Updates to AASHTOWare Pavement ME Design Software Affecting Concrete Pavements: A Synthesis of the Changes to the Software Related to Concrete Pavements

Final Report
September 2021

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16. Abstract

The American Association of State Highway and Transportation Officials' (AASHTO's) AASHTOWare Pavement ME Design software is based on the Mechanistic-Empirical Pavement Design Guide (MEPDG) methodology and is a comprehensive pavement design software solution in use by a number of state departments of transportation (DOTs). Since its 2013 branding, the software has continued to be modified and improved to incorporate new research and an enhanced quality of data inputs.

This synthesis covers the changes to the Pavement ME Design software as specifically related to concrete pavements. While the changes to the concrete models are minimal as compared to the asphalt models, the changes still have an impact on the results in using the software to design concrete pavements. This synthesis covers these changes and also compares Pavement ME Design to the previous empirical AASHTO pavement design methods.

Readers will gain a better knowledge of the Pavement ME Design software, the changes with the different versions, and the future plans for changes.

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UPDATES TO AASHTOWARE PAVEMENT ME DESIGN SOFTWARE AFFECTING CONCRETE PAVEMENTS

A Synthesis of the Changes to the Software Related to Concrete Pavements

September 2021

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ACRONYMS, ABBREVIATIONS, AND INITIALISMS

AADT	average annual daily traffic
AADTT	average annual daily truck traffic
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
AC	asphalt concrete
ACI	American Concrete Institute
ACPA	American Concrete Pavement Association
ANN	artificial neural network
ARA	Applied Research Associates
AVC	automatic vehicle classification
BcT	Backcalculation Tool
CAT	Calibration Assistance Tool
CBR	California bearing ratio
CD	compact disc
CMS model	climate-materials structural model
COA-B	concrete on asphalt–bonded
COA-U	concrete on asphalt–unbonded
COC-B	concrete on concrete–bonded
COC-U	concrete on concrete–unbonded
CPR	concrete pavement rehabilitation
CP Tech Center	National Concrete Pavement Technology Center
CRCP	continuously reinforced concrete pavement
CRREL	U.S. Cold Regions Research and Engineering Laboratory
CTB	cement-treated base
CTE	coefficient of thermal expansion
DARWin	Design, Analysis, and Rehabilitation for Windows
DCP	dynamic cone penetrometer
DE	differential energy
DOT	department of transportation
DRIP	Drainage Requirement in Pavements
E_c	elastic modulus of concrete
EICM	enhanced integrated climate model
E/RM	elastic or resilient modulus
ESAL	equivalent single-axle load
FE	finite element
FEM	finite element model
FHWA	Federal Highway Administration
FI	freezing index
FWD	falling weight deflectometer
GDOT	Georgia DOT
GMAO	Global Modeling and Assimilation Office
GPS	(JPCP) General Pavement Study
GSFC	Goddard Space Flight Center
HDF	hourly distribution factor

ICM	Integrated Climate or Climatic Model
ID model	infiltration and drainage model
IGGA	International Grooving and Grinding Association
InTrans	Institution for Transportation
IRI	international roughness index
JPC	jointed plain concrete
JPCP	jointed plain concrete pavement
LF	load factor
LTE	load transfer efficiency
LTPP	Long Term Pavement Performance
MDF	monthly distribution factor
MEPDG	Mechanistic-Empirical Pavement Design Guide
MERRA	Modern Era Retrospective Reanalysis for Research and Applications
MoDOT	Missouri DOT
MOP	Mechanistic-Empirical Pavement Design Guide: A Manual of Practice
MOR	modulus of rupture
NALS	normalized axle load spectra
NARR	North American Regional Reanalysis
NASA	National Aeronautics and Space Administration
NCDC	National Climatic Data Center
NCEI	National Centers for Environmental Information
NCEP	National Centers for Environmental Prediction
NCHRP	National Cooperative Highway Research Program
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
Pavement ME Design	Pavement Mechanistic-Empirical Design software
PCC	portland cement concrete
PMED	Pavement ME Design
PO	punchout
RM	resilient modulus
SCF	scaling factor
SEE	standard error of the estimate
SF	site factor
SHRP2	Second Strategic Highway Research Program
SJPCP	short jointed plain concrete pavement
SPS	Specific Pavement Study
TMG	FHWA Traffic Monitoring Guide
TPF	transportation pooled fund
TTC	truck traffic classification
TTCC	Technology Transfer Concrete Consortium
TTI	Texas Transportation Institute
USDA	U.S. Department of Agriculture
UTCOL	ultra-thin concrete overlay
w/c	water-to-cement
WIM	weigh-in-motion

INTRODUCTION

This synthesis provides an overview of the changes to the American Association of State Highway and Transportation Officials (AASHTO) Pavement Mechanistic-Empirical Design (Pavement ME Design) software affecting concrete pavement design. This is not a user's manual or software guide for Pavement ME Design users. You do not even need to be a user of the software to benefit from this synthesis.

This synthesis is intended as a tool to understand the apparent changes in the Pavement ME Design software. This synthesis also provides information on the concrete pavement related aspects of the software for those who have never used the software and those who are new to or existing users of the software.

- For those who have never used the software, the intent is to provide a basic understanding of Pavement ME Design and how it is different from previous pavement design methods.

- For new users, the intent is to provide lessons learned.

- For existing users, the intent is to provide answers on why they hear that nothing has changed with the concrete models, but they still obtain different results with the Pavement ME Design software over time.

Pavement ME Design is based on the Mechanistic-Empirical Pavement Design Guide (MEPDG) (ARA 2004) and is a comprehensive pavement design software solution in use by a number of state departments of transportation (DOTs). The MEPDG was originally developed between 1998 and 2004 as a combination of the best pavement design methods and models available at the time. As compared to the previous AASHTO empirical equations and nomographs that were (and are still) used for pavement design, Pavement ME Design is a very complicated software program with many moving parts. In actuality, real-world pavements are essentially very complicated systems that are affected by many different stimuli, so it makes sense that a model of a pavement system would be complicated.

Report Organization and Content

This synthesis is organized so that, if you are interested in a particular aspect of Pavement ME Design, you can focus on that chapter (i.e., Materials, Climate, Traffic, Concrete Pavements, Local Calibration). This Introduction provides an overall chronology of the Pavement ME Design software changes, introduces the basic premises used for concrete pavement design, and also discusses what has not changed in Pavement ME Design. Tools (e.g., BcT, CAT, DRIP 2.0) that are available for use with the Pavement ME Design software are presented in this Introduction and, in some cases, in more detail in the related section that follows.

The following chapters (Materials, Climate, Traffic, and Concrete Pavements), in turn, also cover the following:

- Pavement ME Design software version changes related to the topic
- General comparison to previous AASHTO empirical methods
- General description of Pavement ME Design as related to the topic

Note that there is not a single AASHTO empirical method, as there were changes in 1972, 1986, 1993, and 1998. Therefore, the comparisons in this synthesis are, in most cases, in general terms not related to a specific version.

The Local Calibration chapter is a discussion on the importance of local calibration and the lessons learned due to local calibration efforts. Similarly, the MEPDG User Group chapter identifies highlights of the lessons learned and shared at the user group meetings.

The final chapters describe the research currently in progress or recently completed that has not been incorporated into Pavement ME Design as yet. The Research in Progress chapter also includes some ideas for potential future research needed, especially in the concrete pavement area. As you will see, Pavement ME Design now consists of models that are 20+ years old, so additional research is definitely needed.

Terminology – Pavement ME Design, MEPDG, and MOP

The terms MEPDG, DARWin-ME, PMED, Pavement ME, and MOP all are or were associated with what is now the current AASHTOWare Pavement ME Design software. The software itself over time has been called MEPDG, DARWin-ME, Pavement ME, and PMED.

- **MEPDG** stands for Mechanistic-Empirical Pavement Design Guide. The original NCHRP 1-37A report was titled Guide for Mechanistic-Empirical Pavement Design, and the software was known as the Mechanistic-Empirical Pavement Design Guide software or MEPDG for short (ARA 2004).

- **DARWin** was the name for the AASHTO software for the Windows version of the 1993 AASHTO Guide for Design of Pavement Structures. DARWin stands for Design, Analysis, and Rehabilitation for Windows.

- **DARWin-ME** is the name AASHTO originally used for the MEPDG software. When AASHTO took over the new MEPDG software from the National Cooperative Highway Research Program (NCHRP), they added ME for mechanistic-empirical to the name of their existing pavement design software. The DARWin-ME software was rebranded (renamed) as **AASHTOWare Pavement ME Design** in 2013. (Note PMED was just a branding name change and the last version of DARWIN-ME was the same as the first version of PMED).

- **AASHTOWare Pavement ME Design** is the current name of the software developed originally from the MEPDG software and **PMED** is the acronym used in the current Manual of Practice (MOP).

- **MOP** is the Mechanistic-Empirical Pavement Design Guide: A Manual of Practice. The current version of the MOP is version 3, last updated in 2020. First produced in July 2008, as an interim 1st edition, it is intended to guide the designer in making decisions for the proper use of the software. The 2nd edition was published July 2015 and the 3rd edition in 2020. The 2nd edition combined Chapters 5 and 6. Other changes mainly involved correcting original errors, making general updates, and revising the software name to AASHTO PMED. The 3rd edition included major model changes and additions (especially for flexible pavements), changed a number of calibration factors, and added functionality, including the new short jointed plain concrete pavement (SJPCP) design.

Both MEPDG and PMED are often still seen used interchangeably, but this document considers that **MEPDG** is the methodology that is used by the **Pavement ME Design** software and described in the **MOP**, where the software is referred to as PMED for short. So MEPDG is the models, algorithms, and transfer functions, etc. Pavement ME Design or PMED is the actual software, and MOP describes the MEPDG method utilized by the Pavement ME Design software. (To further complicate matters, prior to AASHTO formally adopting the software, both the software and the models were known as MEPDG and the current MOP also refers to itself as the MEPDG in places.) See Appendix A for details on the history before AASHTO.

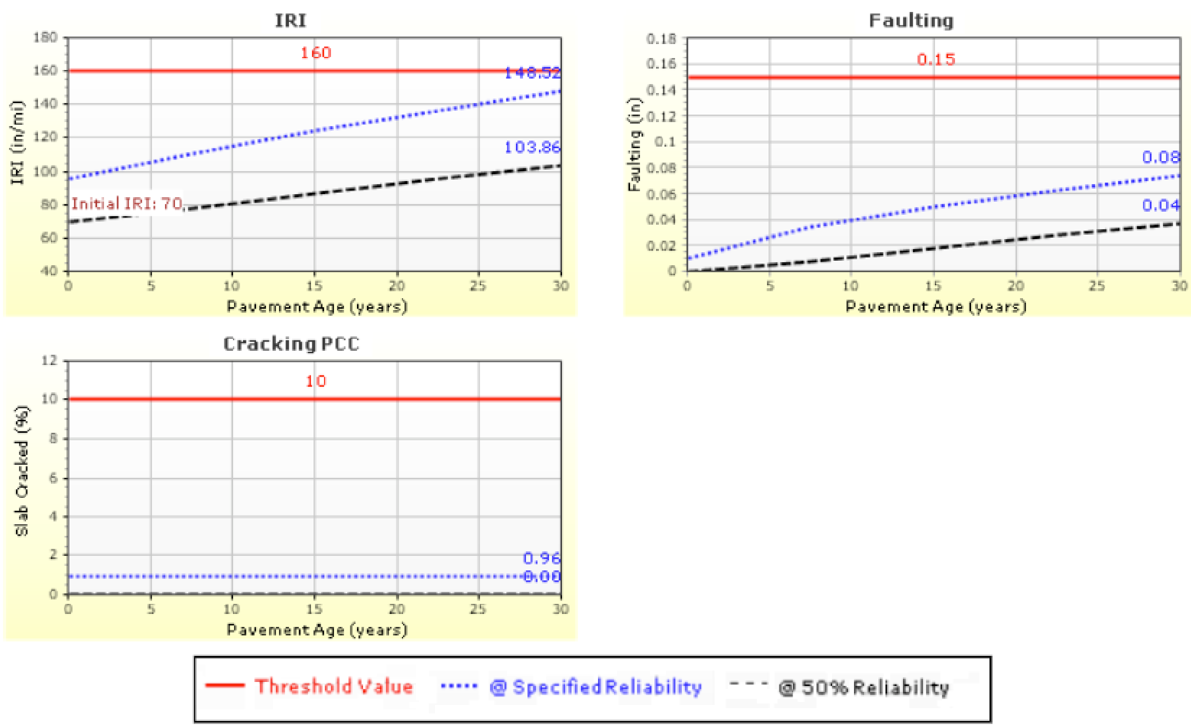
The Pavement ME Design software creates a .dpgx file for storage of inputs, called a project. After running a project, the software produces a project folder with a large number of output files. The main output is a multipage (~16 pages) pdf report, which includes the outputs (results) along with the inputs and calibration factors used in the design. Figure 1 is an example of the design output shown for a jointed plain concrete pavement (JPCP) in a .pdf report.

Design Outputs

Distress Prediction Summary

Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in/mile)	160.00	148.52	90.00	94.64	Pass
Mean joint faulting (in)	0.15	0.08	90.00	99.99	Pass
JPCP transverse cracking (percent slabs)	10.00	0.96	90.00	100.00	Pass

Distress Charts



AASHTOWare Pavement ME Design, used with permission

Figure 1. Sample Pavement ME Design output

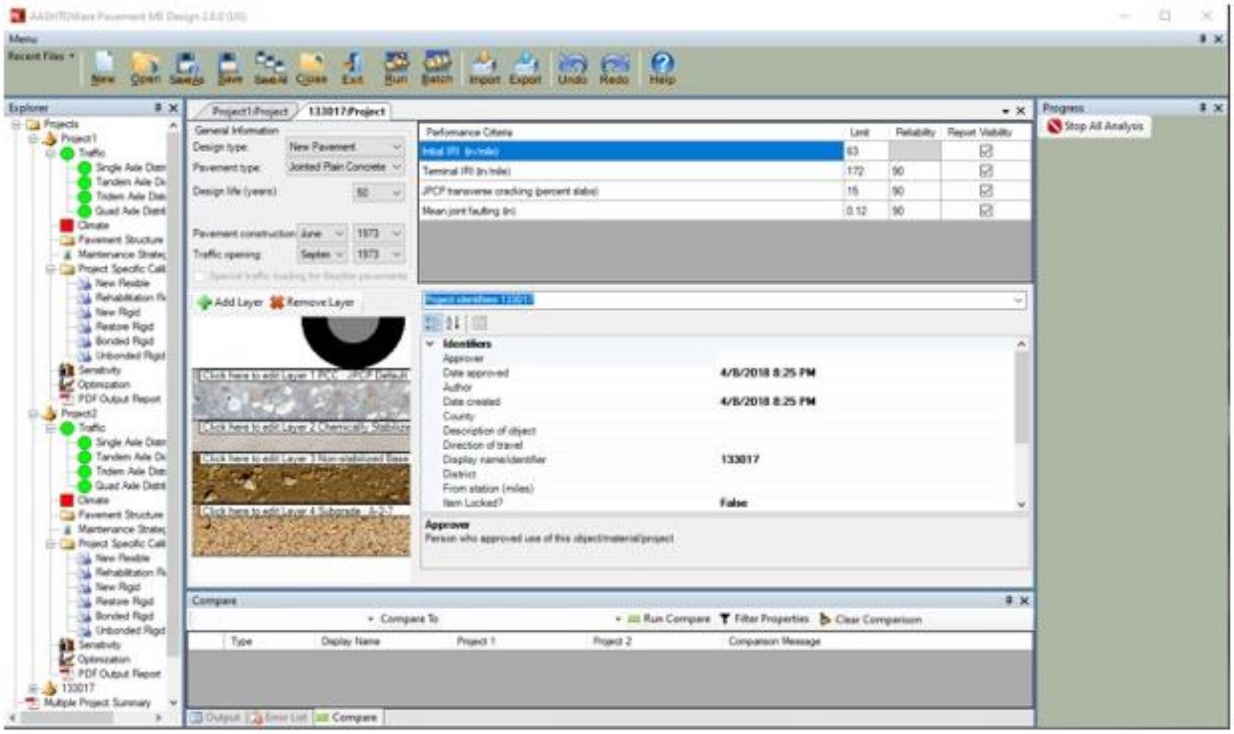
A large number of additional files (more than 50 files, .csv, .txt, and others) also populate the output folder. These files can be used to look at the results in more detail or for local calibration purposes.

The next section presents the chronology for the AASHTOWare Pavement ME Design software.

History of AASHTOWare Pavement ME Design

This section provides an overview of the general changes and/or versions of the AASHTO Pavement ME Design software from early 2013 up to early 2021.

- AASHTOWare Pavement ME Design v2.6, shown in Figure 2, is the current version of the software, released July 1, 2020.



AASHTOWare Pavement ME Design, used with permission

Figure 2. AASHTOWare Pavement ME Design v2.6 software

- The Mechanistic Empirical Design Guide: A Manual of Practice (MOP), 3rd edition with 2021 supplements is the current version of the MOP.

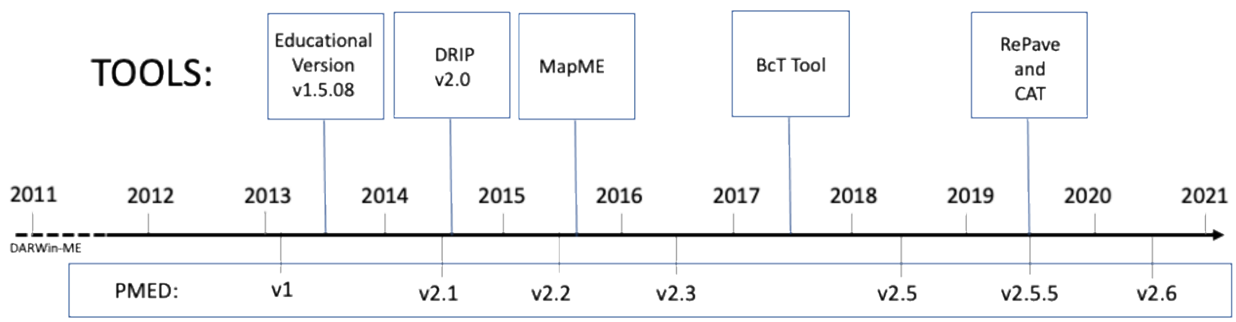
Some of the models from the original NCHRP 1-37A MEPDG research have changed over time (primarily on the flexible pavement side), with the latest version of the MOP (3rd edition) documenting the changes up through the end of 2018 (Pavement ME Design version 2.5.3).

The software that is now called AASHTOWare Pavement ME Design, or Pavement ME Design for short, was developed over time under the guidance of the AASHTO Joint Technical Committee on Pavements (now a Technical Subcommittee of the AASHTO Committee on Material and Pavements) from a number of NCHRP research projects, starting with NCHRP Project 1-37 in 1996.

