type
0.020 mm	Software default available	Depends on material type
# 200	Software default available	Depends on material type
# 100	Software default available	Depends on material type
# 80	Software default available	Depends on material type
# 60	Software default available	Depends on material type
# 50	Software default available	Depends on material type
# 40	Software default available	Depends on material type
# 30	Software default available	Depends on material type
# 20	Software default available	Depends on material type
# 16	Software default available	Depends on material type
# 10	Software default available	Depends on material type
# 8	Software default available	Depends on material type
# 4	Software default available	Depends on material type
3/8"	Software default available	Depends on material type
1/2"	Software default available	Depends on material type
3/4"	Software default available	Depends on material type
1"	Software default available	Depends on material type
1 1/2"	Software default available	Depends on material type
2"	Software default available	Depends on material type

ME Field	Type of Input	
	Requirement	Software Default Value
2 1/2"	Software default available	Depends on material type
3"	Software default available	Depends on material type
3 1/2"	Software default available	Depends on material type
Plasticity		
Plasticity Index (PI)	Software default available	Depends on material type
Liquid Limit (LL)		
Compacted or Uncompacted?	Software default available	Compacted
Calculated/Derived Parameters		
Maximum Dry Unit Weight (pcf)	Software default available	Depends on material type
Specify Gravity of Soils (Gs)	Software default available	Depends on material type
Saturated Hydraulic Conductivity (ft/hr)	Software default available	Depends on material type
Optimum Gravimetric Water Content (%)	Software default available	Depends on material type
Soil Water Characteristic Curve Parameter (af, bf, cf, hr)	Software default available	Depends on material type
Layer (Subgrade)		
Unbounded Material (type)	Required	
Thickness (in)***	Required	
Strength Properties*		
Poisson's Ratio	Software default available	0.35
Coefficient of Lateral Pressure (Ko)	Software default available	0.5
Material Modulus Type	Required	
Material Modulus Value	Required	
Integrated Climate Model (ICM)		
Gradation (Percent Passing)		
0.001 mm	Required***	
0.002 mm	Required***	
0.020 mm	Required***	
# 200	Required	
# 100	Required***	
# 80	Required***	
# 60	Required***	
# 50	Required***	
# 40	Required***	
# 30	Required***	
# 20	Required***	
# 16	Required***	
# 10	Required***	
# 8	Required***	
# 4	Required***	
3/8"	Required***	
1/2"	Required***	
3/4"	Required***	
1"	Required***	

ME Field	Type of Input	
	Requirement	**Software Default Value**
1 1/2"	Required***	
2"	Required***	
2 1/2"	Required***	
3"	Required***	
3 1/2"	Required***	
Plasticity		
Plasticity Index (PI)	Software default available	Depends on material type
Liquid Limit (LL)		
Compacted or Uncompacted?	Software default available	Compacted
Calculated/Derived Parameters		
Maximum Dry Unit Weight (pcf)	Software default available	Depends on material type
Specify Gravity of Soils (Gs)	Software default available	Depends on material type
Saturated Hydraulic Conductivity (ft/hr)	Software default available	Depends on material type
Optimum Gravimetric Water Content (%)	Software default available	Depends on material type
Soil Water Characteristic Curve Parameter (af, bf, cf, hr)	Software default available	Depends on material type
Layer (Bedrock)		
Unbounded Material (type)	Required	
Thickness (in)****	Required	
General Properties		
Unit Weight (pcf)	Software default available	140
Poisson's Ratio	Software default available	0.15
Resilient Modulus (psi)	Software default available	500000
Software default available:	This is the default value in the software. Please use actual value, if different from default.	
Required:	These items are required for running the program, cells in this color should be filled in.	
Please use dropdown lists to make selection		
*All available (MEPDG) layer types are listed. If your project did not use one or more of the listed layers, leave the Input area blank. If your project's layers are not in the order listed here, please number the layers, with the surface being layer 1. If you have additional layers of pavement structure, please use the area below.		
**If you have Level 1 or 2 data, submit the data in the format used by the MEPDG		
***At least five enteries must be entered for grain size distribution		
***If this layer is the last one, do not input the thickness.		

3.6. Pavement Performance

The input variables in this spreadsheet are not required for executing the M-E PDG program. The Pavement Performance Input Parameters spreadsheet is illustrated in Table 7. This sheet includes the field performance data, as measured by agencies, for comparing with output from the M-E PDG. As mentioned earlier, and shown in Table 1, there are seven distresses for flexible pavement and four distresses for rigid pavement. Although the M-E PDG can project the distresses at every month, it would be difficult to gather the distress data every month. Thus, the spreadsheet collects annual distress values for 20 years. Again, the list of parameters for rigid pavement is included in the CD.

Table 7 Pavement Performance Input Parameters (Flexible Pavement)

ME Field	Type of Input	
	Requirement	Software Default Value
Section ID (automatically copied from General Info sheet)	Required	
IRI (in/mile)		
Initial	Required	
Year 1	Required	
Year 2	Required	
Year 3	Required	
…	…	
Year 20	Required	
More than Year 20	Required	
AC Surface Down Cracking (Long. Cracking) (ft/mi)		
Initial	Required	
Year 1	Required	
Year 2	Required	
Year 3	Required	
…	…	
Year 19	Required	
Year 20	Required	
More than Year 20	Required	
AC Bottom Up Cracking (Alligator Cracking) (%)		
Initial	Required	
Year 1	Required	
Year 2	Required	
Year 3	Required	
…	…	
Year 20	Required	
More than Year 20	Required	
AC Thermal Fracture (Transverse Cracking) (ft/mile)		
Initial	Required	
Year 1	Required	
Year 2	Required	
Year 3	Required	
….	…	
Year 20	Required	
More than Year 20	Required	
Chemically Stabilized Layer (Fatigue Fracture) (%)		
Initial	Required	
Year 1	Required	
Year 2	Required	
Year 3	Required	
…	…	
Year 20	Required	
More than Year 20	Required	
Permanent Deformation (Total Pavement) (in)		
Initial	Required	
Year 1	Required	
Year 2	Required	
Year 3	Required	
…	…	

ME Field	Type of Input	
	Requirement	**Software Default Value**
Year 20	Required	
More than Year 20	Required	
Permanent Deformation (AC Only) (in)		
Initial	Required	
Year 1	Required	
Year 2	Required	
Year 3	…	
…	Required	
Year 20	Required	
More than Year 20	Required	
Required:	These items are required for running the program, cells in this color should be filled in.	
*Historical pavement performance data are necessary. Please provide available pavement performance data with the greatest frequency possible.		

3.7. Summary

In order to collect the pavement data for the M-E PDG, a uniform database structure was developed. The database structures were developed to be as simple as possible and include functions that help the state transportation agencies complete the forms.

Two databases, one for flexible pavements and one for rigid pavements, were developed using Excel spreadsheets. Each spreadsheet file has five work sheets; four for gathering input for the M-E PDG and one for gathering data of actual performance.

4. DATA SOURCE and COLLECTION

4.1. Introduction

Pooling of pavement material, structure, and pavement performance data from multiple states requires coordination with the participating states, a common data collection format, and similar levels of data availability. The database structure, previously described, was used for this purpose.

To request data, WisDOT sent an e-mail letter to the state highway agencies in the Midwest region describing the project and inviting participation. The states contacted were Illinois, Indiana, Iowa, Michigan, Minnesota, and Ohio. Iowa, Michigan, and Ohio replied positively. A conference call was arranged to give the participants an opportunity to ask questions before gathering data.

The following steps were followed to collect the pavement data:

Step 1: An e-mail letter was sent to the state highway agencies in the Midwest region, requesting participation
Step 2: An entry database was developed
Step 3: The database was sent to the states
Step 4: A conference call was held
Step 5: The participating states submitted their data via e-mail.

The following sections describe details for gathering data from the participating state highway agencies.

4.2. Wisconsin

After discussion with pavement experts at WisDOT, the research team developed the algorithm shown in Figure 2 to mine the agency's pavement data.

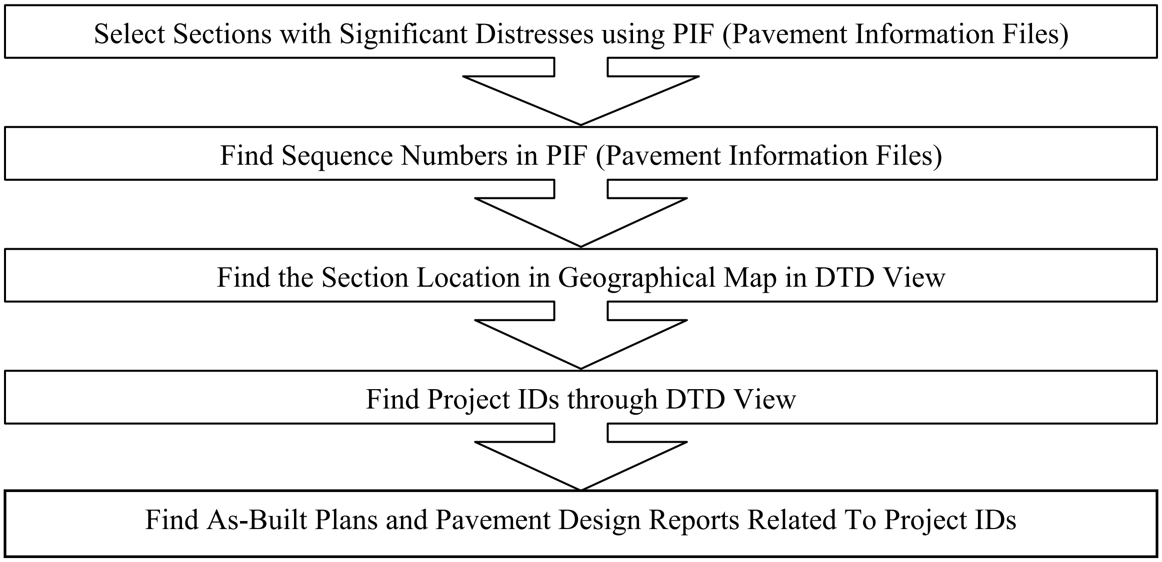


Figure 2 Pavement Information Query Flow in Wisconsin

4.2.1. Pavement Sections

To develop the pavement database for Wisconsin, sections with significant distresses were considered. To select sections, the research team used the Pavement Information Files (PIF), WisDOT's primary pavement performance database. Sections with significant distresses are defined as having total rutting greater than 0.25-inch, International Roughness Index (IRI) greater than 172 in./mile and Pavement Distress Index (PDI) greater than 65. PDI is a mathematical expression for pavement condition rating 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 in the section and is used primarily for network-level evaluation (WisDOT's PDI Survey Manual). Table 8 shows the specific values of criteria for selecting the sections in Wisconsin.

Table 8 Initial Selection Criteria in Wisconsin

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

Initially, 12 flexible pavement sections and 12 rigid pavement sections were selected. However, it was discovered during data collection that the required input data for the M-E PDG program were not available for many of the sections. Thus, additional sections were selected: 11 flexible and 13 rigid pavements. Among them, the research team found only 9 sections for flexible pavement and 5 sections for rigid pavement had available information. Table 9 and Table 10 list the representative sections for flexible and rigid pavements respectively with required data available. The sequence number shown is the primary key in the PIF database used to identify each section.

Table 9 Wisconsin Sections with Significant Distress in 2006 (Flexible Pavement)

Sequence #	County	High way #	Pavement Performance					
			Rutting (inch)	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

Table 10 Wisconsin Sections with Severe Distress in 2006 (Rigid Pavement)

Sequence #	County	High Way #	Pavement performance			
			IRI (in./mi)	Transverse Cracking (%)	Mean Joint Faulting (inch)	PDI*
124670	LAFAYETTE	151	87	100	0-0.25	86
6100	WAUPACA	96	245	90	0-0.25	80
12770	COLUMBIA	13	225	90	0.25-0.5	87
57560	ROCK	43	213	0	0.25-0.5	84
113850	MILWAUKEE	100	301	50	0-0.25	87

* PDI: Pavement Distress Index

4.2.2. Sources of Input Requirements

WisDOT's pavement design reports provide required data details such as expected traffic opening year, traffic volume and traffic growth rate, and pavement layer information including specific material type. However, the pavement design reports are stored at regional offices and typically kept for only five years after construction. Since most of the selected pavement sections were constructed in the 1980s, the pavement design reports are no longer available. When pavement design reports were not available, the research team used project IDs related to the sections to retrieve the as-built plans. Fortunately, some as-built plans were available in DTD View on WisDOT's intranet. In addition to the as-built plans, material testing data from WisDOT's Materials Lab at Truax, and internet based soil survey data were used to populate the database.

If the required input data were not available, the research team used default values or best estimates. The following are brief descriptions of the input data and sources.

General Input Data

General input data includes pavement design life, pavement construction year, initial IRI, and project location. Most of this information, except traffic opening year/month and initial IRI, can be obtained from as-built plans. Traffic opening year/month was assumed to be the year/month following construction completion. If unknown, the M-E PDG initial default value for IRI, 63 (in/mi), was applied. In terms of project location, the specific location could be determined by matching geographic maps and location information in PIF.

Traffic Input Data

Traffic volume, operational speed, type of highway, and traffic growth factors are required items. As-built plans provide traffic volume and operational speed. Also future traffic volume, which was projected out 20 years, allowed the research team to back calculate an assumed compound traffic growth rate. For example, if the traffic volumes are 1,800 in year 1982 and 2,500 in year 2,000, the compound traffic growth rate is 1.6% per year (Blank and Tarquin 2005).

$$Future\ Traffic\ Volume = Current\ Traffic\ Volume \times (1 + Growth\ Rate)^{projection\ Period}$$

Highway type can be determined from highway functional classes presented in PIF and shown in Table 11.

Table 11 Highway Functional Class in Wisconsin

Rural Area		Urban Area	
Class	Description	Class	Description
10	Principal Arterial	50	Principal Arterial Freeway
20	Minor Arterial	60	Other Principal Arterial
30	Major Arterial	70	Minor Arterial
40	Minor Collector	80	Collector
45	Local	90	Local

Climate Input Data

The M-E PDG software includes links to obtain climate data if the latitude and longitude are known. The specific location information of selected sections was obtained from PIF and then located on a geographical map. In the M-E PDG program, the location of the weather station nearest the project location was used.

The groundwater table depth was obtained from the U.S. Geological Survey (USGS) website and Wisconsin Department of Natural Resources (WisDNR) for the specific location of each section. The annual average value for one year was used as the input. (http://waterdata.usgs.gov/nwis/gwsi?search_criteria=state_cd&submitted_form=introduction, http://www.dnr.state.wi.us/landscapes/maps/state/waterdepth.htm, accessed in October, 2006)

Structure and Material Input Data

Detailed material properties were difficult to obtain, especially for older pavements. Though some default values in the software are available, much specific material information is required to run the software. Most of these, such as aggregate gradation of asphalt mix and penetration grade of asphalt binder, were not available in as-built plans. The research team had several meetings with WisDOT asphalt pavement experts to determine material properties. For subgrade information, Soil Survey Reports from the United States Department of Agriculture were the source for the type and gradation of the soils (http://websoilsurvey.nrcs.usda.gov/app/, accessed in October, 2006). When default values were used, they were compared to typical values for Wisconsin.

Pavement Performance Input Data

Most pavement performance data are available in PIF. However, PIF measures pavement performance differently from the M-E PDG. M-E PDG uses one continuous unit, such as inch per mile or percentage, to quantify values of certain distress, while PIF uses two categorical units, severity and extent. For example, longitudinal cracks are measured in feet per mile in M-E PDG, while PIF uses extent level 0-3 and severity levels 0 to 3. Table 12 and Table 13 show the conversions of pavement distress measurement units from PIF to M-E PDG for flexible and rigid pavements, respectively.

The pavement performance value for each station is taken to be the average value. For example, consider a 100-foot pavement section with longitudinal cracking of extent level 1 (1 to 100 feet) and severity level 2 (greater than ½-inch width). Figure 3 shows the steps for conversion. The following explains the steps.

1) There are three severity levels for each extent level and a range of cracking extent for each severity level. For longitudinal cracking, severity level 1 is 1 to 33.3 feet per station, severity level 2 is 33.3 to 66.9 feet, and severity level 3 is 66.9 to100 feet.

2) For each extent and severity level, average cracking per station is computed.
3) The average value of each range is converted to the appropriate unit applicable to the M-E PDG (here, ft/mile). Finally, for extent level 1 and severity level 2, the estimated cracking per mile is 2475 as shown in Figure 3.

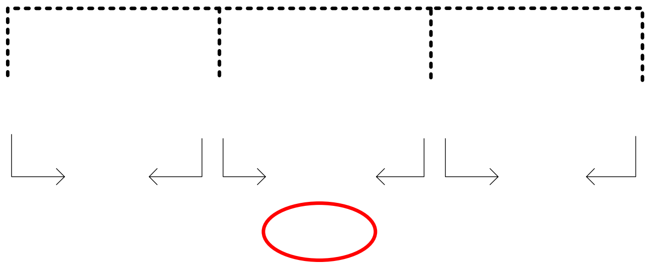


Figure 3 Example of Unit Conversion from PIF to M-E PDG (Longitudinal Crack with Extent Level 1 and Severity Level 2)

Table 12 Unit Conversion in Flexible Pavement

Flexible Pavement						
			Unit		Conversion	
M-E PDG	Unit	PIF	Extent	Severe	PIF	M-E PDG
IRI	in./mi	IRI	in/mi			
AC Surface Down Cracking (Longitudinal Crack)	ft/mi	Lcrk (Longitudinal Crack)	0 = None	0 = None 1 = less than 1/2 inch in width 2 = greater than 1/2 inch in width 3 = multiple cracks	**ft/station**	**ft/mi**
			1 = 1 to 100 ft/station*		17, 49.5, 83	850, 2475, 4150
			2 = 101 to 200 ft/station*		117, 149.5, 183	5850, 7475, 9150
			3 = 201 to 300 ft/station*		217, 249.5, 283	10850, 12475, 14150
			4 = greater than 300 ft/station*		300	15000
AC Bottom UP Cracking (Alligator Crack)	%	Blk (Block/Alligator Cracking)	0 = None	0 = None 1 = cracks less than 1/2 inch in width 2 = cracks greater than 1/2 inch in width 3 = dislodgement	**%**	**%**
			1 = 10 to 24%		4, 12, 20	4, 12, 20
			2 = 25 to 49%		29, 37, 45	29, 37, 45
			3 = 50 to 74%		54, 62, 70	54, 62, 70
			4 = 75% +		79, 87, 96	79, 87, 96
AC Thermal Fracture (Transverse Crack)	ft/mi	Tcrk** (Transverse Crack)	0 = None	0 = None 1 = less than 1/2 inch in width 2 = greater than 1/2 inch in width 3 = band cracking (multiple cracks)	**number/station**	**ft/mi**
			1 = 1 to 5 cracks per station*		1.67, 3, 4.33	1058, 1900,2743
			2 = 6 to 10 cracks per station*		6.67, 8, 9.33	4226, 5069, 5911
			3 = greater than 10 cracks per station*		10	6336
Permanent Deformation (Total)	in.	Rut (Rutting)		0 = rutting not represent 1 = rutting 1/4 to 1/2 inch in depth 2 = rutting 1/2 to 1 inch in depth 3 = rutting greater than 1 inch in depth	**in.**	**in.**
					0.375	0.375
					0.75	0.75
					1	1

* 1 station = 100 ft = 0.0189 mi

** A transverse crack should be six (6) feet in length to be counted

Table 13 Unit Conversion in Rigid Pavement

Rigid Pavement						
M-E PDG	Unit	PIF	Unit		Conversion	
			Extent	Severe	PIF	M-E PDG
IRI	in./mi	IRI	in/mi			
Transverse Crack	%	Sbkup (Slab Break Up)	% of each severe level	0 = intact slab 1 = two or three large blocks per slab 2 = level 1+ beginning of interconnecting cracks 3 = additional interconnecting longitudinal cracks resulting in fragmented slabs 4 = level 3 severity+ the lateral and/or vertical movement of the blocks	% of each severity level	% of break-up slab
Mean Joint Faulting	in.	Flt (Transverse Faulting)	0 = none	0 = distress not present	**in./station***	**in.****
			1 = less than 1 per station*	1 = faulting less than 1/4 inch	0.125, 0.375, 0.5	0.125
			2 = 1 - 2 per station*	2 = faulting between 1/4 and 1/2 inch	0.1875, 0.5625, 0.75	0.375
			3 = More than 3 per station*	3 = faulting greater than 1/2 inch	0.375, 1.125, 1.5	0.5

* 1 station = 100ft = 0.02mi

** Maximum value of Joint Faulting is 0.5"

4.2.3. Data Quality and Assumptions

As-built plans were available for 11 flexible pavement sections and 10 rigid pavement sections. The plans were obtained from DTDView at Wisconsin DOT's intranet website. Criteria for the study sections are listed below.

1) sections with severe distresses
2) sections with no rehabilitation and no overlay
3) sections more than 5 years old

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. These activities might not be recorded in PIF. Specifically, two flexible pavement sections had been resurfaced and five rigid pavement sections had been overlaid. One of the flexible pavements was actually an overlay of a rigid pavement. As a result, the applicable sections for calibration were reduced to nine flexible pavement sections and five rigid pavement sections.

Additionally, the research team recognized an irregularity in the distress measures. Occasionally, distress quantities appear to increase then drop back down without explanation. After discussion with WisDOT's pavement design experts, two possible explanations exist: First, minor maintenance may have been applied. Minor maintenance activities are not considered as restoration or reconstruction that can be designed by the M-E PDG. They usually focus on the ride quality rather than structural improvement. The distresses seem to disappear for a while but they rise a few years later. Second, the irregularity may be due to human factors. 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. Using new equipment and removing region variability both caused adjustments to the PIF data.

Figure 4 to Figure 7 0show examples of large variations in pavement performance data. This variation is manifested in both flexible and rigid pavements. Here, "MEPDG" represents the predicted pavement performance from M-E PDG while "PIF" is the pavement performance data from WisDOT. As shown, the performance illustrates large variance then consistency after 2000 (Figure 4 and Figure 6). Thus, the research team decided to use the data collected after 2000. Equipment started to be used in 1999 and some of sections were monitored by the new equipment automatically while others were not. Longitudinal cracks in Section 5 (Figure 4) shows the measurement changed in 1999. In Section 4, faulting measurement (Figure 7) changed in 2000. In conclusion, the research team decided to use measurement data after 2000 for calibration.

