Final Report

Guidelines for Implementing NCHRP 1-37A M-E Design Procedures in Ohio: Volume 1— Summary of Findings, Implementation Plan, and Next Steps

Jagannath Mallela, Leslie Titus Glover, Michael I. Darter, Harold Von Quintus, Alex Gotlif, Mark Stanley, Suri Sadasivam

Applied Research Associates, Inc.
100 Trade Centre Drive, Suite 200
Champaign, IL 61820

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16. Abstract

Highway agencies across the nation are moving towards implementation of the new AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG) for pavement design. The benefits of implementing the MEPDG for routine use in Ohio includes (1) achieving more cost effective and reliable pavement designs, (2) lower initial and life cycle costs to the agency, and (3) reduced highway user impact due to lane closures for maintenance and rehabilitation of pavements. Implementation of the MEPDG is a process that requires time and agency resources (staffing, training, testing facilities including equipment, and so on). A key requirement is validating the MEPDG's nationally calibrated pavement distress and smoothness prediction models when applied under Ohio conditions and performing local calibration if needed. Feasibility of using the MEPDG's national models in Ohio was investigated under this study using data from a limited number of LTPP projects located in Ohio. Results based on limited data showed inadequate goodness of fit and significant bias in a number of the MEPDG new HMA pavement and JPCP performance prediction models. Limited recalibration of these models showed promising results indicating that a full-scale recalibration effort using a more extensive database assembled from projects located throughout the state is feasible. This report, which is Volumes 1 of 4, summarizes the findings of the entire Ohio MEPDG implementation effort (literature review, sensitivity analysis, and local validation and calibration of MEPDG models) conducted as part of this study. In addition, this volume presents future steps ODOT needs to consider to fully implement the MEPDG in Ohio.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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CHAPTER 1. INTRODUCTION

BACKGROUND

The *American Association of State Highway Transportation Officials (AASHTO) Guide for Design of Pavement Structures* is the primary document used by state highway agencies to design new and rehabilitated highway pavements. The FHWA's 1995-1997 National Pavement Design Review found that some 80 percent of the States make use of either the 1972, 1986, or 1993 versions of the AASHTO Pavement Design Guide. While previous versions of the AASHTO Guide have served well for several decades, many serious limitations exist for their continued use as the nation's primary pavement design procedures. In recognition of the limitations of earlier Guides, AASHTO initiated an effort to develop an improved Guide. This work was completed over the past decade (beginning in 1997) under two major research projects—National Cooperative Highway Research Program (NCHRP) Projects 1-37A and 1-40 and easily qualifies as the largest single research effort of the NCHRP. The end products of these research efforts are the development of a mechanistic-empirical pavement design guide (MEPDG) and the accompanying software (ARA 2004, Darter et al., 2006). In late 2007, the MEPDG was successfully approved as an Interim AASHTO pavement design standard (Von Quintus et al., 2007).

The change from an empirical basis to a more mechanistic-empirical (M-E) basis constitutes a major paradigm shift in pavement design. The M-E approach, with its ability to directly predict critical pavement performance indicators that affect user comfort and ride quality, while explaining the scientific basis for pavement deterioration, is indeed a powerful tool that can provide for strong, durable, reliable, safe, and comfortable pavements.

The M-E procedure has adequate flexibility built into it to enable agencies to adopt it in a manner that is commensurate with the resources available to them at any given time. This flexibility is afforded by (1) the three hierarchical levels at which a majority of the design inputs can be configured, (2) "nationally calibrated" performance models, and (3) "nationally established" default input values for several parameters. However, before successfully adopting this procedure, several implementation issues will likely need to be addressed by state highway agencies (SHAs). Two of the more important implementation issues are (1) verification of the reasonableness of national defaults for program inputs using locally generated/used site and design information and establishment of local defaults and (2) validating and, if necessary and feasible, calibrating the nationally calibrated prediction models using agency-specific data. In this report, the terms validation and calibration are defined as follows:

- *Validation* refers to a systematic process that examines a model to determine if the desired accuracy expressed in terms of bias and error exists between its predictions and an independent set of observed data.
- *Calibration* refers to a systematic process that employs statistical methods to (1) eliminate any bias between observed or measured results (e.g., the measured mean rut depth in a pavement section) and predicted results from the model (e.g., predicted mean rut depth from a permanent deformation model) and (2) minimize residual errors between observed and measured data. This is accomplished by modifying empirical calibration parameters associated with the prediction models in a systematic manner to achieve the design objectives.

Despite the large dataset used in calibrating and developing the national MEPDG models, it is possible that certain local issues may not have been well represented due to data or modeling limitations. For this reason alone, it may be necessary to *validate* the nationally calibrated performance models using data more representative of local conditions. However, it is important to note that, unlike the AASHTO design equation developed at the AASHO Road Test, the MEPDG performance models do not necessarily have to be *calibrated* before they can be used. This is because they are based on engineering mechanics and on data drawn from hundreds of pavement sections representing a wide range of site and design conditions. In this sense, calibration needs to be performed only if found necessary through validation studies in order to address any identified model limitations (e.g., data deficiencies, bias in distress estimations). By contrast, validation is deemed a necessary step in the implementation process along with, input confirmation and input library creation, and examination of model sensitivity to locally developed inputs.

STUDY OBJECTIVES AND SCOPE OF WORK

The primary objective of this study is to develop guidelines for the implementing MEPDG procedure by the Ohio Department of Transportation (ODOT). The major items of interest include the following:

- An assessment of ODOT's needs in terms of new and rehabilitation designs, laboratory and field testing equipment, and traffic data collection and processing to implement the MEPDG procedure.
- Default values (means and ranges) for those inputs that have adequate data from previous research applicable to Ohio conditions.
- Results of validation efforts for each distress and smoothness model in the MEPDG procedure of interest to ODOT. This includes comparison of predicted with measured distresses for a variety of Ohio pavement sections (specifically the Ohio Strategic Highway Research Program [SHRP] Test Road sections) and further analyses which will (1) either confirm or reject the national calibration factors and (2) provide practical results from a sensitivity analysis to demonstrate the relationships of outputs (distress, smoothness) to design inputs.

  ***<u>Note</u>**: Based on discussions with ODOT at the project startup meeting, the validation efforts were expanded to cover pavements beyond the SHRP Test Road to include all Long Term Pavement Performance (LTPP) sections in Ohio.*

Because, the MEPDG provides several pavement design options, e.g., new versus rehabilitation, concrete versus asphalt, etc., not all of which are of interest to ODOT, the scope of the work is limited to the following pavement types:

- New flexible or hot mix asphalt (HMA) pavements (including conventional, deep strength, and full depth).
- Jointed plain concrete pavements (JPCP).
- HMA overlays of rubblized portland cement concrete (PCC) slabs.
- Unbonded PCC overlays (excluding CRCP).

  ***<u>Note</u>**: Model validation effort was limited to only new or reconstructed HMA pavements and JPCP. HMA overlaid rubblized PCC and unbonded JPCP overlays of existing PCC pavement were not considered in this validation study due to lack of data.*

Furthermore, the pavement distress types of interest for the various pavement types were noted as being the following from the project startup meeting:

- HMA pavements and layers
  - Thermal cracking
  - Load related (fatigue) cracking
  - Terminal IRI value
  - Rut depth in HMA layers

- JPCP
    - Terminal smoothness
    - Transverse cracking
    - Mean joint faulting

Note: *Although longitudinal cracking in HMA pavements and JPCP was identified by ODOT as an important distress, it was not considered in this study since the MEPDG does not currently have reliable models for predicting this distress.*

SIGNIFICANCE OF WORK TO ODOT

Ohio has a very large highway infrastructure. Of the 116,963 miles of public roadways in Ohio, some 22,530 miles fall under the State jurisdiction. There are 4,345 miles on the National Highway System, which includes 1,571 miles on the Interstate highway system. These thousands of miles of roadways have been constructed, rehabilitated, and maintained over almost the entire previous century and represent a huge investment that has provided a safe and comfortable means of transportation for both private and commercial vehicles. This efficient means of transportation has contributed significantly to the economic growth of the State.

These highways carry millions of automobiles, buses, and heavy trucks every day. The extent of heavy truck traffic on Ohio's highways is very high and constantly increasing. Due to the central location of Ohio and its strong industrial and farming base, there are many major national and other truck routes (e.g., I-70, I-80, I-90, I-71, I-75, and I-77). To illustrate these points, the maps in Figure 1 and Figure 2 show the 1998 and 2020 forecast truck volumes. These maps show highway width related to truck volumes. They dramatically illustrate the large number of highways crisscrossing the State of Ohio and the forecasted growth over the next two decades. It appears that many Ohio routes will carry traffic in the 15,000 to 30,000 Average Annual Daily Truck Traffic (AADTT) range in the future. This high level of truck traffic will obviously impact pavement performance and the cost to construct and maintain these pavements. Improved pavement design and rehabilitation procedures are needed to design these pavements and rehabilitations more efficiently and reliably, to meet future demands.

Pavement structures wear down and deteriorate under heavy loadings and exposure to the elements. As the highway system ages, the ODOT and local agencies are committing significant resources toward pavement maintenance and rehabilitation, which is in-step with the overall national trend. The sheer magnitude of annual expenditures on pavements justifies the application of the best available design procedures to optimize the use of highway funds. Any improvements in this area will have significant and sizeable implications in reducing the cost of maintaining these highway pavements.

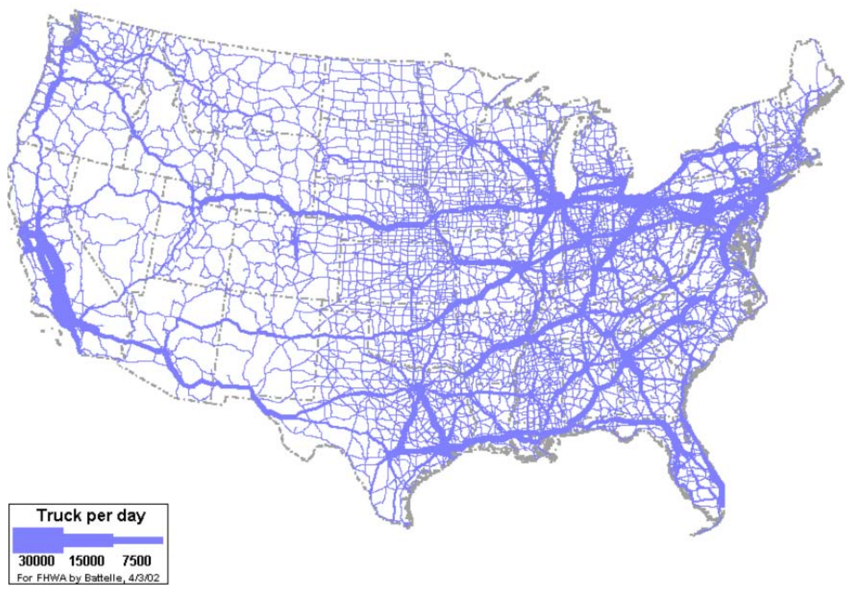

Figure 1. Truck volumes in 1998 (Battelle, 2002).

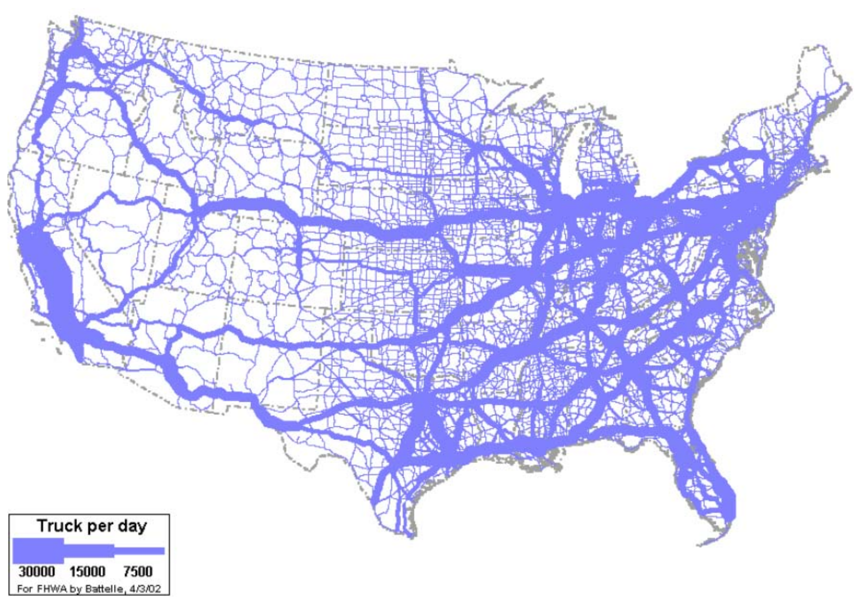

Figure 2. Forecast truck volumes in 2020 (Battelle, 2002).

The 1993 version of AASHTO's *Guide for Design of Pavement Structures*, which is predominantly used by ODOT today, is based on empirical principles and was derived primarily from observations on a pavement experiment conducted in the late 1950s and early 1960s in Ottawa, Illinois. Being an empirical procedure, the design methodology has not been able to adapt to changing and varied conditions. Moreover, there were no experiments conducted on pavement rehabilitation techniques (structural overlays) in the original experiment, which is of foremost concern to the modern highway engineer engaged in managing the aging road networks. However, the unavailability of a more scientific or mechanistic basis for design that can be used by a practicing engineer and the lack of adequate computing power have forced highway agencies to adopt these procedures, extrapolate on them, and adjust them over the past several decades. As a result, there has been a wide range in the observed performance of pavements designed using the AASHTO procedures. The general consensus of the pavement design community is that the AASHTO procedure, which has served us so well to date, needs to be replaced with something better.

It is a widely held notion in the pavement community that the MEPDG, when fully implemented within an agency, will present several benefits over traditional approaches to pavement design. However, since the MEPDG represents a marked departure from the way pavements are currently designed and specified in the ODOT, it is advisable to study its suitability to local conditions and to develop a coordinated and holistic approach that fully engages all the affected stakeholders prior to its adoption and routine use.

To date, the ODOT has sponsored a number of research studies that have a direct bearing on the MEPDG implementation process. For example, the Ohio SHRP Test Road built in 1996 and the WAY30 Experimental Test Road built recently and all the associated field and laboratory studies will facilitate MEPDG implementation activities. Other examples include work performed under the ODOT research program by several researchers including materials characterization studies, pavement performance studies, traffic studies, climatic effects studies, and so on. The data and guidance developed under these projects will no doubt be very useful to ODOT in checking the suitability of the MEPDG for local conditions. This project is another step in the direction of evaluating the suitability of the MEPDG to ODOT. It will (1) provide a preliminary validation of the suitability of the MEPDG models to ODOT conditions, (2) help identify gaps in ODOT's data to populate default libraries and to perform full-scale calibration, and (3) outline the next steps in full-scale calibration should ODOT decide to pursue full implementation of the MEPDG as a design standard.

REPORT ORGANIZATION

The report is organized into the following four volumes which document the findings of the work conducted under the various tasks of this project:

- Volume 1 – Summary of Findings, Implementation Plan, and Next Steps (this volume).
- Volume 2 – Literature Review.
- Volume 3 – Sensitivity analysis.
- Volume 4 – Validation/Calibration Detailed Results.

Volume 1 (this volume) summarizes the entire research effort and presents the major findings related to the literature review, sensitivity analysis, and model validation and calibration tasks. Volume 1 draws from detailed information presented in Volumes 2 through 4. In addition, Volume 1 also discusses the steps ODOT could undertake in the future to fully implement the MEPDG.

Volume 2 presents a detailed overview of the nationwide activities related to the MEPDG and, more importantly, documents MEPDG related work performed to date under ODOT's research program.

Volume 3 presents the details of the sensitivity analysis performed using typical ODOT new and rehabilitation designs and ranges of ODOT specific input properties.

Finally, Volume 4 presents details of the local validation/calibration exercise conducted as part of this study using ODOT's new HMA pavement and JPCP LTPP sections.

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CHAPTER 2. LITERATURE REVIEW SUMMARY

SYNTHESIS OF NATIONAL MEPDG LITERATURE

Overview

A review of published literature related to the MEPDG reveals an overwhelming interest in this design methodology both nationally as well as internationally. Several MEPDG related online discussion and information exchange forums, regional summits, conference sessions, and training sessions have taken place to date and many are planned for the future. Some examples of stakeholder organizations with a high level of interest in the MEPDG include the Federal Highway Administration's (FHWA's) Design Guide Implementation Team (DGIT), North Central Region MEPDG User Group, FHWA Lead States (includes 19 states), State Pavement Technology Consortium (SPTC) comprising of Minnesota, Texas, California, and Washington, Northeast States, and Rocky Mountain States. Nearly two dozen states have active projects related to the MEPDG in particular. AASHTO is planning the development of a next generation, production-grade pavement design software based on the MEPDG called DARWin ME by 2009.

All the aforementioned interest has resulted in hundreds of publications in various transportation journals exploring various aspects of the MEPDG. These studies collectively represent a vast reservoir of information and can provide several "lessons learned" for ODOT. The information will (1) help prevent avoidable problems and pitfalls that may have been experienced in the past by agencies in similar situations and (2) provide ready answers to problems that may be common to across agencies attempting to implement the MEPDG.

The most popular MEPDG issues of interest for researchers at the international, national and State levels include:

- Characterization of input parameters such as traffic loading, layer material and subgrade foundation properties, climate, and other design features.
- Sensitivity of performance models to agency specific inputs.
- Validation and calibration of the pavement distress prediction models.
- Agency business plans and strategies for local implementation of the MEPDG.

Summary of National Literature Review Findings

Volume 2 of this report provides an overview of some of the publications covering each of these aspects. Key findings from some of these studies are summarized in the discussion below. Due to the exhaustive nature of the available literature, this summary (as well as Volume 2) does not purport to cover each and every publication but rather provides a flavor for some of the findings.

The MEPDG has continuously evolved since its first published version in the early 2000s. This timeframe roughly coincides with the period over which a majority of the work reviewed was performed. Understandably, much of the research has been done using versions of the MEPDG prior to the latest version. Therefore, one main rule that was applied in reviewing the literature for use in ODOT's work included examining the relevance of the findings noted in the literature with the latest version of the MEPDG software (http://trb.org/mepdg) and procedures manual (Von Quintus et al., 2007). For example, some of the issues raised in the literature at a given time, e.g., model instability, if addressed in successive versions of the MEPDG, were not considered in the literature summary presented herein or in Volume 2 of this report.

- Traffic related studies and findings
    - A majority of the literature reviewed focused on the estimation of the axle load spectra, forecasting of traffic volume growth, and seasonal traffic patterns, comparison of estimated load spectra with MEPDG defaults, and sensitivity of the MEPDG models to traffic.
    - A detailed review and preparation of weigh-in-motion (WIM) and automatic vehicle classification (AVC) is beneficial for the implementation of the MEPDG. Even though some studies showed that the MEPDG's nationally established axle load and truck class defaults were acceptable, others showed that there were considerable variances necessitating a thorough review by each agency.
    - Historical traffic data of a minimum of 6 years was suggested as being necessary for conducting a thorough traffic study. This roughly coincides with the traffic monitoring period of the LTPP.
    - Models such as rutting in HMA pavements and cracking in JPCP were more sensitive to traffic inputs. Therefore, characterizing traffic at the highest level possible is beneficial for critical design situations.

    - MEPDG distress prediction models were very sensitive to overloads present in the load spectra.
- Climate related studies and findings
    - MEPDG distress and smoothness predictions appear to be very sensitive, on occasion, to the climate data (i.e., weather station data) used in modeling. There is a need to investigate the quality of the climate data and improve it with locally available information.
    - A limited verification of the enhanced integrated climatic model (EICM)—the main climate modeling engine in the MEPDG—showed realistic predictions of moisture contents in unbound materials when compared with field measurements.
    - Depth to ground water table (GWT) could have significant impact on some distress predictions.
- Materials studies and findings
    - HMA materials
        - A majority of the literature on materials characterization dealt with HMA materials and that too on the subject of dynamic modulus |E*|.
        - The MEPDG |E*| predictive equation was reported to provide acceptable estimates of this critical input property at level 2. Some researchers found variances in the estimates at low loading frequencies or higher temperatures.
        - The level 2 |E*| predictive equation's accuracy was found to be improved if better characterization of asphalt binder properties was available.
        - Conducting level 1 |E*| testing was recommended for the most critical projects due to the sensitivity of rutting prediction to this parameter.
        - For recycled asphalt pavement (RAP) mixes, it was reported that the hierarchical input level used for |E*| and assumed performance grade (PG) binder type were critical in performance predictions.
        - Several studies were performed to develop libraries of level 1 |E*| inputs for typical HMA mixes used by agencies around the country. Some of these studies were performed before the AASHTO provisional standards were finalized for |E*| testing rendering the data questionable for use with the MEPDG.
        - To improve testing accuracy, a test program including four measuring instruments per specimen and two specimens per

mix type is recommended for development of |E*| databases using the AASHTO TP 62-03 protocol.

    - Based on a laboratory evaluation it was determined that larger aggregates combined with aged materials tend to have high |E*|-values at high temperatures. However, both the |E*|and frequency sweep at constant height (FSCH) tests could not correctly rank the permanent deformation characteristics of six HMA mixes tested. However, test results from the flow number and Hamburg tests were found to correlate fairly well, and both tests were sensitive to the permanent deformation characteristics for the mixtures evaluated. This study points to the deficiency of using the |E*| test for rutting characterization.
    - Some deficiencies were noted in obtaining inputs for rehabilitation design. Alternate means of testing existing pavement layers in the laboratory and correlating those properties with dynamic modulus values was suggested.
    - A correlation was proposed to relate the creep compliance measurements from the indirect tension testing and the bending beam rheometer testing. It was concluded that a mix-specific correlation exists which can be used to predict thermal cracking with approximately the same accuracy.
- PCC materials
    - The coefficient of thermal expansion (CTE) was identified as a key input for JPCP design. A comprehensive laboratory test program including 1800 LTPP test samples conducted by the FHWA revealed that (1) there is no correlation between mean CTE and CTE variability (2) the results of a single CTE test may not necessarily be representative of the CTE of a mixture due to test variability and (3) it is important to decrease the test variability by ensuring high testing standards and quality assurance/quality control (QA/QC) in the process of qualifying a mixture.
    - CTE test programs with local aggregates were recommended.
    - Interaction effects of concrete material properties and design features (e.g., thickness, joint spacing) are encouraged to be considered when drawing conclusions regarding MEPDG distress model prediction stability.