NCHRP Project 1-37 got the discussion started on a more advanced pavement design method and led to NCHRP 1-37a, which produced the original software, methods, and the Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures (ARA 2004). The versioning of the MEPDG software was standardized in 2013 when it was rebranded under the AASHTOWare name as AASHTOWare Pavement ME Design. An educational version was also first released in 2013. Version 2 was released in July 2014, and the software has been changed in some way each year since then. This year (2021) may be an exception as the next version will be a key transformation that will take time. The next major change is anticipated to be a web-based version of the software currently anticipated to be released in July 2022.

Summary of Major Changes in the Software Related to PCC Pavements

Figure 3 shows the timeline of major versions of Pavement ME Design as affecting concrete pavements and when tools were added to the website.



Georgene Geary

Figure 3. AASHTOWare Pavement ME Design chronology for concrete pavements

Tools are related software programs outside of the Pavement ME Design software. The tools are not required to run the Pavement ME Design software, but each adds certain capabilities.

Each of the versions and the tools are described in more detail in the following section.

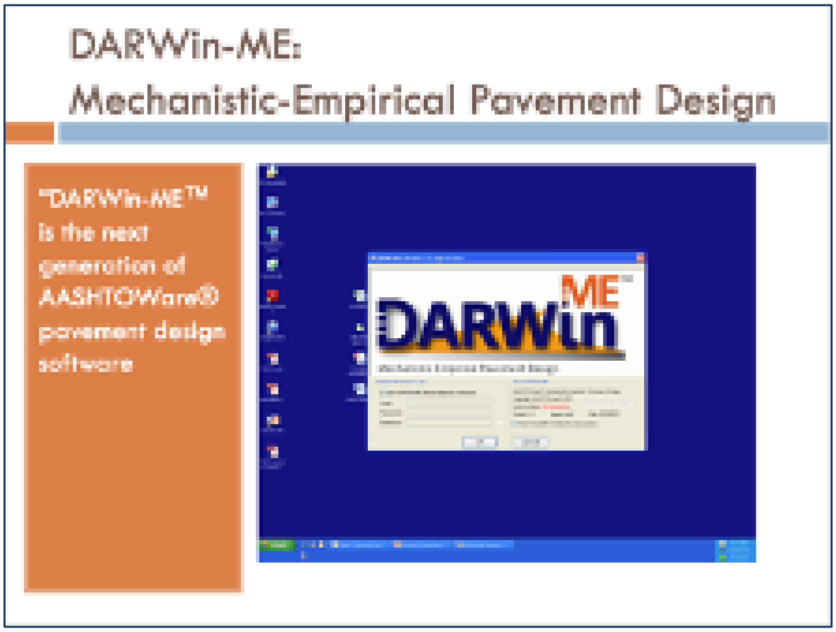
AASHTOWare Pavement ME Design Updates and Tools by Year

This section describes in more detail the changes shown in Figure 3. This includes AASHTOWare Pavement ME Design and ancillary tools added to the AASHTO website. The Appendix includes Table B.1 that identifies the Pavement ME Design versions and whether recalibration was/is necessary, and Table B.2 that describes the webinars on the https://me-design.com/MEDesign/ website and what changes are covered in each webinar.

Prior to 2013

A research version of the MEPDG software was released on compact disc (CD) by NCHRP for review by state agencies in June 2004. The first MOP was released in 2008 as an interim edition. The Guide for the Local Calibration of the MEPDG was released in 2010. The first version of AASHTO software based on the MEPDG was released in 2011 under the name AASHTO DARWin-ME. It was based on the research version of the MEPDG, with some additional user interface improvements. AASHTO added the ME at the end of the name to differentiate it from their existing pavement software, DARWin 3.1. The existing AASHTO Windows-based pavement DARWin software at the time (the one without the “ME”) was based on the AASHTO

Empirical 1993 Design Guide. Figure 4 is from a presentation in Burlington, Vermont, at the Annual AASHTO Materials meeting in 2011 where the DARWin-ME software was introduced to the Subcommittee on Materials. (See Appendix A for additional details on history prior to 2013.)



AASHTOWare DARWin-ME, used with permission

Figure 4. DARWin-ME software opening screen

2013: AASHTOWare Pavement ME Design v1

Based on an effort to brand all the AASHTO software consistently, the DARWin-ME name was changed to AASHTOWare Pavement ME Design in early 2013. This also was a time when the MEPDG was coming into more use by state DOTs. The Federal Highway Administration (FHWA) sponsored a series of 10 educational webinars starting in late 2012 and going through 2013 to educate users on the software. Figure 5 is from one of the early webinars, where the pending software name change was discussed.

AASHTOWare Pavement ME Design and DARWin-ME, used with permission

Figure 5. DARWin-ME and AASHTOWare Pavement ME Design logos

The webinars cover a range of topics involving the software including climate, traffic, materials, new pavements, and overlays. The webinars are posted on the https://me-design.com/MEDesign/ website and discussed more in Appendix B.

Pavement ME Design Educational Version

A limited functionality Pavement ME Design version was released for use by universities for training purposes in 2013. The education version is free for university use for training purposes only and has a limited number of seats (25) per professor. The educational license must be applied for each year. In the 2020 ME Users Group meeting, it was noted that 55 educational licenses were issued in that year, up from 39 reported in the 2017 ME Users Group meeting (APT 2018).

2014: Pavement ME Design v2.1

The 2014 version of the software included some bug fixes for portland cement concrete (PCC) pavements and the ability to vary subgrade moduli for the Sensitivity analysis function.

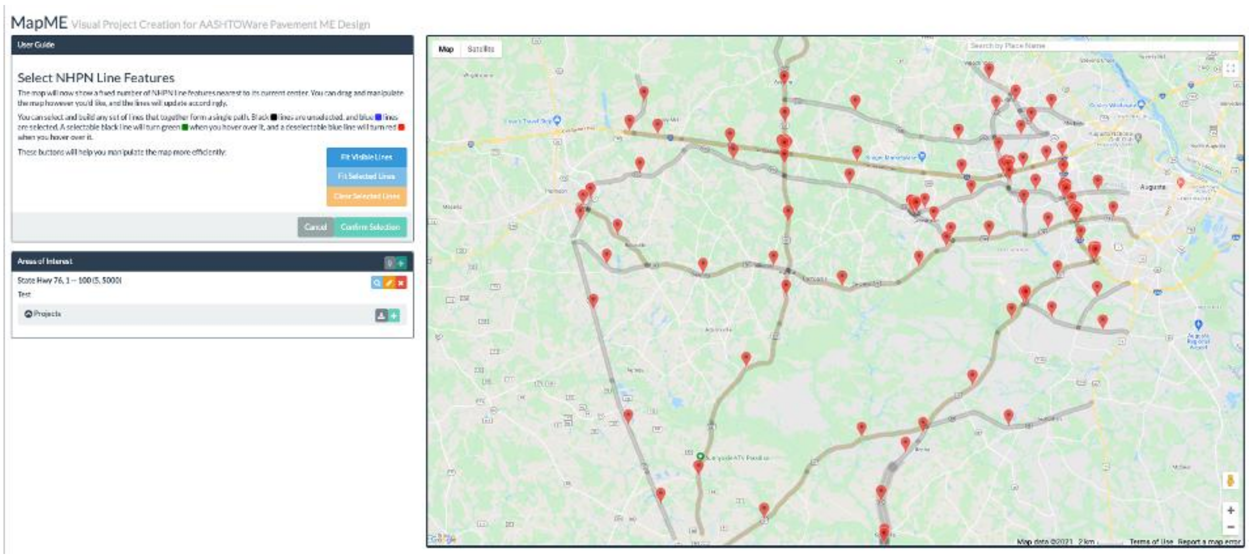
- The Sensitivity function allows the user to run a number of different software runs with varied input values in batch mode to compare the results. The ability to also vary subgrade moduli was added in v2.1.
- DRIP 2.0 was added as a TOOL to the website.

2014 was also when three webinars that went into detail on local calibration were presented. These webinars are also located on the website and discussed more in Appendix B.

2015: Pavement ME Design v2.2

Version 2.2 included a major change for PCC pavements as follows:

- Incorporated the new global calibration factors based on the corrected coefficient of thermal expansion (CTE) values (see Materials chapter for details)
- Added three default normalized axle load spectra (NALS) (see Traffic chapter for details)
- Modified some capabilities of modeling existing structures for PCC overlays over asphalt (see Concrete Pavements chapter for details)
- Added MapME, a tool to gather available data geographically for a .dpgx file (see Figure 6).



AASHTOWare Pavement ME Design, used with permission, Map data ©2021 Google INEGI

Figure 6. MapME interface

2016: Pavement ME Design v2.3

Version 2.3 included climate input changes that could affect concrete pavements and added a new model for SJPCPs.

- The climate data were improved by adding North American Regional Reanalysis (NARR) files. In some cases, this can cause large differences between the results of the previous version, potentially due to the old climate data being incomplete (see Climate chapter for details).
- The SJPCP option was added (see Concrete Pavements chapter for details).

*2017: Pavement ME Design v2.4**

No Release Notes were issued for what is termed v2.4 in some documents. The software version was noted as v2.3.1 on the website, not v2.4* (APT 2018). BcT 1.0 was released at the time a v2.4 would have come out.

2018: Pavement ME Design v2.5

Version 2.5 changes did not affect concrete pavements unilaterally, but some changes could affect concrete pavement design.

- The previous version only provided an option for designs up to 50 years, while v2.5 allowed designs up to 100 years. A software bug in the faulting model prevented bonded overlay designs (PCC over PCC or continuously reinforced concrete pavement [CRCP]) from running the full 100 years, but this was corrected in an October update (v2.5.3).
- Semi-rigid pavements (asphalt over chemically stabilized bases) were calibrated for the first time.
- A comparator tool was added that allows the user to compare .dgpx files to identify differences in design files.
- A preventive maintenance function was also added. This allows the user to reset the international roughness index (IRI) and faulting to a lower level to mimic the effect of diamond grinding (described in the MOP Section 3.4).
- An April 8, 2019 enhancement (v2.5.4) updated the climate user interface to add the familiar Google Maps background (see Climate chapter for details).

2020: Pavement ME Design v2.6

No changes to concrete models were made in the 2020 version, but some improvements were made to speed and some bug fixes were accomplished, along with some major asphalt pavement model updates (which are not covered in this report).

Versions, Global Calibration, and Webinars

Appendix B includes two tables also related to the different versions of the software. Table B.1 identifies the changes by version and whether or not the change was such that it required a global recalibration. The table also notes if an official Release Note or Addendum is associated with the version. Table B.2 identifies the associated Pavement ME Design training webinars. The Release Notes, Addendums, and webinars can all be found on the https://me-design.com/MEDesign/ website.

Tools

Outside of the Pavement ME Design software, a number of tools may be used as part of pavement design. These tools are also located on the https://me-design.com/MEDesign/ website and are described in this section. The previous Figure 3 included tools and dates when the tools were first added to the website.

- **XML Validator:** Custom .xml files can be created to input Climate, Traffic, or falling weight deflectometer (FWD) data into the Pavement ME Design software. The XML validator provides a check for errors in the data format or data values (outside absolute or recommended ranges) of these files. Currently there are separate tabs for v2.3 and v2.5 of the Pavement ME Design software.

- **DRIP 2.0:** Drainage Requirements in Pavements (DRIP) is a Windows based microcomputer program, created by the FHWA and Applied Research Associates (ARA) to perform hydraulic design computations for the subsurface drainage analysis of pavements (see the Drainage section later in this chapter).

- **MapME:** MapME links to a separate website where a user can create and download a Pavement ME Design project file (.dpgx) prepopulated with climate, traffic, and subgrade soils data based on the location and type of pavement selected, as shown in the previous Figure 6. MapME uses several different sources for the data, including soil information from the U.S. Department of Agriculture (USDA) National Resources Conservation Services.

- **RePave:** The RePave Scoping Tool was developed during the Second Strategic Highway Research Program (SHRP2) research effort. RePave is focused on best practices for rehabilitation of existing pavements for long life.

- **CAT:** The Calibration Assistance Tool (CAT) allows the user to submit design files and performance data and look at the predicted versus measured performance for cracking and faulting of jointed plain concrete (JPC) and punchouts for CRCP (see the Local Calibration chapter for more details.)

- **BcT:** BcT is a backcalculation tool for use with FWD data. The tool was upgraded to Build v1.0.4 in June 2020 and v1.0.6 in December 2020 (see the Materials chapter).

Pavement Performance Models Used for PCC Pavements

MEPDG is an iterative process that predicts specific pavement distresses over time, based on stresses including environmental effects and traffic. The final distresses that are predicted are pavement type dependent. The distresses predicted for the different types of PCC pavement are as follows:

- JPCP = transverse cracking, faulting, IRI
- SJPCP = longitudinal cracking
- CRCP = punchouts and IRI

When using the iterative process to develop an optimized slab thickness, computed design thicknesses for the concrete slab can be driven by the different distress models (i.e., cracking, faulting, or IRI). This can lead to potentially unusual results. The mode of failure should always be considered when identifying design life. Some states are only looking at cracking distress as a failure mode for thickness design.

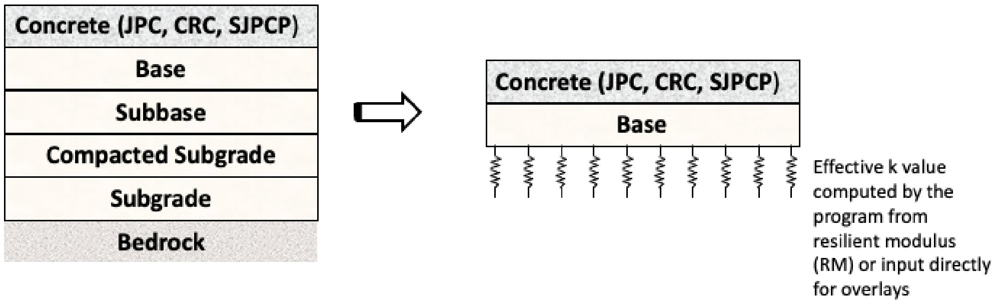
The predicted pavement distresses (cracking, faulting, punchouts, IRI) are empirically adjusted to more accurately align with actual pavement section distress observed in the real world. The Long Term Pavement Performance (LTPP) database, which includes time history data for thousands of pavements in the US and Canada, was used to globally calibrate the asphalt and concrete models so that the distresses that are predicted align with the observed distresses in real world pavements (FHWA 2020). The pavement sections used for calibration should resemble the pavement sections actually used as much as possible; that is why local calibration, using local data, is also used to more accurately align predicted and measured results for agencies.

Algorithms and Models Used for PCC Pavements

NCHRP 1-37A documentation goes into detail on the methods used to develop the algorithms and models used in the MEPDG for JPCP and CRCP. Only a general overview of the algorithms and models used for JPCP and CRCP and SJPCP are presented in this document (in the Concrete Pavements chapter). The original MEPDG documentation (ARA 2004) can be consulted for more detailed background information.

The models and equations for JPCP and CRCP have not changed from the NCHRP 1-37A documentation. An SJPCP model was added to the software in version 2.2.3. The model predicts longitudinal cracking instead of transverse cracking, but it was implemented in the software in a similar manner to the original JPCP cracking model. The SJPCP addition was based on work by the University of Pittsburg (Li and Vandenbossche 2013).

Materials degradation or materials related distresses (i.e., alkali-silica reactivity [ASR] or D-cracking) of the concrete slab is not considered in the MEPDG design process. Concrete pavements are modeled as "an equivalent structure of PCC slab, base, and an effective dynamic k-value" (ARA 2004 MEPDG Chapter 4) as shown in Figure 7.



Christopher et al. 2006, derived from NHI course on Geotechnical Aspects of Pavements

Figure 7. Representation of layers below the base in concrete pavements

The resilient modulus of the subgrade is converted into a modulus of subgrade reaction (k value) by the software. Any subbase or compacted subgrade are also used to convert the k value into an effective k value. The effective k value is computed for new designs based on the properties of the subbase and subgrade layers, but it is a direct input for rehabilitation designs. The effective k is modeled as a spring and is noted as representing the compressibility of the layers beneath the base.

See the Concrete Pavements chapter for additional details on the design of concrete pavements in Pavement ME Design.

What has not Changed in Pavement ME Design?

Basic Mechanistic Models for Cracking and Faulting

Although the name of this document is Updates to AASHTOWare Pavement ME Design Software affecting Concrete Pavements: A Synthesis of the Changes to the Software Related to Concrete Pavements, there really have not been any changes to the actual concrete pavement related models from the original research project that identified and compiled them into a software tool.

The inversely proportional relationship of cracking to fatigue damage (AASHTO 2020 MOP Equation 5-19) is used both for concrete and asphalt fatigue cracking. Miner’s hypothesis is also used for both asphalt and concrete fatigue. It is a linear relationship between allowable and applied loads to failure.

The calculation of IRI has changed slightly from the original NCHRP 1-37A documentation, but the changes were early, before the first version of the Pavement ME Design software and even before the first edition of the MOP. While the global calibration values for cracking and faulting have changed, the global calibration factors for the computation of IRI have not changed from the first edition of the MOP.

The original NCHRP 1-37A research project was designed to gather the best available existing mechanistic models for pavement design and produce a document and software tool that could be used with those existing models. The scope of NCHRP 1-37A specifically noted that it did not include new research for new models. As the original documentation is now more than 17 years old (with the NCHRP 1-37A report dated from June 2000–March 2004 and the research grade software first released in 2004), the models have not changed, so we are currently still using decades old technology. (Note that the first iphone was released in 2007!)

Although the models have not changed in almost two decades, improvements have been made, and our understanding of the models that the software uses have advanced. The models and software are composed of numerous elements, with some being intertwined. Due to the variety of inputs and the potential interrelation, the models and software can produce unusual results at times.

Drainage

The AASHTO 93 and 98 empirical methods addressed drainage in concrete pavements by the use of the AASHTO drainage coefficient, C_d. The concrete pavement design equation used in the 1993 Guide is shown in Figure 8.

$$log_{10}W_{18} = Z_R * S_0 + 7.35 * log_{10}(D+1) - 0.06 + \frac{log_{10}\left[\frac{\Delta PSI}{4.5-1.5}\right]}{1+\frac{1.624*10^7}{(D+1)^{8.46}}} + [4.22 - 0.32 * p_t] * log_{10}\left[\frac{S_c' * C_d * [D^{0.75} - 1.132]}{215.63 * J\left[D^{0.75} - \frac{18.42}{\left(E_c/k\right)^{0.25}}\right]}\right]$$

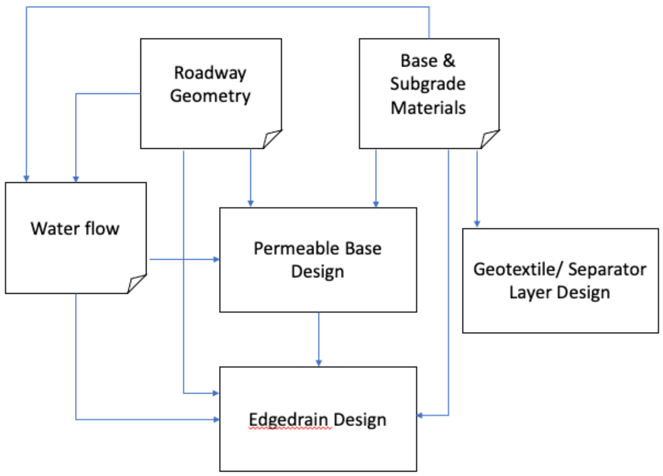
Figure 8. AASHTO 93 concrete pavement design equation

AASHTO 93 noted that C_d was an adjustment factor (C_d varied from 0.7 to 1.25) that accounted for “the effect of moisture on subgrade strength and on base erodibility (for concrete pavements)” (AASHTO 1993).

