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# MECHANISTIC-EMPIRICAL PAVEMENT DESIGN GUIDE (MEPDG) IMPLEMENTATION ROADMAP

FINAL REPORT
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**16. Abstract**

The American Association of State Highway and Transportation Officials (AASHTO) *Guide for Design of Pavement Structures* served as the official pavement design procedure for most State Highway Agencies (SHAs) for many years and continues to be used by some agencies today. However, a shift from this empirical design procedure to a mechanistic-based approach has been ongoing for more than two decades, and this shift was facilitated in 2008 with the publication of the AASHTO *Mechanistic-Empirical Pavement Design Guide (MEPDG): A Manual of Practice (MOP)* and the subsequent (2011) release of the accompanying software program, AASHTOWare Pavement ME Design (PMED). Following the early adoption of MEPDG and PMED by a few lead SHAs, the number of implementing agencies has steadily grown, with around 16 SHAs reported as implemented for one or both pavement types (asphalt and concrete) in 2019. Since then, however, the number of agencies transitioning to Pavement ME has stagnated for a variety of technical and other reasons.

In response to the reduced implementation activity, an MEPDG Implementation Roadmap Workshop was conducted in June 2022 to gather information on the implementation challenges that several SHAs have experienced and the strategies they used to successfully overcome those challenges. This document conveys the information obtained from the workshop and presents it in a clear and concise manner for use by SHAs in their quest to fully adopt Pavement ME.

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# 1.0 INTRODUCTION

## BACKGROUND

In 2008, the American Association of State Highway and Transportation Officials (AASHTO) published an interim edition of the *Mechanistic-Empirical Pavement Design Guide (MEPDG): A Manual of Practice (MOP)* (AASHTO 2008). That groundbreaking document presented the first mechanistic-empirical (ME) pavement design procedure based on nationally calibrated pavement performance prediction models. Second and third editions of the MOP containing updated information, additional guidance, and improved nationally calibrated models were published in 2015 and 2020, respectively, and a supplement to the third edition was issued in 2021 (AASHTO 2015; 2020; 2021). In 2010, AASHTO published the *Guide for the Local Calibration of the MEPDG* (AASHTO 2010), which provided instruction and guidance to highway agencies for calibrating the national models to their local conditions.

An accompanying software program, AASHTOWare Pavement ME Design (PMED), was developed and released in 2011. Multiple updates have been made to the software since its initial release, with the latest web-based version (v3.0) made available in July 2022. Various supplemental analysis tools, such as the Deflection Data Analysis and Backcalculation Tool (BcT) and the Calibration Assistance Tool (CAT), have also been developed and made available to support highway agencies in developing effective pavement designs. Collectively, the MEPDG procedure and the AASHTOWare PMED software and support tools provide an improved process for conducting pavement analyses and for developing designs based on ME principles.

The implementation of the MEPDG in North America began shortly after its 2008 release. Fifteen state highway agencies (SHAs) served as lead states in the implementation of the design procedure, with some of the agencies adopting it in the first few years. The early adopters, as well as the planned implementation timelines of many state and provincial highway agencies, were indicated in a 2013 survey reported in NCHRP Synthesis 457 (Pierce and McGovern 2014). The implementation map from that 2013 survey is shown in figure 1.

Since that 2013 baseline survey, the number of implementing agencies has continued to grow as the result of a variety of educational resource opportunities (e.g., training courses, webinars, regional peer exchanges, national user group meetings). Those resources have helped agencies identify and, in some cases, perform the activities (e.g., sensitivity testing, developing design inputs, establishing design criteria, calibrating models, developing guides/manuals, training staff and consultants) needed to transition to the use of Pavement ME (i.e., the combined use of the MEPDG procedure and PMED software).

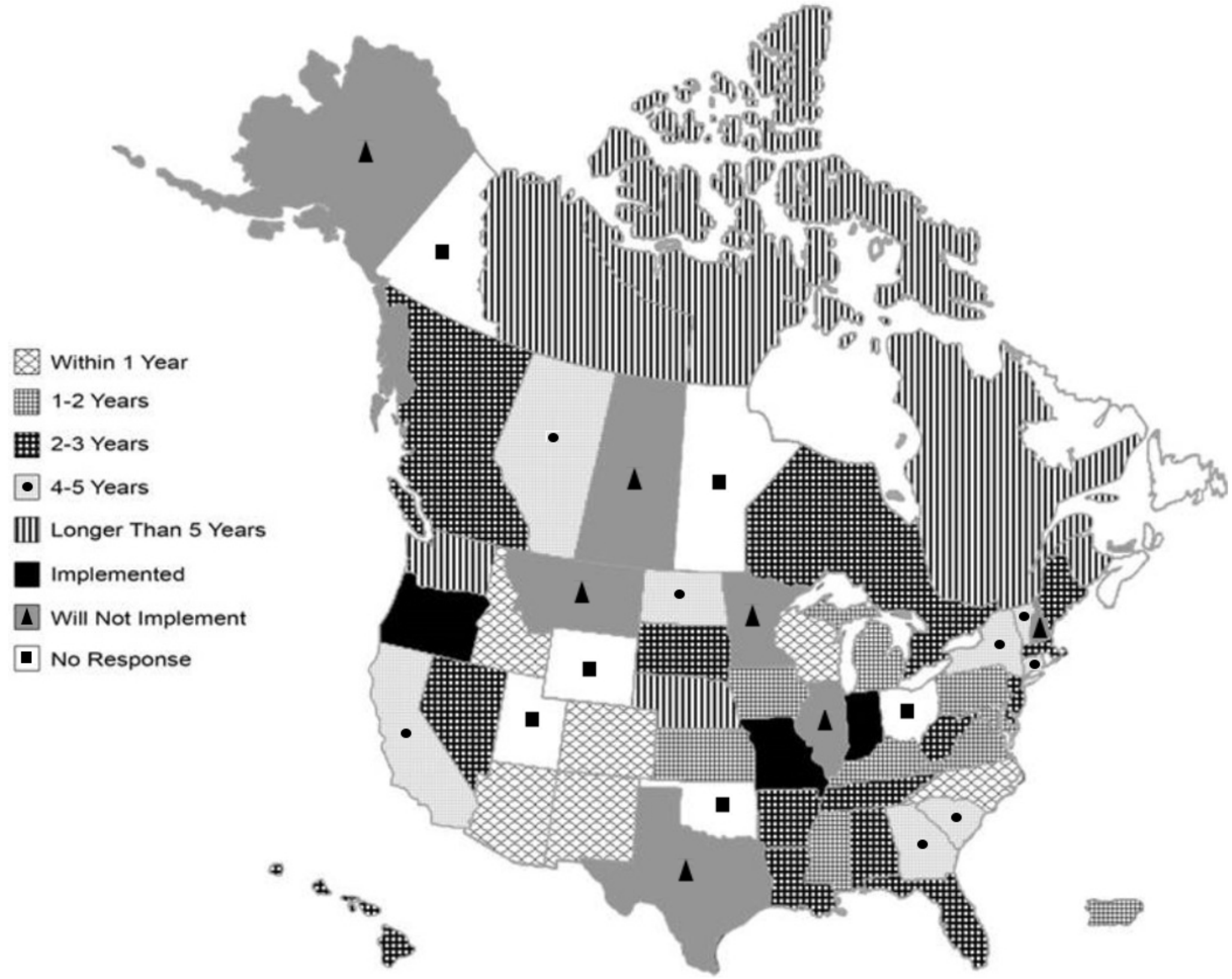
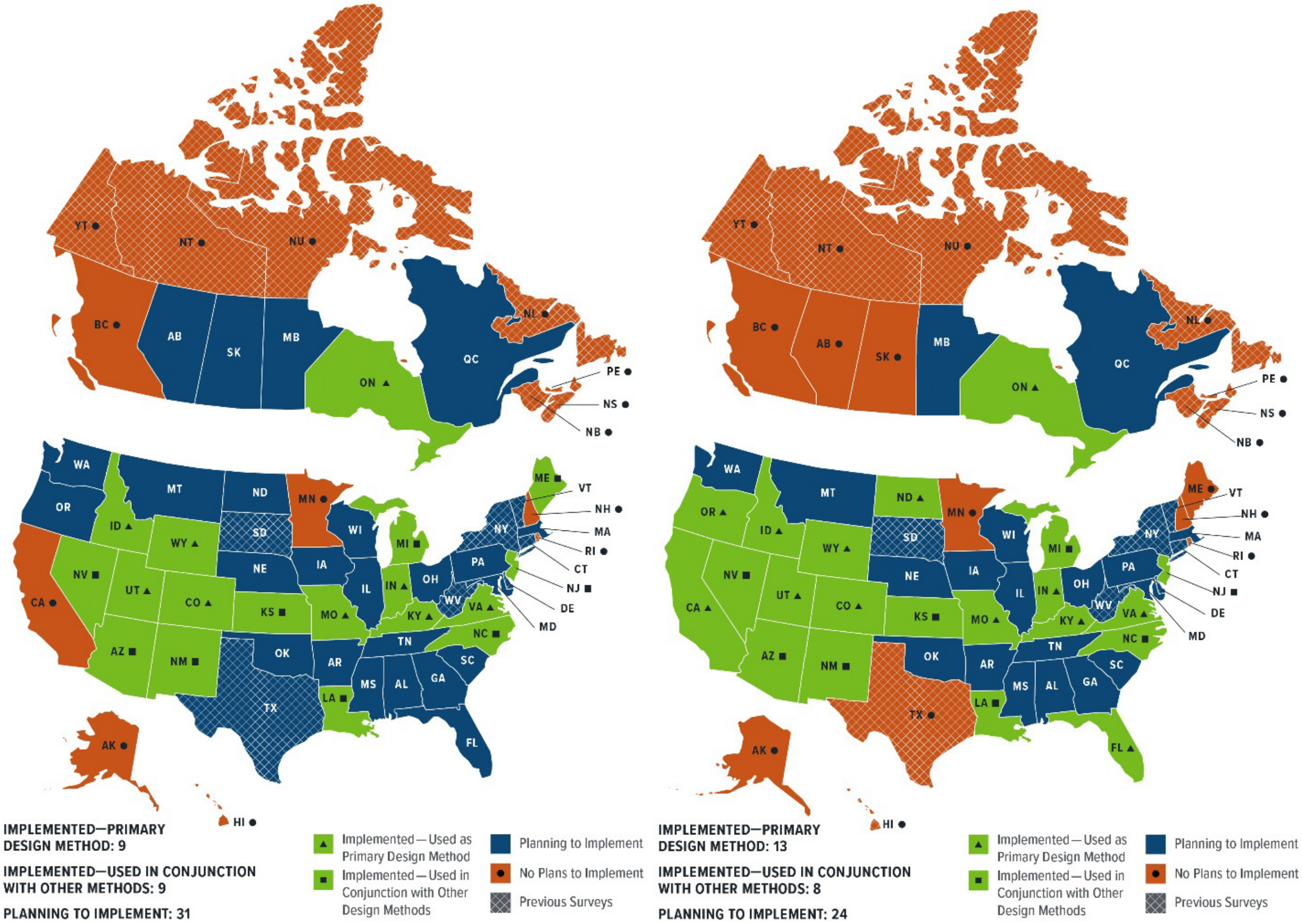


