Implementation of the NCHRP 1-37A Design Guide

Final Report
Volume 1:
Summary of Findings and Implementation Plan

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Executive Summary

The various versions of the AASHTO Pavement Design Guide have served well for several decades. However, the low traffic volumes, dated vehicle characteristics, short test duration, narrow range of material types, single climate, and other limitations of the original AASHO Road Test have called into question the continued use of the empirical AASHTO Design Guide as the nation's primary pavement design procedure. These perceived deficiencies were the motivation for the development of a new mechanistic-empirical pavement design guide (M-E PDG) in NCHRP Project 1-37A.

The adoption of the M-E PDG by MDSHA will have significant ramifications for material testing and pavement design procedures. The mechanistic-empirical procedures upon which the M-E PDG is based will require greater quantity and quality of input data in four major categories: traffic; material characterization and properties; environmental influences; and pavement response and distress models. The new M-E PDG provides agencies the greatest possible flexibility for applying and calibrating the design procedures to local conditions and approaches.

The principal objective of this project was to develop a coherent plan for MDSHA to transition from its current pavement design procedures to the new M-E PDG. The findings from the project are detailed in this final report, which is divided into two volumes. This first volume provides a comprehensive summary of all project findings and recommendations. It is organized as follows:

1. Introduction (this section)
2. Suitability of M-E PDG to Maryland Conditions
3. Data Needs for M-E PDG Implementation in Maryland
4. National Adoption Schedule for M-E PDG
5. M-E PDG Implementation Plan for Maryland
6. Summary Recommendations

The second volume documents extensive application of the M-E PDG procedure to typical Maryland design scenarios and the sensitivity of the M-E PDG pavement designs and performance predictions to variations of the key design input parameters of most interest to the implementation of the procedure in Maryland.

In the first part of the study, the suitability of the M-E PDG to Maryland conditions was examined three ways:

1. General comparisons of pavement designs from the M-E PDG against those from the current AASHTO procedure.
2. Evaluation of the sensitivity of the M-E PDG performance predictions and designs to variations in the design inputs within the context of typical Maryland conditions.
3. Comparisons of specific pavement designs from the M-E PDG against those from the current AASHTO procedure for selected Maryland projects.

Key findings from this portion of the study are summarized as follows:

- Using predictions from the M-E PDG as the benchmark, the results consistently suggest that the 1993 AASHTO Guide overestimates pavement performance (i.e., underestimates amount of pavement distress) for traffic levels substantially beyond the 2 million ESALs experienced at the AASHO Road Test. This has particular significance for Maryland, given the high...
traffic volumes and truck percentages on many of the roads under MDSHA jurisdiction.

- These results consistently show that the concept of equivalent traffic (ESALs) is not adequate for representing traffic loading in M-E designs. This is particularly true for permanent deformations predictions and for designs having high traffic volumes. Accurate traffic load spectra must be compiled for use in the M-E PDG.

- Relative to the M-E PDG predicted performance, the 1993 AASHTO Guide overestimates performance (i.e., underestimates distress) for pavements in warm locations. Although Maryland does not have an excessively hot climate, this could still be an issue in the summer on the Eastern shore and central Piedmont regions of the state.

- Even within a relatively small state like Maryland, intrastate variations in climate conditions were found to have a non-negligible influence on the M-E PDG performance predictions. One implementation activity should therefore be to ensure that there is adequate coverage of the state in the weather station database incorporated in the M-E PDG software.

- The M-E PDG predictions for rutting are surprisingly insensitive to the volumetric properties of the asphalt concrete, at least when level 3 estimates of dynamic modulus are used. This in part is due to issues concerning the current $|E^*|$ estimation model (to be addressed in Stage 2 of NCHRP Project 1-40D) and deficiencies in the HMA rutting model (the focus of the current NCHRP Project 9-30A). Nonetheless, the findings from the evaluation studies suggest the importance of compiling level 1 measured dynamic modulus data in order to better differentiate the performance of different HMA mixtures. This is especially important if the M-E PDG is to be used to help set rational pay factors based on HMA volumetric, gradation, and other parameters.

- The M-E PDG procedure in its present form cannot realistically predict the rutting performance of SMA mixtures, regardless of whether level 3 or level 1 inputs are used. Given the extensive and successful use of SMA in Maryland, this is a significant limitation of the current M-E PDG. This problem should be addressed in NCHRP 9-30A, which is focused on improving the HMA rutting model in the M-E PDG. Coordination and cooperation with the NCHRP 9-30A effort should be an important implementation activity.

- The M-E PDG (like the 1993 AASHTO Guide) uses resilient modulus as the primary material property for characterizing unbound materials. Implementation activities should therefore include as a minimum the compilation and/or measurement of resilient modulus for typical granular base, subbase, and subgrade materials encountered in Maryland. The M-E PDG predictions for fatigue cracking are reasonable sensitive to unbound resilient modulus values, particularly for very low values associated with soft subgrade soils. The M-E predictions for total rutting are insensitive to the resilient moduli of either the base or subgrade. There is speculation that the current unbound rutting models in the M-E PDG are flawed and that they will likely be revised and enhanced in the future.

- The M-E PDG less credit to the structural contributions of the unbound pavement layers than does the 1993 AASHTO design method. It is impossible to determine whether this is because the M-E PDG underestimates the contributions of the unbound layers or whether the 1993 AASHTO Guide overestimates them. Arguments can be made for both possibilities, and the likelihood is that reality lies somewhere between the two. It is expected that this topic will
receive further attention during future enhancements and revisions to the M-E PDG.

- MDSHA will need to determine appropriate policy regarding design limits for rutting, fatigue cracking, and other distresses. The default values in the M-E PDG, while reasonable, should probably be viewed as upper bounds. M-E PDG analyses of 1993 AASHTO designs for Maryland conditions and low to moderate traffic levels suggest that 0.6 inches of total surface rutting at 95% reliability may be a reasonable design limit for Maryland. Similar estimates of reasonable design limits for fatigue cracking and other distresses cannot be made at this time because these distresses did not appear to control the design for any of the cases examined in this study; maximum bottom-up fatigue cracking observed in any of the design scenarios was only about 16% of the lane area. Determining MDSHA policies for these design limits will be an important implementation activity.

- The influence of reliability on pavement performance and design is similar for both the 1993 AASHTO Guide and the M-E PDG. This suggests that existing MDSHA policies regarding appropriate reliabilities for different road functional classes can continue to be used during initial implementation of the M-E PDG.

- The sensitivity of predicted performance to the distress model calibration coefficients is substantially greater than for most other design parameters considered in this study. This makes a compelling argument for including local calibration as a major implementation activity. However, it must be understood that local calibration requires a very high level of effort and that it is dependent upon other prior implementation activities (e.g., compiling databases of traffic, material properties, performance, and other data for a sufficiently large set of pavement sections).

A comprehensive set of key M-E PDG implementation activities are identified in this report, with qualitative estimates of priority and required effort levels, the group expected to perform the activity (MDSHA, consultant, or University), and the optimal time frame. Related activities are grouped into larger research projects for the planning purposes and the development of Research Problem Statements. The total cost for the proposed implementation research plan is $1,460K. Of this total, $300K corresponds to activities in which MDSHA in-house staff will have sole or major responsibility and effort, and $200K is for an optional pooled fund study, the need for which will depend upon the outcome of the current NCHRP Project 9-30A. Total duration of the proposed research effort is 6 years.

Adoption and execution of this implementation plan for the M-E PDG will enable the MDSHA to remain at the forefront of pavement engineering within the U.S. Full implementation of the M-E will assist the MDSHA in meeting its objectives of evaluating the benefit/cost ratio of paving projects, increasing the percentage of constructed mileage with acceptable ride quality through application of more advanced pavement design procedures, and increasing mileage with acceptable asphalt mix through better insight and quantification into what defines an acceptable asphalt mix. The end result will be improved pavement design and better estimates of pavement performance for the many heavily trafficked highways within the state.
1. Introduction

The various versions of the AASHTO Pavement Design Guide have served well for several decades. However, the low traffic volumes, dated vehicle characteristics, short test duration, narrow range of material types, single climate, and other limitations of the original AASHO Road Test have called into question the continued use of the empirical AASHTO Design Guide as the nation's primary pavement design procedure. These perceived deficiencies were the motivation for the proposed major revision to the AASHTO Pavement Design Guide developed in NCHRP Project 1-37A. The new design methodology, commonly termed the Mechanistic-Empirical Pavement Design Guide (M-E PDG), is based on mechanistic-empirical principles. Structural responses (i.e., stresses, strains and deflections) are mechanistically calculated (using multilayer elastic theory or finite element methods) for given material properties, environmental conditions, and loading characteristics. Thermal and moisture distributions are also mechanistically determined (using the Enhanced Integrated Climate Model). These responses are used as inputs to empirical models for predicting permanent deformation, fatigue cracking (bottom-up and top-down), thermal cracking, and roughness. The models were calibrated using data from the LTPP database for conditions representative of the entire U.S. This proposed revision is currently under final review by NCHRP before forwarding to the AASHTO Joint Task Force on Pavements for approval. The state-of-the-art mechanistic-empirical pavement design procedures in the new M-E PDG will provide the foundation for mechanistic-empirical design for the next 10 to 25 years and will likely set the worldwide standard for pavement design.

At present, the only comprehensive documentation for the M-E PDG methodology that is available to the general public is the web-based version provided by the Transportation Research Board at http://www.trb.org/mepdg/. An evaluation version of the M-E PDG software is also available for downloading from this site. The main body of the M-E PDG documentation not including the numerous and extensive appendices runs to over 850 pages and cannot be printed from the TRB site. Consequently, a concise description of the key aspects of the M-E PDG methodology is included as Appendix A.

The adoption of the M-E PDG by MDSHA will have significant ramifications for material testing and pavement design procedures. The mechanistic-empirical procedures upon which the M-E PDG is based will require greater quantity and quality of input data in four major categories: traffic; material characterization and properties; environmental influences; and pavement response and distress models. The new M-E PDG provides agencies the greatest possible flexibility for applying and calibrating the design procedures to local conditions and approaches. Local material properties and traffic characteristics in particular are expected to receive significant attention. Local calibration of distress prediction models is also being considered by many agencies. The MDSHA will need to evaluate the quality and quantity of existing historical data for use in the new procedures. This will undoubtedly require establishment of a data collection program to ensure that any gaps in current MDSHA material, traffic, environmental, and other data are addressed during the implementation of the new M-E PDG.

The principal objective of this project was to develop a coherent plan for MDSHA to transition from its current pavement design procedures to the new M-E PDG. The work was organized into the following five tasks:

Task 1. Project Kick-Off Meeting
Task 2. Review Current MDSHA Pavement Design Procedures
Task 4. Develop MDSHA Implementation Plan
Task 5. Final Report

The products of these work tasks are detailed in this final report, which is divided into two volumes. This first volume provides a comprehensive summary of all project findings and recommendations. It is organized as follows:

7. Introduction (this section)
8. Suitability of M-E PDG to Maryland Conditions
9. Data Needs for M-E PDG Implementation in Maryland
10. National Adoption Schedule for M-E PDG
11. M-E PDG Implementation Plan for Maryland
12. Summary Recommendations

The second volume, which is based upon a Master of Science thesis completed by R.L. Carvalho as part of this project, documents extensive application of the M-E PDG procedure to typical Maryland design scenarios and the sensitivity of the M-E PDG pavement designs and performance predictions to variations of the key design input parameters of most interest to the implementation of the procedure in Maryland. A paper based on this work entitled “Comparisons of Flexible Pavement Designs: AASHTO Empirical vs. NCHRP 1-37A Mechanistic-Empirical” was presented at the 2006 Annual Meetings of the Transportation Research Board where it was designated as a Design and Construction Practice-Ready Paper. This paper is currently scheduled for publication in the Transportation Research Record.

Note that as this project was being completed the first publications from the NCHRP 1-37A project started to become available. Many of these publications focus on sensitivity of the M-E performance predictions to design inputs and other parameters, typically on a national level. Noteworthy recent publications related to this topic include Carvalho and Schwartz (2006), Darter et al. (2005), El-Basyouny and Witczak (2005), El-Basyouny et al. (2005a, 2005b), Hall and Beam (2005), Kannekanti and Harvey (2006), Khazanovich, Darter, and Yu (2004), Rao et al. (2004), and Timm (2006a, 2006b).
2. Suitability of M-E PDG to Maryland Conditions

Before embarking on any implementation activities, it is prudent to first evaluate the general suitability of the M-E PDG for pavement design under Maryland conditions. Since the M-E PDG is intended for national use and calibrated with pavement sections from across the country, the expectation is that the procedure should be suitable for Maryland conditions in general. The purpose of this evaluation is therefore to confirm this and to identify any particular conditions that may require special attention during local implementation.

The evaluation of the suitability of the M-E PDG to Maryland conditions was examined three ways:

1. General comparisons of pavement designs from the M-E PDG against those from the current AASHTO procedure.
2. Evaluation of the sensitivity of the M-E PDG performance predictions and designs to variations in the design inputs within the context of typical Maryland conditions.
3. Comparisons of specific pavement designs from the M-E PDG against those from the current AASHTO procedure for selected Maryland projects.

The extensive study performed to address all of these points is documented in Volume 2 of this report. Key findings from this study are summarized in the following subsections. Implications of the findings for implementation of the M-E PDG in Maryland are summarized in the concluding subsection.

It should be noted here that the emphasis of this study is on flexible pavement design. The reasons for this emphasis are: (a) Maryland designs and builds relatively few rigid pavements; and (b) prior studies have found generally reasonable trends and good agreement between 1993 AASHTO and M-E PDG designs for rigid pavements (e.g., Kannekanti and Harvey, 2006).

2.1 General Comparisons: M-E vs. AASHTO Designs

The interactions between geometrics, material properties, traffic, and environmental conditions in the M-E PDG approach is more pronounced than in the AASHTO Guide. As illustrated in Figure 1, layer thicknesses are obtained through an iterative process in which predicted performance is compared against the design criteria for the multiple predicted distresses until all design criteria are satisfied to the specified reliability level.
In addition to the underlying conceptual differences between empirical and mechanistic-empirical design approaches, there are several important operational differences between 1993 AASHTO and M-E PDG procedures. The most important include:

- The 1993 AASHTO Guide designs pavements to a single performance criterion, PSI, while the M-E PDG approach simultaneously considers multiple performance criteria (e.g., rutting, cracking of various types, and roughness for flexible pavements). Appropriate design limits must be specified for each performance measure.
- Many more variables are required in the M-E PDG procedure, especially environmental and material properties. The procedure also employs a hierarchical concept in which one may choose different input quality levels, depending upon the level of information and resources available and the importance of the project.
- The 1993 AASHTO guide was developed based on limited field test data from only one location (Ottawa, IL). The seasonally adjusted subgrade resilient modulus and the layer drainage coefficients are the only variables that can arguably account for environmental conditions. The M-E PDG utilizes a set of project-specific climate data (i.e., air temperature, precipitation, wind speed, relative humidity, etc.) and the Enhanced Integrated Climate Model (EICM) to determining the material properties for different environmental condition throughout the year (i.e., temperature-adjusted asphalt concrete dynamic modulus and moisture-adjusted resilient modulus of unbound materials).
- The 1993 AASHTO guide uses the concept of equivalent single axle load (ESAL) to define traffic levels, while the M-E PDG defines traffic in terms of load spectra.

All of these differences between the design procedures make a direct head-to-head comparison very difficult. Most of the evaluations of the M-E PDG to date have focused on sensitivity studies and tests of “engineering reasonableness” (El-Basyouny et al., 2005a; El-Basyouny et al., 2005b; Yang et al., 2005). However, head-to-head comparisons are essential to gain confidence in the newer mechanistic-empirical approach as a potential replacement for the aging empirical procedure. At the very least, the mechanistic-empirical approach should give designs and/or predicted performance that are broadly similar to those from the 1993 AASHTO Guide for

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1The 1993 AASHTO Guide does include specific procedures for incorporating the effects of frost heave and expansive subgrades into the pavement design, but these are not widely used.
“standard” types of design scenarios—i.e., modest traffic, routine material types, and benign environmental conditions.

The most direct approach for comparing the 1993 AASHTO and M-E PDG methodologies would be to use each to design pavement sections for the same project scenario. However, there are several complications that make this direct approach difficult. First, the number and types of input parameters are significantly different for the two design methodologies, making it difficult to specify “equivalent” design scenarios for each. Second, even within a single methodology there are usually multiple designs that satisfy the performance requirements—e.g., 6 inches of asphalt over 12 inches of crushed granular base has approximately the same Structural Number (and therefore the same predicted performance) as 4 inches of asphalt over 17 inches of base in the 1993 AASHTO procedure (for \( a_1=0.44 \), \( a_2=0.18 \), and \( m_2=1.0 \)). And lastly, the required pavement section depends upon the design criteria specified in each methodology. While there is some general agreement based on experience regarding appropriate performance criteria for the 1993 AASHTO Guide (e.g., initial PSI \( \approx 4.2 \), terminal PSI \( \approx 2.5 \), \( \Delta \)PSI \( \approx 1.7 \) for flexible pavements), consensus is still evolving regarding quantitative design limits for rutting, bottom-up and top-down fatigue cracking, thermal cracking, and roughness. These and other reasons make direct comparisons of the pavement section designs very difficult.

An alternate approach is to evaluate whether both design methodologies predict performance in a consistent way across a range of design conditions. Designs for different conditions developed using the 1993 AASHTO Guide are prescribed to have the same level of performance in terms of PSI (e.g., \( \Delta \)PSI \( \approx 1.7 \)). One would then expect to see consistent levels of predicted performance (e.g., rut depth, fatigue cracking) from the M-E PDG across the same set of designs. Any discrepancies in the trends would suggest that one of the design methodologies is more/less conservative than the other under certain conditions. The method of comparison adopted for the present study is therefore based on the following: (1) the 1993 AASHTO Guide is used to design pavement sections for a range of environmental conditions, material properties, and traffic levels; (2) the performance of these design sections is evaluated using the M-E PDG methodology; and (3) the predicted performance levels are compared for broad consistency across the range of design conditions. In other words, the study is intended to identify trends in performance behavior—and in particular, the consistency of these trends for the 1993 AASHTO vs. M-E PDG approaches—for different traffic levels and environmental conditions. The comparisons focus on permanent deformations and bottom-up fatigue cracking, which are among the most common distresses in flexible pavements in Maryland.\(^2\) If broad consistency is found between the AASHTO and M-E PDG approaches, then the performance predictions may also shed some light on appropriate design criteria for permanent deformations and bottom-up fatigue cracking that are consistent with the AASHTO \( \Delta \)PSI criterion.

Thermal cracking distress is not considered in this study because it will not be a factor in all of the locations considered here. Top-down longitudinal cracking is also excluded, in part because the M-E PDG model for this distress is immature; an enhanced top-down cracking model is the expected product from NCHRP Project 1-42A currently underway. And although reflection cracking is arguably the most important distress in rehabilitated flexible and composite pavements, it is not included in the present study because the reflection cracking model in the current version (v0.700) of the M-E PDG is intended only as a very rough “placeholder” until a more accurate and reliable reflection cracking model can be developed; this work is currently underway in NCHRP Project 1-41. Roughness was originally intended for consideration in this

\(^2\) Thermal cracking is encountered in western Maryland; the thermal cracking portion of the M-E PDG is evaluated in Section 2.2.3.
study, but preliminary results suggested that the roughness predictions were more a function of the environmentally-related “site factor” rather than to pavement section, and as a consequence predicted roughness was dropped from further consideration.

2.1.1 Pavement Designs
The pavement structures considered in this study were simple three layer flexible structures, consisting of an asphalt concrete mixture (AC) on top of a granular aggregate base (GB) over subgrade. Designs were developed for five different states representing a range of climate and soil conditions in the U.S. Figure 2 shows the approximate locations of the “project sites” in the five states. A survey was conducted of DOT personnel in each of the states to determine appropriate or typical values for the pavement design parameters (e.g., subgrade resilient modulus, structural layer coefficient, and drainage coefficient) at each location. Details of the pavement design parameters are given in Chapter 4 of Volume 2 of this report and in Carvalho and Schwartz (2006).

![Figure 2. Locations selected for comparison study.](image)

Three traffic levels were considered for this study: low (3.8M ESALs), medium (15M ESALs), and high (55M ESALs). The vehicle class distributions assumed for the three traffic levels were based on the M-E PDG default vehicle distributions for minor collector, local routes and streets, and principal arterial/interstate, respectively. The axle load distributions and other traffic data for all traffic levels were assumed equal to the default values in the M-E PDG software. For the AASHTO design procedure, the M-E PDG traffic data were converted to ESALs using the load equivalency factors in 1993 Guide. This procedure guaranteed consistent traffic inputs for the 1993 AASHTO and M-E PDG design scenarios.

Typical local values for the subgrade type, subgrade resilient modulus and base structural layer coefficient were obtained from the DOT survey. The survey also asked for the values typically assumed for the structural layer coefficient for asphalt concrete and the drainage coefficient for the granular base. All the answers were consistently 0.44 and 1.0, respectively – a demonstration that the “default” values from the original AASHO Road Test are still often used today regardless of location and environmental conditions (although some states include drainage effects
implicitly in the structural layer coefficient rather than explicitly through the drainage coefficient).

The design period for all cases was 15 years. The reliability level was set at 95\% with a standard deviation ($S_0$) equal to 0.45. The 1993 AASHTO design procedure was used to calculate the final design thicknesses of the base and the asphalt concrete layers summarized in Table 1. None of the design thicknesses have been rounded as they would in a practical design in order to avoid clouding the comparisons between the different designs. Frost heave and/or swelling soil influences were not explicitly considered in any of the 1993 AASHTO designs.

Table 1. Layer thicknesses (inches) for the 1993 AASHTO designs.