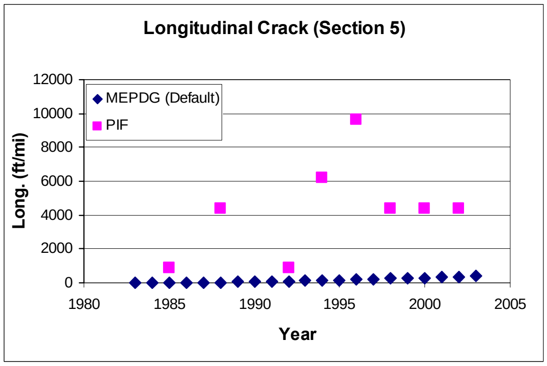


Figure 4 Longitudinal Cracking in Section 5 (Flexible pavement in Wisconsin)

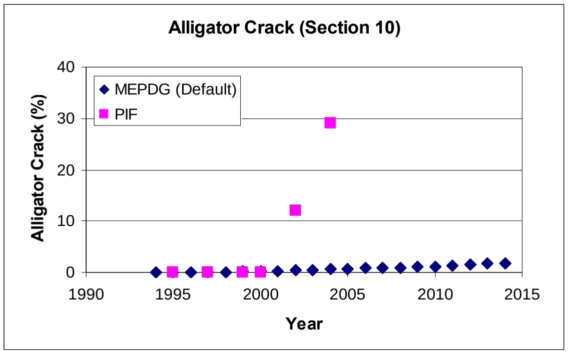


Figure 5 Alligator Cracking in Section 10 (Flexible pavement in Wisconsin)

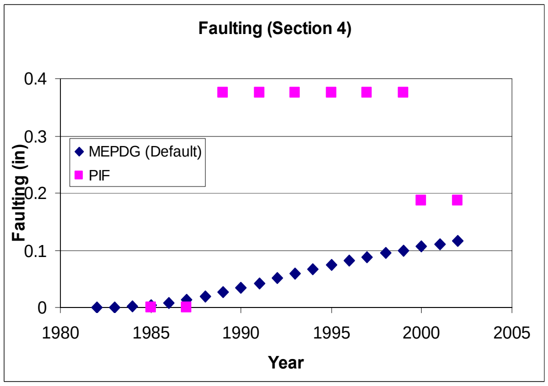


Figure 6 Faulting in Section 4 (Rigid pavement in Wisconsin)

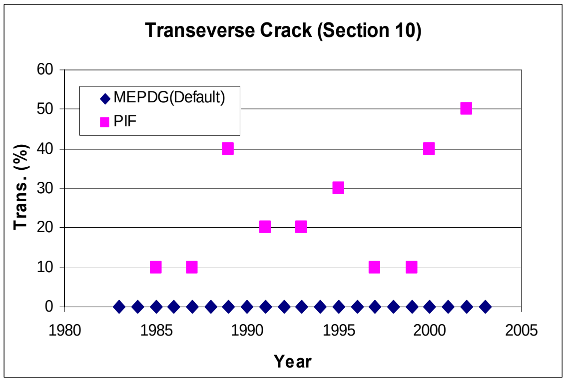


Figure 7 Transverse Cracking in Section 10 (Rigid pavement in Wisconsin)

4.3. Other State Highway Agencies in the Midwest Region

At the beginning of this project, a cooperation request letter was sent to states in the Midwest region. Three states agreed to participate: Michigan, Ohio and Iowa. The pavement database structures were delivered to the states as Excel spreadsheet files. The states agencies were asked to complete the spreadsheets for at least five flexible pavement sections and five rigid pavement sections.

Michigan and Ohio delivered five sections for flexible pavement and five sections for rigid pavement. Iowa sent five sections for rigid pavement. The data from Michigan were collected statewide, while Ohio chose one highway. Thus, the sections selected by Ohio were constructed at the same time and were open to the public at the same time. Moreover, because they picked the same highway, information for traffic volumes and vehicle classifications are same through all sections. But, due to different locations in one highway, material properties and pavement performance are different.

Even though the states made efforts to provide the pavement data, the research team encountered critical obstacles to conducting the calibration. Required data items were missing. It is impossible to run the M-E PDG without these items significantly impacting the output from the M-E PDG. The research team attempted to obtain the missing required data from generally accessible databases on the internet. For example, the subgrade soil conditions were obtained from http://websoilsurvey.nrcs.usda.gov/app/

(accessed October 2006) based on the specific project location. Moreover, some of the data collected by the state transportation agencies did not follow the same format the research team suggested. Specifically, Ohio sent the detailed traffic monthly adjustment factors, which are different from the format available for the M-E PDG. M-E PDG uses 13 different truck classifications, while Ohio uses 15. For some missing data, the default values were used.

The pavement performance data from Ohio, Michigan and Iowa show trend irregularities similar to Wisconsin's. Most of the sections selected by the state transportation agencies were constructed in the late 1980s and early 1990s. It is not likely these sections have yet been rehabilitated. Figure 8 and Figure 9 show large variations in pavement performance. Here, "MEPDG" stands for the output from the M-E PDG and "MI PMS" means the actual field data collected by Michigan DOT. All other sections are presented in Appendix A.

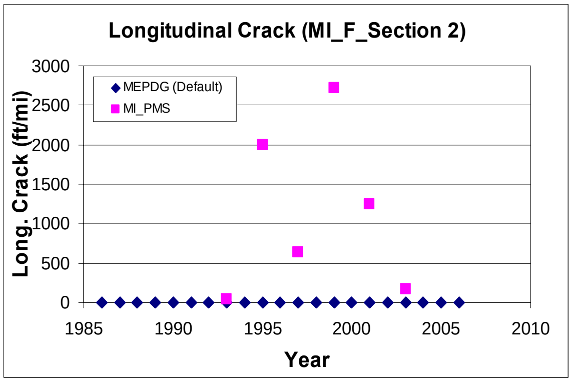


Figure 8 Longitudinal Cracking in Section 2 (Flexible pavement in Michigan)

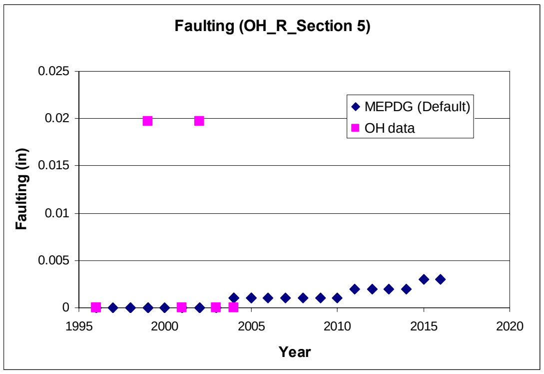


Figure 9 Faulting in Section 5 (Rigid pavement in Ohio)

Given the irregularities that could not be explained, the research team decided to use Wisconsin's data and information for calibration. After determining calibration values with Wisconsin's data, the field-collected pavement performance data from other states was compared to two plots: prediction models using default calibration values in the M-E PDG and 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.

4.4. Summary

Four state transportation agencies agreed to provide data for the project: Michigan, Ohio, Iowa and Wisconsin. For all states, data was far more difficult to obtain than expected.

Wisconsin data was delivered first. The research team spent considerable effort to investigate and assure quality for the Wisconsin data. Data from Ohio, Michigan, and Iowa showed irregular trends. Due to the difficulty in supplementing data from these states, the research team did not calibrate using this data. It was decided that calibration would be done using only Wisconsin's data, and then comparisons to this calibration would be performed for the other states.

5. CALIBRATION of PREDICTION FACTORS in the M-E PDG

5.1. Methodology

The calibration factors in the M-E PDG prediction models can be determined from analysis of 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 M-E PDG were applied initially and then the calibration factors were adjusted to reduce the difference between collected, or observed and predicted pavement performance. The best fit minimizes the difference between M-E PDG prediction and observed performance. For the range of possible values for the calibration factors, the research team used the range of values suggested in the M-E PDG (NCHRP 2004). The calibration process is as follows:

Step 1: Identify the adjustable calibration factors in the M-E PDG prediction models.
Step 2: Compare the predicted performance to field data.
Step 3: Select calibration values that minimize the squared difference between predicted and actual performance data.

5.2. Flexible Pavement

5.2.1. Calibration of Fatigue Cracking Model

Calibration of the fatigue cracking model in the M-E PDG was conducted based on the model presented in Appendix II-1 of the Mechanistic-Empirical Pavement Design Guide (NCHRP 2004) and the TRB 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 due to 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

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

Where:
$D = \text{Damage}$
$T = \text{total number of periods}$
$n_i = \text{actual traffic for periods } i$
$N_i = \text{allowable failure repetitions under conditions prevailing in period } i$

The general mathematical form for the number of load repetitions is also shown in the Guide. 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).

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

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, $\beta_{f1}, \beta_{f2}, \beta_{f3}$ 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 inches. In this research, because the total thickness of the asphalt layer is more than 3 inches, 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 Guide, three values of β_{f2} and three values of β_{f3} were applied for the 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 MS-1 model (NCHRP 2004). Table 14 lists the possible combinations of calibration values.

Table 14 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 percent damage 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 visual distresses of longitudinal and alligator cracks.

5.2.2. Calibration of the Longitudinal Fatigue Cracking Model

The damage transfer function used in the M-E PDG for longitudinal (surface-down) fatigue cracking is in the form shown.

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

Where:

$F.C. = \text{fatigue cracking (ft/mile)}$

$D = \text{Damage in percentage}$

$C_1, C_2 = \text{regression coefficients}$

In the M-E PDG, the regression coefficients, C_1 and C_2, were evaluated using a Microsoft Solver numerical with more than 100 sections nation-wide so the research team decided to use the default values of each C (C_1=7.0, C_2=3.5). Damage in percentage, D, can be calculated by the fatigue-cracking model (Section 5.2.1). All combinations of calibration values were applied to discover the best ones.

Two sections of Wisconsin flexible pavements were selected for calibrating longitudinal fatigue cracking: sections 5 and 10 and Figure 10 and Figure 11, respectively show the longitudinal cracking over time. The behavior for these sections illustrates the typical prediction of longitudinal cracking and good potential for improving the predictions by calibrating the model. Here, "MEPDG" represents the output from M-E PDG and "PIF" represents the actual collected pavement data from Wisconsin DOT.

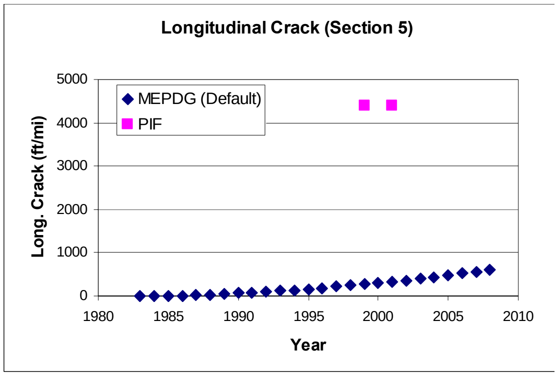


Figure 10 Longitudinal Cracking in Section 5 in Wisconsin (Default)

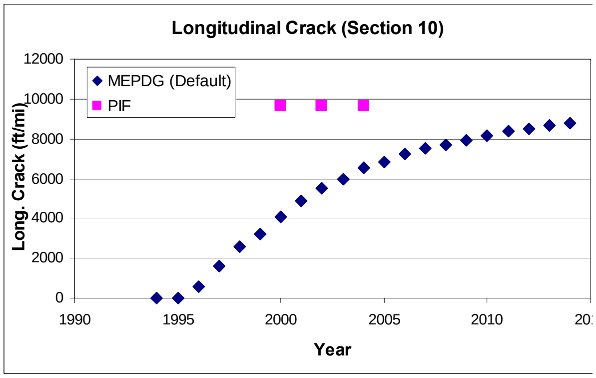


Figure 11 Longitudinal Cracking in Section 10 in Wisconsin (Default)

Nine runs for each section were conducted and the outputs were evaluated by the "Sum of Squares" for each plot. Sum of Squares is defined below.

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

Where,

$n = \text{number of data points}$

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 12 and Figure 13 are the plots of the output from the M-E PDG 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. The other plots with different calibration values are shown in Appendix B.

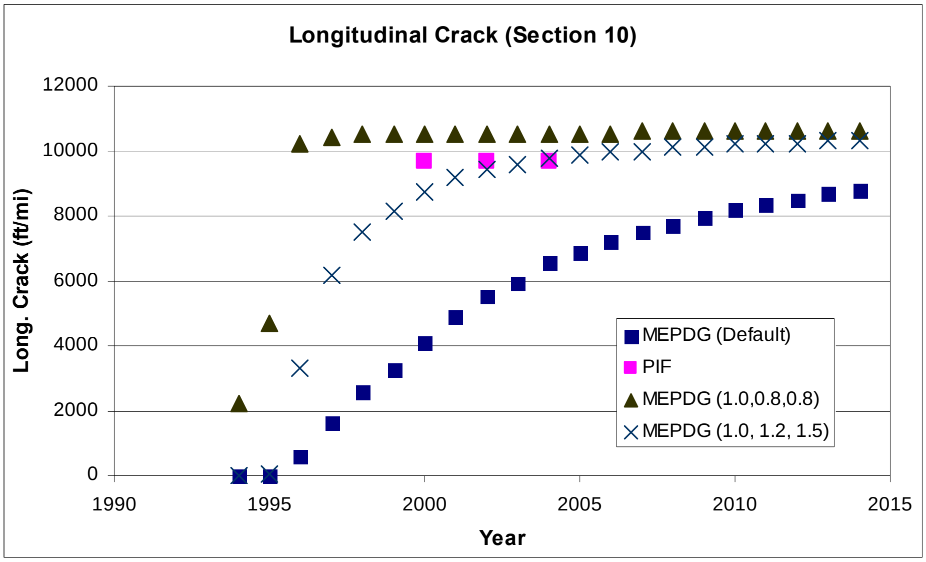


Figure 12 Prediction of Longitudinal Cracking in Wisconsin Section 10 for Various Calibration Values

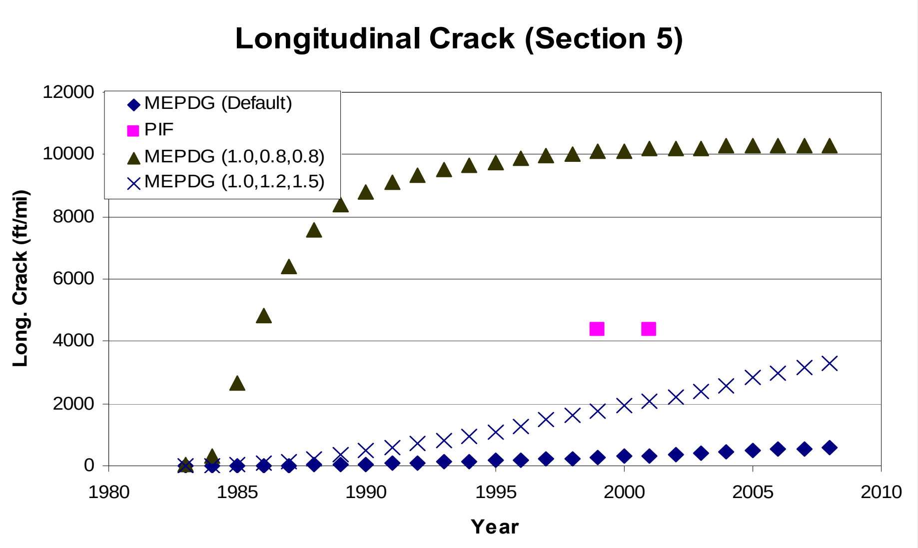


Figure 13 Prediction of Longitudinal Cracking in Wisconsin Section 5 for Various Calibration Values

Table 15 and Table 16 show the Sum of Squares (SS) for each section. The results indicate a prediction model with β_{f1}=1.0, β_{f2}=1.2 and β_{f3} =1.5 has the least SS value and thus the best fit. The least SS for these sections seems high (8.83E+05 and 1.07E+07). To investigate further, the research team evaluated the possible combinations of calibration factors for all sections. Figure 14 to Figure 16 show plot comparisons of actual pavement performance versus predicted pavement performance for each calibration set. If there is no difference between actual and predicted performance, ideally the data points should fall on the 45 degree line (y=x in graphs). From the figures, the plot for β_{f2}=1.2 and β_{f3} =1.5 show the best fit for longitudinal cracking which is consistent with the SS analysis.

Table 15 Comparison of Sum of Squares for Longitudinal Cracking (Section 10 in Wisconsin)

β_{f1}	β_{f2}	β_{f3}	Sum of Square(SS)
1.0	1.0	1.0	5.81E+07
1.0	0.8	0.8	2.10E+06
1.0	**1.2**	**1.5**	**8.83E+05**

Table 16 Comparison of Sum of Squares for Longitudinal Cracking (Section 5 in Wisconsin)

β_{f1}	β_{f2}	β_{f3}	Sum of Square(SS)
1.0	1.0	1.0	3.28E+07
1.0	0.8	0.8	6.65E+07
1.0	**1.2**	**1.5**	**1.07E+07**

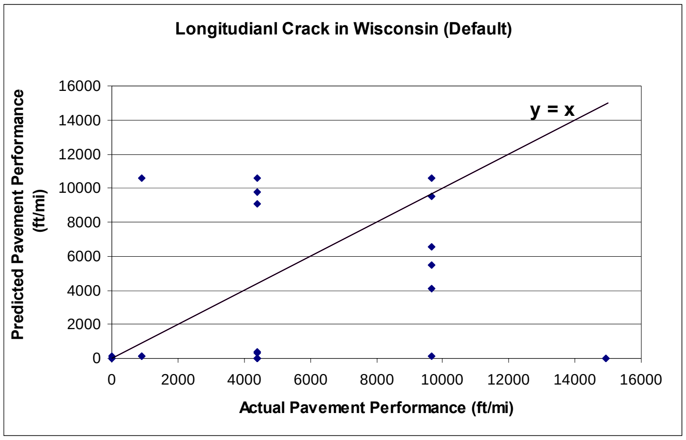


Figure 14 Longitudinal Cracking Comparison Plot in Wisconsin (Default)

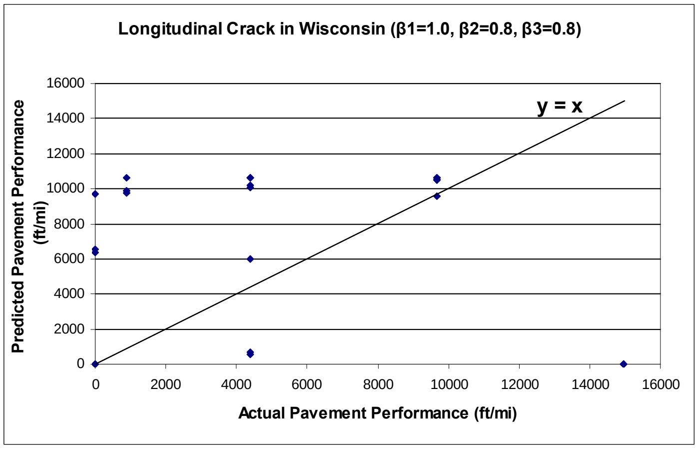


Figure 15 Longitudinal Cracking Comparison Plot in Wisconsin (β_{f1}=1.0, β_{f2}=0.8, β_{f3} =0.8)

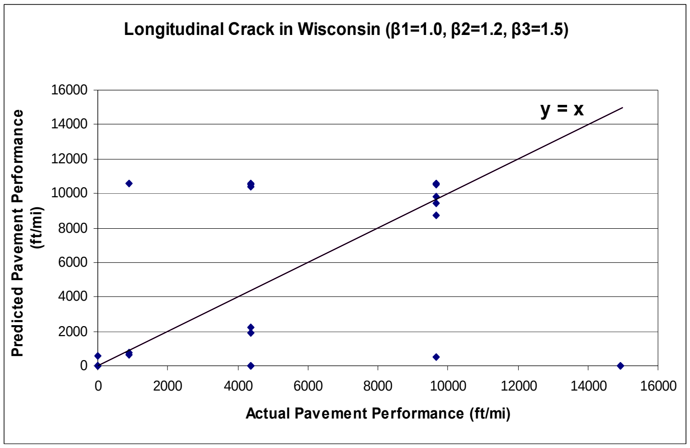


Figure 16 Longitudinal Cracking Comparison Plot in Wisconsin (βf1=1.0, βf2=1.2, βf3 =1.5)

5.2.3. Calibration of the Alligator Fatigue Cracking Model

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

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

Where,

$F.C.$ = fatigue cracking (% of lane area)

D = Damage in percentage

C_1, C_2 = regression coefficients

The process used for longitudinal cracking in Section 5.2.2 can find calibration factors for alligator cracking. Default values for C_1 and C_2 were found using more than 100 sections nation-wide. Similar to longitudinal cracking, the default values are being used in this calibration. Damage in percentage, *D*, depends on the fatigue cracking model in Section 5.2.1. The fatigue cracking model in Section 5.2.1 is applicable for both alligator and longitudinal cracking. The research team used Sections 5 and 10 from Wisconsin to calibrate the alligator fatigue-cracking model. Figure 17 and Figure 18 compare predicted (MEPDG) and observed (PIF) cracking.

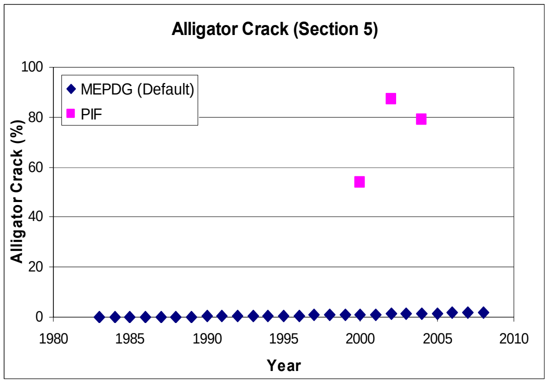


Figure 17 Alligator Cracking in Section 5 in Wisconsin

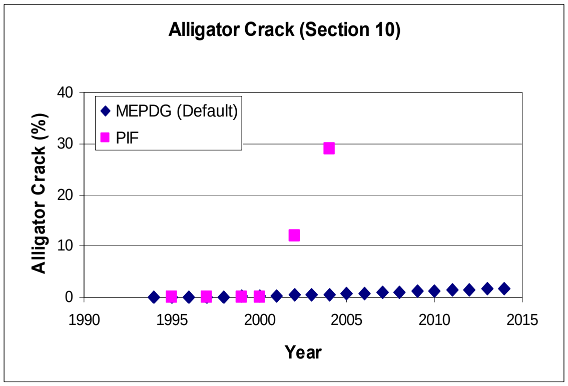


Figure 18 Alligator Cracking in Section 10 in Wisconsin

To find the calibration values for alligator cracking, nine runs were conducted for each section and Sum of Squares evaluated the output from the M-E PDG.

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

Where,

$n = \text{number of data points}$

Similar to the longitudinal cracking, comparing the outputs from the M-E PDG by changing the calibration factors could determine the appropriate β_{f2} and β_{f3} which can show the least calculation of SS. Nine trials for each section illustrated 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. Here are the plots of the output from M-E PDG by 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" and denotes the collected pavement performance data in the figures. The other plots with different calibration values are shown in Appendix B.

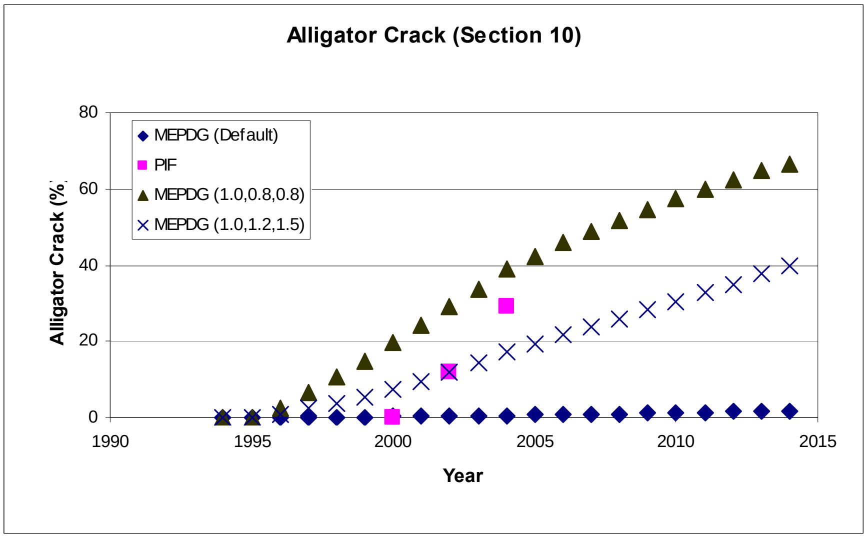


Figure 19 Alligator Cracking in Section 10 in Wisconsin by Various Calibration Values

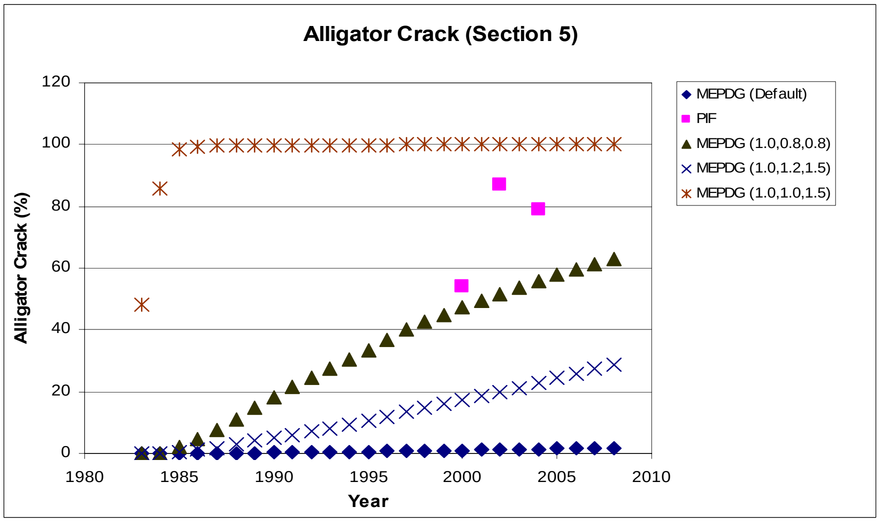


Figure 20 Alligator Cracking in Section 5 in Wisconsin by Various Calibration Values

Table 17 and Table 18 also show Sum of Squares (SS) for each section. These tables suggest that the prediction model with β_{f2}=1.2 and β_{f3} =1.5 can show the least SS values for Section 10 and one with β_{f2}=0.8 and β_{f3} =0.8 for Section 5.