- Unbound materials
    - Problems were noted with adopting the resilient modulus (M_r) values proposed in the MEPDG software for design. These M_r values were generally found to be greater than expected resulting in an overestimation of distresses.
    - A comprehensive evaluation of MEPDG default M_r recommendations for soils found that, when interpreted correctly (i.e., after taking into account stress dependency), the default values appear to be reasonable.
- Model sensitivity analysis
  - Sensitivity analysis of the MEPDG distress and smoothness models appears to be a very popular topic as researchers and agencies try to understand the impact of the new design procedure on their pavement designs. Note that extensive amount of sensitivity analysis was also performed and reported as part of the original MEPDG documentation (ARA, 2004).
  - To date, sensitivity analyses have been completed and published under contract for Arkansas, California, Florida, Indiana, Iowa, Kansas, Minnesota, Montana, New Jersey, South Dakota, Texas, Utah, Virginia, and Wisconsin among others.
  - All the sensitivity studies were performed on globally calibrated models.
  - Sensitivity analyses were performed for a variety of reasons including to:
    - Identify the level of importance for each input parameter.
    - Identify the input parameters that can be modified to satisfy the predetermined pavement performance criteria.
    - Check the reasonableness of the model predictions, to identify problems in the software, and to help understand the level of difficulty involved in obtaining the inputs.
    - Compare MEPDG with local design approaches.
    - Develop design guide implementation plans.
  - One general observation regarding the work done on this topic so far is that researchers have seldom tried to account for interdependencies between inputs when performing the analyses. This is extremely important to consider for obtaining accurate estimates of model behavior. For example, PCC strength and modulus vary together along with other properties such as CTE and shrinkage. JPCP thickness is often linked to dowel diameters in design. In this sense, most of the sensitivity analysis reported

    - has limited applicability for factors that are supposed to be treated holistically but were not.
    - Another observation is that the interaction effects between materials and climate or between design and materials were not always considered except by some researchers. Such interactions should be based on agency specific practices and should be factored into sensitivity studies in order to obtain more realistic estimates of model behavior.
- Pavement design related studies and findings
    - Comparative studies of various aspects of the MEPDG based designs with agency designs were conducted by some researchers. In one case it was determined that the AASHTO 1993 design method overestimates flexible pavement thicknesses in warm locations and at high traffic levels. Trends of pavement performance with reliability level were similar for both methodologies.
    - On the subject of design reliability one researcher found that if the measurement error was removed from the total error of each model, the model statistics (R^2 and standard error) improve significantly.
    - An alternate means of including design reliability into the MEPDG design process was proposed by one researcher. The method was based on Monte Carlo (MC) simulations.
- Performance model validation and findings
    - Local calibration efforts were undertaken by some researchers using limited amount of roadway section and accelerated pavement testing data. The validations studies conducted as part of this work indicated that local calibration is perhaps necessary in many instances. A common theme related to flexible pavements is that the MEPDG overestimates total rutting. However, the statistical validity of some of the analyses undertaken could not be readily determined from the publications.

SYNTHESIS OF ODOT LITERATURE

ODOT has sponsored a number of research projects within the last decade that were targeted at improving the overall pavement performance standards in Ohio. A majority of these projects were focused on improved characterization of pavement materials and to the understanding of fundamental properties of various paving materials. A few of these studies also looked into traffic issues, pavement performance, and pavement construction and management databases. As a result of these extensive research efforts, several ODOT publications with very useful information have been published to date. Some of the ODOT studies with a high degree of relevance to the MEPDG are summarized in this section.

Materials Testing

Key research reports that contain materials testing information with varying degrees of relevance to the MEPDG are summarized in Table 1 and Table 2.

Table 1. ODOT sponsored research projects and reports.

Item	ODOT Sponsored Research Report
HMA dynamic modulus test	Liang and Saleeb (2004), Sargand et al (1991), Masada and Sargand (2002)
HMA IDT Tensile Strength	Liang (1998), Liang (2001), Abdulshafi (2002), Masada and Sargand (2002)
HMA IDT Unconfined Creep and Recovery Test	Liang (2001), Sargand and Kim (2001), and Masada and Sargand (2002)
Asphalt Pavement Analyzer (Georgia Loaded Wheel Tester)	Liang (2001), Sargand and Kim (2001)
Thermal Conductivity and Heat Capacity of Asphalt Mixtures	Colony and Wolfe (1980)
Unit Weight of PCC	Sehn (2002) and Masada and Sargand (2002)
28-day PCC Elastic Modulus	Abdulshafi et al (1994), Sargand and Cinadr (1997), Sargand et al (2002), Masada and Sargand (2002)
HMA and PCC Poisson's Ratio	Masada and Sargand (2002)
28-day PCC MR	Abdulshafi et al (1994), Sargand (2001), and Sehn (2002)
28-day PCC Compressive Strength	Sargand (2001), Sargand et al (2002), Masada and Sargand (2002), and Sehn (2002)
28-day PCC Split Tensile Strength	Abdulshafi et al (1994) and Sargand et al (2002), Sargand (2001), Masada and Sargand (2002), Sehn (2002).
PCC CTE	Masada and Sargand (2002)
Drying shrinkage coefficient of concrete	Sehn (2002)
Effects of Larger Sized Coarse Aggregate in PCC; Effects of Larger Sized Coarse Aggregate and Microsilica on Environmental Properties of PCC Pavements and Structures	Ioannides et al. (2006)
M_r of Base/Subbase/Subgrade	Abdulshafi et al (1994), Sargand et al (1998), Sargand et al (2001)
Thermal Conductivity and Heat Capacity of jointed reinforced concrete pavements	Colony and Wolfe (1980)
Other properties for Rigid Pavement Design	Sargand et al (1993), Sargand and Cinadr (1997), and Sargand et al (2001), Masada and Sargand (2002), Ioannides et al. (2002), Sargand and Morrison (2007)

Table 1. ODOT sponsored research projects and reports, continued.

Item	ODOT Sponsored Research Report
Resilient Modulus Test (Base and Subbase)	Liang (2007), Sargand et al (1991), Abdulshafi et al (1994), Randolph et al (2000), Sargand and Edwards (2000), Sargand et al (2001), Figueroa (2001), Masada and Sargand (2002), Sargand and Edwards (2002)
Resilient Modulus Test (Subgrade)	Liang (2007), Sargand et al (1991), Figueroa (1994), Sargand (1998), Sargand et al (1999), Sargand et al (2001), Masada and Sargand (2002), Figueroa (2004), Wolfe and Butalia (2004), Sargand and Edwards (2004).
Asphalt-Treated Base (ATB)	Abdulshafi et al (1994), Figueroa (2004), Masada and Sargand (2002), Sargand and Edwards (2002)
Permeable Asphalt Treated Base (PATB) Materials	Liang (2007), Figueroa (2004), Masada and Sargand (2002), and Sargand and Edwards (2002).
Permeable Cement Treated Base (PCTB)	Liang (2007), Masada and Sargand (2002), Sargand and Edwards (2002)
Lean concrete Base (LCB)	Masada and Sargand (2002) and Sargand and Edwards (2002)
Lime and Cement Stabilized Subgrade	Chou et al (2004)
Binder Tests	Liang (2001),Sargand and Kim (2001), Abdulshafi et al (2002), Masada and Sargand (2002)

Some of the testing performed in the above referenced research efforts is not consistent with the MEPDG test protocols. Table 2 summarizes the usefulness of the testing data from the projects noted in Table 1 to the ODOT implementation effort after taking into account the protocol variances between the ODOT testing efforts and the MEPDG test protocol recommendations and the types of characteristics of the data available. A more detailed summary of the testing efforts listed in Table 1 and their usefulness to the MEPDG implementation efforts is presented in Volume 2 of this report.

Table 2. Comparison of test protocols used in ODOT research and the usefulness of the test results to develop MEPDG input libraries.

Material Classification	Material Property	Test Protocol and Standards	Test Procedure used by ODOT Research Projects	Implementation Implication	Comment
Unbound Materials and Soils	Particle Size Analysis of Soils	AASHTO T 88	ASTM D422 , AASHTO T88, & ASTM C 136	Both standards give almost the same results	Data can be used.
	Determining the Liquid Limit of Soils	AASHTO T 89	ASTM D4318, AASHTO T 89	Both standards give almost the same results	Data can be used.
	Determining the Plastic Limit and Plasticity Index of Soils	AASHTO T 90	ASTM D4318, AASHTO T90	Both standards give almost the same results	Data can be used.
	The Moisture-Density Relations of Soils Using a 2.5-kg (5.5-lb) Rammer and a 305-mm (12-in) Drop	AASHTO T 99	ASTM D698 & AASHTO T 99	No fundamental difference between the two methods	Data can be used.
	Specific Gravity and Absorption of Coarse Aggregate	AASHTO T 85	AASHTO T 85 & ASTM C 127	No fundamental difference between the two methods	Data can be used.
	Specific Gravity and Absorption of Fine Aggregate	AASHTO T 84	AASHTO T 84 & ASTM C 128	No fundamental difference between the two methods	Data can be used.
	Specific Gravity of Soils	AASHTO T 100	ASTM D854 & AASHTO T 100	No fundamental difference between the two methods	Data can be used.
	Moisture-Density Relations of Soils Using a 4.54-kg (10-lb) Rammer and an 457-mm (18-in) Drop	AASHTO T 180	AASHTO T 180	The same AASHTO standard was used	Data can be used.

Table 2. Comparison of test protocols used in ODOT research and the usefulness of the test results to develop MEPDG input libraries, continued.

Material Classification	Material Property	Test Protocol and Standards	Test Procedure used by ODOT Research Projects	Implementation Implication	Comment
Unbound Materials and Soils	Permeability of Granular Soils (Constant Heat)	AASHTO T 215	AASHTO T 215 OR ASTM D2434	No fundamental difference between the two methods.	Data can be used.
	Laboratory Determination of Moisture Content of Soils	AASHTO T 265	AASHTO T 265 & ASTM D 2261	No fundamental difference between the two methods	Data can be used.
	Determining the Resilient Modulus of Soils and Aggregate Materials	AASHTO T 307 or NCHRP 1-28A	SHRP P46, ASHTO T46, AASHTO T294-94 & AASHTO T 274	AASHTO T 307 is the recent upgraded version of AASHTO T 294	M_r measured by AASHTO T 294 version may still usable by the new MEPDG. However, some comparison testing is needed.
	Classification of Soils for Engineering Purposes	ASTM D 2487	ASTM D 2487	The same standard is used	Data can be used.

Table 2. Comparison of test protocols used in ODOT research and the usefulness of the test results to develop MEPDG input libraries, continued.

Material Classification	Material Property	Test Protocol and Standards	Test Procedure used by ODOT Research Projects	Implementation Implication	Comment
Asphalt Binder	Kinematic Viscosity of Asphalts (Bitumens)	AASHTO T 201	AASHTO T 201	The same standard is used	Data can be used.
	Viscosity of Asphalts by Vacuum Capillary Viscometer	AASHTO T 202	AASHTO T 202	The same standard is used	Data can be used.
	Specific Gravity of Semi-Solid Bituminous Materials	AASHTO T 228	ASTM D 70	Not applicable.	Not applicable.
	Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)	AASHTO T 315	AASHTO TP5	Very similar standards	Data can be used.
	Viscosity Determination of Asphalt Binder Using Rotational Viscometer	AASHTO T 316	ASTM D4402 AND AASHTO TP48	Very similar standards	Data can be used.
	Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures	AASHTO T 319	AASHTO T 319	The same standard is used	Data can be used.
Hot Mix Asphalt & Asphalt Treated/Stabilized Mixtures	Sieve Analysis of Fine and Coarse Aggregate	AASHTO T 27	AASHTO T 27	The same standard is used	No difference
	Specific Gravity and Absorption of Fine Aggregate	AASHTO T 84	AASHTO T 84	The same standard is used	No difference

Table 2. Comparison of test protocols used in ODOT research and the usefulness of the test results to develop MEPDG input libraries, continued.

Material Classification	Material Property	Test Protocol and Standards	Test Procedure used by ODOT Research Projects	Implementation Implication	Comment
Hot Mix Asphalt & Asphalt Treated/Stabilized Mixtures	Quantitative Extraction of Bitumen from Bituminous Paving Mixtures	AASHTO T 164	ASTM D 2172		
	Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens	AASHTO T 166	ASTM D 2726, SHRP P07, ASTM D4123 OR AASHTO T 166	The same AASHTO standard is used	Data can be used.
	Theoretical Maximum Specific Gravity and Density of Hot-Mix Asphalt Paving Mixtures	AASHTO T 209	ASTM D 2041		
	Percent Air Voids in Compacted Dense and Open Asphalt Mixtures	AASHTO T 269	AASHTO T 269	The same standard is used	Data can be used.
	Preparing and Determining the Density of Hot-Mix (HMA) Specimens by Means of the Superpave Gyratory Compactor	AASHTO T 312	AASHTO TP4-94		

Table 2. Comparison of test protocols used in ODOT research and the usefulness of the test results to develop MEPDG input libraries, continued.

Material Classification	Material Property	Test Protocol and Standards	Test Procedure used by ODOT Research Projects	Implementation Implication	Comment
Hot Mix Asphalt & Asphalt Treated/Stabilized Mixtures	Determining the Creep Compliance and Strength of HMA using the Indirect Tensile Test Device	AASHTO T 322	SHRP P06 OR ASTM D3515	Incompatibility in the testing protocol.	Data cannot be used as is due to testing differences and inadequate amount of data collected.
	Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures	AASHTO TP 62	ASTM D 3497	Incompatibility in the test protocols used.	Data cannot be used as is due to testing differences and inadequate amount of data collected.

Table 2. Comparison of test protocols used in ODOT research and the usefulness of the test results to develop MEPDG input libraries, continued.

Material Classification	Material Property	Test Protocol and Standards	Test Procedure used by ODOT Research Projects	Implementation Implication	Comment
Portland Cement Concrete & Cement Treated/Stabilized Base Mixtures	Compressive Strength of Cylindrical Concrete Specimens	AASHTO T 22	ASTM C39	Very similar standards	Data can be used.
	Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)	AASHTO T 97	ASTM C78	Very similar standards	Data can be used.
	Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete	AASHTO T 121, M/T 121	ASTM C642	Very similar standards	Data can be used.
	Splitting Tensile Strength of Cylindrical Concrete Specimens	AASHTO T 198	ASHTO T198	The same AASHTO standard is used	Data can be used.
	Dry Shrinkage Coefficient	ASTM C157	ASTM C157	The same standard is used	Data can be used.
	Coefficient of Thermal Expansion of Hydraulic Cement Concrete	AASHTO TP 60	AASHTO TP 60	The same standard is used	Data can be used.
	Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression	ASTM C 469	ASTM C 469	The same ASTM standard is used	Data can be used.

Traffic Studies

Traffic data are key inputs for the analysis and design of pavement structures in the MEPDG. In the past, the AASHTO Design Guides quantified traffic in terms of equivalent single axle loads (ESALs). However, the MEPDG requires a lot more detailed traffic data. Essentially, the MEPDG requires the raw traffic data used to estimate ESALs, namely, the weight distributions on each axle for each month of the design period. The MEPDG also requires other traffic inputs not usually considered in pavement design, but recognized as being very important for pavement design, such as wheel wander, 24-hour truck counts, wheelbase distribution (i.e., distance between the drive axle and the first axle on the trailer), etc. The traffic data needs are summarized in the original MEPDG documentation (ARA, 2004) and the MEPDG Manual of Practice (Von Quintus et al., 2007).

An overview of the ODOT traffic data collection efforts revealed that ODOT collects WIM, AVC, and traffic volume information. ODOT has approximately the following number of permanent sites of each type:

- 44 permanent WIM sites
    - 2 Bending plate WIM sites.
    - 31 Piezo WIM sites.
    - 11 WIM sites through LTPP (these have been analyzed in this study and reported in Volume 3).
- Approximately 50 AVC sites to determine length based class.
- Approximately 50 volume sites.

However, much of this information has not been analyzed to date for MEPDG purposes. Recently, Sargand et al. (2007) completed a research project titled "Evaluation of Pavement Performance on DEL 23" for ODOT. This research provided a detailed evaluation of the unique traffic pattern on the Ohio SHRP Test Road pavement where all the LTPP SPS experiments (SPS 1, SPS 2, SPS 8, and SPS 9) in Ohio are located. A Mettler-Toledo WIM system was installed to monitor traffic loading in all four lanes of the test road. The data from this report was further analyzed and used as a basis for the local validation and calibration exercise undertaken in this study (see Volume 4 for details).

Pavement Performance Data

Pavement performance data collected on Ohio-specific pavements that is compatible with the MEPDG is extremely critical for local validation and calibration efforts. A literature review reveals that there are several studies conducted for ODOT to document typical pavement performance in Ohio, e.g., Sargand, et al. (1998), Sargand and Edwards (2000), Sargand, et al. (2006), Sargand et al. (2007), Liang (2007), and Chou, et al. (2008). The focus areas for each of these studies and their broad findings are listed below. A more detailed summary of the study findings are provided in Volume 2 of this report:

- Sargand et al. (1998) – forensic investigation of section 390101 of Ohio SHRP Test Road which failed rapidly after construction due to excessive rutting. Data collected included Falling Weight Deflectometer (FWD), transverse profiling, Dynamic Cone Penetration tests (DCP), and Cone Penetration Test (CPT). Trenching data were also obtained.
- Sargand and Edwards (2000) – the effects of various base materials and design features on the performance of Portland concrete pavement were investigated. FWD tests were conducted to determine load transfer on the test sections. Cracks in slabs were also evaluated through inspection and the cause was determined to be top-down cracking. Unstabilized and permeable cement treated base (PCTB) were found to have high incidences of distresses with the permeable asphalt treated base (PATB) exhibiting lower quantities of distress.
- Sargand, et al. (2006) – a forensic investigation was performed on sections 390103, 390108, 390109, and 390110 of Ohio SHRP Test Road. A series of non-destructive and destructive tests to determine the cause of rutting and localized distresses that had developed in these four pavement sections. Non-destructive testing included photographs of selected areas and referenced by station, distress surveys conducted according to LTPP SHRP-P-338 Distress Identification Manual, FWD tests, and transverse profiles. DCP tests, trenching studies, and HMA laboratory testing on selected cores were also performed. The collected data was utilized to determine the causes of the localized distresses.
- Sargand et al. 2007 – the response and the performance of many of the original 40 test sections and several sections constructed later to replace the lighter designs on DEL-23 were monitored. The structural response data collected is a unique aspect of this study.

- ODOT Experimental Projects – ODOT has been monitoring the performance of other experimental pavements in Ohio during the past few years. These pavements include sections of ATH 50, LOG 33, ERI/LOR 2, and WAY 30. A brief description of the nature of each project follows:
    - In 1997, an experimental high-performance jointed concrete pavement was constructed on US 50 east of Athens, Ohio (ATH 50). DCP profiles were collected in the eastbound driving lane between Stations 381 and 463 on May 25, 2004 to determine the cause of some severe slab cracking after two years of service. As a result, seventeen DCP profiles were obtained for this task. On May 24, 2004, a comprehensive set of FWD measurements was made to provide additional insights on the performance of various experimental features incorporated into the ATH 50 project.
    - Five test sections were constructed on LOG 33 to evaluate the effects of different drainable bases on the overall performance of AC pavement. All sections had a HMA layer thickness of 11 inches. Base materials included: PATB, PCTB, ODOT unstabilized drainable base with New Jersey and Iowa gradations, and ODOT 304 aggregate base. Monitoring was halted after Novachip was placed on all sections after the 2001 evaluation. Deflection, serviceability, distress, and pavement condition rating data are available from these sections.
    - ERI/LOR 2 test pavement was constructed in the westbound lanes of ERI/LOR 2 to evaluate the combined effects of 13- and 25-foot joint spacing with different types of base materials on the performance of PCC pavements. Among the materials used in the bases were PATB, PCTB, and ODOT unstabilized with New Jersey and Iowa gradations. Deflection, serviceability, distress, and pavement condition rating data are available from these sections.
    - WAY 30 experimental project on US 30 near Wooster is a $54 million, 8-mile-long test road which will compare the longevity of asphalt "perpetual" pavements and concrete "long-life" pavements. This project is expected to provide valuable information to MEPDG validation studies.

In the study conducted by Chou, et al. (2008), Infrastructure Information System Laboratory at the University of Toledo has developed a Pavement Management Information System (PMIS) database for ODOT. The database is in Microsoft Access database format. The ODOT PMIS is a set of reporting tools to extract the data necessary for pavement performance analysis.

The Ohio specific pavement performance data reviewed in the above could be used for both validating and calibrating the MEPDG approach. Table 3 and Table 4 provide a summary of the availability of the pavement performance indicators extracted from the cited ODOT sponsored studies for both flexible and rigid pavements. It can be seen that no performance data was available for Continuous Reinforced Concrete Pavements (CRCP). This is of little consequence since, at this time, ODOT is not planning to build CRCP.

Table 3. Flexible and rigid pavement performance indicators collected by ODOT.

Pavement Type	**Performance Indicator**	**Sources**				
		Sargand, et al. (1998)	Sargand and Edwards (2000)	Sargand, et al. (2006)	Sargand and his associates (2007)	Liang (2007).
HMA Pavement	Rut Depth (Total, HMA, & Unbound Layers)	x		x	x	
	Transverse Cracking					
	Alligator Cracking (Fatigue Cracking)	x			x	
	Top-Down Cracking			x	x	
	Reflective Cracking					
	Smoothness				x	x

Table 4. Flexible and rigid pavement performance indicators, continued.

Pavement Type	**Performance Indicator**	**Sources**				
		Sargand, et al. (1998)	Sargand and Edwards (2000)	Sargand, et al. (2006)	Sargand and his associates (2007)	Liang (2007).
JPCP	Mean Joint Faulting					
	Transverse Cracking		x		X	
	Smoothness					
	Load Transfer efficiency					
	Punchouts					
	Smoothness					

It is worthwhile to mention here that Ohio also has several LTPP SPS and GPS test sections for both flexible and rigid pavements. The data from these sections can be used as a starting point to validate and calibrate the MEPDG distress prediction models.

Pavement Construction Databases

ODOT has an extensive construction database for exploration. This database could be linked to the ODOT PMIS database to extract the necessary information for MEPDG validation purposes using ODOT-specific sections.

Climate Related Studies

Climatic conditions have a significant effect on the performance of both flexible and rigid pavements. Climatic factors, such as precipitation, temperature, freeze-thaw cycles, and frost penetration depth, play a key role in affecting the material properties and the performance of the pavement. Consequently, the susceptibility of the pavement materials to moisture and freeze-thaw induced deterioration, the drainability of the paving layers, the infiltration potential of the pavement, also define the extent to which the pavement will react to the climatic conditions.