Pavement ME Design, like the research version of the MEPDG, assumes that drainage is addressed outside the software. The depth to water table and environmental effects on unbound materials do have an effect on pavement design, but the software itself does not directly consider drainage (like ditches for rural sections or storm drains for urban sections). A desire to incorporate drainage into Pavement ME Design has been expressed at previous ME User Group meetings (APT 2018). The DRIP tool does address drainage, but it is a separate program, listed as a Tool on the https://me-design.com/MEDesign/ website. The DRIP 2.0 tool is briefly described in the next section.

DRIP 2.0

DRIP 2.0 is available on the https://me-design.com/MEDesign/DRIP.html website under Tools for download without the requirement of being a Pavement ME Design user. The User's Guide link for DRIP 2.0 on the website brings up Appendix TT of the original NCHRP 1-37A project. Appendix TT provides the general flow of the software as shown in Figure 9.



After ARA, Inc., ERES Consultants Division 2004, NCHRP Project 1-37A Appendix TT

Figure 9. DRIP general flowchart

The figure shows the interconnectedness of the inputs and outputs. It also shows that the program can consider roadway geometry, base and subgrade materials, and water flow. From these inputs, the program can design permeable bases, edgedrains, and a geotextile separator layer. There is also an archived DRIP 2.0 user manual with three example problems located on the FHWA website at: https://www.fhwa.dot.gov/pavement/pub_details.cfm?id=43.

Since the MEPDG assumes drainage is covered separately, DRIP was added to the website to provide a method outside the Pavement ME Design software to address drainage. The software has the following capabilities:

- Computations:
  - Drainage path on the roadway
  - Porosity of base and subgrade
  - Surface infiltration

- Design:
  - Permeable bases
  - Geotextile or aggregate separator layers
  - Fin or pipe edgedrains

Note that the DRIP software on the website was also last updated as part of NCHRP 1-37A in the early 2000s.

Sensitivity Analysis in the Pavement ME Design Software

The Pavement ME Design software has had a function called Sensitivity from the first version. For concrete pavements, the user can vary average annual daily truck traffic (AADTT), slab thickness, width, and spacing, dowel diameter, CTE, and modulus of rupture (MOR). The ability to also vary the modulus for base and subgrade was added in v2.1. This provides the user the ability to conduct a mini-sensitivity study for a project. Note that it can take extensive time to run if several variables are chosen.

The following three chapters (Materials, Climate, and Traffic) cover the main inputs into Pavement ME Design.

MATERIALS

> **Version 2.2 Change Related to Materials**
>
> A major change related to materials occurred with v2.2 of the software released in 2015. The change involved a complete recalibration of the cracking and faulting models due to the CTE values that were used in the initial global calibrations. The CTE issue is discussed more later in this chapter.

General Difference Between MEPDG and Previous AASHTO Empirical - Materials

AASHTO Empirical: The previous empirical AASHTO Pavement design method used limited material inputs, being limited somewhat to the types of materials used in the full scale pavement tests upon which the empirical equations were based. The Pavement ME Design software greatly increased the ability to characterize materials for pavement design. It is anticipated that this will allow evaluation of newer materials or deviations from existing materials in a quantitative manner.

AASHTO 93 and 98 inputs for PCC included the 28-day MOR (for flexural strength), elastic modulus, and Poisson's ratio. Of these, MOR had the most importance, as the other two were typically defaults (AASHTO 1993, AASHTO 1998). Pavement ME Design uses these three values as inputs but also includes 16 others.

MEPDG: Materials inputs in Pavement ME Design have hierarchical levels (1, 2, and 3), which identify the amount of specific information known. Level 1 is the most information (from actual laboratory testing), and Level 3 is the least information (from estimation and defaults). Pavement ME Design uses the inputs of MOR, elastic modulus, Poisson's ratio, unit weight, air content, CTE, cement type, water-to-cement (w/c) ratio, curing method, and 10 other inputs.

Concrete Surface Layer (JPCP, SJPCP, CRCP)

Pavement ME Design inputs consist of 19 different values related to concrete surface materials, which include general mixture and thermal/shrinkage properties (AASHTO 2020 MOP Tables 10-4 and 10-5). Level 1 testing for elastic modulus and strength involves inputting time-based values (i.e., 7, 14, 28, and 90 day test results) for flexural strength and elastic modulus. Inputs are based on expected mean values at the time of construction, not minimum values.

Testing PCC for 19 different properties would be onerous, and some of the properties do not even have testing protocols (i.e., PCC zero-stress temperature). In addition, in most typical design-bid-build situations, the exact materials that will be used are unknown; usually only a range from past projects or a minimum from the specifications is really known. So, in most cases, a combination of Level 1, 2, and 3 are used for the material values, and some of the values actually used are defaults based on specifications or estimates based on other values that are input. But the inclusion of the different properties allows potential modeling of newer materials with different combinations of properties.

Pavement ME Design allows input of actual time-based material testing values. Values can be input for MOR and elastic modulus (Level 1) or compressive strength, f'_c (Level 2). Values for 7-day, 14-day, 28-day, 90-day, and the ratio of 20-year to 28-day strength can be directly input. Typically, 1.4 is used for the ratio of 20-year to 28-day strength. While flexural strength, elastic modulus, compressive strength, or some combination are all commonly tested materials inputs for PCC that would be directly input, in most cases, they will be input just for the 28-day test values (Level 3).

When Level 3 input is used, the time dependency equations built into the software are used. The significant part of this is that the method computes incremental damage using the time-dependent values of MOR and E_c, so it uses a default age-related equation to estimate changes if time-dependent values are not input. Another important input that will be discussed in more detail is the CTE.

While there is a focus in the concrete pavement industry on performance engineered mixtures (PEMs) for concrete pavement, which include optimized gradation, Pavement ME Design does not provide for direct gradation inputs for PCC mixes (while it does have this capability for asphalt mixes). Pavement ME Design does include some mixture properties, like unit weight and w/c ratio. Generally speaking, the inputs of most importance to Pavement ME Design for concrete surfaced pavements (JPCP, CRCP, SJPCP) are related to concrete strength (MOR), stiffness (elastic modulus or E_c), and thermal (CTE) properties. Additional information on the most common tests used for these inputs follow.

PCC Material Properties

Strength

- MOR/flexural strength – AASHTO T 97 (ASTM C78) third-point loading beam test, which loads a simply supported beam at two points spaced at 1/3 the length, such that the beam is contacted four times
    - AASHTO T 177 (ASTM C293) center-point load beam test (also known as the three-point beam test, which loads a simply supported beam at one point spaced at 1/2 the length, such that the beam is contacted three times) must be converted to equivalent T 97 values to use in Pavement ME Design given that T 177 results will be much higher than T 97 values
    - Compressive strength, f'_c – AASHTO T 22 (ASTM C39) is considered Level 2 and the software converts it to MOR

- CRCP also uses indirect tensile strength – AASHTO T 198 (ASTM C496) splitting tensile strength for mean transverse crack spacing used in punchout estimation

Stiffness

- Elastic modulus (E_c) – ASTM C469 can also be found using equation (1) where unit weight is assumed to be 144 pcf.

$$E_c \cong 57{,}000 \sqrt{f_c'} \qquad \textbf{(1)}$$

Thermal

- CTE – AASHTO T 336

The MEPDG documentation (ARA 2004 MEPDG Part 2 Chapter 2) uses the American Concrete Institute (ACI) equations for normal strength concrete to convert between E_c, f'_c, and MOR, as shown in equations (2) and (3) (where ρ = unit weight, pcf).

$$f_c' = \left(\frac{MOR}{9.5}\right)^2 psi \qquad \textbf{(2)}$$

$$E_c = 33\, \rho^{3/2}\, (f_c')^{\frac{1}{2}}\, psi \qquad \textbf{(3)}$$

- Note that the equation for E_c (equation 1 under Stiffness) uses 57,000, since it assumes the density is 144 pcf and 33×(144 pcf)$^{3/2}$ = 57,000.

Compressive strength (f'_c) is the most familiar test to concrete engineers and has been found to typically provide the most consistent testing result trends over time as compared to MOR or E_c. This may be a result of the inherent variability in the tests themselves and/or the simple fact that f'_c is the more common test in use. Researchers have still recommended using 28-day MOR and 28-day E_c testing values instead of f'_c for concrete inputs to Pavement ME Design (Schwartz et al. 2011).

It has been noted in the research that the standard ACI equations (1, 2, and 3 above) are based on all types of concrete, not just pavement concrete, so the relationships may not be appropriate for all concrete pavement mixes (Rao et al. 2012). This is one reason many states evaluate some of their own concrete mixes through testing programs that include testing MOR, f'_c, and E_c.

Table 1 compares typical default values found in different state DOT’s user’s manuals or pavement design manuals for MEPDG and the defaults found in the current Pavement ME Design software (PMED Default row).

Table 1. Default values for strength, stiffness, CTE, and unit weight found in select state pavement design user manuals and Pavement ME Design defaults

State, year	28-day MOR (psi)	f'_c (compressive) (psi)	E_c (× 10^6 psi)	CTE (× 10^{-6}/°F)	Unit weight (pcf)
Georgia, 2015	705	6,097	4.5	5.1 (granite or dolomite) 4.5 (limestone)	150
Indiana, 2020	700	N/A	N/A	4.7–6.1 (5.4 typical)	145
Maryland, 2016	685	N/A	4.371	3.8–6.5	150
Michigan, 2015	N/A	5,600	N/A	5.0 (dolomite) 4.4 (limestone)	N/A
Oklahoma, 2016	620	N/A	N/A	4.5	N/A
Virginia, 2017	650	N/A	5	5.5 (granite)	150
Pavement ME Design Default	690	5,275.3	4.2	4.9*	150

* The default CTE value in the latest version of the MOP notes 5.5, while it should be 4.9, the same as the software (see CTE discussion that follows)
N/A signifies a default was not found in the state's user manual

CRCP is not used by many states, but Maryland includes a default f'_t, indirect tensile value of 590 psi for CRCP in their design manual. Pavement ME Design does not have a default value for f'_t, as the indirect tensile value is only used for Level 1 inputs.

Coefficient of Thermal Expansion (CTE)

The CTE is a measure of the amount of length change per degree temperature change (microstrain/°F or 10^{-6}/°F of hardened concrete. The test that provides the CTE value is a measure of how much a hardened concrete cylinder changes length under certain conditions of saturation and temperature. This movement is important for pavements as related to slab movement under typical outside environmental conditions. Coarse aggregate typically has more influence on the CTE of the concrete than the fine aggregate does (Hall and Tayabji 2011).

AASHTO T 336 – CTE Test

The only major global recalibration of the rigid pavement models to date was recalibration related to the CTE value. The concrete model coefficients for cracking and faulting were required to be recalibrated due to an issue related to the CTE test.

The original CTE per AASHTO Provisional Standard TP 60 was adopted in 2000. It was moved to a full standard, T 336, in 2009. As noted below, the test itself really did not change substantially, just the value used to calibrate the testing apparatus changed and was clarified later in T 336 due to the CTE issue.

An early version of T 336 (T 336-09) had a note that "When using version 1.0 of the MEPDG software, AASHTO TP 60-00(2007) should be used instead of T 336-09." T 336 now includes a specific section describing the Calibration (5.4) and Verification (5.8) Specimen requirements and Calibration and Verification procedures (7.1). It also includes reporting requirements for the calibration and verification CTE values. One way to ensure your CTE test results are based on the appropriate calibration factors is if the results include the material used for both calibration and verification specimens and their associated CTE values. (T 336 Section 9.1.12 – 9.1.15).

More on the Prior CTE Issue

An interlaboratory study initiated by the FHWA identified an issue with the AASHTO TP 60 test being used to measure the CTE (Tanesi et al. 2010). The test is calibrated with a class 304 stainless steel specimen. The CTE test is performed at temperatures of 50 to 122°F, but the calibration specimen CTE value commonly used was based on much higher test temperatures, so it was a higher value. The researchers also identified a minor variation in the CTE value based on the calibration specimen length or specific composition of the stainless steel. The calibration value for the Grade 304 stainless steel calibration specimen was being used as one value, 9.6×10^{-6}/°F (for 32°F to 932°F), when it was actually on the order of 8.8 to 9.0 ($\times10^{-6}$/°F) for the required CTE test temperature values of 50 to 122°F; as noted, it also varied slightly based on the actual specimen composition. Therefore, when they used the actual (lower) steel calibration values, the CTE of the concrete specimens tested in the FHWA study were typically lower than what was previously found.

The CTE values used in the original NCHRP 1-37A models and NCHRP 1-40 calibration were also based on this incorrect calibration value. This affected both the JPCP (transverse cracking and faulting) and CRCP (crack width and punchout) models as most CTE testing up to that point had used the incorrect calibration values. The LTPP database had incorrect (too high of) CTE values, so the models needed to be recalibrated to address the correct CTE values (Sachs et al. 2015).

Two NCHRP 20-07 projects (Task 288 and Task 327) were performed to recalibrate the software to address the CTE issue. While the original issue was identified prior to 2010, Task 288 was performed from February 2010 through December 2011. Local calibration performed with the Task 288 values identified some instances of very different thicknesses for pavement using the new calibration factors; therefore, Task 327 was pursued to address the issue further. Task 327 was performed from November 2012 through May 2014. The results were presented in Savannah, Georgia, at the annual AASHTO Joint Technical Committee on Pavements meeting in 2014. An addendum was released in July 2015 addressing the new calibration coefficients included in Pavement ME Design version 2.2 based on the Task 327 findings.

It should be noted that the CTE values shown in Table 10.5 of the current MOP (3rd edition) are the same as those in the original MOP (prior to the CTE readjustment), except that Chert was removed. The values in the current MOP are incorrect; the correct CTE values are shown in Table 2.

Table 2. Average CTE values, uncorrected and corrected (microstrain/°F)

Coarse Aggregate	Default CTE noted in current MOP (not corrected)	Avg CTE, projects with single coarse agg type	Avg CTE, projects with multiple coarse agg type
Andesite	5.3	–	4.4
Basalt	5.2	4.4	4.4
Diabase	4.6	5.2	4.6
Gabbro	5.3	–	–
Granite	5.8	4.8	4.9
Schist	5.6	4.4	4.7
Chert*	*	6.1	5.9
Dolomite	5.8	5	4.9
Limestone	5.4	4.4	4.4
Quartzite	6.2	5.2	5.3
Sandstone	6.1	5.8	5.2
Expanded Shale	5.7	–	–
Default	5.5	4.9	

– Not included in the Task 288 data
* Removed from the Table in MOP version 3

The values in the MOP will be adjusted in the next revision. Most states have developed their own defaults based on testing, so the incorrect table values have probably not been used much in practice. The average (Avg) CTE values in Table 2 are from the NCHRP Task 288 report (which is not available online). Similar values have been reported in the past based on the LTPP standard data release 25 (first version corrected for the T 336 CTE values) along with the standard deviation for the CTE values (Hall and Tayabji 2011).

Missouri found in their latest local calibration that CTE less than or equal to 5 microstrain/°F resulted in the prediction of no transverse cracking in 30 years as compared to the same design with CTE of 6 microstrain/°F, which failed their cracking criteria of 15 percent in just 7.5 years (Titus-Glover et al. 2020). CTE has likewise been found to be an important input by other states.

Concrete Pavement Bases

Six different options are possible for base and subbase types for JPC pavements: flexible, chemically stabilized, sandwich granular, non-stabilized base, subgrade, and bedrock. Material properties for chemically stabilized and non-stabilized/subgrade (unbound materials as in aggregate and subgrade) are described in the following sections.

Chemically Stabilized Materials

Cement-treated bases (CTBs) or cement-treated aggregate and lean concrete bases use elastic modulus (E_c) as an input. The recommended typical value of E_c for a lean concrete base is 2,000,000 psi, and half that value (1,000,000 psi) is recommended for a cement-treated aggregate base. Flexural strength (MOR) is only required for CTBs in asphalt pavement designs (semi-rigid pavements).

Chemically stabilized bases and subbases (lime-cement, lime-fly ash, lime, and soil cement) also use elastic or resilient modulus (E/RM) instead of MOR for strength/stiffness. The default value for E/RM for all the types of bases is shown as 2,000,000 psi in the software, but the MOP provides different recommended values for E/RM, resilient modulus (RM), and Poisson's ratio by the different base types. The recommended typical E/RM value for soil cement is 500,000 psi. It can also be derived based on unconfined compressive strength testing of the materials. The MOP also provides equations to compute E/RM using relationships based on different compressive strength test methods. RM is described more in the next section on unbound materials.

Unbound Aggregate Base Materials and Engineered Embankments

Unbound materials use maximum density and optimum moisture content relationships and RM (Level 1 input). The RM value used is based on the laboratory value, which is typically less than the values obtained using in situ testing (i.e., dynamic cone penetrometer [DCP] or FWD). Level 2 input is based on correlations with other properties like DCP or California bearing ratio (CBR) values. RM is also based on optimum moisture and density, whereas CBR tests are typically based on saturated conditions, so CBR values also need to be adjusted to correlate to the RM. Level 3 input uses typical default values.

AASHTO T 307 Resilient Modulus Test

At least eight different test protocols have been identified for RM testing in the literature, including AASHTO T 247, T 292, T 294, T 307, and LTPP P 46 and NCHRP 1-28 Appendix E, 1-27A, and 1-37A (Christopher et al. 2006, ARA 2004). AASHTO T 307 or NCHRP 1-28A test methods are identified by the MOP as the RM testing methods for the Pavement ME Design software. T 307 was adopted by AASHTO as a standard test method in 1999. T 274 is noted in previous literature (TRB 2007) and in the 1993 and 1998 AASHTO Design Guide as the RM test. T 274 was deleted by AASHTO in 1997, and T 307 was adopted a few years later when it was realized that the MEPDG needed an AASHTO-sponsored RM test.

The T 307 test is similar to a confined triaxial test used for geotechnical purposes and uses similar equipment. The cylindrical sample can be generated by tube sampling or from materials remolded and compacted in the laboratory. The sample is placed in a chamber and subject to confining pressure. Load is applied to the top of the specimen in a cyclic manner in a specific sequence required by the test method and type of sample (soil subgrade or granular base). The applied stress divided by the average strain for the last five cycles is averaged to compute the RM.

T 307 has not been modified since it was formally adopted by AASHTO in 1999, more than 20 years ago. T 307 does not have a precision or bias section. Both of these indicate that the test is not being extensively used. It may be that states use some type of correlation to RM in pavement design or have done testing for a sampling of materials and use those values instead of doing regular T 307 testing.