<table>
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<tr>
<th></th>
<th>Traffic level</th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>Alabama</td>
<td>AC</td>
<td>5.5</td>
<td>6.8</td>
<td>8.3</td>
</tr>
<tr>
<td></td>
<td>GB</td>
<td>11.5</td>
<td>13.5</td>
<td>15.5</td>
</tr>
<tr>
<td>Arizona</td>
<td>AC</td>
<td>5.5</td>
<td>6.8</td>
<td>8.3</td>
</tr>
<tr>
<td></td>
<td>GB</td>
<td>7.7</td>
<td>9.2</td>
<td>10.5</td>
</tr>
<tr>
<td>Maryland</td>
<td>AC</td>
<td>6.7</td>
<td>8.3</td>
<td>10.0</td>
</tr>
<tr>
<td></td>
<td>GB</td>
<td>18.6</td>
<td>21.3</td>
<td>24.3</td>
</tr>
<tr>
<td>South Dakota</td>
<td>AC</td>
<td>6.9</td>
<td>8.5</td>
<td>10.3</td>
</tr>
<tr>
<td></td>
<td>GB</td>
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<td>Washington</td>
<td>AC</td>
<td>6.2</td>
<td>7.7</td>
<td>9.4</td>
</tr>
<tr>
<td></td>
<td>GB</td>
<td>9.5</td>
<td>11.0</td>
<td>12.4</td>
</tr>
</tbody>
</table>

The pavement sections shown in Table 1 were analyzed using the April 2004 Version 0.700 of the M-E PDG software and national field calibration coefficients. This is the final version of the software submitted at the end of the NCHRP Project 1-37A.\(^3\) Environmental inputs were based on the assumed project locations within each state as shown in Figure 2. The EICM model interpolated among the three closest weather stations available to define the environmental parameters of interest for the analysis.

The M-E PDG requires many engineering properties for the layer materials in order to perform the mechanistic analysis of the pavement response. For flexible pavements, the key properties are the dynamic moduli of the asphalt concrete and the resilient moduli for all unbound materials, including the subgrade. Level 3 was selected as the most appropriate input level because of the lack of better quality data and the judgment that this level is more consistent with the quality of material inputs most commonly used in practice in 1993 AASHTO designs.

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\(^3\) At the time of submission of this report, Version 1.00 of the M-E PDG had been completed under NCHRP Project 1-40D and was being reviewed by FHWA. This version is expected to be released to the public in the spring of 2007.
A typical 19 mm dense-graded mixture having a 9% effective binder content by volume and 6.2% air voids was assumed for the asphalt concrete layer. The LTPPBIND® software (LTPPBIND®, version 2.1, 1999) was used to determine the optimal binder grade at each geographical location. For the medium and high traffic levels, the high temperature binder grade was increased by one grade, consistent with Superpave mix design specifications.

The resilient moduli of the base layers were calculated from the layer coefficient values in the DOT survey using the correlation provided in the 1993 AASHTO Guide. Additional required geotechnical inputs for the granular base layer were set equal to the default values in the M-E PDG software for crushed stone. For each design location, the typical local subgrade soil type was provided by the agencies as part of the survey, along with the resilient modulus typically assumed for design. Additional required subgrade inputs were taken as the default values in the M-E PDG software for the respective soil classification.

The material properties in the M-E PDG methodology are also environment-dependent, in that daily and seasonal variations in temperature and moisture affect their values. The computed temperature and moisture profiles from the EICM are combined with appropriate material models, such as the dynamic modulus master curve for asphalt concrete, to predict the seasonal variations of material properties.

### 2.1.2 Results

The 1993 AASHTO designs are all based on the same loss of serviceability (ΔPSI). The objective of the M-E PDG analyses was to evaluate how predictions of individual structural distresses varied in relation to traffic and environmental conditions. The predicted distress magnitudes should be similar for all designs if the 1993 AASHTO empirical and NCHRP 1-37A mechanistic-empirical methodologies reflect the influence of traffic level and environmental conditions in a consistent manner.

Although all of the designs were based on the same ΔPSI, the individual distress predictions from the M-E PDG showed much more variable behavior of rutting and fatigue cracking performance. As shown in Figure 3, the M-E PDG performance predictions differed significantly among locations as well as with traffic. The performance predictions for the high traffic condition exceeded acceptable limits, with up to 1.4 inches of rutting and 33% of total lane area fatigue cracking at the 95% reliability (Arizona case). In the case of rutting, for example, a survey conducted by Witczak among pavement engineers in several state agencies suggests an acceptable rutting limit of 0.5 inches on average before adjustment for reliability (Witczak, 2004). The default design criteria in the M-E PDG software are 0.75 inches for total rutting and 25% of total lane area for fatigue cracking, both after adjustment for reliability.
Pavements located in the warmest zone (Alabama and Arizona) consistently exhibited poorer performance than sections located in mild to low temperature areas. The AASHO Road Test site, the data source for developing the 1993 AASHTO Guide, was located in Ottawa, IL, a low temperature region. This result suggests that, at least according to the M-E PDG, the empirical 1993 AASHTO Guide overestimates the performance of pavement sections at locations having warmer temperatures than the original AASHO Road Test site.

It can also be noted from Figure 3 that the performance consistently deteriorated for both rutting and fatigue cracking as traffic increased in all five states. These results suggest that the 1993 AASHTO Guide overestimates pavement performance (i.e., underestimates amount of pavement distress) for traffic levels substantially beyond the 2 million ESALs experienced at the AASHO Road Test. Of course, the alternate interpretation is that the M-E PDG may be overestimating rutting and fatigue cracking, but this seems less likely given the larger set of field pavement sections incorporated in its calibration.

The applicability of the empirical 1993 AASHTO Guide for very high traffic volumes has always been questionable; this was arguably one of the main motivations for undertaking the development of the mechanistic-empirical alternative in M-E PDG. Figure 4 and Figure 5 respectively show the M-E PDG fatigue cracking and permanent deformation predictions vs. traffic level for all locations. These predictions (at the design reliability of 95%) show that predicted distresses are scattered over broader ranges as traffic level increases. The variability observed in these figures suggests that the 1993 AASHTO designs may at the very least be less reliable for high traffic levels than for low traffic. This observation is not entirely unexpected as the traffic level applied during the AASHO Road Test was a little less than 2 million ESALs. The designs for low traffic conditions in states with mild to low average temperatures (Maryland, South Dakota and Washington) are the only cases meeting the default design criteria in the M-E PDG software. For these cases, the average predicted rutting was 0.65 inches and the average fatigue cracking was 16% after adjustment for reliability. It seems reasonable to assume that the 1993 AASHTO Guide, given its empirical database, is more likely to produce pavement structural designs having performance within acceptable thresholds for traffic levels and environmental conditions that are closer to the original AASHO Road Test traffic. For these conditions, the results from the analyses in this study suggest that the M-E PDG default design
criteria of 0.75 inches for rutting and 25% of lane area for fatigue cracking (both after adjustment for reliability) are of approximately the correct magnitude, or perhaps slightly conservative.

Figure 4. Range of M-E PDG fatigue cracking predictions.

Figure 5. Range of M-E PDG permanent deformation predictions.

2.1.3 Conclusions
Different pavement sections designed for the same serviceability loss in the empirical 1993 AASHTO methodology showed considerable variations in rutting and fatigue cracking as
predicted using the M-E PDG. Locations with higher average temperatures exhibited worse performance (as predicted by the M-E PDG) than those in locations with mild to low average temperatures. This suggests that, at least relative to the M-E PDG predicted performance, the 1993 AASHTO Guide overestimates performance (i.e., underestimates distress) for pavements in warm locations.

AASHTO designs for the same serviceability loss at different levels of traffic did not show uniform levels of rutting and fatigue cracking as predicted by the M-E PDG; predicted rutting and cracking consistently increased with traffic level at all locations. The results also showed that the variability in the predicted performance increased with increasing traffic level. These results suggest that the 1993 AASHTO Guide may overestimate performance (underestimate distress) at traffic levels significantly beyond those applied in the original AASHO Road Test. This conclusion is of particular significance in the evaluation of the M-E PDG suitability for Maryland conditions, as many of the roads under MDSHA responsibility have very high traffic volumes and truck percentages.

It should be remembered that there is an implicit assumption throughout this study, that the M-E PDG results are more “correct” than those from the empirical 1993 AASHTO procedure. It is fair to say that the jury is still out on this point. However, it is also fair to say that the new M-E methodology is (or at least has the potential to be) more robust than the current empirical approach and that the M-E PDG has been calibrated against a wider range of pavement conditions than has the AASHTO Guide. Comparisons such as the ones in this study are just one of many avenues for evaluating the ultimate suitability of the M-E PDG for pavement design.

### 2.2 Sensitivity of M-E PDG to Design Inputs

Parametric sensitivity studies are an important step in any implementation of the M-E PDG as a new pavement design standard for any highway agency. The results and conclusions are useful for developing knowledge about the procedure, finding weaknesses and problems within the local agencies’ practice that need to be addressed, and defining priorities for the implementation and calibration tasks.

The objective of the parametric study described in this section is to provide useful and relevant data analyses of performance prediction sensitivity to input parameters and to evaluate the results against engineering expectations of real field performance. The pavement structure designed with the 1993 AASHTO guide for low traffic Maryland conditions (see Table 4) was the reference case for this parametric study. The variables selected for study were the following:

- Asphalt and base layer thickness
- Traffic
- Environment
- Material properties
- Performance model calibration coefficients
- Reliability Level

Only level 3 inputs were used in this parametric study. Parameters were varied by a percentage of their reference design values. When percentage variation was not possible, distinct cases were selected for comparison purposes (i.e., mixture type, vehicle class distribution, climate conditions, etc.).

The key findings regarding the sensitivity of pavement performance to each of these inputs as predicted by the M-E PDG are summarized in the following subsections. Complete details of the parametric sensitivity study are given in Chapter 5 of Volume 2 of this report.
2.2.1 Layer Thicknesses

Granular Base

The thickness of the granular base layer was varied 20% above and below the reference design thickness of 18.6 inches. The results in Figure 6 indicate that base layer thickness has little influence on rutting or fatigue cracking performance in the M-E PDG methodology. Alligator fatigue cracking slightly decreases with increased base thickness, while the permanent deformation variation is negligible. These results are significantly different from trends in the 1993 AASHTO Guide where the base layer makes considerable contribution to the structural number (SN) and consequently has a significant effect on PSI prediction. The results shown in Figure 6 also contradict field expectations that a greater base layer thickness produces a stronger pavement and consequently improves performance, everything else being equal. It can be shown that the M-E PDG results are a direct consequence of the multilayer linear elastic theory used for predicting stresses and strains within the pavement structure. Mechanistic-empirical design analyses by Das and Pandey (1999) also found that increases in granular base layer thickness did result in much reduction in the asphalt layer thickness to meet the same performance criterion. It therefore appears that M-E design procedures in general and the M-E PDG procedure in particular underestimate the contribution of the unbound pavement layers as compared to the 1993 AASHTO design method. Since this runs counter to engineering intuition and experience, it is expected that this topic will receive further attention during future enhancements and revisions to the M-E PDG.

![Figure 6. Sensitivity to base thickness.](image)

Asphalt Layer

The thickness of the asphalt concrete layer was varied 20% below and above the reference value of 6.7 inches while holding all other variables constant. Figure 7 summarizes the results for fatigue cracking and rutting performance predicted by the M-E PDG. In this case, the results are more consistent to what would be expected from the 1993 AASHTO guide and field
performance. The results showed in Figure 7 are also in agreement with MLET analysis. Increasing the AC thickness reduces the tensile strains at the bottom of the AC layer and consequently mitigates bottom-up fatigue cracking. Increasing the thickness of the stiff asphalt layer also reduces the vertical compressive strain in all layers underneath it, thereby reducing rutting in all of the underlying layers as shown in Figure 8.

![Figure 7. Sensitivity to AC thickness.](image)

![Figure 8. M-E PDG rutting predictions versus AC thickness.](image)
2.2.2 Traffic

The comparison study presented in Section 2.1 demonstrated that performance predicted by the M-E PDG deteriorated with increasing traffic levels for sections designed using the 1993 AASHTO guide. The parametric sensitivity study found that the M-E PDG performance predictions are also significantly influenced by vehicle class and axle load distributions.

The first exercise compared performance predictions using load spectra vs. ESAL characterizations of traffic. The 1993 AASHTO reference design for low traffic (3.8M ESALs) under Maryland conditions was used as the reference. Performance predictions based on the load spectrum (M-E PDG default vehicle class and axle load distributions for low volume roads) vs. ESAL characterization of traffic are summarized in Figure 9 and Figure 10. The annual average daily traffic (AADT) was adjusted to produce the target 3.8M ESALs at the end of the design period for both cases. The results in Figure 9 show that the full traffic load spectrum, although having the same equivalent number of ESALs, induces more rutting than the ESALs-only traffic (18 kip single axles only), especially for total surface rutting. Curiously, fatigue cracking sensitivity to traffic characterization was negligible; Figure 10 shows almost identical quantities of predicted fatigue cracking for the load spectrum and ESAL cases.

![Figure 9. Rutting performance sensitivity to traffic load type at 15 years.](image-url)
Figure 10. Fatigue cracking performance sensitivity to traffic load type at 15 years.

The sensitivity of performance predictions to vehicle class distribution was also evaluated. Traffic volume and other parameters (i.e., percentage in design direction and lane, etc.) were kept constant. Only the vehicle class distribution was altered. Three different default distributions from the M-E PDG software library having significantly different class 5 and class 9 trucks were examined (Figure 11). The predicted performance summarized in Figure 12 shows that rutting and fatigue cracking increased as the vehicle distribution changed from minor collector to principal arterial—i.e., as the ratio of more-damaging class 9 to less-damaging class 5 trucks increases.
Figure 11. Class 5 and class 9 percentages for different vehicle distribution scenarios.

Figure 12. Performance for different vehicle class distributions.

These results plus those from the design comparisons in Section 2.1 consistently show that the concept of equivalent traffic (ESALs) is not adequate for representing traffic loading in M-E designs. This is particularly true for permanent deformations predictions and for designs having high traffic volumes. Full traffic load spectra must be compiled for use in the M-E PDG.

2.2.3 Environment
Sensitivity of performance predictions to climate effects was quantified by analyzing three different locations within the state of Maryland: the Eastern shore, the central Piedmont region,
and the western mountains. Although these locations are relatively close to one another, their climate characteristics are sufficiently different to illustrate the effects of the Enhanced Integrated Climate Model (EICM) on a small region. Table 2 summarizes the average low and high temperatures for each location and the appropriate asphalt binder grade as determined using the LTPPBind program (v3.1 beta) for low traffic conditions. For the analyses in this study, the binder grade was kept constant at a PG 64-22, the required grade for the western Maryland region.

Table 2. Climate and binder properties for Maryland regions (from LTPPBind v3.1).

<table>
<thead>
<tr>
<th>Region</th>
<th>Location</th>
<th>Weather Station ID</th>
<th>High Air Temperature(^1) (°C)</th>
<th>Low Air Temperature(^2) (°C)</th>
<th>Binder Grade(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern</td>
<td>Salisbury</td>
<td>MD8000</td>
<td>33.4</td>
<td>-14.2</td>
<td>PG 64-16</td>
</tr>
<tr>
<td>Central</td>
<td>Baltimore City</td>
<td>MD0470</td>
<td>35.3</td>
<td>-12.4</td>
<td>PG 64-16</td>
</tr>
<tr>
<td>Western</td>
<td>Hagerstown</td>
<td>MD3975</td>
<td>33.6</td>
<td>-18.2</td>
<td>PG 64-22</td>
</tr>
</tbody>
</table>

1 Mean value of yearly high temperature for the hottest seven day period.  
2 Mean value of the yearly low temperature.  
3 Low traffic conditions and 90% reliability.

Figure 13 shows that the permanent deformation and fatigue cracking performance predictions for the reference design in the three different locations agree with expectations. Rutting and fatigue performance tends to decrease with increasing temperature and precipitation (for a fixed binder grade), as would be expected.

![Figure 13. Sensitivity to local climate conditions.](image)

Local climate conditions are also be expected to have an impact on thermal cracking—e.g., no thermal cracking in warm locations such as the eastern shore of Maryland, potentially more thermal cracking in the colder mountain elevations in western Maryland. However, no thermal cracking was predicted at any of the three regional locations within Maryland. It is speculated that the use of appropriate Superpave performance graded binders is responsible for the absence of thermal cracking.
2.2.4 Material Properties

The main properties considered in the parametric sensitivity study include: (a) asphalt concrete—binder grade, volumetrics, and gradation; and (b) unbound base and subgrade materials—resilient modulus and material classification. Level 3 default values were assumed for all other material and design inputs. Only key findings are summarized here; details can be found in Chapter 5 of Volume 2 of this report.

**Asphalt Concrete**

Binder grade (related to viscosity), mixture volumetrics (air voids and effective binder content), and mix type (primarily a function of maximum aggregate nominal size and gradation) are the most important level 3 input properties for asphalt concrete in the M-E PDG. These properties are the inputs to the Witczak empirical model for dynamic modulus \(E^*\), which is the primary asphalt material property in the M-E PDG analyses.

Figure 14 summarizes predicted rutting and fatigue cracking performance for a 19mm dense graded asphalt mixture as a function of binder type for the reference pavement section of 6.7 inches of asphalt over 18.6 inches of granular base (low traffic Maryland conditions). As expected, fatigue cracking and rutting decrease with increasing binder grade (high temperature limit, in this case) – high grade binders are stiffer at high temperatures and have high viscosity values. Although conventional wisdom holds that asphalt mixtures with stiffer binders are more prone to cracking, this applies primarily to thinner pavements than considered here.

Air voids and binder content are important sources of variability in construction and among the most influential parameters determining the mixture stiffness and hence pavement performance. One of the benefits of the M-E methodology is the ability to evaluate the effect of “as-constructed” conditions that are often different from the design assumptions. For this exercise, air voids and effective binder volume were each varied 10% above and below their base values. Figure 15 clearly shows that effective binder volume primarily affects fatigue cracking
performance, which agrees with expectations. Mixtures rich in binder generally have better tensile strength and better cracking performance. Conversely, it is expected that mixtures with high binder content have poor rutting performance. The level 3 dynamic modulus predictive equation in the M-E PDG, captures the influence of excessive binder content by reducing the value of $|E^*|$. Low $|E^*|$ values produce higher compressive strain values and consequently more rutting. However this trend is not clearly observed in the M-E PDG results in Figure 15.

Figure 16 illustrates the predicted performance sensitivity to AC mixture air voids. As expected from field performance, cracking is more likely when air voids are high. Figure 16 clearly shows that the M-E PDG is able to capture this effect. Air voids are also expected affect permanent deformation. Lack of adequate field compaction results in high air voids in the mat, which generates premature permanent deformations as the mixture densifies under traffic. However, this expected trend is not clearly evident in the M-E PDG rutting predictions in Figure 16.

![Figure 15. Sensitivity to effective binder content (% by volume).](image)
Gradation was evaluated for three dense graded mixtures plus one Stone Matrix Asphalt (SMA) mixture frequently used in the state of Maryland. The gradations of these mixtures, summarized in Table 3, are representative of typical values commonly used in pavement projects throughout the state.

<table>
<thead>
<tr>
<th>Aggregate gradation</th>
<th>12.5 mm</th>
<th>19 mm  (reference)</th>
<th>37.5 mm</th>
<th>19 mm  SMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>% passing #34 (19mm)</td>
<td>100</td>
<td>96</td>
<td>78</td>
<td>100</td>
</tr>
<tr>
<td>% passing #38 (9.5mm)</td>
<td>83</td>
<td>73</td>
<td>55</td>
<td>63</td>
</tr>
<tr>
<td>% passing #4 (4.75mm)</td>
<td>46</td>
<td>44</td>
<td>27</td>
<td>27.4</td>
</tr>
<tr>
<td>% passing #200 (0.075mm)</td>
<td>3</td>
<td>6</td>
<td>4</td>
<td>8.5</td>
</tr>
<tr>
<td>Mix volumetrics</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effective binder content, by volume (%)</td>
<td>9.1</td>
<td>9</td>
<td>10.1</td>
<td>12.1</td>
</tr>
<tr>
<td>Air voids (%)</td>
<td>6.2</td>
<td>6.2</td>
<td>5.8</td>
<td>3.6</td>
</tr>
</tbody>
</table>

All three dense graded mixtures were analyzed and compared. Figure 17(a) shows that the level 3 estimated dynamic modulus increases with coarser mixtures—e.g., $|E^*|_{37.5}$ is higher than $|E^*|_{12.5}$—implying better performance. Figure 17(b) shows that fatigue cracking performance follows this trend (for the relatively thick asphalt layer considered here). The results were not as conclusive as for the rutting performance trends in Figure 17(b), although there is some improvement when moving from the 12.5 mm mixture to the 19 mm.
Performance comparisons between a conventional dense graded mixture and Stone Matrix Asphalt (SMA) are summarized in Figure 18. The state of Maryland has had great success using SMA in most of their high volume highway projects to reduce rutting (Michael et al., 2003). The M-E PDG performance predictions for SMA mixtures are consequently of great importance. Unfortunately, when SMA is analyzed using the M-E PDG its rut-resistant benefits cannot be observed. Figure 18(a) illustrates the performance of a 19mm SMA mixture compared to an equivalent dense graded mixture. The SMA exhibits higher rutting than dense graded mixture,
which contradicts field experience. Figure 18(b) shows the seasonal variations of level 3 estimated dynamic modulus for 19mm SMA and dense graded mixtures. The dynamic modulus predicted in the M-E PDG for SMA is lower than for the dense graded mixture, which is consistent with the higher rutting predicted for the SMA. Note that the dynamic modulus of SMA mixtures as measured in laboratory from conventional unconfined uniaxial frequency sweep tests is also lower than that of similar dense graded mixtures. Some researchers claim that testing under confined conditions is necessary to reflect realistically the true stiffness and strength of SMA mixtures. The level 3 $|E^*|$ predictive model, however, is based on a database that includes very few SMA mixtures and no confined dynamic modulus test results. The principal conclusion that must be drawn from these results is that the M-E PDG procedure in its present form cannot realistically predict the rutting performance of SMA mixtures. Continuing research on this subject includes the ongoing NCHRP Project 9-30A focused on improving the asphalt concrete rutting model in the M-E PDG.
From the parametric study of asphalt concrete properties, it can be concluded: (a) the M-E PDG predicted performance trends agree with expected fatigue cracking performance for the variations in input parameters considered here; (b) the expected trends for permanent deformations could not be clearly observed in the M-E PDG predictions; and (c) the M-E PDG rutting predictions do not capture the performance benefits of SMA mixtures. Additional research is needed for the empirical asphalt concrete rutting model.

