



TRC0602

**Development of a Master Plan for
Calibration and Implementation of the
Mechanistic Empirical Pavement Design
Guide**

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Final Report

2015

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16. Abstract The Arkansas State Highway and Transportation Department (AHTD) seeks to implement the Mechanistic-Empirical Pavement Design Guide (MEPDG), a mechanistic-empirical pavement design system developed under National Cooperative Highway Research Program (NCHRP) project 1-37. Specific key tasks necessary to implement the MEPDG in Arkansas involve: (1) development of appropriate input values to the process; (2) 'local' calibration of the design (pavement performance prediction) models in the MEPDG; (3) selection of appropriate design criteria (acceptable levels of pavement distress); and (4) training related to using the MEPDG in routine design practice. AHTD has completed a significant amount of work related to the implementation effort – most notably related to the development of design inputs and local calibration of the flexible pavement performance prediction models contained in the MEPDG. Remaining implementation-related tasks include continued training related to the MEPDG, ongoing local calibration efforts, and the incorporation of associated software to aid the compilation and analysis of input data.					
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DEVELOPMENT OF A MASTER PLAN FOR CALIBRATION AND IMPLEMENTATION OF THE MECHANISTIC EMPIRICAL PAVEMENT DESIGN GUIDE

PROJECT OBJECTIVES

The Arkansas State Highway and Transportation Department (AHTD) seeks to implement the Mechanistic-Empirical Pavement Design Guide (MEPDG), a mechanistic-empirical pavement design system developed under National Cooperative Highway Research Program (NCHRP) project 1-37. The primary global objective for TRC-0602 is to create a master plan for implementation of the MEPDG in Arkansas. Specific objectives follow.

- *Identify critical implementation tasks; develop a plan for accomplishing those tasks.*
- *Recommend initial values for design inputs related to pavement design .*
- *Recommend initial values for pavement performance criteria related to pavement design.*

RECOMMENDATIONS

Major findings from the study include:

1. Sensitivity of pavement performance prediction models contained in the MEPDG has been established – which identified ‘critical’ design inputs;
2. Materials (asphalt, concrete) and traffic input values have been developed for Arkansas-specific conditions;
3. Initial “local” calibration of pavement performance prediction models contained in the MEPDG is complete for new flexible pavement; calibration of rigid pavement models and rehabilitated pavement models is not complete;
4. Initial values for pavement performance criteria are recommended for use in routine pavement design;

ADDITIONAL WORK

The study recommends additional work related to implementation efforts:

- Additional training to using the MEPDG in routine design practice – particularly related to rehabilitation design;
- Local calibration – particularly related to new concrete pavements; rehabilitated pavements; and processes for ‘ongoing’ data management for future calibration efforts as the MEPDG evolves.
- Incorporation of PREP-ME.
 - Project TRC-1203 will deliver an ‘external’ software package, PREP-ME, to AHTD; PREP-ME will allow AHTD to efficiently analyze traffic load spectra data and prepare traffic input files for the MEPDG.
 - After delivery of the software, AHTD personnel (and consulting engineers) should be trained in the use of PREP-ME.

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FINAL REPORT

TRC 0602

**DEVELOPMENT OF A MASTER PLAN FOR CALIBRATION AND
IMPLEMENTATION OF THE MECHANISTIC EMPIRICAL PAVEMENT DESIGN
GUIDE**

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**University of Arkansas
January 2015**

ABSTRACT

The Arkansas State Highway and Transportation Department (AHTD) seeks to implement the Mechanistic-Empirical Pavement Design Guide (MEPDG), a mechanistic-empirical pavement design system developed under National Cooperative Highway Research Program (NCHRP) project 1-37. Specific key tasks necessary to implement the MEPDG in Arkansas involve: (1) development of appropriate input values to the process; (2) ‘local’ calibration of the design (pavement performance prediction) models in the MEPDG; (3) selection of appropriate design criteria (acceptable levels of pavement distress); and (4) training related to using the MEPDG in routine design practice. AHTD has completed a significant amount of work related to the implementation effort – most notably related to the development of design inputs and local calibration of the flexible pavement performance prediction models contained in the MEPDG. Remaining implementation-related tasks include continued training related to the MEPDG, ongoing local calibration efforts, and the incorporation of associated software to aid the compilation and analysis of input data.

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CHAPTER 1: INTRODUCTION

The structural pavement design system currently used in Arkansas is based on the procedures given in the 1993 Edition of the *AASHTO Guide for the Design of Pavement Structures* (**Error! Reference source not found.**). The basic framework of the pavement design procedures contained in the 1993 *Guide* were developed from data collected during the AASHO Road Test, a full-scale accelerated load experiment carried out between 1957 and 1962 in Ottawa, Illinois. The first published AASHO pavement design procedures arising from the Road Test appeared in 1972; a subsequent update to the procedures was published in 1986. The 1993 *Guide* repeated the “new pavement” procedures from the 1986 edition and added a comprehensive design process for rehabilitation, i.e. overlay design. Arkansas subsequently adopted/implemented the 1993 *Guide* and continues to use the AASHTO procedures for new pavement design.

The pavement design procedures contained in the 1993 *Guide* are empirical in nature. That is, the procedures are based on observations of performance of various pavement structures under various loading conditions – namely, those conditions present at the AASHO Road Test. While the current AASHTO system has served the pavement community well, it has long been noted that the AASHO Road Test was limited in scope in terms of the variety of featured loads, subgrade support conditions, and environmental conditions. As the understanding has grown of how such factors affect pavement performance, the need for a more “fundamental” approach to pavement design has been recognized.

One fundamental approach to structural pavement design is termed “mechanistic” design. In a mechanistic design process, pavement performance is related to stresses and strains induced in pavement structures by traffic loads and environmental conditions. The basic framework of a mechanistic pavement design system is shown in Figure 1. In a sense, mechanistic design uses a

mathematical model of a pavement structure – the materials used in the structure are modeled using (typically) elastic properties, i.e. modulus and Poisson’s ratio. Traffic loads are applied to this structure, and environmental conditions are considered by their effect on the properties of the materials in the structure. The application of loads induces stress (and accompanying strain) in the pavement layers. These stresses and strains are estimated using a variety of techniques, most of which are based on “classic” mechanics approaches developed by Boussinesq and Westergaard. Over the years, computer models have been developed to automate the calculations necessary for estimating pavement responses.