The MEPDG, through the use of the Enhanced Integrated Climatic Model (EICM) module embedded within its software, provides the pavement designers with a powerful means to account for the impacts of climatic factors and their interaction with pavement materials, pavement foundation, and traffic inputs when performing pavement design. The MEPDG considers month-by-month changes to unbound layer modulus values as a function of moisture changes and frost penetration, daily curling and warping gradients through PCC slabs, temperature dependency of HMA material dynamic modulus, etc. in predicting pavement distresses. While these computations are complex and increase the run-time of the MEPDG, they are necessary to fully integrate climatic effects into pavement design. However, the climate input requirements of the MEPDG are hourly temperature, precipitation, wind speed, cloud cover, and relative humidity data covering the design period. These data can be obtained from historical climate records at a weather station situated close to the project site. Another key input used in climate calculations is the depth to the ground water table (GWT).

There are several ODOT sponsored studies related to climate condition in Ohio and its effects on pavement performance – Figueroa (2004), Sargand et al. (2007), and Liang (2007). Table 5 summarizes the various climate effects modeling factors available from these studies.

The depth to GWT along with the latitude and longitude coordinate of several sections at Ohio SHRP test road were provided by ODOT and summarized in Table 6. Figure 3 shows the variation of water table with time for three sections.

Table 5. Types of climate data analyzed in ODOT studies.

Sources	**Weather Station Parameters**						**Ground Water Table Depth, GWT (ft)**
	Air Temperature	**Wind speed (mph)**	**Wind Direction**	**Solar Radiation**	**Precipitation (in)**	**Relative Humidity (%)**	
Liang (2007)	X	X	X	X	X		X
Sargand and his associates (2007)	X	X	X	X	X	X	X
Figueroa (2004)	X	X	X	X	X	X	

Table 6. Ohio SHRP Test Road GPS coordinates and depth to GWT (Office of Pavement Engineering, ODOT).

SHRP Section No.	**Section Coordinates**			**Average Depth of Water Table, ft**
	Latitude (degree. minutes)	**Longitude (degree. minutes)**	**Elevation (ft)**	
390102	40º 24' 46" N	83º 04' 32" W	953.7	5.20
390103	40º 25' 32" N	83º 04' 31" W	955.4	8.75
390104	40º 24' 13" N	83º 04' 32" W	956.0	3.50
390108	40º 25' 05" N	83º 04' 35" W	953.4	6.7
390901	40º 23' 16" N	83º 04' 31" W	955.5	8.48
390201	40º 24' 15"N	83º 04' 27" W	954.9	5.31
390204	40º 23' 04"N	83º 04' 29" W	955.6	8.61
390208	40º 25' 16"N	83º 04' 33" W	954.4	8.49
390212	40º 23' 23"N	83º 04' 29" W	957.2	5.55

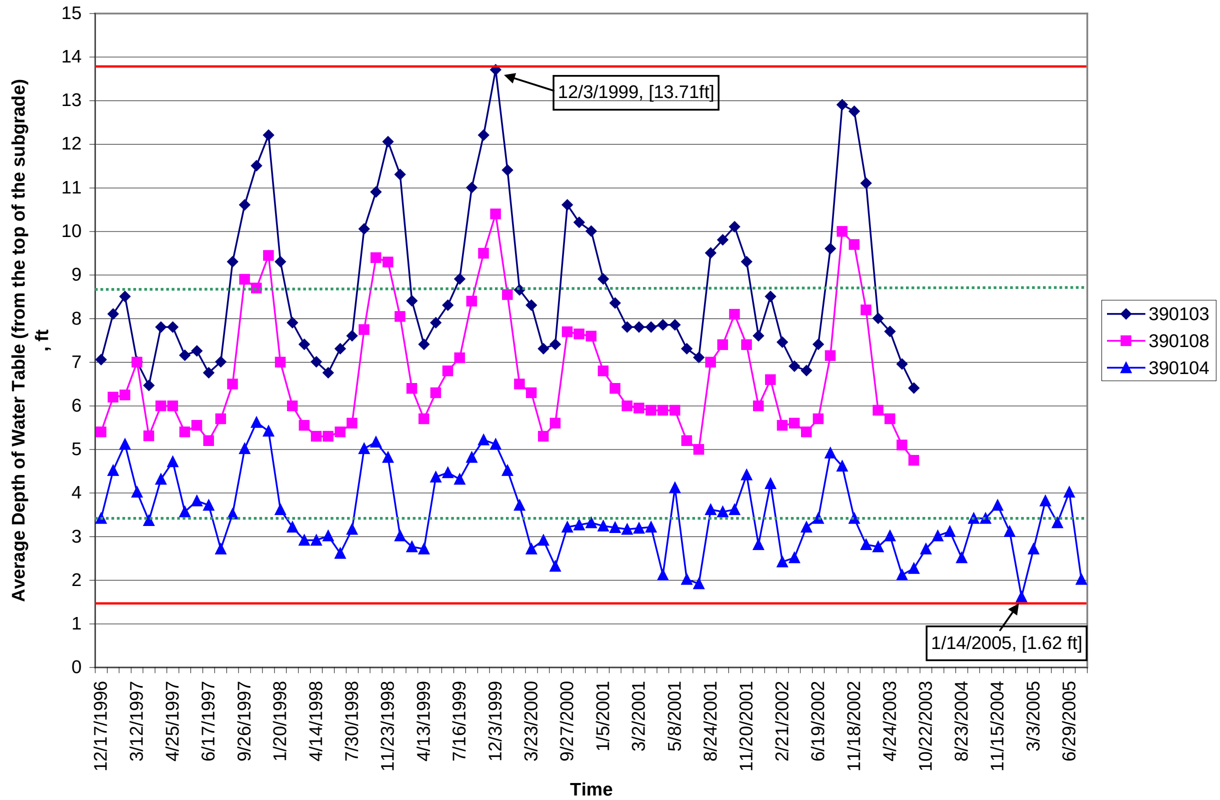

Figure 3. Water depth variation with time.

ODOT'S MEPDG INPUT DEFAULTS AND DEFAULT LIBRARIES

The MEPDG procedure requires greater quantity and quality of input data than the current ODOT design procedure in four major categories: traffic, material characterization and properties, environmental influences, and pavement response and distress models. However, the design guide uses a hierarchical approach for inputs which allows the designer flexibility in selecting the design inputs based on the importance of the project and available resources or information. The three hierarchical inputs levels are as follows:

- Level 1 (highest) - Level 1 input requires the highest quality of data. The input data is obtained from direct testing on the actual project material in question; e.g., dynamic modulus testing of an asphalt concrete mix.
- Level 2 (intermediate) - Level 2 input is used when direct test results for a given parameter cannot be obtained but results from other related tests are available which can then be correlated to the required input. For example, if the required Level 1 data parameter is the resilient modulus,

M_r of soil but it is not available, then the resilient modulus values are determined through correlations with other more standard testing procedures, such as California Bearing Ratio (CBR) or from soil gradation and plasticity index, etc.

- Level 3 (lowest) - This level of data input requires the lowest level of accuracy and intended for use for lower volume roadways. At Level 3, not only are direct test results (Level 1) unavailable, but secondary test results (e.g., CBR) (Level 2) are also not available. Level 3 permits the user to enter a estimated input value for a given parameter (based on historical agency specifications, test results, or MEPDG supplied national defaults). Typical material property default values derived from the Ohio-specific LTPP database or Ohio construction or PMIS databases can be used for this level of input.

It is possible for a designer to mix and match the levels of input for a specific project during design or even for local calibration.

In a production type application of the MEPDG design procedure, agencies are expected to use libraries of inputs to define typical project materials, foundation conditions, traffic factors, or climatic variables encountered in their respective States. Level 1 testing of actual project materials will perhaps be done only for the most critical projects. To this end, several agencies are currently undertaking efforts to define these properties as part of their MEPDG implementation activities. These data are being stored in databases for future use as well to confirm/reject national MEPDG defaults.

Volume 2 summarizes the level 2 and 3 defaults data developed for several inputs based on Ohio specific information.

CHAPTER 3. SENSITIVITY ANALYSIS SUMMARY

INTRODUCTION

By some classical definitions, (Cacuci et al. 2005), sensitivity analysis is the study of how the variation (uncertainty) in the output of a mathematical model can be apportioned, qualitatively or quantitatively, to different sources of variation in the input of a model. The MEPDG includes several pavement distress and smoothness models. Using these models, the user can determine the adequacy of a given design. Needless to say, the models outputs are affected by the design and site related inputs to the procedure. The degree to which a given model is affected by a given input is largely a function of the phenomenological linkage between the two. To a large degree, these linkages have been well established in published MEPDG literature (ARA 2004) for each distress or smoothness model. This information can be used to investigate MEPDG distress and smoothness model sensitivity to Ohio specific inputs.

The objective of the sensitivity analysis task performed under this study is to (1) establish the impact of Ohio-specific site and design related inputs on the key design types and models of interest to ODOT and (2) establish relative importance of the various model inputs to the design process. Based on this work, the effort required to test

The pavement types and models investigated were those discussed under the *Study Objectives and Scope of Work* section.

ANALYSIS METHODOLOGY

The following discussion illustrates the steps followed in performing the sensitivity analysis.

1. For each design type of interest, determine key inputs from published literature and ODOT and project team's experience.
2. For applicable inputs, research ODOT design documents, specifications, databases, and research reports to establish ranges of inputs that encompass the typical values each input assumes during actual production work.

3. Establish a "baseline" or a typical cross-section for each pavement design of interest based on ODOT's current practice.
4. Using the baseline design from step 3, create alternate designs by varying, one at a time, the key inputs identified in step 1. Interdependence of some of the inputs, e.g., HMA mix types and mix properties, PCC strength and modulus, was recognized as much as possible during the sensitivity study. However, it was not possible to handle all the potential interactions between inputs since the relationships between some of the inputs could not be established from literature or are too site- or material specific. Further, two or more inputs were not varied at the same time.
5. Rank order the inputs based on their impact on the models of interest.

Version 1.00 of the MEPDG was used to perform the sensitivity study. The nationally calibrated MEPDG distress/IRI models were used for this analysis.

SENSITIVITY ANALYSIS FINDINGS

New HMA Pavements

<u>Baseline Design</u>

Figure 4 presents the pavement cross-section and materials used as a baseline new HMA pavement. Table 7 presents assumed values for the various MEPDG inputs that are associated with the baseline design. Table 8 lists key inputs whose impact on the MEPDG outputs was studied along with the ranges over which these inputs were varied.

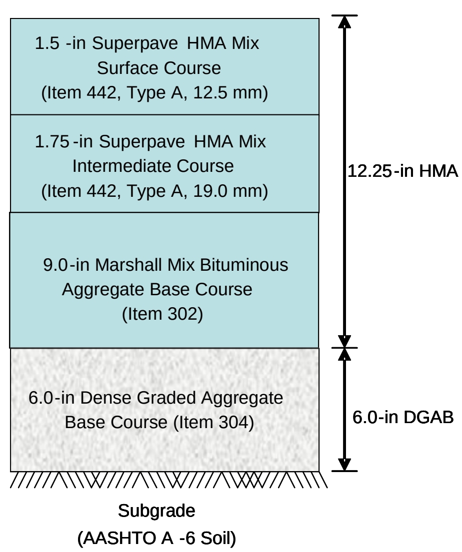

Figure 4. Baseline conventional new HMA pavement design to be used in sensitivity analysis.

Table 7. MEPDG inputs assumed for the baseline HMA pavement section.

Input Category and Assumed Input Value	Input Category and Assumed Input Value
• Base Construction Month: September • Pavement Layer Construction Month: October • Traffic Open Month: November • Initial IRI: 63 in/mile • Traffic: Data from LTPP 39_9006 applied. See Volume 3 for more details. Some key inputs include: o Cumulative trucks over 20 years = 70 million (design lane) o Percent trucks = 27.1 o 2-way AADTT = 12,893 o Directional distribution = 50 percent. o Lane distribution factor = 82.5 percent o Growth rate 8.4 percent (linear). o Vehicle distribution: Rural Principal Arterial (80% Class 9). o MEPDG defaults for all other lanes.	• Climate: Newark, OH (central location). • Material properties o HMA materials: see Volume 3 table 3 & Figures 19-22 o Base type: Dense graded aggregate o Base layer resilient modulus (Mr): 20,000 psi o Subgrade type: A-6 o Subgrade layer Mr: 10,000 psi

Table 8. Ranges of inputs used in the new HMA models sensitivity analysis.

MEPDG Input Parameter	Levels of Input (*indicates the baseline representative design)
Traffic composition	13 LTPP pavement sites representing urban and rural traffic in Ohio (refer figure 2 of Volume 3 for WIM site locations).
Climate (weather stations)	• Cleveland (Cleveland-Hopkins International-airport) • Columbus (Port Columbus International airport) • Covington/Cincinnati (Cincinnati/NRN KY International airport) • Dayton (J M Cox Dayton airport) • New Philadelphia (Harry Clever Field airport) • Newark (Newark-Heath airport)* • Toledo (Toledo Express airport) • Parkersburg, WV (Wood County airport) • Wheeling, WV (Wheeling-Ohio County airport)
HMA type (surface course)***	• Superpave HMA Mix Surface Course, ODOT Item 442, Type A, 12.5mm, (MEPDG Layer 1) • SMA surface course (Item 443)
HMA thickness	8-, 10-, 12.25-*, 14-, 16-in (varying the bituminous base thickness only)
HMA air voids content	5.5*, 6.5, 7.5, 8.5, 9.5, 10.5 percent
HMA volumetric binder content	Baseline binder content (surface course = 11.1 percent, intermediate course = 9.6 percent and base course = 8.7 percent) +4.0, +2.0, -2.0, and -4.0 percent of the baseline binder content across all three HMA layers.

Table 8. Ranges of inputs used in the new HMA models sensitivity analysis, continued.

MEPDG Input Parameter	Levels of Input (*indicates the baseline representative design)
Base type	• Dense graded aggregate base course (Item 304)* o Resilient modulus = 20,000 psi o Plasticity Index = 1 o Liquid Index = 6 o See Table 3 of Volume 3 for more details • Bituminous or asphalt concrete base (Items 301 and 302) o Unit weight = 140 pcf. o See Table 6 of Volume 3 for more details.
Subgrade stabilization	• Natural A-6 material with top 12-in compacted. • Natural A-6 material with top 12-in lime stabilized and compacted. • Natural A-6 material with top 12-in cement stabilized and compacted • Natural A-2-4 material with top 12-in compacted • Natural A-2-4 material with top 12-in cement stabilized and compacted
Natural Subgrade type/modulus**	• Coarse (A-1-a, A-1-b, A-2-4, A-2-5, A-2-6, A-2-7 and A-3) • Fine (A-4, A-5, A-6*, A-7-5 and A-7-6)

*Baseline project values.

**Default MEPDG gradations will be used, where applicable.

***For the sensitivity analysis, two other HMA materials types—SuperPave (Item 442, Type A, 12.5-mm) and stone matrix asphalt (SMA) (Item 443) were considered. For Superpave, the equivalent ODOT SuperPave surface and intermediate course mixes were used to replace the 1.75-in surface course and 1.75-in intermediate course of the baseline design. For SMA, only the 1.75-in surface course was replace with the SMA surface course.

Sensitivity Analysis Results for New HMA Design

Table 9 summarizes the impact of each of the inputs on the MEPDG predicted HMA pavement distress and smoothness outputs in terms of:

- Magnitude of impact
    - None—negligible variance in measured output when compared to baseline over the entire range of input considered.
    - Low— 1 to 5 percent variance in measured output when compared to baseline over the entire range of input considered.
    - Moderate—5 to 20 percent variance in measured output when compared to baseline over the entire range of input considered.
    - High—greater than 20 percent variance in measured output when compared to baseline over the entire range of input considered.
- Directionality of impact – Direct proportionality or inverse proportionality represented by symbols (↑) and (↓), respectively.

Table 9. Summary of the relative sensitivity of various ODOT-specific design inputs on MEPDG new HMA pavement distress and smoothness predictions.

Input Variable	HMA Distress/Smoothness Model				
	Longitudinal Fatigue Cracking	**Thermal (Transverse) Cracking**	**Alligator Fatigue Cracking**	**Rutting**	**IRI**
Traffic Composition	None	None	Moderate	High	Low
Climate (Warm Temperatures)	None	High↓	Moderate ↓	Moderate ↑	Low
HMA type (surface course stiffness)	Low	Low↑	Low	Low	Low
HMA thickness	< 8 in—High ↓ > 8 in—None	Moderate↓	High ↓	High ↓	High ↓
HMA air voids content	None[1]	Low↑	Moderate[2] ↑	Moderate[3] ↑	Low[3] ↑
HMA volumetric binder content	None	High↓	High ↓	High ↑	Low ↓
Base type (Base Modulus)	None	High↓	High ↓	High ↓	Moderate ↓
Subgrade stabilization (Modulus)	Low	None	Moderate ↓	Moderate ↓	Moderate ↓
Natural Subgrade type/modulus**	None	None	Moderate ↓	Moderate ↓	Low ↓

1 To understand the sensitivity of this model, the voids in the top HMA layer (12.5mm, 442) were changed.

2 To understand the sensitivity of this model, the voids in the bottommost HMA layer (302) were changed.

3 To understand the sensitivity of this model, the voids in the top two HMA layers (12.5mm and 19mm 442) were changed.

The following broad observations can be drawn from the table for each model:

- Longitudinal cracking
  - This model seems to be mostly affected by thickness of the HMA layer alone. The MEPDG predicts a very high amount of longitudinal cracking for thinner pavement sections. For thicker sections, almost negligible amount of longitudinal cracking is predicted.

    - To a very small degree, the stiffness of the mix seems to impact the development of longitudinal cracking with the stiffer SMA mix (ODOT 443) showing slightly lower cracking than the Superpave HMA (ODOT 442).
    - Unexpectedly though, the subgrade and base stiffness did not influence the longitudinal cracking much. This is perhaps attributable to the relatively thick HMA layer chosen for the baseline design. It is expected that these variables will have a bigger impact for thinner HMA layers.
- Transverse cracking
    - The predictions show that transverse cracking is highly affected by climate, volumetric binder content, and surprisingly, base type. Among climate variables that affect low temperature cracking predictions, the lowest temperatures achieved over the life of the project seems to be the most important variable. From this standpoint, it is very important to have accurate and reliable weather station data to minimize erroneous predictions. Higher binder contents produce lower temperature cracking due to the lower stiffness of the mix. Also, stiffer bases seem to have a strong tendency to reduce thermal cracking possibly by reducing the tensile strains at the surface.
    - HMA thickness has a moderate influence on thermal cracking with thicker asphalt pavements showing lower thermal cracking.
    - HMA surface layer air voids and ODOT surface mix type (HMA versus SMA) have a low impact on the predicted cracking.
- Alligator cracking
    - The model predictions show that alligator cracking is significantly affected by HMA thickness and asphalt binder content. Higher thicknesses and higher asphalt contents lead to lower alligator cracking.
    - HMA air voids seem to have a moderate impact with higher air voids leading to higher amounts of alligator cracking.
    - Base type (DGAB versus asphalt treated) also seems to have a major impact with sections with asphalt bases producing lower alligator cracking. This is as expected.
    - Percentage of heavy trucks (class 9 or greater) for a fixed volume of total trucks seems to affect alligator cracking moderately with higher percentages of heavy trucks generally yielding greater amount of alligator cracking.

- Ohio climate seemed to have a moderate impact on the predicted alligator cracking for this design with warmer climates generally exhibiting the higher amounts of alligator cracking. A temperature analysis showed that the mean annual average temperatures in Cleveland, OH were among the lowest and Parkersburg, WV the highest. Accordingly, these two sites have the lowest and highest predicted alligator cracking.
- The impact of stabilizing the top 12 inches of the subgrade with lime or cement was found to be moderately significant when compared to non-stabilized subgrades.
- Subgrade type seems to have a moderate impact on the predicted alligator cracking with coarse grained soils exhibiting lower alligator cracking.
- Predictably, the mix type used in the surface course (SMA versus Superpave HMA) did not seem to have much impact on the predicted alligator cracking for this design.

- Total Rutting (includes HMA layer, base, and subgrade rutting)
  - Percentage of heavy trucks has a large impact on rut development with higher percentages yielding higher amounts of rutting.
  - HMA thickness and asphalt binder content appear to have a significant but opposite impact on the predicted rutting. It appears that higher the pavement thickness, lower the rutting. However, higher the binder content, higher the rutting which is as expected.
  - Base type also has a significant impact on rutting with pavement sections with asphalt treated bases showing lesser rutting than those with a DGAB.
  - Climate has a moderate impact on the predicted rutting. An analysis of the hottest three consecutive month temperatures (not shown here) showed that Parkersburg, WV and New Philadelphia, OH had the highest summer temperatures and Dayton, OH and Cleveland, OH the lowest. Accordingly, rutting accumulation is the greatest in the former locales and the least in the latter.
  - Air voids in the top two HMA lifts have a moderate impact on HMA rutting with higher air voids leading to increased rutting.
  - Subgrade type and subgrade stabilization both have a moderate impact on rutting with coarse grained and stabilized subgrades showing lower amounts of rutting.
  - The HMA mix type—SMA versus Superpave HMA—did not in itself result in a significant impact on rutting. However, it is expected that the impact of the mix type will be greater when

combined with climate with better predicted rutting expected from SMA mixes in warmer climates.

- Ride Quality or IRI
    - The impact of the various site and design factors studied on IRI prediction can, for the most part, be estimated by examining how they impact alligator cracking and rutting. For example, if an increasing value of given factor increases alligator cracking and rutting, it can be expected to increase IRI by the same magnitude. On the other hand, if it has equal but opposite effect on alligator cracking and rutting, it can be expected to have a minimal impact on IRI.
    - It is observed that pavement thickness has the most significant effect on IRI with thicker pavements exhibiting lower IRI.
    - Base stiffness and the stiffness of a stabilized subgrade layer have a moderate effect on IRI; sections with stiffer layers having a more beneficial IRI.
    - The remaining factors studied have a low impact on IRI.

Another way to interpret the results of the sensitivity analysis is to estimate the importance of the variables by examining how many models they affect to strength of their impact. Using this criterion, and narrowing the focus to those factors that are within the designer's control, it can be seen that HMA thickness, base type (asphalt stabilized versus DGAB) are the key inputs affecting pavement performance the most. They are followed by HMA air voids at construction and subgrade stabilization.

New JPCP

<u>Baseline Design</u>

Figure 5 presents the pavement cross-section and materials used as a baseline new JPCP. A majority of the input values in terms of site and design factors were similar to the new HMA baseline design discussed in the previous section with the obvious exception of material inputs for the PCC layer.