A recent survey of 46 states related to unbound aggregate bases reported that 21% of the respondents indicated that they use RM testing in the laboratory, but the majority (50%) used some type of correlation to another test like CBR (Tutumluer 2013). An even older synthesis reported 29% (12) of the respondents used laboratory methods to characterize RM out of 41 respondents, but only six of them specifically noted using T 307 or NCHRP 1-28A. As in the later synthesis, the majority of the respondents used some type of correlation test (Puppala 2008).

In situ soils, as compared to excavated and compacted embankment, are non-homogenous materials that will of course provide different testing values depending on the location, depth, and local conditions at the test site. It is therefore reasonable to use some type of average or representative value for subgrade soils in most cases. Excavated and remixed soils should be more uniform than in situ soils but are still subject to variation due to mixing and compactive efforts.

RM for Bases and Subgrades

The MOP/Pavement ME Design includes recommended RM values for base/subbases and subgrades based on AASHTO soil classifications. The first two versions of the MOP included an MR value for bases for all 12 AASHTO soil classifications (A-1-a through A-7-6). These values were the same as those recommended in the original MEPDG documentation (ARA 2004 MEPDG Part 2 Chapter 2). In the latest MOP, only A-1-a (40 ksi) and A-1-b (38 ksi) soils were recommended as inputs for base/subbase (while the Pavement ME Design software still also allows bases of types A-2 and A-3). The RM values given for bases/subbases are the same values for both asphalt and concrete, but the values in the MOP are different for subgrades/embankments for asphalt and concrete pavements. The MOP notes this is due to differing confining pressure. The software converts the RM value for unbound materials into an effective k value for concrete pavements.

Backcalculation Tool (BcT)

The AASHTO Pavement ME Design website includes a tool for analyzing FWD measurements. FWD is used to measure the elastic modulus of existing pavement structures. The

Backcalculation Tool (BcT) was released in July 2017. It is not part of the Pavement ME Design software but is provided as a separate tool if you use the Pavement ME Design software. The output is conveniently formatted to be input directly into Pavement ME Design.

BcT is based on a computer program, EverCalc, developed by the Washington State DOT (WSDOT). The BcT tool imports FWD inputs, preprocesses the data by removing unexpected trends and bad data, performs backcalculation, which computes the elastic modulus for each layer over the length of the testing, and outputs a .dgpx file that can be used in Pavement ME Design rehabilitation design. For concrete roadways, the BcT tool generates Level 3 inputs for PCC strength (elastic modulus) and can identify joint load transfer efficiency (LTE) as well as the presences of voids. Deflections from the unloaded and loaded side of a joint are used to compute percent LTE for JPCP pavements.

CLIMATE

Pavement ME Design Version 2.3 Changes and v2.5.5 Enhancements

Pavement ME Design version 2.3 included totally new, more detailed, and more comprehensive default climate data in the form of the NARR climate data. The importance of this is described later in this chapter.

In Pavement ME Design v2.5.5, a Google map-based application was added to the software to allow choosing weather stations using a visual map format. The v2.5.5 enhancement was mainly a user functionality enhancement and did not have an impact on the models or prediction results.

General Differences Between MEPDG and Previous AASHTO Empirical – Climate

AASHTO Empirical: The American Association of State Highway Officials (AASHO) Road Test was conducted at one location (Ottawa, Illinois) (Highway Research Board 1962), so all climate considerations for pavement design were developed outside the AASHO Road Test. In the empirical AASHTO 98 version, climate factors included average annual values for wind speed, temperature, and precipitation by state or region within a state. It also used a freezing index (FI), where FI = number of degree days between the highest cumulative degree days (above freezing) and the lowest cumulative degree days (below freezing). FI has long been correlated with frost depth (Yoder and Witczak 1975). Two examples of a degree day used for FI include the following:

- If the temperature is≤ 31°F for 10 days = 10-degree days
- If the temperature is 21°F for 1 day, that also =10-degree days (31-21=10)

The FI accounts for freezing temperatures but also addresses the duration of freezing temperatures (AASHTO 1998).

MEPDG: Pavement ME Design uses actual weather data collected over time and reuses previous values to account for future conditions. The concrete models use the following detailed weather data:

- Hourly air temperature (°F)
- Hourly precipitation (in.)
- Hourly wind speed (mph)
- Hourly percent sunshine (varied, see discussion later)
- Hourly relative humidity (%)

The weather data is input into an enhanced integrated climate model (EICM), which simulates the changes in the concrete slab and the subgrade materials due to climatic effects. The model uses hourly temperature and moisture conditions to “age” the pavement. The model accounts for the effect that temperature variations have on stresses in the pavement components. It also models the effect of moisture changes on unbound materials. It is noted in the MEPDG documentation that it computes and predicts for every pavement layer “temperature and water content, modulus changes, pore water pressure, frost and thaw depths, and frost heave” (ARA 2004 MEPDG Part 2 Chapter 3). For both asphalt concrete (AC) and PCC pavements, the EICM adjusts the user RM input of the unbound material (MR) based on changes in moisture and temperature, including freeze-thaw conditions.

The original NCHRP 1-37A documentation also notes that additional tasks are performed in relation to PCC pavements. For PCC pavements, the EICM creates a temperature and moisture profile in the slab that is used to model curl and warp stresses. The temperature profile is used in the faulting and cracking models and the CRCP punchout model (ARA 2004 MEPDG Part 2 Chapter 3). The specific additional tasks for PCC are noted as follows:

- Hourly temperature profiles are developed, which are used to model slab curling
- Monthly relative humidity values are used to model slab warping
- FI and freeze-thaw cycles are used in the IRI calculation

EICM - Enhanced Integrated Climate Model

The original MEPDG included the EICM to incorporate environmental effects on the pavement over time. The main changes related to AASHTOWare Pavement ME Design versions and the EICM involve the data inputs (or climate files). First, a brief description of the EICM is included for readers not familiar with the EICM models.

As with all of the models used in the MEPDG, the EICM was compiled from existing models identified as the best models at the time. The Integrated Climate or Climatic Model (ICM) on which the EICM was based, was developed originally for the FHWA by the Texas Transportation Institute (TTI) at Texas A&M University. They, in turn, combined a model that they had developed for infiltration and drainage with two other models. The three models that composed the original 1989 ICM were as follows:

- Infiltration and drainage (ID) model developed by Texas A&M
- Climate-materials structural (CMS) model, a temperature model using convection and radiation, developed by the University of Illinois
- Frost heave and thaw settlement model developed by the U.S. Cold Regions Research and Engineering Laboratory (CRREL) that models heat and moisture flow in the subgrade in near freezing conditions

The ICM was improved in 1997 and 1999 leading to ICM 2.1. The original MEPDG EICM used the ICM 2.1 as a basis. Some minor improvements were made to improve the moisture content prediction capability of subgrade soils using LTPP seasonal site data and documented under the NCHRP 1-37A project. As a result, EICM 2.6 was the version included in the original MEPDG released in 2004 (ARA 2004 MEPDG Appendix DD and Part 2 Chapter 3). NCHRP Report 602 (based on NCHRP Project 9-23) documents the improvements made to the EICM and incorporated into version 1.0 of the MEPDG released in 2007 as part of the NCHRP 1-40 project (Zapata and Houston 2008). Both of these changes were prior to the AASHTOWare Pavement ME Design version of the software. As noted earlier, the major changes related to AASHTOWare Pavement ME Design versions and the EICM involve the data inputs (or climate files). The next section describes the climate date files.

Climate Data Evolution (Original NCDC to NARR to MERRA)

NCDC – National Climatic Data Center (Original Climate Data)

The EICM uses climate data that is inputted as .hcd files. It requires a minimum of 24 months of climate data. The original data were based on 800 National Climatic Data Center (NCDC), which is now called the National Centers for Environmental Information (NCEI), weather stations used by the LTPP program. The records included data starting from 1995. The NCDC data for the US was last updated in 2006 (so it only had 10 years of data, for 1995 through 2005 when the Pavement ME Design software was released in 2013).

The data are cycled to account for longer design periods. Some weather stations only had 2 or 3 years of data, and these were also cycled to account for longer periods. The NCDC data has been found to have some limited incomplete or inaccurate data, and some areas of the US are not well covered.

In fact, it was identified that Nebraska did not have any weather stations in the original climate files (Brink et al. 2017). In addition, specific state studies (Zaghloul et al. 2006) and national efforts (Johanneck and Khazanovich 2010) have documented issues with the original climate data. Michigan had found that transverse cracking was very sensitive to the climate stations used (Haider et al. 2017).

NARR – North American Regional Reanalysis (Climate Data Now in Use for PCC Pavements)

NARR data are managed by the National Centers for Environmental Prediction (NCEP), which is an organization under the National Weather Service (NWS) under the overall direction of the National Oceanic and Atmospheric Administration (NOAA). NARR data are a compilation of data sets of actual weather data. NARR data cover data from the time period of 1979 through the present but are for North America only. NARR data are a little different and more detailed than the previous NCDC data. Figure 10 shows an example of NARR data sites in the Pavement ME Design software.

AASHTOWare Pavement ME Design, used with permission

Figure 10. Sample NCDC and NARR climate locations in Pavement ME Design

MERRA 2– Modern Era Retrospective Reanalysis for Research and Applications (Future)

Modern Era Retrospective Reanalysis for Research and Applications (MERRA) (1979–February 2016) and MERRA2 (1980–present) are satellite-based data produced by the National Aeronautics and Space Administration's (NASA's) Goddard Space Flight Center (GSFC) Global Modeling and Assimilation Office (GMAO). MERRA data are gridded at approximately 30x30 miles as shown in Figure 11 (but note this is currently only for AC pavements).

AASHTOWare Pavement ME Design, used with permission

Figure 11. Sample MERRA data locations in Pavement ME Design

The FHWA evaluated the MERRA data extensively in a project for LTPP. Based on a sensitivity analysis as part of the FHWA project, they found that the annual average temperature could have a moderate effect on JPC design, but it was dependent on slab thickness and appeared to be inconsistent (Schwartz et al. 2015). They also found that PCC transverse cracking was more sensitive to climate than faulting.

Others have found differences between results using NARR and MERRA for asphalt pavements when using the Pavement ME Design software (Ziedan et al. 2019). The latest version of Pavement ME Design, v2.6, uses NARR data for PCC pavements and MERRA2 data for asphalt surfaced pavements, as the asphalt pavements were just recalibrated with MERRA2 data. MERRA2 data will be used for the next global recalibration of the concrete pavement models.

A basic tenet of the EICM is that temperature affects both bound and unbound materials, but moisture has more effect on unbound materials. It also must be recognized that the MEPDG only predicts the effect of water from groundwater, and not from lateral flow due to lack of proper drainage.

In addition to climate data inputs, other factors can have an amplified effect due to the EICM. Pavement Construction Month and Year is used to estimate “zero-stress” temperature in JPCP/CRCP, which affects curling stresses. The Construction Month and Year can also affect crack spacing and width computations for CRCP.

EICM as Related to Performance Measures

While no systematic bias between the NARR and previous .hcd data has been found overall (Brink et al. 2017), if there are inconsistencies between the NARR and .hcd data that a state is using, it can have an effect on the design. This can be from previously incomplete data, previously erroneous data, or potentially different data definitions.

Sensitivity analysis of climate components are complicated. Schwartz found that, in regard to concrete pavements, average annual and daily temperature ranges were the most sensitive, followed closely by percent sunshine (Schwartz et al. 2015). Georgia data showed percent sunshine had a high impact (Durham et al. 2019). Michigan, however, found percent sunshine was not sensitive in their analysis (You et al. 2015). These differences can also be the result of the distress that is being considered: transverse cracking, faulting, or IRI.

Michigan found that the use of different climate stations for the same pavement section had a negligible effect on transverse cracking but did effect predictions of faulting and IRI. They found that changes in wind speed, precipitation, and percent sunshine did not seem to affect their concrete pavement designs, but faulting was greatly affected by changes in relative humidity in certain areas of the state (You et al. 2015). Conversely, Georgia found that transverse cracking and IRI prediction was highly affected by climate, but faulting was negligibly affected.

Durham also looked at the original climate data in comparison to the NARR and MERRA data. The report indicates that percent sunshine had an effect on the design, and wind speed and percent sunshine appeared to be different for the various sources of climate data that they compared (original .hcd, NARR, and MERRA) (Durham et al. 2019).

Percent Sunshine: Percent sunshine is a term that has changed in meaning with the newer climate data sets. Percent sunshine is used (in the CMS portion of the EICM model) along with the surface shortwave absorptivity value (default = 0.85) and other components to estimate the pavement temperature. Pavement temperature in concrete pavements directly affects curling stresses. The NARR percent sunshine definition for granularity is different than the definition used previously for the original MEPDG (NCDC) data. The original MEPDG used five values from 0 to 100% to represent percent sunshine based on descriptions of clear to overcast. Table 3 shows the definition used by the original MEPDG and the similar average values used in NARR and MERRA data (Schwartz et al. 2015).

Table 3. Percent sunshine differences

Description	MEDPG Percent Sunshine*	Measured Percent Sky Cover (range)	Measured Percent Sunshine (midpoint)
Clear (CLR)	100	> 87 to ≤ 100	93.5
Few Clouds (FEW)	75	> 50 to ≤ 87	68.5
Scattered Clouds (SCT)	50	> 25 to ≤ 50	37.5
Broken Clouds (BKN)	25	> 5 to ≤ 25	15
Overcast (OVC)	0	0 to ≤ 5	2.5

*Percent sunshine was computed using 100 minus percent cloud cover
Source: Adapted from Schwartz et al. 2015

The NARR and MERRA data for cloud cover are continuous, whereas the original NCDC climate data were discrete.

Climate data are complicated, used in many areas of the MEPDG models, and overall have an important effect on the MEPDG models. Therefore, changes in climate data should warrant verification of the calibration factors used in design.

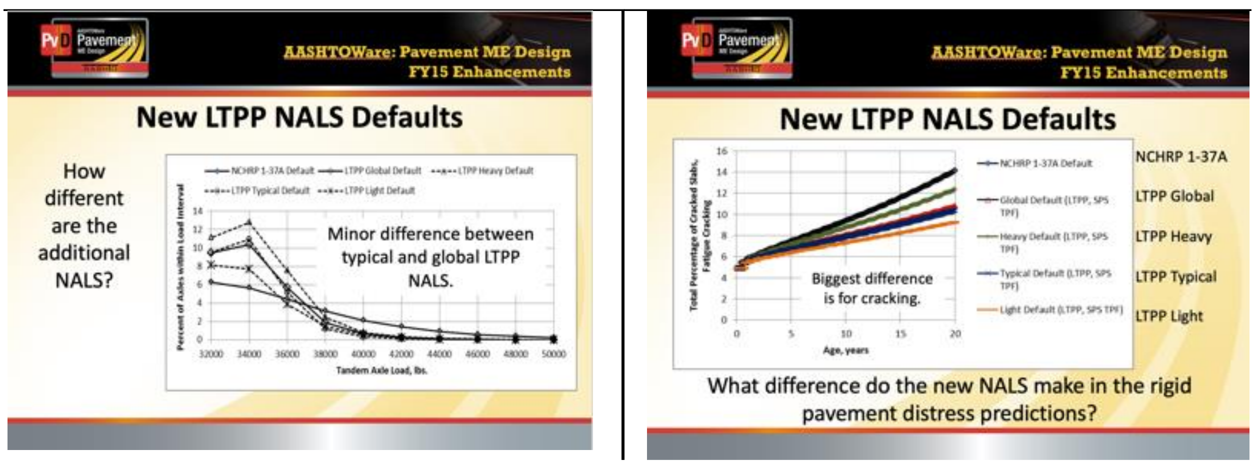
TRAFFIC

Pavement ME Design Version 2.2 Changes

In relation to the Pavement ME Design software, the only change to traffic was the addition of additional default NALS (described later in this chapter) in 2015 with version 2.2. The original NCHRP 1-37A default NALS were identified as potentially having too many heavy vehicles for the most common truck class (Class 9).

The new default values for traffic are noted in the software now as global, light, typical, and heavy NALS. The original traffic defaults provided in the original software are now termed NCHRP 1-37A NALS. Figure 12 shows two slides from the v2.2 webinar that show the differences between the five different default NALS and the effect on cracking in JPCP pavements.

The new defaults were added due to research performed for the Transportation Pooled Fund project TPF-5(004) (Selezneva et al. 2016), which identified that the original traffic data appeared to exhibit many more overloaded vehicles than expected and that these heavy vehicles had a significant impact on pavement design. Many states have also developed their own regional defaults based on actual traffic data, and several tools are available to manage the immense amount of traffic data involved.



AASHTOWare Pavement ME Design, used with permission

Figure 12. Pavement ME Design version 2.2 NALS effect on concrete pavements

General Differences Between MEPDG and Previous AASHTO Empirical – Traffic

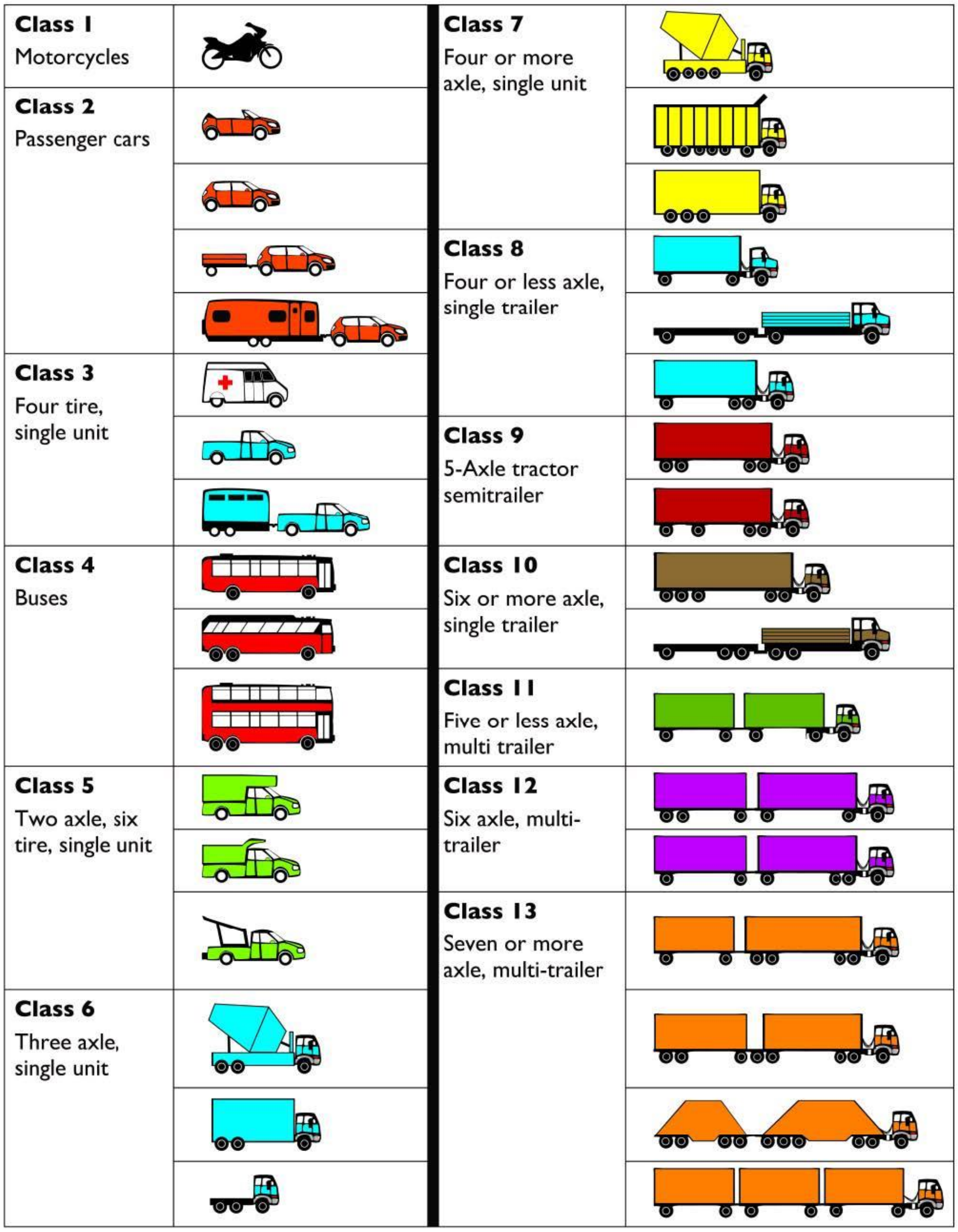
The MEPDG created a major change in how traffic was considered for pavement design. Traffic is, of course, an important component of pavement design. It has recently been confirmed that, in comparison to flexible pavements, traffic loading is what does the most damage to concrete pavements over time when compared to environmental issues alone (Titus-Glover et al. 2019).