The key, in a sense, to the mechanistic approach is the relationship of the estimated stress and strain in pavement layers to the performance of the structure – shown in Figure 1 as the “transfer functions”. Transfer functions relate induced stress and strain to the number of applications of the given load that the pavement can experience prior to failure, or in some cases, the distress or “damage” done to the pavement by the induced stress and strain. Once this damage is estimated for a given load, the mechanistic system loops to apply the next given load and repeats for all the traffic loads expected during the design life of the pavement. If the pavement structure can “survive” all expected loads without reaching some pre-determined level of damage, the structure is considered to be adequate. If the damage to the pavement becomes too severe before all loads are applied, the structure must be redesigned and the process repeated. This iterative approach results in the design pavement structure.

In the late 1980’s, the National Cooperative Highway Research Program (NCHRP) sponsored project 1-26, aimed at collecting and summarizing the techniques developed and used around the world for performing mechanistic pavement design (**Error! Reference source not found.**). This study was not geared towards the development of a fully-functional design

procedure; rather, it was to be the basis or foundation for later projects relating to mechanistic design.

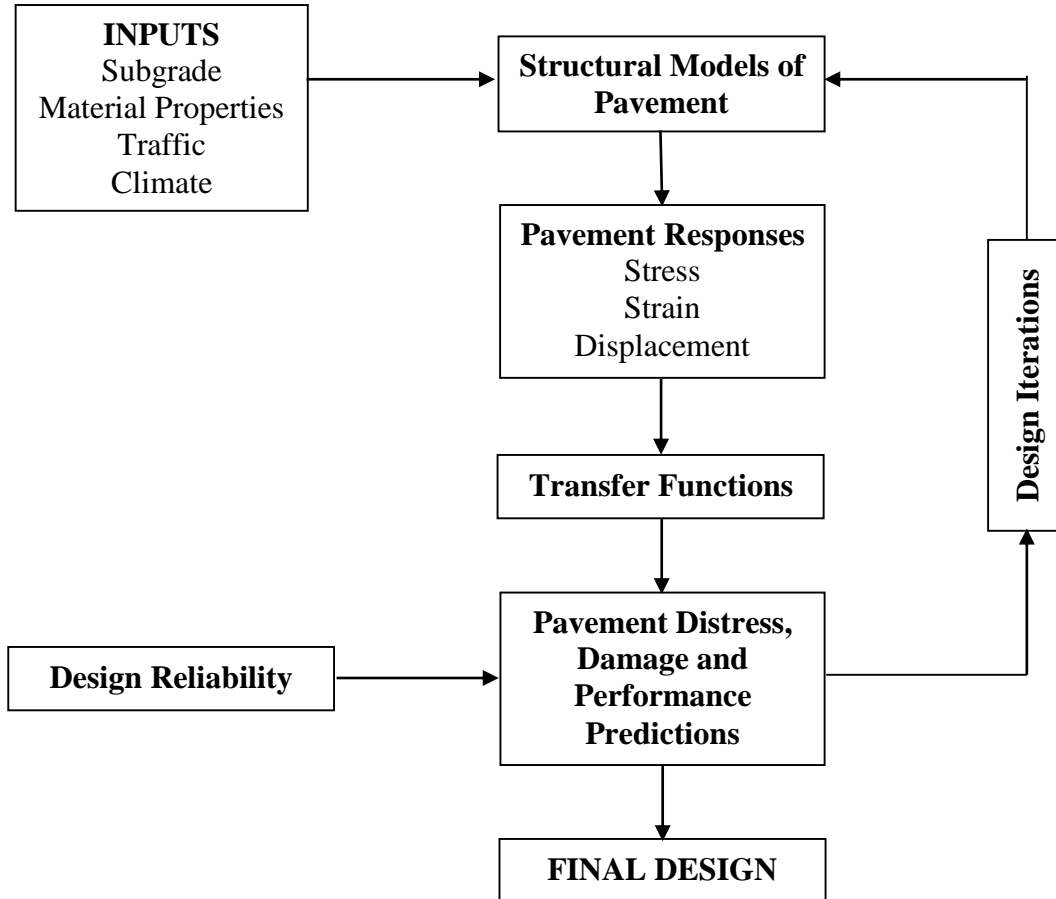


FIGURE 2. General Framework for Mechanistic-Empirical Pavement Design

Using the concepts collected in NCHRP 1-26, efforts were undertaken to develop a comprehensive mechanistic design procedure. In 1998, NCHRP sponsored project 1-37 (and subsequently project 1-37A), *Development of the 2002 Guide for the Design of New and Rehabilitated Pavement Structures* (**Error! Reference source not found.**). This broad-scope project was aimed at providing a “new” AASHTO *Guide* that uses mechanistic design principles and procedures, replacing the empirical system that has been in place since the AASHTO Road

Test. The final product of NCHRP 1-37A, a comprehensive M-E pavement analysis system/software (the MEPDG), was delivered in early 2004. In 2013, AASHTO produced its first ‘public’ version of pavement design software containing the design processes developed for the MEPDG, currently titled “Pavement-ME Design”.

A number of states have undertaken research activities designed to facilitate implementation of the MEPDG. The Arkansas State Highway and Transportation Department (AHTD) sponsored this research project (TRC-0602) was to develop a master plan for those efforts supporting the implementation of the MEPDG in Arkansas.

CHAPTER 2: MASTER PLAN FOR IMPLEMENTATION

Specific tasks necessary to implement the MEPDG in Arkansas are related to the general mechanistic-empirical pavement design approach illustrated in Figure 1. The keys to successful implementation involve: (1) development of appropriate input values to the process; (2) ‘local’ calibration of the design (pavement performance prediction) models in the MEPDG; (3) selection of appropriate design criteria (acceptable levels of pavement distress); and (4) training related to using the MEPDG in routine design practice. The Arkansas State Highway and Transportation Department has completed (or is in the process of completing) a series of studies which correspond to the keys to successful implementation. Table 1 lists these studies.

TABLE 1. Research Projects Related to the MEPDG Sponsored by AHTD

Project Number	Project Title	Status
TRC-0302	AASHTO 2002 Pavement Design Guide Design Input Evaluation Study	Completed
TRC-0304	Dynamic Modulus and Static Creep Behavior of Hot-Mix Asphalt Concrete	Completed
TRC-0402	Projected Traffic Loading for Mechanistic-Empirical Pavement Design Guide	Completed
TRC-0602	Development of a Master Plan for Calibration and Implementation of the M-E Pavement Design Guide	Active
TRC-0702	Database Support for the New Mechanistic-Empirical Pavement Design Guide	Completed
TRC-0708	PCC Materials Input Values for Mechanistic-Empirical Pavement Design Guide	Completed
TRC-1003	Calibration of the M-E Design Guide	Completed
TRC-1203	Data Preparation for Implementing DARWin-ME	Active

Subsequent chapters of this report assemble the primary findings from completed studies related to MEDPG implementation, and provides a summary of ongoing work.