Table 10 lists the key inputs whose impact on the MEPDG outputs for this design type was studied in the sensitivity analysis attempted here. The table also presents the ranges over which these inputs were varied. This table also notes the PCC material and other design inputs used in the baseline design.

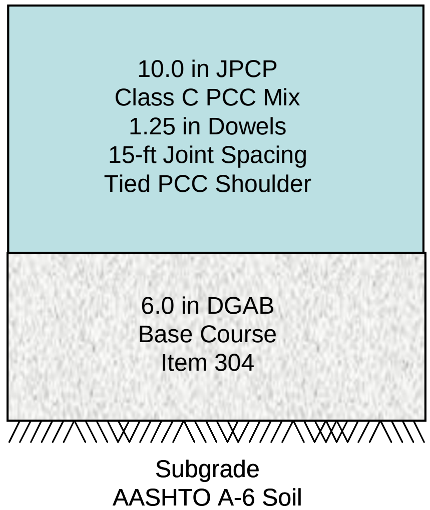

Figure 5. Baseline conventional new JPCP design to be used in sensitivity analysis.

Table 10. Input parameters of interest used for new JPCP models sensitivity analysis.

MEPDG Input Parameter	Levels of Input (*Indicates the Baseline ODOT Representative Design)
Traffic composition	TTC group R1 through 7 (for Rural traffic; R6*) and U1 through 6 (for Urban traffic), refer figure 2 of Volume 2 for WIM site locations
Climate (weather stations)	• Cleveland (Cleveland-Hopkins International airport) • Columbus (Port Columbus International airport) • Covington/Cincinnati (Cincinnati/NRN KY International airport) • Dayton (J M Cox Dayton airport) • New Philadelphia (Harry Clever Field airport) • Newark (Newark-Heath airport)* • Toledo (Toledo Express airport) • Parkersburg, WV (Wood County airport) • Wheeling, WV (Wheeling-Ohio County airport)
PCC thickness and dowel diameter	8-, 9-, 10-*, 11-, 12-, 13-, and 14-in

Table 10. Input parameters of interest used for new JPCP models sensitivity analysis, continued.

MEPDG Input Parameter	Levels of Input (*Indicates the Baseline ODOT Representative Design)
PCC concrete type	Class C*, and high early strength concrete For the sensitivity analysis, other commonly used ODOT PCC material types were used. Specifically the following were considered: • ODOT class C concrete with limestone (PCC CTE = $5.4*10^{-6}/^{o}F$). • ODOT class C concrete with gravel (PCC CTE = $6.4*10^{-6}/^{o}F$). • ODOT class C concrete with slag (PCC CTE = $6.3*10^{-6}/^{o}F$). • ODOT class S concrete with limestone (PCC CTE = $5.4*10^{-6}/^{o}F$). • ODOT class S concrete with gravel (PCC CTE = $6.4*10^{-6}/^{o}F$). • ODOT class S concrete with slag (PCC CTE = $6.3*10^{-6}/^{o}F$). Additional properties for the class C concretes are as follows: • Cement type: Type I. • Cementitious content: 600 Ibs/yd^3. • Aggregate type: Limestone, Gravel, or Slag (limestone selected for baseline design). • 28-day flexural strength: 650 psi (Masada et al. 2004). • Water-to-cementitious material ratio: 0.5. Additional properties for the class S concretes are as follows: • Cement type: Type I. • Cementitious content: 715 Ibs/yd^3. • Aggregate type: Limestone, Gravel, or Slag. • 28-day flexural strength: 800 psi (Masada et al. 2004). • Water-to-cementitious material ratio: 0.44. Default MEPDG values assumed for other properties e.g., unit weight, Poisson's ratio, etc.
PCC flexural strength and elastic modulus	601-, 650-*, 736-, and 850-psi
PCC aggregate type	Gravel, Limestone*, and Slag
PCC CTE	5.2-, 5.4-*, and $6.7x10^{-6}/^{o}F$
PCC slab joint spacing	12.5-, 15.0-*, 17.5-, 20.0-, 22.5-ft
Transverse joint load transfer efficiency (LTE)	No dowel (0-in), 1.0-, 1.25-*, and 1.5-in
PCC slab width	12-*, 13-, and 14.0-ft
Base type (See tables 5 and 6 of Volume 3 for details)	• Dense graded aggregate base course (Item 304)* • Bituminous or asphalt concrete base (items 301 and 302)
Shoulder type	Tied PCC* and no tied PCC
Subgrade type	• Natural A-6 material with top 12-in compacted* • Natural A-6 material with top 12-in lime treated and compacted • Natural A-6 material with top 12-in cement treated and compacted • Natural A-2-4 material with top 12-in compacted • Natural A-2-4 material with top 12-in lime stabilized and compacted • Natural A-2-4 material with top 12-in cement stabilized and compacted

*New JPCP baseline design.

**Default MEPDG gradations used, where needed.

Sensitivity Analysis Results for New JPCP Design

Table 11 summarizes the impact of each of the inputs on the MEPDG predicted JPCP distress and smoothness outputs.

Table 11. Summary of the relative sensitivity of various ODOT-specific design inputs on MEPDG new JPCP distress and smoothness predictions.

Input Variable	**JPCP Distress/Smoothness Model**		
	Mid-Slab or Fatigue Cracking[1]	**Faulting**	**IRI**
Traffic composition	High ↑	Low ↑	Low ↑
Climate (Warm Temperatures)	High ↓	Low ↓	Moderate ↓
PCC thickness (and dowel diameter for faulting analysis)	High ↓	High ↓	High ↓
PCC Coefficient of Thermal Expansion (CTE)	High ↑	High ↑	High ↑
PCC Flexural Strength (MR) and Modulus (E)	High ↓	Low ↓	Low ↓
PCC Mix Type and Coarse Aggregate Type[2]	High	Low	Low
PCC Joint Spacing	High ↑	High ↑	High ↑
PCC Slab Width	High ↓	High ↓	High ↓
Pavement Edge Support	High ↓	Low ↓	Low ↓
Base type (Base Modulus)	Moderate ↓	Moderate ↓	Moderate ↓
Subgrade stabilization (Modulus)	Moderate ↓	None	None ↓
Natural Subgrade type/modulus	Moderate ↑	Low ↓	Moderate ↓

[1] Includes both top-down and bottom-up cracking.
[2] Two PCC mix types—Class S and Class C—were considered. The main differences between these mix types are in MR, E, aggregate gradation, cement content. Three aggregates types commonly to Ohio were chosen for each of these mixes. More details are provided in Volume 3.

The following broad observations can be drawn from the table for each model:

- Mid-slab or fatigue cracking
    - Traffic composition, specifically, the number of percentage of short wheelbase vehicles, e.g., Class 5 through 8 trucks, in the truck mix, seem to affect cracking significantly. Higher the proportion of these vehicles in the mix, greater its impact for the joint spacing

selected for the baseline (15 ft). It is likely that, if the joint spacing is increased, the impact of these vehicles may not be as much.

- Climate seems to have a significant impact on the predicted cracking. Local climate seems to have a large impact on the predicted cracking. This, in turn, means that the weather station data will need to be carefully populated to remove any erroneous readings or anomalies.
- As expected, slab design features such as thickness, transverse joint spacing, and slab width/tie bars (edge support) all have a major impact on the predict amount of transverse cracking.
- Among material properties, CTE or aggregate type and flexural strength and elastic modulus of PCC have a significant impact on the predicted cracking. Interestingly, as far as CTE is concerned, limestone based concrete mixes show a significantly different performance when compare to gravel or slab aggregate mixes.
- ODOT S-class concrete seems to produce significantly lower cracking when compared to C-class concrete for the same aggregate owing primarily to the differences in strength and modulus. However, when interpreting these results, it should be noted that there are other concrete materials properties, e.g., shrinkage, temperature at set, etc., which could be significantly different between these mix types. These have not been considered in the sensitivity analysis presented here due to lack of data.
- Base stiffness also appears to have a moderate impact on reducing the predicted mid-panel cracking with asphalt bases exhibiting lower cracking than DGAB. However, care should be exercised when trying to interpret this finding. Very stiff bases, such as a cement-treated bases, although have a potential to reduce long-term fatigue cracking, are more prone to early age cracking due to non-load related issues if certain design, materials selection, and construction risk factors are not eliminated.
- Subgrade type also has a moderate impact on slab cracking. Coarse grained or stiffer subgrades predict a higher amount of cracking than fine grained subgrades due to increased temperature stresses.

- Joint Faulting
  - The combined effect of PCC thickness and dowel diameter is large. In the sensitivity study, the dowel diameter was varied with slab thickness using standard ODOT design practices. However, the large effect of this combined parameter can mostly be attributed to the dowel diameter alone.

- Short jointed or widened slab pavements seem to have significantly lower faulting when compared to long jointed slabs and standard width pavements, respectively.
    - Among material properties, CTE has a significant impact on the predicted faulting with higher CTE concrete producing higher faulting.
    - ODOT S-class concrete seems to produce marginally lower faulting when compared to C-class concrete for the same aggregate owing primarily to the differences in strength and modulus. Therefore, the mix type does not seem to be a sensitive parameter for joint faulting.
    - Base type also appears to have a moderate impact on reducing the predicted faulting primarily due to the erodibility class definition associated with each base and their respective stiffnesses.
    - Tying the concrete shoulder to the mainline PCC slab did not have much influence on faulting (low impact).
    - Subgrade type and subgrade stabilization have a low to no impact on joint faulting.
    - Traffic composition and climate have a low impact on predicted joint faulting.
- Ride Quality or IRI
    - Not surprisingly, the impact of the various site and design factors studied on IRI prediction can, for the most part, be estimated by examining how they impact joint faulting.
    - PCC thickness and dowel diameter, CTE, slab width, transverse joint spacing, and edge support are all key parameters to reduce IRI.
    - The remaining factors studied have a lower impact on IRI.

Another way to interpret the results of the sensitivity analysis is to estimate the importance of the variables by examining how many models they affect to strength of their impact. Using this criterion, and narrowing the focus to those factors that are within the designer's control, it can be seen that PCC thickness, joint spacing, slab width, and CTE affect JPCP performance the most. They are followed by base type, edge support provided by tied shoulders, and PCC flexural strength and modulus combination.

HMA Overlays of Rubblized Concrete Pavements

Baseline Design

Figure 6 presents the pavement cross-section and materials used for the baseline HMA over Rubblized PCC design. As can be noted from the figure, the layer types and layer thicknesses of the HMA overlay are similar to those used in new HMA design. The existing JRCP layer is assumed to be rubblized and rolled per ODOT 320 specifications.

Table 12 lists the key inputs whose impact on the MEPDG outputs for this design type was studied in the sensitivity analysis attempted here. The table also presents the ranges over which these inputs were varied.

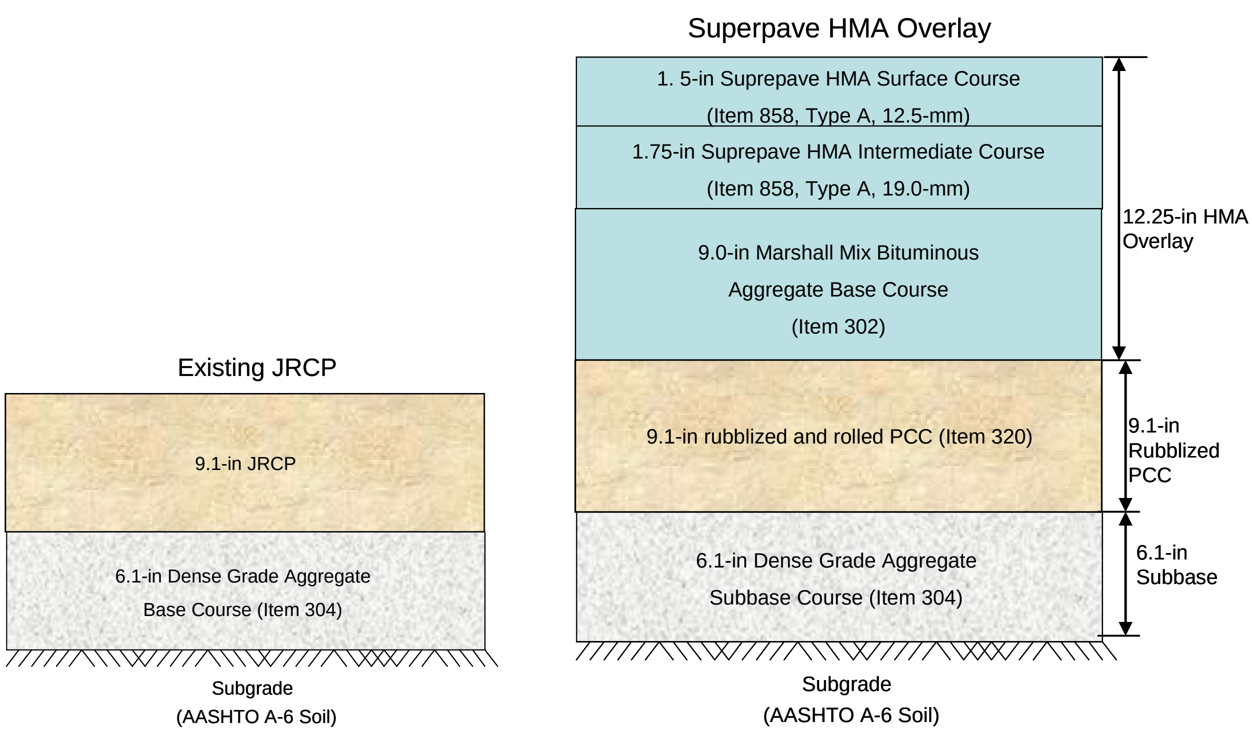

Figure 6. Baseline HMA over Rubblized PCC pavement design used in the sensitivity analysis.

Table 12. Input parameters of interest to be used for HMA over Rubblized PCC sensitivity analysis.

MEPDG Input Parameter	Levels of Input (*indicates the baseline representative design)
HMA overlay thickness	7-, 9-, 12.25*-, 14-, 16-in (varying the bituminous base thickness only)
HMA overlay air voids content	6.5-, 7.5-, 8.5-*, 9.5-, 10.5 percent
HMA overlay volumetric binder content	9-, 10-, 11.1-*, 12-, 13-percent
HMA overlay surface course type	• Superpave HMA Mix Surface Course, ODOT Item 442, Type A, 12.5mm, (MEPDG Layer 1)* • SMA surface course (Item 443), refer table 7of Volume 3 for more details
Rubblized PCC modulus	30,000-*, 75,000-, 150,000-psi
Rubblized PCC thickness	7-, 9-*, 11-in

* HMA over Rubblized PCC baseline project.

** Default MEPDG gradations will be used, where applicable.

*** For the sensitivity analysis, another HMA material type—stone matrix asphalt (SMA) (Item 443) was considered. For SMA, the 1.5-in surface course was replaced with the SMA surface course.

Sensitivity Analysis Results for HMA Overlay of Rubblized PCC Design

Table 13 summarizes the impact of each of the inputs varied on the MEPDG predicted HMA distress and smoothness outputs. Note that by and large trends in the sensitivity of the distress and smoothness predictions for the HMA over Rubblized PCC design are similar to that of a new HMA pavement built on a thick DGAB layer. All other inputs were kept the same as those assumed for the new HMA pavement model sensitivity study described previously in this chapter.

Based on the results, it is apparent that the HMA overlay thickness is perhaps the most important factor for this type of design followed by as-placed air voids and the stiffness of the rubblized layer. Interestingly, the thickness of the rubblized layer and the stiffness of the surface course (SMA versus conventional HMA) did not have much of an impact.

Table 13. Summary of the relative sensitivity of various HMA overlay factors on predicted distresses and smoothness for HMA over Rubblized PCC design using the MEPDG.

Input Variable	HMA Distress/Smoothness Model				
	Longitudinal Fatigue Cracking	**Thermal (Transverse) Cracking**	**Alligator Fatigue Cracking**	**Rutting**	**IRI**
HMA overlay type (surface course stiffness)	Low	Low	Low	Low	Low
HMA overlay thickness	< 7 in—High ↓ > 7 in—None	None	High ↓	High ↓	High ↓
HMA air voids content	None[1]	None[1]	High[2] ↑	Moderate[3] ↑	Low[3] ↑
Rubblized PCC Modulus	None	None	High ↓	Low ↓	Low ↓
Rubblized PCC Thickness	None	None	Moderate ↓	Low ↓	Low ↓

Unbonded JPCP Overlay

<u>Baseline Design</u>

Figure 7 presents the pavement cross-section and materials used for the baseline JPCP unbonded overlay of an existing JRCP. The JRCP is assumed to have 60-ft panels with transverse cracking approximately spaced at third points on each panel. Since it is not possible to specify a JRCP layer type in the MEPDG, the existing JRCP layer was modeled as a JPCP. This is not expected to affect the performance predictions of interest to this design.

Table 14 lists the key inputs whose impact on the MEPDG outputs for this design type was studied in the sensitivity analysis described in this section. The table also presents the ranges over which these inputs were varied. All other inputs were kept the same as those assumed for the new JPCP model sensitivity study described previously in this chapter.

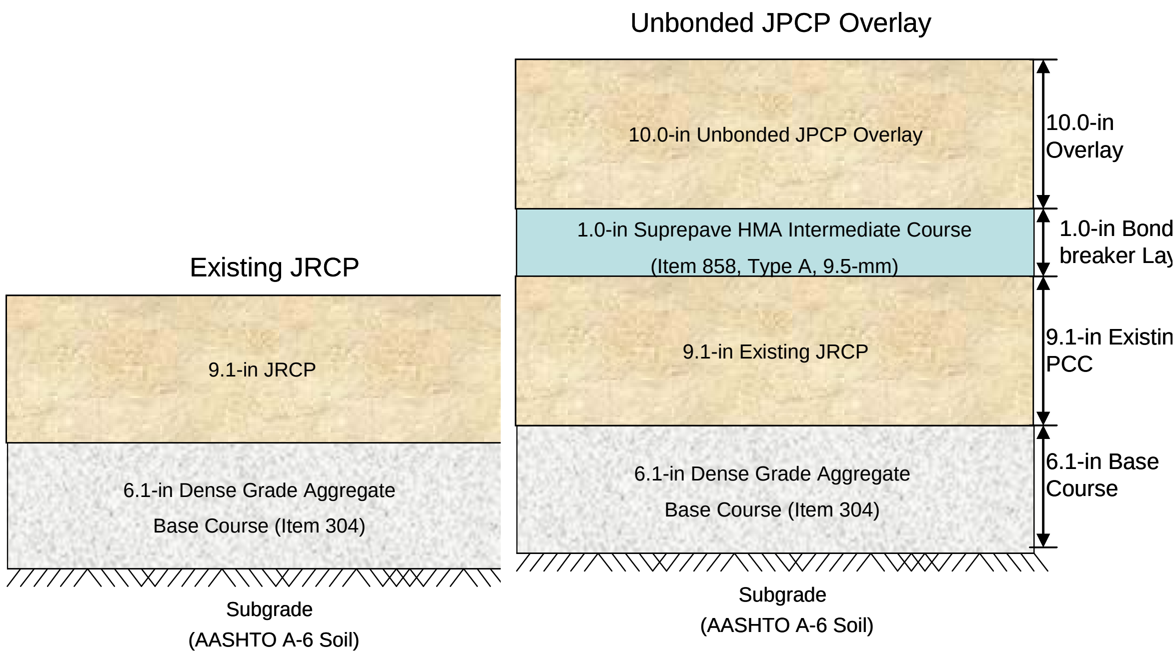

Figure 7. Baseline JPCP overlay over existing JRCP design (modeled as a JPCP).

<u>Sensitivity Analysis Results for Unbonded JPCP Overlay Design</u>

Table 15 summarizes the impact of each of the inputs varied on the MEPDG predicted JPCP distress and smoothness. By and large trends in the sensitivity of the distress and smoothness predictions for the unbonded JPCP overlay are similar to that of a new JPCP pavement on a strong base layer.

Based on the results, it is apparent that PCC overlay thickness, slab features (width, transverse joint spacing) and the CTE are the most important factors for this type of design. In this sense, this design type is very similar to a new JPCP design. The elastic modulus of the existing pavement layer, a surrogate parameter for the condition of the layer, also appears to be quite significant. Finally, as expected, the HMA interlayer thickness has low to no impact on the overlay design.

Table 14. Input parameters to be used for the unbonded overlay design sensitivity analysis.

MEPDG Input Parameter	Levels of Input (*Indicates the Baseline ODOT Representative Design)
HMA bond-breaker layer thickness	1.0-*,1.5-, and 2.0-in
Transverse joint load transfer efficiency (LTE) (for JPCP Overlay)	No dowel (0-in), 1.0-, 1.25-*, and 1.5-in
Limestone PCC CTE (for JPCP Overlay)	5.2-, 5.4-*, and 6.7x10^{-6}/^{o}F
PCC flexural strength and elastic modulus (for JPCP Overlay)	601-, 650-*, 736-, and 850-psi
PCC overlay thickness	8-, 9-, 10-*, 11-, 12-, 13-, and 14-in
PCC slab length (joint spacing) (for JPCP Overlay)	12.5-, 15.0-*, 17.5-, 20.0-, 22.5-ft
PCC slab width (for JPCP Overlay)	12-*, 13-, 14.0-ft
PCC concrete type (for JPCP Overlay)	Class C*, and high early strength concrete For the sensitivity analysis, other commonly used ODOT PCC material types were used. Specifically the following were considered: • ODOT class C concrete with limestone (PCC CTE = 5.4*10^{-6}/^{o}F). • ODOT class C concrete with gravel (PCC CTE = 6.4*10^{-6}/^{o}F). • ODOT class C concrete with slag (PCC CTE = 6.3*10^{-6}/^{o}F). • ODOT class S concrete with limestone (PCC CTE = 5.4*10^{-6}/^{o}F). • ODOT class S concrete with gravel (PCC CTE = 6.4*10^{-6}/^{o}F). • ODOT class S concrete with slag (PCC CTE = 6.3*10^{-6}/^{o}F). Default MEPDG input values were assumed for other PCC properties such as unit weight, Poisson's ratio, etc.
PCC aggregate type (for JPCP Overlay)	Gravel, Limestone*, and Slag
Existing JRCP elastic modulus	528,930; 1,301,981*; 2,400,527
Shoulder type	None (i.e., gravel, asphalt, and non-tied PCC) and tied PCC

Table 15. Summary of the relative sensitivity of various ODOT-specific design inputs on MEPDG unbonded JPCP overlay distress and smoothness predictions.