As related to traffic, the MEPDG considers the actual axle loads and vehicle classifications, as these have a direct mechanistic connection to pavement damage.

AASHTO Empirical: AASHTO empirical methods and the MEPDG both use the term average annual daily truck traffic (AADTT) to characterize the number of trucks. AADTT can also be found as average annual daily traffic (AADT) multiplied by the percentage of trucks. The AASHTO empirical method converts AADTT and axle types to equivalent single-axle loads (ESALs) and uses ESALs in the empirical equations.

What is an ESAL?

To understand how traffic is handled differently from what was used prior to the MEPDG, an understanding of ESALs is first necessary. Prior to the MEPDG, traffic loading for pavement design was expressed as ESALs. The AASHO Road test developed the concept of ESALs. The AASHO Road Test had six loops, each two lanes wide. Four of the loops were loaded by semi-trucks with different loading and different axle combinations (and they would be considered FHWA Class 8 and 9 trucks (see Figure 13).



FHWA

Figure 13. FHWA vehicle classes 1–13

Each lane on the four loops had a different truck configuration (with different axle spacing and axle loads), for eight different combinations. The trucks were driven on the different loading loops to identify the different damage created by the different configurations and loading. Each loop had an asphalt portion and a concrete portion of roadway. A relationship between the loading and the damage was developed for each pavement type and thickness empirically using the distress data collected. These empirical values were developed into load factors (LFs) for asphalt and concrete pavements (Highway Research Board 1962).

ESALs are the sum of the number of truck loads (AADTT) multiplied by the appropriate LF (with LF representing the equivalent loading of an 18 kip [where 1 kip = 1,000 lb] axle and is based on the number of truck axles and axle locations, pavement type, and pavement thickness). This is how ESALs are specific to the pavement type (rigid or flexible) and pavement thickness. See the FHWA traffic pocket guide for these and other related traffic terms (FHWA 2018).

ESAL also incorporates estimated traffic growth, and that traffic growth can be uniform, exponential, or variable.

MEPDG: The MEPDG uses the AADTT and a representation of the actual distribution of truck axles and loadings per axle (in the form of NALs) in an iterative method to provide the loading that is mechanistically converted to stress and eventually distress. Estimated traffic growth rates can be different for each truck class (i.e., constant or exponential), but the rate is assumed to be the same over the design life (but limited to a maximum value per lane).

One important difference in the inputs is that the AASHTO empirical methods typically used one-way AADTT as a direct input and Pavement ME Design typically uses two-way AADTT, but it is based on all lanes. (To complicate matters more, the one-way AADTT can be entered if the percent of trucks in the design lane is set to 100 in Pavement ME Design.) Confusing this difference can cause a significant design error.

What is the NALS?

The NALS is a representation of the expected axle loads for a class of vehicles. Pavement ME Design recognizes 10 classes of vehicles. The NALS can be viewed as a histogram or graph, as shown in Figure 14, for individual vehicle classes and axle types.

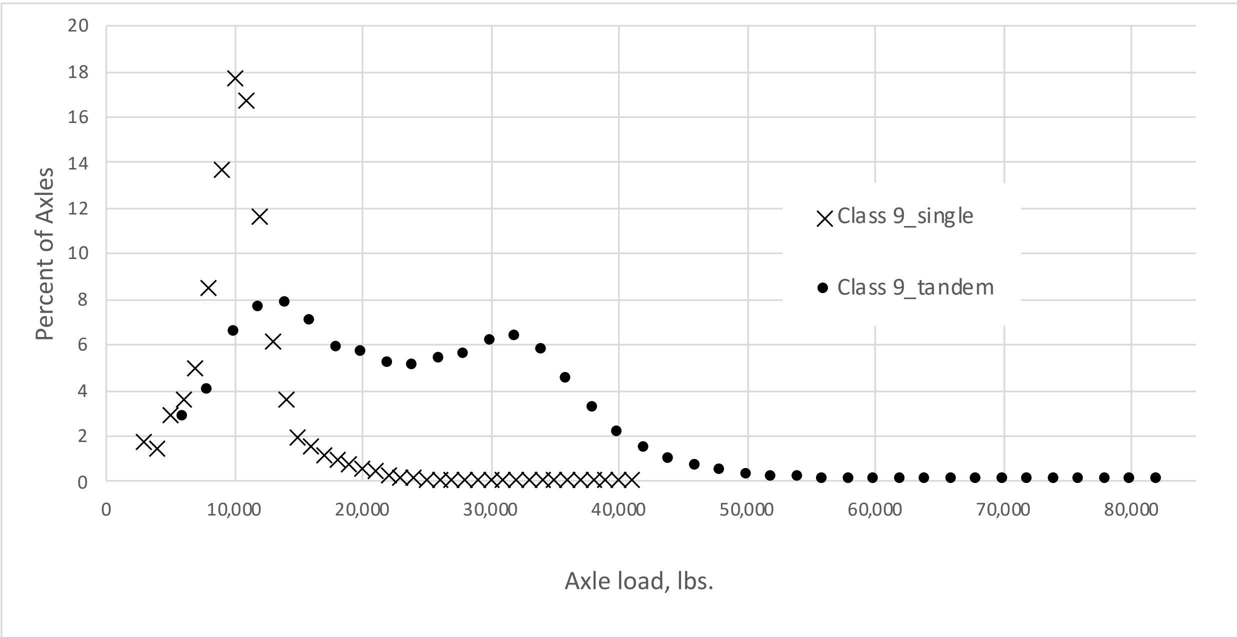


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Figure 14. Single and tandem distribution for Class 9, default NCHRP 1-37A NALS

The figure shows an example of single-axle and tandem-axle NALS for a Class 9 vehicle based on the default NCHRP 1-37A NALS. The expected value of a single-axle load is concentrated around 10,000 lb, while the expected value of the tandem load varies more and has peaks near 12,000 and 32,000 lb. The single-axle load is typically under the cab, while tandem axles carry most of the weight of their cargo. The two peaks in the tandem load represent trucks that are empty (near the load of a single) and fully loaded (~34,000 lb). In comparison, Federal Interstate weight limits are 20,000 lb for a single axle and 34,000 lb for a tandem axle. See the following link for the FHWA Bridge Formula weights: https://ops.fhwa.dot.gov/FREIGHT/publications/brdg_frm_wghts/index.htm.

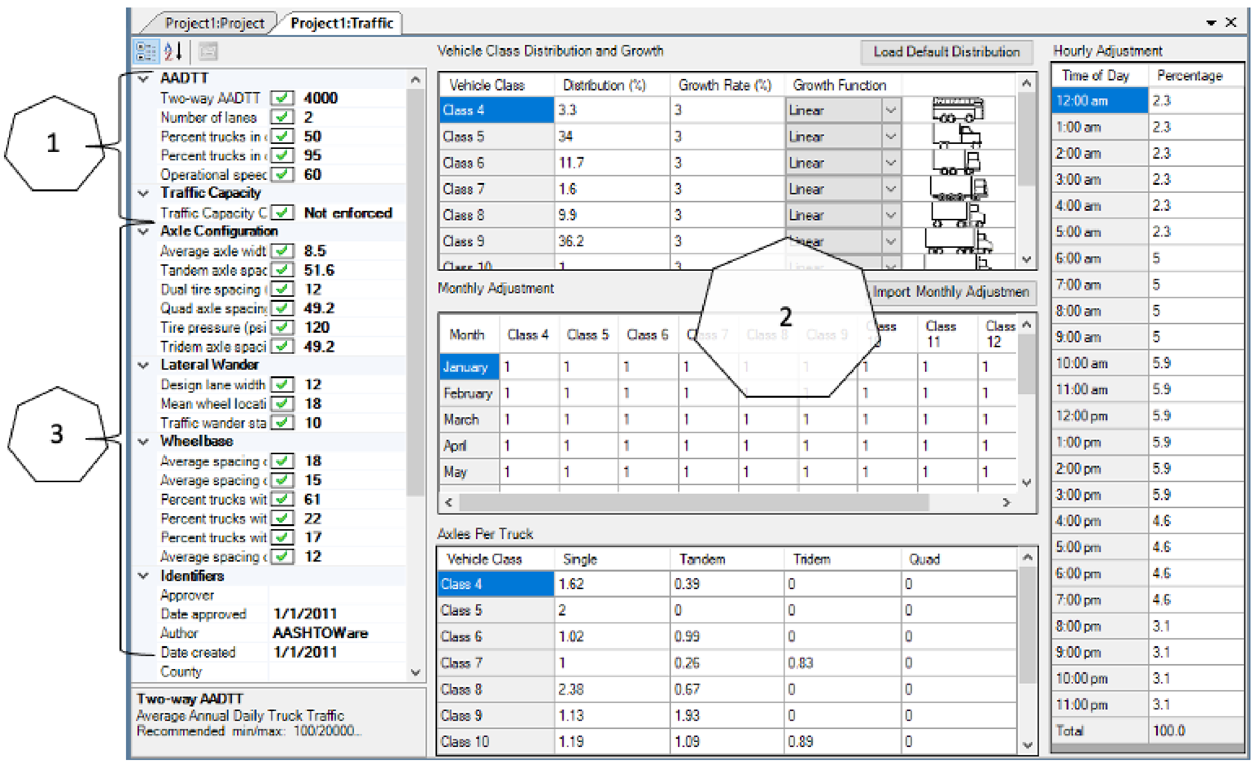
MEPDG/Pavement ME Design uses the actual number and type of vehicles and the estimated weight of the vehicles' axles (single, tandem, tridem, and quad) for loading purposes. Each vehicle class is defined by an axle load spectra (see previous Figure 12), which is a histogram of the axle load weights for a vehicle class. Five different default NALS values are included as part of the Pavement ME Design software. Many state DOTs have also developed their own regional or state NALS. It defines the expected value of the axle load for each vehicle of the same vehicle class.

Traffic data are characterized in the MOP by the following categories and found in the Pavement ME Design software, as shown in Figure 15, which is a screenshot of the software:

- **Roadway specific:**
  - AADTT (two-way), # lanes, directional and lane distribution of trucks, speed, traffic growth

- **Weigh-in-motion (WIM)-related loading specific inputs:**
  - Axle load distribution factors (normalized axle load spectra or NALS)
  - Truck traffic classification (TTC) group (vehicle class distribution)
  - Axle configuration (i.e., tandem, tridem, or quad)
  - Monthly and hourly distribution factors (MDFs and HDFs, respectively)

- **General traffic inputs (defaults):**
  - Dual tire spacing, tire pressure, wander, truck wheelbase



AASHTOWare Pavement ME Design, used with permission

Figure 15. Pavement ME Design Traffic screen

1. Shown as Category 1 in the figure, roadway specific inputs are described in the MOP and are site-specific traffic-related values.

2. Category 2, WIM- related inputs, require site-specific vehicle class, vehicle class percent, and axle loads per vehicle class data for Level 1 inputs. In the case of a new road, this information must be estimated as it obviously cannot be measured. The equipment to measure the weight data, in particular, is expensive and not particularly portable. Therefore, in most cases, defaults are chosen based on the character of a road. The WIM-related inputs are described in more detail in the next section.

3. The software defaults are typically used for the Category 3 inputs, General traffic.

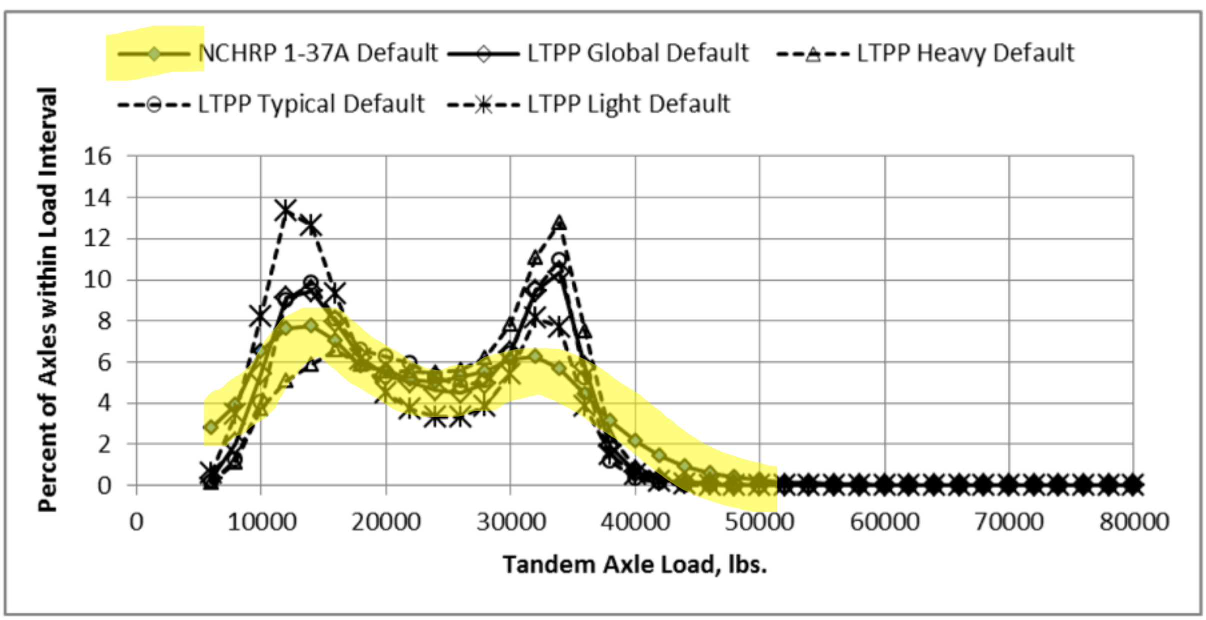
WIM-Related Inputs

Traffic data are collected historically using automatic vehicle classification (AVC) and WIM equipment. AVC provides the type and percentage of different vehicle classes. Vehicle class alone does not indicate the loading on each axle in the vehicle. WIM data provide the loads, but WIM systems are expensive to install and maintain, so, historically, WIM data have been limited (Hazlett et al. 2020). Typically, a state will identify state specific WIM-related inputs. Each of the WIM-related inputs are described below:

NALS – Normalized Axle Load Spectra

NALS define the axle loading for the different types of vehicles (classes 4–13) and the different types of axles (single, tandem, tridem, and quad). NALS is axle and load related, so the spectra are directly tied to WIM. As previously noted, five different default NALS values are available in Pavement ME Design.

Original traffic in Pavement ME Design was the best data at the time, based on 134 sites associated with LTPP sites. Since then, efforts like the LTPP Specific Pavement Study (SPS) Traffic Data Collection Pooled Fund TPF-5(004) have recognized limitations of the original traffic data (Selezneva et al. 2016). The original NCHRP 1-37A NALS has a heavy tail (i.e., included a large number of overloaded vehicles). This is especially important since the MEPDG is sensitive to heavy loads. This “tail “can be seen in Figure 16 as the original NCHRP 1-37A NALS or Class 9 tandem axle has a higher percentage of tandem axle loads over 40,000 lb as compared to the new global, light, typical, and heavy default NALS.



AASHTOWare Pavement ME Design, used with permission

Figure 16. Comparison of NALS

TTCs – Truck Traffic Classifications

TTCs set the percentage of different truck vehicle classes in a traffic stream. TTCs are related vehicle classes so are directly tied to use of AVC equipment. In the NCHRP 1-37A research, it was identified that functional class did not align well with truck classifications, so separate TTCs were developed.

TTCs are defined by 17 groupings (ARA 2004 MEPDG Appendix AA), which were designed based on a focus on differences in truck Classes 5 (single-unit), 9 (single-trailer), and 13 (multi-trailer). An example of the single-axle distribution of Classes 5, 9, and 13 for the default 1-37A NALS is shown in Figure 17.

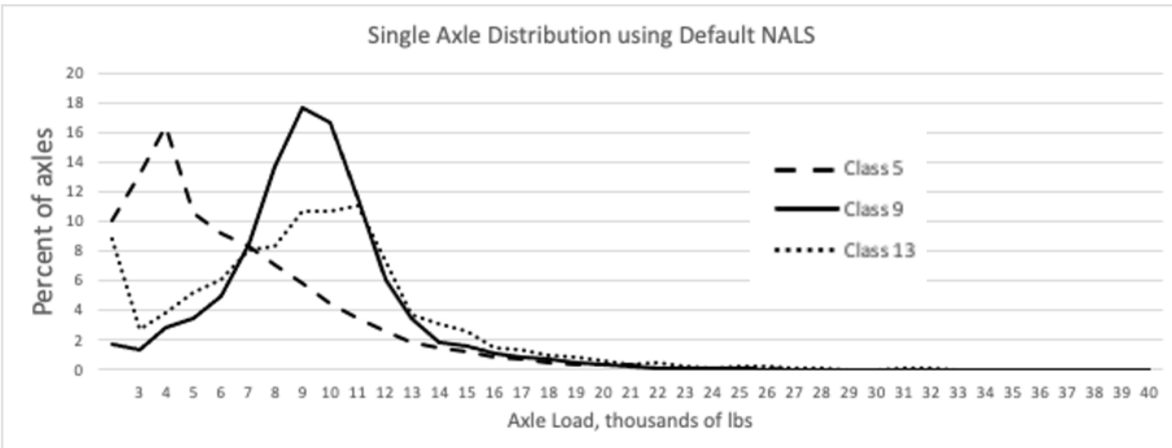


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Figure 17. Sample vehicle classes used to develop TTCs

The TTCs do include all vehicle classes 4–13. These groupings are not tied to the traditional functional class (which is geometry and access based), but a TTC value that is instead based more on pavement performance. The default TTC in Pavement ME Design is TTC 9. (which is different than vehicle Class 9.)