CHAPTER 3: SENSITIVITY ANALYSIS OF THE MEPDG

Pavement performance prediction models contained in the MEPDG – and the associated constitutive materials and climatic models – require a significant number of inputs to be supplied by the pavement designer. It is fitting, then, to estimate the relative ‘importance’ of specific inputs to the design process, so that research-related efforts may be best directed to the development of accurate values for those ‘important’ inputs.

AHTD research project TRC-0302, “AASHTO 2002 Pavement Design Guide Design Input Evaluation Study”, was among the first published systematic sensitivity analyses of the MEPDG. (4,5) Numerous similar studies have followed. The sections which follow provide a summary of the findings of TRC-0302.

Rigid Pavement Design

The MEPDG contains a rather complex system of models that have been developed based on a large database of field pavement sections. Additionally, the results of the models generally follow the industry’s “conventional wisdom” concerning concrete pavements, the distress mechanisms, and the distresses that result. Despite this, there are still new parameters required by the program with which pavement designers are typically not familiar because they have not been explicitly considered in the past. Some of these new parameters prove to have a significant impact on the results of the performance models and others do not. Table 2 delineates which of the inputs are significant to the performance models and those that have almost no impact on the models.

The information in Table 2 can be used to streamline the pavement design process because it shows pavement designers which inputs can be ignored, in a sense, by accepting the default values and which inputs they should concentrate on to produce as accurate of a performance model as possible. However, once again, remember that the accuracy of the model, no matter how good the inputs, can only be as good as the calibration that has been

Table 2. Summary of the Significance of Concrete Material Inputs

JPCP Concrete Material Characteristics	Performance Models		
	Faulting	Cracking	Smoothness
Curl/warp Effective Temperature Difference	S	S	S
Joint Spacing	S	S	S
Sealant type	I	I	I
Dowell Diameter	S	I	S
Dowell Spacing	I	I	I
Edge Support	S	S	S
PCC-Base Interface	I		I
Erodibility index	I	I	I
Surface shortwave absorptivity	I	S	I
Infiltration of Surface Water	I	I	I
Drainage path length	I	I	I
Pavement cross slope	I	I	I
Layer Thickness	S	S	S
Unit Weight	S	S	S
Poisson's ratio	I	S	I
Coefficient of thermal expansion	S	S	S
Thermal conductivity	I	S	I
Heat capacity	I	I	I
Cement type	I	I	I
Cement content	I	I	I
Water/cement ratio	I	I	I
Aggregate type	I	I	I
PCC set temperature	I	I	I
Ultimate shrinkage at 40% R.H.	I	I	I
Reversible shrinkage	I	I	I
Time to develop 50% of ultimate shrinkage	I	I	I
Curing Method	I	I	I
28-day PCC modulus of rupture	I	S	S
28-day PCC compressive strength	I	S	S

S = Significant to the performance models.

I = Insignificant to the performance models.

put into the models. For this reason, if an agency wants accurate performance models, the agency must undergo a rigorous calibration effort. Another direct use of the data from this research summarized in Table 2 is that pavement designers know which inputs to target

when performance models do not meet the performance criteria to determine acceptance of the design. For instance, if a particular design meets the faulting and smoothness criteria, fails to meet the cracking criteria, the designer can use Table 2 to determine which inputs to the program, or aspects of the pavement design, to alter to improve the pavement's resistance to cracking.

The Need for Additional Research – Rigid Pavements

While there were many questions answered and applicable knowledge gained through this research, this research also unveiled several areas where additional research will be required to achieve the fullest use of the MEPDG. Many of the inputs shown as significant in Table 2 are not commonly known for specific mix designs. Since the models have proven to be sensitive to these inputs, each of these parameters should be known for agency-approved mix designs that will be used on various projects. This could be accomplished by periodic testing of the mix designs used by different mixing plants. Such testing is imperative if the MEPDG is used to the fullest benefit of the users.

One area that was not a part of this study, but is very important to be able to fully understand the inputs to the software, is the interactions between inputs. When one input is changed, what other inputs should also change as a result? And, ultimately, how would these interactions affect the performance models?

While many of these parameters were not tested for in the past because the information was not needed, many of the tests required would be costly to the agencies or designers. Since these tests will become more frequent, additional research should focus on improving these tests, not only to provide more precise results, but also to simplify the testing procedures, thus reducing the cost of these tests. This will then encourage more

testing and therefore increasing once again the accuracy of the performance models generated by the software.

Flexible Pavement Design

The MEPDG software can be hailed as a much needed breakthrough in the pavement industry. The software presents state of the art pavement performance modeling techniques developed by researchers through the use of extensive database of field pavement databases from all over the United States. Furthermore, the complex models used in the software were developed based on both sound theory and conventional wisdom in the industry in relation to asphalt pavements, the distress mechanisms, and the distresses that follow. However, there are many new parameters introduced in this software that have not been considered by pavement engineers. Some of the parameters were proven to be influential while others were not, with respect to pavement performance. The main objective of this study was to determine the sensitivity as well as the degree of impact of these parameters with respect to pavement performance. Table 3 shows the results of this study summarizing the significance or non-significance of each parameter considered. Using the information provided by Table 3, pavement designers can work more efficiently with the knowledge of which parameter (or parameters) may be emphasized in terms of the accuracy of input values. Table 3 can also help provide insight into which parameters can be adjusted to affect the desired pavement performance. For instance, if the designer knows that the pavement section designed was meeting BUD damage specifications but not IRI specifications, he or she may then choose to adjust only the parameters that are significantly affect IRI to obtain better pavement performance.

Table 3: Summary of the Significance of HMA Material Inputs

HMA Material Characteristics	Performance Models			
	SDC Cracking	BUD Cracking	Rutting	IRI
Poisson's Ratio	I	I	I	I
Surface Shortwave Absorptivity	I	I	I	I
Heat Capacity	I	I	I	I
Thermal Conductivity	I	I	I	I
Air Voids (12.5mm mixes)	S	S	I	S
Air Voids (25.0mm mixes)	I	S	I	I
Binder Grade (12.5mm mixes)	I	I	I	I
Binder Grade (25.0mm mixes)	I	I	I	I
Total Unit Weight (12.5mm mixes)	I	I	I	I
Total Unit Weight (25.0mm mixes)	I	I	I	I
Percent Binder Effective (12.5mm mixes)	S	S	I	S
Percent Binder Effective (25.0mm mixes)	I	S	I	I

S = Significant to the performance models.

I = Insignificant to the performance models.