Figure 1. MEPDG implementation status from the 2013 NCHRP survey (Pierce and McGovern 2014).

The growth in the number of implementing agencies was most notable during the 2010-2020 timeframe, with around 13 SHAs reported as implemented for one or both pavement types (asphalt and concrete) in 2016 and around 16 SHAs reported as implemented in 2019, based on surveys associated with the annual national user group meetings. Implementation trends since then, however, suggest a degree of stagnation, with some previously "implemented" agencies reverting to parallel use with their previous design method (usually the empirical-based *AASHTO Guide for Design of Pavement Structures*) or even sole use of their previous method. As illustrated in figure 2, feedback on implementation from the 2021 national user group meeting shows Pavement ME as the primary flexible pavement design method for 9 state/provincial highway agencies and the primary rigid pavement design method for 13 agencies. It also shows that many other agencies continue to pursue adoption of the MEPDG procedure and official use of the PMED software. It should be noted that these apparent trends in reduced SHA adoption may be in part the result of a standard definition as to what is meant by "implementation."



(a) Asphalt pavements and/or overlays

(b) Concrete pavements and/or overlays

Figure 2. Pavement ME implementation status, based on the 2021 national user group meeting.

## ROADMAP WORKSHOP

The breadth of activities available to aid Pavement ME implementation has remained fairly constant since the publication of NCHRP Synthesis 457 in 2014. Training on the design procedure and software, on the development of design inputs, and on the interpretation of design results have been a primary focus, along with an emphasis on local calibration and model improvement. The establishment of a dedicated AASHTO Pavement ME website, the creation of a Pavement ME user group, and the development and release of the AASHTOWare CAT tool have all contributed to the implementation effort, but the need for additional actions and considerations remains acute.

One avenue recently pursued was the conduct of an Implementation Roadmap workshop focused on sharing and documenting valuable information on state department of transportation (DOT) implementation efforts. Sponsored by the Federal Highway Administration (FHWA), the objective of this workshop was to identify proven practices for expediting (i.e., shortening the time frame) and streamlining the Pavement ME implementation process. The workshop was organized as a 1.5-day event and convened representatives from 12 selected DOTs with extensive implementation experience and knowledge to share, while also including eight representatives from industry and academia that possess additional perspectives on implementation. The workshop was held in Chicago, Illinois on June 1-2, 2022 and focused on identifying best practices in addressing challenges in the following areas:

- Design policy.
- Design inputs.
- Verification, calibration, and validation.
- Application and use.

The results of the Implementation Roadmap workshop provide the basis for this report. The information presented is intended to help DOTs and other highway agencies navigate through the complexities and impediments of putting Pavement ME into formal practice. It is recognized that agencies are at varying stages of implementation and that some do not intend to implement Pavement ME (they may have their own ME-based design procedure). Because this report covers many different facets of implementation and transcends to some degree all ME design approaches, it should be beneficial to a wide range of highway agencies.

## ROADMAP OBJECTIVE

The overall objective of the Roadmap is to aid highway agencies in shortening the timeframe for Pavement ME implementation by communicating the successful practices of some of the experienced agencies.

## REPORT ORGANIZATION

The *MEPDG Implementation Roadmap* is organized into five chapters, including this introductory chapter. Chapter 2, Implementation Planning, describes the very important first step of developing and executing a well strategized implementation plan. Chapter 3, Administrative-Level Activities, addresses the many administrative activities that help establish a path for implementation and provide the high-level support needed for successful implantation. Chapter 4, Technical-Level Activities, covers the many technical aspects associated with adopting the MEDPG procedure and officially using the PMED software. Lastly, Chapter 5, provides some closing remarks about implementation, as well as the need for linking Pavement ME design with other business areas within the highway agency.

# 2.0 IMPLEMENTATION PLANNING

> *"Begin with the end in mind."*
> *– Stephen R. Covey*

> *"If you don't know where you are going, any road will get you there."*
> *– Lewis Carroll*

As discussed in Chapter 1, one of the difficulties in the Pavement ME User Group meetings has been effectively defining which states have implemented Pavement ME successfully. There is no standard definition of implementation and agencies take different approaches to implementation depending on their circumstances. Some agencies have limited implementation to a specific pavement type (e.g., asphalt, concrete) or construction type (e.g., new construction, rehabilitation), while others have implemented Pavement ME for both new and rehabilitated designs and both surface types. This emphasizes the need for agencies to start the implementation journey with clear goals and timelines for all parties involved in the process. Furthermore, developing and following an implementation plan can identify activities that can be performed concurrently and helps foster buy-in from customers and stakeholders throughout the implementation process.

## IMPLEMENTATION OBJECTIVES AND SCOPE

A key to any successful implementation of new technology is defining success. For many who are engaged in implementing a new practice or technology, it is difficult to know when they have completely reached the goal line and can move from implementation to production. As SHAs begin the process of implementing Pavement ME, one of their first activities should be to define what successful implementation for their agency will look like. Successful implementation can vary from agency to agency, dependent upon their existing pavement design practice, needs, and resources. SHAs could define successful implementation in a variety of ways, such as:

- Use of Pavement ME to develop optimal designs.
- Documented increases in pavement performance.
- Documented increased reliability and decreased variability.
- Ability to duplicate present pavement designs with the new methodology and achieve more efficient designs (e.g., thinner or optimized pavements) in some cases.
- Adoption of a newer pavement design methodology.
- The ability to model newer materials in pavement design.
- The ability to model pavement sustainability initiatives in pavement design.
- Use of Pavement ME for new pavement designs.

- Use of Pavement ME for rehabilitation designs.
- Use of Pavement ME for only one surface type.
- Use of Pavement ME but limited to specific models (e.g., cracking only, rutting only).
- Use of Pavement ME to develop equivalent designs for pavement type selection or alternate design alternate bid (ADAB) processes.

The workshop participants noted that using Pavement ME in rehabilitation applications is much more complicated than for new construction or reconstruction applications. They suggested that SHAs implement Pavement ME for new designs before starting on rehabilitation designs.

When defining success, it is also important to establish a timeline for implementation. The timeline needs to be reasonable, consider resources and support available, and allow for flexibility as unexpected issues arise. Besides the overall timeline, intermediate milestones should be set and tracked for the implementation plan; for example:

- Year 1 – Develop material and traffic libraries and begin calibration.
- Year 2 – Complete calibration.
- Year 3 – Perform parallel designs with present pavement design procedures for new designs.
- Year 4 – Soul use of Pavement ME for new designs.
- Year 6 – Add the use of Pavement ME for rehabilitation design.
- Year 8 – Validate Pavement ME.

**Virginia DOT Staged Implementation**

The Virginia DOT was one of fifteen lead agencies in MEDPG implementation and began planning its implementation efforts around 2007. The department completed several research projects to support the development of materials, traffic, and climate inputs for the design procedure and provided extensive training for its pavement designers.

Proceeding into the calibration stage, the DOT determined that a staged approach to implementation would be appropriate, with the initial focus on calibrating new HMA and CRC pavements located on interstate and primary routes and a subsequent focus on rehabilitation design for pavements on these routes. A goal of implementing the MEPDG/PMED for new construction, reconstruction, and lane widening projects on January 1, 2018 was successfully achieved and now the agency is working on the calibration of models and the implementation of the rehabilitation design procedure.

## IMPLEMENTATION PLAN DEVELOPMENT

SHAs that have implemented Pavement ME reported that they did not have formal documented plans for implementation but did have a plan in place. They believed that an informal plan provided more flexibility in the implementation of Pavement ME in responding to changes and unforeseen issues. Nevertheless, having a plan is key to implementing Pavement ME in a timely manner.

In developing an implementation plan, several items should be considered and addressed as discussed in the following sections of this chapter.

## Resources for Implementation.

Resources necessary for the successful implementation of Pavement ME consist primarily of human resources along with financial considerations. Management's commitment to the implementation effort is key to providing adequate human and financial resources. Management should be informed of the expected resource demand, actual usage, and implementation progress.

### Human Resources

The human resources necessary for the implementation of Pavement ME come from a variety of sources for an SHA. First, there is a team of people internal to the SHA that are the principal players in the Pavement ME implementation. Secondly, most SHAs have used outside or external resources in their implementation process.

#### Internal Human Resources

For a successful Pavement ME implementation, a commitment of time for multiple staff within an SHA is necessary. These staff will include a champion, steering committee, and multiple technical committees as discussed in Chapter 3. The timely implementation of Pavement ME is dependent on adequate resources being allocated to the process and the personnel living up to their commitments. A team charter may be considered to sanction the group's commitment to the implementation process. Management should also be aware of staff turnover and account for that risk.