MDFs and HDFs – Monthly and Hourly Distribution Factors

MDFs and HDFs are factors to account for seasonal (MDFs) or daily (HDFs) variations in truck traffic. HDFs are only used for concrete pavements.

Wait…What is a Vehicle Class?

The FHWA Traffic Monitoring Guide (TMG) defines the different types of vehicles in classes (FHWA 2016). Trucks are considered FHWA vehicle classes 4 through 13, where Class 9 is the most common truck type (a semi-trailer truck with a cab with one axle and a single trailer with four axles for a total of five axles). The classes and their descriptions (from the TMG) are shown in Table 4 and the previous Figure 13.

Table 4. Definitions and axles for FHWA vehicle classes

Class	Definition	# of axles
1	Motorcycles	2
2	Passenger Cars	2, 3, or 4
3	Other	2, 3, or 4
4	Buses	2 or 3
5	Single-unit truck	2
6	Single-unit truck	3
7	Single-unit truck	4 or more
8	Single-trailer truck	3 or 4
9	Single-trailer truck	5
10	Single-trailer truck	6 or more
11	Multi-trailer truck	4 or 5
12	Multi-trailer truck	6
13	Multi-trailer truck	7 or more

Source: FHWA 2016

Original Default Traffic Inputs in Pavement ME Design

Accurate traffic loading estimation is dependent on the truck type (local or through trucks), what the trucks are carrying, and the distribution of truck types. Traffic in a state with ports or local regulations (such as allowable loads for trucks on state routes are higher than the interstate restrictions) can have an effect on the expected load spectra.

CONCRETE PAVEMENTS

Pavement ME Design v2.2 Modifications and v2.3 Addition of SJPCP

A major recalibration of the JPCP and CRCP rigid pavement models was performed for v2.2 due to an issue with an important input, CTE. (See the Materials chapter for a more detailed description of the CTE issue)

An enhancement to the PCC overlay over asphalt was also included in v2.2 that allowed two additional options for defining the condition of the existing asphalt to be overlaid. Level 1 includes a value for transverse cracking per mile, and Level 2 includes a percent of fatigue cracking. Prior to this version, the existing asphalt was only able to be characterized in generic Level 3 terms (i.e., excellent/good/bad/poor).

A new model for thinner SJPCP was added in v2.3. SJPCP is discussed in more detail later in this chapter.

General Differences Between MEPDG and Previous AASHTO Empirical – Concrete Pavements

AASHTO Empirical: The previous AASHTO empirical methods were based on an overall change in pavement condition. This overall change in pavement condition was based on the difference between a terminal serviceability value as compared to an initial serviceability value, termed the change in present serviceability index (ΔPSI). Even the ΔPSI was empirically based; it was derived from rankings based on a panel of raters including highway employees and "men with materials…trucking…automobile…interests…" and it was empirically related to distresses in the pavement.

Two things to recognize when considering the concrete models that came out of the original AASHO Road Test is that all of the concrete pavements were doweled (there were no continuously reinforced pavements) and the pavements were all new pavements, with no overlays (Highway Research Board 1962).

MEPDG: Besides the differences in material inputs, climate inputs, and traffic inputs described in the previous chapters, the MEPDG predicts actual distresses of cracking and faulting and the resulting change in smoothness (IRI) of a JPCP pavement. The MEPDG predicts punchouts and IRI for CRC pavements. Pavement ME Design predicts longitudinal cracking of short jointed (thin) concrete pavements. Each of the different pavement types (JPCP, CRCP, and SJPCP) and how they are treated in Pavement ME Design are described next.

New Jointed Plain Concrete Pavement (JPCP)

Pavement ME Design uses the previously mentioned inputs related to materials, climate and traffic for JPCP design. In addition, it also provides for inputs of slab width (widened slabs) and joint spacing, joint sealant, dowel diameter and spacing, tie bars, shoulder type, and built-in temperature gradients. Pavement ME Design predicts the percent of slabs with transverse cracking, the average faulting, and the average IRI (smoothness) of a JPCP over time due to loading and environmental conditions based on the design and materials used for the JPCP. Minimum thickness for design in Pavement ME Design for a JPCP pavement is 6 in. Each distress is discussed in the next section.

JPCP Distresses – Transverse Cracking, Faulting, IRI

Transverse Cracking: Transverse cracking is computed based on fatigue equations using incremental damage, which considers loading and environmental stresses on the pavement. A finite element (FE) program named ISLAB2000 was used as the basis for the analysis. The software does not use the FE model (FEM) program directly due to speed considerations. For computational speed, artificial neural networks (ANNs) were trained using the outputs from ISLAB 2000, and ANNs are used in the software. Neural networks are essentially complicated regressions, so their accuracy is controlled by the data used to create the regressions.

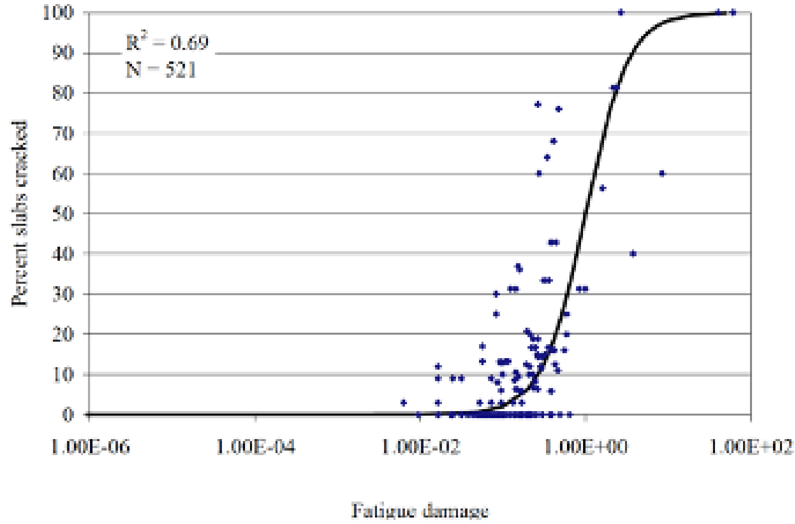
For transverse cracking, depending on the location of loading, the major stress can occur in the bottom or top of the slab in the transverse direction. Pavement ME Design computes both top-down (CRK_{TD}) and bottom-up (CRK_{BU}) cracking and reports the total cracking as % of cracked slabs. The final transverse cracking (TC) value is computed using the traditional equation for the union of two sets of data that are independent (so slabs with CRK_{BU} and CRK_{TD} cracking will not be counted twice).

$$TC = CRK_{BU} + CRK_{TD} - (CRK_{BU} \times CRK_{TD}) \quad \textbf{(4)}$$

CRK_{BU} and CRK_{TD} are found from the computed distress (DI) or fatigue damage, as shown in Equation 5.

$$CRK = \frac{1}{1+C_4 * (DI)^{C_5}} \quad \textbf{(5)}$$

C_4 and C_5 are calibration factors that change the regression curve shown in Figure 18.



ARA, Inc., ERES Consultants Division 2004, NCHRP Project 1-37A

Figure 18. Cracking relationship to fatigue damage

The fatigue damage (DI) is found using algorithms that accumulate the ratio of applied loads to allowable loads for numerous factors (change in material [PCC slab and subgrade] properties over time, material [PCC slab and subgrade] changes due to moisture and temperature changes, and traffic loading). The computation of distress is incremental over time, uses actual climate information, and includes many factors that can be interrelated, as follows:

- The effective k value can be affected by water table depth, bedrock location, and frost penetration

- Bending stress in PCC is also affected by factors that do not change over time: (thickness, unit weight, joint spacing) and factors that do change either monthly or over time (PCC properties like strength and CTE, temperature and moisture in slab [curl/warp], LTE, base properties, and loading, where LTE is the ratio of deflections of unloaded and loaded slabs)

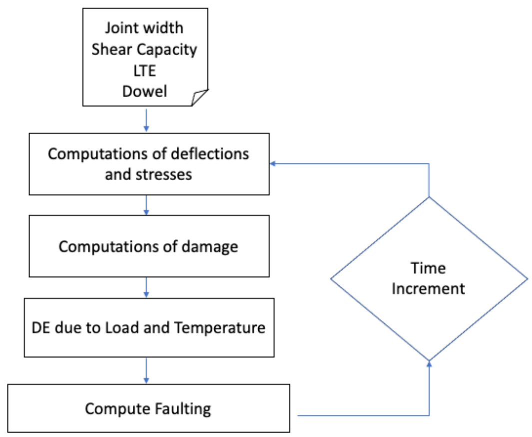
As compared to the one equation used in previous empirical design methods (see previous Figure 8), the equations used are too numerous to present.

Faulting: Faulting is also an incrementally computed value. Pavement ME Design computes monthly average faulting using mainly empirical models that include factors for load transfer, base erodibility, and differential energy of subgrade deformations. The percent of fines in the subgrade and climate in terms of the number of wet days are also included. Since the AASHO Road Test consisted of only doweled pavements, other models developed from LTPP-related sources were used for the faulting models in the MEPDG. The PaveSpec 3.0 faulting model, developed for performance related specifications, was modified to address an incremental damage approach (ARA 2004 MEPDG Appendix JJ).

The MEDPG (in Appendix JJ) notes four main components for faulting considerations as follows:

- Damage due to loading
- Load transfer
- Erodibility of the foundation (accounted for by type, gradation, and percent fines)
- Water (accounted for indirectly by changing stiffness of foundation materials)

The MEPDG documentation includes a flowchart (shown in Figure 19) that identifies joint width, shear capacity, LTE, and dowel stiffness as the initial properties in the model.



ARA, Inc., ERES Consultants Division 2004, NCHRP Project 1-37A

Figure 19. Faulting flowchart

The model incrementally computes changes in these properties over time while also addressing the differential energy (DE) related to the foundation. The faulting rate is considered to increase at a rate relative to the amount of faulting, and then stabilizes at a certain level over time.

Earlier versions of the MOP have always included a discussion on faulting, but the latest version of the MOP has been reorganized slightly as related to faulting, and additional equations have been added to it. It has been noted that the faulting model has been changed since the NCHRP 1-37A project, but those changes have not been documented (Khazanovich and Tompkins 2017). It appears those apparent changes may have just been bug fixes to the software code, as the changes and discussion added to the current MOP are from the original NCHRP 1-37A documentation.

The current MOP includes more than 20 equations used in the faulting computation. Through local calibration efforts, an issue in one of the equations was identified (Ceylan et al. 2015). It is anticipated to be addressed in the next edition of the MOP and the correct version of MOP Eq 5-23c is shown in equation 5.

$$FAULTMAX_i = FAULTMAX_{i-1} + C_7 \times \frac{\sum_{j=1}^{m} DE_j}{10^6} \times Log(1 + C_5 \times 5.0^{EROD})^{C_6} \quad \textbf{(5)}$$

The equation is related to the incremental faulting analysis. Due to the sheer number of equations, similar to the cracking model, they are not all repeated here.

IRI (or Smoothness): IRI prediction uses an empirical equation that combines the computed cracking and faulting while also addressing spalling and foundation conditions. Each component (except for initial IRI) has a calibration value associated with it. IRI initially had an additional term for patching, but it was not incorporated into the final report or into the original software (ARA 2004 MEPDG Appendix NN). The five components to predict future IRI are as follows:

IRI = Initial IRI + Transverse Cracking + Faulting + Spalling +
Site Factor (subgrade/climate) **(6)**

The calibration factors CJ1–CJ4 for IRI are the same as they were for the original NCHRP 1-37A project. The calibration factors were based on analysis of 183 LTTP sites (ARA 2004 MEPDG Part 3 Chapter 4). The equation used in the MOP and the calibration factors for IRI are as follows:

$$IRI = IRI_i + CJ1 \times CRK + CJ2 \times SPALL + CJ3 \times TFAULT + CJ4 \times SF \quad \textbf{(7)}$$

where CJ1 = 0.8203, CJ2 = 0.4417, CJ3=1.4929, and CJ4 = 25.24.

The CRK and TFAULT are based on the predicted distresses of cracking and faulting respectively, as previously described. SPALL is an empirical equation that focuses heavily on pavement age but also includes a spalling prediction scaling factor (SCF), which includes concrete properties, age, joint sealant, and freeze-thaw cycle components.

Site factor (SF) is also used in the CRCP IRI equation. The SF for both JPCP and CRCP is essentially the same and is represented by equation 7:

$$SF = AGE\ (1 + 0.5556 \times FI)\ (1 + P_{200}) \times 10^{-6} \quad \textbf{(7)}$$

where FI is the freezing index (see the Climate chapter for description of FI) and P_{200} is the percent of fines in the subgrade. (Note: CRCP is only different in that it uses 0.556 instead of 0.5556 as related to the FI.)

Continuously Reinforced Concrete Pavements (CRCP)

Pavement ME Design v2.2 Change

Except for the changes to the calibration constants in v2.2 due to the CTE adjustment (described in the Materials Section), the CRCP models in Pavement ME Design have not changed.

Two major changes were made to the CRCP model after the original NCHRP 1-37A project, but they were incorporated prior to the original AASHTO Pavement ME Design software as follows (Rao and Darter 2013):

- The base erosion model was improved
- The definition of a punchout was modified to remove low severity level punchouts and consequently the recommended failure criteria was reduced from 20 to 10 punchouts a mile

General Difference Between MEPDG and Previous AASHTO Empirical – CRCP

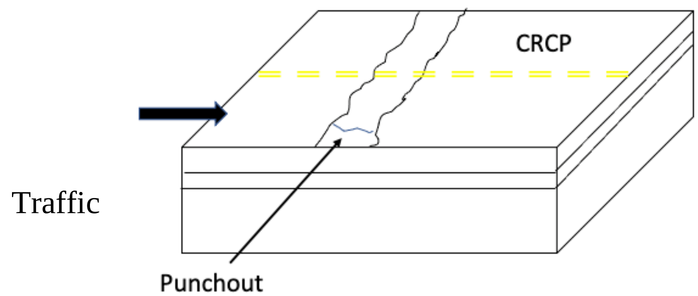
AASHTO Empirical: It should be recognized that the original AASHO Road test did not even include CRCP. Half of the AASHO pavements were JRCP with wire mesh reinforcement and 40 ft joint spacing and the other half were JPC at 15 ft. The CRCP model used in the AASHTO 93 Guide only predicted longitudinal reinforcement required for CRCP. Punchouts (a primary distress for CRCP) were not considered. The design thickness was determined using the JPCP equations and criteria. Some states reduced the JPCP thickness an inch for CRCP to compensate for the additional cost of the steel.

MEPDG: Besides the differences in material inputs, climate inputs and traffic inputs described in previous sections, MEPDG predicts distresses in the form of punchouts and the resulting change in smoothness, or IRI.

CRCP Distresses – Punchouts and IRI

Pavement ME Design uses the previously mentioned inputs related to materials, climate, and traffic for CRCP design. In addition, it also provides for inputs of shoulder type, longitudinal reinforcement bar size, percent, and depth. Crack spacing and base/slab friction along with slab temperature gradients can be input or computed by the software. The CRCP design combines a mechanistic model for crack width, spacing and LTE across cracks and an empirical punchout prediction model. The punchout distress and a site factor (SF is the same as used for JPCP) are used for IRI prediction. Minimum thickness for design in Pavement ME Design for a CRCP pavement is 7 in.

Punchouts: Punchouts are distresses particular to CRC pavements. Transverse cracking in CRCP is normal and expected. Punchouts are a fatigue distress that can occur over time due to movement of the transverse cracks and a loss of load transfer across the cracks, along with longitudinal cracking. The punchouts (POs) usually occur near the shoulder as shown in Figure 20, as it also typically involves a loss of foundation support, somewhat similar to faulting.



Adapted from ARA, Inc., ERES Consultants Division 2004, NCHRP Project 1-37A

Figure 20. CRCP punchout

Punchouts are modeled by predicting spacing, width, and LTE of the transverse cracks. The transverse cracks are affected by the foundation support, loading, and slab movement due to environmental conditions. Crack spacing calculations for CRCP use values related to the size and percent of longitudinal steel and the indirect tensile strength (f'_t) value for the concrete. The program computes the mean crack spacing and iterates over time the mean crack width. The crack width combined with the LTE and loading and environmental conditions combine to predict punchouts per mile based on accumulated fatigue damage (ARA 2004 MEPDG Appendix LL).

Equation (8) is the CRCP PO equation, which is similar to equation (5) for JPCP.

$$PO = \frac{C_3}{1 + C_4 \times DI^{C_5}} \quad \textbf{(8)}$$

IRI (or Smoothness): uses an empirical equation that combines the computed PO distress and the SF. The PO and SF each have a calibration value.

IRI =Initial IRI + C1 × POs + C2 × SF (subgrade/climate) **(9)**

The FHWA's CRCP Manual (Roesler and Hiller 2013) is a good source for additional information on CRCP and specifically covers the use of Pavement ME Design for CRCP.

Concrete Overlays

Concrete overlays involve placing a new concrete layer over an existing asphalt, composite, or concrete layer. The Guide to Concrete Overlays from the National Concrete Pavement Technology (CP Tech) Center presents the basic principles for designing and constructing concrete overlays on most types of existing pavements (Fick et al. 2021).

The original NCHRP 1-37A MEPDG project and the Guide to Concrete Overlays use the terminology bonded and unbonded to describe a key design consideration for concrete overlays on existing asphalt, composite, or concrete pavements. A bonded overlay is designed with the assumption that the existing pavement layer will bond with the new concrete layer, while an unbonded overlay either is designed without this assumption or is purposely designed with a separation layer to prevent bonding.

The Guide to Concrete Overlays uses COC and COA as groupings and the following terminology for concrete overlays (Fick et al. 2021):

- COC = concrete on concrete
  - COC-B = bonded
  - COC-U = unbonded
- COA = concrete on asphalt
  - COA-B = bonded
  - COA-U = unbonded

The most common COC in use is COC-U. A separation layer is normally used to ensure unbonding in COC-U overlays. COC-B overlays have been used, but since they are almost akin to a continuous partial depth slab repair and are only applicable when the existing pavement is in good to excellent condition, they are mainly used to remedy surface distress in otherwise sound concrete when traffic volumes or loads are anticipated to increase significantly beyond the original design levels (Fick et al. 2021).

For concrete overlays of asphalt, COA-B are generally thinner than COA-U overlays because of the increased structural capacity afforded by designing the concrete as bonding with the underlying asphalt layers. The Guide to Concrete Overlays recommends a minimum of 3 in. of existing asphalt for proper bonding of a COA-B (Fick et al. 2021).

The Guide to Concrete Overlays also notes that thicker concrete overlays (over asphalt) can be so stiff that the underlying asphalt does not contribute in the same way as for thinner overlays, so at a certain overlay thickness they should be designed as COA-U overlays (Fick et al. 2021). Anecdotally, this value has been noted to be at about 6.5 in.