Need for Further Research – Asphalt Pavement

Although there were many questions asked and answered through the course of this research, many more came to mind after this research was completed. Firstly, due to the narrow time frame of this research, difficulties experienced with the software, and sheer number of parameters involved, several parameters were not explored and tested in this research. Due to the inability of the software to complete Level 1 or Level 2 runs, important parameters such as E* and the GAS model used in the software could not be tested. In time, the future versions of the software should be able to resolve these simulation problems and future researchers may then conduct sensitivity analyses on the parameters not covered by this research.

Secondly, the most important assumption during the course of this research was that there was no interaction between each input. By common knowledge, this assumption was incorrect, but was necessary as it was the only viable and cost effective way to conduct this research. Some of

the inputs tested in this research such as AV and Pbe are clearly interrelated; the unanswered question relates to what degree and how much does this interaction affect pavement performance.

Global Sensitivity Study: NCHRP 1-47

Perhaps the most ‘global’ of sensitivity studies was completed under NCHRP 1-47. (6) This study, conducted primarily at the University of Maryland, addressed many of the issues identified as ‘needs’ arising from studies such as TRC-0302, e.g. the need to consider the *interaction* of design inputs in the MEPDG. The information which follows summarizes the major pertinent findings of NCHRP 1-47.

Flexible Pavements

- Only the HMA properties were most consistently in the highest sensitivity categories: the E* master curve δ and α parameters (i.e., the lower and upper shelves of the master curve), thickness, surface shortwave absorptivity, and Poisson’s ratio. None of the base, subgrade, or other properties (e.g., traffic volume) was as consistently in the two highest sensitivity categories.
- The magnitudes of the sensitivity values for longitudinal cracking, AC rutting, and alligator cracking were consistently and substantially higher than the values for IRI and thermal cracking.
- The sets of sensitive design inputs for longitudinal cracking, alligator cracking, AC rutting, total rutting, and IRI had very little overlap with the set of sensitive design inputs for thermal cracking. This is not unexpected because the former are primarily load-related distresses while thermal cracking is exclusively environment-driven.
- Although the lower (δ) and upper ($\delta+\alpha$) shelves of the HMA dynamic modulus master curve were consistently the highest ranked inputs for all distresses except thermal cracking, these high sensitivities are mitigated to some degree because δ and α do not vary over a wide range.
- The computed sensitivities for HMA air voids and effective binder volume are in addition to any influence they may have on HMA dynamic modulus. The GSA simulations used synthetic Level 1 inputs for the HMA dynamic modulus. Formulating these properties in terms of the Level 3 empirical relations would increase the sensitivities attributable to air voids and effective binder volume (see Section 5.1).
- Little or no thermal cracking was predicted when using the correct binder grade recommended by LTPPBind (98% reliability). The low temperature binder grade had to be shifted 2 to 3 grades stiffer (warmer) in order to generate sufficient thermal cracking distress for evaluating the sensitivity metrics.
- The thermal conductivity and heat capacity of the stabilized base in the HMA Over Stiff Foundation scenarios were found to be sensitive design inputs for longitudinal cracking and, to a lesser extent, for alligator cracking and asphalt rutting. This is problematic in practice, as these properties are very difficult to measure. These might also be sensitive inputs for conventional granular bases, but the MEPDG does not permit input of these values for nonstabilized materials.
- A moderately high sensitivity of longitudinal cracking and AC rutting on traffic speed was noted in the HMA Over Stiff Foundation results. This is likely due to its influence on HMA dynamic modulus.
- Poisson’s ratio was an unexpectedly sensitive input for HMA and, to a lesser extent, for the subgrade. Poisson’s ratio is conventionally thought to have only minor effect on pavement performance and consequently a typical value is usually assumed for design

- HMA unit weight was also an unexpectedly sensitive input. The reasons for the high sensitivity are unclear. Further investigation is warranted.
- The sensitivity of thermal cracking to the HMA dynamic modulus lower shelf (δ) was larger in absolute value terms than its sensitivity to the upper shelf ($\delta+\alpha$). The influence of lower shelf stiffness on thermal cracking was positive; as the lower shelf stiffness δ increases (which also increases the upper shelf stiffness, for fixed α), thermal cracking also increases.

Guidance for the pavement designer on how to address high sensitivity or critical design inputs varies depending upon the specific design input. Some high sensitivity inputs can be specified very precisely, e.g., HMA thickness. Other properties need to be measured or estimated. The high sensitivity to the HMA dynamic modulus indicates a need for careful characterization of this property. Mix-specific laboratory measurement of dynamic modulus may be appropriate for high-value projects. The high sensitivity of Poisson's ratio suggests that more attention should be given to defining this property for the actual materials in the design rather than just using typical values. The high sensitivities to surface shortwave absorptivity for all asphalt surfaces and the thermal conductivity and heat capacity of stabilized bases are more problematic as these properties cannot be readily measured and guidance on realistic values for specific paving materials is lacking. For these as well as all other high sensitivity design inputs, the pavement designer should perform project-specific design sensitivity studies to evaluate the consequences of uncertain input values.

Rigid Pavements

- Slab width was consistently the highest sensitivity design input, followed by the PCC layer properties (PCC unit weight, PCC coefficient of thermal expansion, PCC strength and stiffness properties, PCC thickness, surface shortwave absorptivity) and other geometric properties (design lane width, joint spacing). The high sensitivity of PCC strength and stiffness inputs suggests that care is required to avoid implausible estimates of PCC stiffness and strength gains with time that can cause large errors in predicted rigid pavement distresses.
- The magnitudes of the sensitivity values for faulting, transverse cracking, and IRI were similar. However, the range of sensitivity values for faulting was significantly larger than for transverse cracking and IRI.
- The sensitivity to design lane width was evaluated under three different edge support conditions (no edge support, tied shoulder edge support with 80% LTE, and widened slab edge support condition). Design lane width under widened slab edge support showed high sensitivity for transverse cracking but was not sensitive for either no edge support or tied shoulder edge support conditions.

Guidance for the pavement designer on how to address high sensitivity or critical design inputs varies depending upon the specific design input. Some high sensitivity inputs can be specified very precisely, e.g., PCC thickness or design lane width. Other inputs need to be measured or estimated. The high sensitivity of performance to the PCC strength and stiffness properties indicates a need for careful characterization of these values. Mix-specific laboratory measurement of Level 1 PCC modulus of rupture and modulus of elasticity may be appropriate for high-value projects. Other properties like the PCC coefficient of thermal expansion are very difficult to measure, and testing protocols are still evolving. The high sensitivity to surface shortwave absorptivity is more problematic as this cannot be readily measured and guidance on realistic values for specific PCC surface conditions is lacking. For this as well as all other high sensitivity design inputs, the pavement designer should perform project specific design sensitivity studies to evaluate the consequences of uncertain input values.