#### Outside or External Human Resources

Most SHAs do not have sufficient, available staffing to implement Pavement ME using only internal resources. The two typical outside or external sources used by SHA are consultants and universities. Numerous SHAs have used consultants in their Pavement ME implementation. Many SHAs also have an established relationship with one or more universities in their state that perform research related to pavement design and performance and can be used to supplement their staffing in the implementation process.

SHAs typically use these consultant and university resources to perform such activities as specialized material testing, building libraries of traffic and material data, assisting in the calibration process, and investigating special issues. Resources from consultants and universities can be procured in the normal manner used by the SHA, but there are some factors to consider in this procurement.

- Understand what level of knowledge and experience the consultant or university has in Pavement ME versus what is required for the planned work. Consideration of knowledge of the SHA's operating procedures may also be a consideration.
- Determine the need for any specialized testing or evaluation and how that can be best obtained.
- Ascertain if the consultant or university has a Pavement ME license.
  - Consultants may not have a license for Pavement ME based on its cost and the low volume of pavement design work they perform.

  - Many universities have an educational license that can only be used for instructional purposes.
- Evaluate the potential impacts of staff or graduate student turnover during the project.

Project management of the consultant or university project should also be a consideration when entertaining this option.

### Financial Resources

Financial resources dedicated to the implementation and use of Pavement ME are required for:

- Procurement of consultant or university resources to assist in the implementation process as discussed in the Human Resources section of this chapter.
- Software license for Pavement ME Design – The 2022 annual license fee for the Pavement ME Design software is shown in table 1.
- Additional testing or test equipment to provide material properties required for Pavement ME.
- Additional traffic data collection equipment and analysis.
- Training on the Pavement ME methodology and software.
- Travel funding for peer exchanges, user groups, workshops, and regional meetings.

Table 1. Pavement ME Design software licensing fees (AASHTO 2022).

| License Type | Annual Fee |
|---|---|
| Single User | $8,000 |
| Up to 9 concurrent users | $32,050 |
| Up to 14 concurrent users | $48,050 |
| Up to 20 concurrent users | $64,050 |

## Schedule

The Implementation Plan should include a schedule with the major milestones outlined. The schedule should be reviewed on at least an annual basis with adjustments made as necessary to the schedule and other activities.

## Inputs

The inputs for Pavement ME can be overwhelming when taken as a whole. The Implementation Plan should include a breakdown of the inputs considering their source, confidence in the reported value, and whether they will be included in one of the libraries. The Implementation Plan may also include a sensitivity analysis of the inputs so that importance of the input can be matched with the confidence obtained and the cost of the data.

## Role of Industry

The Implementation Plan should consider the role that local industry will play in the implementation of Pavement ME. Industry can supply technical expertise, knowledge of new materials, and practical experience, all of which can contribute to the overall implementation. Industry may also be invited to participate in technical committees and to review documentation, results, and procedures.

Actively involving industry in the implementation may minimize questions and criticisms later in the process. The industries have an interest in protecting their market and in ensuring the validity of the resultant designs and are concerned about changes that may occur due to the adoption of new procedures.

## Outputs

Numerous outputs result from the implementation of Pavement ME, from the format of the designs themselves to guidance documents that are created to assist the designers in the production runs of the Pavement ME Design software.

### Designs

Gaining credibility for Pavement ME based solely on the outputs produced by the software is difficult. Users are left wondering what pavement structural design the previous method would have produced. Users have also noted that the design process may be labor intensive for routine designs. The following two sections discuss methodologies to reduce implementation and operational time and build confidence in the overall design approach.

#### Concurrent or Parallel Design

The use of concurrent or parallel designs using an SHA’s existing pavement design methodology can quicken the adoption of Pavement ME, as it provides the user with increased confidence in the results and minimizes abrupt changes in pavement designs. Most SHAs that have implemented Pavement ME have utilized parallel designs over an initial transition period, but they noted several considerations in that process:

- SHAs should not expect the results of two or more different design methodologies to match exactly. Most other pavement design procedures are not mechanistically based and utilize different performance criteria than Pavement ME. The comparison between the methodologies should be evaluated with those limitations in mind and SHAs should expect a reasonable comparison rather than an exact match.
- Engineering judgment must be applied, as otherwise very rigid rules about interpreting results will create difficulties.

### Design Catalog

Many SHAs have included pavement design catalogs in the Pavement ME implementation to both speed implementation and ease the burden of use on the designer. Catalogs provide a simple approach for the user to select a structural design. Typically, design catalogs contain a listing of common loading, environmental conditions, geographic location, materials, and the corresponding recommended pavement structures. The user should be aware of any assumptions that were used in the design procedure that went into the development of the design catalog.

Catalogs are typically applied to new pavement and overlay designs for one or both surface types or to special conditions such as low-volume routes, bridge approach replacements, etc. In the latter case, the application of catalogs reduces the workload of pavement designers performing low-risk designs for numerous applications. The designs in the catalog may be based solely on Pavement ME results or developed using parallel designs as discussed in the previous section of this chapter.

### Manuals and Procedures

The following three sections outline documentation that SHAs may want to include in the implementation planning.

#### Kentucky Transportation Cabinet Design Catalog

Since the late 1990s, the Kentucky Transportation Cabinet has used a catalog to enable its staff and consultants to quickly and effectively develop pavement designs for its roads. The original design catalog was developed using the Kentucky 1981 pavement design curves that were then modified to use layer coefficients from the *AASHTO Guide for Design of Pavement Structures*. Around 2016, the agency embarked on a mission to update the catalog to reflect mechanistic-empirical pavement design.

As part of the update, the agency conducted thousands of PMED design runs covering the spectrum of Kentucky's new pavement structures, traffic levels, and subgrade conditions. The designs used Kentucky-specific design inputs and performance criteria, as well as performance model calibration coefficients derived from surrounding states. Verification of the updated design catalog was performed in 2017 using approximately 30 calibration/verification sites across the state along with comparison to historical pavement designs. The performance model coefficients continue to be refined using data from the local calibration sites.

The online design catalog is available for use by agency engineers/officers and consultants engaged in developing pavement designs.

### Input Guide and Software Manual

Two common complaints about the Pavement ME Design software are that it requires numerous and varied inputs and that the software is complex to run. To mitigate those issues, SHAs have developed:

- Input guides, which assist the designer with sourcing, reasonable values, and sensitivity of inputs required for the Pavement ME Design software. The guide may refer to libraries or other sources of traffic and materials data.
- Software manuals, which provide step-by-step (screen-by-screen) instructions for the user on inputs and operating the software. The input guide may be incorporated into the user manual but this may make updating more complicated.

Input guides and software manuals typically address:

- General information.
- Performance criteria.
- Design reliability.
- Traffic inputs.
- Climate inputs.
- Structure and materials inputs.
- Rehabilitation inputs and designs.
- Performance outputs.
- Instructions for performing overlay designs.
- Example designs.

The use of these documents is very valuable in training staff during the implementation of Pavement ME, and when staff turnover occurs and training of new staff is required. Additionally, the guide and manual provide consistency for SHAs that use consultants to perform pavement designs. As with any documentation, they should be updated regularly to maintain their value.

**Virginia DOT Pavement ME User Manual**

In 2018, the Virginia DOT implemented the MEPDG/PMED for the design of new construction, reconstruction, and widening projects on interstates and primary roads. The implementation followed many years of research and development, including an initial local calibration effort for HMA and CRC pavement in 2015.

Recognizing the tremendous shift from using the 1993 *AASHTO Guide for Design of Pavement Structures* and corresponding DARWin software to the MEPDG and PMED, the agency developed the AASHTOWare Pavement ME User Manual for use by VDOT staff, consultants, and contractors. The document provides an overview of ME pavement design; guidance in selecting the many design inputs; and information and illustrations for entering the inputs, running the design analysis, and evaluating the outputs from the PMED software. The user manual is posted on the Virginia DOT business webpage, along with PMED materials, traffic, and climate input files.

### Pavement Design/Rehabilitation Manual

The implementation plan should also address updating the pavement design and rehabilitation manual(s) as appropriate for the level of implementation desired by the SHA. Again, there may be some overlap with the input guide, but the design manual will also address policy issues such as:

- The pavement design philosophy for the SHA.
- Pavement design life definition and explanation.
- Pavement ME input level usage.
- Performance criteria definition and explanation and may include a hierarchy for the evaluation of designs.
- Minimum layer thicknesses and explanation.
- Traffic growth rates.
- Application of engineering judgment.

The major difference between the input guide and the pavement design manual is that the pavement design manual typically supplies some of the philosophy behind the design decisions.

**Colorado DOT Mechanistic-Empirical Pavement Design Manual**

The Colorado DOT fully implemented MEPDG/PMED in 2014. A very important piece of its implementation was the development of a comprehensive manual containing guidance and instructions for performing mechanistic-empirical (ME) pavement designs. This manual built on the knowledge and information in previous design manuals (based on 1993 *AASHTO Guide for Design of Pavement Structures* ) and incorporated the procedures and recommended inputs for ME design of Colorado roads.

The Colorado ME Pavement Design manual has been updated annually to reflect changes in the models and recommended design inputs. The manual is posted on the Colorado DOT business webpage with other relevant documents.

### Standard Operating Procedures

SHA should also examine existing standard operating procedures (SOPs) to see if they need to be updated or augmented with the implementation of Pavement ME. Potential SOP updates could involve:

- Material testing and reporting.
- Traffic reporting, calculation, and prediction.
- File naming convention.
- Library inputs and updating.
- Pavement ME Design software updates.
- Application of a pavement design catalog versus a formal, project-specific pavement design.