Table 17 Comparison of Sum of Squares for Alligator Cracking (Section 10 in Wisconsin)

β_{f1}	β_{f2}	β_{f3}	**Sum of Square(SS)**
1.0	1.0	1.0	9.43E+02
1.0	0.8	0.8	7.87E+02
1.0	**1.2**	**1.5**	**1.90E+02**

Table 18 Comparison of Sum of Squares for Alligator Cracking (Section 5 in Wisconsin)

$\beta1$	$\beta2$	$\beta3$	Sum of Squares
1.0	1.0	1.0	1.62E+04
1.0	**0.8**	**0.8**	**1.84E+03**
1.0	1.2	1.5	8.97E+03
1.0	1.0	1.5	2.73E+03

Two sets of calibration values (β_{f2}=0.8, β_{f3} =0.8 and β_{f2}=1.2, β_{f3} =1.5) were applied to other sections. The research team attempted to acquire the proper calibration values to plot comparison graphs with actual pavement performance versus predicted pavement performance rather than by Sum of Squares. If there is no difference between actual performance data and predicted performance data, ideally the dots should be on the perfect 45-degree line. Here are the comparison plots with default calibration factors (β_{f2}=1.0 and β_{f3} =1.0) and the other calibration factors (β_{f2}=0.8, β_{f3} =0.8 and β_{f2}=1.2, β_{f3} =1.5)

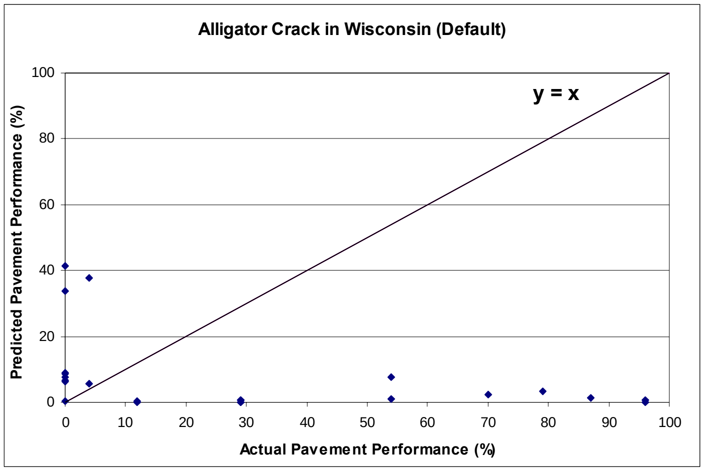


Figure 21 Alligator Cracking Comparison Plot in Wisconsin (Default)

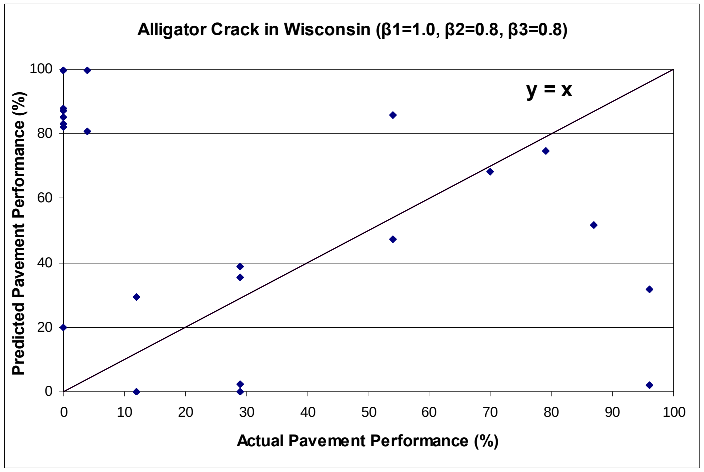


Figure 22 Alligator Cracking Comparison Plot in Wisconsin (β_{f1}=1.0, β_{f2}=0.8, β_{f3} =0.8)

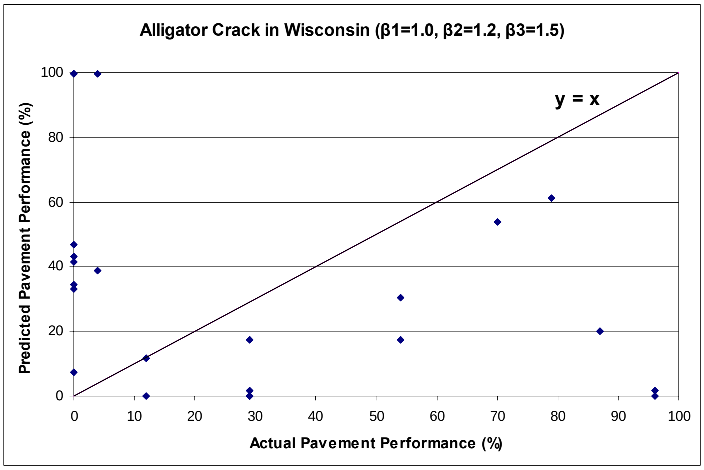


Figure 23 Alligator Cracking Comparison Plot in Wisconsin (β_{f1}=1.0, β_{f2}=1.2, β_{f3} =1.5)

From these three figures, it is difficult to determine which set is the best. Definitely, the plot with default values is the worst. But the plots in Figure 22 and Figure 23 were spread out. Thus, it can be discussed that both of the calibration sets can be applied for alligator cracking in Wisconsin. However, one is not allowed to input different calibration factors for longitudinal cracks and alligator cracks in the M-E PDG. Thus, the research team concluded the proper calibration values for fatigue cracking are β_{f2}=1.2 and β_{f3} =1.5.

5.3. Rigid Pavement

For jointed-plain rigid pavement sections, three distresses are predicted: faulting, transverse cracking, and IRI. IRI is numerically calculated by the other two distresses. It is not an easy task to calibrate distress models for rigid pavement because there are too many unknown variables in the prediction model. Furthermore, the M-E PDG does not propose ranges of values for the factors. The following sections compare predict distresses with default calibration values to the observed pavement performance.

5.3.1. Faulting

According to the M-E PDG, the mean transverse joint faulting is predicted using an incremental approach. The faulting for each month is determined as a sum of faulting increments from all previous months in the pavement life.

As can be seen, there are seven calibration factors for predicting faulting and the M-E PDG default values are based on performance of 248 field sections. To obtain calibration factors for the Midwest, more sections are necessary and variables such as Freezing ndex should be known.

$$Fault_m = \sum_{i=1}^{m} \Delta Fault_i$$

$$\Delta Fault_i = C_{34} * (FAULTMAX_{i-1} - Fault_{i-1})^2 * DE_i$$

$$FAULTMAX_i = FAULTMAX_0 + C_7 * \sum_{j=1}^{m} DE_j * \log\left(1 + C_5 * 5.0^{EROD}\right)^{C_6}$$

$$FAULTMAX_0 = C_{12} * \delta_{curing} * \left[\log(1 + C_5 * 5.0^{EROD}) * \left(\frac{P_{200} * WetDays}{P_s} \right) \right]^{C_6}$$

Where,

$Fault_m =$ mean joint faulting at the end of month *m*, in

$\Delta Fault_i =$ incremental change (monthly) in mean transverse joint faulting during month *i*, in

$FAULTMAX_i =$ maximum mean transverse joint faulting for month *i*, in

$FAULTMAX_0 =$ initial maximum mean transverse joint faulting, in

$EROD =$ base/subbase erodibility factor

$DE_i =$ differential deformation energy accumulated during month *i*

$\delta_{curing} =$ maximum mean monthly slab corner upward deflection PCC due to temperature curing and moisture warping

$P_s =$ overburden on subgrade, lb

$P_{200} =$ precent subgrade material passing #200 sieve

$WetDays =$ average annual number of wet days

Here, C_1 through C_8 and C_{12}, C_{34} are national calibration constants.

$$C_{12} = C_1 + C_2 * FR^{0.25}$$
$$C_{34} = C_3 + C_4 * FR^{0.25}$$

$C_1 = 1.29$ $\quad$ $C_5 = 250$

$C_2 = 1.1$ $\quad$ $C_6 = 0.4$

$C_3 = 0.001725$ $\quad$ $C_7 = 1.2$

$C_4 = 0.0008$

$FR =$ base freezing index defined as percentage of time the top base temperature is below freezing (32°F) temperature

Figure 24 and Figure 25 show the predicted output from the M-E PDG ("MEPDG" in the plots) and field observed pavement performance ("PIF" in the plots). The plots of all Wisconsin sections are presented in Appendix A. Because collected field data has a large range, illustrated in Figure 24, it is difficult to verify whether the prediction from default calibration values is good enough. Figure 25 shows better prediction than the plot in Figure 24 but there is still a large difference between predicted and field pavement performance data.

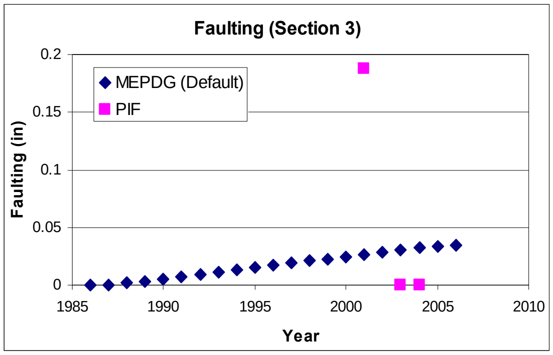


Figure 24 Faulting in Section 3 in Wisconsin with Default Calibration Value

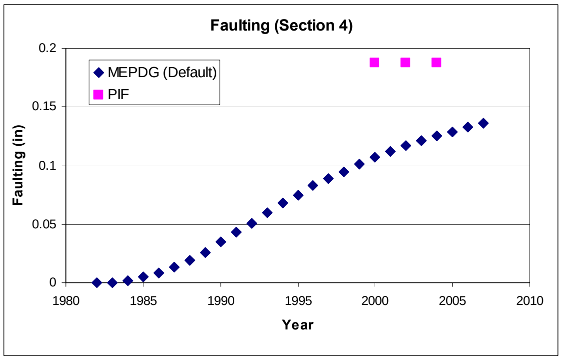


Figure 25 Faulting in Section 4 in Wisconsin with Default Calibration Value

5.3.2. Transverse Cracking

M-E PDG considers both bottom-up and top-down modes for transverse cracking. Rigid pavement slabs crack bottom-up or top-down but not both. A single model is used for both cases (NCHRP 2004). The main cause of cracking is fatigue damage in the rigid pavement and the general expression for fatigue damage accumulations for transverse cracking is as follows:

$$FD=\sum_{i=1}^{T}\frac{n_{i,j,k,l,m,n}}{N_{i,j,k,l,m,n}}$$

Where:

$FD =$ total fatigue damage (top-down or bottom-up)

$T =$ total number of periods

$n_{i,j,k,...} =$ applied number of load application at condition $i, j, k, l, m, n.$

$N_{i,j,l,...} =$ allowable number of load application at condition $i, j, k, l, m, n.$

$i =$ age (accounts for change in PCC modulus of rupture)

$j =$ month (accouts for change in base and effective dynamic modulus of subgrade reaction)

$k =$ axle type

$l =$ load level (incremental load for each axle type)

$m =$ temperature difference

$n =$ traffic path

The allowable number of load applications is determined using the following fatigue model:

$$\log\left(N_{i,j,k,l,m,n}\right)=C_1\left(\frac{MR_i}{\sigma_{i,j,k,l,m,n}}\right)^{C_2}+0.4371$$

Where:

$N_{i,j,k\ldots}$ = allowable number of load applications at combined condition i, j, k, l, m, n

MR_i = PCC modulus of rupture at age i, psi

$\sigma_{i,j,k\ldots}$ = applied stress at combinde condition i, j, k, m, n

C_1 = calibration constant=2.0

C_2 = calibration constant = 1.22

At the M-E PDG output, the damage for fatigue cracking is presented by percentage and theoretically, fatigue cracking should occur at an accumulated damage value of 100%. Transverse cracking is measured by the percent of slabs with transverse cracks and is predicted using the following model:

$$CRK = \frac{1}{1 + C_4 * FD^{C_5}}$$

Where:

CRK = predicted amount of bottom-up or top-down cracking

FD = Fatigue damage calculation

C_4 = calibration constant=1.0

C_5 = calibration constant = -2.0

The total amount of cracking is determined as follows:

$$TCRACK = (CRK_{Bottom-up} + CRK_{Top-down} - CRK_{Bottom-up} * CRK_{Top-down}) * 100\%$$

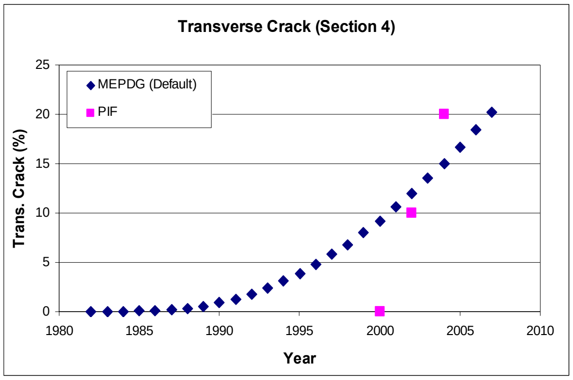
Where

$TCRACK$ = total cracking (percent)

$CRK_{Bottom-up}$ = predicted amount of bottom-up cracking

$CRK_{Top-down}$ = predicted amount of top-down cracking

Regarding calibration factors, it was decided that all default values would apply for this research. Here are two examples that show the predicted output from the M-E PDG ("MEPDG" in the plots) and field collected pavement performance data ("PIF" in the plots). The plots of all Wisconsin sections are presented in Appendix A. As can be seen, for Section 4, prediction with default calibration values is matched relatively well to the field pavement data (Figure 26) while the plot in Figure 27 does not verify that the default values predict well.



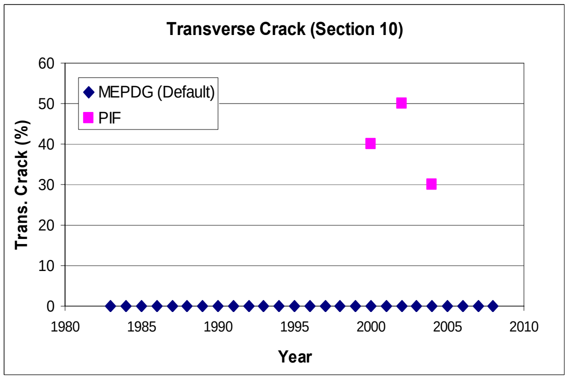


Figure 26 Transverse Cracking in Section 4 in Wisconsin with Default Calibration Value

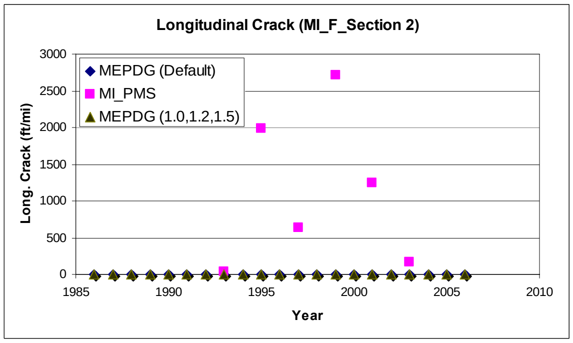
Figure 27 Transverse Cracking in Section 10 in Wisconsin with Default Calibration Value

5.4. Calibration Fit for Michigan and Ohio

The calibration values were determined only from Wisconsin data. Due to time and budget limitations, the research team did not prepare calibration factors for Michigan and Ohio. Instead, this section presents comparisons of the calibration: predicted performance using M-E PDG, predicted performance using Wisconsin's calibrated model and observed field pavement performance. Because the research team found two calibration values for fatigue in flexible pavement, only two distresses are presented: longitudinal cracking and alligator cracking. Two sections from each state were selected and shown here for example. Comparisons of all sections from other states are presented in Appendix B.

5.4.1. Michigan

The calibrated predictions for longitudinal cracks are not matched well for Michigan. Figure 28 and Figure 29 compare the outputs of longitudinal cracking from the M-E PDG and field collected pavement performance data. Both plots show neither of the two predictions from the M-E PDG predicts well. Especially in Figure 29, prediction from the default values is better than from the calibrated values.



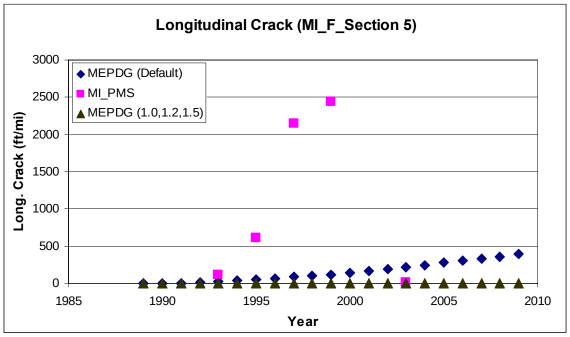


Figure 28 Longitudinal Cracking in Section 2 in Michigan

Figure 29 Longitudinal Cracking in Section 5 in Michigan

Unlike longitudinal cracking, the calibrated M-E PDG predicted the alligator crack well for Michigan. Figure 30 shows the calibrated prediction can reduce the difference between prediction and field collected data. Figure 31 suggests the prediction with default calibration is better than with calibrated values. However, if deterioration rate of field data is considered, prediction with calibrated values may match better than default values.

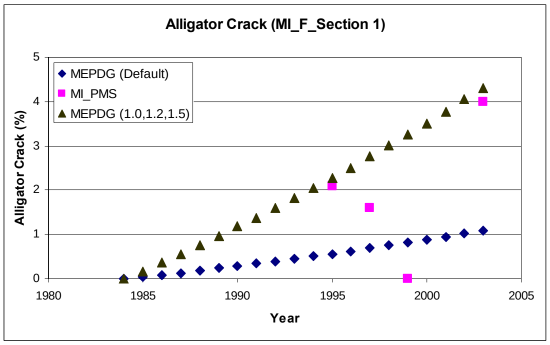


Figure 30 Alligator Cracking in Section 1 in Michigan

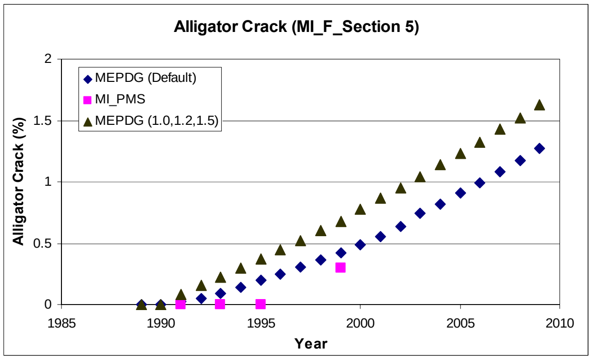


Figure 31 Alligator Cracking in Section 5 in Michigan

5.4.2. Ohio

The collected field data from Ohio does not seem suitable for calibration. As can be seen in Figure 37 and Figure 38 below, the collected longitudinal data stay at ”0” or jump up so high and reach 6000 ft/mi. in only a couple of years. Thus, it is difficult to judge whether the calibrated prediction is good for longitudinal cracking in Ohio. Figure 32 and Figure 33 show the two predictions from M-E PDG and collected field performance data.

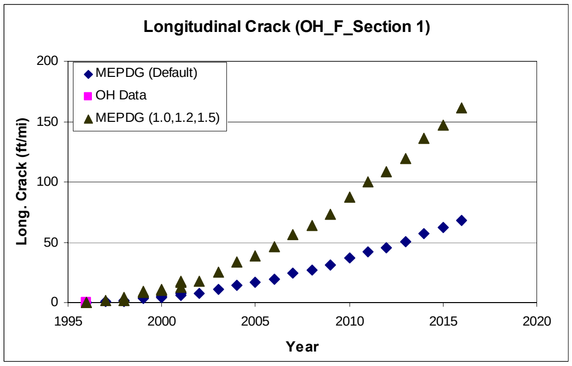


Figure 32 Longitudinal Cracking in Section 1 in Ohio

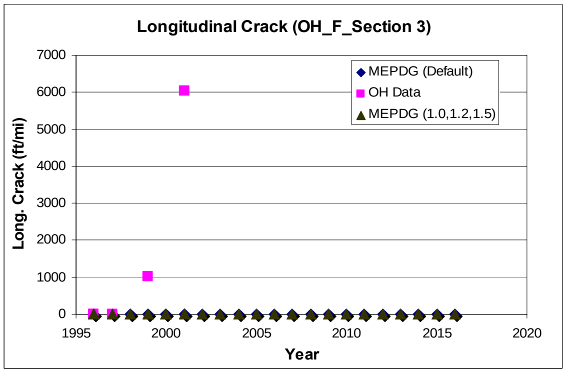


Figure 33 Longitudinal Cracking in Section 3 in Ohio

The collected pavement performance data is still not good enough for alligator cracks. Because the pavement has deteriorated too quickly, neither of two models could predict alligator cracking well for Ohio. Figure 34 illustrates alligator cracks increase 0 to 6% in five years which is a 20 times greater increase compared to Michigan data (Figure 31). Thus, it is difficult to predict the alligator cracking in Ohio with default or calibrated values.

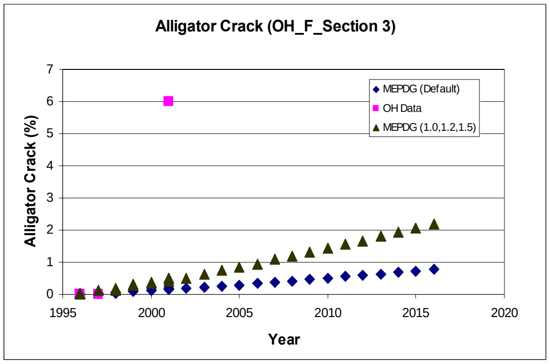


Figure 34 Alligator Cracking in Section 3 in Ohio

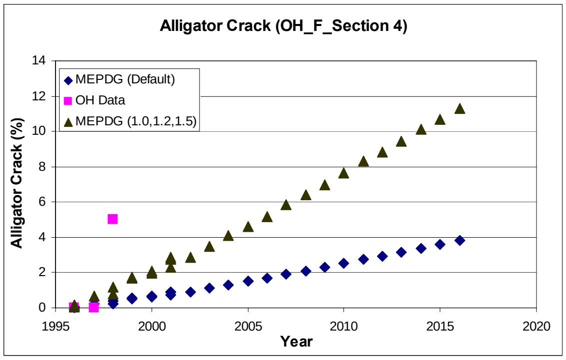


Figure 35 Alligator Cracking in Section 4 in Ohio

5.5. Summary

One of the main purposes of this project was to evaluate or verify the calibration factors in the distress prediction models in the M-E PDG. To achieve this goal, the research team attempted to determine appropriate calibration values first from Wisconsin data. The calibrations were done by comparing the collected pavement performance with the predicted pavement performance using various calibration values. The visual graphs and statistical calculations were applied to obtain the best calibration factors and two calibration values were determined for the fatigue damage model.