CHAPTER 4: INPUT VALUES – ASPHALT MATERIALS

AHTD Research Project TRC-0304, “Dynamic Modulus and Static Creep Behavior of Hot-Mix Asphalt Concrete” provides vital data regarding the material properties of asphalt materials for use in the MEPDG. The information which follows summarizes the findings of TRC-0304. (7)

Dynamic Modulus (E^*) Testing

- Among different approaches recommended in the AASHTO TP 62-03 to determine the peak stress and peak strain from the raw data acquired from the dynamic modulus testing, the curve fitting technique using the numerical optimization method was relatively easy to accomplish using a spreadsheet.
- The statistical analyses of the LVDT measurements showed that the differences between the LVDT responses were not significant. In addition, the testing order of the replicates was randomized, so the testing order should not be a sensitive factor in the test variability. Therefore, the dynamic modulus test results obtained in this project have no defects caused by the test measurement errors.
- The variability of the dynamic modulus test results was evaluated using the coefficients of variation, which is capable of normalizing the test variability across the test temperatures and frequencies. Two types of coefficient of variation were determined: (1) the “within” coefficient of variation that measured the variability between the individual LVDT measurements in a specimen; and (2) the “between” coefficient of variation that measured the variability between the average parameters of the replicates. The effects of mixture properties and test parameters on the variability of the test results are as follows:
 - The “within” and “between” coefficients of variation were higher with increasing nominal maximum aggregate size;

- The “within” coefficients of variation were higher with increasing air void content; and
- The test variability was higher at higher temperatures or higher frequencies. The differences between the lowest and highest coefficients of variation for both temperature and frequency sweeps were about 1.5 percent for “within” values and about 0.6 percent for “between” values.
- The variability of the test results obtained in this study were much lower than those in other studies. However, it was noted that other studies used a different testing program that featured two replicate specimens instrumented with two LVDTs per specimen, compared to three replicates instrumented with four LVDTs used in this study.
- The confidence interval of the dynamic modulus test results was calculated based on the CVs. The average 95-percent confidence interval for the dynamic modulus test results obtained in this study was ± 13.56 percent, which was less than the required value of ± 15 percent, as specified in AASHTO TP 62-03.
- The dynamic modulus test results can be presented using the master curves. The master curves can be used to determine the dynamic modulus in a broader range of frequency and temperature without performing a complex testing program. The master curves of the test data were constructed using a spreadsheet developed in this project based on the sigmoidal function developed at the University of Maryland (*Error! Reference source not found.*), and the sigmoidal function fits the test data very well.

- A testing program featuring three replicate specimens instrumented with four LVDTs per specimen is recommended for the future dynamic modulus testing.
- Based on the variability analyses of the dynamic modulus test results, it is recommended that the dynamic modulus values obtained in this study be used for level 1 $|E^*|$ inputs in the M-E Design Guide.

Use of Level 3 E^* Predictive Equation

The laboratory dynamic modulus test results were used to evaluate the Witczak predictive equation, and the analysis results are as follows:

- Overall, the predicted dynamic modulus values agreed quite well with the laboratory measured dynamic modulus values. The evaluation statistics for level 2 $|E^*|$ inputs were even better than the calibrated statistics ($R^2 = 0.886$ and $S_e/S_y = 0.338$ in arithmetic space), and those for level 3 $|E^*|$ inputs compared favorably to the calibrated statistics.
- It was observed that comparing to level 1 inputs, level 2 predicted dynamic modulus values were more accurate than those of level 3, and the dynamic modulus for HMA mixtures was slightly over predicted using level 3 inputs.
- Even though level 2 inputs seemed to predict the dynamic modulus values better than level 3, further investigation showed that both input levels overpredicted the dynamic modulus of the mixtures at high temperatures (compared to test results). These systematic errors (bias) may influence predicted pavement performance.

The M-E Design Guide 2002 design software (version 0.007) was used to investigate the effects of level 2 and 3 $|E^*|$ predictions on predicted pavement performance, and the investigation results are as follows:

- Based on the analyses of predicted pavement performance using the measured and predicted dynamic modulus values, the differences between level 2 and 3 predicted distresses were not significant.
- The pavement distresses predicted using the predicted $|E^*|$ inputs were relatively close to those using the measured $|E^*|$ inputs.

Since many mixtures used in the future would not be the same as those studied in this project, the sensitivity analysis of the inputs of the Witczak equation was performed to help designers determine the effects of the mixture changes on predicted pavement performance. The sensitivity analysis results are as follows:

- The sensitivity analysis showed that the test temperature is the most sensitive factor to the predicted dynamic modulus. Increasing test temperature from the lowest [-10C (14F)] to the highest [54C (130F)] caused 367 percent change in $|E^*|$.
- Among volumetric properties, air void content is the most sensitive factor, but its variation through its range just causes up to 20 percent change in the predicted $|E^*|$. In contrast, percent retained on No. 4 sieve seems to be a moderately sensitive factor, but its variation through its range can cause up to 50 percent change in the predicted $|E^*|$. Therefore, the influence of a mix parameter on predicted $|E^*|$ should be determined based on the combination of the parameter variation range and sensitivity.
- Based on the sensitivity analysis results, the Witczak model exhibits some errors in predicting the dynamic modulus across test temperatures and does not account for the interaction effects between air voids and test temperature. This observation helps partially explain the prediction errors of the Witczak model at high temperatures.

- Based on the evaluation of the Witzczak predictive equation, level 3 $|E^*|$ input can be used instead of level 1 and 2 $|E^*|$ inputs for initial implementation of the M-E Design Guide. However, the effects of the dynamic modulus predictions on predicted pavement performance should be re-evaluated when the performance data of in-service pavements become available.
- It is recommended that the design software add a new feature that allows the users to input state/regional calibration factors for the Witzczak predictive model incorporated in level 3 predicted dynamic modulus inputs. This feature would be useful for many states in which the Witzczak predictive model requires some modifications to reasonably predict the dynamic modulus of local HMA mixtures.
- It is recognized that the dynamic modulus test results obtained in this project were based on the laboratory compacted specimens. A new plant-mixed specimen study is highly recommended.

TRC-0304 provided a series of “Level 1” data sets corresponding to specific Arkansas asphalt mixtures, which could be used directly in the MEPDG. These data sets are provided in the form of an “input guide” for AHTD and other designers.