### Communication Plan

Rounding out the components of the implementation plan is a clear communication plan. The communication plan should consider both internal and external communication about the implementation process from conception to final production. Furthermore, the communication plan should consider the partners and stakeholders involved in the implementation as well as their perspectives and informational needs. The methods of communication may include newsletters, briefings, presentations at conferences, annual workshops, etc. Proactive communication builds trust and solicits feedback promptly rather than waiting for complaints and criticisms to filter in (particularly when Pavement ME may be ready to enter the production phase).

Internal communication could be directed towards management, other central office divisions (e.g., traffic, materials, research), and districts/regions, if applicable. Regular communication could address progress on the implementation, data needs, outstanding issues, schedule updates, and upcoming training opportunities.

External communication addresses industry, consultants, and university stakeholders. These organizations may be interested in how the implementation may affect their market share, contracting opportunities, training needs, etc.

Communication with both the internal and external groups should be used to promote buy-in to the Pavement ME implementation and answer the "why" questions that both groups will be asking, such as:

- Why are we implementing Pavement ME?
- Why is the change necessary when what we have is working well?
- Why do we need more detailed traffic data?
- Why do we need more detailed materials data?
- Why make this change now?

## IMPLEMENTATION PLAN SUMMARY

Overall, the development and execution of an implementation plan can shorten the implementation timeline by:

- Defining and communicating the goals and objectives to allow for the measurement of success.
- Identifying activities that can be performed concurrently.
- Focusing on new design implementation before moving on to rehabilitation designs.
- Promoting buy-in to Pavement ME during implementation.
- Reducing complaints and criticisms.

SHAs that have completed the implementation noted that the plan does not have to be written and formalized, but they did see advantages in that as long as flexibility was maintained. The ability to adapt to changes, whether they be organizational or the use of new materials, was seen as a key item in the implementation process.

# 3.0 ADMINISTRATIVE-LEVEL ACTIVITIES

Numerous administrative-level activities are required to successfully implement Pavement ME at an SHA. This chapter addresses implementation requirements for human resources, policy, and training.

## HUMAN RESOURCES

Chapter 2 discussed the importance of adequate human resources, both internal and external to the SHA, that are necessary to successfully implement Pavement ME in a timely manner. This section concentrates on the SHA's internal human resources and their roles in implementation.

### Champion

Implementation champions have been used by SHAs for years to successfully adopt new technologies. SHAs that have implemented Pavement ME noted that the role of a champion will vary depending on the organizational structure and access to resources (both human and funding) of the pavement design unit within the SHA.

A champion is an individual who is "the face" of an implementation effort—one "who dedicate[s] themselves to supporting, marketing, and driving through an implementation, overcoming indifference or resistance that the intervention may provoke in an organization" (Powell et al. 2015), all with an intrinsic risk to their reputation. There are two types of champions, emergent and appointed. Emergent champions are those individuals who assumed the role for a cause they believe in. Appointed champions are simply someone appointed by management. The differences between emergent and appointed champions have been studied (Damschroder et al. 2009; Soo et al. 2009), but there is no conclusive evidence on the effectiveness of one over the other. Properly selecting and preparing personnel as a champion is one of the more important implementation strategies (Waltz et al. 2015).

SHAs that have implemented Pavement ME noted that the champion should ideally be located in the central office for better access to other groups that will be involved in the implementation process. Ideally, the champion would have a working knowledge of the SHA and its pavement design practices and be provided training opportunities for Pavement ME. The champion will need access to and support from upper management for both resources and to deal with organizational and political issues.

### Steering Committee

The role of a Pavement ME implementation steering committee is, as its name suggests, to steer a project from start to finish. Many times, the steering committee is formed from staff completely internal to an SHA (including districts/regions) or even a subgroup of an existing SHA committee. The steering committee may also include members from outside of the SHA including FHWA, industry, universities, and consultants who are either partners/stakeholders in the process or can provide specific expertise. It is useful to include an end user of Pavement ME (again this may be at the district or region level) as a member of the steering committee. This allows the district or region personnel that will be developing the pavement design to provide their input and ensure the implemented product is useable.

Typical steering committees used by SHAs for Pavement ME implementation included representatives from the following SHA sections:

- Materials.
- Design.
- Research.
- Traffic.
- Construction.
- Pavement management.
- Geotechnical.
- Districts if the SHA plans on using decentralized design.

The steering committee should assist, and not hinder, the champion by providing advice and ensuring delivery of outputs of the process, so membership should be considered carefully. The steering committee tasks may include:

- Providing input to the implementation process.
- Providing input on the implementation objectives and scope as discussed in Chapter 2.
- Providing advice on the budget.
- Identifying implementation priorities.
- Identifying and monitoring risks and opportunities.
- Providing advice on task assignment and contracting methods.
- Monitoring timelines.
- Monitoring implementation quality.
- Providing advice about changes as they develop.

Since the steering committee provides support, guidance, and oversight of progress, the members do not usually work on the implementation themselves.

## Technical Committees

The work of the implementation process can be focused in the technical committees. These committees either perform or direct the work of the implementation process. The technical committees provide a two-way conduit of data needs, usage, and quality requirements for Pavement ME implementation. SHAs have formed technical committees to address the following data needs:

- Pavement distress.
- Traffic.
- Materials.
  - PCC.
  - Asphalt.
  - Aggregate and soils.
- Climate.

## Education

Both initial and continuous training was noted by SHAs as a key in the implementation and operation of Pavement ME. Forming an education committee to coordinate those training activities can accelerate the adoption of Pavement ME. The committee’s charge would be to find or develop training that targets specific SHA users such as:

- Pavement designers in the central office.
- Ancillary staff.
  - District/regions.
  - Materials.
  - Traffic.
- Management.

Each of these groups has very different needs, from the detailed knowledge required by pavement designers to the broad overview useful to management.

Some external stakeholders should be trained to facilitate the implementation and operation of Pavement ME. These external stakeholders include:

- The pavement industry – to better understand how their market share may be affected by the implementation of Pavement ME.
- Consultants – who may be performing pavement designs using Pavement ME.

### Management

The SHA management contributes to the effective implementation of Pavement ME in a variety of roles. First, management is responsible for selecting and charging the champions and committees that will oversee and perform the actual implementation. Additionally, management also controls the resources, people, and funding used to facilitate the implementation process. And, besides resource allocation, management can set the overall direction of the implementation and usage of within the SHA providing by promoting its advantages. Finally, management will assume responsibility for addressing criticisms from outside the SHA.

## TRAINING

The implementation of Pavement ME requires training for a variety of staff and stakeholders on a multitude of topics. Training should be part of the implementation process from the beginning and should transition in form and content throughout the implementation process and into the production use of Pavement ME.

The training can be accomplished through a variety of means. Formal training courses developed either internally or from outside sources are a standard method of providing training. Training opportunities may be available from FHWA, AASHTO, and local universities. These courses may vary from the basics of mechanistic pavement design to the operation of the Pavement ME software. Typical audiences for this type of training include both internal SHA employees and consultants that may be performing pavement designs for the SHA. SHAs should also consider the level of expertise required for various staff members. Personnel performing the actual pavement design need a higher level of expertise than a district or region staff engineer or personnel from materials or traffic who are supplying data for a pavement design.

Webinars are another means of providing training on specific topics to broad audiences within an SHA. AASHTO provides numerous training opportunities through webinars covering items from basic features of the software to advanced applications as well as software updates.

Another training opportunity that SHAs can take advantage of are user groups (national or regional) and peer exchanges. These venues are focused on a small audience, but allow practitioners to exchange information on successful and not-so-successful practices utilizing Pavement ME. Mobile laboratory support from the FHWA and others can provide both training opportunities and exposure for staff to new testing methods that may apply to Pavement ME.

When Pavement ME moves from the implementation to the production phase, the need for training is reduced. A key item to account for is staff turnover both at SHAs and consultants. New employees will require the same varied level of training based on their position, from detailed training for pavement designers to a more general overview for others.

Certification of pavement designers using Pavement ME was also noted by SHAs as a method of ensuring that the personnel performing the design are knowledgeable of the Pavement ME software and methods. There is no national level of certification, so each SHA would set its minimum requirements.

## POLICY DEVELOPMENT

The successful implementation of Pavement ME by an SHA requires the development of several policies. The policies form the basis for the application of Pavement ME to design projects. The policies may be adapted from those previously used by the SHA for its existing pavement design method. Policies should be researched, both in background and consequences, to avoid unintended consequences as Pavement ME is implemented.

Policies that need to be addressed include:

- Performance criteria – SHAs need to decide which performance criteria to utilize and what level of distress will be acceptable. Implemented SHAs indicated that table 7-1 from the *Mechanistic-Empirical Pavement Design Guide: A Manual of Practice, 3rd Edition* (AASHTO 2020) should be used as a starting point. SHAs may also choose to omit one or more of the failure criteria based on their confidence in the modeling and the prevalence of that distress in their state. New adopters of Pavement ME should also check the alignment of their selected performance criteria with their asset management, pavement management, and pavement design policies and practices.
- Reliability – Likewise, SHAs need to select reliability levels that work with the performance criteria in the design process. Reliability levels generally vary based on the system for which the pavement is being designed, can range from Interstate to local roadways. Implemented SHAs referenced table 7-2 from the *Mechanistic-Empirical Pavement Design Guide: A Manual of Practice, 3rd Edition* (AASHTO 2020) as the starting point for selecting the reliability level.
- Design period – For the initial implementation, workshop participants noted that using a 20-year design period may mitigate some of the issues with performance criteria and reliability that SHAs have encountered during the implementation process. For concrete pavements, the user may consider a 30-year design period more appropriate.