One other important issue is the compatibility between the M-E PDG and perpetual pavement design concepts. Perpetual pavement design focuses on eliminating any possibility of deep-seated failure—e.g., bottom-up alligator cracking of the asphalt layer—that would require removal and
replacement of an entire pavement layer and/or reconstruction of the entire section. A key component of perpetual pavement design is the use of fatigue resistant asphalt concrete at the bottom of the asphalt layer and/or maintaining strains beneath the fatigue endurance limit.

Although what constitutes a fatigue resistant asphalt mixture varies depending upon whether the layer is thick or thin, this issue is explicitly addressed within the M-E PDG methodology. Optional specification of an endurance limit has been included in the M-E PDG v0.900 software released after the conclusion of the present project. The user may now specify the magnitude of the endurance limit strain; guidelines for this strain value will be forthcoming from NCHRP Project 9-38 currently underway.

**Unbound Materials**

The fundamental unbound material property required for the M-E PDG is the resilient modulus (M<sub>R</sub>). For level 3 inputs, M<sub>R</sub> is given as a default value at optimum density and moisture content for a given soil type. The soil type also defines the default material properties required by the environmental model, including the soil-water characteristic curve, saturated hydraulic conductivity, and degree of saturation at equilibrium moisture conditions.

Base resilient modulus is intuitively expected to affect the overall pavement performance. Stiffer base layers reduce the tensile strains at the bottom of the asphalt layer, thus reducing fatigue cracking; vertical compressive strains are also reduced within the base layer and subgrade, consequently reducing permanent deformation. As shown in Figure 19, the reduction in permanent deformation as predicted by the M-E PDG is not as pronounced as for predicted fatigue cracking. It is interesting to note in Figure 19 the negligible reduction in AC rutting with variations in base layer resilient modulus. Due to the large |E<sub>AC</sub>|/M<sub>R,base</sub> ratio, the influence of base layer modulus on the vertical compressive strains in the AC layer and thus on predicted rutting of the asphalt layer is small.

![Figure 19. Sensitivity to granular base resilient modulus.](image-url)
Subgrade resilient modulus is another important parameter affecting pavement performance. Figure 20 shows that weaker subgrades, represented by low $M_R$ values, are associated with poorer performance; predicted fatigue cracking and rutting decrease with increasing subgrade stiffness, which all agree with expectations. Although not shown in these results, it is expected that the sensitivity of predicted pavement performance to subgrade stiffness will increase sharply for $M_R$ values significantly below 3000 psi.

![Figure 20. Sensitivity to subgrade resilient modulus.](image)

### 2.2.5 Performance Model Calibration Coefficients

The field calibration of the empirical distress models was done using LTPP sections selected throughout the country to cover all climatic zones and a wide variety of pavement sections. The calibration coefficients of the models used for predicting permanent deformation and bottom-up fatigue cracking are evaluated as part of the overall sensitivity study. Details of the empirical performance models, their calibration coefficients, and the sensitivity analyses are all provided in Chapter 5 of Volume 2 of this report.

Figure 21 and Figure 22 show percentage of rutting variation versus percentage of calibration coefficient variation for the asphalt concrete and base layer calibration coefficients, respectively. Each coefficient was varied separately from the others and the results reflect the percentage change in performance compared to the unchanged condition. As clearly shown in Figure 21, a small variation in any one of the calibration coefficients in the asphalt concrete rutting model has a substantial impact on the performance predictions. Conversely, Figure 22 illustrates that the unbound rutting model is less sensitive to calibration coefficient variation.
Figure 21. Sensitivity to AC rutting model calibration coefficients.

Figure 22. Sensitivity to base layer rutting model calibration coefficient.

Figure 23 summarizes the sensitivity of predicted fatigue cracking to variations in the model calibration coefficients. Except for $\beta_1$, the prediction fatigue cracking is very sensitive to the calibration coefficients.
Figure 23. Sensitivity to fatigue cracking model calibration coefficients.

The sensitivity of predicted performance to the distress model calibration coefficients is substantially greater than for most other parameters considered in this study. This makes a compelling argument for the need for local calibration of these models. However, it must be understood that local calibration requires a very high level of effort. A significant number of calibration sections must be identified, and a complete set of pavement input data and historical performance data must be assembled for each. Trench data are often essential, particularly for accurate apportionment of rutting to the various layers within the pavement structure. Without trench data, total rutting must be allocated over the layers based on *ad hoc* assumptions, which introduces substantial uncertainties to the calibration process. Lastly, the computational burden for local calibration is quite substantial and can be very time consuming. Despite these difficulties, however, it is expected that most agencies that are serious about implementing the M-E PDG will eventually engage in local calibration of the performance models to their particular conditions.

### 2.2.6 Reliability Level

Sensitivity studies of the 1993 AASHTO Guide show that reliability is one of the design inputs having the greatest influence on the final pavement structural design. The reliability factor is applied directly to the design traffic in the 1993 AASHTO Guide, but it (along with the standard deviation $S_0$) is intended to represent all of the uncertainties in the design (traffic, material inputs, environmental conditions, model uncertainty, etc.). Although reliability is incorporated in a slightly different manner in the M-E PDG, consistency of the effects of reliability in both approaches can be evaluated using an approach similar to that used to evaluate traffic level.

The 1993 AASHTO Guide was used to design two alternative pavement sections for the Maryland location, low traffic, and other design inputs as described earlier but with reliability levels of 80% and 90%. The design pavement structures at each reliability level are summarized in Table 4. These structures can then be analyzed using the NCHRP 1-37A mechanistic-empirical procedure (at the adjusted reliability levels) to evaluate the consistency in the predicted distresses.
Table 4. 1993 AASHTO pavement designs at different reliability levels (Maryland location, low traffic).

<table>
<thead>
<tr>
<th>Reliability level</th>
<th>80%</th>
<th>90%</th>
<th>95%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maryland</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC</td>
<td>5.9</td>
<td>6.3</td>
<td>6.7</td>
</tr>
<tr>
<td>GB</td>
<td>16.8</td>
<td>18.0</td>
<td>18.6</td>
</tr>
</tbody>
</table>

Figure 24 shows that structures designed using the 1993 AASHTO Guide at different reliability levels for conditions of low traffic and mild to low average temperatures exhibited similar rutting and fatigue cracking as predicted by the M-E PDG. The predicted rutting and fatigue cracking values (after adjustment for the appropriate reliability level) were also consistent with the default design criteria incorporated in the M-E PDG software. In practical terms, these findings suggest that: (a) existing MDSHA policies for required reliability levels for different road functional classes can be left unchanged during at least the initial implementation of the M-E PDG; and (b) the default design limits for rutting and fatigue cracking in the M-E PDG are reasonable starting values during implementation of M-E PDG in Maryland.

Figure 24. Influence of reliability on the M-E PDG performance predictions.

### 2.3 Comparisons of Specific Maryland Pavement Designs

The objective of this portion of the study was to evaluate the M-E PDG flexible pavement design procedure for typical Maryland conditions and policies. Three Maryland projects provided by the Maryland State Highways Administration (MDSHA) were selected for this exercise:

- I-95 at Contee Road
- US-219
- ICC – Inter-County Connector

Details of the traffic, material property, climate, and other design inputs for each project are detailed in Chapter 6 of Volume 2 of this report.
The 1993 AASHTO designs provided by MDSHA for the three projects were as follows:

- **I-95 at Contee Road (AADTT=5781)**
  - Asphalt concrete: 12 inches
  - Granular base: 12 inches

- **US-219 (AADTT=864)**
  - Asphalt concrete: 9 inches
  - Granular base: 18 inches

- **ICC (AADTT=7362)**
  - Asphalt concrete: 15 inches
  - Granular base: 15 inches

In all three projects studied, MDSHA specified the upper 2 inches of the asphalt concrete layer as an SMA mixture. As previously discussed, the M-E PDG is not able to fully capture the benefits of gap-graded mixtures in its current formulation. The alternative adopted to overcome this limitation was to consider the asphalt concrete layer as a full 19mm dense mixture with the same PG 76-22 binder grade normally used with SMA mixtures in Maryland.

As summarized in Figure 25 through Figure 27, rutting was the controlling distress for all three projects in the M-E PDG calculations. Fatigue cracking was limited to less than 2% of the wheel path area and no thermal cracking was predicted in each case. The M-E PDG procedure requires specification of a design limit for each distress (and a corresponding reliability level) in order to determine the design pavement section. The default limit for total rutting in the M-E PDG software is 0.75 inches. This value, although not unreasonable, is an arbitrary selection that probably represents an upper bound to acceptable surface rutting. M-E PDG analysis of the AASHTO designs for the three projects yielded end-of-life predicted rutting values of about 0.6 inches for I-95 and US-219 and about 0.66 inches for the more heavily trafficked ICC. As has been the case several times before in this study, the performance predicted by the M-E PDG for AASHTO pavement designs deteriorates as traffic increases.

![Figure 25. I-95 project performance predictions.](image-url)
Figure 26. US-219 project performance predictions.

Figure 27. ICC project performance predictions.

Table 5 to Table 7 show a comparative analysis of AC thickness for the two total rutting limits of 0.5 and 0.6 inches.
The results observed in this exercise for three Maryland projects agree with the findings of the comparative and the sensitivity analysis studies. There seems to be good agreement between the 1993 AASHTO Guide and the M-E PDG for a rutting criterion of 0.6 inches when environmental conditions and traffic characteristics resemble those at the AASHO Road Test. The 1993 AASHTO designs for high traffic levels are likely to experience premature permanent deformation, according to the M-E PDG.

### 2.4 Implications for M-E PDG Implementation

The purpose of all of the studies reported in this chapter is to evaluate the general suitability of the M-E PDG for pavement design under Maryland conditions. Since the M-E PDG is intended for national use and calibrated with pavement sections from across the country, the expectation is that the procedure should be suitable for Maryland conditions in general. The purpose of the evaluation studies is therefore to confirm this and to identify any particular conditions that may require special attention during local implementation.

Specific findings bearing on the implementation of the M-E PDG in Maryland include the following:

1. The results consistently suggest that the 1993 AASHTO Guide overestimates pavement performance (i.e., underestimates amount of pavement distress) for traffic levels substantially beyond the 2 million ESALs experienced at the AASHO Road Test. This has particular significance for Maryland, given the high traffic volumes and truck percentages on many of the roads under MDSHA jurisdiction. For example, these findings suggest that the 1993 AASHTO Guide may significantly underdesign the pavement sections for the new Inter-County Connector and that the M-E PDG should be considered for this project, even if only

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<table>
<thead>
<tr>
<th>Table 5. I-95 structural designs.</th>
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</thead>
<tbody>
<tr>
<td>1993 AASHTO</td>
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<tr>
<td>AC 12''</td>
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<td>GAB 12''</td>
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<table>
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<th>Table 6. US-219 structural designs.</th>
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<tr>
<td>1993 AASHTO</td>
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<td>AC 9''</td>
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<td>GAB 18''</td>
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<table>
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<th>Table 7. ICC structural designs.</th>
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<tbody>
<tr>
<td>1993 AASHTO</td>
</tr>
<tr>
<td>AC 15''</td>
</tr>
<tr>
<td>GAB 15''</td>
</tr>
</tbody>
</table>

NA* - Not achievable within reasonable AC thickness variation.
in a supplementary role.

2. These results consistently show that the concept of equivalent traffic (ESALs) is not adequate for representing traffic loading in M-E designs. This is particularly true for permanent deformations predictions and for designs having high traffic volumes. Accurate traffic load spectra must be compiled for use in the M-E PDG.

3. Relative to the M-E PDG predicted performance, the 1993 AASHTO Guide overestimates performance (i.e., underestimates distress) for pavements in warm locations. Although Maryland does not have an excessively hot climate, this could still be an issue in the summer on the Eastern shore and central Piedmont regions of the state.

4. Even within a relatively small state like Maryland, intrastate variations in climate conditions were found to have a non-negligible influence on the M-E PDG performance predictions. One implementation activity should therefore be to ensure that there is adequate coverage of the state in the weather station database incorporated in the M-E PDG software.

5. The M-E PDG predictions for rutting are surprisingly insensitive to the volumetric properties of the asphalt concrete, at least when level 3 estimates of dynamic modulus are used. This in part is due to issues concerning the current $E^*$ estimation model (to be addressed in Stage 2 of NCHRP Project 1-40D) and deficiencies in the HMA rutting model (the focus of the current NCHRP Project 9-30A). Nonetheless, the findings from the evaluation studies suggest the importance of compiling level 1 measured dynamic modulus data in order to better differentiate the performance of different HMA mixtures. This is especially important if the M-E PDG is to be used to help set rational pay factors based on HMA volumetric, gradation, and other parameters.

6. The M-E PDG procedure in its present form cannot realistically predict the rutting performance of SMA mixtures, regardless of whether level 3 or level 1 inputs are used. Given the extensive and successful use of SMA in Maryland, this is a significant limitation of the current M-E PDG. This problem should be addressed in NCHRP 9-30A, which is focused on improving the HMA rutting model in the M-E PDG. Coordination and cooperation with the NCHRP 9-30A effort should be an important implementation activity.

7. The M-E PDG (like the 1993 AASHTO Guide) uses resilient modulus as the primary material property for characterizing unbound materials. Implementation activities should therefore include as a minimum the compilation and/or measurement of resilient modulus for typical granular base, subbase, and subgrade materials encountered in Maryland. The M-E PDG predictions for fatigue cracking are reasonable sensitive to unbound resilient modulus values, particularly for very low values associated with soft subgrade soils. The M-E predictions for total rutting are insensitive to the resilient moduli of either the base or subgrade. There is speculation that the current unbound rutting models in the M-E PDG are flawed and that they will likely be revised and enhanced in the future.

8. The M-E PDG less credit to the structural contributions of the unbound pavement layers than does the 1993 AASHTO design method. It is impossible to determine whether this is because the M-E PDG underestimates the contributions of the unbound layers or whether the 1993 AASHTO Guide overestimates them. Arguments can be made for both possibilities, and the likelihood is that reality lies somewhere between the two. It is expected that this topic will receive further attention during future enhancements and revisions to the M-E PDG.
9. MDSHA will need to determine appropriate policy regarding design limits for rutting, fatigue cracking, and other distresses. The default values in the M-E PDG, while reasonable, should probably be viewed as upper bounds. M-E PDG analyses of 1993 AASHTO designs for Maryland conditions and low to moderate traffic levels suggest that 0.6 inches of total surface rutting at 95% reliability may be a reasonable design limit for Maryland. Similar estimates of reasonable design limits for fatigue cracking and other distresses cannot be made at this time because these distresses did not appear to control the design for any of the cases examined in this study; maximum bottom-up fatigue cracking observed in any of the design scenarios was only about 16% of the lane area. Determining MDSHA policies for these design limits will be an important implementation activity.

10. The influence of reliability on pavement performance and design is similar for both the 1993 AASHTO Guide and the M-E PDG. This suggests that existing MDSHA policies regarding appropriate reliabilities for different road functional classes can continue to be used during initial implementation of the M-E PDG.

11. The sensitivity of predicted performance to the distress model calibration coefficients is substantially greater than for most other design parameters considered in this study. This makes a compelling argument for including local calibration as a major implementation activity. However, it must be understood that local calibration requires a very high level of effort and that it is dependent upon other prior implementation activities (e.g., compiling databases of traffic, material properties, performance, and other data for a sufficiently large set of pavement sections).
3. Data Needs for M-E PDG Implementation in Maryland

The input data required for the M-E PDG is much more extensive than for the current AASHTO procedure. summarizes by major category most of the design inputs required by the M-E PDG. Although some of the data for the M-E PDG is similar to that for the AASHTO Guide (e.g., annual average daily truck traffic, vehicle class distributions, subgrade resilient modulus, concrete modulus of rupture and modulus), much is significantly different and/or much more detailed input information required as well (e.g., axle load distributions by axle type, asphalt concrete dynamic modulus, thermo-hydraulic properties for unbound materials, etc.). A major focus of this study was therefore to develop a mapping between the data needs in the M-E PDG and the data available under the current MDSHA pavement design procedures.

The major data areas that are expected significant attention and effort include traffic, environmental, material properties, and performance. Each of these is detailed in the following subsections.
Table 8. Material tests and properties required for each hierarchical input level for the M-E PDG software (after Von Quintus et al., 2004).

<table>
<thead>
<tr>
<th>Data Category</th>
<th>Data Element/Input</th>
<th>Input Levels</th>
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<td>Depth to a Water Table</td>
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<td>Daily Number of Axles in Each Weight Category for Single, Tandem, Tridem, and Quads for Truck Classes 4-13</td>
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<td>Directional Distribution Factor</td>
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<td>Average Daily Minimum by Month and Year</td>
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Table 8 (continued).

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<tr>
<td>• Layer Thickness</td>
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<td>• Air Void System Parameters (Durability)</td>
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<td>Dowels</td>
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<tr>
<td>• Bar Dimensions (Length, I.D., O.D.)</td>
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<tr>
<td>• Corrosion Protection Layer</td>
<td>Dowels</td>
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<td>Phase Angle - Binder</td>
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<td>Indirect Tensile Creep Compliance&lt;sup&gt;1&lt;/sup&gt;</td>
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<td>• Bulk Specific Gravity of Coarse Aggregate</td>
<td>HMA &amp; ATB</td>
<td>X</td>
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<tr>
<td>• Bulk Specific Gravity of Fine Aggregate</td>
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<td>X</td>
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<td>Core Examination - Rehabilitation only</td>
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<td>Air Voids - The following properties are required to calculate air voids of the HMA/ATB layers.</td>
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<td>Bulk Specific Gravity, Mix</td>
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<tr>
<td>Maximum Specific Gravity, Mix</td>
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<td>Asphalt Ring &amp; Ball Temperature</td>
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<td>Asphalt Consistency - Binder, Only one of the following tests/properties is required.</td>
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<td>HMA &amp; ATB</td>
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<td>• Viscosity of Asphalt Cement</td>
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<td>• Performance Grade of Asphalt Cement</td>
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<td>Back-calculated Elastic Modulus, E-values</td>
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Table 8 (continued).

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<th>Material Property</th>
<th>Layer or Material Type</th>
<th>Input Level</th>
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<td>Third Point Modulus of Rupture</td>
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<td>Sieve Gradation</td>
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<td>CBR/R-Value²</td>
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<tr>
<td></td>
<td>Subgrade Soil</td>
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</tbody>
</table>

Notes:
(1) Test protocol uses different temperatures than required for the Superpave thermal cracking model.
(2) Depends on the amount passing the number 200 sieve.
(3) Required material property used for design and analysis, but will be estimated from experience.
(4) Only one of these tests is required for the level 3 inputs.

3.1 Traffic Data

The current AASHTO Pavement Design Guide defines traffic inputs in terms of ESALs. The M-E PDG, on the other hand, requires a more complete characterization of traffic in terms of load spectra. The evaluation studies reported in Chapter 2 (and others) have found that the M-E performance predictions can be quite sensitive to details of the traffic load spectra. Consequently, accurate characterization of traffic in terms of load spectra must be given high priority.

The main parameters for defining traffic load spectra are include: Average Daily Truck Traffic; vehicle class distribution; axle load distribution; and seasonal variations of the data (if significant). Site-specific traffic load spectrum data are typically collected using Automated
Vehicle Classification (AVC) and Weigh-in-Motion (WIM) devices. Default traffic load spectra (e.g., based on road functional class) can be extracted from the LTPP database and/or obtained from the M-E PDG software.

Information provided by MDSHA personnel and/or specified in the MDSHA Pavement Design Guide regarding the availability and quality of traffic load spectra data for the state can be summarized as follows:

- The MDSHA has reasonably accurate traffic count (total volume) and percent trucks data. These data are typically provided by the Office of Planning and Preliminary Engineering (OPPE), Travel Forecasting Section of the Project Planning Division. If traffic volume information cannot be obtained from OPPE, it may be estimated from adjacent/older projects, the Highway Location Reference Manual, the SHA GIS, or from information provided by the project owner.
- Highway Information Systems Division (HISD) is responsible for collecting vehicle classification data. Al Blazucki is the OMT liaison with HISD.
- Vehicle class distributions are available for LTPP sections within Maryland and from project level design information. LTPP data availability for Maryland and surrounding states is summarized in Table 9. Note that project level design data do no necessarily use all the same vehicle classifications as for LTPP. In particular, the MDSHA Pavement Design Guide suggests that the MDSHA 6 class system may be used instead of the FHWA 13 classes.
- Existing axle load distribution data are of questionable quality. Most are about 20 years old and would probably not pass LTPP quality requirements. Barbara Ostrum of MACTEC has studied MDSHA on axle load distributions in the past and developed a report documenting the inadequacies/inaccuracies of current axle load distribution data.