CHAPTER 5: INPUT VALUES – CONCRETE MATERIALS

AHTD Research Project TRC-0708, “PCC Materials Input Values for Mechanistic-Empirical Pavement Design Guide” provides vital data regarding the material properties of concrete materials for use in the MEPDG. The information which follows summarizes the findings of TRC-0708. (8)

- CTE value of PCC mixtures can be determined satisfactorily using automated CTE measuring equipment as per the AASHTO recommended CTE test method TP 60. The variability of CTE values determined in this project using the automated CTE measuring equipment favorably compared to that reported in other studies.
- The type of coarse aggregates in the PCC mixture significantly influenced the CTE and pavement performance predictions. Other parameters including cementitious content and concrete age does not have considerable effect on concrete CTE. But there is appreciable difference in CTE of Coarse aggregate and cement paste. Thus, the proportion and type of coarse aggregates used for a PCC mixture may significantly affect the CTE and subsequent pavement performance predictions.
- In this study of cement paste with fine aggregate sand, a common fine aggregate used in pavement construction, the difference in CTE with the cement paste was significant for all other coarse aggregate except sandstone having similar mineralogical composition. This reinstates the need for standardizing the minimum amount and type of coarse aggregate needed to compensate high CTE of cement matrix and obtain the desired CTE in PCC pavement mixture that helps reduce early pavement distresses.
- The effect of using Level 1 and 3 CTE inputs for PCC mixtures with limestone and sandstone was not significant to validate a change in the aggregate CTE in MEPDG

specific to the state of Arkansas. CTE recommendations for PCC mixtures with gravels were not available in the MEPDG for comparisons.

- Poisson's ratio of concrete is found to be sensitive to the type of coarse aggregate used but not affected by varying cementitious proportion and age of concrete. The sensitivity analysis showed that pavement distress increases with increase in Poisson's ratio, especially the cracking distress. Lower value of Poisson's ratio help reduce cracking distress even when the CTE of PCC mixture is high.
- Compressive strength measured for the 12 batches of concrete at each 7,14,28 and 90 day could be used to obtain the level 2 and level 3 design inputs of elastic modulus, flexural strength and indirect tensile strength in the absence of level 1 design input.
- It is interesting to note that though sandstone exhibited a higher compressive strength comparable to other aggregates, the elastic modulus was considerably less. This may be due to the different mineralogical composition of the sandstone used in this study, which emphasize the importance of knowing the mineralogical properties of coarse aggregate that influence most pavement PCC properties.
- Pearson correlation coefficient shows that Poisson's ratio, elastic modulus and compressive strength exhibit positive correlation with each other except CTE, which has negative correlation. CTE is found to be lower when the value of Poisson's ratio, elastic modulus and compressive strength are higher.
- CTE measured at saturated condition does not vary with concrete age and hence compressive strength. But Poisson's ratio, elastic modulus and compressive strength is found to have linear relationship with compressive strength and concrete age.

- It is recommended that a future testing plan for developing typical PCC inputs especially CTE inputs for implementation of the MEPDG in a state or region include all aggregate types used for concrete materials in rigid pavement construction.
- CTE recommendations for Level 3 input in the MEPDG should be updated to include more aggregate types, especially gravels, which had higher CTE values than other types of aggregate in this study.
- It is also advisable to standardize the minimum proportion of coarse aggregate required to be used in pavement PCC to reduce early distresses based on the available aggregate CTE and other PCC input parameter test results specific to each state or region.
- Due to the sensitivity of cracking distress to Poisson's ratio, it is recommended that always a level 1 input of laboratory measured value of Poisson's ratio be used in MEPDG.
- The regression equation for elastic modulus of concrete with coefficients optimized for each 4 types of aggregates used in the study could be used to predict their concrete elastic modulus at any age.

Since the CTE and other properties including Poisson's ratio, elastic modulus and compressive strength are mainly influenced by the mineralogical composition of the coarse aggregate, it is recommended that for aggregates used in pavement PCC, the mineral composition and properties are known.

TRC-0708 provided a series of "Level 1" data sets corresponding to specific Arkansas concrete mixtures, which could be used directly in the MEPDG. These data sets are provided in the form of an "input guide" for AHTD and other designers.

CHAPTER 6: INPUT VALUES – TRAFFIC LOADING

AHTD Research Project TRC-0402, “Projected Traffic Loading for Mechanistic-Empirical Pavement Design Guide” provides vital data regarding traffic loading (axle load spectra) for use in the MEPDG. The information which follows summarizes the findings of TRC-0402. (9)

- Traffic data collected at 55 stations in Arkansas were used in this study. The data were not available from many stations in several months for analyses. Among the 55 WIM stations, only 25 sites provided enough data for evaluation of monthly variation of traffic.
- Two FHWA’s file formats for classification and weight data are useful for storing massive WIM data. They can be easily transferred and imported into Microsoft Excel[®] for post-processing. However, some files were not readable and repairable in this project. They may be corrupted during the writing process.
- During quality control checks of the classification data collected at the 25 WIM sites, no errors were found in the data collected at 17 stations, and all of the data collected at these sites were accepted. For other 7 stations, errors were detected in the data in several months, and the erroneous data were rejected. The data collected at the 7 stations were partially accepted. All of data collected at one station were not accepted because the remaining data did not allow the evaluation of monthly variation after several months of data were rejected.
- Quality control checks of the weight data collected at the 25 WIM sites were performed based on the procedure recommended in the FHWA and LTPP publications. The procedure evaluates the weight data collected at a WIM station based on load distributions of the front axle, drive tandem and gross vehicle weight of Class 9 trucks. Only 10 of the 25 WIM sites which provided “good” weight data based on the evaluation

procedure were selected for developing statewide axle load spectra. The weight data collected at other stations were not accepted because the scales were failed or the calibration was off.

- A sensitivity analysis performed in this study shows that the quality control checks are very important, especially for weight data. If the WIM data are maximally misestimated by 4,000 lb. as allowed in the FHWA and LTPP procedure, the design thickness of asphalt layer can be different by one inch from the value based on the “true” data using the *1993 Guide*, or the normalized difference in the predicted pavement life can be nine percent using the MEPDG software. If the WIM data are misestimated by 8,000 lb., the difference in the design thickness of asphalt layer can be two inches from the values based on the true data using the *1993 Guide*, or the normalized difference in the predicted pavement life can be 25 percent using the MEPDG.
- For development of statewide traffic inputs for Arkansas, the *Traffload* program was first used. The software could read the classification data in C-Card files, but it was not able to import the weight data in W-Card files. No mistakes in the weight data files were found. The error is still unknown. Thus, it was decided that the *Traffload* program not be used in this study. It is not sure if the software can be used to generate the traffic inputs for MEPDG in Arkansas in the future.
- Instead of using the *Traffload* software, two computer programs, named “CLASS.xls” and “WEIGHT.xls”, were developed. These programs help perform quality control checks for the classification and weight data, and they are used to develop Level 1 traffic inputs for MEPDG. The traffic data used for these programs are based on the FHWA file formats. Each file contains all classification or weight data collected at the active WIM sites in

Arkansas in a specific month. The program can generate site specific monthly distribution factors, hourly distribution factors, vehicle class distribution factors, and axle load spectra for the MEPDG software. In order to use the programs, users are required to know the FHWA and LTPP quality control procedure and the procedure for developing traffic inputs in MEPDG.

