

Incorporating local calibrations into M-E rigid design tables based on the AASHTO M-E design procedure

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ABSTRACT

The paper describes the development of an agency-specific rigid design procedure using the AASHTO M-E design procedure. Furthermore, this local design procedure can include local calibrations of the mechanistic-empirical models used in the AASHTO M-E procedure. The local procedure restricts the user to pre-determined design input parameters, but in these restrictions provides the agency with the opportunity to closely investigate and design for local issues in pavement design. These parameters can include special climate files (or considerations), design cross-sections unique to an agency, traffic load spectra based on weigh-in-motion data, and special inputs related to local concretes. Furthermore, the localization of the AASHTO M-E procedure allows the agency the opportunity to develop an alternative to the AASHTO reliability analysis. The final local procedure can be implemented in whatever software the agency chooses. The final procedure is then beneficial in many aspects: 1) It provides a simplified design scheme that provides pavement engineers with near instantaneous design results, 2) The design results take advantage of the AASHTO M-E models yet include local calibrations and agency design considerations, and 3) The agency design procedure is under the control of the agency and can be modified, localized, upgraded, etc. at the discretion of the agency.

INTRODUCTION

Many state agencies are considering or working toward updating their standard thickness design procedures for rigid pavements. For many of these agencies, this update represents a significant step in moving from their locally developed empirical procedures. Many of these state procedures are based conservative empirical design procedures, such as the American Association of State Highway Transportation Officials (AASHTO) 1993 procedure for rigid pavements, commonly referred to as “AASHTO93” (AASHTO, 1993). In considering the change from an older, trusted procedure to a modern, mechanistic-empirical (M-E) alternative, agencies often hesitate to act given the challenges and time involved.

One alternative for agencies is to adopt the AASHTO M-E design procedure, and in turn, its associated software, such as the Mechanistic-Empirical Pavement Design Guide (MEPDG), DARWin-ME, or AASHTOWare Pavement M-E Design. However, these software packages can be difficult for state and local engineers to embrace due to the extent of design parameters in the AASHTO M-E design procedure. The vast amount of parameters to be varied can be intimidating to an engineer looking for a “first estimate” design tool, such as was provided by the older, trusted AASHTO 93-based design tool.

Thus, an ideal design solution at the state/local agency level is one that utilizes the current AASHTO M-E procedure yet requires inputs that resembling those (in number and

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specification) of previous state design tools. This paper details an approach that allows the agency to create a companion design tool for the AASHTO M-E software that gives access to AASHTO M-E design results using a simplified design process. The local design tool is guided by four main objectives:

1. M-E Design: The replacement procedure should be based upon the AASHTO M-E design procedure and associated software.
2. Limit design parameters: Design input parameters should be distilled to the most influential and relevant to pavement design.
3. Localization: The developed procedure should take advantage of A) local climate and traffic data and B) local calibrations of AASHTO M-E distress models.
4. Accessible software: The developed procedure should be easy to use and should be implemented in software that can be easily distributed and maintained by the agency.

In addition to these basic objectives, the agency can include additional objectives, such as additional, more advanced design inputs or improved reliability analysis that accounts for state/local perspectives. The end product of this approach is a simple design tool, described according to the approach objectives in the following subsections.

DETERMINE A M-E DESIGN BASIS

The first step in developing a local design tool is to determine the larger M-E design procedure to be used as a design basis. For state agencies, the AASHTO M-E design procedure represents the state-of-the-art in pavement design. (For agencies in other areas, other procedures may be appropriate.) This paper describes the effort to build a design tool using the AASHTO M-E procedure and its associated software. The selected software can then be used to conduct sensitivity analyses of performance predictions to important design inputs. Later, the selected software will be used to build a database of pavement design projects that represent the projects of interest to the agency. This database is effectively the new design tool – or “look-up table” – for the agency.

The selection of an appropriate software basis for the design tool should be considered carefully. Some factors in the agency selection of a procedure and software include:

- Are agency research staff familiar with the procedure and software?
- Does the agency have immediate access to the software, and can the software be used easily? The development of the design tool requires a large number of project files and simulations in selecting design inputs and building a project database.
- Can the procedure be related to previous agency research design and/or model calibration efforts?

For this paper, the assumed design basis is that of the AASHTO M-E procedure as implemented in MEPDG version 1.1 (NCHRP, 2003) and detailed in the MEPDG Manual of Practice (AASHTO, 2008). However, the methods described in this paper are appropriate for any other version of the AASHTO M-E design software.