### State DOT Pavement ME Design Policies

The Colorado and Indiana DOTs are just two of the highway agencies with detailed prescriptions for Pavement ME design life, reliability, and performance. The information can be found in the pavement design manuals of these respective agencies:

Colorado: Pages 108-112 of the 2021 Colorado DOT Pavement Design Manual

Indiana: Pages 19-23 of Chapter 601 (rev. 2022) of the 2013 Indiana DOT Design Manual

- Input level(s) – SHAs that have implemented Pavement ME noted that using all Level 1 inputs was unrealistic and probably not cost-effective. Higher level inputs required additional effort and expense with limited benefits according to the users. The suggestion was to strive for Level 2 if they could be reasonably obtained, but that Level 3 was acceptable for the setup and early application of Pavement ME.
- Equivalent design/alternate design-alternate bid (ADAB) comparison definition – Most SHAs require the development of equivalent design for asphalt and concrete pavements for pavement type determinations or ADAB. Defining equivalent design can be both time-consuming and controversial. SHAs may use their defined performance criteria and reliability levels for that purpose. SHAs that had implemented Pavement ME noted that using the values from table 7-1 and table 7-2 of the *Mechanistic-Empirical Pavement Design Guide: A Manual of Practice, 3rd Edition* (AASHTO 2020) could facilitate this process for initial implementation. Other issues to be considered include:
    - Providing equal foundations for the two alternatives.
    - Providing designs that promote competition.
    - Selecting appropriate design lives and analysis periods.
    - Using Pavement-ME outputs to inform rehabilitation and maintenance schedules in the economic analysis.
- Construction practices – It was suggested that a policy statement considering construction practices should be included as part of the Pavement ME implementation. The designer should be aware of field practices regarding materials, thickness, and construction practice variability. The awareness of the variability in field construction is partially accounted for in the reliability value selected but also in the effort in determining inputs. Construction practice variations that designers should be aware of include:
    - The density of pavement layers will vary due to several factors (e.g., gradation, moisture, compaction effort, stiffness of underlying layers) and that variation affects properties input into Pavement ME.
    - Contractors generally overbuild pavement thickness to avoid penalties or increase quantities, so constructed thickness typically exceeds design thickness. This is not the case for all agencies that may have different tolerance requirements.

### Missouri DOT ADAB Practices

The Missouri DOT has a long-standing policy of promoting innovation and fostering competition in highway construction. A major way of effecting this policy is through the use of alternate pavement bidding on large projects involving new full-depth pavement and pavement rehabilitation. The agency implemented Pavement ME in 2009 and has used it successfully to develop equivalent asphalt and concrete designs for hundreds of ADAB projects. Additional information on this practice can be found on Missouri DOT's optimal and alternate pavement designs webpage.

  - Changes in aggregate, asphalt cement, portland cement, or additives may occur in the middle of a project resulting in changes in material properties.
- Engineering judgment – Setting policies related to Pavement ME is an important step in the implementation process but workshop participants noted that engineering judgment needs to be a part of the design process. For instance, there may be times when increasing thickness is not the best solution to reducing distress or when exceeding a particular performance criterion in a design analysis is acceptable.

## ADMINISTRATIVE-LEVEL ACTIVITIES SUMMARY

The successful implementation of Pavement ME involves numerous administrative-level activities. These include naming a champion for the implementation along with steering and technical support committees to support and assist the champion. SHA management needs to support the implementation activities both inside and outside of the SHA. SHAs should also provide training to both internal and external staff to support Pavement ME implementation.

The development of carefully planned and implemented policies outlining the usage of Pavement ME is required for the successful implementation of Pavement ME. The *Mechanistic-Empirical Pavement Design Guide: A Manual of Practice, 3rd Edition* (AASHTO 2020) and reports from the NCHRP 1-37A project can be used in the development of these policies.

# 4.0 TECHNICAL-LEVEL ACTIVITIES

Mechanistic-empirical pavement design procedures require a number of inputs related to climate, traffic, and materials for the prediction of pavement performance. This chapter examines the technical aspects of Pavement ME implementation by discussing the Pavement ME input parameters and performance prediction models needed to successfully conduct a design analysis.

## BUILD LIBRARIES OF COMMON INPUT PARAMETERS

Pavement ME allows the user to develop and use data libraries covering the more common inputs. In this manner, the user selects the specific parameter (e.g., dense-graded asphalt mixture, cement stabilized base) from the data library and then imports the file containing the populated inputs for that parameter into the PMED software. This process greatly expedites the process of manual data entry and eliminates data entry errors. An example of a data library is provided in table 2.

Table 2. Example subgrade soil data library (adapted from VDOT 2017).

| **Input** | **AASHTO Soil Classification** | | |
|---|---|---|---|
| | **A-4** | **A-5** | **A-6** |
| No. 4 Sieve | 97.7 | 98.9 | 96.4 |
| No. 40 Sieve | 85.4 | 88.1 | 83.0 |
| No. 60 Sieve | 77.3 | 82.4 | 76.2 |
| No. 200 Sieve | 55.4 | 64.6 | 59.4 |
| Liquid Limit (%) | 27 | 44 | 33 |
| Plasticity Index (%) | 4 | 5 | 15 |
| Maximum Dry Density (lb/ft$^3$) | 115.7 | 100.8 | 116.2 |
| Optimum Moisture Content (%) | 13.7 | 21.3 | 14.0 |
| Resilient Modulus (lb/in$^2$) | 8,000 | 8,500 | 13,500 |

> *“The ability to mix and match input levels is a good feature of Pavement ME.”*
> *– New Jersey DOT*

Pavement ME also utilizes different hierarchical input levels that can be used based on the sources and accuracy of the data. Design-build projects typically use Level 1 inputs while designs for other projects generally include a mix of design input levels. Agencies have different approaches for developing Pavement ME design inputs; some use historical information, and others use a range of laboratory and in situ testing to generate the best possible input values. With the possible exception of design-build projects, a combination of hierarchical input levels for the various design inputs can be expected for most projects. The desired strategy is to use the highest possible input level for the most critical/sensitive inputs. Hierarchical levels are defined as (AASHTO 2020):

- Level 1: Input is measured directly (site- or project-specific) and represents the "greatest knowledge" of the parameter. This level of input also represents designs having "unusual site features, materials, or traffic conditions" outside the inference space used to develop Level 2 and 3 inputs.
- Level 2: Input is "estimated from correlations or regression equations." Inputs for this level also represent non-project-specific or regional values.
- Level 3: Input is "based on best-estimated or default values." Inputs for this level are global or regional default values, typically determined as the "median value from a group of data with similar characteristics."

Workshop participants noted several considerations related to the selection of input level.

- Some inputs are more critical than others, and those inputs need to be based on the best data. Critical inputs are determined through a sensitivity analysis.
- Users have to use what they have, which sometimes means compromising on input level.

## Traffic

Characterization of traffic (e.g., truck traffic volumes by class, growth rates, axle and tire configurations) is one of the most important inputs required for pavement design and analysis. Pavement material selection and thickness determination are in direct response to the anticipated truck traffic loads; therefore, quantification of current traffic and projection of future traffic loadings are essential elements of all pavement design procedures.

Traffic information is typically characterized using weigh-in-motion (WIM), automated vehicle classification (AVC), and vehicle count systems, as described below.

**New Jersey DOT Traffic Library**

Truck traffic loadings have a significant effect on predicted pavement performance. Thus, having the best possible estimates of commercial truck volumes, truck class distributions, axle load configurations, and other traffic characteristics is critical to ensuring a suitable pavement thickness design.

The New Jersey DOT has developed traffic clusters for regions and functional classification. The traffic clusters are based on weigh-in-motion (WIM) data and include axle load spectra, vehicle class distribution, and axle truck ratio. The traffic input files are available for use by in-house staff and design consultants at the New Jersey DOT pavement design and technology webpage. Additionally, Average Annual Daily Traffic (AADT) with truck percentages are available on the New Jersey DOT traffic count stations website. The agency updates its traffic library annually based on research and implementation efforts.

- WIM systems are installed into the pavement surface and continuously measure site-specific axle loads (e.g., number of axles, weight, and spacing) and tire characteristics (e.g., tire pressure and spacing) from which average annual daily truck traffic (AADTT), truck distributions, truck volumes, and other factors can be determined.
- AVC systems can be permanent or portable and can continuously count and classify site-specific vehicle traffic, detect the number of axles, vehicle speed and weight, and other information (e.g., vehicle length, width, height).
- Vehicle count systems are typically portable and continuously count the total number of vehicles in a specified vehicle class.

Since it is not practical to instrument all roadway segments with traffic monitoring equipment, a cluster analysis is conducted that utilizes measured traffic data and applies it to roadways with similar characteristics. Cluster analysis is a multivariate technique that includes data mining and statistical data analysis.

Pavement ME contains default traffic characterization information; however, it was noted in the workshop that the default traffic values are based on higher volume roads and may not apply to low-volume roads. Agencies are quantifying traffic using site-specific WIM data and/or cluster analysis. Pavement ME site-specific traffic inputs are summarized in table 3.

Table 3. Traffic inputs (data source: AASHTO 2020).

| Site Specific | WIM | Non-WIM |
|---|---|---|
| • Initial two-way AADTT obtained from WIM, AVC, or vehicle count.<br>• Percent trucks in the design lane (primary truck class) obtained from AVC or vehicle count.<br>• Percent of trucks in the design direction obtained from AVC or vehicle count<br>• Operational speed.<br>• Truck traffic growth rate.<br>• Lane capacity (estimated from AASHTO Green Book). | • Axle load distribution (single, tandem, tridem, and quads).<br>• Normalized truck volume distributions (used to determine total axle-load distribution with limited WIM data).<br>• Axle spacing and wheelbase.<br>• Monthly distribution factors.<br>• Hourly distribution factors estimated from WIM, AVC, or vehicle count. | • Dual tire spacing (use default value of 12 in. unless predominant truck type has special loading conditions).<br>• Tire pressure (use default value of 120 psi unless known from previous studies or special loading conditions).<br>• Lateral wander of axle loads (default value of 10 in., use 8 in. for roadway widths less than 10 ft, and 12 in. for roadway widths greater than 12 ft).<br>• Truck wheelbase (use 12 ft. for short, 15 ft for medium, and 18 ft for long wheelbases). |

While the accuracy of measuring traffic loadings has improved over the last several decades, predicting future traffic loadings continues to be a challenge (e.g., potential increase in truck weights, changes in axle configurations, expansion of commerce). Before the advent of Pavement-ME, Desai et al. (1986) provided the following in regard to traffic characterization and prediction for pavement design:

- "Good" data may be more valuable than more data.
- Establish traffic sampling plans to obtain representative data.
- Traffic projections should also consider economic, political, and other circumstances (evaluate previous impacts to evaluate potential future impacts).
- Changes in legal load limits, vehicle styles, and loading practices can significantly impact pavement damage.
- Forecasting models should be able to accommodate the amount and reliability of available data.