- The primary truck class observed on most interstates and four-lane highways in Arkansas is Class 9. This class comprises up to 70 percent of truck traffic. Therefore, most analyses are based on Class 9 trucks. The next major truck class is Class 5.
- Since considerable variability in truck distribution was observed on roadways within the same functional classification, the statewide volume adjustment factors were developed based on the truck traffic classification (TTC) system. The TTC system appeared to better define roadway groups than the functional classification system. Three statewide volume adjustment factors, including monthly distribution factors, hourly distribution factors, and vehicle class distribution factors, were developed for seven TTC groups, including TTC 3, 6, 7, 9, 10, 12, and 13.
- The differences in the predicted distresses based on the statewide and default monthly and hourly distribution factors are not significant. However, the differences in the predicted distresses using the statewide and default vehicle class distribution factors are significant.
- One set of statewide axle load spectra was developed based on the weight data. The single axle load spectra are similar for all stations. Thus, the single axle load spectra for all stations are grouped to develop the statewide single axle load spectra.

- It is more difficult to group tandem axle load spectra into clusters that have similar load distribution characteristics. The TTC system cannot be used to groups tandem axle load spectra. One method used to group tandem axle load spectra in this study is based on the loading condition of the truck: fully loaded, partially loaded, and unloaded. This method should be used to group tandem axle load spectra when more WIM stations are available in the future.
- Since a small sample size of 10 WIM stations which can provide “good” weight data is used in this study, it is decided that tandem axle load spectra for all stations be best grouped to develop the statewide axle load spectra.
- The statewide tridem axle load spectra are developed in the same manner as for the statewide tandem axle load spectra. Since very few quad axles are observed in the WIM data, the statewide quad axle load spectra are not developed in this study.
- The differences in the predicted distresses based on the statewide and default axle load spectra are significant.
- Calibration of WIM scales should be carefully monitored.
- Traffic data should be evaluated before they are used for design purposes, especially weight data. The process can be performed based on the evaluation procedure recommended in the FHWA and LTPP documents.
- Two programs developed in this project can be used to facilitate the evaluation process, and users are required to know the evaluation process before using the programs. It is emphasized that the two programs are developed for analyses in this study and should not be considered as a product of this project. It should be recognized that production-graded software should require significant efforts in the future.

- Annual average daily truck traffic (AADTT) should be site specific or Level 1.
- The statewide vehicle class distribution factors for TTC groups 3, 6, 7, 9, 10, 12, and 13 should be used for the design.
- The statewide axle load spectra should be used instead of the default axle load spectra.
- Default or user-defined values can be used for other inputs, such as monthly distribution factors, hourly distribution factors, and general traffic inputs unless specific information is obtained.
- Statewide vehicle class distribution factors and axle load spectra should be updated every three years unless no significant changes in these inputs are observed in the future.

TRC-0402 provided specific load-spectra data which could be used directly in the MEPDG.

These data sets are provided in the form of an “input guide” for AHTD and other designers. It is also noted that TRC-1203 will deliver a software package, PREP-ME, which is ‘external’ to the MEPDG. PREP-ME will automate the process for checking and preparing axle load spectra data for use in the MEPDG.

CHAPTER 7: CALIBRATION OF THE MEPDG

AHTD Research Project TRC-1003, “Local Calibration of the M-E Design Guide” provides Arkansas-specific calibration factors for pavement performance prediction models used in the MEPDG. However, it is stressed that the calibration effort was successful for only the flexible pavement performance models. Pavement performance data collected on rigid pavements in Arkansas was insufficient for the calibration process. The information which follows summarizes the findings of TRC-1003 for flexible pavements. (10)

Observations

It is observed that predicted distresses do not match well with measured distresses, particularly for longitudinal and transverse cracking. However, it should be pointed out that most of the field data points group near the origin. For example, 94 percent of measured alligator cracking is lower than 10 percent; in addition, all predicted longitudinal cracking are lower than 1000 ft/mi. In general, the pavement sections available for this study are in good condition (on average, only 2.1% alligator cracking, 860 ft/mi longitudinal cracking, 131 ft/mi transverse cracking, 0.19 inches total rutting, and 72.9 in/mi for IRI). Additional observations related to the results follow.

- **Fatigue Cracking:** Both alligator cracking and longitudinal cracking predicted by MEPDG are forms of fatigue cracking. Transfer functions are used to predict visual cracking from mechanistic “damage” at the bottom and top of HMA layers. This makes the HMA layer thickness to be an extremely significant factor affecting performance predictions.
- **Asphalt Treated Base (ATB):** Although it is a type of stabilized base, ATB is not modeled as “Stabilized Base” but as “Asphalt” (albeit with a reduced stiffness). Therefore, the HMA layer in the sections with asphalt treated base becomes very thick in the MEPDG, which reduces the stress and strain at the bottom and top of the HMA layer, in turn reducing the predicted alligator cracking and longitudinal cracking. The other method to model ATB is

by considering it as “Granular Base”, which is moisture sensitive instead of temperature sensitive. However, both methods may induce errors in predicted distresses.

- **Transverse Cracking:** In the MEPDG, transverse cracking is primarily related to thermal cracking, caused by thermal stress in pavement. However, transverse cracking in LTPP database and PMS are measured according to the *LTPP Distress Identification Manual*, in which transverse cracking is defined as *cracks that are predominately perpendicular to pavement centerline* (11). The implementation of Performance-Graded (PG) binders for HMA in Arkansas has all-but eliminated thermal cracking in flexible pavements; accordingly the MEPDG predicts no thermal cracking for Arkansas climate and a properly selected PG binder. However, transverse cracking is recorded in distress surveys, suggesting that additional cracking mechanisms may be predominate in Arkansas.
- **Rutting:** Eighty percent of the pavement sections have 0.1 to 0.3 inches of rutting, even for the sites older than 15 years. This suggests either: (a) rutting reached a maximum of 0.3 inches by consolidation under traffic, without plastic failure; or (b) rutting measurements (typically by straightedge) were recorded as a maximum of 0.3 inches regardless of the actual measurement.