Input Variable	JPCP Distress/Smoothness Model		
	Mid-Slab or Fatigue Cracking[1]	**Faulting**	**IRI**
HMA bond-breaker layer thickness	Low ↓	None	None
PCC overlay thickness (and dowel diameter for faulting sensitivity analysis)	High ↓	High ↓	High ↓
PCC overlay CTE	High ↑	High ↑	High ↑
PCC overlay MR and E	High ↓	Low ↓	Low ↓
PCC overlay mix type and coarse aggregate type[2]	High	Low	Low
PCC overlay joint spacing	High ↑	High ↑	Low ↑
PCC overlay slab width	High ↓	High ↓	High ↓
Overlay pavement edge support	High ↓	Low ↓	Low ↓
Transverse joint LTE of JPCP overlay	None	High ↓	High ↓
Elastic modulus of existing JRCP (indirect factor for condition)	High ↓	Moderate ↓	Moderate ↓

[1] Includes both top-down and bottom-up cracking.

[2] Two PCC mix types—Class S and Class C—were considered. The main differences between these mix types are in MR, E, aggregate gradation, cement content. Three aggregates types commonly to Ohio were chosen for each of these mixes. More details are provided in Volume 3.

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CHAPTER 4. VALIDATION OF MEPDG DISTRESS PREDICTION MODELS USING ODOT LTPP SECTIONS

BACKGROUND

The backbone of the design methodology proposed in the MEPDG is distress and smoothness prediction models. The prediction models in the MEPDG were calibrated using data mostly from the LTPP database. The LTPP database contains pavement design, materials, climate, traffic, and performance data from several thousand flexible and rigid pavement projects from across the country including in Ohio. These distress and smoothness models are popularly known as "nationally" or "globally" calibrated models.

It has been recognized in the MEPDG that these nationally calibrated models will not necessarily predict pavement performance accurately for all local design, materials, and other conditions, or for a specific geographic area or State. Local calibration adjustments may thus be needed if (1) the inference space used in the national model development is not representative of the local site and design factors and (2) if significant differences are found between the predicted and measured distresses and smoothness.

Given this, it should be pointed out that local calibration should only be performed after a rigorous validation study indicates that there is a bias or error in pavement performance predictions for a local condition. Also, since the MEPDG has a sound mechanistic basis, the validation can be performed with relatively fewer data points than a purely empirical approach.

Thus, for this project, a validation exercise was performed as the first step to determine if the nationally calibrated models were sufficiently accurate when used to predict the performance of the real-world pavements in Ohio.

SCOPE

Although both new and rehabilitated pavements were of interest to Ohio, the model validation effort was limited to only new or reconstructed HMA pavements and JPCP. Although, HMA overlaid rubblized PCC and unbonded JPCP overlays of existing PCC pavement were also of interest to ODOT, they were not considered in this validation study due to lack of data required to complete a meaningful validation study. The following performance indicators and thus, MEPDG prediction models, were investigated in this project:

- HMA pavements
  - Total rutting.
  - Load related alligator cracking, bottom initiated cracks.
  - Transverse "thermal" cracking.
  - Smoothness (measured as International Roughness Index [IRI]).
- JPCP
  - Mean transverse joint faulting.
  - Load related transverse slab cracking (includes both bottom and surface initiated cracks).
  - Smoothness (IRI).

These performance indicators/models are the predominant structural and functional distress that occurs on the selected pavement types in the State and are the basis for triggering maintenance and rehabilitation. Other models such as longitudinal (top down) cracking of HMA pavements, although of interest to ODOT, were not investigated since they are subjects of active national research at this point in time.

Note that a detailed description of these models has been presented in Volume 4 of this report.

LTPP PROJECTS USED FOR MODELS EVALUATION

The Ohio LTPP database contains design, materials, construction, site (i.e., traffic, climate, and subgrade), and performance information for wide ranging pavement project types in Ohio. A majority of these sections were either new HMA pavements or JPCP and are designated LTPP SPS-1, SPS-2, SPS-8, SPS-9, or GPS-3 experiments. Figure 8 shows the geographic distribution of these projects, and Table 16 presents the basic design information from these projects. More detailed information on these projects can be obtained from Volume 4 of this report.

The LTPP SPS-1, SPS-2, SPS-8, and SPS-9 projects are located on a 3.3-mi section of U.S. Route 23 in Delaware County, 25 miles north of Columbus (also known as the Ohio SHRP Test Road or the DEL 23 site). The site's flat topography and uniform soil conditions and climate make it ideal for pavement experiments.

Figure 8. Map showing selected Ohio LTPP projects used for model validation.

Table 16. Detailed summary of project type and design features.

SPS-1 (Southbound)				
Section	Station	AC Thickness (in.)	Base Type and Thickness	Drains
390101	355+00-350+00	7	8" DGAB	No
390102	375+00-370+00	4	12" DGAB	No
390103	420_75-415+75	4	8" ATB	No
390104	341+00-336+00	7	12" ATB	No
390105	392+50-387+50	4	4" ATB/4" DGAB	No
390106	348+00-343+00	7	8" ATB/4" DGAB	No
390107	363+00-358+00	4	4" PATB/4"DGAB	Yes
390108	399+75-394+75	7	4" ATB/8" DGAB	Yes
390109	406+50-401+50	7	4" PATB/12" DGAB	Yes
390110	413+50-408+50	7	4" ATB/4" PATB	Yes
390111	333+00-328+00	4	8" ATB/4" PATB	Yes
390112	325+00-320+00	4	12" ATB/4" PATB	Yes
390159	433+00-428+00	4	15" ATB/4" PCTB/6" DGAB	Yes
390160	382+00-377+00	4	11" ATB/4"DGAB	Yes
SPS-8 (Ramp)				
Section	Station	AC Thickness (in.)	Base Type and Thickness	Drain
390803	19+19-14+90	4	8" DGAB	No
390804	13+50-8+50	7	12" DGAB	No
SPS-9 (Southbound)				
Section	Station	AC Thickness (in.)	Base Type and Thickness	Drain
390901	282+5-277+75	4 (AC-20)	12" ATB/4" PATB/6" DGAB	Yes
390902	302+50-297+50	4 (PG58-28)	12" ATB/4" PATB/6" DGAB	Yes
390903	291+00-286+00	4 (PG64-28)	12" ATB/4" PATB/6" DGAB	Yes

Table 16. Detailed summary of project type and design features, continued.

SPS-2 (Northbound)						
Section	Station	PCC Layer		Lane Width (ft.)	Base Type and Thickness	Drain
		Strength (psi)	Thickness (in.)			
390201	343+00-348+00	ODOT	8	12	6" DGAB	No
390202	319+00-324+00	900	8	14	6" DGAB	No
390203	384+00-389+00	ODOT	11	14	6" DGAB	No
390204	275+50-280+50	900	11	12	6" DGAB	No
390205	335+75-340+75	ODOT	8	12	6" LCB	No
390206	327+50-332+50	900	8	14	6" LCB	No
390207	391+25-396+25	ODOT	11	14	6" LCB	No
390208	397+75-402+75	900	11	12	6" LCB	No
390209	350+25-355+25	ODOT	8	12	4" PATB/4" DGAB	Yes
390210	303+50-308+50	900	8	14	4" PATB/4" DGAB	Yes
390211	369+00-374+00	ODOT	11	14	4" PATB/4" DGAB	Yes
390212	294+00-299+00	900	11	12	4" PATB/4" DGAB	Yes
390259	265+50-270+50	900	11	12	6" DGAB	Yes
390260	311+50-316+50	ODOT	11	12	4" PATB/4" DGAB	Yes
390261	357+75-362+75	ODOT	11	14	4" PCTB/4" DGAB	Yes
390262	405+25-410+25	ODOT	11	12	4" PCTB/4" DGAB	Yes
390263	414+50-419+50	ODOT	11	14	6" DGAB	Yes
390264	422+50-427+50	ODOT	11	12	6" DGAB	Yes
390265	376+10-381+10	ODOT	11	12	4" PATB/4" DGAB	Yes

SPS-8 (Ramp)						
Section	Station	PCC Layer		Lane Width (ft.)	Base Type and Thickness	Drain
		Strength (psi)	Thickness (in.)			
390809	25+90-20+90	550	8	11	6" DGAB	No
390810	32+50-27+50	550	11	11	6" DGAB	No

Section	**Station**	**PCC Layer**		**Lane Width (ft)**	**Base Type and Thickness**	**Drain**
		Strength (psi)	**Thickness (in)**			
393013	21.7	880	8.3	12	4″ Soil Cement	No
393801	12.33	750	9.2	12	4.4′ CTB	Yes

*Strength = 14-day PCC flexural strength.

- Three of the four LTPP experiments at this site are located on new traffic lanes built in the median of U.S. 23 as follows:
    - The new northbound lane contains an LTPP SPS-2 experiment, which compares the performance of different structural designs for PCC pavements.
    - The new southbound lane contains an SPS-1 experiment, which compares different structural designs for asphalt concrete pavements.
    - The new southbound lane also includes an SPS-9 experiment to validate the SuperPave binder specification and to evaluate the performance of SuperPave mixes relative to the ODOT's own asphalt mix.
- Two LTPP SPS-8 experiments (HMA and JPCP) intended to isolate the effects of climate on PCC and HMA pavements are located on a southbound on-ramp to the old lanes of U.S. 23 are now serving as low-volume frontage roads.
- The SPS-1, SPS-2, and SPS-9A pavements carried an average annual daily traffic (ADT) of 26,000 vehicles, 20 percent of which are trucks when opened to traffic in 1996.

The LTPP GPS-3 (new JPCP) projects, LTPP 39_3013 and 39_3801, were constructed in 1970 and 1983, respectively. LTPP 39_3013 is located on the southbound (outer lane) of US 68, southeast of Cincinnati, approximately 1.7 mi north of St-125 and south of Hamer Road. LTPP 39_3801 is located on the southbound (outer lane) of US 7, south of Wheeling, approximately 0.46 mi south of St-147.

Six LTPP SPS 1 projects failed and were replaced soon after they were constructed and opened to traffic and were replaced shortly after. Both the failed projects and replacements were not used in analysis. Also, SPS 8 projects were excluded from analysis due to (1) the JPCP's designs were not typical and thus could not be modeled by the MEPDG, and (2) the two HMA sections failed prematurely.

MEPDG MODEL VALIDATION

The comparisons between MEPDG predicted and field measured distress/IRI for new HMA as well as new JPCP pavements are summarized in this section. Details of model validation effort are presented in Volume 4 of this report.

Both statistical and non-statistical methods were used singly or in combination to evaluate model adequacy. Non-statistical methods were used for situations where field measured distress or IRI was mostly zero or close to zero. For such situations, computation of diagnostic statistics such as coefficient of determination (R^2) and standard error of the estimate (SEE) used to evaluate model adequacy was either not possible or meaningless. The measured and predicted distress/IRI was categorized into many groups with their range determined based on engineering judgment. A simple comparison was made of these groups to determine how often measured and predicted distress/IRI remained in the same group. Measured and predicted distress remaining in the same group implied reasonable and accurate predictions, while measured and predicted distress residing in different groups suggested otherwise.

Statistical methods were used for model validation when the measured distress/IRI values were well above zero. The MEPDG predictions were compared with measured distress/IRI using statistical analysis to evaluate the model adequacy. Model adequacy was determined using the diagnostic statistics:

Determine Model Prediction Capability:

The predictive capability of a given performance model was assessed by determining the correlation between the predicted and measured distress/IRI. The coefficient of determination, R^2 was used as the diagnostic statistic to evaluate model adequacy. The estimated R^2 was compared with R^2 obtained from Table 17. Engineering judgment was then used to determine the reasonableness of the estimated R^2. A poor correlation (R^2<50) implied the MEPDG distress/IRI prediction model was not predicting distress/IRI reasonably and may need to be recalibrated to improve prediction capability.

Estimate Model Accuracy

The standard error of the estimate (SEE) was used as the diagnostic statistic to determine model accuracy. The estimated SEE was compared with SEE obtained from Table 17. Engineering judgment was then used to determine the reasonableness of the SEE.

Determine bias

Bias was determined by performing linear regression using the measured and predicted distress/IRI and performing the following three hypothesis tests in the sequence listed.

- Hypothesis 1: Determining whether the linear regression model developed using measured and MEPDG predicted distress/IRI has an intercept of zero.
- Hypothesis 2: Determine whether the linear regression model developed using measured and MEPDG predicted distress/IRI has a slope of 1.0.
- Hypothesis 3: Determine whether the measured and MEPDG predicted distress/IRI represented the same population of distress/IRI using a paired t-test.

A significance level (α) of 0.05 or 5 percent was assumed for all hypothesis testing. A rejection of any of the null hypothesis implied that the model was biased and therefore the identified bias should be removed through recalibration. Models that successfully passed all three tests were deemed to be unbiased.

Both the non-statistical and statistical methods were as appropriately applied to determine the overall adequacy of MEPDG distress/IRI models. The models were recalibrated where they were deemed inadequate for Ohio conditions, and evaluated again for their prediction capacity, accuracy, and bias. For this study, statistical analysis was performed using the SAS statistical software. (SAS 2004).

Table 17. Summary of NCHRP 1-40D new HMA and new JPCP model statistics.

Pavement Type	**Performance Model**	**Model Statistics**		
		Coefficient of Determination, R^2	**Standard Error of Estimate, SEE**	**Number of Data Points, N**
New HMA	Alligator cracking	0.275	5.01 percent	405
	Transverse "thermal" cracking	Level 1*: 0.344 Level 2*: 0.218 Level 3*: 0.057	—	—
	Rutting	0.58	0.107 in.	334
	IRI	0.56	18.9 in./mi.	1926
New JPCP	Transverse "slab" cracking	0.85	4.52 percent	1505
	Transverse joint faulting	0.58	0.033 in.	1239
	IRI	0.60	17.1 in./mi.	163

*Level of inputs used for calibration.

Comparison of Measured and Predicted Distress/Smoothness for New HMA Pavements

HMA Alligator Cracking

Validation and Recalibration

As discussed in chapter 3 of Volume 4, the alligator cracking data recorded on the LTPP SPS-1 and SPS-2 projects were confounded with premature longitudinal cracking associated with construction defects. It was not possible to separate construction related premature cracking from fatigue related bottom-up (or alligator) or top-down cracking; hence, the alligator cracking model was not evaluated or recalibrated due to a lack of adequate data for analysis.

HMA Transverse Cracking

Validation

For the LTPP projects selected for model validation, it was reported that the majority of the sites had minimal transverse cracking with approximately 90 percent of the measured values ranging between 0 to 20 ft/mi. Hence, there was not sufficient data to assess model accuracy and bias using conventional statistical methods. Therefore, a simple non-statistical comparison of measured and predicted transverse cracking was adopted based on the approach described earlier. The results presented in Table 18 indicate that all the measured and predicted transverse cracking fell in the same group of 0-250 ft/mile. Therefore, it is recommended that ODOT use the nationally calibrated MEPDG transverse cracking model for routine design. However, based on the researchers' experience with MEPDG implementation efforts with other agencies, the MEPDG default inputs for HMA overestimate the true creep compliance of HMA mixes and underestimate thermal cracking. This discrepancy is more profound in colder climates than warmer regions. Therefore, it is recommended that ODOT reassess the thermal cracking model using data from northern Ohio sites before making a final decision.

Recalibration

Although the predictions for the SPS-1 and 9 sites selected are reasonable, given the fact that all these sites are located in a single climatic region, it is recommended that the model's prediction capability be reassessed using data from colder sites in Ohio.

Table 18. Comparison of measured and predicted transverse cracking.

MEPDG Measured Transverse Cracking, ft/mi	MEPDG Predicted Transverse Cracking, ft/mi			
	0-250	**250-500**	**500-1000**	**1000-2000**
0-250	71	0	0	0
250-500	0	0	0	0
500-1000	0	0	0	0
1000-2000	0	0	0	0

HMA Rutting

Validation

The measured rutting from the LTPP projects used for model validation ranged from 0.06 in. to 0.41 in. with a mean of 0.17 in. A statistical analysis of measured and predicted rutting was performed to assess the adequacy of the nationally calibrated HMA rutting model. The results of the statistical analysis are presented in Table 19 and Figure 9. As indicated in Figure 9, the MEPDG nationally calibrated rutting model consistently overpredicted rutting. The statistics in Table 19 indicated the following:

- Only a fair correlation (R^2 = 0.64) between measured and MEPDG predicted rutting.
- SEE less than that reported for the national MEPDG rutting model.
- More importantly, significant bias between the measured and predicted rutting.

The model intercept was greater than zero thus indicating overpredicting nature of MEPDG nationally calibrated rutting model. The measured rutting was statistically not equal to predicted rutting. Therefore, to improve the model accuracy of the nationally calibrated rutting model, an attempt was made to recalibrate the model.

Given the fact the data set considered for model recalibration is small and all sections were from a single location, this recalibration effort should be viewed more as a feasibility or model exercise. A more rigorous effort involving a larger data set of sections that are more representative of the diverse design and site factors that exist in Ohio will be needed for the results to be valid for a general design/analysis use.

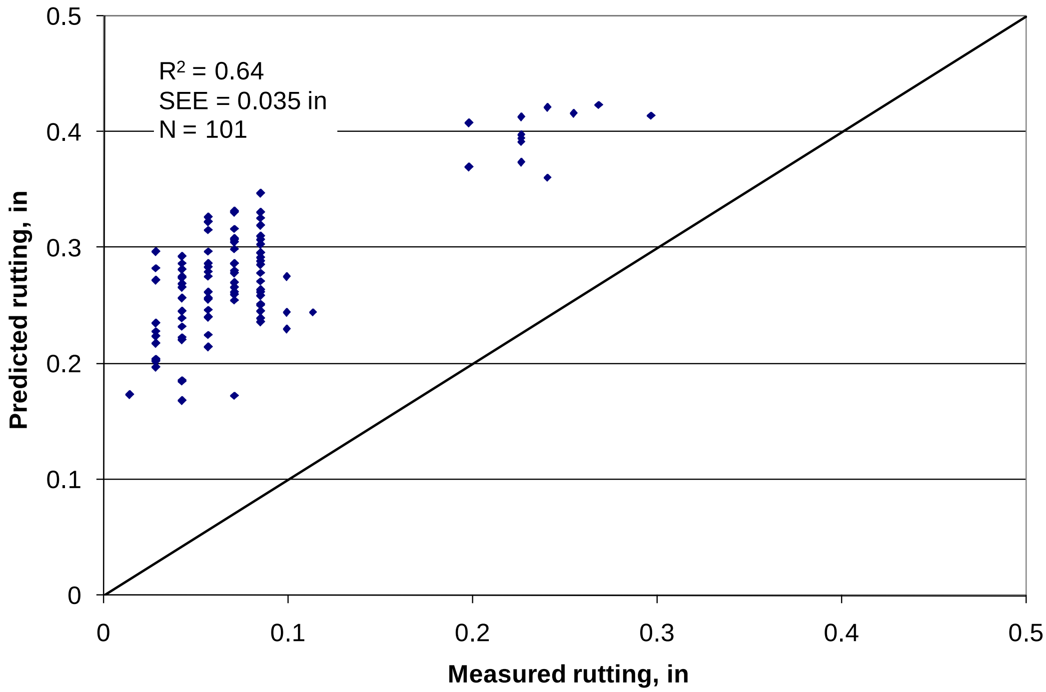

Figure 9. Plot of measured versus MEPDG predicted HMA pavement total rutting.

Table 19. Statistical comparison of measured and predicted rutting data.

Goodness of Fit

N = 101
R^2 = 0.64
Adj R^2 = 0.64
SEE = 0.035 in

Hypothesis Testing

Hypothesis	DF	Parameter Estimate	Std. Error	t Value	p-value (Pr > |t|)	95 Percent Confidence Limits	
(1) Ho: Intercept = 0	1	0.2178	0.0059	36.8	<0.0001	0.21	0.23
(2) Ho: Slope = 1.0	1	1.02280	0.0571	13.49	<0.0001	0.65	0.88
(3) Ho: Measured Rutting – MEPDG Predicted Rutting = 0	101			-52.7	<0.0001		

Recalibration

In the process of model recalibration, a thorough review of rutting predictions by individual structural layers was performed. Findings of this review are described below:

- Considering the fact that most of the SPS-1 and SPS-9 sections have relatively thick HMA layers, the contribution of HMA layer rutting (about 17 to 44 percent) to total rutting was proportionately higher. Therefore, the contribution from unbound layers and subgrade to total rutting needed to be reduced by adjusting the submodel coefficients for unbound base (β_{S1}) and subgrade (β_{S2}).

- The slope of the rutting versus age (traffic) curve was not matched adequately by the MEPDG. As a result, the MEPDG over-predicted rutting for the lower magnitudes of measured rutting and under-predicted rutting for the higher magnitudes of measured rutting. This requires an adjustment to the β_{2r} and β_{3r} of the HMA rutting submodel. Adjustments to these coefficients should be based on laboratory investigation of accumulation of permanent deformation with repeated loadings.

Based on the findings of the review, recalibration was limited to modifying the local calibration coefficient β_{1r} of the HMA rutting submodel and the local calibration coefficients β_{S1} and β_{S2} of the base and subgrade rutting submodels. The recalibrated model is presented below:

$$TRUT = 0.51*ACRUT + 0.32*BASERUT + 0.33*SUBGRUT$$

Where,

TRUT = Total rutting
ACRUT = Rutting in the asphalt layers predicted using the 1-40D models
BASERUT = Rutting in the base layer predicted using the 1-40D models
SUBGRUT = Rutting in the subgrade layer predicted using the 1-40D models
β_{1r} = HMA rutting prediction local calibration factor = 0.51
β_{B1} = Unbound base rutting prediction local calibration factor = 0.32
β_{s1} = Subgrade rutting prediction local calibration factor = 0.33

A detailed description of the models is presented in chapter 2 of Volume 4.

A statistical evaluation of the recalibrated HMA rutting model was performed to determine accuracy and precision. The results, presented in Figure 10 and Table 20, indicate the following:

- A fair correlation (R^2 = 0.63) between measured and MEPDG predicted rutting.
- SEE much less than that reported for the national MEPDG rutting model.
- Significant bias in predicted and measured rutting, as indicated by the results of hypotheses (1) and (3).

Although the goodness of fit of the recalibrated model was adequate, the model predictions still were significantly biased, suggesting that the revised model is still deficient. The presence of bias post recalibration was due mainly to the inability of the MEPDG to match the shape of the rutting versus age (traffic) curve. A more comprehensive evaluation of ODOT HMA pavement mixtures and a larger calibration data set will be necessary to calibrate the models for ODOT conditions.