In addition, the FHWA *Traffic Monitoring Guide* (FHWA 2016) provides information related to "…policies, standards, procedures, and equipment typically used in traffic monitoring programs." The *Traffic Monitoring Guide* also includes appendices for establishing a quality control and acceptance program as well as information on using traffic data for pavement design purposes.

## Materials

Testing for characterizing pavement materials can be an extensive, expensive, and time-consuming process. Pavement ME allows for the characterization of asphalt and concrete mixtures, unbound base/subbase layer, and subgrade soils (see table 4).

> *"Do not underestimate the time and effort required for material testing."*
> *– multiple workshop participants*

Table 4. Material types included in Pavement ME (data source: AASHTO 2020).

| **Bound Materials** | **Unbound Materials** | **Subgrade** |
|---|---|---|
| • Asphalt<br>– Stone matrix asphalt (SMA)<br>– Asphalt concrete (dense- and open-graded, stabilized base, sand asphalt)<br>– Cold-mix asphalt (central plant processed and in-place recycled)<br>• Concrete<br>– Intact slabs (high strength and lean concrete)<br>– Fractured slabs (crack/seat, break/seat, and rubblized)<br>• Chemically stabilized<br>– Cement-stabilized aggregate<br>– Soil cement<br>– Lime cement fly ash<br>– Lime fly ash<br>– Lime-stabilized soils<br>– Open-graded cement-stabilized aggregate | • Granular base<br>• Granular subbase<br>• Sandy subbase<br>• Recycled asphalt pavement (RAP) | • AASHTO Classification<br>– Gravely soils<br>– Sandy soils<br>– Silty soils<br>– Clayey soils |

Hierarchal levels include conducting comprehensive laboratory testing, including deflection testing and backcalculation (Level 1), quantifying based on correlations with known properties (Level 2), and estimating based on experience (Level 3). Based on a study conducted by Schwartz et al. (2011), critical Pavement ME material inputs by pavement type include (inputs identified as hypersensitivity):

- Asphalt Pavement.
  - Dynamic modulus (E*).
  - Thickness.
  - Surface shortwave absorptivity.
  - Poisson’s ratio.
- Jointed Plain Concrete (JPC) Pavement.
  - Slab width.
  - Coefficient of thermal expansion (CTE).
  - Unit weight.
- Continuously Reinforced Concrete (CRC) Pavement.
  - Thickness.
  - Strength and stiffness.
  - Reinforcing steel properties.
  - Unit weight.
  - CTE.
  - Surface shortwave absorptivity.

Workshop participants indicated conducting Level 1 testing to quantify:

- Asphalt Mixtures.
  - Asphalt binder properties.
  - Asphalt mixture properties.
- Concrete Mixtures.
  - CTE.
  - Flexural or compressive strength.
- Bound and Unbound Base and Subbase.
  - Resilient modulus.
- Subgrade.
  - Resilient modulus.

The extent of testing is an agency-based decision and can be influenced by the availability of testing equipment, previous research or test results, and expertise in materials and pavement performance. For example, several agencies noted characterizing asphalt mix properties by testing typical materials obtained from contractors, selecting the most common mix on a regional basis, or using one mix type statewide. Similarly, subgrade resilient modulus was characterized based on past research, project-level resilient modulus and/or falling weight deflectometer (FWD) testing, historical data, or from the database developed by Zapata and Cary (2012).

**Indiana DOT Materials Library**

The Indiana DOT developed input files for various HMA surface, intermediate, and base mixes for use in PMED v2.3. The input files are grouped by the six agency districts and by three SuperPave binders (PG 64-22, PG 70-22, and PG 76-22) and are designated by type/size (9.5, 12.5, 19.0, and 25.0 mm nominal maximum aggregate size) and gradation (dense-graded, gap-graded).

Indiana DOT's HMA input files include Level 2 dynamic modulus data, indirect tensile strength and creep compliance data, binder test data, and other inputs (binder content, air voids, Poisson's ratio, etc.) for each mix. The files are located on the Indiana DOT pavement design webpage.

## Pavement Rehabilitation Properties

Pavement rehabilitation design not only requires characterization of similar inputs for new and reconstructed pavements, but also requires characterization of the existing pavement structure. Rehabilitation design can also be expected to entail much greater variability than new and reconstructed designs. Pavement ME is capable of analyzing the following rehabilitation strategies (AASHTO 2020):

- Asphalt overlays of:
    - Existing asphalt-surfaced pavements (flexible and semi-rigid).
    - Existing fractured slabs (crack/seat, break/seat, and rubblization).
    - Existing concrete pavements (JPC and CRC).
    - Existing composite pavements (asphalt over concrete) and second overlays of original concrete pavements.
    - Seal coats over existing asphalt-surfaced pavements.
    - Interlayers over existing asphalt-surface pavements.
- Unbonded JPC overlays of:
    - Existing intact concrete pavements.
    - Fractured concrete pavements.
    - Existing composite pavements.

- Unbonded CRC overlays of:
  - Existing concrete pavement.
  - Fractured concrete pavements.
- Bonded concrete overlays of JPC or CRC pavements in fair or better condition.
- JPC and CRC overlays of existing asphalt pavements.

Characterization of the existing pavement is essential for quantifying the needed rehabilitation treatment type and thickness. Tables 5 and 6 provide a summary of techniques for characterizing the existing asphalt and concrete pavement structures, respectively, by input level. Specific inputs, by input level, for pavement rehabilitation are summarized in tables 7 through 10 for asphalt, semi-rigid, JPC, and CRC pavements, respectively.

Table 5. Methods for quantifying existing asphalt pavements.

| Activity | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| Condition survey | Cracking, rutting, and raveling | Cracking, rutting, and raveling | Not required |
| Ground penetrating radar (GPR) survey | Layer thickness, subsurface anomalies, and stripping | Not required | Not required |
| Deflection testing | Layer moduli | Layer moduli | Not required |
| Coring and boring | Confirm GPR, stripping, and depth to bedrock and water table | Confirm GPR, stripping, and depth to bedrock and water table | Limited borings |
| Trench studies | Rutting per layer, and crack initiation and propagation | Not required | Not required |
| Dynamic Cone Penetrometer (DCP) testing | Estimate unbound layer in-place modulus | Not required | Not required |
| Subsurface drainage features | Edge drain condition and check for positive drainage | Not required | Not required |
| Laboratory testing | Gradation, Atterberg limits, unit weight, moisture content, and asphalt mix stiffness (strength) | Estimate modulus from DCP and deflection testing for unbound layers, and volumetric properties of bound layers | Not required |

Table 6. Methods for quantifying existing concrete pavements.

| Activity | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| Condition survey | Cracking, faulting, and D-cracking | Cracking, faulting, and D-cracking | Not required |
| GPR survey | Layer thickness, subsurface anomalies, and presence of voids | Not required | Not required |
| Deflection testing | Layer moduli and load transfer efficiency (LTE) | Layer moduli and LTE | Not required |
| Coring and boring | Confirm GPR, presence of voids, and depth to bedrock and water table | Confirm GPR, presence of voids, and depth to bedrock and water table | Limited borings |
| Trench studies | Crack initiation and propagation | Not required | Not required |
| DCP testing | Estimate unbound layer in-place modulus | Not required | Not required |
| Subsurface drainage features | Edge drain condition and check for positive drainage | Not required | Not required |
| Laboratory testing | Gradation, Atterberg limits, unit weight, moisture content, concrete CTE, and concrete strength | Estimate modulus from DCP and deflection testing for unbound layers, and volumetric properties of bound layers | Not required |

Table 7. Rehabilitation design inputs for asphalt pavements.

| Input | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| Transverse cracking (ft/mi) | Length of predominant severity level | Length of predominant severity level | Not required |
| Alligator cracking (% area) | Visual survey, include previous repaired areas | Visual survey, include previous repaired areas | Not required |
| Rutting (in.) | Trench study, each layer | Coring, proportion to each layer | Coring, proportion to each layer |
| Pavement rating | Not required | Not required | Windshield survey (see table 12-1 of MEPDG MOP) |

Table 8. Rehabilitation design inputs for semi-rigid pavements.

| Input | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| Transverse cracking (ft/mi) | Length of predominant severity level | Length of predominant severity level | Not required |
| LTE transverse cracks (%) | FWD testing or based on severity level | Based on severity level | Not required |
| Alligator cracking (% area) | Visual survey, include previous repaired areas | Visual survey, include previous repaired areas | Not required |
| Rutting (in.) | Trench study, each layer | Coring, proportion to each layer | Coring, proportion to each layer |
| Pavement rating | Not required | Not required | Windshield survey (see table 12-1 of MEPDG MOP) |

Table 9. Rehabilitation design inputs for JPC pavements.

| Input | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| Transverse cracked slabs (%) | Visual survey | Visual survey | Visual survey |
| LTE | Good if dowels are present, else poor or use results of FWD testing, good > 60% and test temperature > 80°F | Good if dowels are present, else poor or use results of FWD testing, good > 60% and test temperature > 80°F | Good if dowels are present, else poor or use results of FWD testing, good > 60% and test temperature > 80°F |
| Slab thickness (in.) | Mean thickness from coring or GPR testing | Mean thickness from coring or GPR testing | Mean thickness from coring or GPR testing |
| Joint spacing and skew | Mean spacing from visual survey, add 2 ft if skewed joints | Mean spacing from visual survey, add 2 ft if skewed joints | Mean spacing from visual survey, add 2 ft if skewed joints |
| Shoulder type | Visual survey, if concrete shoulders determine if tied | Visual survey, if concrete shoulders determine if tied | Visual survey, if concrete shoulders determine if tied |