Due to the poor quality of pavement performance data from other states, the research team decided not to consider other state data for calibration but to show the calibrated prediction model compared to field collected data. Collected pavement performance data were plotted with two prediction models: one with default calibration model and the other with the Wisconsin calibrated model. These comparisons may help the state transportation agencies to determine their calibration values.

6. QUANTIFYING BENEFITS of USING the M-E PDG

6.1. Introduction

A case study was the first step in verifying the achievable benefits from the M-E PDG in the real world. Pavement sections that were not used for national calibration were the focus of the study. Performance and design of the pavement structure from two different design tools are compared. For the purposes of the comparison, results of WisDOT's WisPAVE are compared to results of the M-E PDG. Current pavement section, which was designed by WisPAVE, is selected and the design is compared to the output from M-E PDG. The comparison covers two perspectives: expected performance of the WisPAVE design and maintenance/rehabilitation plan compared to expected performance from the M-E PDG and comparison of the current (WisPAVE) design with M-E PDG results to achieve the originally expected performance.

6.2. Case Study of the Benefits from M-E PDG

For this case study, pavement sections in Middleton, Wisconsin were chosen. The case study encompasses new construction of a four-lane divided freeway bypass functioning as a principal arterial. Output from the M-E PDG is compared to the pavement design from WisPAVE. Detailed data is obtained from project reports provided by WisDOT (Strand Associates 2000). Construction was completed in 2005 with a 20-year design life and 50-year maintenance and rehabilitation plan. The construction year's average daily traffic was 25,688 and predicted to increase at a compound growth rate of 1.17%. A directional factor of 0.5 was used.

WisPAVE Design

Two pavement designs were recommended from WisPAVE; one for flexible pavement the other for rigid pavement. Life Cycle Cost Analysis over 50 years was used to determine final design: a jointed-plain rigid pavement with dowels, 4 inches of Open Graded Base Course, 6 inches of Crushed Aggregate Base Course, and 18 inches of Breaker Run Stone. This structure has a 20-year design life (traffic) and maintenance/rehabilitation activities for the 50-year analysis period. Table 19 shows the maintenance and rehabilitation schedule used in this analysis. This maintenance and rehabilitation schedule can assist in the comparison of design results from WisPAVE and the M-E PDG.

Table 19 Maintenance Scenarios for Rigid Pavement Design (Strand Associates 2000)

Description	Year
Minor Joint Repair	15
Minor Joint Repair	24
1st Rehabilitation (Pavement Repair at 5%, and Grind)	32
Minor Joint Repair	36
Minor Joint Repair	40
2nd Rehabilitation (Pavement Repair at 5%, and Overlay)	44
Minor Joint Repair	48

M-E PDG Design

For comparison with WisPAVE output, all inputs to M-E PDG were the same as used for the WisPAVE design. However, the required data for M-E PDG is much more detailed and specific than for WisPAVE. Default values in the M-E PDG were used for unknown inputs.

General Information

The general information inputs cover design life, construction month, traffic opening month, pavement type (JPCP or CRCP), initial smoothness (IRI), and allowable limitation and reliability level of each distress criteria. Though 20 year design life was applied by WisPAVE design, M-E PDG considers pavement design life as 50 years to project distresses when maintenance/rehabilitation activities provided by WisDOT were scheduled. All default values in the M-E DPG were applied as distress allowable limits: 63 in/mi for initial IRI, 172 in/mi for terminal IRI, 15% slabs cracked for transverse cracking and 0.12 inches for mean joint faulting.

Traffic

Traffic data is one of the key elements required for the M-E PDG analysis to predict pavement performance. For traffic volume, the basic required information is AADT (Average Annual Daily Traffic) for the year of construction and percent of trucks in the design direction. Initial AADTT (Average Annual Daily Truck Traffic) is calculated from AADT and percent of trucks. A traffic growth factor can project the volume of traffic for the design life. In this study, the AADT is 25,688; percent of heavy vehicles is 6.8% and traffic growth rate is 1.17%, which is compounded annually. 85 percent of trucks were assigned to the design lane. Due to different classifications of heavy vehicles, the truck classes used in WisPAVE were converted to the M-E PDG classifications. As a result, AADTT was distributed to 5 classes; 33.8% for class 5, 33.8% for class 6, 14.7% for class 7, 16.2% for class 9 and 1.5% for class 12. For this study, all other required traffic inputs such as monthly and hourly truck distribution, axle load distribution, and some other general traffic inputs, were derived from Design Level 3 default values in the M-E PDG.

Climate

Pavement performance is significantly affected by environmental conditions. The case study used weather station information for Madison, Wisconsin, which is less than 5 miles away from the selected project location. Annual average ground water table depth used was 10 feet, obtained from US Geological Survey (http://wi.water.usgs.gov/public/gw/MONTHLY/monthly.html, accessed in December, 2006).

Pavement Structure

The pavement structure was based on the WisPAVE results. The pavement structure consists of four layers: type 1 Portland cement concrete with doweled joints over two different base layers, and one subbase with compacted unbound material.

The inputs required for the PCC layer were layer thickness, material unit weight, Poisson's ratio, coefficient of thermal expansion, cement type, cement content, water-cement ratio, aggregate type, modulus of rupture, modulus of elasticity, compressive strength, etc. In this study, 10 inches for the concrete slab, 4 inches of drained base, 6 inches of dense-graded base, and 18 inches of subbase were used. Again, all other required structure inputs such as Poisson's ratio, PCC modulus of rupture, gradation, and plasticity index were derived from the default values in M-E PDG.

Evaluation of Pavement Structure at Middleton Bypass

This previously mentioned pavement structure design, using a 50-year analysis period, was fed into the M-E PDG. The resulting design reliability summary is shown in Table 20. Although the in-place pavement structure was designed with 20-year design life by WisPAVE, the case study was performed for a 50-year period in order to display the distresses when maintenance/rehabilitation was planned.

Table 20 Projected Distresses at 90% Reliability in Year 50 (WisPAVE Design)

Performance Criteria	Failure	Distress Predicted	Acceptable
IRI (in/mi)	172	118.8	Pass
Transverse Cracking (% slabs cracked)	15	1.5	Pass
Mean Joint Faulting (in)	0.12	0.014	Pass

The outputs from the M-E PDG verify all performance criteria were satisfied meaning the design is acceptable for the given traffic volume and climate conditions even with 50 years without any maintenance or rehabilitation. Predicted distresses of all performance criteria were much better than failure limits. Considering the original pavement design life, 20 years, it can be regarded as a conservatively designed pavement. The thickness of each layer could be reduced to get a more cost effective pavement structure over its projected pavement design life.

The M-E PDG cannot directly determine or evaluate a maintenance schedule for the certain pavement design. But pavement distresses can be predicted for the certain times. The pavement distresses can be projected every month by the M-E PDG and this approach allows the designer to anticipate the pavement performance at a certain time. Table 21 shows projected distresses at the times when maintenance and rehabilitation activities were planned in the WisPAVE process. The average value of recommended reliability level for an urban principal arterial, 90%, which is the highway classification type of the selected section, is applied for analysis (Huang 2004).

Table 21 Projected Distresses at Maintenance Scheduled Years (WisPAVE Design)

Performance Criteria	Failure	Distress Measure (% of Failure Target) in Years						
		Year 15	Year 24	Year 32 (Rehab)	Year 36	Year 40	Year 44 (Rehab)	Year 48
IRI (in/mi)	172	105 (61.0%)	111.2 (64.7%)	120.4 (70.0%)	126.7 (73.7%)	133.6 (77.7%)	140.9 (81.9%)	148.1 (86.1%)
Transverse Cracking (% slabs cracked)	15	6.3 (42.0%)	6.6 (44.0%)	6.9 (46.0%)	7.1 (47.3%)	7.3 (48.7%)	7.6 (50.7%)	7.9 (52.7%)
Mean Joint Faulting (in)	0.12	0.021 (17.5%)	0.026 (21.7%)	0.031 (25.8%)	0.034 (28.3%)	0.036 (30.0%)	0.039 (32.5%)	0.042 (35.0%)

In the maintenance plan, minor joint repairs are planned to be conducted in years 15, 24, 36, 40 and 48. M-E PDG projects mean joint faulting of 0.021 inches at year 15 and

0.0042 inches at year 48, which are only 17.5% and 35% of failure target (0.12 in) respectively. The pavement maintenance schedules appear to be conservative. One of the two planned minor joint repair efforts, planned before each rehabilitation activity, might not be necessary.

For rehabilitation, the original plan has pavement repair and grind at year 32, and repair and overlay at year 44. At year 32, transverse cracking reaches almost 50% of the failure and roughness of pavement reaches 65% of the failure criteria. Thus, the first rehabilitation deserves to be performed and the initial plan should be executed. The next rehabilitation activity is planned to be performed at year 44. Projected IRI and transverse cracking will be 82% and 51% without first rehabilitation. Table 21 shows the distress deterioration without any maintenance or rehabilitation activity along time. The result of the first rehabilitation may determine the necessity of a second rehabilitation. Because Table 21 cannot verify whether the second rehabilitation is essential, second rehabilitation is assumed to be conducted. Figure 36 presents the projected distresses, percentage of failure, at 90% reliability at scheduled maintenance times for the 50-year analysis period.

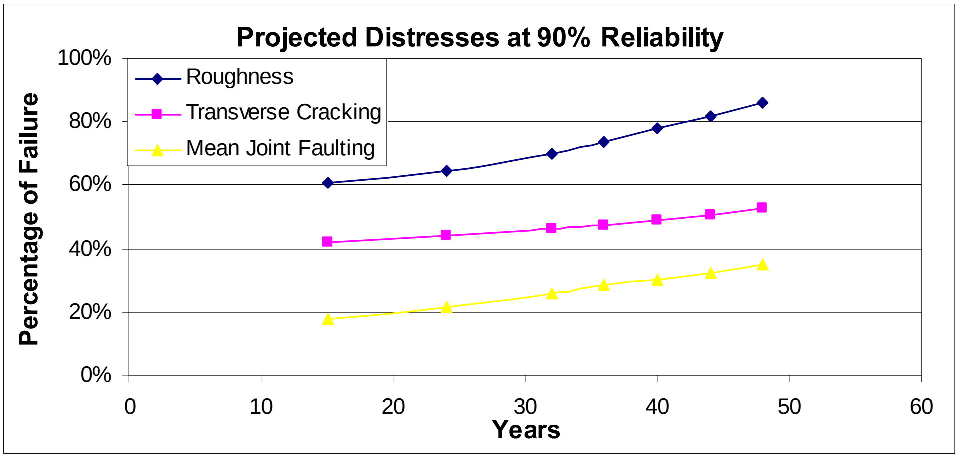


Figure 36 Projected Distresses at 90% Reliability for 50 Years (WisPAVE Design Structure)

Thus, half of the minor maintenance costs could be saved. If total maintenance is assumed to cost $3,470 per one kilometer (Strand Associates 2000), then half of it, $1,700/km could be saved. Considering the whole length (5.6 km), $9,500 could be saved WisDOT does not consider user costs.

M-E PDG Design for Middleton Bypass

For analysis, a new pavement design was developed for the bypass. Only two layers were selected: a 10-inch concrete slab and 4-inch crushed aggregate base course. Several trials were conducted to reduce the thickness of the concrete slab. However, a concrete slab less than 10 inches thick resulted in critical failure in transverse cracks before the end of the design life. Table 22 shows the design reliability summary of new pavement design for a 20-year pavement design life.

Table 22 Projected Distresses at 90% Reliability in Year 20 (M-E PDG)

Performance Criteria	Failure	Distress Predicted	Acceptable
IRI (in/mi)	172	70.9	Pass
Transverse Cracking (% slabs cracked)	15	0.4	Pass
Mean Joint Faulting (in)	0.12	0.004	Pass

The new pavement design meets all performance criteria at 90% reliability level and this design will be suitable for given traffic and climate conditions in its 20-year design life. Predicted distresses are less than the determined failure targets with only two layers: concrete slab and one base layer. Rigid pavement design with a 2-inch thinner dense graded base layer and without the open graded base and the breaker run subbase still satisfies the performance criteria. As a result, output from M-E PDG shows the initial construction budget may be reduced by $18,653/km from reduced base layer and $14,570/km from absence of two layers. A total $184,800 ($33,000/km) can be saved from reduced pavement structure even if all other maintenance activities will be performed as planned. Table 23 below summarizes the possible economic benefit by applying M-E PDG for the case study.

Table 23 Possible Economic Benefits for the Case study

Item	Total Savings	Source
Maintenance	$ 9,500 ($1,700/km)	Without two minor maintenance activities
Construction	$ 184,800 (33,000/km)	Reduced base layers

Discussion of the Case Study

The case study briefly shows a quantified benefit from using the M-E PDG. Marriage of mechanistic and empirical techniques provides reliable pavement performance predictions. However, there are needs to discuss for applying M-E PDG in the case study.

Calibration of pavement prediction process

Pavement performances are accurately predicted from mechanistic-empirical procedures. In the case study, pavement design analysis was performed using national calibration factors. However, more reliable prediction is achieved by calibrating prediction models integrated in M-E PDG. Each of the projected distresses should be calibrated based on local pavement performance data.

State Policy for Pavement Design

Structural safety and pavement performance prediction are not all that determine optimal and/or cost effective pavement design. State agencies sometimes have other, specific, requirements. In this case study, the in-place pavement structure includes 18-inches of Breaker Run Stone for a subbase, based on WisDOT’s statewide policy recommendations. In the new design, this recommendation has not been taken into account.

Complex Input Variables

Ability to perform customized design for state highway agencies is one of the benefits of using M-E PDG. Detailed input variables enable one to design pavement confidently for a specific location. However, unavailable detailed data forces the designer to use the Level 3 default values. In the case study, many nation-wide default values are applied when local values were not available.

6.3. Summary

This chapter presents potential expected benefits of adopting the M-E PDG for one case study. WisPAVE pavement design outputs were compared to the analysis results generated using the M-E PDG. This case study applied the M-E PDG to evaluate the design of a new pavement also. Possible dollar value savings adopting M-E PDG were then estimated. Future studies could explore the possible benefits that can be estimated by a better calibrated M-E PDG, not only for rigid pavement but also for flexible pavement.

7. CONCLUSION and RECOMMENDATION

7.1. Summary of Findings

This report presents the results of an effort to calibrate the M-E PDG models. Pavement data from state transportation agencies in the Midwest region: Michigan Ohio, Iowa and Wisconsin were collected in a uniform template as input variables in the M-E PDG. Data collection was tremendously laborious causing delays in getting data. Due to time limitations, the data from Iowa, Michigan and Ohio could not be included in the calibration analysis. Comparison of predicted pavement distresses from the M-E PDG with collected field pavement performance reveals recommended calibration values for the Midwest region. Moreover, a case study was conducted for quantifying benefits by M-E PDG design.

The project outcome has three parts: development of the regional pavement database for calibration, calibration of predicted factors in the M-E PDG, and quantification of benefits using the M-E PDG.

Development of the Regional Database for Calibration

The uniform database formats were developed using Excel spread sheets for both flexible and rigid pavements and sent to the state transportation agencies in the Midwest region. The pavement data from Michigan, Ohio, Iowa and Wisconsin were collected to perform regional calibration. Due to constraints, calibration was conducted using Wisconsin's data only. Default values or generally accessible databases were consulted to assign values to required variables if the agencies did not provide values. Table 24 summarizes the number of sections from the state transportation agencies.

Table 24 Number of Sections from State Agencies in Midwest Region

State Agencies	Flexible Pavement	Rigid Pavement
Michigan	5	5
Ohio	5	5
Iowa	0	5
Wisconsin	9	5

Calibration of Prediction Factors in the M-E PDG

Calibration factors for the M-E PDG were analyzed for the Midwest region. Three parameters for flexible pavement and two parameters for rigid pavement were sought. From the study, a set of calibration factors for the flexible pavement fatigue-cracking model was recommended. The field pavement performance data in Wisconsin were employed for calibration initially and the distresses predictions with these calibrated factors were compared to field pavement performance in the other states.

For rigid pavement sections, the distresses predicted by default calibration factors were compared to the field collected distresses for each state. The comparisons revealed the default calibration values do not predict the distresses observed in the Midwest. Due to the limited data, calibration of distress prediction for rigid pavement could not be performed. Table 25 summarizes the default and recommended calibration factors for distress models in the M-E PDG.

Table 25 Calibration Factors for Prediction Models in the M-E PDG

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 Crack	$F.C. = \left(\frac{1000}{1+e^{C_1 - C_2 * LogD}}\right) * (10.56)$	C_1	7.0	Default
			C_2	3.5	Default
	Alligator Crack	$F.C. = \left(\frac{6000}{1+e^{C_1 - C_2 * LogD}}\right) * \left(\frac{1}{60}\right)$	C_1	1.0	Default
			C_2	1.0	Default
Rigid Pavement	Faulting	$Fault_m = \sum_{i=1}^{m} \Delta Fault_i$ $\Delta Fault_i = C_{34} * (FAULTMAX_{i-1} - Fault_{i-1})^2 * DE_i$ $FAULTMAX_i = FAULTMAX_0 + C_7 * \sum_{j=1}^{m} DE_j * \log\left(1 + C_5 * 5.0^{EROD}\right)^{C_6}$ $FAULTMAX_0 = C_{12} * \delta_{curing} * \left[\log(1 + C_5 * 5.0^{EROD}) * \left(\frac{P_{200} * WetDays}{P_s}\right)\right]^{C_6}$ (see 5.3.1)	C_1	1.29	Default
			C_2	1.1	Default
			C_3	0.001725	Default
			C_4	0.0008	Default
			C_5	250	Default
			C_6	0.4	Default
			C_7	1.2	Default
	Transverse Crack	$CRK = \frac{1}{1 + C_4 * FD^{C_5}}$	C_4	1.0	Default
			C_5	-2.0	Default

Quantified Benefits of the New Pavement Design Guide

To quantify the benefits of the new pavement design guide, a case study was conducted. Pavement sections were selected and the current design was evaluated by the M-E PDG. For the case study, the following benefits may be achievable:

- The analysis found that approximately half of the minor life-cycle maintenance activities may be unnecessary for the case study project. Accordingly, a maintenance budget savings of $1,700/km. was estimated.
- The WisPAVE pavement structure was found to be conservative. The M-E PDG pavement design with modified base layers may reduce the construction budget by approximately $33,000/km.

7.2. Future Study and Recommendations

This research project was intended to deliver regional pavement data for the M-E PDG and to evaluate calibration values for the Midwest region. Due to the lack of reliability in collected pavement data, however, the calibration factors were evaluated based on Wisconsin data. Most of the field pavement performance data were not suitable for calibrating performance prediction models. For a future study, more reliable pavement data should be collected. The data collection template will enable that effort.

The final goal of calibration in the pavement performance prediction is the implementation of the M-E PDG in the regional state transportation agencies. Thus, DOT staffs 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 M-E PDG should be implemented correctly.

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APPENDIX A. Plots of Prediction Models by M-E PDG Default Values and Field Pavement Performance Data

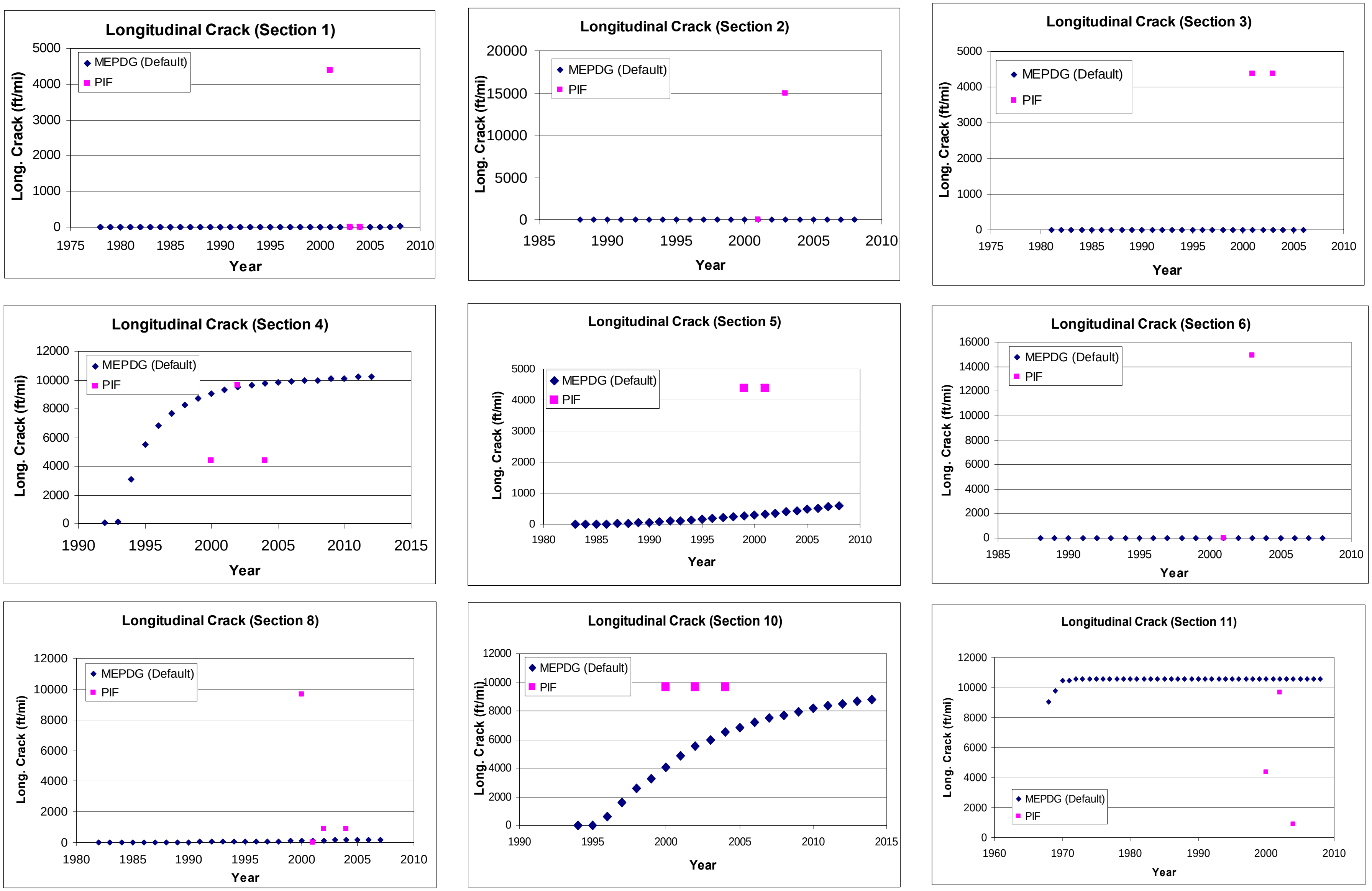
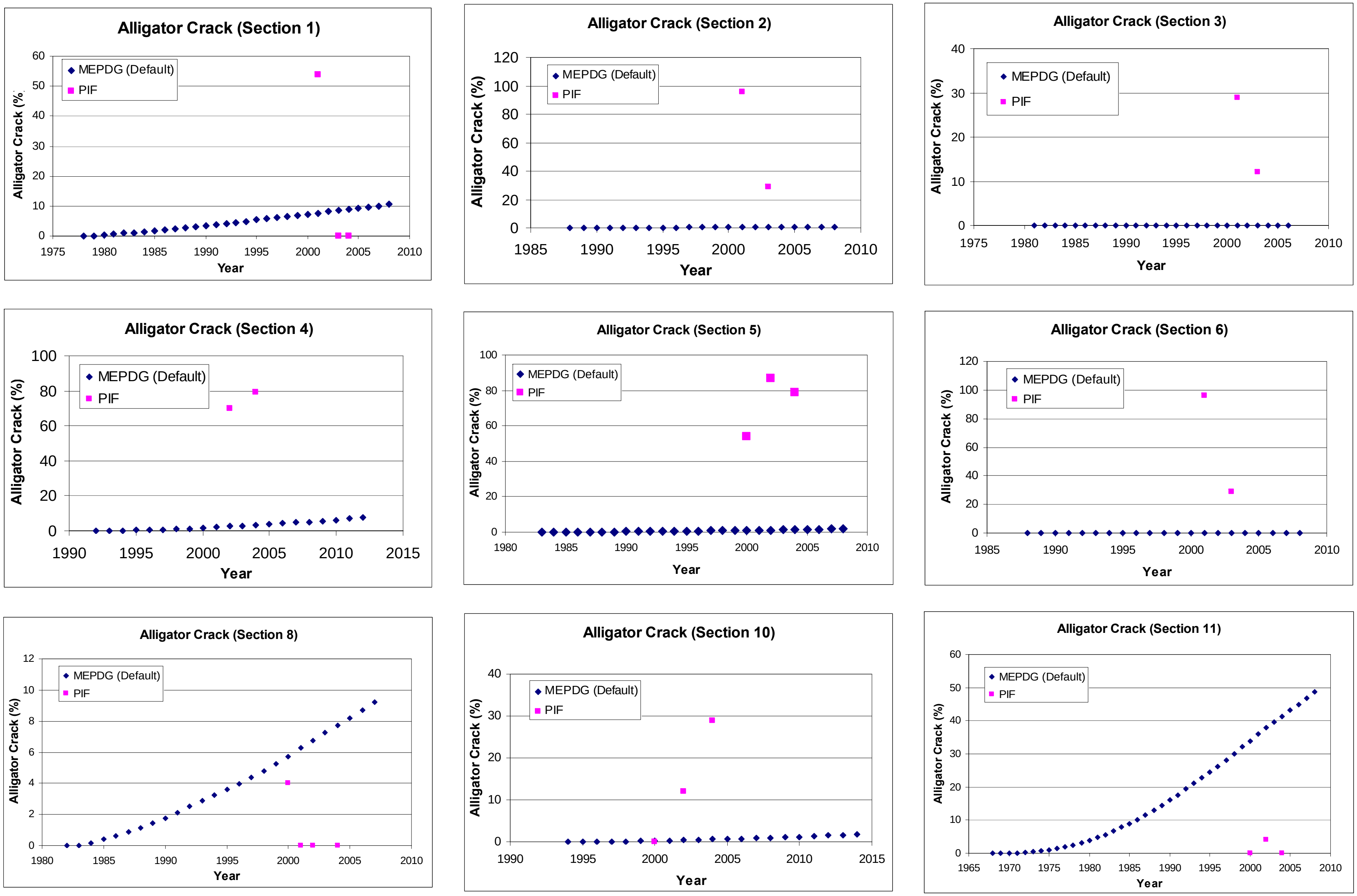