<table>
<thead>
<tr>
<th>State</th>
<th>LTPP State Code</th>
<th>Number of sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>DE</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>DC</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>MD</td>
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<tr>
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<td>11</td>
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<tr>
<td>WV</td>
<td>54</td>
<td>5</td>
</tr>
</tbody>
</table>

Subsequent conversations with Barbara Ostrum of MACTEC elaborated upon the issues/deficiencies with current MDSHA axle load distribution data:

- There are four separate sets of axle load distribution data available for roads in Maryland.
  - Data Set 1 was collected from bridge WIM equipment (strain gauges on bridges plus vehicle class counts) during the mid to late 1980s. Data were collected at two to three dozen sites distributed across the state. Data are limited, as they were collected only

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Subsequent to the collection of data for this report, Mr. Blazucki left the MDSHA.
for a short time period over the summer. The MDSHA traffic group has consolidated all of this information into four distributions that they “like” in the sense that they result in pavement designs having the “right” thickness, but the bias introduced in this approach is obvious. Ostrum’s overall assessment for this data set is that the quality is good but that the sample sizes are small (both in number of counts and temporal duration) and that 20-year old data may not be representative of today’s traffic.

- Data Set 2 was collected at permanent weigh station sites from the late 1990s onward. These comprise the data in the LTPP database (TRF_MONITOR_LTTP_LN and TRF_MONITOR_AXLE_DISTRIB tables). The availability of LTPP vehicle class and axle load distribution data for Maryland and surrounding states is summarized in Table 9 and Table 10, respectively. Although there is some axle load distribution data available in the LTPP database, the quality of the calibration of the weight station sites is variable and often questionable (some was done using only a single dump truck) and consequently the quality of the data is also variable and questionable. The RECORD_STATUS field in the TRF_EQUIPMENT_MASTER indicates the data quality for most data from 2000 onward.

- Data Set 3 was collected using portable WIM equipment. This equipment never worked correctly, and consequently the data from this set are of poor quality at best.

- Data Set 4 is from an SPS1 WIM pooled fund study on Route 15 near the Potomac River. At the time of the conversation (spring 2006), there were persistent problems with the equipment. However, the expectation was that these problems would be resolved and that the final data set should be of very high quality, albeit limited to just a single road and location.

- Fixed location weight stations are administered by the State Police. Since there primary concern is law enforcement, they only determine whether or not a vehicle is overweight and they do not store the precise axle load, particularly if the vehicle is within allowable weight limits. It is interesting to note that the calibration of axle weight equipment used for law enforcement is done to a much higher standard than even for LTPP Level E quality. Ostrum suggested that it might be possible to ask the State Police to save their screening data for limited periods of time to provide additional axle load distribution data. This might be pursued if other avenues for collecting this data are unproductive.

- Ostrum cautioned that some project-level vehicle class distributions may be suspect. These data are usually collected by consultants, and the quality of the data will be dependent to some degree on the QC checks imposed by MDSHA.

Table 10. LTPP sections within/near Maryland having axle load distribution data (from TRF_MONITOR_AXLE_DISTRIB data table, LTPP SDR 19.0).

<table>
<thead>
<tr>
<th>State</th>
<th>LTTP State Code</th>
<th>Number of sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>DE</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>DC</td>
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<tr>
<td>VA</td>
<td>51</td>
<td>11</td>
</tr>
<tr>
<td>WV</td>
<td>54</td>
<td>5</td>
</tr>
</tbody>
</table>
The traffic activities required during implementation of the M-E PDG in Maryland are clear:

1. All existing MDSHA AVC and WIM data that is of acceptable quality should be compiled in a standardized format. Available information suggests that the existing AVC data may be of sufficient quality but that the existing WIM data may not.

2. Additional traffic data should be compiled for Maryland locations and regions where sufficient data of adequate quality do not at present exist. Ideally, these new data would be collected from AVC/WIM stations as part of a comprehensive traffic study. As an alternative (or supplement), if may be possible to compile typical local vehicle class and axle load distributions from the LTPP dataset for sites in Maryland and in immediately neighboring states (e.g., Pennsylvania, Virginia, and West Virginia), provided the quality of the data in the LTPP tables is adequate.

The final fallback position is to use the default vehicle class and axle load distributions included in the M-E PDG software. However, these distributions are national defaults and may not be representative of the high volume, high truck percentage traffic on many Maryland roads.

### 3.2 Environmental Data

The key environmental input data required by the M-E PDG are available from the weather station database included in the M-E PDG software. However, the current M-E PDG contains weather station data for only four Maryland locations: Baltimore, Hagerstown, Ocean City, and Salisbury.

The evaluation studies described in Chapter 2 found that even climate differences within the state of Maryland can have a significant influence on pavement performance. The same pavement section when located on the Eastern Shore, for example, will exhibit more rutting than when located in the western mountains. It is therefore important that appropriate climate data be available for use in pavement design for all subregions of the state.

Accordingly, an important implementation activity will be to incorporate additional Maryland weather station data into the M-E PDG database. Weather station data are available from the National Climate Data Center (NCDC—http://www.ncdc.noaa.gov/oa/ncdc.html) within the National Oceanic and Atmospheric Administration (NOAA). The NCDC lists 288 weather stations within the state of Maryland. Forty-one of these have hourly surface climate data as required for the M-E PDG. Climate data is available for a nominal charge (free to .edu domain users) from the NCDC. The NCDC data are available in a variety of well-documented ASCII text formats, which can be easily translated into the text files required for input to the M-E PDG database. Documentation for the M-E PDG format is available on the web at http://trb.org/mepdg/ICM_Formats.htm. Utility programs to convert NCDC files to M-E PDG format may be available from the NCHRP 1-37A or NCHRP 1-40D project teams.

Part of the implementation effort will be to determine weather individual NCDC data sets are of sufficient completeness and duration. If suitable NCDC data are unavailable, local weather stations (e.g., at regional airports) should be evaluated as sources of climate data to be added to the M-E PDG database.

### 3.3 Material Properties

Many material properties are required as inputs to the M-E PDG. Several of these are familiar and/or similar to the inputs required for the 1993 AASHTO Guide (e.g., subgrade resilient modulus). Others are more unfamiliar and very difficult to measure in standard agency
laboratories (e.g., soil thermo-hydraulic properties). The conventional expectation is that default values will likely be used initially for the unfamiliar/difficult to measure properties, in part simply because they are unfamiliar and difficult to measure but also because it is thought (although not definitively established) that pavement performance and designs are less sensitive to these inputs and/or they do not vary substantially among different material types. Most implementation effort regarding material properties will therefore be focused on the mechanical properties of the layer materials—e.g., dynamic modulus for HMA, Young’s modulus and modulus of rupture for PCC, resilient modulus for unbound materials.

The status of M-E PDG mechanical property inputs for typical Maryland materials is summarized below, organized by general material type.

### 3.3.1 Hot Mix Asphalt Concrete

Key level 1 engineering properties for HMA include laboratory-measured dynamic modulus values and binder shear stiffness and phase angle. The MDSHA Western Regional Laboratory is well equipped to measure these properties; it contains the full suite of Superpave binder test equipment, an IPC UTM-25 servo-hydraulic test system for measuring HMA dynamic modulus and other properties under a wide range of loading and environmental conditions, and a first-generation Simple Performance Tester for quickly and economically measuring HMA dynamic modulus, creep, and repeated load permanent deformation properties. Many level 1 inputs (binder properties, in particular) have already been measured at the MDSHA Western Regional Laboratory for typical Maryland mixtures and binders, and the in-house capability clearly exists for measuring whatever additional inputs are deemed necessary.

One important problem that must be investigated is the most appropriate characterization and modeling of Stone Matrix Asphalt (SMA). Maryland uses large quantities of SMA, yet it has been demonstrated repeatedly that the M-E PDG in its present version does not adequately reflect the benefits of SMA. It is recognized that the M-E PDG formulation must be enhanced to reflect the true performance of SMA mixtures. This topic is part of the scope of the current NCHRP 9-30A project; C.W. Schwartz is a Co-Principal Investigator on this project.

Implementation activity regarding development of material inputs for HMA are fairly straightforward:

- **Compile existing laboratory test data for binder properties (dynamic shear modulus, phase angle, etc.) and mixture properties (dynamic modulus, creep compliance, low-temperature tensile strength) for commonly used Maryland materials into a catalog of typical HMA design inputs.** The existing databases (particularly for binder properties) already compiled by the Western Regional Laboratory provide a major initial step toward development of this catalog.

- **Develop and execute a plan for filling gaps in existing laboratory test data for HMA and binder inputs.** It is expected that this can be done in-house by the MDSHA over a period of time as part of continuing construction project activities.

- **Coordinate and cooperate with NCHRP 9-30A in the development of a procedure for better reflecting the benefits of SMA mixtures—in particular, its exceptional rutting resistance—in the current M-E PDG framework.**

### 3.3.2 Portland Cement Concrete

Key level 1 engineering properties for PCC include: 28 day elastic modulus; 28 compressive strength or modulus of rupture; ultimate shrinkage; and coefficient of thermal expansion. Required elastic modulus and compressive strength/modulus of rupture are specified for each
project and monitored via a QC testing program. Consequently, a substantial database of typical values for these properties should already exist.

Ultimate shrinkage and coefficient of thermal expansion are not typically specified or currently measured for PCC mixtures in Maryland. In fact, tests for measuring shrinkage and coefficient of thermal expansion have not yet been fully standardized. Consequently, it is recommended that the default values for these properties provided in the M-E PDG software be used over the near term.

One issue of particular interest to the MDSHA is whether the M-E PDG adequately reflects the benefits of high early strength PCC, a material that is increasingly specified by MDSHA. The PCC material models in the M-E PDG can distinguish several differences in material behavior between high performance (high early strength, in particular) and regular PCC mixes. The aging models can simulate the different rates of strength/stiffness gain over time for these materials; the designer can specify both the ultimate shrinkage/time to shrinkage as well as the gains in elastic modulus and modulus of rupture over time. The level of built-in curling can also be adjusted by the designer, with higher values for mixes showing higher than normal levels of early shrinkage and reduced values for low shrinkage mixes.

Given the project-specific specification of PCC mixtures, the data on typical PCC mixtures that are already available, and the capabilities of the M-E PDG for treating non-standard PCC materials, there is little need for early implementation activities for this class of materials.

### 3.3.3 Stabilized Materials

The MDSHA does not commonly use stabilized base/subbase materials. Consequently, there are no significant implementation issues for this class of materials.

### 3.3.4 Unbound Base/Subbase/Subgrade Materials

The key mechanical property required for unbound base/subbase/subgrade materials is the resilient modulus, $M_R$, at optimum moisture content and density. For level 1 inputs, the stress dependence of $M_R$ must also be included as determined from the AASHTO T307, LTPP TP46, or NCHRP 1-28A test protocols.

Information on current MDSHA testing capabilities and plans was obtained from telephone conversations with J. Withee and R. Kochen. The MDSHA currently possesses equipment for measuring unbound $M_R$ in its geotechnical laboratory. This equipment, which is about 20 years old, was purchased to perform testing under the LTPP program. It is designed to run the older AASHTO T298 protocol, and its electronics will not support the newer T307 protocol. It is also not capable of testing base and subbase coarse aggregates. Although it is not currently used on a routine basis, it is in good condition and is calibrated by the manufacturer annually. A new test system capable of running the current AASHTO T307 protocol on base, subbase, and subgrade materials is currently on order.\(^5\)

The existing resilient modulus test system is currently being used on some projects to help set targets for field compaction control. Samples are prepared in the laboratory at OMC-2%, OMC, and OMC+2% at AASHTO T99 and T180 compaction levels. Field compaction must produce conditions that correspond to a $M_R$ value within a specified range as determined from the

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\(^5\) Subsequent to the drafting of this report, this new resilient modulus test equipment has been delivered and installed at OMT.
laboratory test results. To date, this approach has been tried on some A-2-4 and A-4 subgrade soils in Prince George’s county, with plans to continue on more projects in the future.

R. Kosten wants to extend the subgrade $M_R$ testing to all typical subgrade soils in the state. The largest current problem with this plan is operational, in that his staff cannot always get the access to the site that they require. Kochen hopes to piggyback some $M_R$ testing on the intelligent compaction pooled fund study currently getting underway. He also plans to coordinate laboratory $M_R$ testing of base materials with GeoGauge testing in the field for specific construction projects.

Some $M_R$ data for typical Maryland unbound materials is available from prior studies, both in its own laboratory and in particular from the work done by Rada and Witczak in the 1980s. Additional data will continue to be compiled under current and proposed testing plans. The resilient modulus of the unbound materials has a major influence on pavement performance prediction in the current version of the M-E PDG, particularly for total rutting. The recent recalibration of the M-E PDG distress models completed as part of NCHRP Project 1-40D found substantial improvements in rutting prediction when backcalculated $M_R$ values from the LTPP database were used instead of the level 3 default values for each soil type. (Note: R. Kochen commented that he thought the level 3 default $M_R$ values were much too high for most soil classes, but particularly for the fine-grained subgrade soil types; this is an opinion that has been voiced by pavement engineers in many other states as well.) It is therefore vital that MDSHA’s plans to test all typical unbound materials in the state be well organized and executed and that the MDSHA field crews be given adequate access to all project sites.

### 3.4 Pavement Performance Data

Pavement performance data are required for local calibration of the M-E PDG procedure. Local calibration involves replacement of the national calibration coefficients in the empirical distress prediction models with values more tailored to local conditions. Local calibration requires the identification of a set of field pavement sections for which the M-E PDG inputs can be well quantified (e.g., traffic, environment, material properties) and for which a history of performance data are available (e.g., rutting, fatigue cracking). Local calibration of the M-E PDG procedures in concept can be very beneficial in improving pavement performance predictions for local conditions. However, the considerable amount of effort to perform local calibration should not be underestimated.

Local calibration may be particularly useful for Maryland for two reasons: (1) traffic levels in Maryland may on average be considerably higher than for many of the LTPP sections used in the global calibration in NCHRP 1-37A; (2) pavement performance in Maryland may tend to be better on average than for many of the LTPP sections in the global calibration because of extensive use of SMA, a relatively high level of maintenance, and other reasons. In addition, the global calibration in NCHRP 1-37A was hampered by a lack of measured material property data, and as a consequence all of the calibration was done using only level 3 inputs. Assuming that the data collection implementation activities identified in Section 3.3 and detailed in Chapter 5 are executed, local calibration for Maryland may be able to benefit from the improved accuracy of level 1 or 2 traffic and material property inputs. A final advantage of local calibration is that the distress variability used in the reliability calculations—which be default is based upon the prediction errors from the global calibration—may be able to be reduced.

Some insight into the importance of local calibration can be gleaned by examining the local LTPP sections that were used in the M-E PDG national calibration during NCHRP 1-37A. These sections are listed in Table 11. Unfortunately, no Maryland LTPP sections were used in the
NCHRP 1-37A calibration, but several sections from nearby states were. Predicted vs. measured rutting performance for all sections used in the global calibration in NCHRP 1-37A is summarized in Figure 28. The corresponding predicted vs. measured rutting performance for just the calibration sections in Table 11 from the nearby states is summarized in Figure 29. For the case of rutting, the quality of the predictions for the local states is broadly similar to that for the national data set, although the low $R^2$ values in both cases suggest some potential for improvement. The case for fatigue cracking is much different, however. Errors in predicted alligator fatigue cracking vs. damage for all sections used in the global calibration in NCHRP 1-37A are summarized in Figure 30. The corresponding results for just the calibration sections in Table 11 from the nearby states are summarized in Figure 31. Alligator fatigue cracking is consistently and substantially over predicted by the nationally calibrated distress model. This is a clear example showing where local calibration can be expected to yield substantial improvements in prediction accuracy.

Table 11. LTPP calibration sections within/near Maryland.

<table>
<thead>
<tr>
<th>State</th>
<th>LTPP State Code</th>
<th>Number of sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>DE</td>
<td>10</td>
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</tr>
<tr>
<td>DC</td>
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<td>MD</td>
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<td>NJ</td>
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<td>3</td>
</tr>
<tr>
<td>WV</td>
<td>54</td>
<td>0</td>
</tr>
</tbody>
</table>

$R^2 = 0.399$
$N = 387$
$S_b = 0.121$
$SSE = 6.915$
Figure 28. Predicted vs. measured total rutting for global model calibration in NCHRP 1-37A (NCHRP, 2004).

![Predicted vs. measured total rutting](image)

Figure 29. Rutting in NCHRP 1-37A calibration sections in nearby states (based on data from El-Basyouny, 2004).

![Rutting in NCHRP 1-37A calibration sections](image)
Figure 30. Errors in predicted alligator fatigue cracking for all NCHRP 1-37A calibration sections (El-Basyouny, 2004).

![Graph showing errors in predicted alligator fatigue cracking for all NCHRP 1-37A calibration sections.]

Figure 31. Errors in predicted alligator fatigue cracking for NCHRP 1-37A calibration sections in nearby states (based on data from El-Basyouny, 2004).

The development of local calibration guidelines is the focus of NCHRP Project 1-40B, which is currently nearing completion. The results from this study should be monitored and incorporated into the MDSHA implementation plan. Key steps in the local calibration process will include: (a) identification of an appropriate number and set of field sections for which quality input and performance data can be determined; (b) compilation of relevant input parameters; and (c) compilation of performance histories (rutting, fatigue cracking, roughness, etc.) from the MDSHA pavement management system (PMS). The data collection implementation activities already identified in 3.3 and detailed in Chapter 5 are thus essential pre-requisites for any local calibration attempt. The adequacy of the pavement performance and other data within the MDSHA PMS database for use in local calibration studies must also be evaluated.
4. National Adoption Schedule for M-E PDG

Any implementation of the M-E PDG in Maryland must be accomplished within the context of the national adoption of the procedure by AASHTO. It is therefore worthwhile to review the current status of the national review and adoption plan. The following summary is based largely on Harrigan (2006).

The final reports for NCHRP Project 1-37A were delivered in April 2004. Because of the complexity of the M-E PDG methodology and because it represents such a major shift from the current pavement design approach, NCHRP Project 1-40 “Facilitating the Implementation of the M-E Pavement Design Guide” was initiated to aid in the evaluation and implementation of the new procedure. The primary goals of NCHRP 1-40 are: (a) to prepare an interim M-E PDG for possible adoption by the Joint Task Committee on Pavements; and (b) advance the M-E PDG and software to a routine-use AASHTO product.

In order to separate the review and implementation efforts, NCHRP 1-40 was divided into a series of sub-projects:

- Independent review of the design guide and software (1-40A, 99% completed)
- Guidance for local and regional calibration (1-40B, in progress)
- Verification and local recalibration of HMA and PCC performance models (1-40B, completed)
- Version 0.9 of the M-E pavement design software (1-40D, in progress)
- Version 1.0 of the M-E design guide software (1-40E, FY 2007)
- Practical guide to M-E pavement design and recommended manual of practice (1-40H, FY 2007)
- Support Lead States activities (1-40J, not yet awarded)

In other words, the NCHRP 1-40A subproject is designed to provide an independent review of the product from NCHRP 1-37A while the remaining subprojects are geared toward implementation efforts.

The main review objectives of NCHRP 1-40A are as follows:

- Assess the rationality, soundness, and completeness of the concepts, process, and procedures in the NCHRP 1-37A M-E methodology
- Appraise the consistency and sensitivity of the results
- Evaluate the design reliability methodology
- Compare predicted performance to historical results

The draft reports from NCHRP 1-40A were submitted to and reviewed by the project panel in December 2005. The original NCHRP 1-37A research team has responded to the findings from the NCHRP 1-40A reviewers. A final decision by the project panel regarding publication of the results is pending as of the time of this writing.

The objectives of the first of the implementation subprojects, NCHRP 1-40B, are as follows:

- Verify the initial global calibration using independent data sets for both PCC and HMA pavements
- Attempt a local calibration of the flexible pavement rutting prediction models to reduce residual error and bias
- Prepare guidance for highway agencies attempting local calibration of the prediction models
- Draft AASHTO recommended practice and case studies
The principal findings from the calibration verification for JPCP pavements found that the cracking and IRI models were unbiased with reasonable $R^2$ values but that the faulting model underpredicted field measurements. The corresponding findings for CRCP pavements found that the crack width and punchout models were unbiased with reasonable $R^2$ values but that the crack spacing and IRI models slightly underpredicted field performance. Suggestions were offered for possible causes of the underpredictions and their remedy. Local calibration of the HMA rutting model by incorporating volumetric and gradation factors resulted in very good agreement between predicted and measured rutting, as shown in Figure 32. However, although the unbound material rutting model was found to consistently overpredict the rutting of the unbound layers, no simple method could be devised to improve the predictions.

![Figure 32. NCHRP 1-40B HMA rut depth predictions after local calibration (after Harrigan, 2006).](image)

Enhancements and modifications to the M-E PDG software currently underway during Stage 1 of NCHRP 1-40D include the following:

- Extensive corrections of bugs, including the resolution of the “layer discontinuity” problems in flexible pavements and the reduction of nodal spacing/increase in mesh refinement for rigid pavements
- Inclusion of 9-year weather files
- Recalibration of all performance models using LTPP data through 2004
- Modification of the CRCP and HMA thermal cracking models
- Improvement of the Integrated Climate Model with better moisture content and soil saturation predictions for unbound layers and the subgrade
- Addition of a special axle configuration module
• Improvement of the Level 3 default resilient modulus values for unbound layers
A new version of the software incorporating these enhancements and modifications is expected to be posted on the TRB web site in June 2006. Additional work planned for Stage 2 of the project includes:
  • Capability of user-defined transfer functions (i.e., user-defined empirical distress models)
  • Option of using modified calibration coefficients from 1-40B
  • Implementation of a data transfer interface with the TrafLoad program
  • Output and display of selected structural responses (intermediate stresses, strains)
The Stage 2 modifications are expected to be completed by December 2006.
5. M-E PDG Implementation Plan for Maryland

5.1 Implementation Activities

Effective implementation of the M-E PDG in Maryland will require a coordinated set of activities. Many of these are related to data collection and compilation as described in Chapter 3:

Traffic

- Compile all existing MDSHA AVC and WIM data that is of acceptable quality into a standardized format. It is expected that very little existing WIM data will be of acceptable quality.
- Collect additional traffic data compiled for Maryland locations and regions where sufficient data of adequate quality do not at present exist. It is expected that this work will be contracted to an outside consultant.
- Develop a catalog of representative traffic load spectra for different road functional classes and climatic regions within the state for use in routine design.