Table 10. Rehabilitation design inputs for CRC pavements.

| Input | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| Punchouts (count/mi) | Visual survey, medium and high severity, include previous repairs | Visual survey, medium and high severity, include previous repairs | Visual survey, medium and high severity, include previous repairs |
| Longitudinal reinforcement (%) | Obtain from as-builts | Obtain from as-builts | Obtain from as-builts |
| Slab thickness (in.) | Mean thickness from coring or GPR testing | Mean thickness from coring or GPR testing | Mean thickness from coring or GPR testing |
| Transverse crack spacing (ft) | Visual survey of mean crack spacing, all severity levels | Visual survey of mean crack spacing, all severity levels | Visual survey of mean crack spacing, all severity levels |
| Pavement rating | Not required | Not required | Windshield survey (see table 12-1 of MEPDG MOP) |

## Climate

Climate data are needed to characterize changes in material properties and their impacts on performance prediction. Pavement ME requires a climate data source that provides continuous hourly data (e.g., temperature, precipitation, wind speed) (AASHTO 2020). Pavement ME includes multiple climate sources including ground-based weather stations, North American Regional Reanalysis (NARR), and Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA-2). Climate data can have a significant impact on predicted pavement performance. When calibrating performance models, agencies should use the same climate source data as used for design and analysis.

The Enhanced Integrated Climatic Model (EICM) is used to simulate the impacts of climate conditions on behavioral changes and characteristics of the pavement and subgrade soils (ARA 2004). Specifically, the EICM computes and predicts the following information over the entire pavement and subgrade profile (ARA 2004):

- Temperature.
- Resilient modulus adjustment factors.
- Pore water pressure.
- Water content.
- Frost and thaw depths.
- Frost heave.
- Drainage performance.

Discussions on climate data during the workshop centered around the available data sources during the calibration effort. It was strongly suggested that agencies calibrate the Pavement ME performance prediction models and conduct designs and analysis using the same climatic database (i.e., calibrate using MERRA, design using MERRA).

The existing models all use past weather records as the climate input for PMED. Roadmap workshop participants remarked on modeling considering future climatic changes. For the initial implementation effort, it is suggested for SHAs to use one of the standard approaches due to the complexity of climatic forecasting.

## PERFORMANCE MODEL VERIFICATION, CALIBRATION, AND VALIDATION

The AASHTO *Guide for Local Calibration of the Mechanistic-Empirical Pavement Design Guide* (*Local Calibration Guide*) provided the procedures and guidance needed to analyze the appropriateness of the global Pavement ME performance prediction models for a given location and, if needed, to develop locally calibrated and validated models (AASHTO 2010). The AASHTOWare CAT is a software package developed to assist agencies in the local calibration of performance prediction models. The CAT assists in determining prediction bias, potential sources of the bias, and optimization of the performance model calibration coefficients.

Pavement ME performance prediction models include:

- Asphalt Pavements and Overlays.
  - Rutting (asphalt layer and total).
  - Transverse (thermal) cracking.

  - Fatigue (alligator) cracking (bottom up).
  - Load-related longitudinal cracking (top down).
  - Reflective cracking.
  - International Roughness Index (IRI).
- JPC Pavements and Overlays.
  - Faulting.
  - Transverse cracking.
  - IRI.
- CRC Pavements and Overlays.
  - Punchouts.
  - IRI.

The following provides SHA information related to the verification, calibration, and validation process for Pavement ME performance prediction models.

## Who Conducts the Effort?

The majority of SHAs reported contracting the work for verification, calibration, and validation of the Pavement ME pavement performance prediction models to consultants and universities. However, one SHA noted that this effort was performed in-house.

Several SHA's agreed that the first calibration effort could be difficult and time-consuming; however, future re-calibration efforts are much easier once the calibration database has been generated (and maintained). The expected time for completing a calibration study can vary, but it generally can be completed quicker in-house than via a contract (due to the time it takes to develop the request for proposal, receive the responses, and execute the contract). However, in-house calibration will likely require shifting staff from other work activities.

**Michigan DOT Calibration Effort**

For the Michigan DOT, Michigan State University reported using the AASHTOWare CAT tool for calibrating the rutting and the faulting performance prediction models and used other statistical tools for calibrating the other performance prediction models. The CAT is a stand-alone, web-based tool that automates the calibration process described in the AASHTO *Local Calibration Guide*. This includes the determination of global model prediction bias (verification), the assessment of bias causes (investigation), the adjustment of model calibration factors to eliminate bias and minimize error (calibration), and the confirmation of the adequacy of the adjustment factors (validation).

## Identify Sensitive Calibration Coefficients

Tables 11 and 12 provide recommendations for adjusting calibration coefficients to eliminate bias and reduce the standard error for asphalt and concrete pavements, respectively. Workshop participant strongly suggested identifying the calibration coefficients that have the highest impact on performance model prediction and adjusting those coefficients accordingly. Additionally, it was advised that the global or local calibration results that give the least bias and the lowest standard error be used, but that a reasonableness check be done to back up the results (i.e., if the best calibration gives unreasonable results, then don't use it and look for alternatives).

Table 11. Recommended calibration coefficients to eliminate bias and reduce standard error in asphalt pavement performance models (AASHTO 2010).

| Distress | Eliminate Bias | Reduce Standard Error |
|---|---|---|
| Total rutting | $k_{r1}$, $\beta_{s1}$, or $\beta_{r1}$ | $k_{r2}$, $k_{r3}$ and $\beta_{r2}$, $\beta_{r3}$ |
| Alligator cracking | $C_2$ or $k_{f1}$ | $k_{f2}$, $k_{f3}$, and $C_1$ |
| Longitudinal cracking | $C_2$ or $k_{f1}$ | $k_{f2}$, $k_{f3}$, and $C_1$ |
| Semi-rigid pavement | $C_2$ or $\beta_{c1}$ | $C_1$, $C_2$, and $C_4$ |
| Transverse cracking | $\beta_{t3}$ | $\beta_{t3}$ |
| IRI | $C_4$ | $C_1$, $C_2$, and $C_3$ |

Table 12. Recommended calibration coefficients to eliminate bias and reduce standard error in concrete pavement performance models (AASHTO 2010).

| Distress | Eliminate Bias | Reduce Standard Error |
|---|---|---|
| Faulting | $C_1$ | $C_1$ |
| Fatigue Cracking | $C_1$ or $C_4$ | $C_2$ and $C_5$ |
| Punchouts (fatigue) | $C_1$ | $C_2$ |
| Punchouts | $C_3$ | $C_4$ and $C_5$ |
| IRI – JPCP | $C_4$ | $C_1$ |
| IRI - CRCP | $C_4$ | $C_1$ and $C_2$ |

## Global Models and Local Calibration

The pavement performance prediction models included in Pavement ME have been globally calibrated (and recalibrated) using several datasets, with the Long-Term Pavement Performance (LTPP) database as the primary data source. As noted in the AASHTO *Local Calibration Guide*, agencies are advised to evaluate and verify the application of the global performance prediction models to local conditions. In the event of disparities between predicted and in-service performance, local calibration is advised.

Workshop participants noted that SHAs can use the globally calibrated Pavement ME pavement performance prediction models and evaluate the designs in relation to their current procedures and expertise. This approach is a simple and low-cost first step involving the use of Pavement ME default inputs and pavement performance prediction models.

## Calibration Reliability Level

The *Local Calibration Guide*, Section 2.2, states that a reliability level of 50 percent should always be used for predicting distresses to confirm or adjust the location calibration coefficients. Although considered to be more of a policy question, most participants seemed to subscribe to this approach.

## Accounting for Variability

Participants agreed that while inputs are often based on averages, it is important to know the input variability. Evaluation of historical information includes a broad assessment with variability and SHAs can use construction documents for the most critical inputs. Variability was viewed as a bigger issue for rehabilitation design than new or reconstructed designs (i.e., there’s greater variability for what’s in place than what is produced).

### Michigan DOT Local Calibration Factors

The Michigan DOT currently uses Pavement ME in conjunction with the 1993 AASHTO Guide. The department has conducted two local calibration studies and has initiated a third calibration effort that will tie in with PMED v2.6.

Michigan DOT’s 2021 User Guide for Mechanistic-Empirical Pavement Design contains the full suite of PMED calibration factors to be used for the design of new flexible pavements and overlays and new rigid pavements and overlays. The coefficients (listed in chapter 6 of the document) are a combination of the globally verified models and locally calibrated models for version 2.3 of the PMED software.

## Selection of Calibration Sites

Pavement calibration sites are needed to evaluate how well the Pavement ME performance prediction models reflect actual performance. Site selection is typically dependent on the representation of typical sections and the availability of needed data. All SHA’s have pavement performance data, however, there are many challenges with identifying and selecting pavement segments as calibration sites and obtaining sufficient good-quality data for analysis. The following suggestions for site selection are provided in the Local Calibration Guide (AASHTO 2010):

- Include sections with the fewest number of structural layers and materials.
- Include sections reflecting typical agency designs covering a range of agency material types and soil types.
- Include sections with new/reconstructed and overlaid pavements.

- Use the same test section for all distress types due to the coupling effect between distresses. Minimum sections by distress type include:
  - Rutting and faulting – 20 sections.
  - Load-related cracking – 30 sections.
  - Non-load-related cracking – 26 sections.
  - Reflection cracking – 26 sections.
- Ensure selected sections have at least 3 years of condition surveys. Ideally, selected sections have a similar number of observations per age to establish quantifiable performance trends.
- Include replicate sections if feasible.