Figure A.1 Longitudinal Crack Comparisons (Flexible Pavement in Wisconsin)


Alligator Crack (Section 1)

Alligator Crack (Section 2)

Alligator Crack (Section 3)

Alligator Crack (Section 4)

Alligator Crack (Section 5)

Alligator Crack (Section 6)

Alligator Crack (Section 8)

Alligator Crack (Section 10)

Alligator Crack (Section 11)

Figure A.2 Alligator Crack Comparisons (Flexible Pavement in Wisconsin)

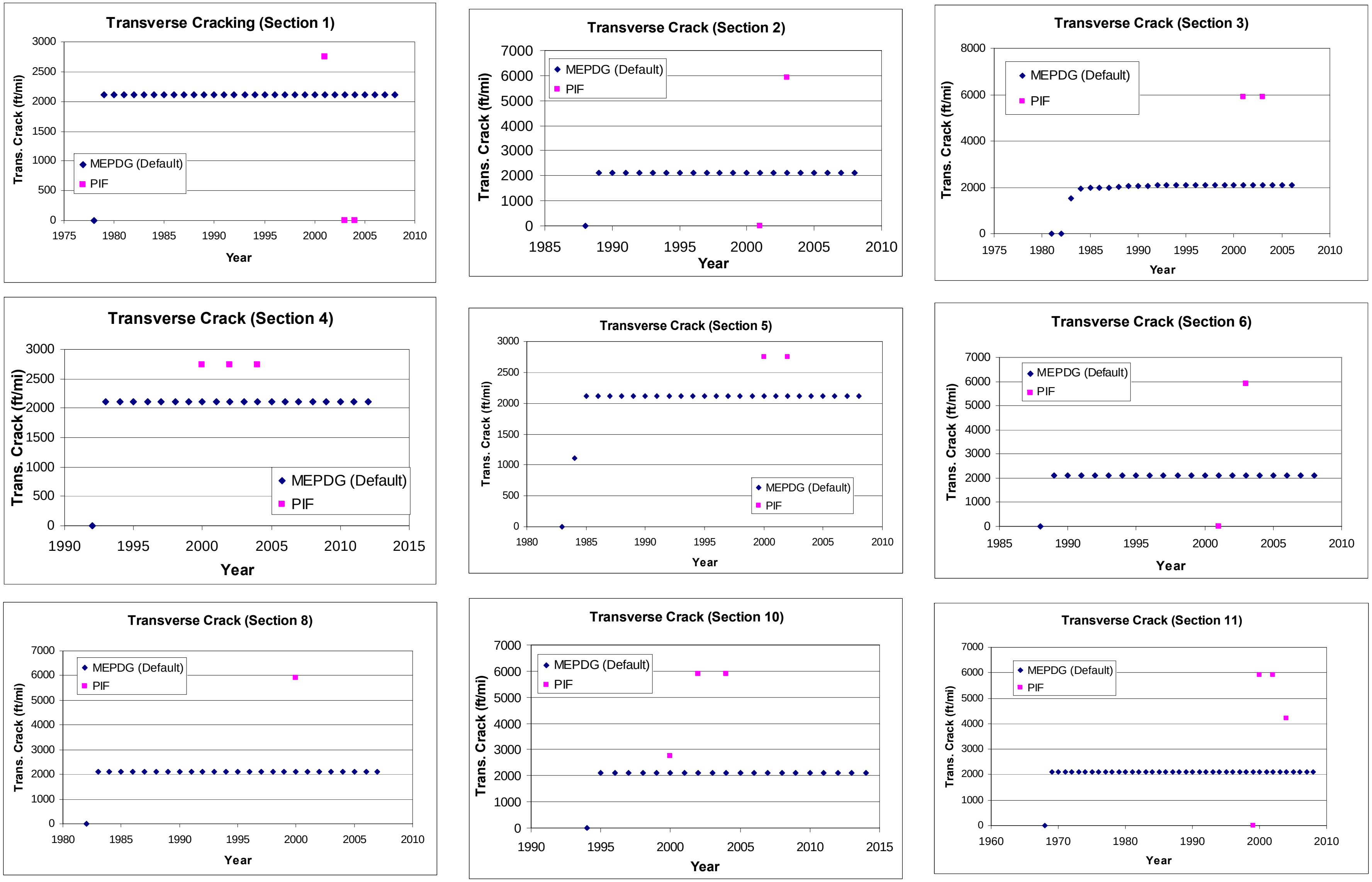


Figure A.3 Transverse Crack Comparisons (Flexible Pavement in Wisconsin)

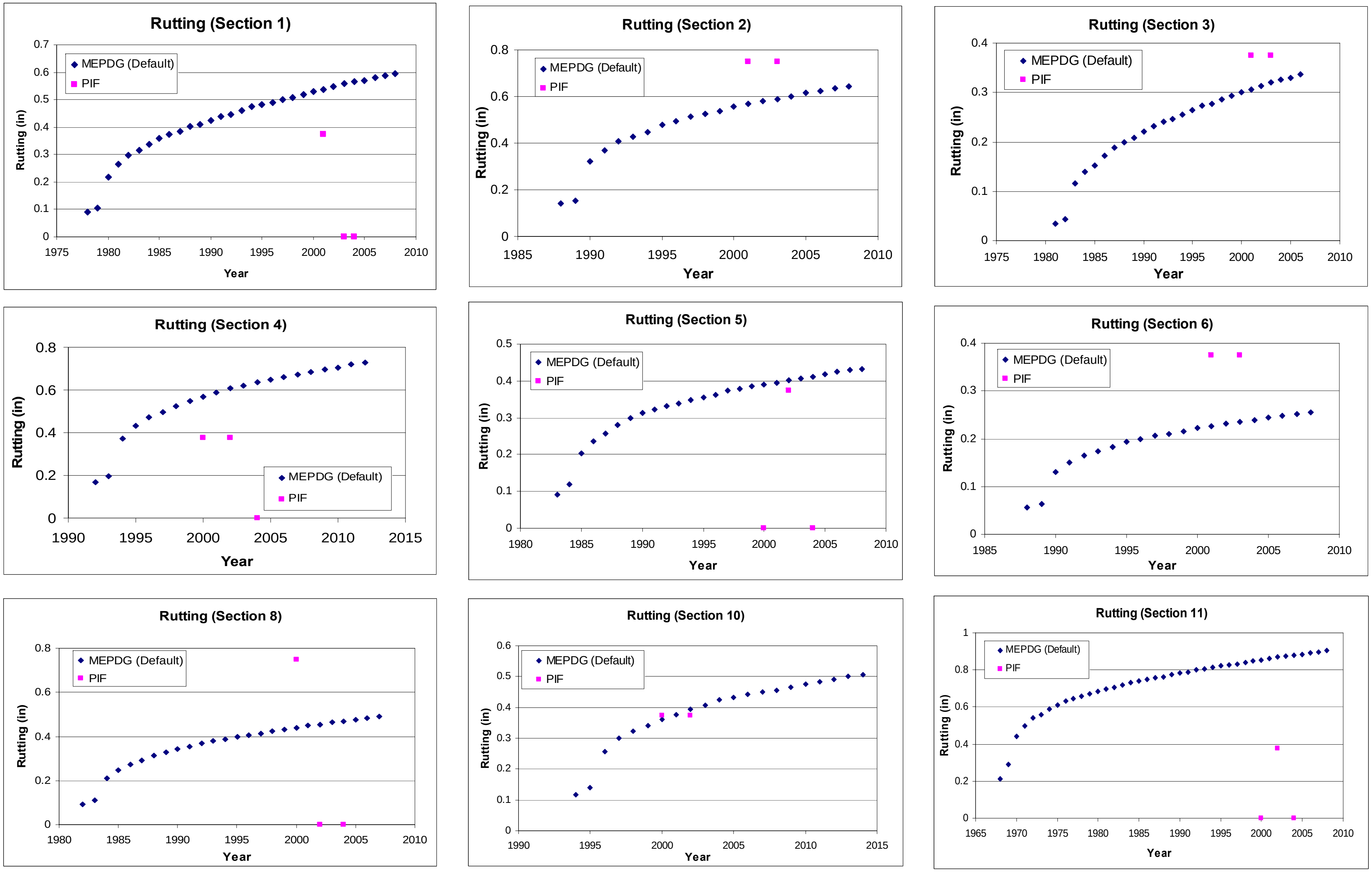


Figure A.4 Rutting Comparisons (Flexible Pavement in Wisconsin)

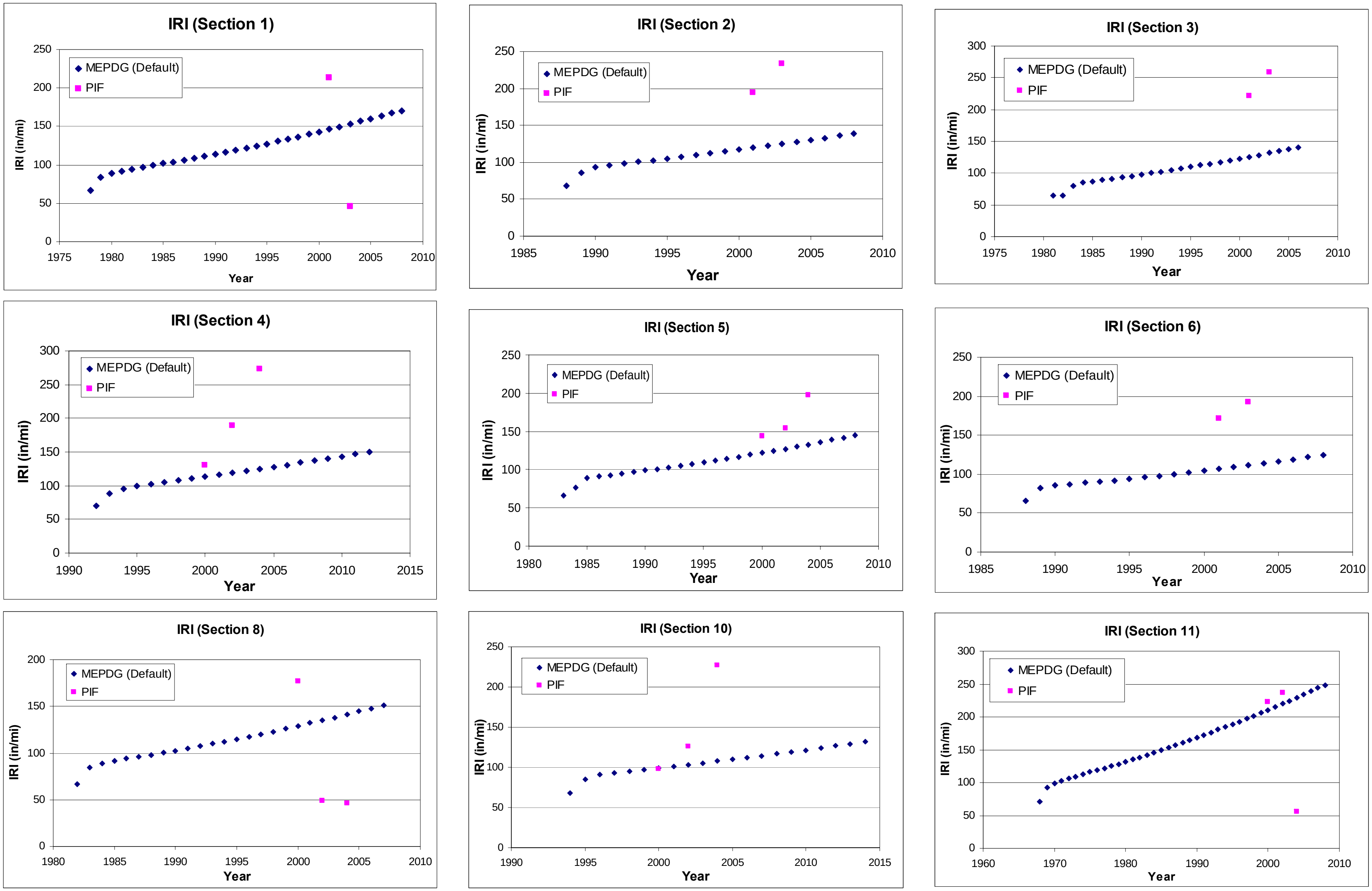


Figure A.5 IRI Comparisons (Flexible Pavement in Wisconsin)

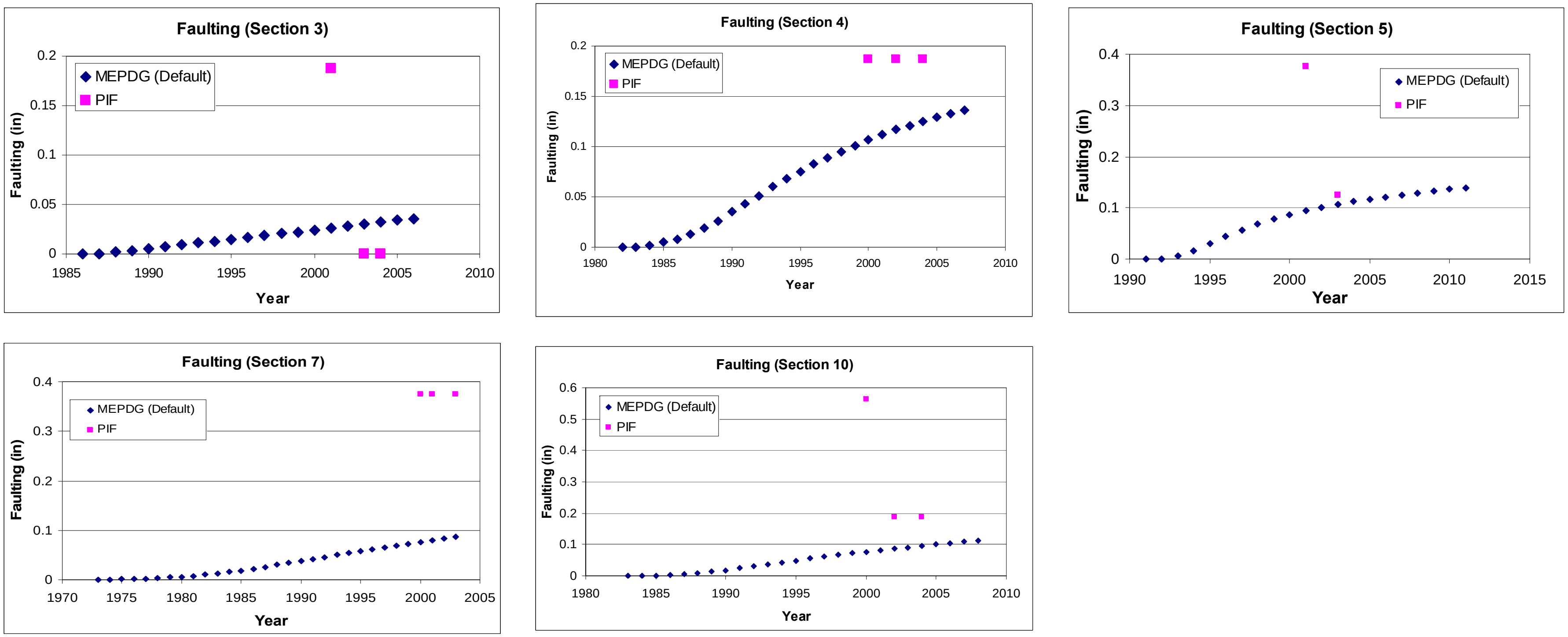


Figure A.6 Faulting Comparisons (Rigid Pavement in Wisconsin)

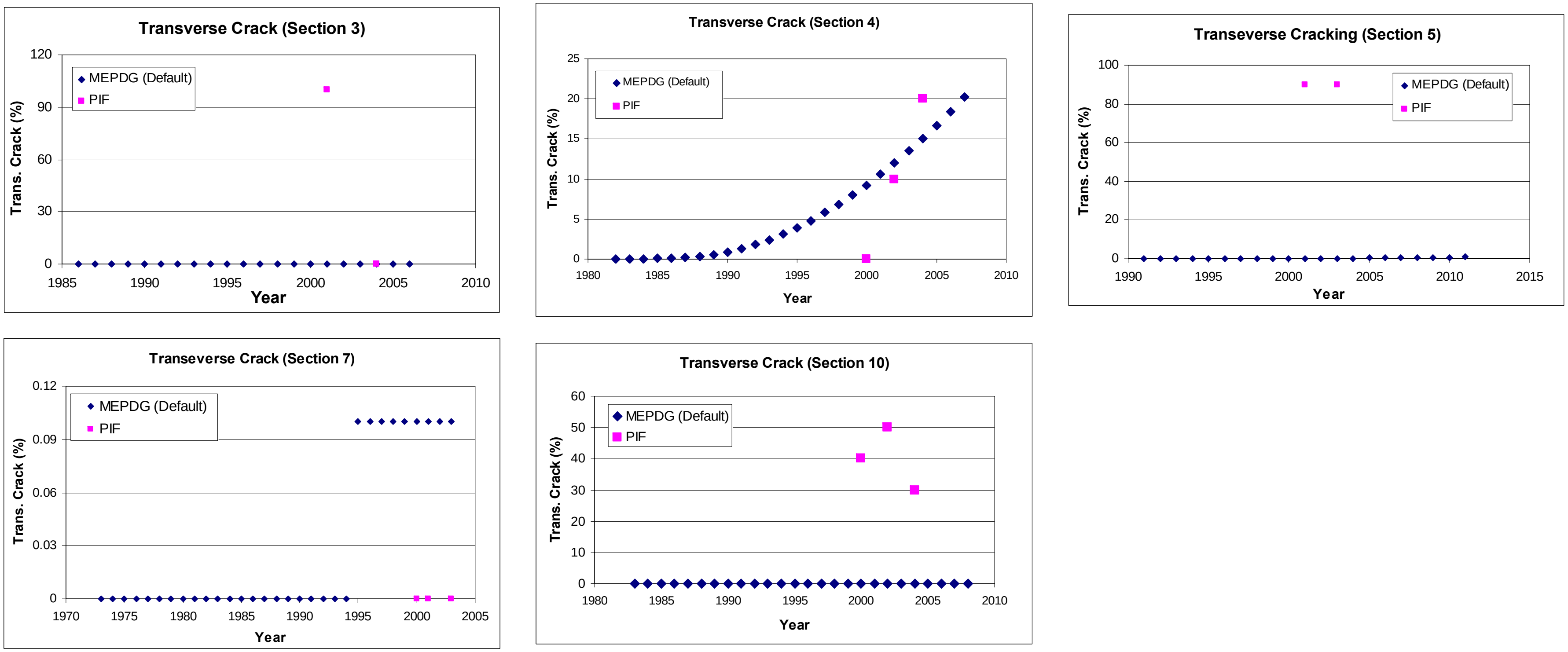


Figure A.7 Transverse Crack Comparisons (Rigid Pavement in Wisconsin)

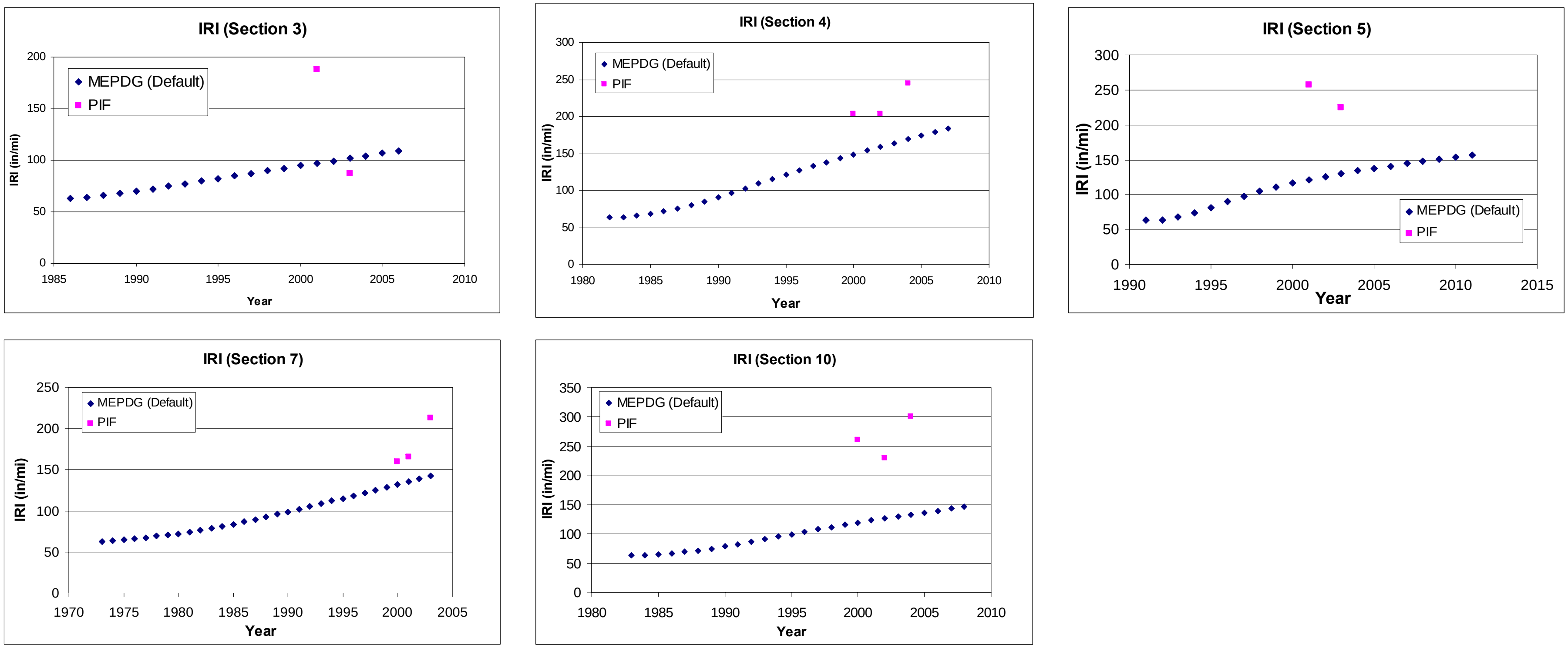


Figure A.8 IRI Comparisons (Rigid Pavement in Wisconsin)