Climate

- Incorporate additional Maryland weather station data into the M-E PDG database.

Hot Mix Asphalt Properties

- Compile existing laboratory test data for binder and mixture properties for commonly used Maryland materials into a catalog of typical HMA design inputs. The existing databases (particularly for binder properties) already compiled by the Western Regional Laboratory provide a major initial step toward development of this catalog.
- Develop and execute a plan for filling gaps in existing laboratory test data for HMA and binder inputs. It is expected that this can be done in-house by the MDSHA over a period of time as part of continuing construction project activities.
- Coordinate and cooperate with NCHRP 9-30A in the development of a procedure for better reflecting the benefits of SMA mixtures—in particular, its exceptional rutting resistance—in the current M-E PDG framework.

Portland Cement Concrete Properties

- Compile existing laboratory test data for Portland cement concrete for common mix designs used in Maryland paving projects in order to develop a catalog of typical PCC design inputs. Data from the recent Salisbury bypass research project can be used as the initial step in the development of this catalog.
- Develop project specifications to include measurement of elastic modulus and flexural tensile strength properties for PCC mixes to augment the material property design inputs database.

Unbound Material Properties

- Review past research by Rada on selected MDSHA unbound materials to determine whether the data are of sufficient quality and completeness to warrant re-analysis for use as inputs to the M-E PDG.
• Execute the MDSHA plan to measure resilient moduli for all typical unbound and subgrade materials in the state. It is expected that this can be done in-house by the MDSHA over a period of time as part of continuing construction project activities.

Performance Data
• Evaluation of the adequacy of the pavement performance and other data within the MDSHA PMS database for use in local calibration.

Several other important implementation activities can also be identified:

Definition of Design Criteria

Pavement design criteria describe the minimum acceptable performance limits. In the 1993 AASHTO procedure, these criteria are the initial and terminal PSI values and the reliability factors ($S_0$ and $Z_R$). Pavement design criteria for the M-E design procedure are more specific and extensive:

- Maximum distress magnitudes for each distress (e.g., maximum total rutting for flexible pavements, maximum average faulting for rigid pavements)
- For roughness, the initial post-construction value of IRI
- Design reliability levels
- Distress variability for each distress

The maximum allowable distress magnitudes and design reliability levels are policy issues. Some guidance can be provided by the current AASHTO design procedure (e.g., for appropriate design reliability levels) and other sources (e.g., Witczak’s survey of State DOT pavement engineers on maximum allowable rutting levels). Initial post-construction IRI is set by specification. The distress variability for each distress can be taken as either the current default values (based on the global calibration from NCHRP 1-37A) or from local calibration results. The development of design criteria for the M-E PDG that are relevant to MDSHA policies and conditions is an essential implementation activity.

Revisions to OMT Pavement Design Guide

MDSHA has created an excellent manual for agency pavement design. The current manual is based on the empirical 1993 AASHTO design guide. An important implementation activity will thus be to revise this manual to reflect the changes in the M-E PDG. It is also possible that a dual-track pavement design procedure may be desired—e.g., 1993 AASHTO for lower traffic/less important pavement designs and the M-E PDG for higher traffic/greater importance designs.

Particular emphasis must be placed on revisions to the rehabilitation design portions of the manual. Rehabilitation represents the bulk of MDSHA’s pavement design activity. The 1993 AASHTO and M-E PDG differ significantly on how they use FWD and visual survey field evaluation data.
Training

The M-E PDG is both new and complex. Training of OMT technical staff will be required for it to be used most effectively. Training to this point has been provided by UMD (short course, June 2001) and the FHWA (workshops by the Design Guide Implementation Team and short courses by the National Highway Institute). The MDSHA pavement design group is quite small, which permits greater flexibility for training activities.

It is expected that continuing and future courses offered by the FHWA DGIT and the NHI should be sufficient for MDSHA training purposes. Workshops recently offered and/or planned for the near future by the FHWA DGIT include the following:

- Mechanistic-Empirical Pavement Design and Construction Methodologies
- Obtaining Materials Inputs for Mechanistic-Empirical Pavement Design
- Use of Pavement Management System Data to Calibrate Mechanistic-Empirical Pavement Design
- Traffic Inputs for M-E PDG
- Climatic Considerations for Mechanistic-Empirical Pavement Design

Current NHI short courses that devote substantial attention to M-E design concepts and the M-E PDG are as follows:

- NHI 31064 - Introduction to Mechanistic Design
- NHI 151018 - Application of the Traffic Monitoring Guide
- NHI 132040 - Geotechnical Aspects of Pavements

The last course (NHI 132040) is a new NHI offering that devotes balanced attention to both the 1993 AASHTO and M-E PDG. This includes many comparisons between designs performed using the two methodologies. This course would be an especially valuable addition to the MDSHA training schedule.6


Coordination

Maryland is one of the lead states for the M-E PDG implementation. From this position, MDSHA should therefore be well situated to keep abreast of current developments in M-E PDG implementation activities and news nationwide.

In addition, MDSHA should track progress of and products from several ongoing NCHRP projects that are addressing various aspects of the M-E PDG and its implementation. Key active NCHRP projects to monitor include the following:


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6 C.W. Schwartz, the author of this report, is one of the co-instructors for this NHI course.
• 1-40D Technical Assistance to NCHRP and NCHRP Project 1-40A: Versions 0.9 and 1.0 of the M-E Pavement Design Software
• 1-41 Models for Predicting Reflection Cracking of Hot-Mix Asphalt Overlays
• 1-42A Models for Predicting Top-Down Cracking of Hot-Mix Asphalt Layers
• 9-30A Calibration of Rutting Models for HMA Structural and Mix Design
• 9-33 A Mix Design Manual for Hot Mix Asphalt

Many of these projects may produce model enhancements that will be implemented in future versions of the M-E PDG software. Provisions should be made for local evaluation of each new version of software as released.

Ancillary Research

The M-E design and performance prediction methodology provides a rich set of capabilities that can be used for a range of special research studies that are not specifically related to pavement design. Some specific obvious examples include: (a) rational determination of pay factors based on impacts of construction variations on predicted performance; (b) highway cost allocation studies; (c) predictions of early-time performance trends for use in monitoring warranty construction projects. It is expected that these and other ancillary research problem statements will be fleshed out during implementation of the M-E PDG.

Table 12 summarizes the key M-E PDG implementation activities identified throughout this report. The table identifies the estimated priority and effort levels in qualitative terms, the group expected to perform the activity (MDSHA, consultant, or University), and the optimal time frame. It is anticipated that many of the activities performed out-of-house could be accommodated by existing contractual agreements between MDSHA and the University of Maryland, Applied Research Associates, Advanced Asphalt Technologies, and other consultants.

High priority items represent activities that are necessary prerequisites for any subsequent implementation activities. Medium priority items are also essential for full implementation, but they may be dependent upon earlier higher priority activities. Low priority items represent activities that are not essential to implementation of the M-E PDG but which will allow MDSHA to garner full benefit from the M-E PDG.

Although it is difficult to put estimate dollar costs for each activity, the level of effort can be qualitatively categorized as: low – less the $100K; medium - $100K to 250K; and high – greater than $250K. For activities that are suggested to be performed in-house by MDSHA, the level of effort estimates are based on the equivalent cost if done by a consultant or University. Actual costs will be less if some/all of the work is done in-house by MDSHA.

Proper staging of implementation activities is clearly important. The time frame for each activity is estimated in one of three categories: near term – within the next 1 to 2 years; medium term – within the next 2 to 4 years; and far term – after 4 years. Some activities like training are ongoing activities throughout the implementation period.

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7 C.W. Schwartz is a member of the NCHRP 1-40D research team.
8 C.W. Schwartz is a Co-Principal Investigator for NCHRP 9-30A.
Related activities can be grouped into larger research projects for the planning purposes and the development of Research Problem Statements. The resulting research projects are summarized in Table 13. Research Problem Statements for each project are provided in the subsequent subsection. Activity 15 “Define ancillary research studies” is not included in the Research Problem Statements because it has a far-term time frame and it is expected that the potential ancillary research studies will be refined during the intervening period. The total cost for the research plan outlined in Table 13 is $1,460K. Of this total, $300K corresponds to activities in which MDSHA in-house staff will have sole or major responsibility and effort, and $200K is for an optional pooled fund study, the need for which will depend upon the outcome of the current NCHRP Project 9-30A. Total duration of the proposed research effort is 6 years.

Table 12. Summary of proposed M-E PDG implementation activities.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Priority</th>
<th>Effort</th>
<th>Who Performs?</th>
<th>Time Frame</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Compile existing MDSHA AVC/WIM data</td>
<td>High</td>
<td>Low</td>
<td>X</td>
<td>Near</td>
</tr>
<tr>
<td>2. Collect supplementary traffic data</td>
<td>High</td>
<td>High</td>
<td>X</td>
<td>Near</td>
</tr>
<tr>
<td>3. Develop catalog of typical traffic load spectra</td>
<td>High</td>
<td>Medium</td>
<td>?</td>
<td>X</td>
</tr>
<tr>
<td>4. Compile additional MD weather station data</td>
<td>Medium</td>
<td>Low</td>
<td>?</td>
<td>X</td>
</tr>
<tr>
<td>5. Compile existing HMA laboratory test data</td>
<td>High/Medium</td>
<td>Low</td>
<td>X</td>
<td>Near</td>
</tr>
<tr>
<td>6. Develop/execute plan for filling gaps in existing HMA data</td>
<td>High/Medium</td>
<td>Medium</td>
<td>X</td>
<td>Near</td>
</tr>
<tr>
<td>7. Develop procedure for better reflecting benefits of SMA in M-E design procedure</td>
<td>High/Medium</td>
<td>Medium</td>
<td>X²</td>
<td>Near</td>
</tr>
<tr>
<td>8. Compile existing unbound M₈ data</td>
<td>Medium</td>
<td>Low</td>
<td>X</td>
<td>Medium</td>
</tr>
<tr>
<td>9. Develop/execute plan for filling gaps in existing unbound M₈ data</td>
<td>Medium</td>
<td>Medium</td>
<td>X</td>
<td>Medium</td>
</tr>
<tr>
<td>10. Develop database of PCC design input data</td>
<td>Low</td>
<td>Low</td>
<td>X</td>
<td>Near</td>
</tr>
<tr>
<td>13. Develop M-E design criteria</td>
<td>High</td>
<td>Low</td>
<td>X</td>
<td>Near</td>
</tr>
<tr>
<td>15. Monitor/evaluate future M-E PDG enhancements and software releases</td>
<td>High</td>
<td>Medium</td>
<td>X³</td>
<td>X³</td>
</tr>
<tr>
<td>16. Attend training workshops/courses</td>
<td>High</td>
<td>Low</td>
<td>X⁴</td>
<td>Ongoing</td>
</tr>
<tr>
<td>17. Define ancillary research studies</td>
<td>Low/Medium</td>
<td>Medium</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

Notes:
1. M=MDSHA, C=Consultant, U=University. Question marks designate secondary party that may perform the work.
2. Should be accomplished within present scope of NCHRP Project 9-30A.
3. Joint effort: MDSHA via participation in M-E PDG Lead States with FHWA and UMD to provide technical background support.
4. Training courses are offered by others (FHWA DGIT and NHI).
Table 13. MDSHA research projects for implementing the M-E PDG

<table>
<thead>
<tr>
<th>Project</th>
<th>Activities (Table 12)</th>
<th>Project Type</th>
<th>Priority</th>
<th>Est. Cost</th>
<th>Project Start Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic Load Spectra for the New M-E Pavement Design Guide</td>
<td>1, 2, 3</td>
<td>External/Consultant</td>
<td>High</td>
<td>$210K</td>
<td>1</td>
</tr>
<tr>
<td>Maryland Climate Data for the New M-E Pavement Design Guide</td>
<td>4</td>
<td>External/University</td>
<td>Medium</td>
<td>$50K</td>
<td>2</td>
</tr>
<tr>
<td>Catalog of Material Properties for Mechanistic-Empirical Pavement Design</td>
<td>5, 6, 8, 9, 10</td>
<td>Joint: Internal + University</td>
<td>High/Medium</td>
<td>$200K</td>
<td>2 – 4</td>
</tr>
<tr>
<td>Stone Matrix Asphalt (SMA) Performance in Mechanistic-Empirical Pavement Design</td>
<td>7</td>
<td>External/University Pooled Fund</td>
<td>High/Medium</td>
<td>$200K</td>
<td>2</td>
</tr>
<tr>
<td>PMS Data for Calibration of M-E Pavement Performance Models</td>
<td>11</td>
<td>External/University</td>
<td>High</td>
<td>$100K</td>
<td>1</td>
</tr>
<tr>
<td>Local Calibration of M-E Pavement Performance Models</td>
<td>12</td>
<td>External/University/Consultant</td>
<td>High/Medium</td>
<td>$300K</td>
<td>4</td>
</tr>
<tr>
<td>Revise OMT Pavement Design Guide</td>
<td>13, 14</td>
<td>Internal</td>
<td>High</td>
<td>$100K</td>
<td>5</td>
</tr>
<tr>
<td>Ongoing Evaluation of M-E PDG Enhancements</td>
<td>15</td>
<td>Joint: Internal +University</td>
<td>High</td>
<td>$300K</td>
<td>1</td>
</tr>
</tbody>
</table>

Notes:
1. HMA properties have higher priority/earlier start date than unbound properties. Research project should be phased accordingly.
2. May be completed as part of NCHRP Project 9-30A. Progress of this NCHRP project should be monitored as part of MDSHA implementation activities.

### 5.2 Research Problem Statements

Draft Research Problem Statements for each of the proposed projects listed in Table 13 are detailed in the following pages.
Maryland State Highway Administration
Research Problem Statement for FFY 2007

Project Title: Traffic Load Spectra for the New M-E Pavement Design Guide

Related SHA Business Plan Objective:

Objective 3.1:
- Assist evaluation of the benefit/cost ratio of paving projects.
- Improve percentage of constructed mileage with acceptable ride quality through application of more advanced pavement design procedures.

Objective 3.3
- Improve percentage of constructed mileage with acceptable asphalt mix by providing better insight and quantification into what defines an acceptable asphalt mix.

Research Problem Statement: A major proposed revision to the AASHTO Pavement Design Guide developed under NCHRP Project 1-37A is currently under final review by the AASHTO Joint Task Force on Pavements. The new pavement design methodology is based on mechanistic-empirical principles that are expected to replace the current empirical pavement design procedures derived from road tests conducted in the late 1950’s. Material types and characterization, traffic levels, and construction practices have changed enormously since the formulation of the empirical methodology underlying the present AASHTO Design Guide. The state-of-the-art methodology in the new mechanistic-empirical pavement design guide (M-E PDG) will provide the foundation for pavement engineering for the next decade and beyond.

The MDSHA is currently one of the lead states examining the future adoption of the M-E PDG. Future adoption of the M-E PDG by MDSHA will have significant ramifications for data collection, material testing, and pavement design procedures. The mechanistic-empirical procedures upon which the Guide is based will require greater quantity and quality of input data in four major categories: traffic; material characterization; environmental variables; and historical pavement performance. Traffic characteristics in particular are expected to require significant attention.

The current AASHTO Pavement Design Guide requires traffic data in ESALs as a major design input. The M-E PDG requires traffic data in the form of traffic load spectra. The main parameters defining a traffic load spectrum include Average Daily Truck Traffic, the distribution of vehicles by class (including seasonal variations, if significant), and the distribution of axle load levels within each class (including seasonal variations, if significant). Data sources for these parameters include site-specific data from AVC and WIM stations and default data from the FHWA LTPP program and the M-E PDG software. Maryland-specific traffic data from these sources is generally acknowledged to be in limited supply and of inferior quality.

Research Objectives: The primary objective of this study is the development of a catalog of realistic traffic load spectra for use as inputs to the new M-E PDG. The cataloged traffic load spectra will likely be functions of road class, geographic region, and perhaps other variables. A
secondary objective is the formulation of traffic data collection policies and procedures that can be used to develop project-specific traffic load spectra for major high-traffic pavement designs.

The study is proposed in three stages:

*Phase 1*: Assessment of existing MDSHA traffic data to evaluate the quantity and quality of existing traffic data. This assessment will also enable identification of deficiencies in current data collection and processing procedures.

*Phase 2*: Development of re-engineered traffic data collection and processing procedures and the application of these re-engineered procedures to the collection of new, high-quality traffic data to provide the basis for the traffic load spectra catalog.

*Phase 3*: Compilation of a traffic load spectra catalog to be used with the new M-E PDG.

**Implementation**: The principal products of this study will include: (a) a catalog of traffic load spectra that are representative of the traffic over the various road classes and geographical regions of the state; and (b) documented procedures for collecting and processing high-quality traffic data in the future, e.g. for high-importance, high-traffic specific projects. It is anticipated that the traffic load spectra catalog and the traffic data collection and processing documentation will be included as sections of the MDSHA Pavement Design Guide.

The explicit benefit of this study will be a collection of high-quality traffic data that can be used as inputs to the new M-E PDG. However, this traffic data will also have the implicit benefit of improving designs based on the current AASHTO Pavement Design Guide, since the traffic load spectra can be used to develop improved estimates of design ESALs.

**This problem statement is most appropriate for**: (Please select only one category below, see attached descriptions of research programs)

- [ ] Pooled Fund Study (participation in funding by more than one state)
- [x] Maryland led University Contract Research
- [ ] New Product Evaluation Program
- [ ] National Cooperative Highway Research Program (NCHRP)
- [ ] National Cooperative Highway Research Program Synthesis
- [ ] National Cooperative Highway Research Program IDEA
- [ ] Other (please explain) __________________________________________

**Amount of funding being requested:**

*Phase 1*: $ 30,000
*Phase 2*: $150,000 (depends in part on findings from Phase 1)
*Phase 3*: $ 30,000

Total funding: $210,000
Anticipated duration of research project:

*Phase 1*: 3 months (includes 1 month for report review by MDSHA). The end product will be a report documenting the needs and approach for Phase 2.

*Phase 2*: 13 months (includes 1 month for review by MDSHA). The end product will be a report and database (in electronic form) documenting the traffic data collection and analysis procedures and compiling the collected traffic data.

*Phase 3*: 4 months (includes 1 month for review by MDSHA). The end product will be a traffic load spectra catalog in a format suitable for inclusion in the MDSHA Pavement Design Guide.

Technical Liaison Info:

Name: Tim Smith, Pavement Division Chief  
Office/Division: Office of Materials Technology  
Phone number: (410) 321-3110  
E-mail: TSmith2@sha.state.md.us

SHA Senior Manager Concurrence:

Name ____________________________  
Date ____________________________
Types of Research Programs

**Pooled Fund Study** – A FHWA sponsored or state led research study of significant or widespread interest with funding participation by more than one state or agency. All contributing partners have a role on the steering committee for the study. (Note: There is an option to have TRB or FHWA administer State led studies, but their services must be paid for as part of the study.) For a state like Maryland, pooled fund study contributions typically range from $5,000 - $20,000 per year.

**Maryland led University Contract Research** – SHA sponsored transportation research and technology transfer conducted by universities, e.g. University of Maryland College Park. (Note: Procurement regulations give preference to public institutions, though partnerships with private universities are not prohibited.)

**New Product Evaluation Program** – There are various alternatives for the testing and evaluation of new products. SHA has a New Products Committee to fulfill this need in Maryland. There are also national entities like the Highway Innovative Technology Evaluation Center (HITEC) that serve this purpose.

**National Cooperative Highway Research Program (NCHRP)** – Is a significant national highway research program sponsored by AASHTO member departments that produces solutions to problems common to state highway agencies. TRB staff administers the program in cooperation with FHWA with oversight from the AASHTO Standing Committee on Research (SCOR). Costs for NCHRP projects are typically in the range of $150,000-$250,000/year.

**National Cooperative Highway Research Program-Synthesis** – Suggestions for NCHRP syntheses are solicited annually where there is a nationally recognized need to gather information regarding the current state of practice in transportation development and operational issues and to document state-of-the-art/best practices. Cost for NCHRP Synthesis projects are $25,000 plus administrative expenses.

**National Cooperative Highway Research Program IDEA** – This is a NCHRP program that funds Innovations Deserving Exploratory Analysis (IDEA), which are initial investigations of innovative, but untested concepts with potential for breakthroughs in transportation practice. Proposals are of two types: those aimed at demonstrating and idea will work, and those aimed at developing a prototype. Costs for NCHRP IDEA project awards typically range from $75,000 - $100,000 per proposal. (Note: current cap for a proposal is $100,000.)

**Other** – This could be in-house research done by SHA staff or by entities other than described above. Note: All SHA staff cost estimates must include SHA’s administrative overhead.
Project Title: Maryland Climate Data for the New M-E Pavement Design Guide

Related SHA Business Plan Objective:

Objective 3.1:
- Assist evaluation of the benefit/cost ratio of paving projects.
- Improve percentage of constructed mileage with acceptable ride quality through application of more advanced pavement design procedures.

Objective 3.3
- Improve percentage of constructed mileage with acceptable asphalt mix by providing better insight and quantification into what defines an acceptable asphalt mix.