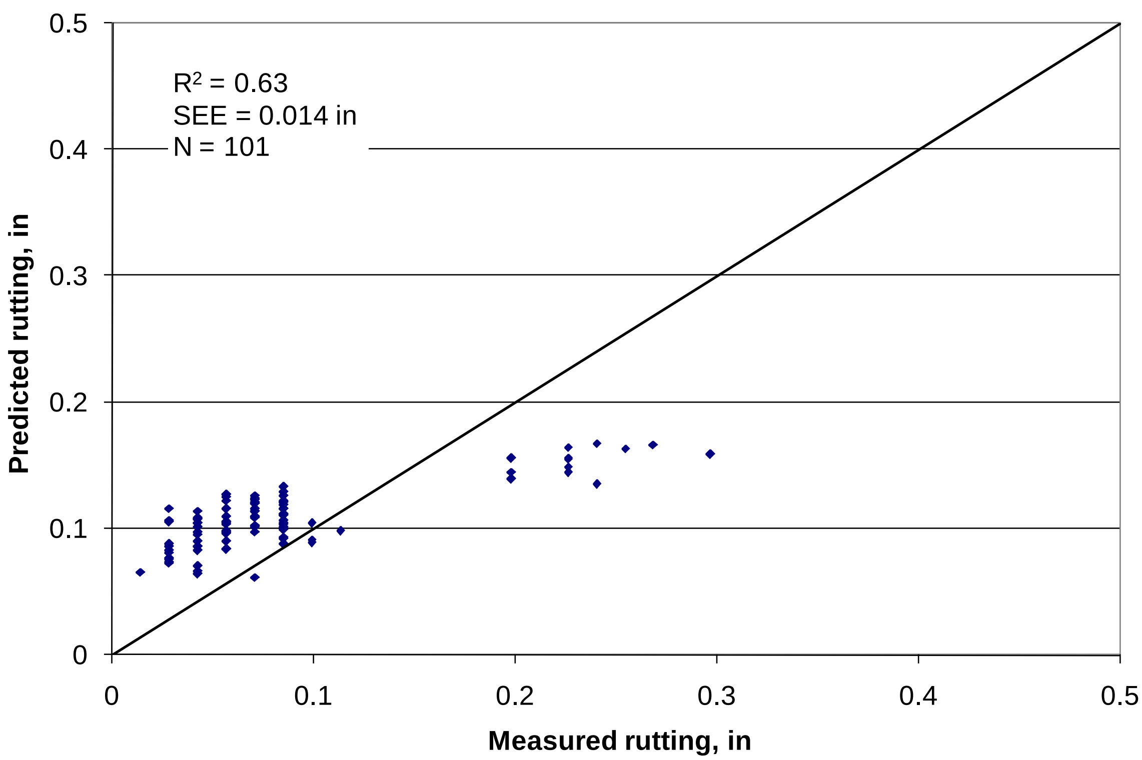

Figure 10. Plot of measured versus MEPDG predicted HMA total rutting.

Table 20. Statistical comparison of measured and recalibrated rutting model predicted rutting data.

Goodness of Fit

N = 101
R^2 = 0.63
Adj R^2 = 0.63
SEE = 0.014 in

Hypothesis Testing

Hypothesis	DF	Parameter Estimate	Std. Error	t Value	p-value (Pr > |t|)	95 Percent Confidence Limits	
(1) Ho: Intercept = 0	1	0.083	0.0024	34.4	< 0.0001	0.078	0.087
(2) Ho: Slope = 1.0	1	0.952	0.049	19.4	0.3395	0.855	1.05
(3) Ho: Measured Rutting – MEPDG Predicted Rutting = 0	101			-5.62	< 0.0001		

HMA Smoothness (IRI)

Validation

A statistical comparison of measured and MEPDG predicted rutting was performed to assess the adequacy of the nationally calibrated HMA IRI model. The results of the statistical analysis, presented in Table 21 and Figure 11 indicated the following:

- A poor correlation (R^2 = 0.008) between measured and MEPDG predicted IRI.
- SEE less than that reported for the national MEPDG rutting model.
- There is significant bias in predicted IRI. The slope of the model was much flatter and indicated that the MEPDG over-predicts the IRI for the lower magnitudes of measured IRI and under-predicts it for the higher magnitudes of measured IRI.

The nationally calibrated HMA IRI model was needed to be recalibrated to remove the identified bias in prediction. Just as with the rutting model recalibration effort, this recalibration effort should be viewed as an example or model exercise. To be implementable in design, a broader data set including sections representing the diverse site and design factors in Ohio will be needed.

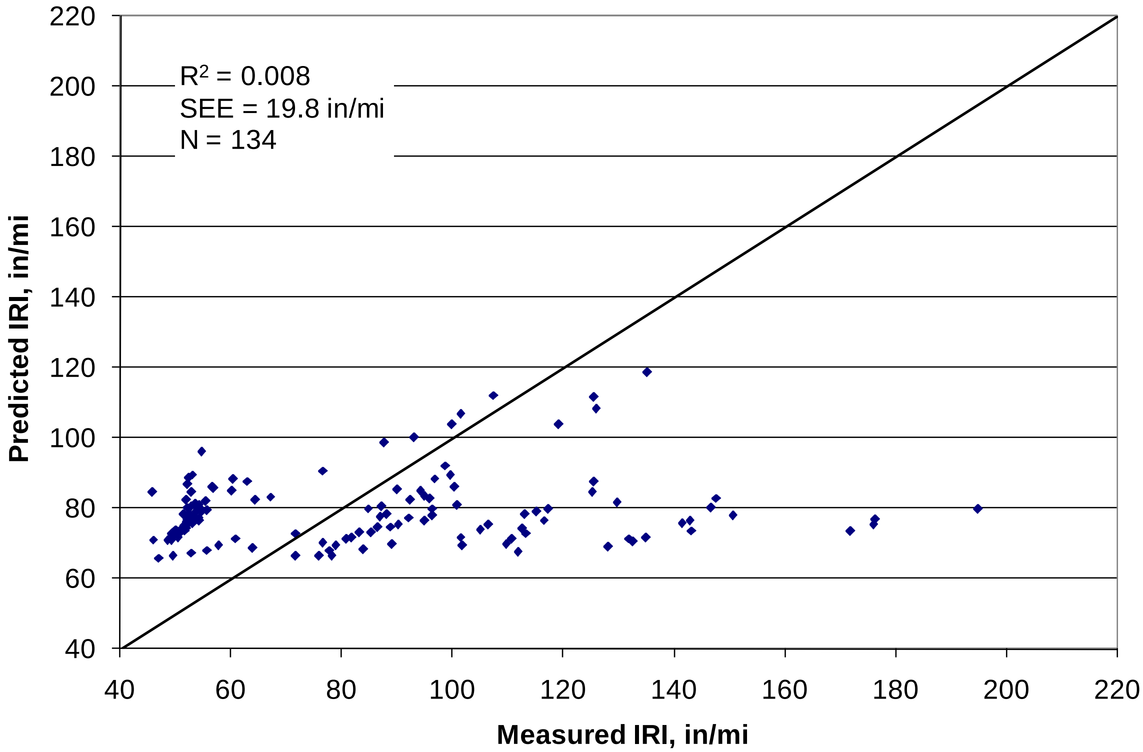

Figure 11. Plot of measured versus MEPDG predicted HMA pavement IRI.

Table 21. Statistical comparison of measured and MEPDG predicted IRI data.

Goodness of Fit							
N = 134 R^2 = 0.008 Adj R^2 = 0.0009 SEE = 9.8 in/mi							
Hypothesis Testing							
Hypothesis	**DF**	**Parameter Estimate**	**Std. Error**	**t Value**	**p-value (Pr > |t|)**	**95 Percent Confidence Limits**	
(1) Ho: Intercept = 0	1	76.6	2.48	30.8	<0.0001	71.7	81.5
(2) Ho: Slope = 1.0	1	1.008	0.032	31.2	0.78	0.94	1.07
(3) Ho: Measured IRI – MEPDG Predicted IRI = 0	134			-4.18	<0.0001		

Recalibration

Recalibration involved modifying the original MEPDG HMA IRI prediction model as follows:

$$IRI = IRI_o + \alpha_1(SF) + \alpha_2(FC_{Total}) + \alpha_3(TC) + \alpha_4(RD)$$

where:

IRI_o	=	Initial IRI after construction, in/mi
SF	=	Site factor
FC_{Total}	=	Percent total lane area fatigue cracking
TC	=	Length of transverse cracking, ft/mi.
NRD	=	Average rut depth
α_1, α_2, α_3, α_4	=	Model coefficients

The site factor is calculated in accordance with the following equation.

$$SF = FROSTH + SWELL * AGE^{1.5}$$

where:

FROSTH	=	LN([PRECIP+1]*FINES*[FI+1])
SWELLP	=	LN([PRECIP+1]*CLAY*[PI+1])
FINES	=	FSAND + SILT
AGE	=	pavement age, years
PI	=	subgrade soil plasticity index
PRECIP	=	mean annual precipitation, in.
FI	=	mean annual freezing index, deg. F Days
FSAND	=	amount of fine sand particles in subgrade (percent of particles between 0.074 and 0.42 mm)
SILT	=	amount of silt particles in subgrade (percent of particles between 0.074 and 0.002 mm)
CLAY	=	amount of clay size particles in subgrade (percent of particles less than 0.002 mm)

Recalibration of MEPDG HMA IRI model was done by modifying the model coefficients, α_1, α_2, α_3 and α_4. The recalibrated model with new model coefficients is presented below:

$$IRI = IRI_o + 0.066(SF) + 1.37(FC_{Total}) + 0.01(TC) + 17.6(RD)$$

where all variables are as already defined.

A statistical comparison of measured and MEPDG predicted HMA IRI was performed to assess the adequacy of recalibrated model. The results are presented in Figure 12 and Table 22.

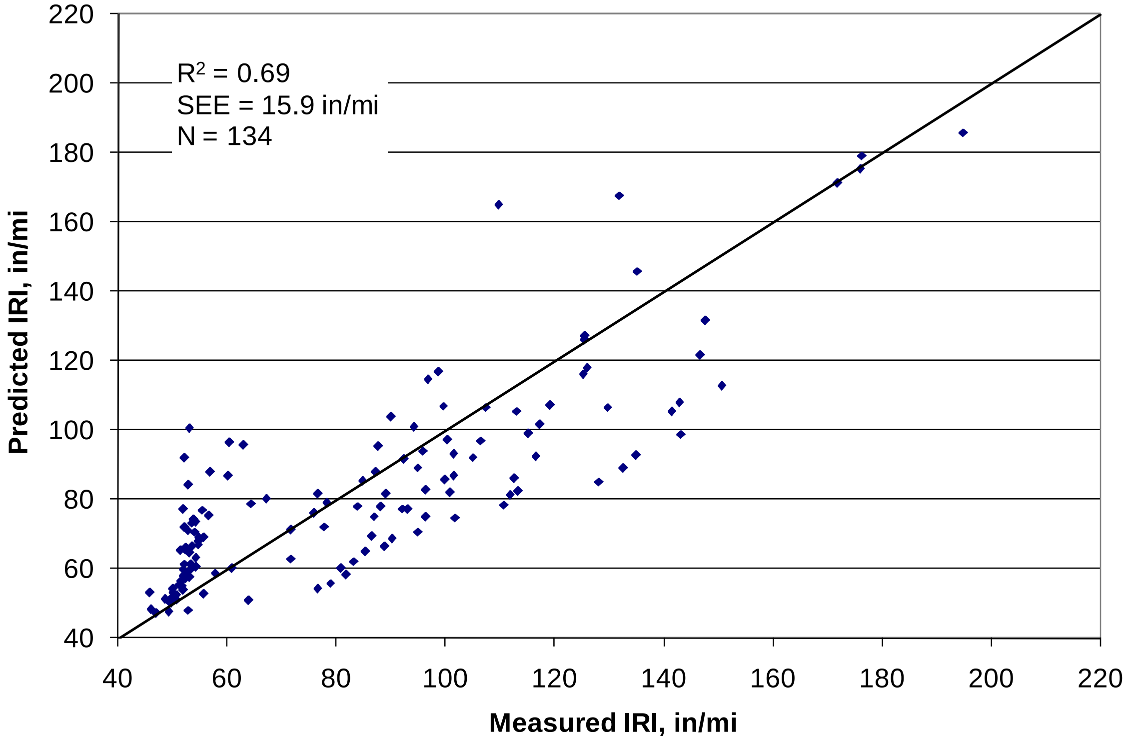

Figure 12. Plot of measured versus MEPDG predicted HMA pavement IRI.

Table 22. Statistical comparison of measured and predicted recalibrated HMA model IRI data.

Goodness of Fit

N = 134
R^2 = 0.69
Adj R^2 = 0.69
SEE = 15.9 in/mi

Hypothesis Testing

Hypothesis	DF	Parameter Estimate	Std. Error	t Value	p-value (Pr > |t|)	95 Percent Confidence Limits	
(1) Ho: Intercept = 0	1	22.9	3.67	6.25	< 0.0001	17.7	30.2
(2) Ho: Slope = 1.0	1	0.95	0.017	54.7	< 0.0027	0.912	0.981
(3) Ho: Measured IRI – Recalibrated Model Predicted IRI = 0	134			0.75	0.455		

The results indicated the following:

- A good correlation ($R^2 = 0.69$) between measured and predicted smoothness from the recalibrated HMA IRI model.
- SEE was about the same as the original MEPDG HMA IRI model.
- Although both hypotheses (1) and (2) were rejected and hypothesis (3) accepted, the levels of bias reported were more reasonable when compared to the nationally calibrated model. Bias in the recalibrated rutting model seems to be reflecting in the IRI model.

Sensitivity Analysis for Recalibrated HMA Rutting and IRI Models

A supplementary sensitivity analysis was performed to assess the reasonableness of recalibrated HMA rutting and HMA IRI models. The goal of this analysis was to compare the predictions of recalibrated and nationally calibrated models to evaluate the effects of key factors that influence HMA rutting and smoothness. The following key factors were selected for sensitivity analysis:

- Base type - Dense graded aggregate base (DGAB) and asphalt treated base (ATB)
- Climate - Cincinnati (South) and Cleveland (North)
- HMA Thickness - 5" and 11"
- Subgrade - Fine-grained (A-7-6) and Coarse grained (A-1-b)
- HMA air voids in bottom layer - 5.5% and 10.5%
- HMA air voids in top layer - 7.5% and 10.5%

The sensitivity analysis indicates that the rutting and smoothness predictions using recalibrated HMA rutting and HMA IRI models were consistently lower for those predictions of nationally calibrated models. The trends indicated that the predictions of the recalibrated models were reasonable and as expected. More detailed information is provided in chapter 5 of Volume 4.

Comparison of Measured and Predicted Distress/Smoothness for New JPCP

Transverse Slab Cracking

Validation and Recalibration

Sixty-six of the 68 reported measurements of percent slabs cracked were zero for the LTPP projects selected for validation of MEPDG JPCP transverse cracking model. Therefore, the non-statistical approach was selected for model evaluation. The results of this evaluation are summarized in Table 23. The results indicate that approximately 97% of the measured and predicted faulting data fell within the same grouping. All of these were for pavements with very little cracking distress. The JPCP transverse cracking model predicted cracking with reasonable accuracy and without significant bias for the distress levels evaluated in this analysis.

Therefore, it is recommended that ODOT use the nationally calibrated MEPDG transverse cracking model for routine design. Recalibration of the MEPDG JPCP transverse cracking model was not warranted at this stage. However, this model has not been evaluated with moderate to highly distressed pavements due to lack of such projects. Therefore, it is recommended to repeat the validation exercise to improve the model accuracy, as additional data becomes available from projects that fully represented Ohio site and pavement design and construction practices.

Table 23. Comparison of measured and predicted transverse slab cracking (percentage of all data points).

Measured Percent Slabs Cracked	MEPDG Predicted Percent Slabs Cracked							
	0-2	2-5	5-10	10-20	20-40	40-60	60-80	80-100
0-2	66	0	0	0	0	0	0	0
2-5	1	0	0	0	0	0	0	0
5-10	1	0	0	0	0	0	0	0
10-20	0	0	0	0	0	0	0	0
20-40	0	0	0	0	0	0	0	0
40-60	0	0	0	0	0	0	0	0
60-80	0	0	0	0	3	8	0	0
80-100	0	0	0	0	0	0	0	0

*Total data points = 68.

Transverse Joint Faulting

Validation and Recalibration

The measured mean joint faulting ranges from 0 to 0.14 in. for LTPP sites selected for model validation. A statistical comparison of measured and MEPDG predicted transverse joint faulting was performed to determine the model adequacy. The results presented in Table 24 and Figure 13 indicated the following:

- A good correlation (R^2=0.71) between measured and MEPDG predicted faulting.
- SEE less than that reported for the national MEPDG faulting model.
- No bias in predicted and measured faulting as indicated by the results of hypotheses (1), (2), and (3).

Therefore, it can be concluded that the MEPDG mean joint faulting model's prediction capacity was very good and had no significant bias. However, recalibration of this model is still warranted given the limited number of sections with higher magnitude of joint faulting. However, as additional data becomes available from pavements with higher levels of joint faulting, the model validation exercise can be repeated to verify the findings and to improve the model accuracy.

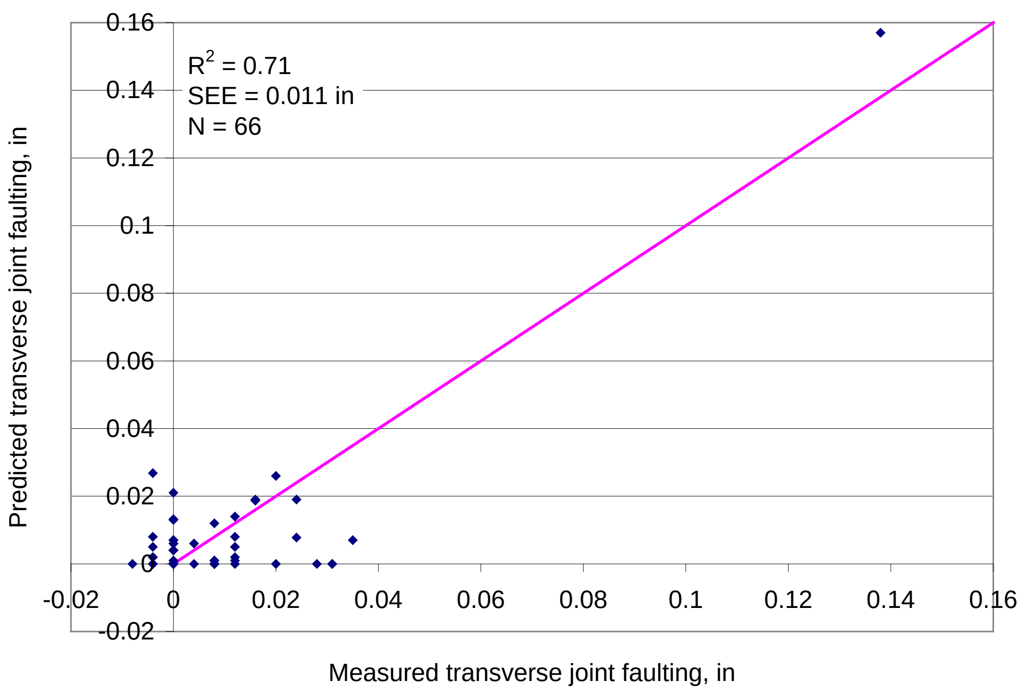

Figure 13. Plot of measured versus MEPDG predicted JPCP faulting.

Table 24. Statistical comparison of measured and MEPDG predicted transverse joint faulting data.

Goodness of Fit							
N = 66 R^2 = 0.71 Adj R^2 = 0.71 SEE = 0.011 in							
Hypothesis Testing							
Hypothesis	**DF**	**Parameter Estimate**	**Std. Error**	**t Value**	**p-value (Pr > |t|)**	**95 Percent Confidence Limits**	
(1) Ho: Intercept = 0	1	0.00009745	0.00141	0.07	0.9452	-0.00272	0.00292
(2) Ho: Slope = 1.0	1	0.88807	0.06499	2.97	0.0897	0.75830	1.01783
(3) Ho: Measured Faulting – MEPDG Predicted Faulting = 0	66			-0.55	0.5823		

JPCP Smoothness (IRI)

Validation

The measured IRI data ranged from 60 to 250 in/mi with a mean of 81 in/mi for the LTPP projects selected for model evaluation. A statistical comparison of the measured and MEPDG predicted IRI was performed. The results, as presented in Figure 14 and Table 25, indicated the following:

- An excellent correlation (R^2=0.98) between measured and predicted IRI.
- SEE less than that reported for the national MEPDG JPCP IRI model.
- Bias in predicted and measured JPCP IRI as indicated by the results of hypotheses (1), (2), and (3).

In spite of excellent predictive capacity of the model, there was a need to recalibrate the nationally calibrated model to remove bias.

Recalibration

The review of measured and predicted JPCP IRI indicated no obvious source of bias. Recalibration involved modifying the coefficients (C1, C2, C3 and C4) of the original MEPDG JPCP IRI prediction model.

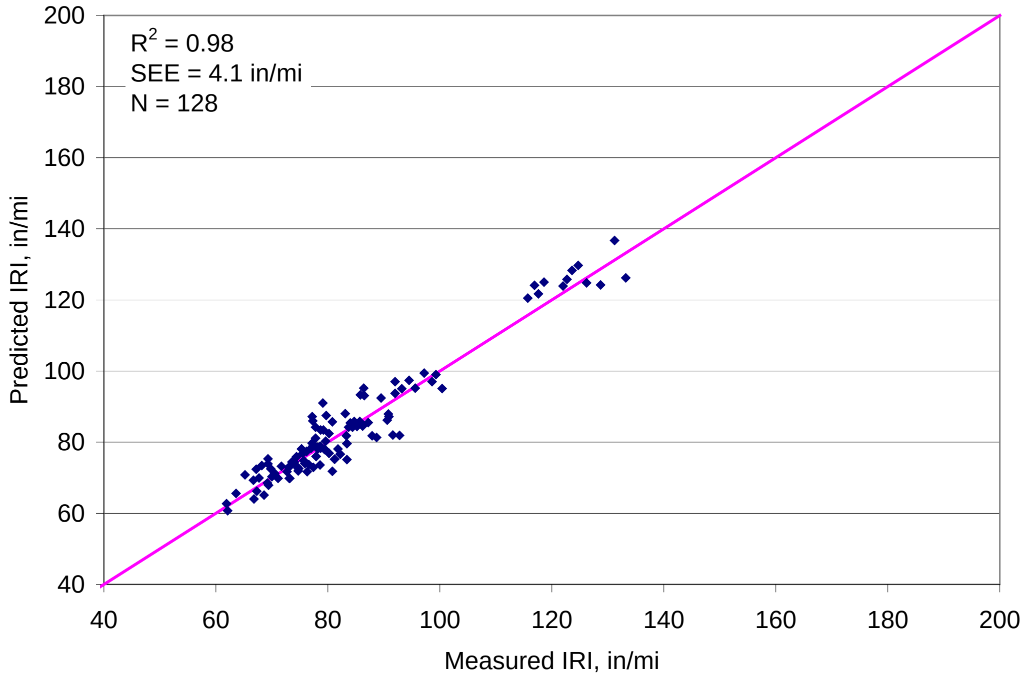

Figure 14. Plot of measured versus MEPDG predicted JPCP pavement IRI.