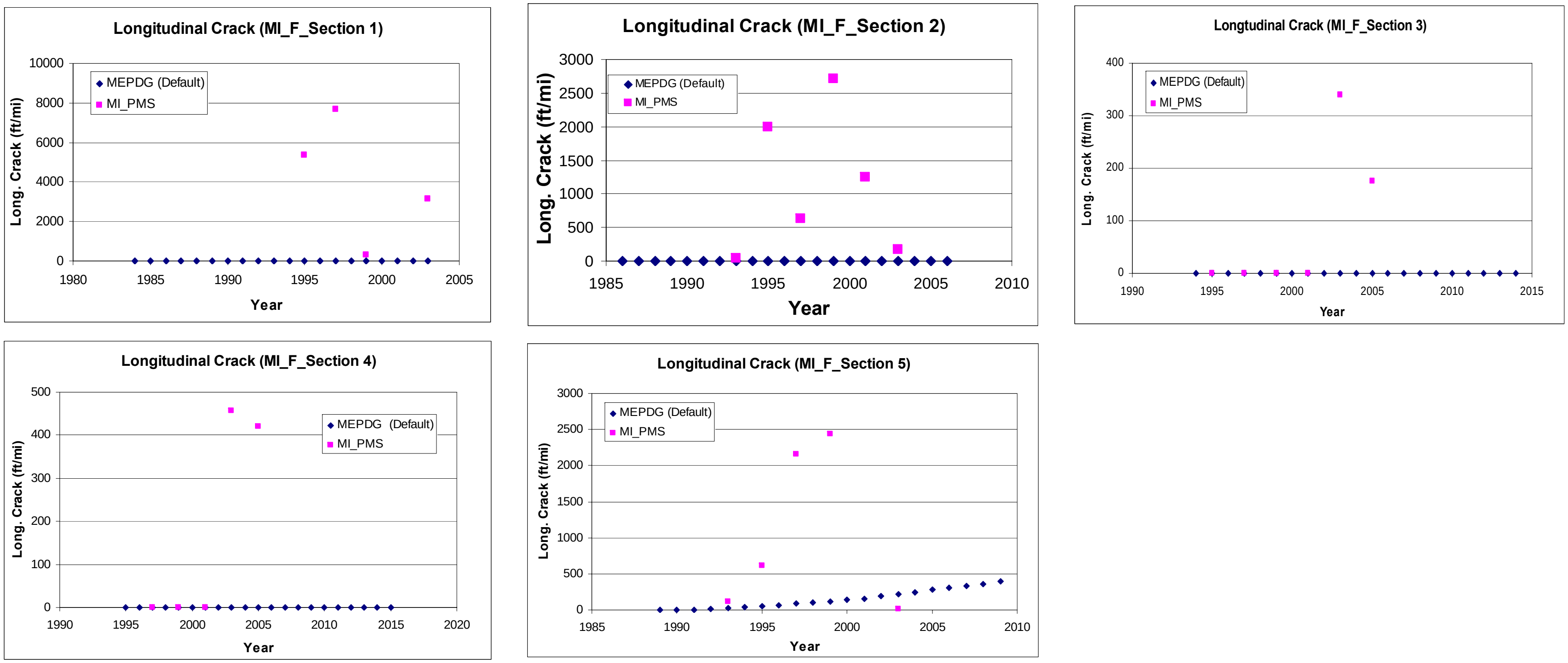


Figure A.9 Longitudinal Crack Comparisons (Flexible Pavement in Michigan)

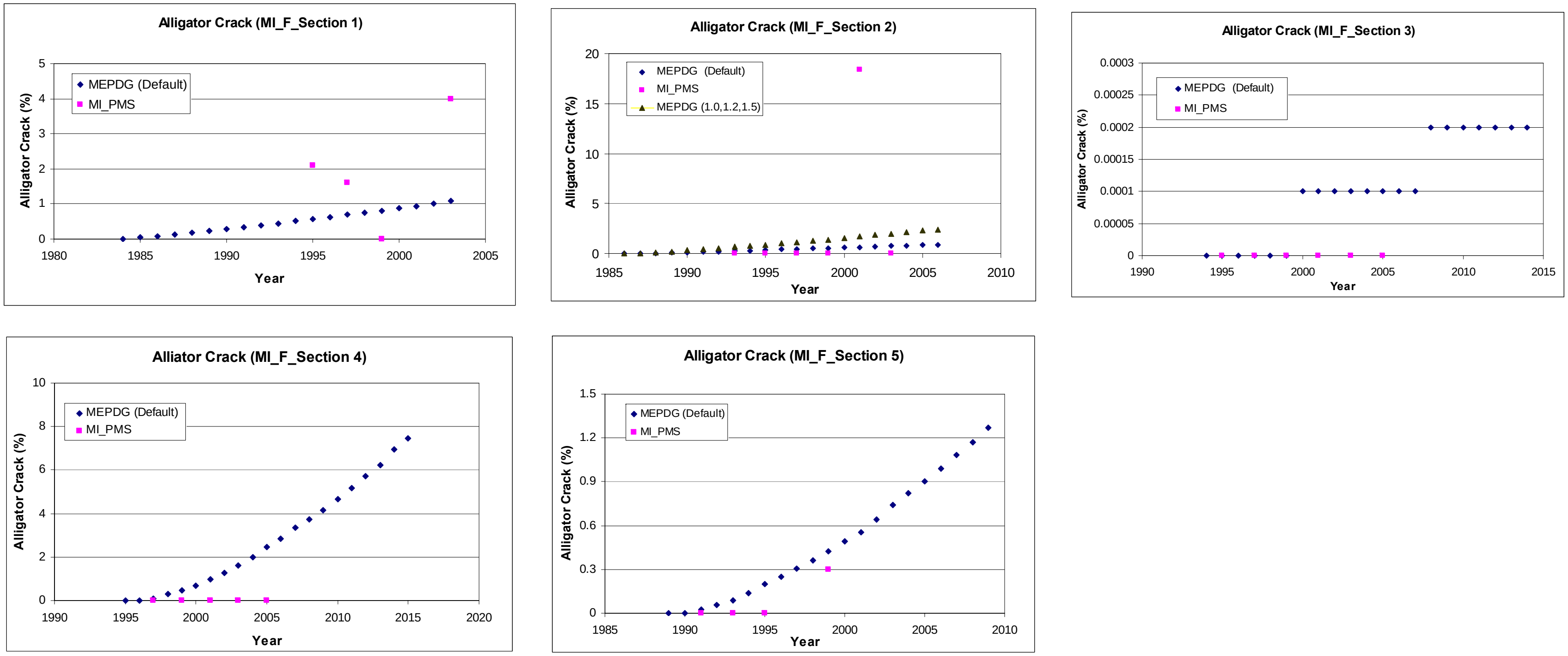


Figure A.10 Alligator Crack Comparisons (Flexible Pavement in Michigan)

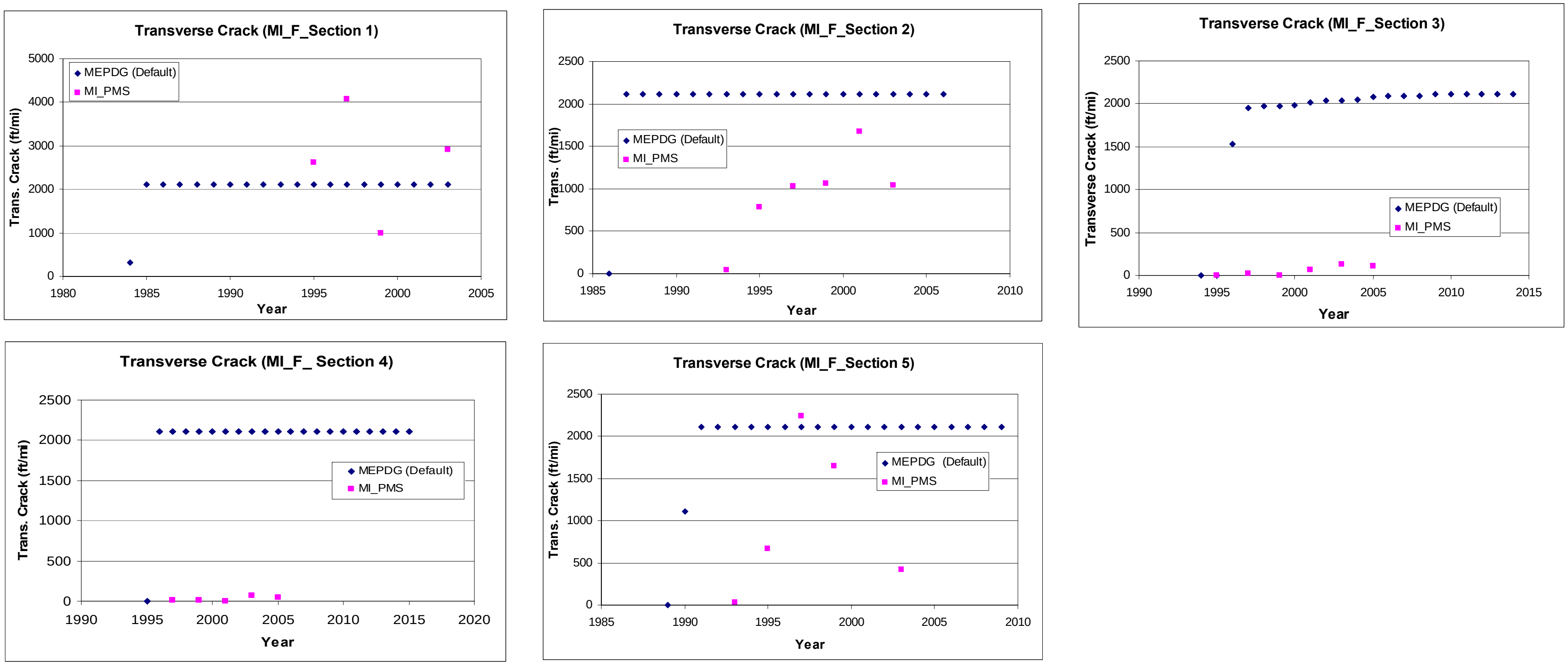


Figure A.11 Transverse Crack Comparisons (Flexible Pavement in Michigan)

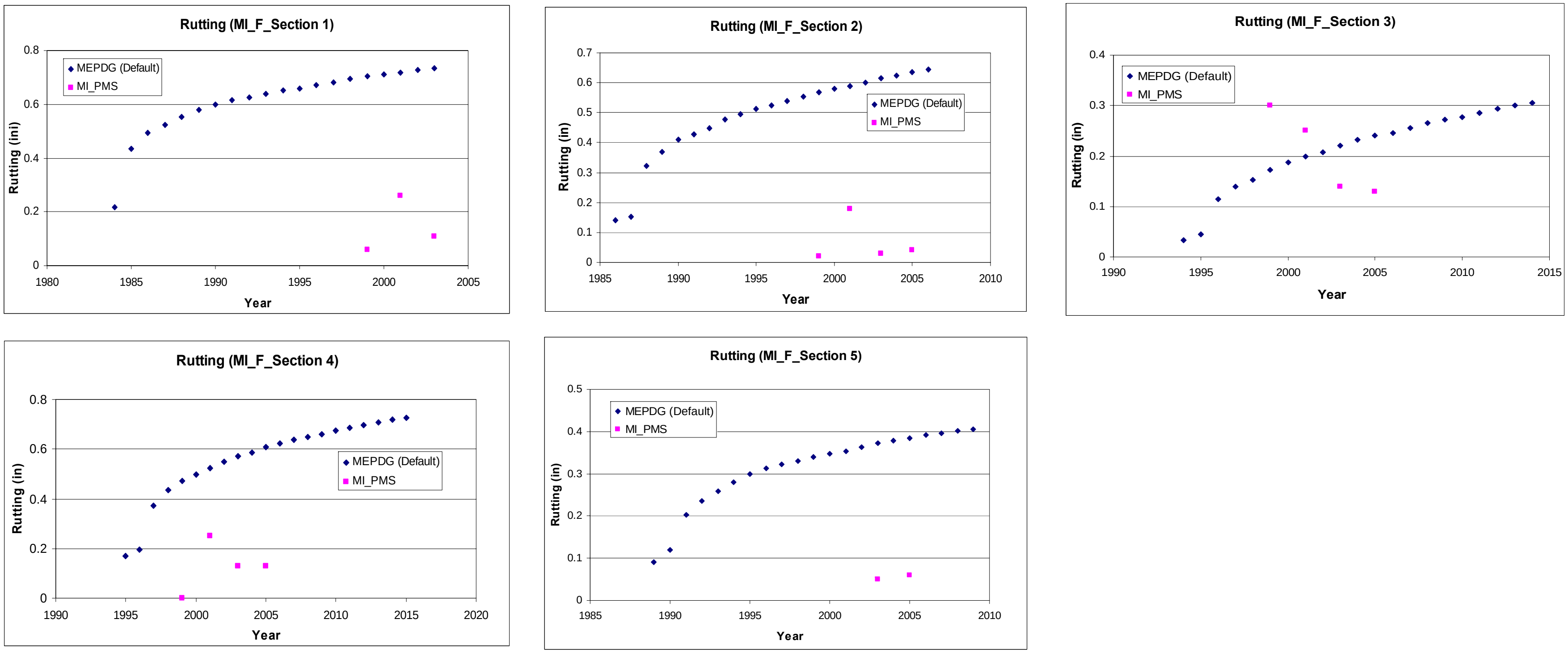


Figure A.12 Rutting Comparisons (Flexible Pavement in Michigan)

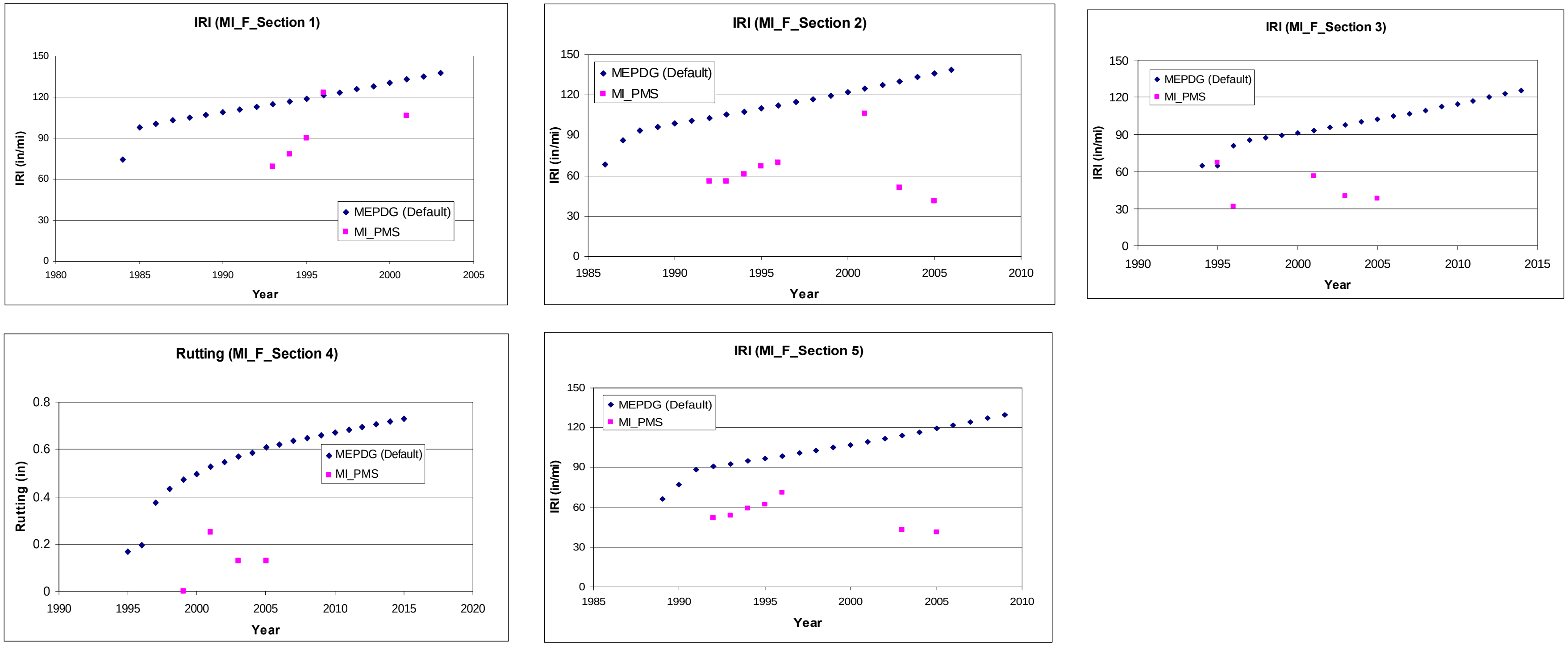


Figure A.13 IRI Comparaisons (Flexible Pavement in Michigan)

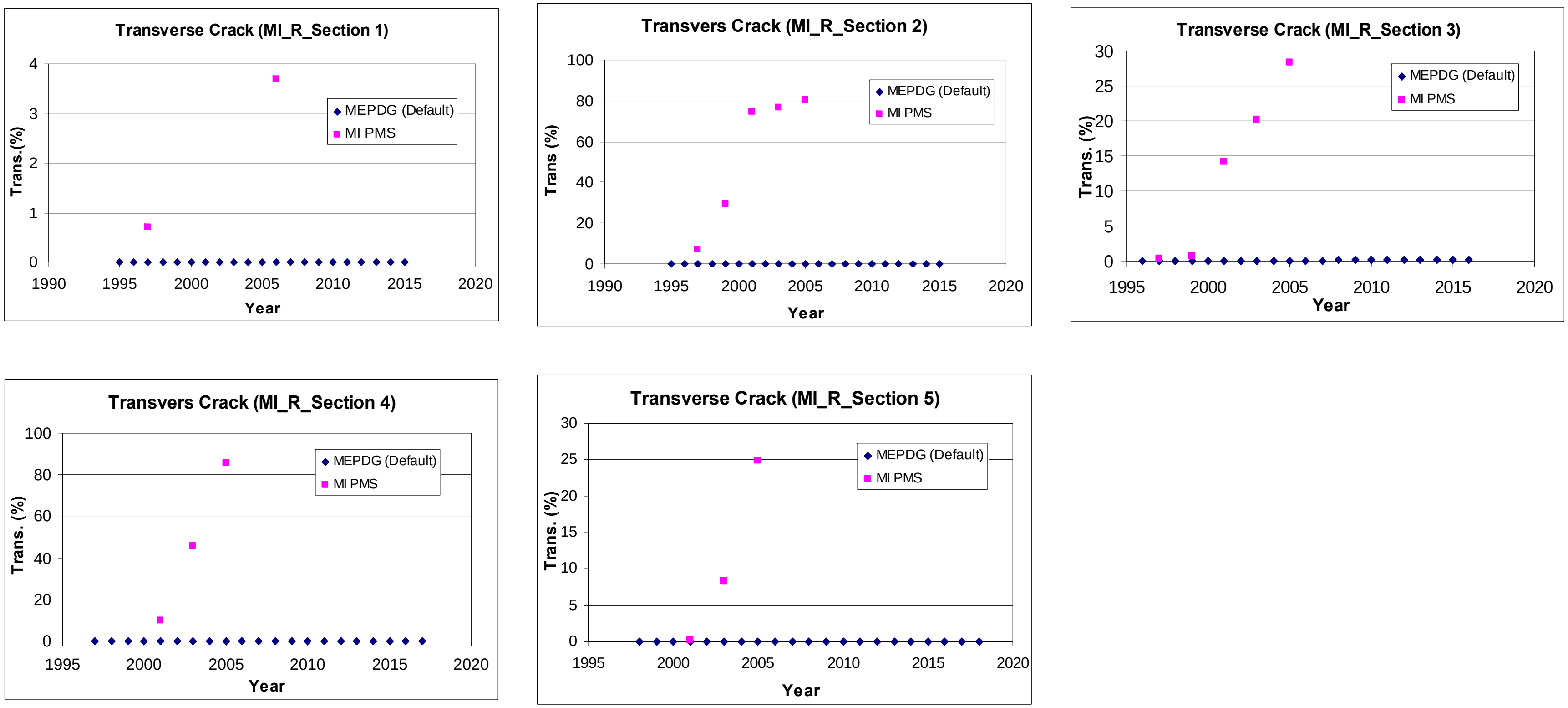


Figure A.14 Transverse Crack Comparisons (Rigid Pavement from Michigan)

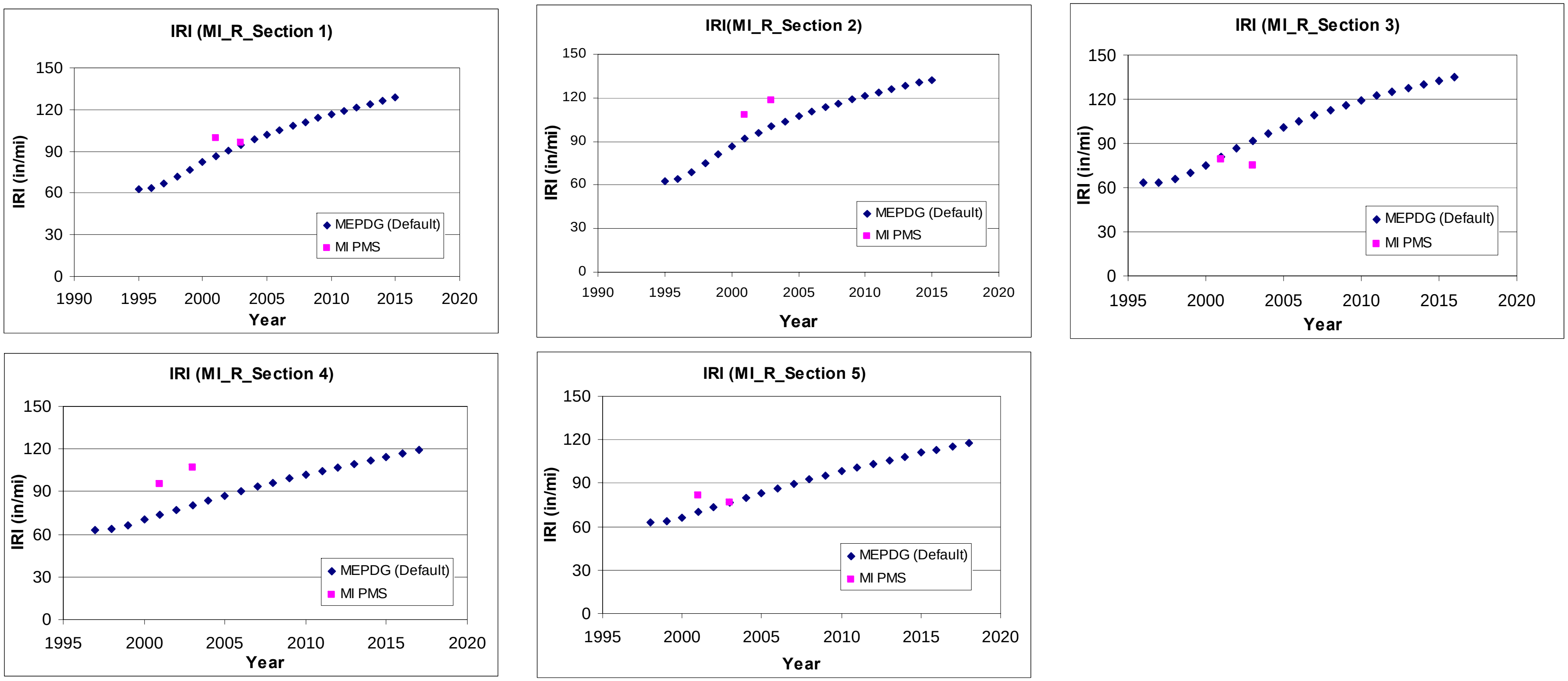


Figure A.15 IRI Comparisons (Rigid Pavement in Michigan)