Research Problem Statement: A major proposed revision to the AASHTO Pavement Design Guide developed under NCHRP Project 1-37A is currently under final review by the AASHTO Joint Task Force on Pavements. The new pavement design methodology is based on mechanistic-empirical principles that are expected to replace the current empirical pavement design procedures derived from road tests conducted in the late 1950’s. Material types and characterization, traffic levels, and construction practices have changed enormously since the formulation of the empirical methodology underlying the present AASHTO Design Guide. The state-of-the-art methodology in the new mechanistic-empirical pavement design guide (M-E PDG) will provide the foundation for pavement engineering for the next decade and beyond.

The MDSHA is currently one of the lead states examining the future adoption of the M-E PDG. Future adoption of the M-E PDG by MDSHA will have significant ramifications for data collection, material testing, and pavement design procedures. The mechanistic-empirical procedures upon which the Guide is based will require greater quantity and quality of input data in four major categories: traffic; material characterization; environmental variables; and historical pavement performance. Traffic characteristics in particular are expected to require significant attention.

The current AASHTO Pavement Design Guide requires site-specific climate data as a major design input. The key environmental input data required by the M-E PDG are available from the weather station database included in the M-E PDG software. However, the current M-E PDG contains weather station data for only four Maryland locations: Baltimore, Hagerstown, Ocean City, and Salisbury. Evaluation studies of the M-E PDG have found that even climate differences within the state of Maryland can have a significant influence on pavement performance. The same pavement section when located on the Eastern Shore, for example, will exhibit more rutting that when located in the western mountains. It is therefore important that appropriate climate data be available for use in pavement design for all subregions of the state.

Research Objectives: The primary objective of this study is to incorporate additional Maryland weather station data into the M-E PDG database. Weather station data are available from the National Climate Data Center (NCDC—http://www.ncdc.noaa.gov/oac/nrdc.html) within
the National Oceanic and Atmospheric Administration (NOAA). The NCDC lists 288 weather stations within the state of Maryland. Forty-one of these have hourly surface climate data as required for the M-E PDG. Climate data is available for a nominal charge (free to .edu domain users) from the NCDC. The NCDC data are available in a variety of well-documented ASCII text formats, which can be easily translated into the text files required for input to the M-E PDG database. Documentation for the M-E PDG format is available on the web at http://trb.org/mepdg/ICM_Formats.htm. Utility programs to convert NCDC files to M-E PDG format may be available from the NCHRP 1-37A or NCHRP 1-40D project teams.

Part of the implementation effort will be to determine weather individual NCDC data sets are of sufficient completeness and duration. If suitable NCDC data are unavailable, local weather stations (e.g., at regional airports) should be evaluated as sources of climate data to be added to the M-E PDG database.

**Implementation:** The principal product of this study will be an enhanced database of climate conditions representative for all geographical regions of the state. This database will be in a format compatible with the M-E PDG software.

**This problem statement is most appropriate for:** (Please select only one category below, see attached descriptions of research programs)

___ Pooled Fund Study (participation in funding by more than one state)
___ Maryland led University Contract Research
___ New Product Evaluation Program
___ National Cooperative Highway Research Program (NCHRP)
___ National Cooperative Highway Research Program Synthesis
___ National Cooperative Highway Research Program IDEA
___ Other (please explain) ____________________________

**Amount of funding being requested:**

Total funding: $50,000

**Anticipated duration of research project:**

Six months.

**Technical Liaison Info:**

Name: Tim Smith, Pavement Division Chief
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Phone number: (410) 321-3110
E-mail: TSmith2@sha.state.md.us
SHA Senior Manager Concurrence:

__________________________  ______________________
Name                       Date
Project Title: Catalog of Material Properties for Mechanistic-Empirical Pavement Design

Related SHA Business Plan Objective:

Objective 3.1:
- Assist evaluation of the benefit/cost ratio of paving projects.
- Improve percentage of constructed mileage with acceptable ride quality through application of more advanced pavement design procedures.

Objective 3.3
- Improve percentage of constructed mileage with acceptable asphalt mix by providing better insight and quantification into what defines an acceptable asphalt mix.

Research Problem Statement: The new pavement design methodology developed in NCHRP Project 1-37A is based on mechanistic-empirical principles that are expected to replace the current empirical pavement design procedures derived from road tests conducted in the late 1950’s. The new mechanistic-empirical pavement design guide (M-E PDG) will require greater quantity and quality of input data in four major categories: traffic; material characterization; environmental factors; and pavement performance (for local calibration/validation). Material characterization for the mechanistic-empirical approach, the focus of this problem statement, is significantly more fundamental and extensive than in the current empirically-based AASHTO Design Guide.

A hierarchical input data scheme has been implemented in the mechanistic-empirical design procedure to permit varying levels of sophistication for specifying material properties, ranging from laboratory measured values (Level 1) to empirical correlations (Level 2) to default values (Level 3). It is expected that most states, including Maryland, will begin implementation of the new design procedure using Level 3 default inputs that are relevant to their local materials and conditions and will, over time, supplement these with typical Level 1 measured data for their most common materials. To accomplish this, databases or libraries of typical material property inputs must be developed for the following categories:

- Binder properties (e.g., binder dynamic modulus $G^*$ and phase angle $\delta$ or binder viscosities $\eta$)
- HMA mechanical properties (e.g., dynamic modulus $E^*$ master curves—either measured directly or predicted empirically)
- PCC mechanical properties (e.g., elastic modulus $E$, flexural tensile strength or modulus of rupture $f_f$)
- Unbound mechanical properties (e.g., resilient modulus $M_r$ or $k_1$-$k_3$ values)
- Thermohydraulic properties (e.g., saturated hydraulic conductivity $k_{sat}$)

Of course, the MDSHA already has considerable information on many of these items. An extensive database of Level 1 binder properties has already been developed by the Western Regional Laboratory. The WRL also plans to begin compiling dynamic modulus data for HMA mixtures using their newly-acquired Simple Performance Test; however, these dynamic modulus data are expected to be incomplete because the SPT cannot test at the lowest temperatures.
required to characterize the full $E^*$ master curve under current protocols. Some PCC design inputs are available from the Salisbury Bypass and other recent projects. Level 3 stiffness information on typical Maryland base course and subgrade soils exists within the pavement and geotechnical groups at MDSHA, but the completeness and organization of this information is unclear. Little or no thermohydraulic data exist within MDSHA beyond the general default values built into the M-E PDG software.

**Research Objectives:**

The objective of the work proposed here is to develop an organized database of material properties for the most common paving materials used in Maryland. This database would provide the material property input data required for the new mechanistic-empirical pavement design guide developed under NCHRP 1-37A. It is expected that the database will contain a full set of Level 3 data and some Level 1 information (primarily for asphalt binder properties, HMA dynamic modulus, and unbound resilient modulus).

The specific tasks required to achieve these objectives are as follows:

*Task 1. Database Design.* A Microsoft Access database will be designed to store all of the material property information required as input to the mechanistic-empirical design procedure. Ideally, this database should be integrated into the larger Maryland Materials Database that has been developed over the past few years. Specific requirements for the material property database is that it tie directly into the required input data for the M-E PDG software and that it include provisions for either Level 1, Level 2, or Level 3 data.

*Task 2. Binder Properties.* Level 1 binder property data have already been measured by the Western Regional Laboratory for most of the binders most commonly used in Maryland. These data will simply need to be imported into the larger material property database. Additional binder testing will be performed in conjunction with future paving projects.

*Task 3. HMA Mechanical Properties.* The Western Regional Laboratory plans to begin $E^*$ testing of asphalt mixtures using the Simple Performance Test. These data will be imported into the larger material property database. Additional mixture $E^*$ testing will be performed in conjunction with future paving projects.

*Task 4: PCC Mechanical Properties.* There is extensive QC data for concrete compressive strength available from past MDSHA rigid pavement projects. This is suitable for Level 2 inputs via correlations with elastic modulus and flexural strength. Some Level 1 laboratory measured values for the elastic modulus and flexural strength are available from the Salisbury Bypass research project and other recent construction projects. These data should be compiled. A plan should also be developed to include some limited laboratory testing of elastic modulus and flexural strength on future rigid paving projects to augment the design inputs database.

*Task 5: Unbound Mechanical Properties.* Nearly all of the existing unbound material property data at MDSHA consists of Level 3 default values of resilient modulus for granular base and subgrade materials. These default values are supplemented in some instances by laboratory resilient modulus test data and/or values backcalculated from FWD testing in the field. In this task, all of these existing information will be compiled from records in the pavement and geotechnical group and entered into the database. Additional Level 1 testing of subgrades and
unbound granular base and subbase materials will be performed in conjunction with future paving projects and the measured data added incrementally to the database.

Task 6: Thermohydraulic Properties. Some limited data may exist within MDSHA on hydraulic properties like the saturated hydraulic conductivity, but virtually no data exist on thermal properties. In this task, whatever existing information there is within MDSHA will be compiled and supplemented by literature and/or default values from the M-E PDG software and entered into the database.

Task 7: Workshop and Final Report. A workshop on the database and project findings will be held for MDSHA personnel prior to submission of the final report. The database design and all data collected in the study will be documented in a final report. This report will also include recommendations for future material property characterization activities.

Note that this project provides an essential prerequisite for an eventual full local calibration/validation of the mechanistic-empirical design procedure for Maryland conditions.

Implementation: Implementation and dissemination of the results from this study will be accomplished via the following:

- Workshop for MDSHA personnel to describe the material property database, summarize the data compiled, and demonstrate how these data are used in the NCHRP 1-37A design software
- Project final report
- Suggestions for revisions to the MDSHA Pavement Design Guide (in collaboration with other projects related to the implementation of the mechanistic-empirical design procedure in Maryland)
- Presentations at regional and national conferences (e.g., TRB Workshops on mechanistic-empirical design implementation)
- Presentations at committee meetings (e.g., TRB; FHWA)
- Communication of findings to the FHWA Design Guide Implementation Team for dissemination to other states

The last implementation item is particularly important in view of Maryland’s position as one of the FHWA Lead States for the mechanistic-empirical design guide implementation.

This problem statement is most appropriate for:

- Pooled Fund Study (participation in funding by more than one state)
- Maryland led University Contract Research
- New Product Evaluation Program
- National Cooperative Highway Research Program (NCHRP)
- National Cooperative Highway Research Program Synthesis
- National Cooperative Highway Research Program IDEA
- Other (please explain) Joint effort between MDSHA in-house staff and external University contract researchers

Amount of funding being requested: $200,000
Anticipated duration of research project: 24 months

Technical Liaison Info:

Submitted as a joint effort between the University of Maryland and the Office of Materials and Technology

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SHA Manager Concurrence:

________________________________________  ______________________________
Name                                      Date
Maryland State Highway Administration
Research Problem Statement for FFY 2008

Project Title: Stone Matrix Asphalt (SMA) Performance in Mechanistic-Empirical Pavement Design

Related SHA Business Plan Objective:

Objective 3.1:
- Assist evaluation of the benefit/cost ratio of paving projects, especially in view of the price premium for SMA mixtures.
- Improve percentage of constructed mileage with acceptable ride quality through application of more advanced pavement design procedures that have been calibrated/validated for Maryland conditions.

Objective 3.3
- Improve percentage of constructed mileage with acceptable asphalt mix by providing better insight and quantification into what defines an acceptable asphalt mix.

Research Problem Statement: Maryland is among the leading states in the U.S. in the placement of stone matrix asphalt (SMA) mixtures for surface paving courses. SMA is a gap-graded hot mix asphalt concrete that combines high quality coarse aggregate with a rich proportion of asphalt cement, producing a stable paving mixture having outstanding rutting resistance and durability. SMA mixtures in Maryland are placed exclusively on high volume, high speed highway segments. An analysis by Michael, Burke, and Schwartz (2004) of nearly 1000 sets of construction quality control test data and approximately 300 sets of pavement performance measurements for up to 10 years of service life that conclusively demonstrated the superior performance of SMA mixes in Maryland.

Unfortunately, the benefits of SMA mixtures cannot at present be easily considered in pavement structural design. The current AASHTO Pavement Design Guide quantifies the structural capacity of pavement materials via an empirical layer coefficient, but there is no guidance on the determination of an appropriate value for the structural layer coefficient of SMA mixtures. The forthcoming mechanistic-empirical pavement design guide (M-E PDG) developed under NCHRP 1-37A provides a framework for incorporating the benefits of higher-quality asphalt mixtures via the dynamic modulus E*, a fundamental engineering property that can be measured in the laboratory. In general terms, higher E* values correspond to less rutting of the asphalt layer. Paradoxically, however, previous studies (by Witczak for MDSHA and by others) have shown that SMA mixtures usually exhibit lower E* values than dense graded mixtures when tested conventionally under unconfined compression conditions. Within the M-E PDG methodology, this would imply greater rutting for SMA mixtures in contradiction to the superior rutting resistance observed over the past decade in Maryland.

Note that the work proposed in this Research Problem Statement may be completed as part of NCHRP Project 9-30A. Progress of this NCHRP project should be monitored as part of MDSHA implementation activities.
**Research Objectives:**

The proposed research will develop and implement suitable refinements to the mechanistic-empirical pavement design guide (M-E PDG) developed under NCHRP 1-37A to improve and validate its ability to predict the performance of SMA mixtures for Maryland conditions. The specific tasks required to achieve these objectives are as follows:

**Task 1: Review Literature.** Two categories of literature are relevant to this study: (a) past studies of E* values for SMA mixtures, particularly in comparison to conventional dense graded mixtures; and (b) evaluations of SMA performance in the field. The paper by Michael, Burke, and Schwartz (2004) and the proceedings of the workshop on *Construction and Performance of Stone Matrix Asphalt Pavements in Maryland: An Update* organized by MDSHA in March 2002 are excellent sources of information for the second category.

**Task 2: Identify Mixtures and Field Sections.** Refinement of the material characterization in the mechanistic-empirical procedure will require laboratory measurement of E* for selected SMA mixtures. Calibration and validation of the procedure will require the identification of suitable field pavement sections.

**Task 3: Perform Laboratory Testing.** The dynamic modulus and repeated load permanent deformation characteristics of the mixtures selected in Task 2 will be measured in the laboratory under conventional unconfined compression as well as other conditions (e.g., confined compression). Emphasis will be placed on the determination of a refined material characterization protocol that better reflects the high rutting resistance of SMA mixtures.

**Task 4: Calibrate/Validate the Rutting Performance Model.** The field calibration coefficients for the rutting performance model will be recalibrated and validated using the field pavement sections identified in Task 2 and the jackknifing statistical procedure recommended by NCHRP Project 9-30. Field calibration/validation will require assembling all of the input data required for the M-E PDG software; these data will be compiled and stored in the database format suggested in NCHRP Project 9-30 so that they will be of more general use to the industry after completion of this project.

**Task 5: Workshop and Final Report.** All findings from the study will be documented in a final report. A workshop on the project findings will be held for MDSHA personnel prior to submission of the final report.

Note that this project will also serve as an excellent pilot for a full local calibration/validation of the mechanistic-empirical design procedure for the full range of pavement and material types commonly used in Maryland.

**Implementation:** Implementation and dissemination of the results from this study will be accomplished via the following:
- Workshop for MDSHA personnel to highlight the findings from the research and to describe how the project results can be used to improve SMA pavement design in Maryland
- Project final report
- Suggestions for changes to the MDSHA Pavement Design Guide (in collaboration with other projects related to the implementation of the mechanistic-empirical design procedure in Maryland)
Presentations at regional and national conferences
Archival journal publications
Communication of findings to the FHWA Design Guide Implementation Team for dissemination to other states

The last implementation item is particularly important in view of Maryland’s position as one of the FHWA Lead States for the mechanistic-empirical design guide implementation.

This problem statement is most appropriate for:

☐ Pooled Fund Study (participation in funding by more than one state)
☐ Maryland led University Contract Research
☐ New Product Evaluation Program
☐ National Cooperative Highway Research Program (NCHRP)
☐ National Cooperative Highway Research Program Synthesis
☐ National Cooperative Highway Research Program IDEA
☐ Other (please explain) __________________________

Amount of funding being requested: $200,000

Anticipated duration of research project: 12 months

Technical Liaison Info:

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SHA Manager Concurrence:

____________________________________  __________________________
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Maryland State Highway Administration
Research Problem Statement for FFY 2007

Project Title: PMS Data for Calibration of M-E Pavement Performance Models

Related SHA Business Plan Objective:

Objective 3.1:
- Assist evaluation of the benefit/cost ratio of paving projects, especially in view of the price premium for SMA mixtures.
- Improve percentage of constructed mileage with acceptable ride quality through application of more advanced pavement design procedures that have been calibrated/validated for Maryland conditions.

Objective 3.3
- Improve percentage of constructed mileage with acceptable asphalt mix by providing better insight and quantification into what defines an acceptable asphalt mix.

Research Problem Statement: A major proposed revision to the AASHTO Pavement Design Guide developed under NCHRP Project 1-37A is currently under final review by the AASHTO Joint Task Force on Pavements. The new pavement design methodology is based on mechanistic-empirical principles that are expected to replace the current empirical pavement design procedures derived from road tests conducted in the late 1950’s. Material types and characterization, traffic levels, and construction practices have changed enormously since the formulation of the empirical methodology underlying the present AASHTO Design Guide. The state-of-the-art methodology in the new mechanistic-empirical pavement design guide (M-E PDG) will provide the foundation for pavement engineering for the next decade and beyond.

The MDSHA is currently one of the lead states examining the future adoption of the M-E PDG. Future adoption of the M-E PDG by MDSHA will have significant ramifications for data collection, material testing, and pavement design procedures. The mechanistic-empirical procedures upon which the Guide is based will require greater quantity and quality of input data in four major categories: traffic; material characterization; environmental variables; and historical pavement performance.

High-quality pavement management system data, in particular, will required for the local calibration of the empirical distress models. Local calibration involves replacement of the national calibration coefficients in the M-E empirical distress prediction models with values more relevant to local MD conditions. Local calibration requires the identification of a set of field pavement sections for which the M-E inputs can be well quantified (e.g., traffic, environment, material properties) and for which a history of performance data are available (e.g., rutting, fatigue cracking). Local calibration of the M-E methodology in concept can be very beneficial in improving pavement performance predictions for local conditions and is conventionally viewed as a vital component in the implementation of the M-E PDG at the agency level. The development of local calibration guidelines is the focus of the nearly-completed NCHRP Project 1-40B.
Local calibration may be particularly useful for Maryland for two reasons: (1) traffic levels in Maryland may on average be considerably higher than for many of the LTPP sections used in the global calibration in NCHRP 1-37A; (2) pavement performance in Maryland may tend to be better on average than for many of the LTPP sections in the global calibration (e.g., because of extensive use of SMA, maintenance efforts, etc.). A secondary benefit of local calibration is that the distress variability used in the reliability calculations—which by default is based upon the prediction errors from the national calibration—may be reduced.

**Research Objectives:** This study will provide an evaluation of existing MDSHA PMS data to determine its suitability for use in calibrating the distress models in the new M-E PDG. This study will also identify the steps the MDSHA should take to prepare for the calibration effort (e.g., data collection plan, analysis plan, etc.).

**Implementation:** The principal benefit of this study will be the development of a set of pavement performance data that can be used for the local calibration of the M-E PDG distress models. This local calibration is an important component of the implementation of the M-E PDG. A secondary benefit of this study will be the identification of possible improvements to the data collection and analysis procedures used to compile pavement performance data in the MDSHA PMS.

**This problem statement is most appropriate for:**

- [X] Maryland led University Contract Research
- [___] New Product Evaluation Program
- [___] National Cooperative Highway Research Program (NCHRP)
- [___] National Cooperative Highway Research Program Synthesis
- [___] National Cooperative Highway Research Program IDEA
- [___] Other (please explain) ______________________

**Amount of funding being requested:** $100,000

**Anticipated duration of research project:** 12 months

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SHA Senior Manager Concurrence:

__________________________________________  ______________________
Name                                           Date
Project Title: Local Calibration of M-E Pavement Performance Models

Related SHA Business Plan Objective:

Objective 3.1:
- Assist evaluation of the benefit/cost ratio of paving projects, especially in view of the price premium for SMA mixtures.
- Improve percentage of constructed mileage with acceptable ride quality through application of more advanced pavement design procedures that have been calibrated/validated for Maryland conditions.

Objective 3.3
- Improve percentage of constructed mileage with acceptable asphalt mix by providing better insight and quantification into what defines an acceptable asphalt mix.

Research Problem Statement: A major proposed revision to the AASHTO Pavement Design Guide developed under NCHRP Project 1-37A is currently under final review by the AASHTO Joint Task Force on Pavements. The new pavement design methodology is based on mechanistic-empirical principles that are expected to replace the current empirical pavement design procedures derived from road tests conducted in the late 1950’s. Material types and characterization, traffic levels, and construction practices have changed enormously since the formulation of the empirical methodology underlying the present AASHTO Design Guide. The state-of-the-art methodology in the new mechanistic-empirical pavement design guide (M-E PDG) will provide the foundation for pavement engineering for the next decade and beyond.

The MDSHA is currently one of the lead states examining the future adoption of the M-E PDG. Future adoption of the M-E PDG by MDSHA will have significant ramifications for data collection, material testing, and pavement design procedures. The mechanistic-empirical procedures upon which the Guide is based will require greater quantity and quality of input data in four major categories: traffic; material characterization; environmental variables; and historical pavement performance.

The M-E PDG provides for the calibration of the empirical distress models to local conditions. Local calibration involves replacement of the national calibration coefficients in the M-E empirical distress prediction models with values more relevant to local MD conditions. Local calibration requires the identification of a set of field pavement sections for which the M-E inputs can be well quantified (e.g., traffic, environment, material properties) and for which a history of performance data are available (e.g., rutting, fatigue cracking). Local calibration of the M-E methodology in concept can be very beneficial in improving pavement performance predictions for local conditions and is conventionally viewed as a vital component in the implementation of the M-E PDG at the agency level. The development of local calibration guidelines is the focus of the nearly-completed NCHRP Project 1-40B.