Table 25. Statistical comparison of measured and MEPDG predicted JPCP IRI data.

Goodness of Fit

N = 128
R^2 = 0.98
Adj R^2 = 0.98
SEE = 4.1 in/mi

Hypothesis Testing

Hypothesis	DF	Parameter Estimate	Std. Error	t Value	p-value (Pr > |t|)	95 Percent Confidence Limits	
(1) Ho: Intercept = 0	1	8.04080	1.04733	7.68	<0.0001	5.96833	10.11327
(2) Ho: Slope = 1.0	1	0.90059	0.01110	81.12	<0.0001	0.87862	0.92256
(3) Ho: Measured IRI – MEPDG Predicted IRI = 0	128			17.72	<0.0001		

The nationally calibrated model is as follows:

$$IRI = IRII + C1*CRK + C2*SPALL + C3*TFAULT + C4*SF$$

where:

IRI	=	Predicted IRI, in/mi
IRI_I	=	Initial smoothness measured as IRI, in/mi
CRK	=	Percent slabs with transverse cracks (all severities)
$SPALL$	=	Percentage of joints with spalling (medium and high severities)
$TFAULT$	=	Total joint faulting cumulated per mi, in
$C1, C2, C3, C4$	=	Recalibration coefficients
SF	=	Site factor

$$SF = AGE\ (1+0.5556*FI)\ (1+P_{200})*10^{-6} \quad (43)$$

where:

AGE	=	Pavement age, yr.
FI	=	Freezing index, °F-days.
P_{200}	=	Percent subgrade material passing No. 200 sieve.

The recalibrated model is provided below:

$$IRI = IRI_I + 0.82*CRK + 3.7*SPALL + 1.711*TFAULT + 5.703*SF \quad (44)$$

All variables are as already defined.

The results of the statistical evaluation of recalibrated model , as presented in Figure 15 and Table 26, indicated the following:

- An excellent correlation between measured and predicted IRI from the recalibrated JPCP IRI model.
- SEE was about the same as the original MEPDG JPCP IRI model which was less than that reported for the national MEPDG JPCP IRI model.
- No significant levels of bias as indicated by the results of hypotheses (1), (2), and (3).

It should be noted once again that the recalibration exercise undertaken here is limited by the constraints imposed by the data set used. It is anticipated that, before finalizing this model for design use, a wider inference space representing the range of site and design factors of interest to ODOT will be used in a future recalibration effort.

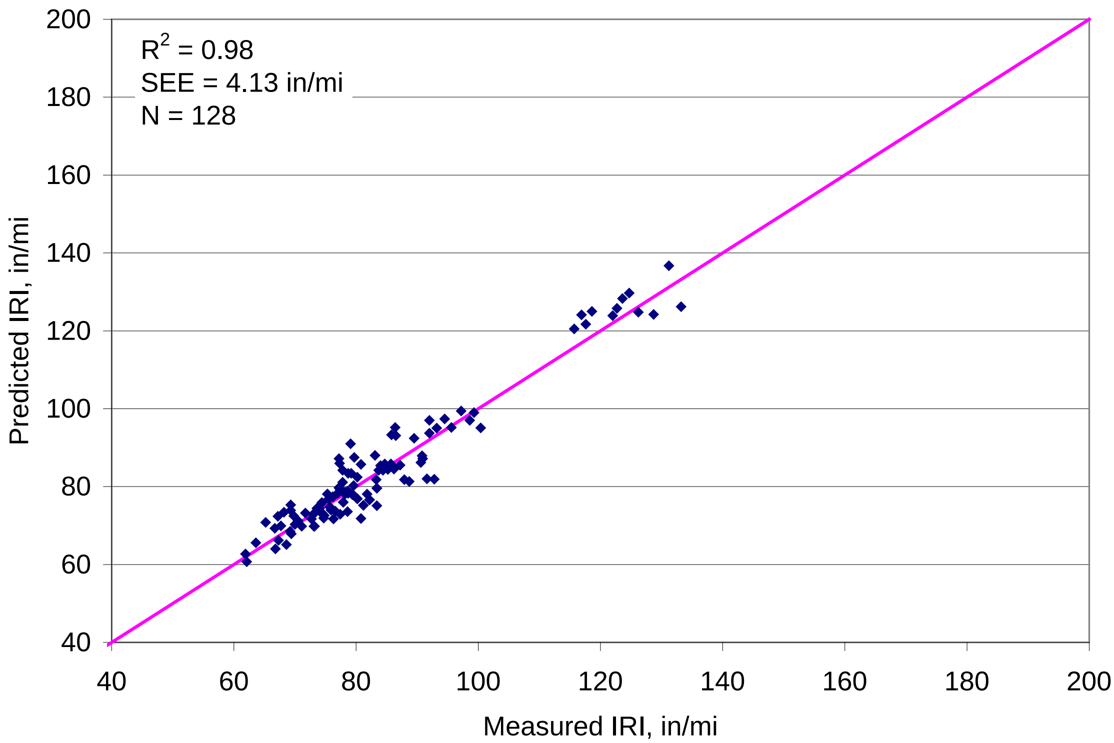

Figure 15. Plot of measured versus recalibrated JPCP IRI model predicted IRI.

Table 26. Statistical comparison of measured and predicted recalibrated JPCP model IRI data.

Goodness of Fit N = 128 R^2 = 0.98 Adj R^2 = 0.98 SEE = 4.13 in/mi							
Hypothesis Testing							
Hypothesis	**DF**	**Parameter Estimate**	**Std. Error**	**t Value**	**p-value (Pr > |t|)**	**95 Percent Confidence Limits**	
(1) Ho: Intercept = 0	1	2.04752	1.05691	1.94	0.0549	-0.04391	4.13896
(2) Ho: Slope = 1.0	1	0.99389	0.00389	2.46	0.1190	0.98618	1.00159
(3) Ho: Measured IRI – Recalibrated Model Predicted IRI = 0	134			-0.81	0.4200		

*Borderline when compared to a significance level of 0.05.

Sensitivity analysis of Recalibrated MEPDG JPCP models

A sensitivity analysis was performed to assess the reasonableness of recalibrated MEPDG JPCP IRI model. The following key factors were selected for sensitivity analysis:

- Climate - Cincinnati (South) and Cleveland (North)
- PCC Flexural Strength – 601 psi and 850 psi
- Joint Spacing – 12.5 ft and 20 ft.
- Subgrade - Fine-grained (A-7-6) and Coarse grained (A-1-b)

The analysis indicated that the predicted roughness increased greatly as the joint spacing increased from 12.5-ft to 20 ft. Other factors such as climate, PCC flexural strength and subgrade had moderate effect on predicted IRI. The trends indicated that the prediction of the recalibrated JPCP IRI model was reasonable and as expected. More detailed information is provided in chapter 5 of Volume 4.

SUMMARY AND CONCLUSIONS

Findings from the validation effort of the MEPDG models for new HMA pavements using Ohio data set are summarized as follows:

1. **Bottom up alligator fatigue cracking**: A full evaluation of this model could not be conducted due to the lack of data.

2. **Transverse "thermal" cracking**: As the majority of projects selected for model validation exhibited no or minimal transverse cracking, a full statistical evaluation of the model could not be conducted. The non - statistical comparison of cracking data indicated that all measured and predicted cracking fell in the same group. On this limited scale, the MEPDG transverse cracking model performed adequately. A more comprehensive review is recommended to determine the adequacy of MEPDG model using data from colder sites in Ohio.

3. **Total rutting**: The nationally calibrated HMA rutting model indicated significant bias and was deemed inadequate. Recalibration produced local calibration factors for all three rutting submodels (HMA, base, and subgrade). Local calibration significantly improved the model accuracy but not the bias. Laboratory testing of typical ODOT HMA mixtures and a larger calibration dataset will be needed to refine this model before it can be used. The sensitivity analysis indicated that the recalibrated HMA

rutting model responded reasonably well to the changes in key influencing factors of rutting.

4. **IRI**: The nationally calibrated HMA IRI model exhibited poor correlation and significant bias in predictions. Local calibration significantly improved on the model accuracy and removed some of the existing bias. The recalibrated model still had some bias in its predictions. The sensitivity analysis indicated that the predictions of the recalibrated HMA IRI model were reasonable and as expected.

Prediction models for new JPCP pavements are as follows for the Ohio field data:

1. **Transverse "slab" cracking**: Sixty-six of the 68 reported measurements of transverse slab cracking were zero for the projects selected for model validation. A non-statistical comparison of measured and predicted transverse cracking was performed. Approximately 97 percent of the measured and predicted transverse cracking fell within the same measured and predicted transverse cracking grouping. There were two data points for which predicted percent slabs cracked was higher than measured. The difference was, however, less than 10 percent and was deemed not significant. The predictions of the JPCP transverse cracking model were reasonable and with no bias for the levels of cracking evaluated in this analysis. However, the model was not evaluated with higher levels of cracking. It is recommended to reassess the adequacy of the model with distress data from moderate to highly deteriorated pavements that represent Ohio conditions.

2. **Transverse joint faulting**: The MEPDG JPCP faulting model predicted faulting with reasonable accuracy and with no bias. Recalibration was not deemed necessary at the present time. However, as additional data becomes available from pavements with higher levels of joint faulting, the model validation exercise can be repeated to verify the findings and to improve the model accuracy.

3. **IRI**: The nationally calibrated JPCP IRI model exhibited excellent correlation but with significant bias in predictions. Local calibration significantly improved model accuracy and removed all significant bias. The sensitivity analysis of recalibrated JPCP IRI model indicated that joint spacing had a significant effect on smoothness predictions, whereas other factors such as climate, PCC flexural strength and subgrade had moderate effect on predictions.

The MEPDG models were reviewed thoroughly for use under Ohio conditions using SPS-1 and SPS-9 projects for new HMA pavements and SPS-2, and GPS-3 projects for new JPCP pavements. The review indicated that some of the MEPDG models predicted distress/IRI reasonably, while others exhibited significant bias and poor model accuracy. The models may be valid only for the limited conditions under which they were evaluated. All the SPS projects used in the calibration effort were relatively young, with approximately 10 years of distress/IRI data. The projects were located mostly at the same site and thus did not represent all of Ohio's site conditions or pavement design and construction practices. A more comprehensive evaluation effort is recommended using a broader set, specifically by including moderately to highly deteriorated pavements. Chapter 5 provides specific recommendation in this regard. However, one noteworthy point from this validation/calibration exercise is that recalibration can be successfully performed to reduce the bias and error resulting from applying the globally calibrated MEPDG models to local data.

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CHAPTER 5. IMPLEMENTATION RECOMMENDATIONS

INTRODUCTION

The implementation of the MEPDG by ODOT requires a well planned and executed process that involves the cooperation of several internal and external stakeholders including several of ODOT's business units and offices, partner organizations in local governments, industry and the academia. As discussed previously in this report, through its research office, ODOT has initiated several activities (including this project) that could prove to be very useful in the ultimate implementation of the MEPDG.

Experience has shown that the overall flow of work for a successful implementation has followed that depicted in Figure 16. Key activities include first defining the scope of the implementation (what pavement applications are of interest to the SHA), development of a database of pavement sections for local validation/calibration, definition of many aspects related to the design inputs through a coordinated program for testing and data collection and analysis, validation of the distress and IRI models, recalibration of the models if needed, and a number of other implementation and usage activities as shown. This figure does not show all the details of implementation, but does indicate the overall flow of work and activities required as a minimum.

The following sections of this chapter elaborate on the key aspects of the flow chart presented in Figure 16 defining ODOT's needs in each area.

SCOPE OF WORK

The MEPDG can analyze up to seventeen (17) pavement and overlay types. Of these, the pavements of interest to the ODOT include the following seven "families" of pavements and rehabilitations:

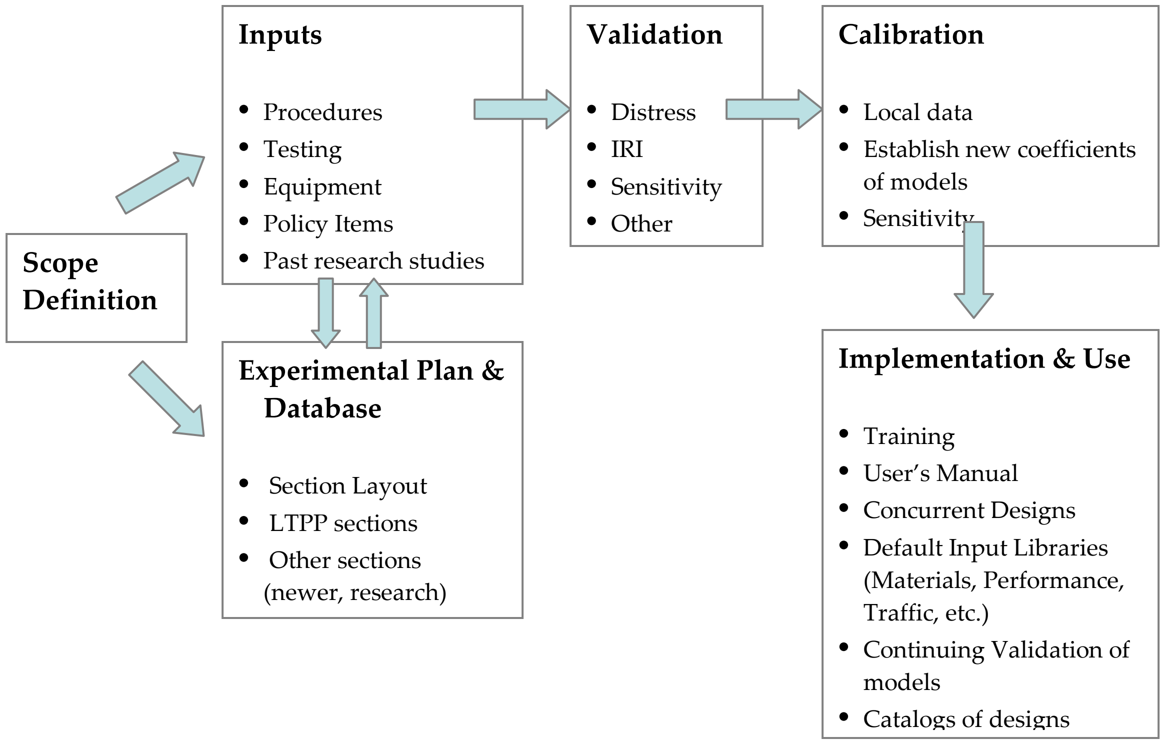

Figure 16. Overall plan for implementing the MEPDG in Ohio.

1. New or reconstructed JPCP—high priority level.
2. Unbonded JPCP overlays of existing PCC pavements—high priority level.
3. New HMA pavements (all types)—high priority level.
4. HMA overlays over rubblized PCC slabs (excluding CRCP)—high priority level.
5. HMA overlays over HMA pavement—moderate priority level.
6. HMA overlays over JPCP—moderate priority level.
7. Restoration – including; CPR and grinding—low priority level.

For the purposes of this discussion, only the pavement types notated as being of highest to ODOT will be considered.

ODOT has built a significant amount of asphalt and concrete pavements in the past. However, the design and materials used in these pavements have changed considerably over time. Some of these older designs are no longer of interest but can prove to be of considerable value in validation and calibration activities. However, the data must also include data on the newer designs to balance the validation/calibration exercise as well as to generate Ohio-specific data libraries.

Developing such data and recalibrating is essentially the overarching need of the future implementation efforts.

EXPERIMENTAL FACTORIALS

The MEPDG performance models were calibrated using data largely drawn from the LTPP experiment primarily owing to the consistency, quality, and extent of the data available in the LTPP database. Data from other experimental test sections/roads such as MnRoad were also used but on a limited basis. However, policies on pavement preservation and maintenance, construction and material specifications, and materials vary from one State to the other and need to be more fully considered in the local calibration process.

The primary objective of local calibration is to reduce bias (consistent under or over prediction of distress/smoothness) in the predicted distresses and smoothness, if it exists, and to increase the precision of the predictions. As part of the local calibration process, predicted distress is compared against measured distress and appropriate calibration adjustment factors are applied through statistical means to accomplish these objectives. Ohio-specific field data will be needed to accomplish local calibration. The MEPDG distress/smoothness model validation effort performed under this research project illustrated using Ohio-specific LTPP data that significant bias and large model errors could occur if the MEPDG models are used without local calibration. The chapter also illustrated how this bias could be removed and model error reduced using this limited dataset. To make the results of such a local calibration more applicable for Ohio conditions, a larger dataset more representative of Ohio's modern pavement designs will be needed. Ohio-specific field and laboratory test data will also be needed for this purpose. Such data are also required for several other important reasons:

- Obtain typical inputs and range of inputs.
- Obtain performance data from the latest standard materials and designs.
- Use as project examples for training ODOT staff in the future.

The collection of appropriate data requires the following steps:

1. Prepare an experimental sampling template that covers the required design/materials (e.g., newer designs and materials).

2. Identify field sections from the LTPP experiment or ODOT pavement management system that will fit into the sampling template where data is available or can be reasonably obtained.
3. Collect and assemble into a database for use in validation and calibration.

The main goals of the experimental plan include:

- Validate or confirm that the national calibration factors or functions are adequate and appropriate for the construction, materials, climate, traffic, and other conditions that are encountered within the Ohio highway system.
- If needed, determine the calibration factors that better represent materials and conditions that now exist in Ohio.
- Determine the desired level of input for key parameters and default input values (including policy type of inputs such as limiting distress) that are appropriate for Ohio.

Sampling Template for New JPCP Pavements and JPCP Unbonded Overlays

Section sampling templates of key factors for the types of PCC pavements under consideration are given in Table 27 and Table 28. The identification of key factors in the templates was based on the findings of the sensitivity study and discussions with ODOT. The key factors required to spread out the sections over an appropriate range are included. In each table, the bullets mark a factorial of pavement sections that are desirable for local validation and calibration work. The database should include sufficient number of sections to cover the practical range of values of key factors; however, the actual make-up of the calibration database will depend on the availability of the actual pavement sections.

Table 27. Experimental factorial for new and reconstructed JPCP sections.

			PCC Thickness, in							
			≤ 10 in				> 10 in			
Climate	Lane Width	Shoulder	DGAB	301/302	Drainable Base	CTB/ LCB	DGAB	301/302	Drainable Base	CTB/ LCB
Northeast Ohio	Standard	Tied	•	•			•	•		
		Other	•	•			•	•		
	Widened	Tied	•	•			•	•		
		Other	•	•			•	•		
Rest of Ohio	Standard	Tied	•	•			•	•		
		Other	•⚐	•	⚐	⚐	•	•	⚐	⚐
	Widened	Tied	•	•			•⚐	•		
		Other	•⚐	•	⚐	⚐	•⚐	•	⚐	⚐

Additional Notes:

• Desirable sections for calibration. Replicate sections are desired within each cell.
⚐LTPP sections in Ohio (SPS-2 sections have untied PCC shoulders).
All sections must be doweled.

Table 28. Experimental factorial for unbonded JCP overlays.

Overlay Thickness	**Pavement condition before overlaying**	Doweled			Nondoweled		
		Std. width slab		Widened slab	Std. width slab		Widened slab
		AC Shoulder	PCC shoulder		AC Shoulder	PCC shoulder	
≤ 8 in	Good		•			•	
	Fair		•			•	
	Poor		•			•	
> 8 in	Good		•			•	
	Fair	•	•	•	•	•	•
	Poor		•			•	

Additional Notes:

• Desirable sections for calibration. Replicate sections are desired within each cell.

Sampling Template for New HMA Pavements and HMA Overlays of Rubblized PCC Pavements

Table 29 presents the factorial developed for new HMA pavements and HMA overlays of Rubblized PCC pavements. It is expected that each identified site within a given factorial can be used to accomplish the experimental objectives.

Table 29. Experimental factorial to perform local calibration of new HMA pavement and HMA overlay of rubblized PCC pavement distress and smoothness models.

		HMA Thickness	4-8 in			> 8 in		
		HMA Mix Type	Marshall	Superpave	SMA/PMA	Marshall	Superpave	SMA/PMA
Pavement Type	Climate	Supporting Layer	Cell Designation					
New Deep Strength and Full Depth HMA	Northeastern Ohio	DGAB	•	•	•	•	•	•
		301/302				•	•	•
		Stabilized Drainable				•	•	•
		Subgrade				•	•	•
	Rest of Ohio	DGAB	⚐•	•	•	⚐•	•	•
		301/302				•	•	•
		Stabilized Drainable	⚐			⚐	⚐	
		Subgrade				⚐•	•	•
HMA Overlay	Northeastern Ohio	Rubblized PCC					•	•
	Rest of Ohio						•	•

Additional Notes:

- • Desirable sections for calibration. Replicate sections are desired within each cell.
- ⚐LTPP sections in Ohio Mixtures with RAP could be included in each family of pavement category.
- Greyed out cells are not applicable.

Note that the LTPP sections populating the factorial are those that were a part of the original experiment. However, several of these sections failed rapidly and were replaced by Ohio-specific supplemental sections. The design, construction, materials, and performance information of these newer sections was not included in the LTPP database. Therefore, for calibration purposes, these sections should be treated with same rigor as pavement management sections as far as the rigor of additional data collection efforts involved are concerned.

Populating the Sampling Templates

It is not required to include sections in all of the cells of Table 27 through Table 29. Also, two or more actual roadway sections within each cell are desired for replication purposes. These two test sections should have different performance measures but be about the same age, if at all possible. It is recognized that not all of the projects defined by the cells may be available in Ohio. This is not a serious limitation; it just limits the factor space over which the MEDPG will be tested to see if it gives appropriate predictions. In other words, a partial factorial should be sufficient to accomplish the experimental objectives. The MEPDG can still be used to "extrapolate" to a reasonable degree beyond the pavements represented by these sections due to its mechanistic foundation

When selecting sections to fit within the factorials defined by Table 27 through Table 29, the following should be borne in mind:

- That the sections should be old enough to have some observed distress. As a rule of thumb, if all the distresses of one type are averaged for all the sections in the factorial, this number should approximately equal 50 percent of the limiting value of that distress as defined by ODOT.
- It is recommended that at least three condition surveys be available for each roadway segment to estimate the incremental increase in distress over time. It is also suggested that this time-history distress data represent at least a 10 year period, if available, to account for material aging. The distresses/smoothness should be collected in units compatible with the MEPDG.
- The sections should have reasonable amounts of inventory, design, and construction data.
- At least a fraction of the sections selected should represent the designs of interest to ODOT at the present time and into the future.