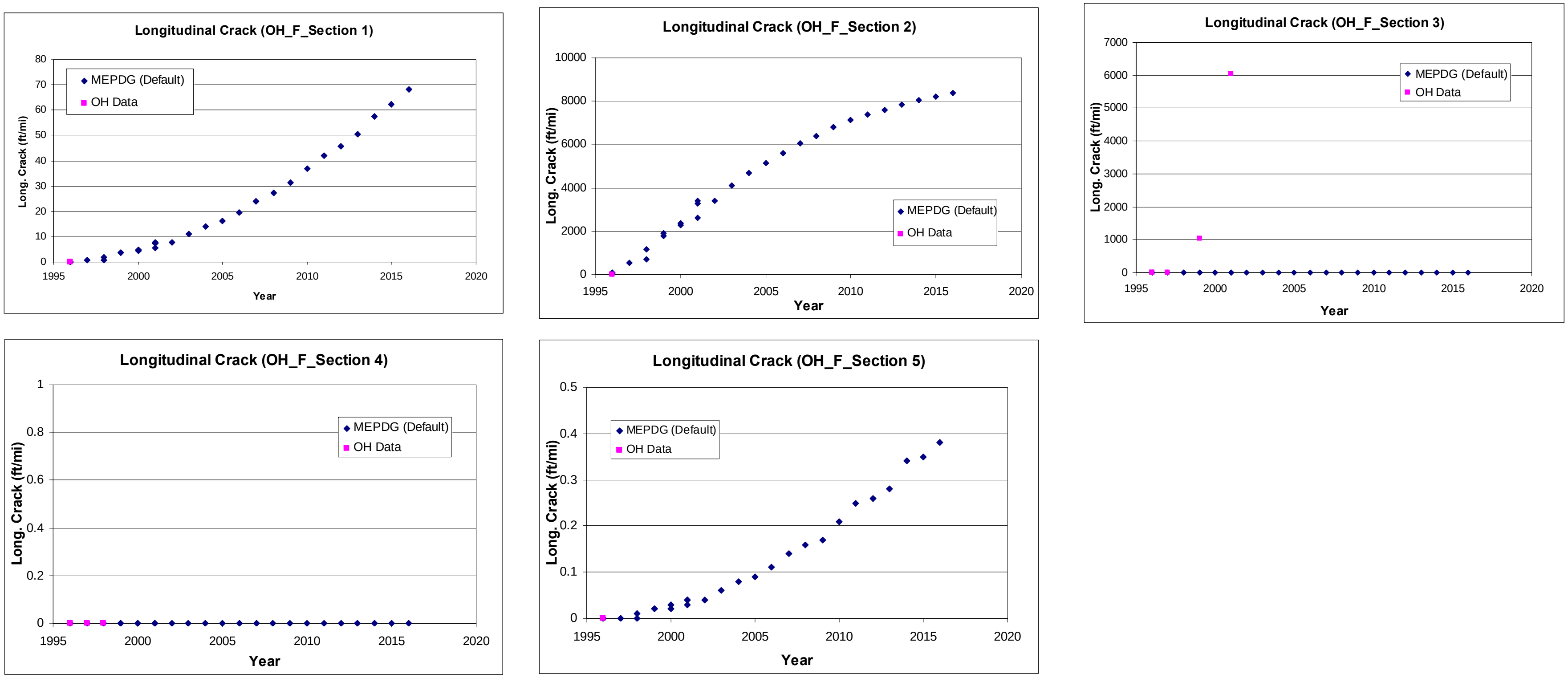


Figure A.16 Longitudinal Crack Comparisons (Flexible Pavement in Ohio)

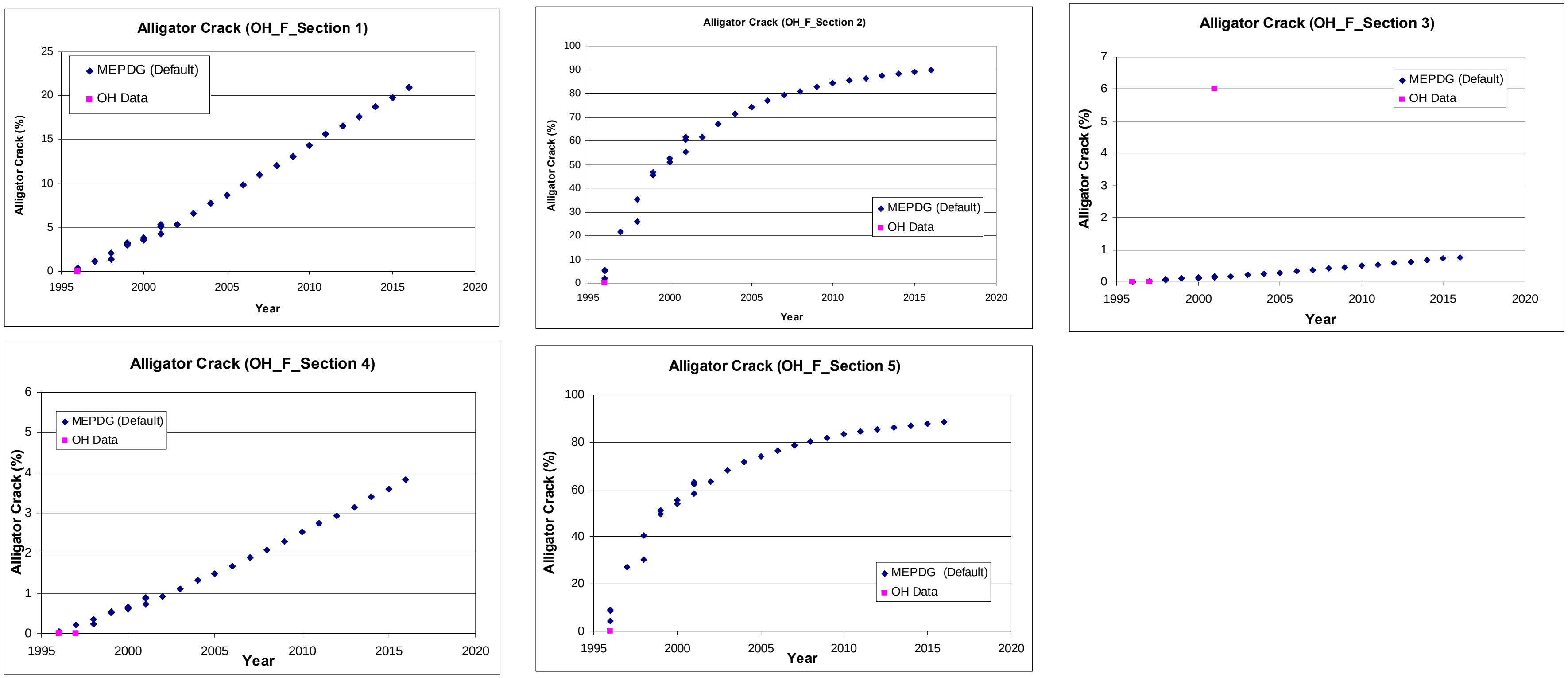


Figure A.17 Alligator Crack Comparisons (Flexible Pavement in Ohio)

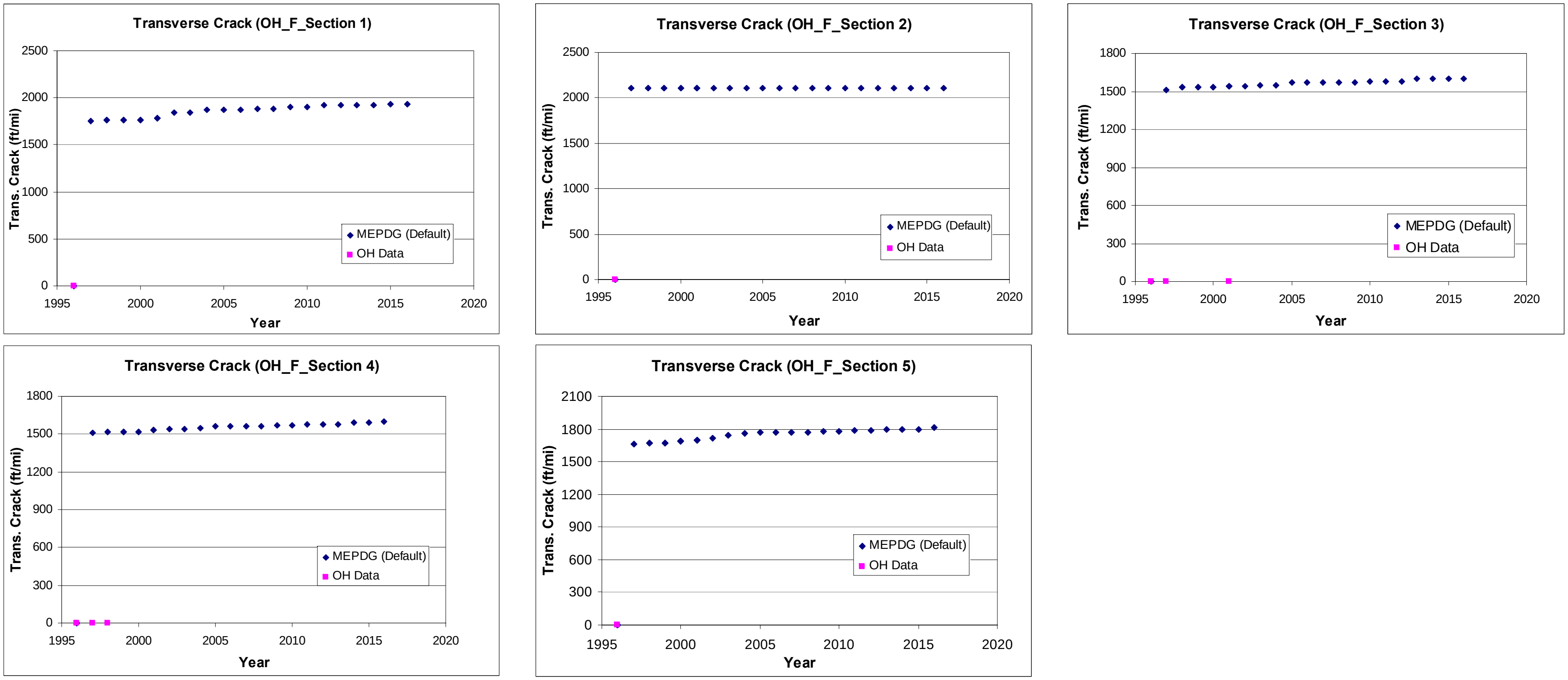


Figure A.18 Transverse Crack Comparisons (Flexible Pavement in Ohio)

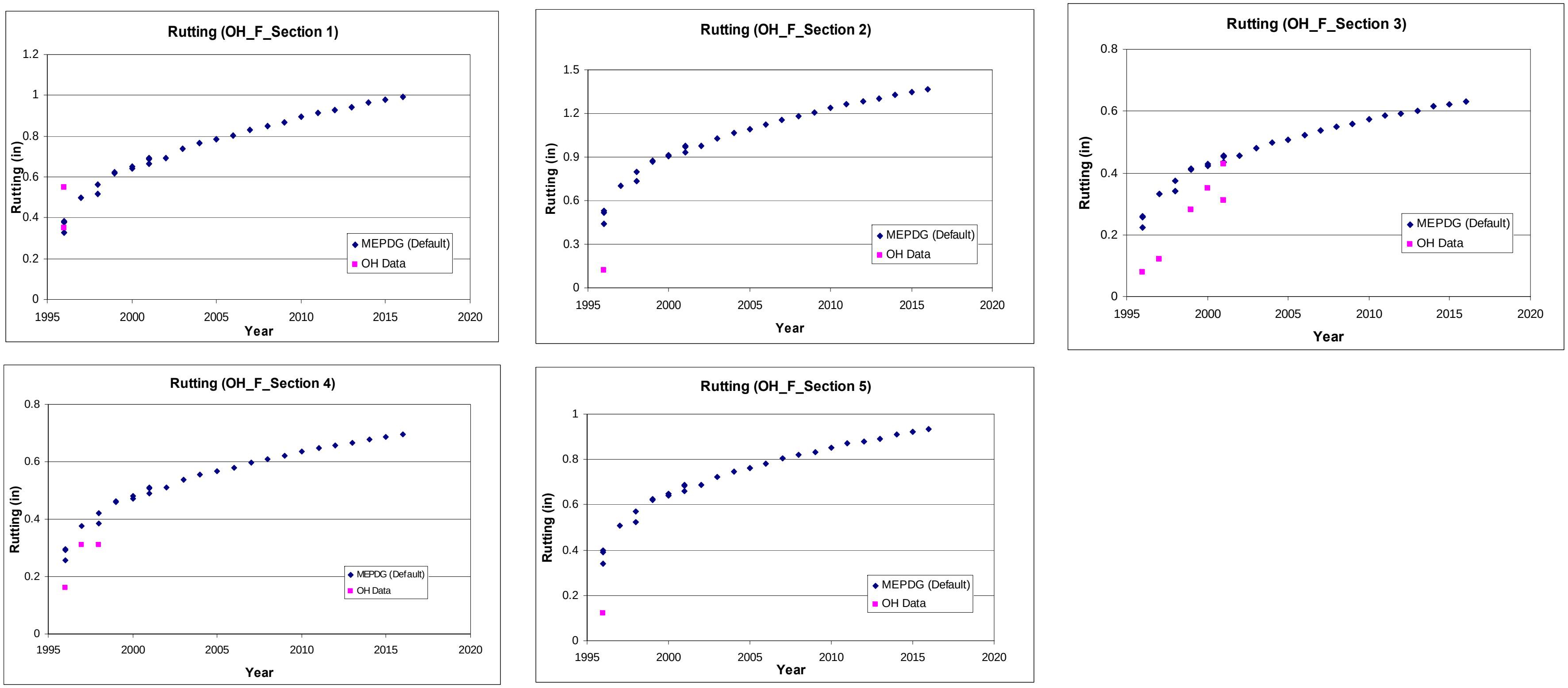


Figure A.19 Rutting Comparisons (Flexible Pavement in Ohio)

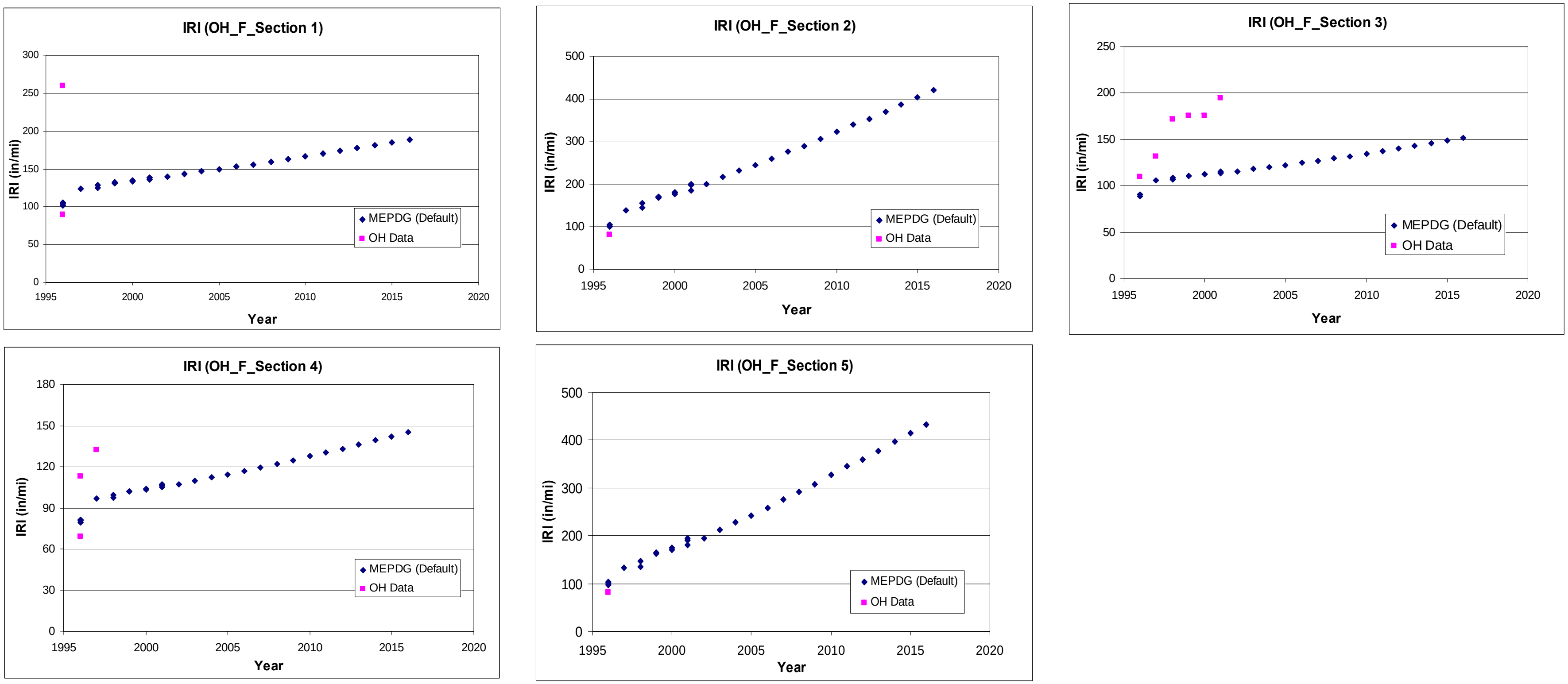


Figure A.20 IRI Comparisons (Flexible Pavement in Ohio)

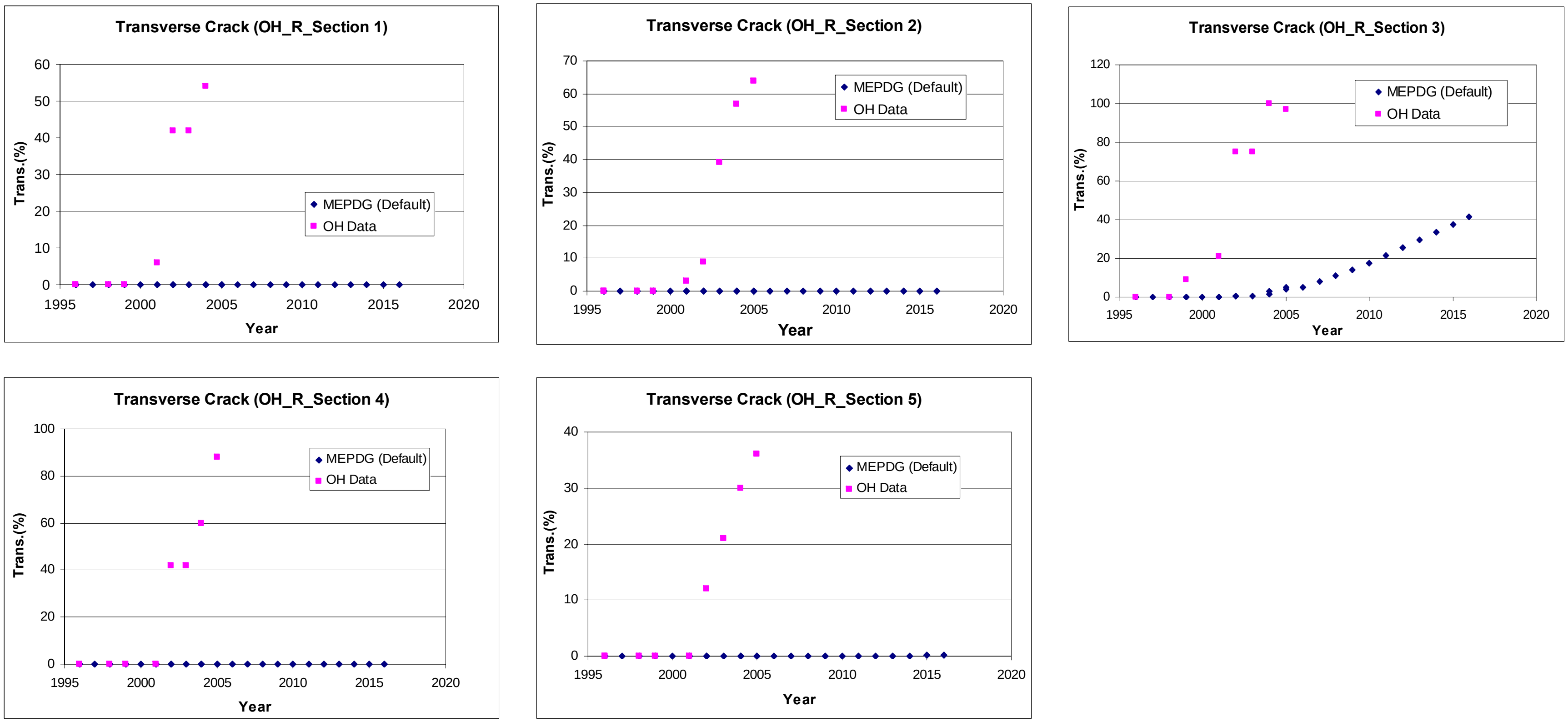


Figure A.21 Transverse Crack Comparisons (Rigid Pavement from Ohio)