Pavement ME Design has, from the beginning, performed designs that would be considered COC-U, COC-B, and COA-U as a part of JPCP and CRCP rehabilitation designs. As noted later in this chapter, a design method for COA-B was added in version 2.3 of the Pavement ME Design software with the addition of the SJPCP design. The MOP and the Pavement ME Design software currently use the following terminology for JPCP rehabilitation designs (the new terminology/grouping is not in the MOP but is noted in parenthesis below):

- CPR for concrete pavement rehabilitation
- Unbonded JPCP overlay of existing rigid pavement (COC-U)
- Bonded PCC overlay of existing JPCP (COC-B)

- JPCP overlay of existing flexible pavement (COA-U)
- SJPCP for short jointed bonded concrete overlay of existing asphalt (COA-B)

And the following for CRCP rehabilitation design:

- Unbonded CRCP overlay of existing rigid pavement (COC-U)
- Bonded PCC overlay of existing CRCP (COC-B)
- CRCP overlay of existing flexible pavement (COA-U)

These are termed Rehabilitation Design with PCC Overlays in the MOP, and the original calibration of the models is documented in Appendix NN of the NCHRP 1-37A report (ARA, Inc. 2004). Appendix NN notes that the algorithms and models in Table 5 were evaluated separately for rehabilitation design.

Table 5. Algorithms and models evaluated for overlays

Algorithm(s):	JPCP and CRCP load transfer efficiency (LTE)	JPCP differential energy of subgrade deformation (DE)	JPCP fatigue damage (CRK_{TD} and CRK_{BU})	CRCP crack width
Model:	JPCP faulting		JPCP cracking	CRCP punchouts

Source: ARA, Inc. 2004, NCHRP 1-37A MEPDG

The original MEPDG used the term ultra-thin concrete overlay (UTCOL) to describe a thinner concrete overlay over asphalt that counted on bonding (now termed COA-B) but also noted that the MEPDG did not include a design procedure to cover it (as previously noted, SJPCP was not part of the original Pavement ME Design software).

Table 6 highlights the current Pavement ME Design methods for JPCP in relation to the terminology in the 2021 Guide to Concrete overlays.

Table 6. Types of JPCP overlays and Pavement ME Design methods

New terminology:	COC-U or COA-U	COA-B	COA-B	COC-B
Historical description:	**Conventional PCC overlay**	**Whitetopping/ thin overlay[1]**	**Ultra-thin whitetopping[1]**	**Bonded concrete overlay**
Pavement ME Design method[2]:	**Unbonded JPCP overlay of existing rigid pavement, and JPCP overlay of existing flexible pavement**	**SJPCP**	**N/A**	**Bonded PCC overlay of existing JPCP**
Appropriate Thickness:	≥ 6 in.	4–8 in.	< 4 in.	2–5 in.
Joint Spacing:	> 10 ft	5–8 ft joints (5x5, 6x6, 7x7, 8x8)	4-6 ft joints (4x4, 5x5, 6x6)	Match underlying concrete
Design Assumptions:	Unbonded (over asphalt, concrete, or composite)	Bonded to existing asphalt	Bonded to existing asphalt	Bonded to existing concrete
Other methods to design using Pavement ME Design:	**Design as new concrete pavement, modeling existing pavement as a base**	**N/A**	**N/A**	**Design as new concrete pavement (final thickness ≅ overlay + existing)**

[1] The terms whitetopping or ultra-thin whitetopping were also used previously in relation to COA-B and are included here for historical purposes only
[2] Other design methods (besides Pavement ME Design) are available for concrete overlays and can be found in the Guide to Concrete Overlays (Fick et al. 2021)

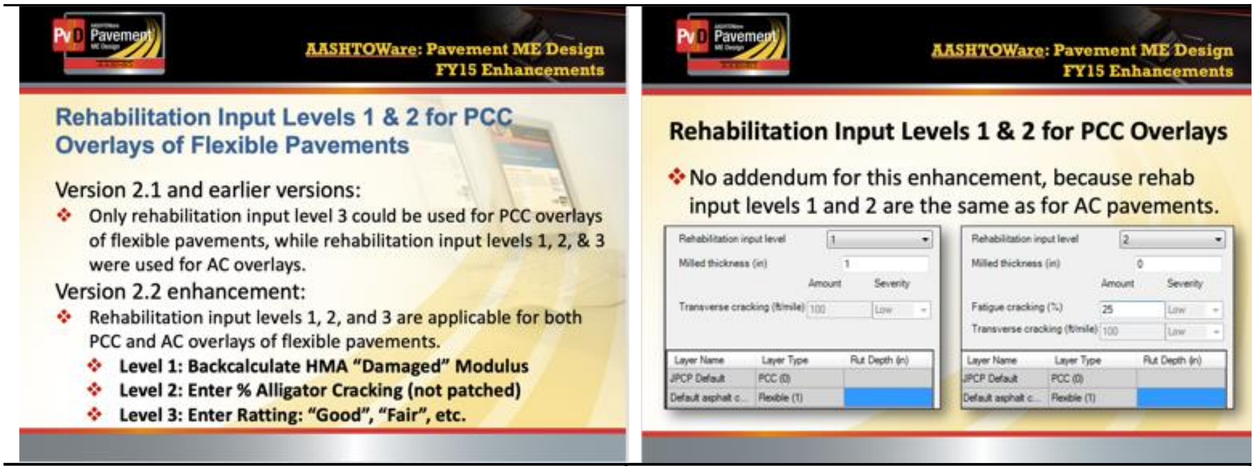
Table 6 provides the historical description for the overlay and the Pavement ME Design method used to design the pavement, along with the appropriate thickness and joint spacing for that design method and the design assumptions. The last row in the table lists potential alternate design methodologies using Pavement ME Design.

Unbonded concrete overlays over concrete (COC-U) are modeled very similar to new concrete pavements in the Pavement ME Design software. The JPCP faulting equations and the CRCP equations are the same as previously noted. JPCP transverse cracking is modified by adding a value of $CRK_{repaired}$, which is the percent of existing transverse cracks repaired as shown at the end of equation (10).

$$TC = [CRK_{BU} + CRK_{TD} - (CRK_{BU} \times CRK_{TD})] \times 100 - CRK_{repaired} \quad \textbf{(10)}$$

The fatigue damage equation also includes an estimate of the past fatigue damage.

One change in the Pavement ME Design software related to concrete overlays involved the way the existing asphalt pavement could be modeled for unbonded concrete overlays over asphalt (COA-U). Version 2.2 of the software allowed the use of input levels 1 (backcalculated HMA modulus), 2 (percent alligator cracking), and 3 (good/fair/poor) for PCC overlays of flexible pavements. The previous version 2.1 only had input level 3 available for describing the existing asphalt for concrete overlays. This change was not included in an addendum since the levels used to describe the existing asphalt were already used in the AC overlay model. However, it was noted in the v2.2 webinar, as shown in Figure 21.



AASHTOWare Pavement ME Design, used with permission

Figure 21. Rehab levels added for PCC over asphalt as described in webinar v2.2

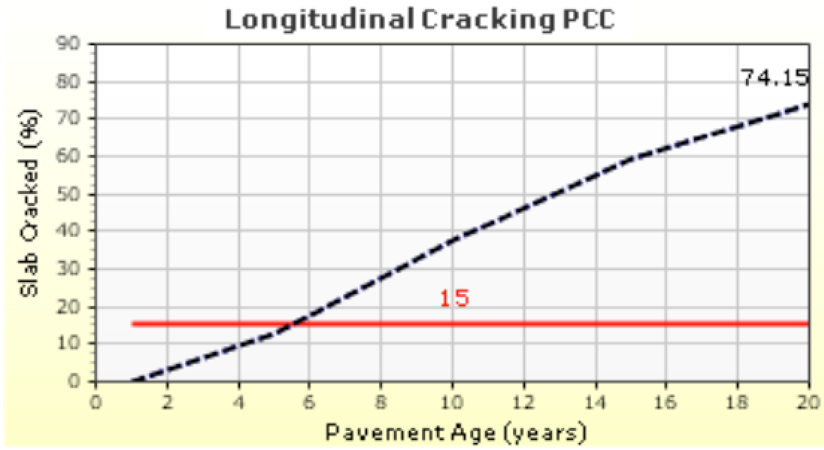
Prior to the v2.2 recalibration (for the CTE issue) new concrete pavements and concrete overlays had different global calibration factors, as they were originally calibrated separately. The last concrete pavement recalibration combined new pavements and overlays. Therefore, global calibration factors for both new concrete pavements and COC-U, COC-B, and COA-U overlays are now the same.

Thin Concrete Overlays (SJPCP)

The major change to Pavement ME Design in relation to overlays was the addition of the SJPCP overlay module in the 2016 version 2.3. This design is for COA-B overlays. The design is limited to slabs 4–8 in. thick and for joint spacings of 5–8 ft. Joints in these types of overlays are typically made such that they are included in square panels (i.e., 6 ft by 6 ft panels in a 12 ft wide lane).

While the mechanistic modeling performed by Pavement ME Design is, in general, similar to the JPCP transverse cracking model (with the use of an FEM to model critical loading locations), the model predicts only bottom-up longitudinal slab cracking. Given the slabs are smaller than conventional JPCP panels, the loading on the slabs is different than for JPCP.

The SJPCP model does not predict transvere cracking, faulting, or IRI at this time, only longitudinal cracking (Li and Vandenbossche 2013). Longitudinal cracking is described as the percent of slabs longitudinally cracked in the wheel path. An example of a distress chart showing predicted cracking over time from the Pavement ME Design output for an SJPCP design (failed at ~6 years) is shown in Figure 22.



AASHTOWare Pavement ME Design, used with permission

Figure 22. SJPCP longitudinal cracking prediction

SJPCP uses a constant default value of 65% fatigue cracking for the underlying asphalt pavement. A value of 80% for LTE is used for calibration, but the software does allow the LTE to be varied from 25 to 95%. For global calibration, the C_1 and C_2 calibration factors are the same as they are for the JPCP model. The C_4 and C_5 factors are different. The graph in Figure 23 shows a comparison of the relationship between predicted cracking and fatigue damage based on the current global calibration factors for JPCP and SJPCP, and the prior global calibration factor for JPCP.

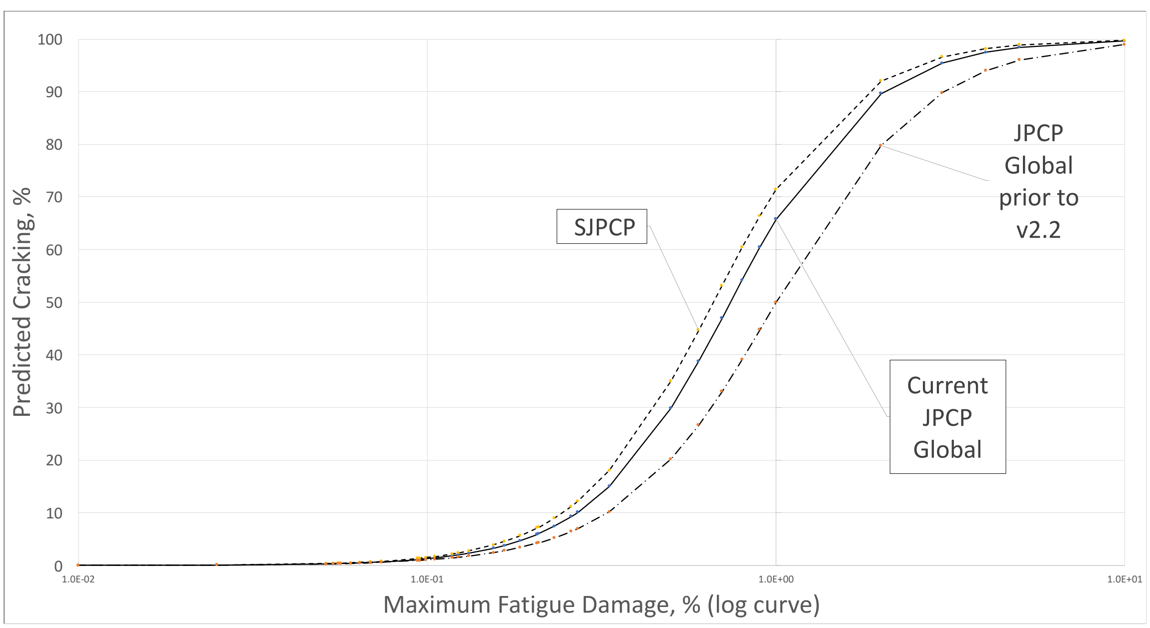


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Figure 23. Comparison of JPCP and SJPCP calibration factors

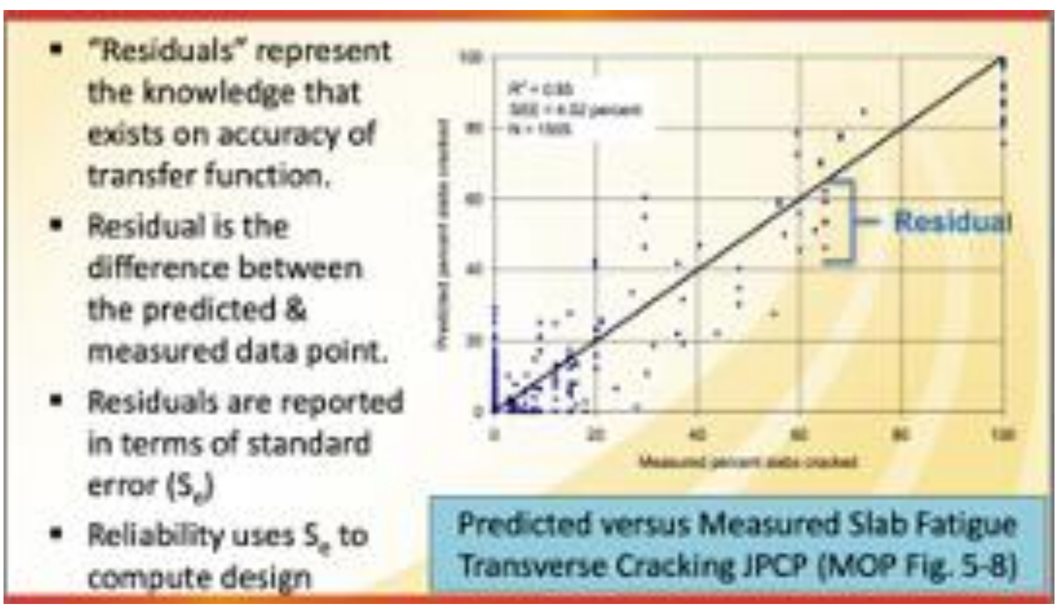
The SJPCP exhibits slightly higher cracking for the same fatigue damage as related to the current JPCP global factors.

LOCAL CALIBRATION

Local verification of AASHTO Pavement ME outputs is recommended to confirm precision of Pavement ME Design designs for both asphalt and concrete surfaced pavements. Local verification involves comparing Pavement ME Design performance outputs (cracking, faulting, IRI) to actual performance measured in real pavement sections used by a state or region.

The global calibration factors used in verification (built into the software) are based on national data, which may not represent the conditions of a particular state or region. The global calibration factors for JPCP currently included in Pavement ME Design are based on 381 LTPP sections, with nine sites from MnROAD and eight sections from the original AASHO Road Test in Ottawa Illinois. The global calibration factors for the CRCP model are based on 94 LTPP sites (Sachs et al. 2015).

If the verification process identifies that the global calibration factors do not accurately reflect local conditions, local calibration is necessary. Local calibration involves adjusting calibration factors such that the performance predicted from the Pavement ME Design software and the actual measured performance is aligned as close as possible. Figure 24 shows an example of a predicted versus measured graph for JPC transverse cracking that was used in the March 13, 2013 webinar.



Line graph: AASHTO Mechanistic-Empirical Pavement Design Guide: A Manual of Practice, used with permission

Figure 24. Residuals in calibration

The line of equality (percent predicted = percent measured) represents a perfectly calibrated model. The difference from the line of equality to the data points are termed the residual values. The smaller these residuals (differences) are, the closer the model is representing actual conditions, representing the accuracy of the model. If the values are found consistently above or below the line of equality, it indicates a bias in the prediction. That means the Pavement ME Design software consistently underpredicts or overpredicts the actual distress. Either bias or a lack of accuracy, or both, are reasons to perform local calibration. SEE, S_e, or standard error of the estimate is used to describe the error and is related to the sum of the residual values.

Local calibration involves some interpretation in both inputs and outputs, as follows:

- The use of existing materials, climate, and traffic data for roadway sections, which may or may not be complete
- Recognizing the differences in definitions for distresses, which may or may not be different than what is used in Pavement ME Design

It is important that the inputs are consistent with the Pavement ME Design definitions (i.e., distresses measured for use in calibration align with the distress definitions used in Pavement ME Design) and that they match the agency's pavement design practices. Recently, LTPP has added downloadable excel files of data for the JPCP General Pavement Study (GPS) 3 and SPS 2 experiments to the InfoPave website (at https://infopave.fhwa.dot.gov/), which will be beneficial in having consistency in the inputs for the LTPP sites used in local calibration. The data on the InfoPave site includes layer properties and basic traffic information and LTPP measured performance. States can use these data combined with their own data to improve the calibration for their conditions.

Calibration Factors

Calibration only affects the "transfer function" portion of the MEPDG. The mechanistic models (fatigue cracking, climatic [EICM], and PCC strength gain) are assumed correct. The transfer functions transfer the pavement responses computed by the models into predicted distress.

The specific calibration factors that can be adjusted for concrete pavements are shown in Table 7 for JPCP, SJPCP, and CRCP pavements.

Table 7. Concrete pavement calibration factors

Distress	# of Cal. Factors	Calibration Factors
Faulting	8(10*)	C1–C8, *C12, and *C34
JPCP transverse cracking	4	C1, C2, C4, C5
SJPCP longitudinal cracking	4	C1, C2, C4, C5
JPCP IRI	4	CJ1 (CRK), CJ2 (SPALL**), CJ3 (TFAULT), CJ4 (SF***)
CRCP punchouts	3	C3, C4, C5
CRCP cracking	2	C1, C2
CRCP Crack width	1	Cc
CRCP IRI	2	C1 (PO), C2 (SF)

*C12 and C34 are combinations of C1, C2, and C3, C4, respectively
**SPALL = function of age, freeze-thaw cycles, joint properties, and concrete slab thickness
*** Site Factor (SF) = AGE(1+0.5556×FI)(1=P200)×10^{-6}, where FI is the freezing index and P200 is the percent fines

Every distress and each input into the IRI equation has a calibration factor. JPCP IRI has four calibration factors (CJ1–CJ4) and CRCP IRI has two (C1 and C2). Note that most local calibration factors are notated using Ci, but they are not totally interchangeable (i.e., C1 for JPCP faulting has no relation to C1 for JPCP cracking). But C1 and C2 for JPCP cracking and CRCP cracking are based on the same cracking fatigue relationships for concrete and are the same global values.