The LTPP test sections located in Ohio should be used as the first priority sites, because of the amount of time-series performance, materials, traffic, and other data that have been collected and are readily available for these test sections (these have already been considered in this study). Chapter 4 discusses the new HMA pavement and JPCP sections in Ohio. These test sections have been located in the appropriate cells for each factorial (Table 27 through Table 29). As shown, relatively few cells have existing LTPP sites available for the overlay designs.

To supplement the LTPP sites in Ohio, those LTPP sites in the adjoining states can also be reviewed for consideration for use in Ohio's experimental plan and factorials.

Finally, pavement management sections from ODOT's PMIS database can be nominated to complete the factorial. It is expected that a majority of the factorial will be populated using these sections. A preliminary search of ODOT's PMIS database to identify the potential pool of pavement projects in Ohio that could be used for calibration resulted in the following numbers of projects:

- Priority System (divided highways with 4 or more lanes):
  - 57 New Flexible (HMA)
  - 33 New Rigid (JPCP)
  - 10 Rubblize and roll
  - 9 New Composite
- General System (two lane routes)
  - 49 New Flexible (HMA)
  - 14 New Rigid (JPCP)
  - Rubblize and roll
  - New Composite

Note that the search was restricted to pavements constructed between 1995 and 2007. This timeframe was chosen because the projects built within this timeframe better represent ODOT's current design, materials, and construction practices. Additional projects identified, either lacked priority designation or belong to urban system (state routes within urban areas). In all, a total of 197 new flexible (HMA), 79 new concrete, 11 rubblize and roll, 19 new composite, and 1 unbonded PCC overlay project were identified during the time period. This is a large pool of potential pavement sections from which a good sampling of sections can be drawn.

Perhaps the biggest challenge of using ODOT specific pavement management sections however is the incompatibility of the Ohio pavement management performance (distresses and smoothness) data collection protocols with the LTPP distress identification protocols. There are two ways to resolve this situation:

- Establish sections from ODOT's pavement network and collect data for the next 3 to 5 years.
- Use approximate data conversion techniques to "translate" ODOT pavement management distress data into LTPP units.

The first approach would require a larger effort and will result in a longer term implementation plan. However, this will likely result in more accurate information and yield an experimental program that can be used to refine the MEPDG models several years into the future. The second approach will require lesser effort and perhaps can be done quicker. However, the use of this approach will have definite disadvantages in terms of ability to reduce model error during local calibration.

DATA NEEDS

A database will need to be prepared that will house all of the inputs for the ODOT sections included in the sampling template presented in tables 5-1 to 5-3. A relational database with unique project identification numbers to locate each project identified in each cell of the sampling templates is recommended. This database can consist of several types of tables and queries for key traffic, materials, climate, and design data. The database will essentially store two types of information—library information and calibration specific information. Library data includes databases of typical values for inputs based on either historical databases or laboratory testing programs specifically designed and executed for the implementation of the MEPDG. Calibration data includes laboratory and field test data, pavement performance data, construction history data, inventory data, etc. specific to the calibration sections identified in tables 5-1 to 5-3. The following paragraphs discuss these two data tables in more detail.

Library Data

ODOT's materials library should include the following:

- Materials testing data. It is recommended that ODOT procure the necessary materials and field testing equipment to obtain Level 1 inputs. Based on a review of the sensitivity analysis findings undertaken in this study, as well as the availability of Ohio-specific materials information from previous research, it is recommended that ODOT test typical project materials for the following key properties:
    - PCC materials: CTE, flexural strength, compressive strength, elastic modulus, and shrinkage as a function of time for a given mix type (i.e., Class C versus Class S for each of the three predominant aggregate types). It is recommended that all the samples for each of these tests be cast from one batch of the material procured from the field or fabricated in the laboratory. Mix design details for each of these batches should be stored.
    - HMA materials: Dynamic modulus, repeated load permanent deformation (tested using confining pressure), static creep compliance and tensile strength estimated using MEPDG protocols (see table 2-2 for details). Materials required for testing could be obtained from field sampling on real world projects. Mixture volumetric information and mix design information for each of these mixtures should also be collected and stored.

- Unbound materials: Considering the importance of base type on pavement distress and smoothness prediction (particularly for HMA pavements), efforts should be made to characterize typical base materials in the laboratory for M_r, gradation, and Atterberg limits as a minimum. Similarly, typical subgrade/foundation materials and foundation improvement layers should also be tested.

- Analyzed and processed traffic data ready for use with the MEPDG. ODOT has 44 permanent WIM sites and the data from these sites should be analyzed as a minimum.
- Processed climate data. The MEPDG software includes climate data from 27 weather stations located in Ohio. However, some areas of the state, e.g., the southeastern and northeastern parts are not well represented and may need more data resolution. More weather stations from within Ohio or from adjacent states could be added. To add weather stations that are not a part of the MEPDG, the Integrated Climatic Model (ICM) tool, which is included with the MEPDG software, could be used to convert raw weather station data into climate files that are compatible with the MPEDG. Further, the climate files included in the MEPDG software contain data for up to 10 years. More data could be added to the existing climate files through an independent analysis with the ICM. Finally, in light of the fact that some of the performance models (JPCP cracking and HMA thermal cracking) are very sensitive to climate inputs, it is suggested that all the weather station data be thoroughly examined for accuracy prior to use.

Each of these data sets will involve a major, coordinated, and optimized research effort that builds on the findings of the sensitivity analysis from this study and leverages any existing studies performed by ODOT. Clearly, in the materials testing area, ODOT has performed several studies to date that can be leveraged. These studies have been discussed in Volume 2 of this report.

Calibration Data

Two types of pavement sections are recommended for use in the local calibration studies: (1) LTPP sections and (2) ODOT non-LTPP roadway sections. Much of the LTPP data for new HMA pavements and JPCP has already been assembled in this study. Data on rehabilitated LTPP sections can be used in addition. Since the LTPP data will not cover the experimental factorials illustrated in Figure 16 through Figure 18 for each pavement and rehabilitation type of interest, it is recommended that 500-ft homogenous sections or sample units be selected for a given pavement type (defined by each individual cell in tables 5-1 through 5-3) from ODOT's PMIS database. Figure 17 illustrates how such sampling can be conducted for a given project. This illustration is taken from Missouri DOT's MEPDG implementation effort (Note: Missouri DOT has decided to use roadway sections drafted from their pavement management database for use in local calibration efforts).

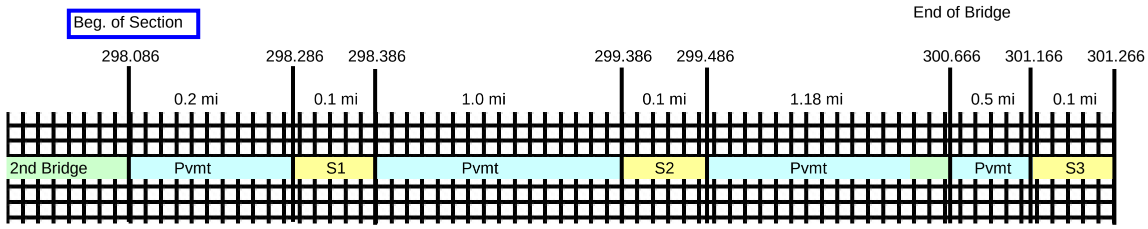

Figure 17. Illustration of sample unit selection from a pavement management section (courtesy: Missouri DOT).

It is also expected that ODOT's experimental test road information (summarized in Chapter 3) will be a part of the local calibration database.

Inputs must be estimated for each of these pavement sections included in the validation and calibration work. These inputs and the sources of information to obtain them for ODOT PMIS roadway sections include:

- Traffic—analysis of WIM/AVC sites close to the project.
- Climate—weather station data from the closest station for which data is available. Ground water table depths can be obtained from historical borings or other sources.
- Subgrade/embankment—obtained either through material sampling and testing or through the use of non-destructive methods.
- Pavement materials—sampling and coring at selected locations along the project to determine a variety of properties. An illustration of a detailed sampling plan for a new HMA section is shown in Figure 18. This plan was followed by Missouri DOT in establishing their calibration materials data libraries.
- Pavement structure and history data—ODOT construction management, PMIS, and inventory databases or flat records.
- Pavement design details – ODOT design documents (e.g., joint design for JPCP, shoulder type, etc.).
- Existing pavement conditions (for rehabilitation projects)—ODOT PMIS.

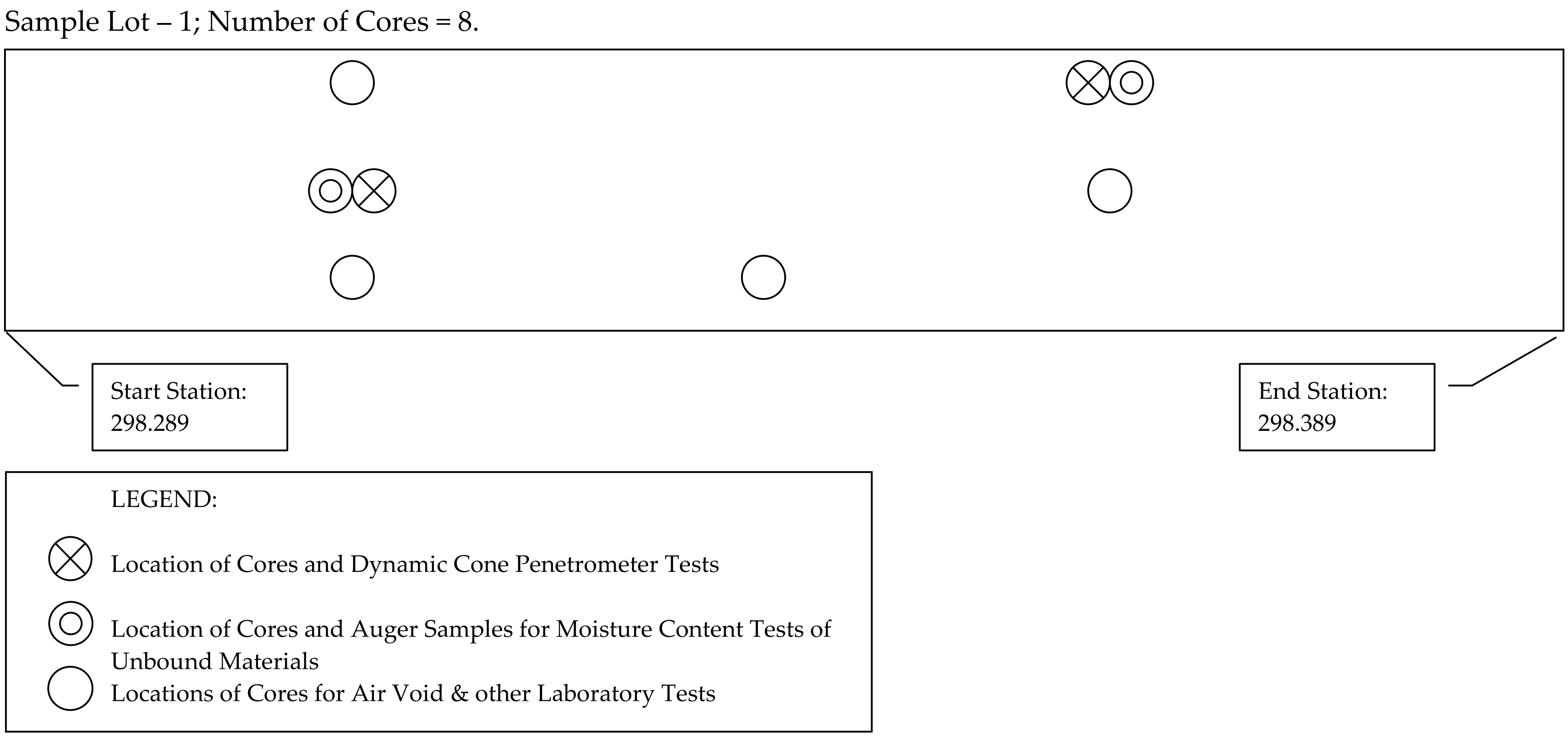

Figure 18. Field testing plan for materials data collection (courtesy: Missouri DOT).

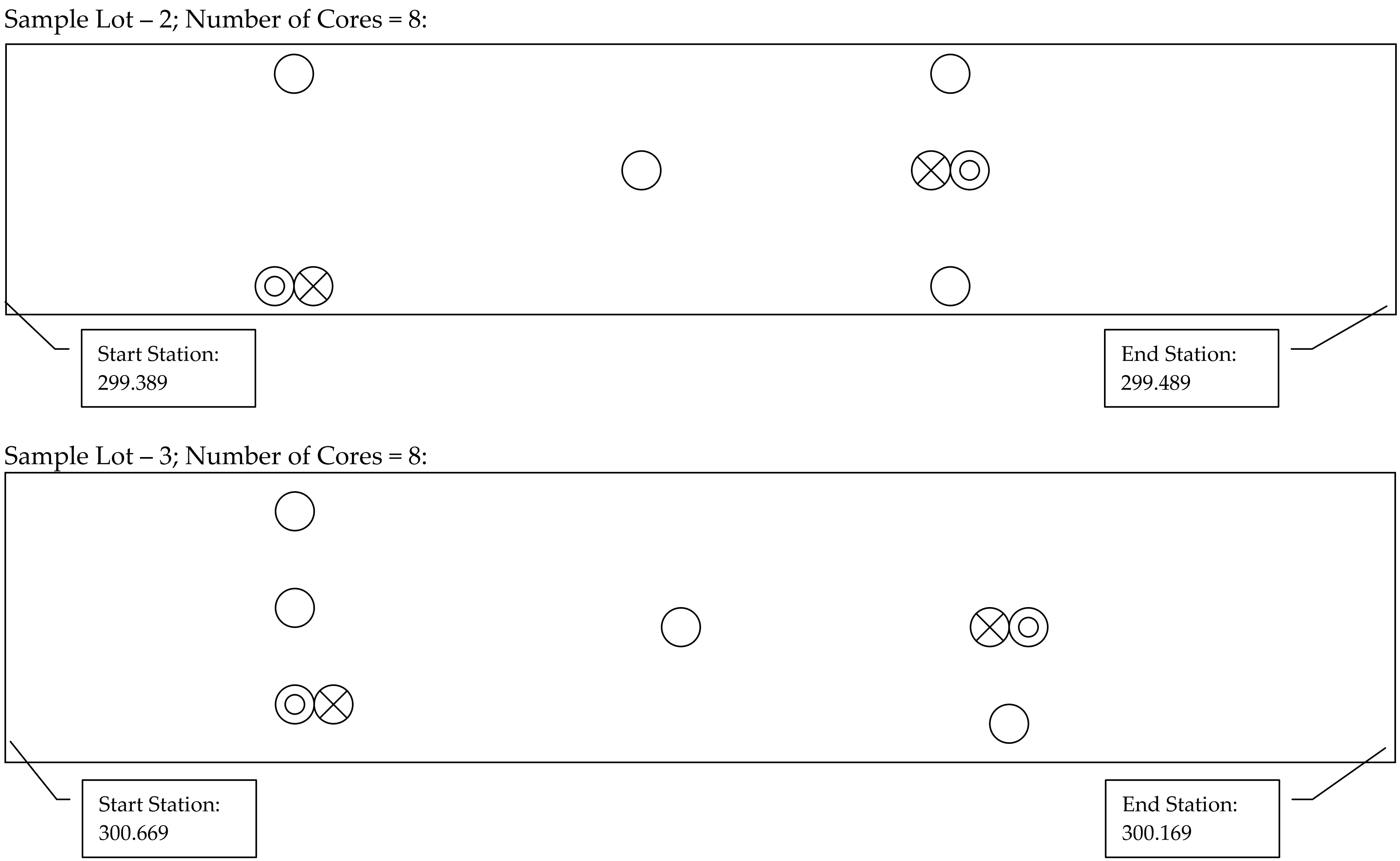

Figure 18. Field testing plan for materials data collection (courtesy: Missouri DOT), continued.

- Performance data—ODOT PMIS database. The data should be compatible with LTPP distress data. If there variance in protocols, the agency can looking to possible "approximate" conversion of the data to LTPP units or perform condition monitoring specifically for the purposes of local calibration in accordance with the LTPP Distress Identification Manual. If the latter is chosen, the implementation plan should be spread over several years to obtain at least three (3) time history points of each distress per section.
- Deflection data—Deflection testing and associated coring of pavement sections is highly recommended to characterize layer moduli and foundation properties for use in calibration.

The process of implementation and calibration of the MEPDG will provide a wealth of information about all of these inputs for ODOT the utility of which is expected to far exceed the immediate scope of this study.

NEEDED RESOURCES FOR IMPLEMENTATION

The full implementation of the MEPDG into day-to-day usage requires a number of activities in addition to those related to obtaining inputs, validation, and calibration. These include training of staff, preparation of a User's Manual, conducting concurrent designs, preparation of default input libraries for designers (materials, performance, traffic, etc.), the continuing validation of models or extension to other materials, and development of catalogs of designs for specific (easier) uses by the State district offices or for city and counties. However, most of the validation and calibration activities feed information directly into all of these activities. These activities can be started prior to completion of validation and calibration, such as training.

Training

The main objective of the training program is to help ODOT staff become familiar and comfortable with the MEPDG. The training plan includes presentations, workshops, and short courses to accomplish this goal that should be held throughout the period of implementation. Training should not be thought of as a one-time activity and should be virtually continuous throughout the period of implementation.

The training plan includes presentations, workshops, and short courses to cover various topics, including the following:

- General background on mechanistic design—coverage of fundamental concepts of mechanistic design and introduction to mechanistic analysis tools.
- Overview of MEPDG design methodology—coverage of the assumptions, theory, and methods behind the MEPDG.
- Design using MEPDG software—a hands-on workshop on how to use the MEPDG software to accomplish pavement designs.

Various courses are available form NHI and the FHWA, however, these would not be State specific as if conducted by the team implementing the MEPDG in Ohio.

User's Manual

A comprehensive User's Manual is essential for designers, materials engineers, and others involved in the MEPDG. This document should include the following major sections and include recommended inputs and defaults, test protocols, sensitivity plots to show impacts of key inputs, and example problems.

- Overview & Software Installation
- General Information
- Performance Criteria
- Design Reliability
- Traffic Inputs
- Climate Inputs
- Structure & Materials Inputs
- Rehabilitation Inputs & Designs
- Performance Outputs
- Performing A Pavement Or Overlay Design
- Example Designs: Flexible Pavement, Rigid Pavement, AC Overlay, PCC Overlay, CPR

Concurrent Designs

After re-calibration is completed and the recommended inputs are available, it is useful to conduct comparison of the current design methodology used by the ODOT with the MEPDG. This can best and most realistically be done through concurrent designs of the same project. This should be done for several designs for each of the "families" of pavement types identified from across the state. Each "design" could be run at varying levels of traffic to see how this key input affects the design. This will provide ODOT staff with an understanding on the differences that may result between the two procedures. It will help fix ODOT-specific design reliability levels and threshold values. Any anomalies can be further studied in more detail with additional examples.

Continuing Validation of Models

The LTPP and Ohio-specific roadway sections used in the local validation and calibration process can be utilized in the future to provide an ongoing validation of the prediction models. Many of the sections with newer designs or materials are not expected to have a long-term history and these sections can be followed into the future to ensure they are producing reliable results which were initially based on relative short lives used in the first validation.

Catalogs of Designs

The MEPDG can be used to prepare relatively simple tables of designs or catalogs as some call them for local applications where the inputs do not vary widely. Actually some highway agencies have begun doing this for their designers. Examples include Florida and California where a rigid pavement design catalogs has now been developed and adopted for use by the State designers in the regions. This may be a good first implementation concept in bringing along the experience level of staff to avoid a major design mistake through erroneous selection of an input for example.

IMPLEMENTATION SCHEDULE AND COSTS

A 3- to 5-year plan is recommended for the fully implementing the MEPDG in Ohio to accommodate an evaluation of long-term effects. The first year's testing program will be the most comprehensive, and initial validation and calibration should be completed based on the results of testing conducted during the first year. However, follow-up testing is needed to validate several key factors, e.g., PCC shrinkage behavior, changes in effective built-in curling over time, etc.

The expected costs are projected on a per section basis for LTPP and ODOT pavement management sections below. As noted in the section titled "Data Needs," two types of data are needed to support a calibration effort—library data and calibration data. The MEPDG recommended protocols to perform the laboratory testing has already been identified in Chapter 3 of this Volume.

A majority of the aforementioned tests can be performed using equipment commonly available in ODOT's materials laboratory. However, specialized apparatus is needed to perform the HMA E* and repeated load permanent deformation testing. The Asphalt Mix Performance Tester (AMPT), which is commercially available, is a viable alternative to perform this testing. Likewise, for PCC CTE testing, commercially available equipment could be used. At current market values, these test devices can be procured for less than $100,000.

Apart from laboratory testing, field sampling and testing is also essential for the sections chosen for calibration. A coring and sampling rig capable of taking cores of various diameters at various depths, an FWD, and field section marking and distress survey equipment are among the primary pieces of equipment needed for field evaluation.

The costs involved with laboratory and field testing are a function of the type of sections being evaluated. For example, LTPP sections do not need much additional information (with the exception of the Ohio-specific SPS 1 sections). On the other hand, sections drafted from ODOT's PMS database need a much larger data collection effort.

The following summarizes the approximate per section costs and total estimated costs for the out-of-study LTPP test sections like the SPS-1 supplemental sections:

Level of effort per test section	80 person-hours
Unit review and evaluation costs	$ 5,000
Materials recovery and laboratory testing costs	3,500
Traffic control costs	1,500
Total unit costs for out-of-study LTPP sections	$10,000

The following itemizes and lists those costs and level of effort required for each ODOT PMS test section:

Initial Evaluation – First Round of Data Collection & Monitoring		
	Level of effort per test section	100 person-hours
	Unit costs – section location/evaluation	$ 8,000
	Traffic control costs	2,000
	Material recovery costs	2,000
	Lab testing costs (HMA, PCC, aggregate base, soils)	5,000
	Field-testing costs (distress, profile, FWD)	3,000
	Initial evaluation costs per test section	$20,000
Additional Evaluation costs (2 or 3 yrs. of monitoring data)		2,000
Total unit costs for the non-LTPP test sections		$22,000

The total estimated cost of the implementation is expected to require $100 to $200k per year over 3 to 5 year time period. The various implementation activities can be phased in logically over time so that progress is continually being made and the ODOT staff can see monitor progress and change course as needed.

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