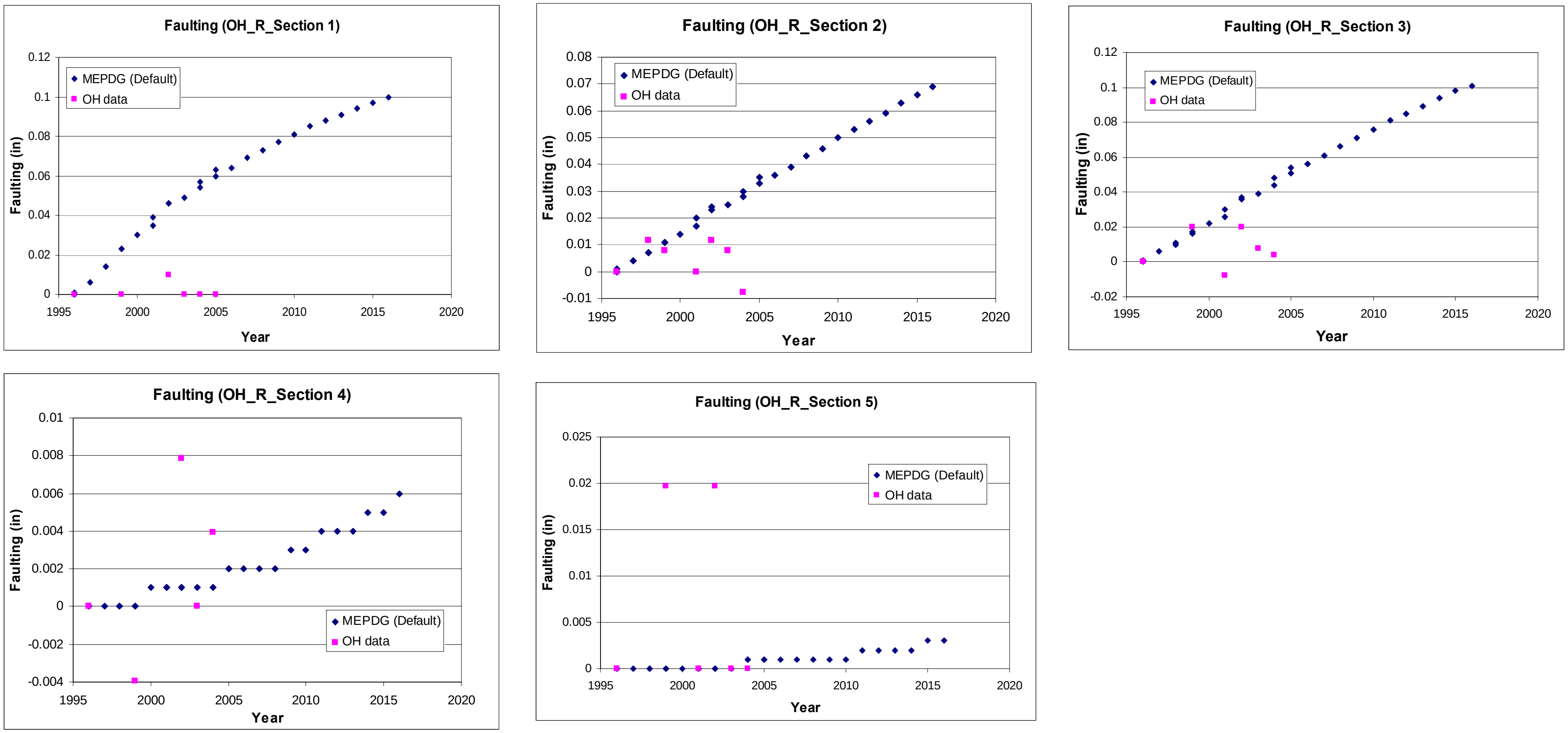


Figure A.22 Faulting Comparisons (Rigid Pavement from Ohio)

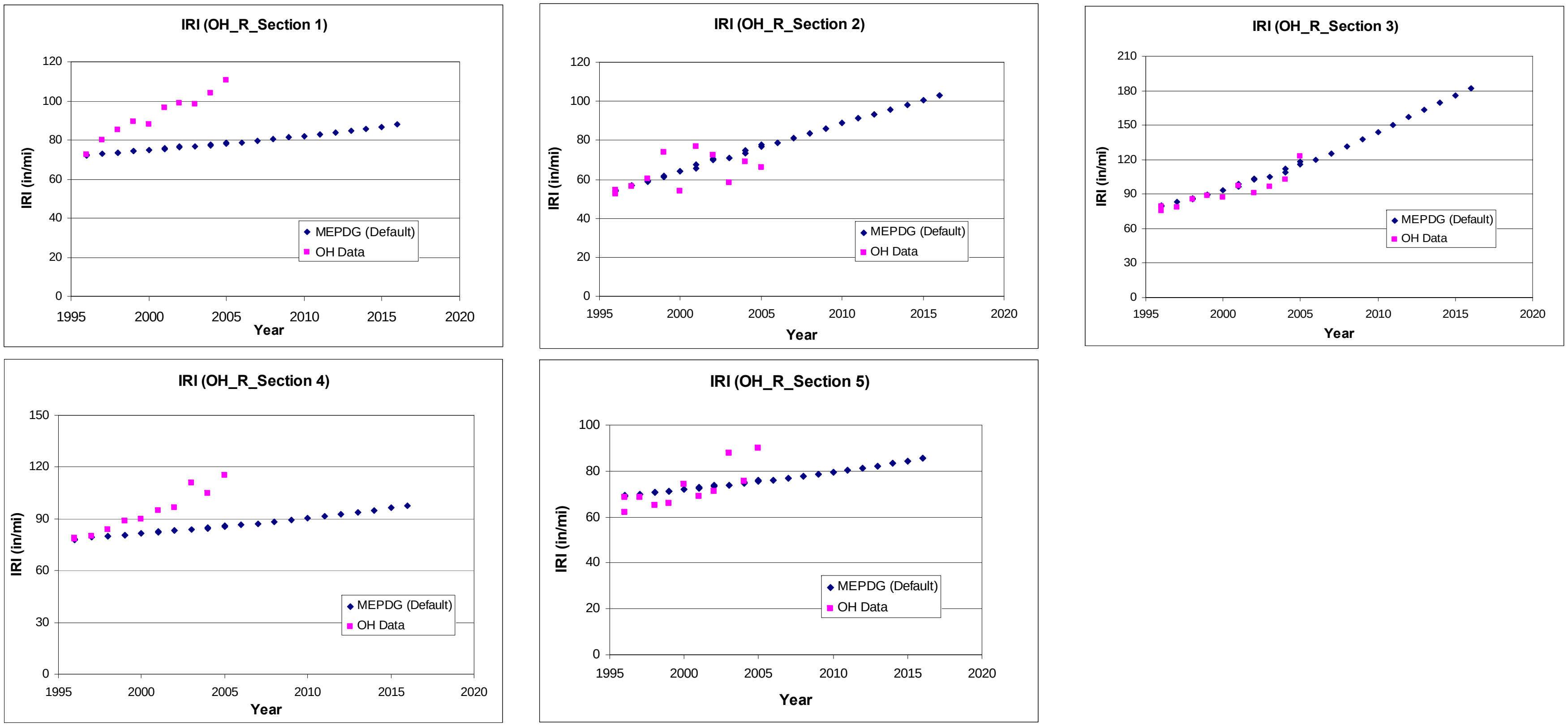


Figure A.23 IRI Comparisons (Rigid Pavement in Ohio)

APPENDIX B. Comparisons of Prediction Models by M-E PDG Default Values, Prediction Models by M-E DPG Calibrated Values and Field Pavement Performance Data

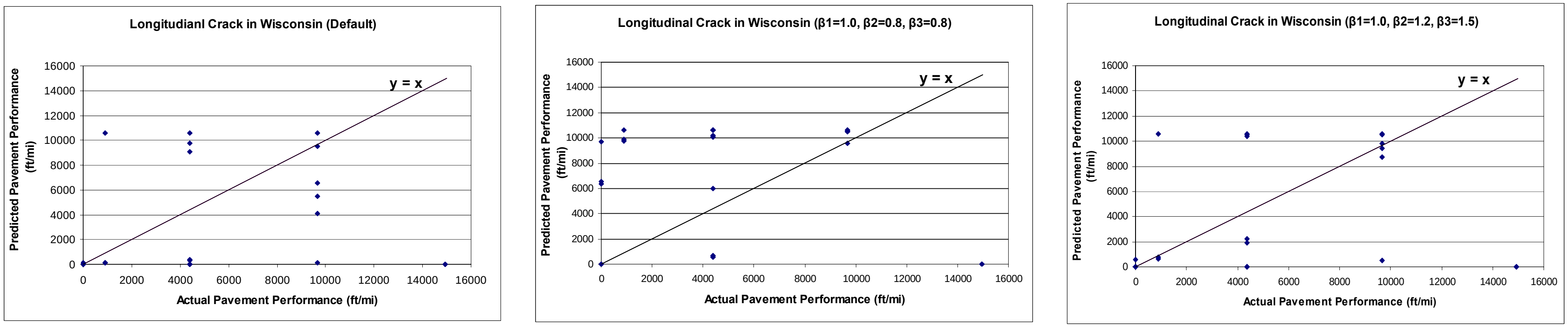


Figure B.1 Longitudinal Crack Comparisons with Various Calibration Factors, Predicted vs. Actual Cracks (Flexible Pavement in Wisconsin)

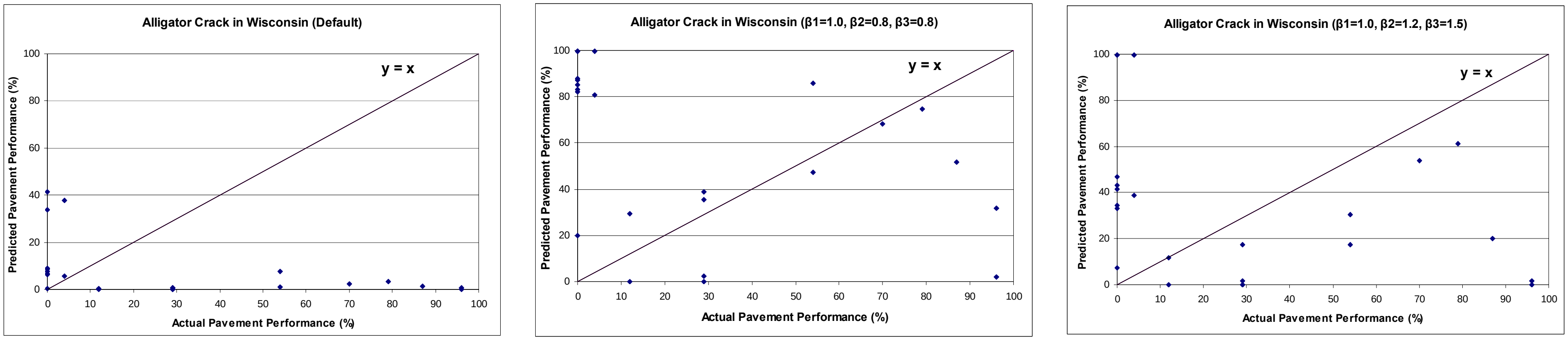


Figure B.2 Alligator Crack Comparisons with Various Calibration Factors, Predicted vs. Actual Cracks (Flexible Pavement in Wisconsin)

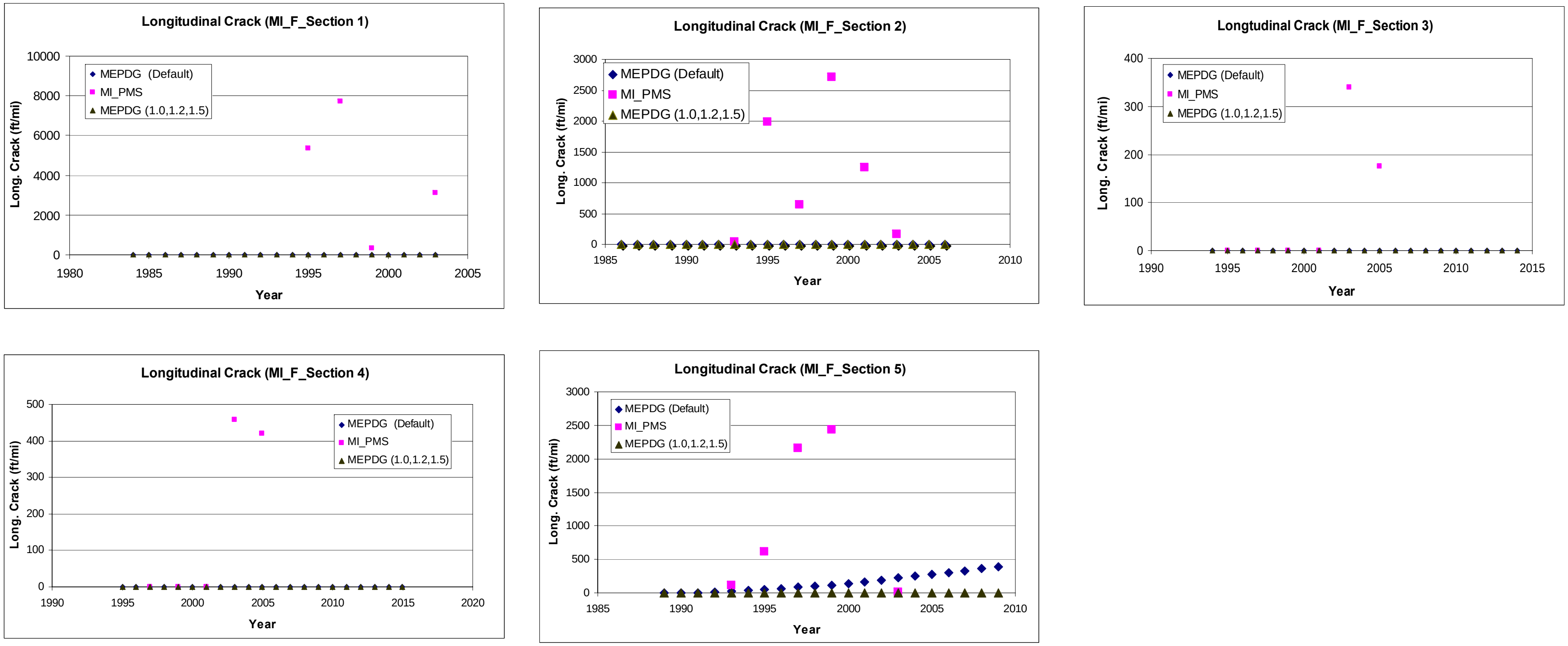


Figure B.3 Longitudinal Crack Comparisons with Calibrated Prediction (Flexible Pavement in Michigan)

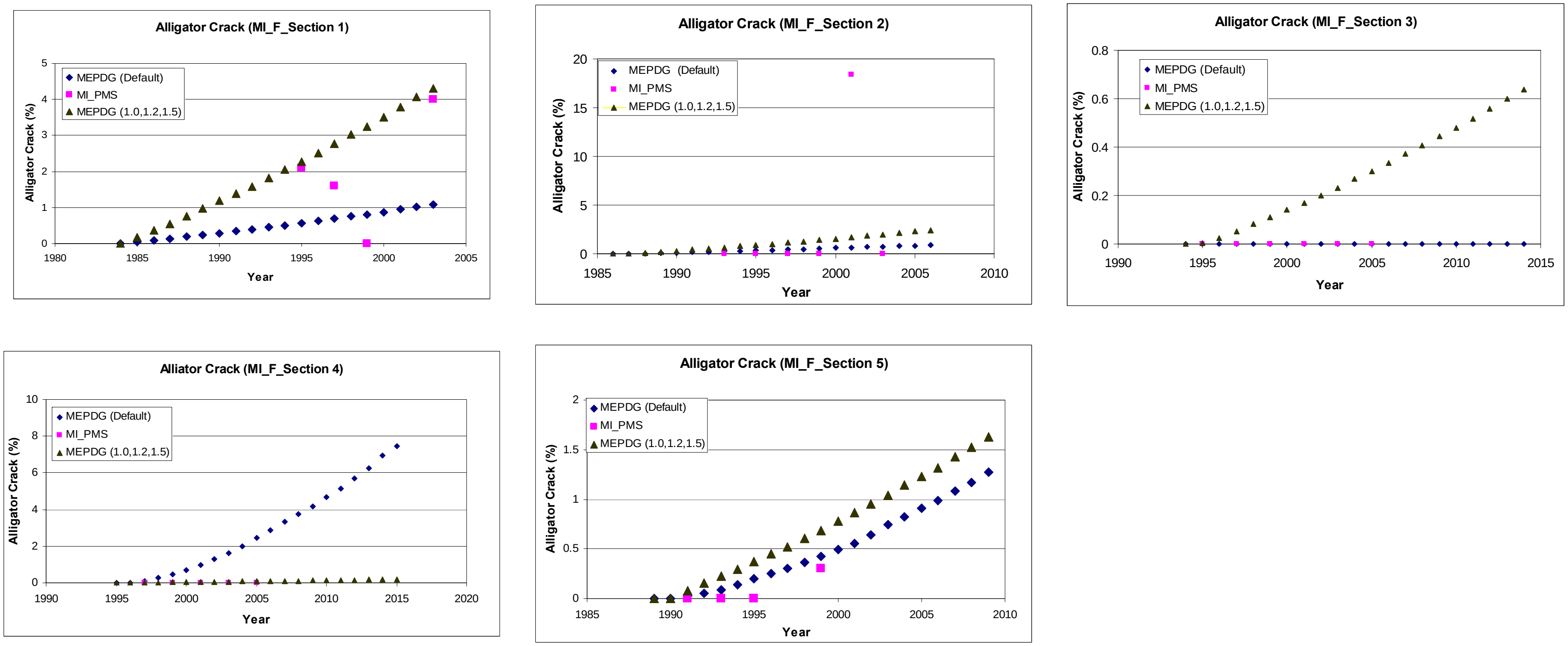


Figure B.4 Alligator Crack Comparisons with Calibrated Prediction (Flexible Pavement in Michigan)

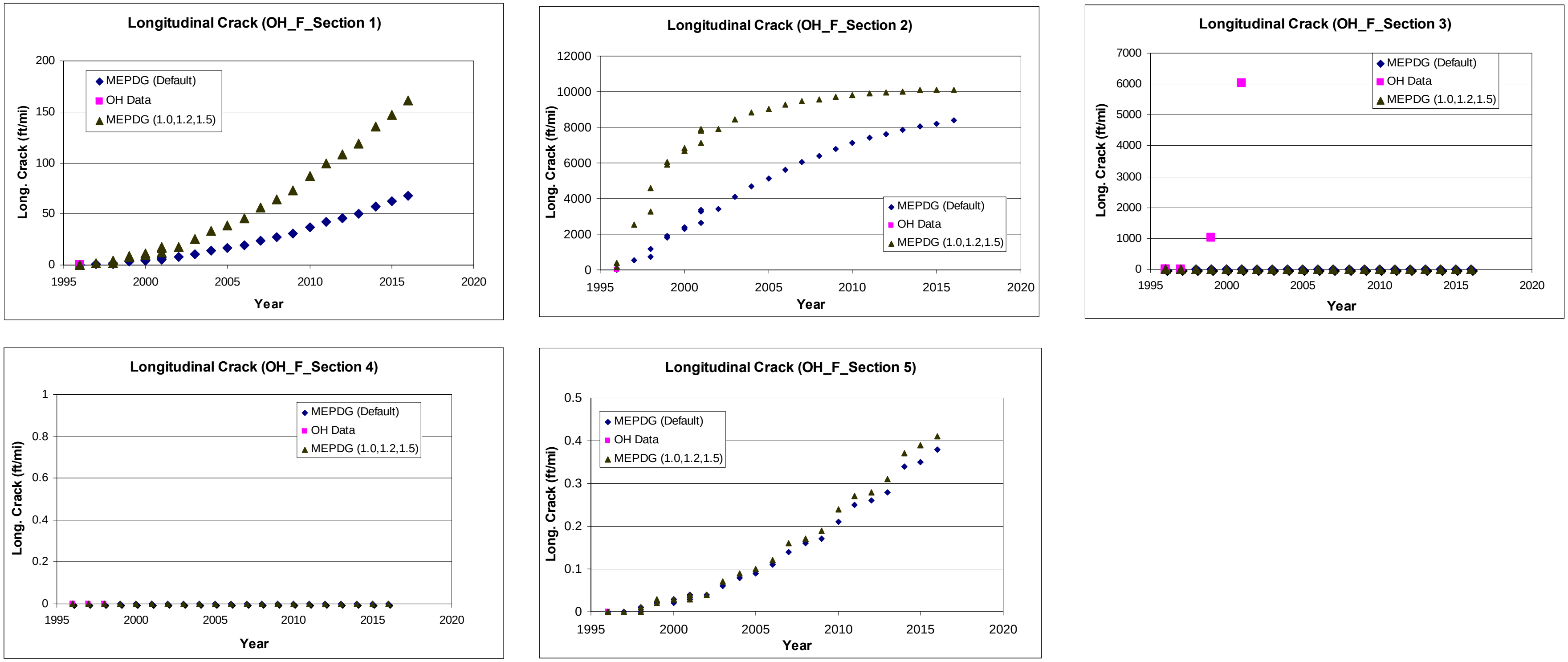


Figure B.5 Longitudinal Crack Comparisons with Calibrated Prediction (Flexible Pavement in Ohio)

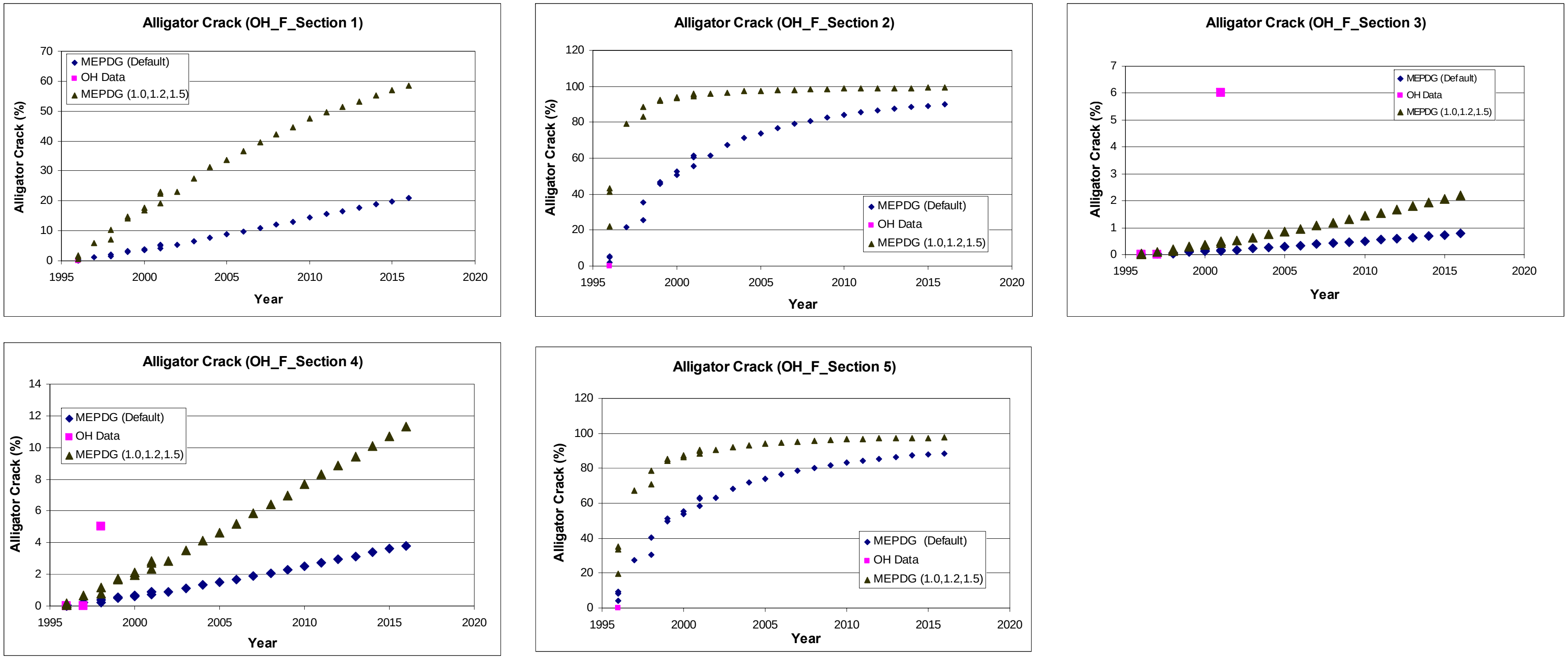


Figure B.6 Alligator Crack Comparisons with Calibrated Prediction (Flexible Pavement in Ohio)