Calibration

Due to the nature of the data, the longitudinal cracking and transverse cracking models were not calibrated. In addition, the smoothness model (IRI) was not calibrated, since the predicted IRI is a function of other predicted distresses. The Solver function within Microsoft Excel was used to optimize the coefficients in the alligator cracking model. Iterative runs of the MEPDG using discrete calibration coefficients were utilized to optimize rutting models. For this analysis, it was assumed that the national rutting model for granular base is the same as it for Arkansas because

rutting mainly occurs in the HMA layers and subgrade; hence, the default coefficient for rutting in granular base was not adjusted. The adjusted calibration coefficients for Arkansas are listed in Table 4.

TABLE 4. Summary of Calibration Factors

Calibration Factor	National Default	Arkansas
Alligator cracking		
C1	1	0.688
C2	1	0.294
C3	6000	6000
AC rutting		
β_{r1}	1	1.20
β_{r2}	1	1
β_{r3}	1	0.80
Base rutting		
Bs1	1	1
Subgrade rutting		
Bs1	1	0.50

Observations based on the calibration process and results follow.

- In general, the alligator cracking and rutting models are improved by calibration. R-square of the alligator cracking is improved. Bias is eliminated by calibration for the rutting model.
- A question remains regarding the suitability of the calibrated models for routine design. The predicted alligator cracking are all less than 10 percent but the measured values range from 0 to 40 percent. The variation of predicted alligator cracking is statistically different from the measured alligator cracking; and it is not improved by calibration.
- Considering the difficulty to classify cracking types, it may be possible to use ranges instead of exact number in MEPDG prediction to accommodate errors from measurement and models. For example, measured alligator cracking of 3.4 percent would be acceptable

if the predicted alligator cracking was in the range of 0 to 5 percent. It is demonstrated that prediction and measurement match better when they are viewed by this new method.

- **Quality of Input Data:** Many default values are used in MEPDG in this study because these data are not available. There is a continuing concern that the quality of input data reduces the accuracy of MEPDG. It is recommended that additional sites be established and a more robust data collection procedure be implemented for future calibration efforts.

Validation

The calibrated models were validated by running the MEPDG on the remaining eight sections using adjusted calibration coefficients in Table 4. Local calibration reduced the difference between predicted and measured distress; additional efforts (sites, data) will be necessary to further reduce this difference further.

Conclusions

- The procedure for local calibration of the MEPDG using LTPP and PMS data in Arkansas is established. Overall, alligator cracking and rutting models were improved by local calibration. However, more sites and data collection are recommended before the full implementation of MEPDG in Arkansas.
- The availability and quality of design, materials, construction, and performance data are critical for local calibration. It is likely that states like Arkansas will need to establish additional calibration sites to supplement available LTPP and PMS data.
- The difference in defining transverse cracking between the MEPDG and LTPP may be critical in terms of data collection and identification. Thermal cracking should be specifically identified in a transverse cracking survey to calibrate the transverse cracking model in MEPDG. Since new features are developed to better handle climate files in

DARWin-ME, it will be necessary to recalibrate the thermal cracking model when DARWin-ME is released.

- Proper modeling of asphalt treated base is vital to producing realistic predictions of alligator cracking and longitudinal cracking, due to the influence of total HMA thickness on the damage predictions at the bottom and top of HMA layer.
- Additional development of database software for data manipulation, pre-processing, and quality control – currently underway in Arkansas – will significantly streamline the calibration process.

CHAPTER 8: ADDITIONAL WORK

Major activities related to the implementation of the MEPDG are listed in Chapter 2, and are repeated below for convenience. As summarized in Chapters 3-7, AHTD has completed a significant amount of work related to the implementation effort; this work is noted in the listing which follows. Finally, work which remains to be completed is identified.

- Development of appropriate input values to the process.
 - TRC-0302; TRC-0304; TRC-0402; TRC-0708
- Local calibration of the design (pavement performance prediction) models in the MEPDG.
 - TRC-1003
- Selection of appropriate design criteria (acceptable levels of pavement distress).

Ultimately, the decision of design criteria rests with AHTD. However, an initial recommendation concerning the criteria is presented in Tables 5 and 6.

Table 5. Recommended Design Criteria for M-E Flexible Pavement Design

Performance Measure	Default Value	Recommended AHTD Criteria
Initial IRI (in/mile)	63	63
Terminal IRI (in/mile)	172	172
AC top-down fatigue cracking (ft/mile)	2000	2000
AC bottom-up fatigue cracking (ft/mile)	25	25
AC thermal cracking	1000	1000
Permanent deformation –total pavement (in)	0.75	0.75
Permanent deformation – AC only (in)	0.25	0.50
<i>Shaded Measures are not recommended for design consideration at this time</i>		

Table 6. Recommended Design Criteria for M-E Rigid Pavement Design

Performance Measure	Default Value	Recommended AHTD Criteria
Initial IRI (in/mile)	63	63
Terminal IRI (in/mile)	172	172
JPCP transverse cracking (percent slabs)	15	15
Mean joint faulting (in)	0.12	0.20

- Training related to using the MEPDG in routine design practice.

To date, AHTD has sponsored three MEPDG-related training sessions. Two sessions featured basic-level information, provided to AHTD and consultant personnel. One session explored project-specific design, using current MEPDG software. Additional training will be necessary as AHTD increases its use of the MEPDG for routine design.

- Ongoing local calibration.

An initial ‘local’ calibration was accomplished only for new flexible pavement design.

Remaining work to be accomplished regarding calibration includes:

- Initial local calibration for new JPCP pavements;
- Initial local calibration for rehabilitation (overlay) – for flexible and rigid;
- Ongoing data collection for calibration-related databases, to allow for periodic review (and possible re-calibration) – particularly as pavement performance prediction models within the MEPDG evolve over time.

- Incorporation of PREP-ME.

Project TRC-1203 will deliver an ‘external’ software package, PREP-ME, to AHTD.

PREP-ME will allow AHTD to efficiently analyze traffic load spectra data and prepare traffic input files for the MEPDG. In addition, PREP-ME contains modules related to MEPDG climatic inputs. Ultimately, it could also serve as the base platform for

assembling materials inputs for routine use in the MEPDG. After delivery of the software, AHTD personnel (and consulting engineers) should be trained in the use of PREP-ME; AHTD should also decide the extent to which PREP-ME will be incorporated into the routine design practice of the agency.

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