Local calibration may be particularly useful for Maryland for two reasons: (1) traffic levels in Maryland may on average be considerably higher than for many of the LTPP sections used in the
global calibration in NCHRP 1-37A; (2) pavement performance in Maryland may tend to be better on average than for many of the LTPP sections in the global calibration (e.g., because of extensive use of SMA, maintenance efforts, etc.). A secondary benefit of local calibration is that the distress variability used in the reliability calculations—which by default is based upon the prediction errors from the national calibration—may be reduced.

**Research Objectives:** This study will develop and execute a plan for local calibration of the M-E PDG empirical distress models. This will build upon prior MDSHA M-E PDG implementation projects.

**Implementation:** The principal benefit of this study will be the development of a set of local calibration coefficients for the M-E PDG distress models.

**This problem statement is most appropriate for:**

- [ ] Pooled Fund Study (participation in funding by more than one state)
- [x] Maryland led University Contract Research
- [ ] New Product Evaluation Program
- [ ] National Cooperative Highway Research Program (NCHRP)
- [ ] National Cooperative Highway Research Program Synthesis
- [ ] National Cooperative Highway Research Program IDEA
- [ ] Other (please explain) __________________________

**Amount of funding being requested:** $300,000

**Anticipated duration of research project:** 24 months

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**SHA Senior Manager Concurrence:**

__________________________________  
Name  Date
**Project Title:** Revise the *OMT Pavement Design Guide*

**Related SHA Business Plan Objective:**

Objective 3.1:
- Assist evaluation of the benefit/cost ratio of paving projects, especially in view of the price premium for SMA mixtures.
- Improve percentage of constructed mileage with acceptable ride quality through application of more advanced pavement design procedures that have been calibrated/validated for Maryland conditions.

Objective 3.3
- Improve percentage of constructed mileage with acceptable asphalt mix by providing better insight and quantification into what defines an acceptable asphalt mix.

**Research Problem Statement:** A major proposed revision to the AASHTO Pavement Design Guide developed under NCHRP Project 1-37A is currently under final review by the AASHTO Joint Task Force on Pavements. The new pavement design methodology is based on mechanistic-empirical principles that are expected to replace the current empirical pavement design procedures derived from road tests conducted in the late 1950’s. Material types and characterization, traffic levels, and construction practices have changed enormously since the formulation of the empirical methodology underlying the present AASHTO Design Guide. The state-of-the-art methodology in the new mechanistic-empirical pavement design guide (M-E PDG) will provide the foundation for pavement engineering for the next decade and beyond.

The MDSHA is currently one of the lead states examining the future adoption of the M-E PDG. Future adoption of the M-E PDG by MDSHA will have significant ramifications for data collection, material testing, and pavement design procedures. The mechanistic-empirical procedures upon which the Guide is based will require greater quantity and quality of input data in four major categories: traffic; material characterization; environmental variables; and historical pavement performance.

MDSHA has created an excellent manual for agency pavement design. The current manual is based on the empirical 1993 AASHTO design guide. An important implementation activity will thus be to revise this manual to reflect the changes in the M-E PDG once fully implemented. It is also possible that a dual-track pavement design procedure may be desired—e.g., 1993 AASHTO for lower traffic/less important pavement designs and the M-E PDG for higher traffic/greater importance designs.

Particular emphasis must be placed on revisions to the rehabilitation design portions of the manual. Rehabilitation represents the bulk of MDSHA’s pavement design activity. The 1993 AASHTO and M-E PDG differ significantly on how they use FWD and visual survey field evaluation data.
Research Objectives: This project will revise the OMT Pavement Design Guide for consistency with the new M-E PDG procedure. The sections in the current guide expected to require major revisions are as follows:

III.E. Traffic Analysis: Replacement of ESALs with load spectra.

(New Section). Environmental Inputs: New section describing requirements for the environmental effects model in the NCHRP 1-37A procedure.

III.F. Pavement Rehabilitation Design: Different methods for evaluating/quantifying remaining structural capacity; details of design procedure.

III.G. New Pavement Design: Different material properties (e.g., no more layer coefficients for flexible pavements, modulus of subgrade reaction for rigid pavements); details of design procedure.

III.N. Verification of Classification Data

VI Pavement Design Policies: Different design parameters will require different design policies.

X.B. Material Properties: Modified to reflect new properties in the NCHRP 1-37A approach—e.g., dynamic modulus $|E^*|$ for HMA, thermohydraulic properties for environmental effects model, resilient modulus $M_r$ for unbound materials. Older properties must be removed—e.g., flexible pavement layer coefficients, rigid pavement modulus of subgrade reaction, drainage coefficients.

An important part of the design guide revision will be the development of pavement design criteria defining the minimum acceptable performance limits. In the 1993 AASHTO procedure, these criteria are the initial and terminal PSI values and the reliability factors ($S_0$ and $Z_R$). Pavement design criteria for the M-E design procedure are more specific and extensive:

- Maximum distress magnitudes for each distress (e.g., maximum total rutting for flexible pavements, maximum average faulting for rigid pavements)
- For roughness, the initial post-construction value of IRI
- Design reliability levels
- Distress variability for each distress

The maximum allowable distress magnitudes and design reliability levels are policy issues. Some guidance can be provided by the current AASHTO design procedure (e.g., for appropriate design reliability levels) and other sources (e.g., Witzak’s survey of State DOT pavement engineers on maximum allowable rutting levels). Initial post-construction IRI is set by specification. The distress variability for each distress can be taken as either the current default values (based on the global calibration from NCHRP 1-37A) or from local calibration results. The development of design criteria for the M-E PDG that are relevant to MDSHA policies and conditions is an essential implementation activity.

Implementation: Implementation will consist primarily of the adoption of the revised OMT Pavement Design Guide as standard MDSHA policy.
This problem statement is most appropriate for:

- Pooled Fund Study (participation in funding by more than one state)
- Maryland led University Contract Research
- New Product Evaluation Program
- National Cooperative Highway Research Program (NCHRP)
- National Cooperative Highway Research Program Synthesis
- National Cooperative Highway Research Program IDEA
- Other (please explain) MDSHA internal effort

Amount of funding being requested: $100,000

Anticipated duration of research project: 12 months

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SHA Senior Manager Concurrence:

Name ___________________________ Date ___________________________
Project Title: Ongoing Evaluation of M-E PDG Enhancements

Related SHA Business Plan Objective:

Objective 3.1:
- Assist evaluation of the benefit/cost ratio of paving projects, especially in view of the price premium for SMA mixtures.
- Improve percentage of constructed mileage with acceptable ride quality through application of more advanced pavement design procedures that have been calibrated/validated for Maryland conditions.

Objective 3.3
- Improve percentage of constructed mileage with acceptable asphalt mix by providing better insight and quantification into what defines an acceptable asphalt mix.

Research Problem Statement: It is expected that the M-E PDG will be continuously enhanced over the next several years to incorporate significant findings from several NCHRP and other projects. Each major enhancement will result in a new software version that will require some local evaluation. The purpose of the research project is to provide ongoing technical capability for monitoring and evaluating future M-E PDG enhancements.

Research Objectives: The project team will track progress of and products from several ongoing NCHRP projects that are addressing various aspects of the M-E PDG and its implementation. Key active NCHRP projects to monitor include the following:

- 1-40D Technical Assistance to NCHRP and NCHRP Project 1-40A: Versions 0.9 and 1.0 of the M-E Pavement Design Software
- 1-41 Models for Predicting Reflection Cracking of Hot-Mix Asphalt Overlays
- 1-42A Models for Predicting Top-Down Cracking of Hot-Mix Asphalt Layers
- 9-30A Calibration of Rutting Models for HMA Structural and Mix Design
- 9-33 A Mix Design Manual for Hot Mix Asphalt

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9 C.W. Schwartz is a member of the NCHRP 1-40D research team.
10 C.W. Schwartz is a Co-Principal Investigator for NCHRP 9-30A.
Many of these projects may produce model enhancements that will be implemented in future versions of the M-E PDG software. The team will provide local evaluation of each new version of software as released.

**Implementation:** This is an ongoing technical support activity. It is envisioned to be a joint effort between MDSHA in-house staff and University technical personnel.

**This problem statement is most appropriate for:**

- [ ] Pooled Fund Study (participation in funding by more than one state)
- [x] Maryland led University Contract Research joint effort with MDSHA in-house staff
- [ ] New Product Evaluation Program
- [ ] National Cooperative Highway Research Program (NCHRP)
- [ ] National Cooperative Highway Research Program Synthesis
- [ ] National Cooperative Highway Research Program IDEA
- [ ] Other (please explain) MDSHA joint effort with UMD

**Amount of funding being requested:** $300,000

**Anticipated duration of research project:** 72 months

**Technical Liaison Info:**

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**SHA Senior Manager Concurrence:**

Name ____________________________ Date ____________________________
6. Summary Recommendations

The various versions of the AASHTO Pavement Design Guide have served well for several decades. However, the low traffic volumes, dated vehicle characteristics, short test duration, narrow range of material types, single climate, and other limitations of the original AASHO Road Test have called into question the continued use of the empirical AASHTO Design Guide as the nation's primary pavement design procedure. These perceived deficiencies were the motivation for the development of a new mechanistic-empirical pavement design guide (M-E PDG) in NCHRP Project 1-37A.

The adoption of the M-E PDG by MDSHA will have significant ramifications for material testing and pavement design procedures. The mechanistic-empirical procedures upon which the M-E PDG is based will require greater quantity and quality of input data in four major categories: traffic; material characterization and properties; environmental influences; and pavement response and distress models. The new M-E PDG provides agencies the greatest possible flexibility for applying and calibrating the design procedures to local conditions and approaches.

The principal objective of this project was to develop a coherent plan for MDSHA to transition from its current pavement design procedures to the new M-E PDG. The study addressed the following topics:

- Suitability of M-E PDG to Maryland Conditions (Chapter 2 plus supplementary Volume 2)
- Data Needs for M-E PDG Implementation in Maryland (Chapter 3)
- National Adoption Schedule for M-E PDG (Chapter 4)
- M-E PDG Implementation Plan for Maryland (Chapter 5)

A comprehensive set of key M-E PDG implementation activities are identified, with qualitative estimates of priority and required effort levels, the group expected to perform the activity (MDSHA, consultant, or University), and the optimal time frame. Related activities are grouped into larger research projects for the planning purposes and the development of Research Problem Statements. The total cost for the proposed implementation research plan is $1,460K. Of this total, $300K corresponds to activities in which MDSHA in-house staff will have sole or major responsibility and effort, and $200K is for an optional pooled fund study, the need for which will depend upon the outcome of the current NCHRP Project 9-30A. Total duration of the proposed research effort is 6 years.

Adoption and execution of this implementation plan for the M-E PDG will enable the MDSHA to remain at the forefront of pavement engineering within the U.S. Full implementation of the M-E will assist the MDSHA in meeting its objectives of evaluating the benefit/cost ratio of paving projects, increasing the percentage of constructed mileage with acceptable ride quality through application of more advanced pavement design procedures, and increasing mileage with acceptable asphalt mix through better insight and quantification into what defines an acceptable asphalt mix. The end result will be improved pavement design and better estimates of pavement performance for the many heavily trafficked highways within the state.
7. References


Appendix A: Mechanistic-Empirical Design Method

A.1 Introduction

The Guide for the Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures (hereafter termed the Mechanistic-Empirical Pavement Design Guide or M-E PDG) developed under NCHRP Project 1-37A is the state-of-the-art procedure for the design of flexible and rigid pavement structures. The mechanistic-empirical approach at the heart of the M-E PDG methodology represents a fundamental paradigm shift for pavement design. In the mechanistic-empirical approach, the response of the pavement—defined in terms of stresses, strains, and other parameters—is analyzed using rigorous theories of mechanics. Critical response quantities—e.g., tensile strain at the bottom of an asphalt or PCC layer—are then related empirically to pavement performance—e.g., fatigue cracking.

Figure 33 provides a flow chart for the mechanistic-empirical design approach as implemented in the M-E PDG procedures. The major steps are:

1. Define the traffic, environmental, and other general design inputs for the project. In the case of rehabilitation designs, this will also include information on existing pavement conditions (e.g., distress survey, FWD testing).
2. Select a trial pavement section for analysis. For rehabilitation designs, this includes identification of an appropriate rehabilitation strategy.
3. Define the properties for the materials in the various pavement layers.
4. Analyze the pavement response (temperature, moisture, stress, strain) due to traffic loading and environmental influences. The pavement response analysis is performed on a season-by-season basis in order to include variations in traffic loading, environmental conditions, and material behavior over time.
5. Empirically relate critical pavement responses to damage and distress for the pavement distresses of interest. Damage/distress are determined on a season-by-season basis and then accumulated over the design life of the pavement.
6. Adjust the predicted distresses for the specified design reliability.
7. Compare the predicted distresses at the end of design life against design limits. If necessary, adjust the trial pavement section and repeat steps 3-7 until all predicted distresses are within design limits.

The corresponding major components to implement this mechanistic-empirical pavement design methodology are:

- Inputs—traffic, climate, materials, others.
- Pavement response models—to compute critical responses.
- Performance models or transfer functions—to predict pavement performance over the design life.
- Design reliability and variability—to add a margin of safety for the design.
- Performance criteria—to set objective goals by which the pavement performance will be judged.
- Software—to implement the mechanistic-empirical models and calculations in a usable form.

Each of these components will be briefly summarized in the following sections.

Figure 33. Flow chart for mechanistic-empirical design methodology.
A.2 Inputs

A.2.1 Hierarchical Inputs
The M-E PDG methodology incorporates a hierarchical approach for specifying all pavement design inputs. The hierarchical approach is based on the philosophy that the level of engineering effort exerted in determining design inputs should be consistent with the relative importance, size, and cost of the design project. Three levels are provided for the design inputs in the M-E PDG:

**Level 1** inputs provide the highest level of accuracy and the lowest level of uncertainty. Level 1 inputs would typically be used for designing heavily trafficked pavements or wherever there are serious safety or economic consequences of early failure. Level 1 material inputs require field or laboratory evaluation. Subgrade resilient modulus measured from FWD testing in the field or triaxial testing in the laboratory is one example of a Level 1 input.

**Level 2** inputs provide an intermediate level of accuracy and are closest to the typical procedures used with the AASHTO Design Guides. This level could be used when resources or testing equipment are not available for Level 1 characterization. Level 2 inputs would typically be derived from a limited testing program or estimated via correlations or experience (possibly from an agency database). Subgrade resilient modulus estimated from correlations with measured CBR values is one example of a Level 2 input.

**Level 3** inputs provide the lowest level of accuracy. This level might be used for designs in which there are minimal consequences of early failure (e.g., low volume roads). Level 3 material inputs typically are default values that are based on local agency experience. A default subgrade resilient modulus based on AASHTO soil class is an example of a Level 3 input.

Any given pavement design may incorporate a mix of input data of different levels; for example, measured HMA dynamic modulus values used with default resilient modulus values for the unbound materials in the pavement structure. However, the algorithms used in the design computations are identical for all input levels. In other words, the NCHRP 1-37 methodology features levels of input data but not levels of design analysis. The composite input level determines the overall accuracy and reliability of the pavement performance predictions used to judge the acceptability of a trial design.

A.2.3 Traffic
Traffic data are key inputs for the analysis and design of pavement structures. Most existing design procedures, including all of the AASHTO Design Guides, quantify traffic in terms of equivalent single axle loads (ESALs). However, the mechanistic pavement response models in the M-E PDG require the specification of the magnitudes and frequencies of the actual wheel loads that the pavement is expected to see over its design life. Consequently, traffic must be specified in terms of axle load spectra rather than ESALs. Axle load spectra are the frequency distributions of axle load magnitudes by axle type (single, tandem, tridem, quad) and season of year (monthly, typically).

State highway agencies typically collect two categories of traffic data. Weigh-in-motion (WIM) data provide information about the number and configuration of axles observed within a set of load groups. Automatic vehicle classification (AVC) data provide information about the number and types of vehicles that use a given roadway as counted over some period of time. Table 14 summarizes the WIM and AVC data that are required at each of the hierarchical input levels in the M-E PDG.
The traffic data required in the NCHRP 137A methodology are the same for all pavement types (flexible or rigid) and construction types (new or rehabilitated). Four categories of traffic data are required:

- **Traffic volume**—base year information
  - Two-way annual average daily truck traffic (AADTT)
  - Number of lanes in the design direction
  - Percent trucks in design direction
  - Percent trucks in design lane
  - Vehicle (truck) operational speed

- **Traffic volume adjustment factors**
  - Monthly adjustment
  - Vehicle class distribution
  - Hourly truck distribution
  - Traffic growth factors

- **Axle load distribution factors by season, vehicle class, and axle type**

- **General traffic inputs**
  - Traffic wander data (mean wheel location and wander standard deviation; lane width)
  - Number axles/trucks
  - Axle configuration (axle width and spacing; tire spacing and pressure)
  - Wheelbase spacing distribution

The M-E PDG design software takes all of these traffic inputs and computes the number of applications of each axle load magnitude by axle type (single, tandem, tridem, quad) and month. These axle load spectra are a primary input to the mechanistic pavement structural response models.

Table 14. Traffic data required for each of the three hierarchical input levels.

<table>
<thead>
<tr>
<th>Data Sources</th>
<th>Traffic load/volume data</th>
<th>Input Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>WIM data – site/segment specific</td>
<td>X</td>
<td>1</td>
</tr>
<tr>
<td>WIM data – regional default summaries</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>WIM data – national default summaries</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>AVC data – site/segment specific</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>AVC data – regional default summaries</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>AVC data – national default summaries</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Vehicle counts – site/segment specific</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Traffic forecasting and trip generation models</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

1Level depends on whether regional or national default values are used for the WIM or AVC information.
2Level depends on input data and model accuracy/reliability.
A.2 3 Environment

Environmental conditions have a significant effect on the performance of both flexible and rigid pavements. External factors such as precipitation, temperature, freeze-thaw cycles, and depth to water table play a key role in defining the impact of environment on pavement performance. Internal factors such as the susceptibility of the pavement materials to moisture and freeze-thaw damage, drainability of the paving layers, infiltration potential of the pavement, and so on define the extent to which the pavement will react to the external environmental conditions.

Variations in temperature and moisture profiles within the pavement structure and subgrade over the design life of a pavement are simulated in the M-E PDG methodology through an analysis tool called the Enhanced Integrated Climatic Model (EICM—described more fully below). The EICM requires a relatively large number of input parameters. As with all other design inputs, EICM input parameters can be provided at any of the hierarchical levels (1, 2, or 3). Since many of the EICM material property inputs are not commonly measured by most agency and geotechnical laboratories, level 3 default values will typically be used for most designs. The inputs required by the EICM fall under the following broad categories:

- **General information**
  - Base/subgrade construction completion date
  - Pavement construction date
  - Traffic opening date
- **Weather-related information**
  - Hourly air temperature
  - Hourly precipitation
  - Hourly wind speed
  - Hourly percentage sunshine (used to determine cloud cover)
  - Hourly relative humidity
- **Ground water related information**
  - Groundwater table depth
- **Drainage and surface properties**
  - Surface shortwave absorptivity
  - Infiltration
  - Drainage path length
  - Cross slope
- **Pavement materials**
  - Asphalt and Portland cement concrete
    - Thermal conductivity
    - Heat capacity
  - Unbound materials
    - Physical properties (specific gravity, maximum dry unit weight, optimum moisture content)
    - Soil water characteristic curve parameters
    - Hydraulic conductivity (permeability)
    - Thermal conductivity
    - Heat capacity
The weather-related information required by the EICM is primarily obtained from weather stations located near the project site. The software accompanying the M-E PDG includes a database from nearly 800 weather stations throughout the United States that can be used to generate the weather-related design inputs.

A.2.4 Material Properties

The material property inputs required for the environmental effects model in the M-E PDG have already been described. Additional material property inputs are required for the structural response models used to calculate the stresses and strains in the pavement. As with all other design inputs, the material property inputs can be provided at any of the hierarchical levels (1, 2, or 3). The material property inputs are most conveniently grouped by material type:

- **Asphalt concrete**
  - Layer thickness
  - Dynamic modulus (measured value for Level 1 or mixture gradation and volumetrics for Level 2 and 3 estimation)
  - Asphalt binder properties (dynamic shear stiffness or viscosity for Levels 1 and 2, binder grade for Level 3)
  - Mixture volumetrics (effective binder content, air voids, unit weight)
  - Poisson’s ratio
  - Thermal cracking properties (low temperature tensile strength, creep compliance, thermal expansion coefficient)

- **Portland cement concrete**
  - Layer thickness
  - Mixture properties (cement and aggregate type, cement content, water/cement ratio, unit weight)
  - Shrinkage characteristics
  - Elastic modulus
  - Poisson’s ratio
  - Compressive strength
  - Modulus of rupture
  - Thermal expansion coefficient

- **Unbound materials**
  - Material type
  - Layer thickness
  - Unit weight
  - Coefficient of lateral earth pressure
  - Resilient modulus
  - Poisson’s ratio

A.2.5 Other

A variety of other input data are required for the M-E PDG. Some of these inputs are dependent upon the particular pavement type (flexible vs. rigid) and construction type (new vs. rehabilitation) being considered. A brief summary of these other inputs are as follows:

- **General project information**
  - Design life
  - Latitude, longitude, and elevation (for accessing weather station database)
• Rigid pavement design features (all rigid pavement types)
  – Permanent curl/warp effective temperature difference
  – Base erodibility index
• JPCP design features
  – Joint spacing, sealant type
  – Dowel bar diameter, spacing
  – Edge support (e.g., tied shoulder, widened slab)
  – PCC-base interface bond condition
• CRCP design features
  – Shoulder type
  – Reinforcement (steel percentage, diameter, depth)
  – Mean crack spacing
• Flexible pavement distress potential (new construction)
  – Block cracking
  – Longitudinal cracks outside wheelpath
• Pre-rehabilitation distresses (overlay over AC surface)
  – Rutting
  – Fatigue cracking within wheelpath
  – Longitudinal cracks outside wheelpath
  – Patches
  – Potholes
• Pre-rehabilitation distresses (overlay over PCC surface)
  – Percent cracked slabs before, after restoration
  – CRCP punchouts
  – Dynamic modulus of subgrade reaction

Note that no design features are included for jointed reinforced concrete pavements (JRCP). The M-E PDG does not include a design capability for this pavement type.