In addition, workshop participants provided the following suggestions related to site selection and data availability:

- Consider the use of construction history, material data, and performance data (pavement management, LTPP, or other research-grade data). Cleanse sites and data to remove:
  - Segments that have received maintenance treatments.
  - Data discontinuities.
  - Segments with significant and unexplainable changes in condition over time.
- For segments without initial IRI data, determine how best to estimate initial IRI. Potentially consider backcasting IRI measurements that were consistent with the ride specification in effect at the time of construction.
- Remove faulting data associated with transverse cracks. The Pavement ME performance prediction model only considered faulting at the transverse joints.
- Examine segments with significant jumps or drops in condition from one year to the next as they could indicate premature distress development, undocumented treatments, or equipment measurement issues.
- Determine the need to “convert” SHA pavement condition data to reflect the pavement distress types used to develop the Pavement ME performance prediction models
- Consider site selection that is representative of current and future designs.
- Evaluate results against successful calibration targets and apply engineering judgment.
- Identify a timeline for future verification, calibration, and validation activities (e.g., additional data, material specification change, implementation of new pavement design).

Workshop participants noted that they typically target and use the pavement management sections associated with the agency’s LTPP sections. Calibration sites, specifically constructed to evaluate Pavement ME, did not appear to be common but were considered preferable.

The Pavement ME performance prediction models were developed and calibrated primarily using data contained within the LTPP database. As a first step, agencies should verify whether the globally calibrated performance models reflect the performance of their in-service pavements. This effort requires the identification and selection of applicable pavement sections, the criteria of which are provided in the *Local Calibration Guide*. In the event the globally calibrated performance prediction models do not reflect in-service pavement performance, local calibration is advised. Efforts for local calibration are also provided in the *Local Calibration Guide* and utilization of the AASHTOWare CAT can assist in identifying and minimizing bias and in establishing calibration coefficients.

## TECHNICAL-LEVEL ACTIVITIES SUMMARY

The following includes a summary of activities identified by the workshop participants for aiding with input parameters and verifying, calibrating, and validating the Pavement ME performance prediction models.

- Traffic characterization data comes down to a choice between WIM or cluster data. Some SHAs indicated only cluster data are needed.
- Backcasting time-series IRI data is one way of obtaining a missing initial IRI value, which can be an important factor in predicting performance.
- Important aspects of the site selection process for calibration studies include establishing an appropriate range of performance data, understanding not all cells in the experimental design matrix will get filled, and identifying sites that have typical performance trends (i.e., removing sites with unique problems).
- Minimize efforts in trying to calibrate coefficients that have little to no effect.
- Be very aware of what each dataset represents and understand their limitations.
- Start using Pavement ME with the global calibration coefficients and compare the results with current procedures and expertise.
- Rehabilitation design can be expected to entail much greater variability than new design.
- With the possible exception of design-build projects, a combination of hierarchical input levels for the various design inputs can be expected for most projects. The desired strategy is to use the highest possible input level for the most critical/sensitive inputs.
- Agencies have different approaches for developing Pavement ME design inputs; some use historical information while others use a range of laboratory and in situ testing to generate the best possible input values.
- When calibrating performance models, agencies should use the same climate source data as used for design and analysis.

# 5.0 CLOSING REMARKS

The *AASHTO Guide for Design of Pavement Structures* served as the official pavement design procedure for most SHAs for many years and continues to be the procedure used by some agencies today. This empirical-based methodology was first developed and circulated in 1961 (under the title *AASHO Interim Guide for the Design of Rigid and Flexible Pavements*) following the completion of the AASHO Road Test in 1960 (AASHTO 1993). Subsequent versions of the Guide were published in 1972, 1981, 1986, and 1993, with each of these versions incorporating a variety of procedural improvements and updated information.

Widespread implementation of the AASHTO Guide did not take place right away. Agencies took the time to learn about the methodology, evaluate its feasibility for use, and assemble the information needed to make it applicable, functional, and reliable for their conditions. Agencies also monitored and evaluated the improvements contained in each new version of the *Guide* and upgraded as they saw fit. While many agencies eventually adopted the 1993 *Guide*, a few adhered to an earlier version.

Nearly two decades have passed since the MEPDG procedure was first introduced and detailed as part of NCHRP Project 1-37A (ARA 2004). While the procedure is much more complicated than the *AASHTO Guide* and requires tremendously more data and information, many of the design concepts are a continuation of those in the *AASHTO Guide*. Moreover, the amount of resources (manuals, software, training courses, webinars, peer exchanges, user group meetings, etc.) that have been made available nationally to support implementation of the MEPDG has been more than proportionate with that of the *AASHTO Guide*.

This Roadmap document represents another resource for SHAs in their advancement to ME pavement design. Agencies are strongly encouraged to consider the information presented as they move forward in their implementation journey. Furthermore, agencies should keep apprised and take advantage of all future educational opportunities, including the following:

- Annual national PMEUG meetings (FHWA- and/or AASHTO-sponsored).
- PMED software training webinars (FHWA- and/or AASHTO-sponsored).
- Pavement ME workshops (FHWA-, AASHTO-, and/or TRB-sponsored).
- AASHTO *MEPDG Manual of Practice* updates.
- AASHTOWare PMED software updates.

Finally, as SHAs progress with their implementation efforts, it is important to ensure that the efforts are in alignment with the established implementation goals and that the goals are in alignment with other business areas (e.g., pavement/asset management, construction, materials, geotechnical). Like most things in the modern world, the technologies, tools, and practices are constantly evolving and the linkages that exist between pavement design and other business areas must be well synchronized for optimum efficiency of the transportation system.

A particularly important linkage is the one between pavement design and pavement management. While it is very challenging to develop a transportation program that optimizes funding for pavements throughout the network and over time, that challenge can be reduced when the performance predictions from Pavement ME (once calibrated and implemented) consistently and closely match the actual performance trends obtained through pavement management. The pavement design–pavement management link requires commonality in performance measures and criteria, shared and continuously updated data sets (design, construction, materials, maintenance, performance, traffic, etc.), and open communication and feedback between the two business areas.

# REFERENCES

American Association of State Highway and Transportation Officials (AASHTO). 2008. *Mechanistic-Empirical Pavement Design Guide: A Manual of Practice, Interim Edition.* Publication No. MEPDG-1. AASHTO, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO). 2010. *Local Calibration of the Mechanistic-Empirical Pavement Design Guide*. AASHTO, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO). 2015. *Mechanistic-Empirical Pavement Design Guide: A Manual of Practice, 2nd Edition.* AASHTO, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO). 2020. *Mechanistic-Empirical Pavement Design Guide: A Manual of Practice, 3rd Edition with 2021 supplement*. AASHTO, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO). 2021. *Supplement to Mechanistic-Empirical Pavement Design Guide: A Manual of Practice, 3rd Edition.* AASHTO, Washington, DC.

American Association of State Highway and Transportation Officials (AASHTO). 2022. *AASHTOWare Pavement ME Design*. AASHTO, Washington, DC.

Applied Research Associates (ARA). 2004. *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures.* Final Report. NCHRP Project 1-37A Transportation Research Board, Washington, DC.

Damschroder, L. J., D. C. Aron, R. E. Keith, S. R. Kirsh, J. A. Alexander, and J. C. Lowery. 2009. "Fostering Implementation of Health Services Research Findings into Practice: A Consolidated Framework for Advancing Implementation Science." *Implementation Science*, 4(1), 50. BioMed Central Ltd.

Desai, H. R., R. Reel, R. C. Deen, H. F. Southgate, R. Noble, V. L. Tabery, M. Hallenbeck, D. Crimmins, and W. Cunagin. 1986. *Traffic Forecasting for Pavement Design.* Report No. FHWA-TS-86-225. Federal Highway Administration, McLean, VA.

Federal Highway Administration (FHWA). 2016. *Traffic Monitoring Guide*. Federal Highway Administration, Washington, DC.

Pierce, L. and G. McGovern. 2014. *Implementation of the AASHTO Mechanistic-Empirical Pavement Design Guide and Software (2014): A Synthesis of Highway Practice*. NCHRP Synthesis 457. National Cooperative Highway Research Program (NCHRP), Washington, DC.

Powell, B. J., T. J. Waltz, M. J. Chinman, L. J. Damschroder, J. L. Smith, M. M. Matthieu, E. K. Proctor, and J. E. Kirchner. 2015. "A Refined Compilation of Implementation Strategies: Results from the Expert Recommendations for Implementing Change (ERIC) Project." *Implementation Science*. 10(1), Article 21. Springer.

Schwartz, C. W., R. Li, S. H. Kim, H. Ceylan, and K. Gopalakrishnan. 2011. *Sensitivity Evaluation of MEPDG Performance Prediction*. Final Report. Transportation Research Board, Washington, DC.

Soo, S., Berta, W., & Baker, G. R. 2009. "Role of Champions in the Implementation of Patient Safety Practice Change." *Healthcare Quarterly*, 12, 123–128.

Virginia Department of Transportation (VDOT). 2017. *AASHTOWare Pavement ME User Manual.* Virginia Department of Transportation, Richmond, VA.

Waltz, T. J., Powell, B. J., Matthieu, M. M., Damschroder, L. J., Chinman, M. J., Smith, J. L., Proctor, E. K., and Kirchner, J. E. 2015. "Use of Concept Mapping to Characterize Relationships among Implementation Strategies and Assess their Feasibility and Importance: Results from the Expert Recommendations for Implementing Change (ERIC) Study." *Implementation Science*, 10(1), Article 109. Springer.

Zapata, C. E. and C. E. Cary. 2012. *Integrating the National Database of Subgrade Soil-Water Characteristic Curves and Soil Index Properties with the MEPDG*. Preliminary Draft Final Report. NCHRP Project No. 9-23B. Transportation Research Board, Washington, DC.