It has been recommended in the webinars to not change the C1 and C2 values for the cracking model just based on a numerical/statistical adjustment. The values are based on typical 15 ft joint spacing. Some states have made modifications based on their use of 20 ft joint spacing instead of 15 ft joint spacing in their JPC pavements (Ceylan et al. 2015, Wu and Xiao 2016). Each model also has a standard error equation that is used in the reliability analysis. The previous Figure 24 shows what the residuals represent and how they are related to standard error (also termed S_e or standard error of the estimate [SEE]). Each calibration factor can have a different effect on the accuracy (bias and error) of the distress prediction.

AASHTO's Local Guide for Calibration, published in 2010, describes the local calibration process in detail. Three training webinars were also developed in 2014 that covered local calibration (see Appendix Table B.2). Since that time, new understanding on the performance data and data inputs, the models, the limitations, and the improvements needed have been uncovered as states have performed local calibration and really looked closely at their data and the predictions from the software in detail. Some of these details and improvements suggested for the Local Calibration guide are in a recent NCHRP online report (Geary 2018). The Calibration Assistance Tool (CAT) was also recently released to aid in local calibration efforts, and the next section briefly describes this new tool.

CAT – Calibration Assistance Tool

The CAT is a recent web-only tool that can assist in verifying global calibration factors and in performing local calibration. Users can upload their own Pavement ME Design (.dgpx) files from local projects along with the measured distresses from those projects. The CAT performs a guided process through the data assessment steps of the local calibration process described in the Local Calibration Guide. Users can upload their own information, combined with that from LTPP sites, to perform the verification and calibration and validation steps of local calibration. Figure 25 is an example of verification results from the one of the webinars related to use of the CAT.

AASHTOWare Pavement ME Design, used with permission

Figure 25. CAT tool sample verification results from webinar

The CAT can produce a file of local calibration coefficients that can be directly imported into Pavement ME Design. See Table B.2 in the appendix for the webinars that cover the CAT.

MEPDG USER GROUP

User Group – What It Is

A transportation pooled fund study—TPF-5(305)—was created to assist in coordination of the implementation of Pavement ME Design by state DOTs and other entities. Twenty-one state DOTs and two Canadian provinces contributed to the pooled fund. Five meetings have been conducted yearly in the fall to provide users of Pavement ME Design an opportunity to share information and learn from others. The locations by year of the past meetings are as follows:

1. Indiana, 2016
2. Colorado, 2017
3. Tennessee, 2018
4. Louisiana, 2019
5. Virtual, 2020

The reports of the meetings are now housed on the AASHTOWare Pavement ME Design website under Information/User Groups along with other User Group training materials (found directly at https://me-design.com/MEDesign/UserGroup.html).

The meetings entail presentations related to Pavement ME Design but also include discussions with the participants related to their implementation efforts and the challenges they are facing or have surmounted.

Past Meetings – Discussion Items

Status and issues related to Pavement ME Design implementation are typical discussion items of the MEPDG User Group meetings, with the intent to share knowledge and identify improvements that can be made for users. Some of the issues noted in prior user group meetings include the following:

- Widened slab option sometimes appears to have a larger than expected effect on pavement performance, appears to provide unrealistically low thicknesses at times, and best to run design with and without widened slab to compare.

- Due to occasional very thin or very thick slab thicknesses from Pavement ME Design, some states have adopted a process where they limit the minimum or maximum slab thickness by running their previous programs (i.e., AASHTO 93 or Portland Cement Association [PCA] method, now available as StreetPave [ACPA 2021]) and using that thickness +/- one inch as a limiting value.

- The DE equation in the faulting model is related to the ratio of steel in the dowel bars to concrete thickness. This sometimes produces an anomaly where a thicker pavement with the same dowel bar size will show worse performance.

- The faulting model itself may drive the thickness in some cases, which may or may not be warranted. Some states are not using the faulting results due to this concern.

- Some states are only using cracking to design thickness, not faulting or IRI. One reason noted for this is that the models for faulting and IRI rely more on empirical components than on the cracking models.

- Realization that sensitivity is not a constant–if the calibration changes, different inputs can become sensitive that were not sensitive previously. For example, Michigan found that CTE became more sensitive in v2.3 then it was in v2.0.

- Only dowel thickness is considered in Pavement ME Design, not dowel type.

- Some states (California and Washington) have created design catalogs using MEPDG.

Michigan noted they implemented Pavement ME Design in 2014 but then went on hiatus and back to their previous design method due to overly thick designs after they recalibrated to version 2.0. They also found a significant decrease in slab thickness when they used the same version 2.0 local calibration factors in version 2.2 (Haider et al. 2018). After recalibration to v2.5.3, they now run both methods (Pavement ME Design and AASHTO 93) and use the Pavement ME Design thickness value if it is within 1 in. of the AASHTO 93 value. Other states (North Carolina, Iowa) have also reported unusual results from recalibrations.

Past Meetings – Survey Comparisons

Prior to the annual meetings, a survey is typically sent out to each state. This section attempts to compare the survey results of the 2016 through 2019 pre-meeting surveys. It should be recognized that the survey has changed some over time and that not all states respond to the survey each year, so the states responding and noted in Table 8 and Table 9 may not be the same from one year to the next.

Table 8. Implemented Pavement ME Design for asphalt?

Year	Total	Yes	%	No	%
2016	25	10	40	15	60
2017	21	9	43	12	57
2018	26	9	35	17	65
2019	29	13	45	16	55

Table 9. Implemented Pavement ME Design for concrete?

Year	Total	Yes	%	No	%
2016	25	6	24	19	76
2017	21	7	33	14	67
2018	26	12	46	14	54
2019	29	14	48	15	52

Looking at the individual surveys and survey respondents over time reveals 39 different respondents in the four years, with 35 state DOTs and 4 Canadian provinces. Overall (based on all four survey years), 18 state DOTs and 1 Canadian province noted that they had implemented Pavement ME Design for concrete. Another 11 state DOTs and 2 Canadian provinces that had not implemented it at the last survey (2019) did note that they planned to implement it. Therefore, more than half of the state DOTs (29) and 3 of the 4 Canadian provinces responding to the survey could potentially implement the concrete portion of Pavement ME Design in the near future.

The surveys also asked what the respondent felt were the top implementation challenges. Table 10 provides the top three issues each year, rated by the number of respondents that selected it as an issue.

Table 10. Top Pavement ME Design implementation issues

Year/ # of respondents	Top issue (# of respondents choosing)	2nd top issue ((# of respondents choosing)	3rd top issue ((# of respondents choosing)
2016/25	Local calibration (12)	Data inputs (8)	Performance data availability (7)
2017/21	Local calibration (10)	Features not in or not calibrated for PMED (5)	Performance data availability (4) HMA inputs (4)
2018/26	Local calibration (13)	Features not in or not calibrated for PMED (8)	Data inputs (6)
2019/29	Local calibration (18)	Data inputs (9)	Features not in or not calibrated for PMED (7) Performance data availability (7)

Local calibration has consistently been a top issue. Lack of data and features not included in the Pavement ME Design software were also consistently in the top three.

Along with the survey results and implementation discussions, the user group meetings also include presentations in new research or specific training for new additions to Pavement ME Design. The five reports and associated appendices are currently available on the Transportation Pooled Fund website at https://www.pooledfund.org/Details/Study/549.

RESEARCH IN PROGRESS

As previously noted, the next version of AASHTO Pavement ME Design, v3.0, is anticipated in July 2022 and will be a web enabled version. This version is also scheduled to include an improvement directly related to concrete pavements. The AASHTO Task Force for Pavement ME Design recently approved these enhancement activities for FY 2022: integrate NCHRP 1-51 results and update the global calibration for concrete pavements using MERRA2 data.

Beyond the web-enabled interface, if the recently approved enhancements are incorporated as expected, v3.0 will be a major revision for concrete pavements. It will incorporate a new slab-base interaction model for both JPCP and CRCP based on NCHRP Project 1-51, which will include new models and a total recalibration for concrete pavements.

The current Pavement ME Design assumes that the built-in curl in the slab is constant and also does not account for changes in bonding between the base and slab over time. The effect of the revisions should be that distress seen in practice from concrete pavements over very stiff bases will be modeled more effectively (Khazanovich and Tompkins 2017). These changes will affect the JPCP transverse cracking and faulting models and the CRCP punchout model. This will not just affect designs with stiff bases, as the revised Pavement ME Design concrete models will also be recalibrated with MERRA2 data, so that MERRA2 data can be used for both asphalt and concrete pavements.

Other NCHRP research projects that were designed to be incorporated into Pavement ME Design are still pending and include NCHRP 1-50 (Lou et al. 2017) on geosynthetics in pavements and NCHRP 1-53 (Lytton et al. 2019) on subgrade and unbound layers. Other national projects that are noted as still active (underway) that may have a future effect on Pavement ME Design include the following:

- NCHRP 1-59, Proposed Enhancements to Pavement ME Design: Improved Consideration of the Influence of Subgrade Soils Susceptible to Shrink/Swell and/or Frost Heave on Pavement Performance: Related to including the consideration of subgrade soils with shrink/swell or frost heave movement

- NCHRP 20-50(20), LTPP Data Analysis: Develop Practical Tools and Procedures to Improve WIM Data Quality: Improve accuracy of WIM data used in traffic

- NCHRP 20-50(21), Enhancements of Climatic Inputs and Related Models for Pavement ME Using LTPP Climate Tool (MERRA-2): Evaluate the impact of the enhancement of climate data with MERRA2 data

CONCLUSION

This synthesis just touches on the complexity of the Pavement ME Design software. Even after reading the 200+ pages of the MOP, you will not be an expert. The original NCHRP 1-37A report includes almost 40 different parts and is well over 4,500 pages of information (ARA 2004). The research that developed the MEPDG and continues to be used to globally and locally calibrate the Pavement ME Design software uses volumes of data from the LTPP program, which is the largest pavement performance database ever developed.

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APPENDIX A: NCHRP 1-37A TO AASHTO DARWIN-ME (BEFORE PAVEMENT ME DESIGN)

- The original MEPDG project (NCHRP 1-37A) started in 1998 as the "Development of the 2002 Guide for the Design of New and Rehabilitated Pavement Structures: Phase II."
- The MEPDG software was first made available to the state DOTs in a compact disc (CD) version released in July 2004. This version has been noted as MEPDG v0.7.
- MEPDG v0.8 was issued in November 2005 and v0.9 was issued in July 2006.
- The 2007 version is noted as MEPDG v1.0.
- MEPDG v1.1 was identified as being released in September 2009.
- AASHTO DARWin-ME released in April 2011 is identified as being based on version 1.1 of the MEPDG.

The actual changes to the software from the timeframe before AASHTOWare Pavement ME Design or PMED are not well documented except for the v0.8 and v0.9 changes (noted below in NCHRP 1-40D). The NCHRP projects and associated reports and most relevant references to consult for additional information on the history are noted below:

- NCHRP 1-37, draft work plan for MEPDG, no report found on the website
- NCHRP 1-37A, Development of the 2002 Guide for the Design of New and Rehabilitated Pavement Structures: Phase II. The original MEPDG documents are all located online (http://onlinepubs.trb.org/onlinepubs/archive/mepdg/guide.htm)
- NCHRP 1-37A(01), original CD version of the software dated July 2004
- NCHRP 1-38, Web Only Document 35: Rehabilitation Strategies for Highway Pavements
- NCHRP 1-39, Traffic, NCHRP Report 509: Equipment for Collecting Traffic Load Data and 539: Traffic Data Collection, Analysis, and Forecasting for Mechanistic Pavement Design (TrafLoad)
- NCHRP 1-40, precursor to 1-40D, no report found on the website
- NCHRP 1-40A, Research Results Digest 307: Independent Review of the Mechanistic Empirical-Pavement Design Guide and Software (http://www.trb.org/Main/Public/Blurbs/158282.aspx)
- NCHRP 1-40B, developed Local Calibration Guide (2010) and Manual of Practice (2008)
- NCHRP 1-40D, Changes to the Mechanistic-Empirical Pavement Design Guide Software Through Version 0.900, July 2006, Research Result Digest xxx (no number) (http://onlinepubs.trb.org/onlinepubs/archive/mepdg/DraftDigest.pdf)
- NCHRP 1-47, Sensitivity Evaluation of MEPDG Performance Prediction, NCHRP Report (http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP01-47_FR.pdf) and NCHRP Research Results Digest 372 (http://www.trb.org/Publications/Blurbs/168712.aspx)
- NCHRP 1-48, Incorporating Pavement Preservation into the MEPDG, NCHRP Report 810: Consideration of Preservation in Pavement Design and Analysis Procedures (http://www.trb.org/Main/Blurbs/172941.aspx)

APPENDIX B: PAVEMENT ME DESIGN VERSIONS, CALIBRATION, AND WEBINARS

Versions and Calibration

Table B.1 provides a chronology of the major versions released, similar in chronology to Figure 3 in the main report, but also notes if recalibration is necessary due to the software change.

Table B.1. Pavement ME Design versions and tools by year released

Version/ Build -or- Tool	Year	Change/improvement	Release Note (RN: date)/ Addendum (#)	Recalibration required for concrete pavement design?
DARWin-ME	2011	DARWin-ME	RN: 8/12/2011 and 12/16/2011	N/A
PMED v1	2013	AASHTO Pavement ME Design (PMED) v1 (Build 1.3.29)	N/A – 3/26/2013	No – Software name changed only
Educational Version	2013	PMED Educational Version Released	RN: 7/1/2013 (Build 1.5.08)	N/A
PMED v2.1 (Build 2.1.22)	2014	Subgrade moduli added to Sensitivity analysis. Bug fix for Bonded PCC over CRCP	RN: 7/28/2014	No
PMED v2.2 (Build 2.2)	2015	CTE recalibrated, affected PCC and CRCP calibration	RN: 8/11/2015 #FY2015.2	Yes, globally recalibrated – affects cracking, faulting, and IRI
" "	2015	3 new traffic NALS added, addressed concern that original NALS included too many heavy axle loads	RN: 8/11/2015 #FY2015.1	No– unless you use the new NALS
" "	2015	PCC overlays modified - added ability to model existing AC pavements with input levels 1 and 2	RN: 8/11/2015	No – unless have data to support
TOOL	2015	MapME, standalone tool to create .dgpx files based on location of project	RN: 8/11/2015	N/A
PMED v2.3	2016	SJPCP model added	RN: 7/1/2016 #FY2016.01	Globally calibrated – local calibration possible if have data to support
PMED v2.3	2016	NARR climate files added	RN: 7/1/2016 #FY2016.02	Not globally recalibrated – but potentially can affect local calibration if 2016 local climate data is very different between old climate data and new NARR
TOOL	2017	Backcalculation Tool added to Website	BcT release notes & User Manual	N/A

Version/ Build -or- Tool	Year	Change/improvement	Release Note (RN: date)/ Addendum (#)	Recalibration required for concrete pavement design?
PMED v2.5	2018	Comparator Tool enhanced, compares 2 project (.dgpx) files	RN: 7/1/2018	No
" "	2018	Preventative maintenance strategy method added	RN: 7/1/2018 #FY2018.6	No
" "	2018	Semi-rigid calibration factors added	RN:7/1/2018 #FY2018.4	First global calibration of semi-rigid (asphalt over chemically stabilized base)
PMED v2.5.5	2019	Climate Selection User Interface added to PMED (Google Maps)	RN: 7/1/2019	No
TOOL	2019	RePave Tool added (from SHRP2 R23)	N/A- links to pavementrenewal.org website	N/A
TOOL	2019	Calibrator Assistance Tool (CAT) added to Website	N/A-Oct. 2019	N/A
Pavement ME Design v2.6	2020	Current Version	RN:7/1/2020	No – not for JPCP, SJPCP, or CRCP

The column labeled Release Note/Addendum indicates if the changes were documented in a Release Note, an Addendum or both. The Release Notes and Addendums can be found on the https://www.me-design.com/ website.

The Release Notes provide a documented trail of the software changes. The Addendums describe the changes and are intended as add-ons to the Manual of Practice (MOP). The contents of the Addendums are formally incorporated into the MOP as it is updated. The wording may change slightly from the Addendum, as the changes are balloted through the AASHTO Committee on Materials and Pavements (COMP) prior to addition to the MOP. All the Addendums noted in Table B.1 have been incorporated into the latest edition (3rd) of the MOP.

Webinars

Table B.2 focuses on the recorded webinars that are currently available on the https://me-design.com/MEDesign/Webinars.html webpage, and the version and information that they cover as related to PCC pavements is listed in the rightmost column of the table.

Table B.2. Pavement ME Design webinars

PMED Webinar	Year	Change/improvement covered
7 original training webinars	2012/2013	AASHTO Pavement ME Design (PMED) v1 basics of climate, traffic, materials, design of new and rehabilitated pavements
3 original training webinars on local calibration	2014	Introduction, Preparing for, and Determining the Local Calibration Coefficients for Local Calibration
Version 2.2	2015	New calibration coefficients for PCC 3 new traffic NALS discussed Rehab level 1 & 2 for PCC over asphalt described
Version 2.3	2016	SJPCP model Map ME discussed New NARR climate files
Backcalculation Tool 1.0	2017	Backcalculation Tool overview
Version 2.5#01	2018	Comparator Tool discussed, compares 2 project (.dgpx) files
Version 2.5#02	2018	Preventive maintenance strategy method added to reset faulting values and IRI to model diamond grinding or ultra-thin overlays mentioned
Version 2.5#03	2018	Semi-rigid calibration factors discussed
PMED v2.5.5, P1	2019	Climate Selection User Interface covered (Google Maps)
PMED v2.5.5, P1&P2	2019	Calibrator Assistance Tool (CAT) described, and examples shown
Pavement ME Design v2.6.0	2020	Current Version of software (webinar covers changes from v2.5.5, which are only related to flexible pavements)
FY21- Webinar Series 1 and 2 on CAT	2020	Getting Started with Local Calibration and Local Calibration Using the Calibration Assistance Tool
BcT	2021	FWD and Backcalculation using the BcT tool (not on the website yet as of August 2021)

The live training started in December 2012. The original webinars were put on with the assistance of the FHWA. The recorded ME Design webinar series is now hosted on the https://me-design.com/MEDesign/Webinars.html webpage.

The webinars site has two tabs, Training and Enhancement Webinars. The Training tab includes a total of 10 webinars: 7 webinars that provide a general overview of the different pieces of the Pavement ME software (climate, traffic, materials, new and rehabilitation design) and 3 on local calibration. The local calibration webinars are Webinar 1 (04/14/2014) which provided a general overview of the local calibration process, including the 11 steps in the process. Webinar 2 (04/21/2014) focuses on steps 1–6 in detail, covering the distress data and inputs. Webinar 3 (05/06/2014) focuses on steps 7–11 in detail, with the mathematical portion of local calibration, including model fitting. (See Local Calibration chapter for details.)

The Enhancement webinars cover the different versions of the software and the added tools. Version 2.2, 2.3., 2.5, 2.5.5, and 2.6 each have training webinars. There are also separate webinars on the Backcalculation Tool (BcT) and the Calibration Tool (CAT). In late 2020, two webinars on the CAT were held and the recordings posted to the website under FY 21 webinars.

A new BcT webinar was held February 23, 2021 to address the latest changes to the BcT Tool, and the webinar will also be added to the website. The previous Table B.2 indicates which Webinar addresses the original change/improvement.

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