A.3 Pavement Response Models
There are two types of pavement response models in the M-E PDG: (a) an environmental effects model for simulating the time- and depth-dependent temperature and moisture conditions in the pavement structure in response to climatic conditions; and (b) structural response models for determining the stresses and strains at critical locations in the pavement structure in response to traffic loads. The same environmental effects model is used for all pavement types. Different structural response models are employed for rigid vs. flexible pavements because of the fundamental differences in their mechanical behavior.

A.3.1 Environmental Effects
Pavement response and distresses are affected by environmental factors. Diurnal and seasonal fluctuations in the moisture and temperature profiles in the pavement structure induced by changes in ground water table, precipitation/infiltration, freeze-thaw cycles, and other external factors are incorporated in the M-E PDG via the Enhanced Integrated Climatic Model (EICM). The EICM is a mechanistic one-dimensional coupled heat and moisture flow program that simulates changes in the behavior and characteristics of pavement and subgrade materials induced by environmental factors. The EICM consists of three major components:
The Climatic-Materials-Structural Model (CMS Model) originally developed at the University of Illinois (Dempsey et al., 1985).

The CRREL Frost Heave and Thaw Settlement Model (CRREL Model) originally developed at the United States Army Cold Regions Research and Engineering Laboratory (CRREL) (Guymon et al., 1986).

The Infiltration and Drainage Model (ID Model) originally developed at Texas A&M University (Lytton et al., 1990).

Each of these components has been enhanced substantially for use in the M-E PDG.

For flexible pavements, the EICM evaluates the following environmental effects:

- Seasonal changes in moisture content for all subgrade and unbound materials.
- Changes in resilient modulus, $M_R$, of all subgrade and unbound materials caused by changes in soil moisture content.
- Changes $M_R$ due to freezing and subsequent thawing and recovery from frozen conditions.
- Temperature distributions in bound asphalt concrete layers (for determining the temperature-dependent asphalt concrete material properties).

For rigid pavements, the following additional environmental effects are simulated by the EICM:

- Temperature profiles in PCC slabs (for thermal curling prediction).
- Mean monthly relative humidity values (for estimating moisture warping PCC slabs).

One of the important outputs from the EICM for both flexible and rigid pavement design is a set of adjustment factors for unbound layer materials that account for the effects of environmental conditions such as moisture content changes, freezing, thawing, and recovery from thawing. This factor, denoted $F_{env}$, varies with position within the pavement structure and with time throughout the analysis period. The $F_{env}$ factor is a coefficient that is multiplied by the resilient modulus at optimum moisture and density conditions $M_{Ropt}$ to obtain the seasonally adjusted resilient modulus $M_R$ as a function of depth and time.

A.3.2 Structural Response

The mechanistic structural response models determine the stresses, strains, and displacements within the pavement system caused by traffic loads and as influenced by environmental conditions. Environmental influences may be direct (e.g., strains due to thermal expansion and/or contraction) or indirect (e.g., changes in material stiffness properties due to temperature and/or moisture effects).

Flexible Pavements

Two flexible pavement analysis methods have been implemented in the M-E PDG computational procedures. For cases in which all materials in the pavement structure can realistically be treated as linearly elastic, multilayer elastic theory (MLET) is used to determine the pavement response. MLET provides an excellent combination of analysis capabilities, theoretical rigor, and computational speed for linear pavement analyses. In cases where the consideration of unbound material nonlinearity is desired (i.e., Level 1 resilient modulus for new construction), a nonlinear
finite element code (FE) is employed instead for determining the pavement stresses, strains, and displacements.

A major advantage of MLET solutions is very quick computation times. Solutions for multiple wheel loads can be constructed from the fundamental axisymmetric single wheel solutions via superposition automatically by the computer program. The principal disadvantage of MLET solutions is the restriction to linearly elastic material behavior. Real pavement materials, and unbound materials in particular, often exhibit stress-dependent stiffness. The materials may even reach a failure condition in some locations, such as in tension at the bottom of the unbound base layer in some pavement structures. These nonlinearities vary both through the thickness of the layer and horizontally within the layer. Some attempts have been made in the past to incorporate these material nonlinearity effects into MLET solutions in an approximate way, but the fundamental axisymmetric formulation of MLET makes it impossible to include the spatial variation of stiffness in a realistic manner.

Some of the limitations of MLET solutions are the strengths of FE analysis. In particular, finite element methods can simulate a wide variety of nonlinear material behavior; the underlying finite element formulation is not constrained to linear elasticity, as is the case with MLET. Stress-dependent stiffness and no-tension conditions for unbound materials can all be treated within the finite element framework. However, the FE computational times are substantially longer than for MLET analyses.

The choice of MLET vs. FE structural response model is made automatically by the M-E PDG software based on the input data from the user (i.e., whether Level 1 new construction inputs are specified for the unbound resilient modulus values). In both cases, the M-E PDG software automatically pre-processes all of the input data required for the analysis (e.g., automatically generates a finite element mesh, automatically performs the season-by-season analyses over the specified pavement design life, and automatically post-processes all of the analysis output data to compute the season-by-season values of the critical pavement responses for subsequent use in the empirical performance prediction models.

Performance prediction requires identification of the locations in the pavement structure where the critical pavement responses (stress or strain) attain their most extreme values. For multilayer flexible pavement systems, these locations can be difficult to determine. Critical responses are evaluated at several depth locations in the M-E PDG analyses, depending upon the distress type:

- **Fatigue Depth Locations:**
  - Surface of the pavement (z=0),
  - 0.5 inches from the surface (z=0.5),
  - Bottom of each bound or stabilized layer.

- **Rutting Depth Locations:**
  - Mid-depth of each layer/sub-layer,
  - Top of the subgrade,
  - Six inches below the top of the subgrade.

The plan (x-y) locations for the extreme values of critical responses are more difficult to determine. The critical location for the simplest case of a single wheel load can usually be determined by inspection—e.g., directly beneath the center of the wheel. The critical location under multiple wheels and/or axles will be a function of the wheel load configuration and the
pavement structure. Mixed traffic conditions (single plus multiple wheel/axle vehicle types) further complicates the problem, as the critical location within the pavement structure will not generally be the same for all vehicle types. The M-E PDG calculations address this problem by evaluating the pavement responses for a set of potential critical locations. Damage/distress magnitudes are calculated from the pavement responses at each location, with the final performance prediction based on the location having the maximum damage/distress at the end of the analysis period.

**Rigid Pavements**

Finite element analysis has been proven a reliable tool for computing rigid pavement structural responses. However, the season-by-season distress/damage calculations implemented in the M-E PDG requires hundreds of thousands of calculations to compute incremental damage over a design period of many years. These computations would take days to complete using existing rigid pavement finite element programs. To reduce computer time to a practical level, neural network models have been developed from a large parametric analysis study performed using the ISLAB2000 finite element program (Khazanovich et al., 2000). The neural network models, which in effect are similar to regression models, make it possible to accurately compute critical stresses and deflections virtually instantaneously. This in turn makes it possible to perform detailed, month-by-month, incremental analysis within a practical time frame (i.e., a few minutes). Appendix QQ in the NCHRP 1-37A final report (NCHRP, 2004) provides a detailed description of the finite element models, parametric study, and neural networks used for the structural analysis of rigid pavements.

A key feature of the rigid pavement structural response model is its treatment of the pavement foundation. The ISLAB2000 analysis program, and the neural network models derived from it, employs a modified version of the conventional slab-on-Winkler springs pavement structural model (also called a “dense liquid” foundation model). As shown in Figure 34, the actual multi-layer pavement structure is replaced by an equivalent 2-layer (slab and base) pavement section resting on a Winkler spring foundation having a stiffness characterized by $k$, the modulus of subgrade reaction. The effective $k$ value in the equivalent 2-layer pavement is determined by matching the surface deflections for the actual multi-layer pavement section. The surface deflection profile of the actual section is determined using MLET, modeling all layers in the structure. This computed deflection profile is then used to backcalculate the effective $k$ value for the equivalent 2-layer section. Thus, the effective $k$ value is an internally computed value, not a direct input to the design procedure (except for rehabilitation analyses, where $k$ determined from FWD testing may be input directly).

The effective $k$ value used in the M-E PDG is interpreted as a dynamic $k$ value (e.g., as determined from FWD testing), which should be distinguished from the traditional static $k$ values used in previous design procedures.
A.4 Pavement Performance Models

Pavement performance is evaluated in terms of individual distress modes in the M-E PDG. A variety of empirical distress models—also sometimes termed “transfer functions”—are incorporated in the M-E PDG for the major structural distresses in flexible and rigid pavements. Empirical models are also provided for estimating smoothness as a function of the individual structural distresses and other factors.

A.4.1 Damage vs. Distress

Some distresses can be evaluated directly during the season-by-season calculations. For example, the empirical model for rutting in the asphalt layers in flexible pavements is of the form:

\[
\frac{\varepsilon_p}{\varepsilon_r} = \beta_1 \alpha_1 T^{\alpha_2} N^{\alpha_3} \beta_3
\]

in which:

- \(\varepsilon_p\) = accumulated plastic strain after \(N\) repetitions of load
- \(\varepsilon_r\) = resilient strain of the asphalt material as a function of mix properties, temperature, and rate of loading
- \(N\) = number of load repetitions
- \(T\) = temperature
- \(\alpha_i\) = regression coefficients derived from laboratory repeated load permanent deformation tests
- \(\beta_i\) = field calibration coefficients

Each asphalt layer is divided into sublayers, and Eq. (1) is evaluated at the midthickness of each sublayer. The contribution \(\Delta R_{di}\) to total rutting \(R_d\) from sublayer \(i\) having thickness \(h_i\) can then be expressed as:

\[
\Delta R_{di} = \varepsilon_p, \Delta h_i
\]
The contributions of all of the sublayers \( l \) can then be summed to give the total rutting for the asphalt concrete layer:

\[
R_d = \sum_{i=1}^{l} \Delta R_{d_i}
\]

(3)

Other distresses cannot be evaluated directly but must be quantified in terms of damage factors. For example, the empirical model for “alligator” fatigue cracking in the asphalt layers in flexible pavements is of the form:

\[
N_f = \beta_1 k_1 (\varepsilon_i)^{-\beta_2} (E)^{-\beta_3}
\]

(4)

in which:

- \( N_f \) = number of repetitions to fatigue cracking failure
- \( \varepsilon_i \) = tensile strain at the critical location
- \( E \) = asphalt concrete stiffness (at appropriate temperature)
- \( k_1, \beta_2, \beta_3 \) = regression coefficients determined from laboratory fatigue tests
- \( \beta_1, \beta_2, \beta_3 \) = field calibration coefficients

Accumulation fatigue damage is based upon Miner’s Law:

\[
D = \sum_{i=1}^{T} \frac{n_{ti}}{N_{f_i}}
\]

(5)

in which:

- \( D \) = damage.
- \( T \) = total number of seasonal periods
- \( n_{ti} \) = actual traffic for period \( i \)
- \( N_{f_i} \) = traffic repetitions causing fatigue failure under conditions prevailing during period \( i \)

The damage factor determined using Eq. (5) is then related to observed fatigue distress quantities (e.g., area of fatigue cracking within the wheel paths) during the field calibration process.

**A.4.2 Distress Models**

Empirical distress prediction models are provided for the following structural distresses in the M-E PDG flexible pavement design methodology:

- Permanent deformation (rutting)
  - Within asphalt concrete layers
  - Within unbound base and subbase layers
  - Within the subgrade
- Fatigue cracking
  - Within asphalt concrete layers
    - Bottom-up (classical “alligator” cracking)
    - Top-down (longitudinal fatigue cracking)
  - Within cement stabilized layers
- Thermal cracking

The empirical structural distress models in for rigid pavements include:

- Transverse joint faulting (JPCP)
- Transverse fatigue cracking (JPCP)
- Punchouts (CRCP)

Note that reflection cracking for asphalt concrete overlays is not included in the current version of the M-E PDG. At the time of the NCHRP 1-37A development, it was judged that no suitable empirical reflection cracking models yet existed. It is anticipated that a suitable model will be developed and added to the M-E PDG in the future.

**A.4.3 Smoothness**

Pavement smoothness is often used as a composite index of pavement quality. Smoothness (or loss thereof) is influenced by nearly all of the distress modes of interest in flexible and rigid pavement systems. Smoothness data is also regularly and routinely collected and stored as part of the pavement management systems at many agencies. Lastly, smoothness is directly related to overall ride quality, the factor of most importance to highway users. Because of these reasons, empirical smoothness prediction models have been incorporated in the M-E PDG.

Pavement smoothness in the M-E PDG is characterized in terms of the International Roughness Index or IRI. IRI is predicted as a function of the initial, as-constructed IRI, the subsequent development of distresses over time, and other factors such as subgrade type and climatic conditions that may affect smoothness through mechanisms such as shrinkage or swelling of subgrade soils and frost heave. The structural distresses influencing smoothness are predicted directly by the mechanistic-empirical methodology. However, nonstructural distresses cannot be evaluated using mechanistic-empirical principles, so the M-E PDG provides the option of specifying the overall potential for these other distresses. Smoothness loss due to soil shrinking/swelling/frost heave and other climatic factors are incorporated into the M-E PDG IRI models through the use of a “site factor.”

The M-E PDG provides IRI prediction models as a function of pavement type (flexible vs. rigid), base type (flexible pavements), and construction type (new vs. rehabilitation). IRI models are provided for the following cases:

- AC (new construction)
  - AC over granular base
  - AC over asphalt treated base
  - AC over cement stabilized material
- AC overlay (rehabilitation)
  - AC over flexible pavement
  - AC over rigid pavement
A.4.4 Field Calibration

The distress prediction models are key components of the NCHRP 1-37A mechanistic-empirical design and analysis procedure. Calibration of these models against field performance is an essential part of the model development. Calibration refers to the mathematical process by which the models are adjusted to minimize the differences between predicted and observed values of distress.

All performance models in the M-E PDG have been calibrated on a global level to observed field performance at a representative set of pavement test sites around North America. Test sections from the FHWA Long Term Pavement Performance (LTPP) program were used extensively in the calibration process because of the consistency of the monitored data over time and the diversity of test sections throughout North America.

However, there were some serious limitations to the M-E PDG field calibration. Many of the material property and site feature inputs required for the M-E PDG analyses were unavailable from the LTPP database. Because of the limited number of pavement test sites with complete input data, the minimal material testing available, the use of calculated properties from correlations (i.e., level 3 inputs), and the global scope of the calibration effort, the predictions from the calibrated models still have a relatively high level of uncertainty and a limited inference space of application. The recently completed NCHRP Project 9-30 (Von Quintus et al., 2003) has formulated a plan for developing an enhanced database for future recalibration of the M-E PDG and other similar pavement models.

The M-E PDG software also includes a provision for entering local or regional field calibration factors instead of the national values derived from the LTPP database. This feature permits local agencies to adjust the mechanistic-empirical performance predictions to better reflect their local conditions.

A.5 Design Reliability

A large amount of uncertainty and variability exists in pavement design and construction, as well as in the traffic loads and climatic factors acting over the design life. In the M-E PDG, the key outputs of interest are the individual distress quantities. Therefore, variability of the predicted distresses is the focus of design reliability.
The incorporation of reliability in the M-E PDG procedure is similar in some respects to the way it is treated in the 1993 AASHTO Guide. In the 1993 AASHTO Guide, an overall standard deviation or “uncertainty” is specified for the design inputs (the $S_0$ value), a desired reliability level is selected based on agency policy, and the combination of the standard deviation and reliability are then used in essence to add a “margin of safety” to the design traffic $W_{18}$.

The M-E PDG differs from the 1993 AASHTO procedure in that the standard deviations and reliability levels are set for each individual distress mode predicted in the mechanistic-empirical computations. The default value for the standard deviation of each predicted distress quantity is based on a careful analysis of the differences between the predicted versus actual distresses during the field calibration of the empirical performance models. These estimates of error represent the combined effects of input variability, variability in the construction process, and model error.

The desired level of reliability is specified along with the acceptable level of distress at the end of design life to define the performance requirements for a pavement design in the M-E PDG. For example, one criterion might be to limit the percent of cracked PCC slabs to 8% at a design reliability of 90 percent. Then, on average for 100 projects, 90 would be expected to exhibit fewer than 8% slabs cracked at the end of the design life. Different reliability levels may be specified for different distresses in the same design. For example, the designer may choose to specify 95 percent reliability for slab cracking, but 90 percent reliability for faulting and IRI. Of course, increasing design reliability will lead to more substantial pavement sections and higher initial costs. The beneficial trade-off is that future maintenance costs should be lower for the higher-reliability design.

### A.6 Performance Criteria

Performance criteria are definitions of the maximum amounts of individual distress or smoothness acceptable to an agency at a given reliability level. Performance criteria are a user input in the M-E PDG and depend on local design and rehabilitation policies. Default performance criteria built into the current version of the M-E PDG software are summarized in Table 15. The designer can select all or some subset of the performance criteria to be evaluated during the design.

<table>
<thead>
<tr>
<th>Distress</th>
<th>Unit</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible Pavements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top-down (longitudinal) fatigue cracking</td>
<td>feet/mile</td>
<td>1000</td>
</tr>
<tr>
<td>Bottom-up (alligator) fatigue cracking</td>
<td>% of wheel path area</td>
<td>25</td>
</tr>
<tr>
<td>Thermal fracture</td>
<td>feet/mile</td>
<td>1000</td>
</tr>
<tr>
<td>Chemically stabilized layer fatigue cracking</td>
<td>% of wheel path area</td>
<td>25</td>
</tr>
<tr>
<td>Total permanent deformation (rutting)</td>
<td>inch</td>
<td>0.75</td>
</tr>
<tr>
<td>Permanent deformation (rutting) in asphalt layer</td>
<td>inch</td>
<td>0.25</td>
</tr>
<tr>
<td>Terminal IRI $^2$</td>
<td>inches/mile</td>
<td>172</td>
</tr>
<tr>
<td>Rigid Pavements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transverse fatigue cracking (JPCP)</td>
<td>% slabs cracked</td>
<td>15</td>
</tr>
<tr>
<td>Mean joint faulting (JPCP)</td>
<td>inch</td>
<td>0.12</td>
</tr>
<tr>
<td>Punchouts (CRCP)</td>
<td>number per mile</td>
<td>10</td>
</tr>
<tr>
<td>Terminal IRI $^2$</td>
<td>inches/mile</td>
<td>172</td>
</tr>
</tbody>
</table>
A.7 Software

The mechanistic-empirical calculations in the M-E PDG cannot be performed by hand or simple spreadsheets. A Windows-based program has been developed to implement the M-E PDG methodology by providing: (1) an interface to input all design variables, (2) computational engines for analysis and performance prediction, and (3) results and outputs from the analyses in formats suitable for use in electronic documents or for making hard copies.

The software presents a series of information and input screens coordinated through a main program layout screen, as illustrated in Figure 35. On this screen, all access points to the information and data input screens are color-coded to guide the designer in providing all data needed to run a design analysis. Green tag indicates screens on which the designer has already entered/reviewed data, yellow tag indicates screens containing default data that have not yet been reviewed/approved by the designer, and red tags indicate screens the have missing required data that must still be entered by the designer before the calculations can be performed. Clicking on any tag brings up the corresponding data input screen; for example, Figure 36 shows an example data entry screen for subgrade material properties.

The main program layout screen provides access to the following five groupings of information and input screens (screens are denoted by the symbol “•”, subordinate screen tabs by the symbol “♦”):

1. **Project Information**
   - General Information
   - Site/Project Identification
   - Analysis Parameters

2. **Traffic Inputs**
   - Traffic Volume Adjustment Factors
     - Monthly Adjustment
     - Vehicle Class Distribution
     - Hourly Distribution
     - Traffic Growth Factors
   - Axle Load Distribution Factors
   - General Traffic Inputs
     - Number of Axles/Truck
     - Axle Configuration
     - Wheelbase

3. **Climate Inputs**
   - Climate
4. Structure Inputs
   - Structure
     ♦ Drainage and Surface Properties
     ♦ Layers
       ─ Layer Material Properties
     ♦ Thermal Cracking

5. Distress Potential

Note that the Structure Inputs listing above is for the case of a new flexible pavement design. The screens will be slightly different for other pavement and construction types, but they all conform to the general organization listed above.

Once all necessary information and input data have been entered into the program, the user clicks the Run Analysis button to carry out all the required computations. Separate areas of the main program layout screen provide (1) the status (% complete) of the analyses in progress and (2) links to summary screens for the inputs to the analyses and their results in both tabular and graphical formats. For example, the design analysis of a conventional flexible pavement design might provide output plots of HMA modulus, alligator cracking, thermal cracking, rutting, and IRI versus pavement age. Figure 37 is an example of the type of output generated by the software. Output can be generated as either Microsoft Excel spreadsheets or as HTML documents.
Figure 35. Main input screen for M-E PDG software.
Figure 36. Typical data entry screen for M-E PDG software.
Figure 37. Typical graphical output from M-E PDG software.

### A.8 References