IMPROVE DATABASE USING LOCAL DATA

Using agency climate data

Given the understanding of environmental loads in pavement response and distress performance, one feature of the AASHTO M-E procedure is the extensive use of climate data to estimate pavement drainage, support conditions, and response to loads. The effect of environment is well understood at the local level, as well, and it is not uncommon for state or provincial agencies to maintain a database of climate information that inform local designs. Thus it follows that agencies would incorporate this climate information into a local procedure for design.

The use of climate information requires that the agency build climate files that accord with the given version of the AASHTO M-E software being used for the project database. This can involve the creation of hourly climate data files (designated *.hcd) or integrated climate files (designated *.icm). Alternatively, the user can build and save these files from within the AASHTO M-E software if more recent versions, such as Pavement ME 2.1.24, are being used. Whatever the decision, the use of agency climate data in the design table project database is manageable and straightforward.

Using agency traffic data

Another important aspect of incorporating the agency experience into a design table is the use of locally available traffic data. For many agencies, this process will utilize axle load spectra developed from agency weigh-in-motion (WIM) data. Unlike the use of climate files, the development of load spectra axle files for the AASHTO M-E procedure is much more involved. While the process is not intellectually demanding, it requires careful accounting to ensure that the agency experience (i.e. the WIM data) is faithfully represented in the final load spectra files.

While there are automated tools available to build these load spectra files, the authors recommend that the agency build them “by-hand” to ensure that they are accurate and uncorrupted. Tompkins et al (2014b) provides step-by-step details on building the axle load spectra intermediate files to be used by the MEPDG – to the best of the authors’ knowledge, the load spectra files that result from the process described in Tompkins et al (2014b) are viable for any other of the software implementations of the AASHTO M-E procedure.

Incorporating agency calibrations of distress models

Given that the design tool is based upon the AASHTO M-E procedure, the design tool can accommodate non-default JPCP transverse cracking or JPCP joint faulting model coefficients as expressed in AASHTO (2008). In this way, local calibration coefficients developed in agency calibration studies for the AASHTO M-E models can be applied to the design tool, as the design tool will ultimately calculate distresses directly given user inputs. More on this topic can be found in the following section, specifically the subsection titled “Distress calculation and design table thickness result.”

SELECT RELEVANT DESIGN INPUTS AND OUTPUTS

The next step in development of a local thickness design tool is to select first important design inputs to be varied by the user of the design tool. With this information, the agency can build and run a full database of pavement design projects. The agency can then use performance

information from intermediate files in completed database to calculate distresses that control the agency's rigid design.

Final design inputs for rigid design database

The selection of design inputs should be based upon a series of sensitivity studies to determine the influence of a given input parameter on performance prediction. For instance, while subbase thickness may be a parameter the agency feels should be considered at many levels, the AASHTO M-E procedure exhibits little sensitivity to this parameter past critically thin values. Thus, while inputs should be relevant to state and local rigid projects, they should also be influential to minimize the number of inputs required of the user. Some important parameters that can be considered are:

- Climate, which can be varied by principality, county, district, city, etc. in a way that is meaningful to the agency;
- PCC modulus of rupture;
- PCC coefficient of thermal expansion;
- Joint spacing;
- Outer lane width; and
- Shoulder edge load-transfer efficiency.

Values for influential parameters that are more difficult to estimate, such as the effective load transfer on the shoulder edge for a paved or unpaved shoulder, should be assumed by the agency based on the results of sensitivity studies.

In addition to inputs that are known to strongly control design thickness, other inputs may be included to be varied in the project if they are of concern to the agency. However, there are both design and computing assumptions in the selection of these parameters and their associated values. For instance, joint spacing could assume a wide variety input values, but it does not make sense to assume values that the agency does not assume in its standard designs. Thus, limiting parameters to a sensible number of values helps to reduce the size of the database.

Defining project basis and creating database

In addition to the design features and properties to be varied for the design table, the agency must also select the inputs that will be held constant for every project in the database. As discussed previously, there are a significant number of inputs required for a given project in the AASHTO M-E procedure. These other inputs – meaning those that will not be varied by the agency – should be assigned values. Often the use of AASHTO default values is adequate. For some inputs (e.g. base thickness, subgrade type, or layer moduli), the agency may wish to create and use its own default values. An example of a final project basis is shown in Table 1, where both single and varied input values are indicated for layer properties.

Table 1. Example of default and varied input values for a design project basis [from Tompkins and Khazanovich, 2014]

MEPDG Design Features							
Curl/Warp Eff Temp Diff	Sealant Type	Joint Design		Base Properties			
		Dowel Diameter	Dowel Spacing	Erodibility Index	PCC-Base Interface	Loss of Friction	
-10	Liquid	1, 1.25, or 1.5 (MnDOT spec)	12	Erosion Resistant (3)	Full friction contact	360	

MEPDG Structure - Layer 1 - JPCP							
PCC General		PCC Thermal		PCC Mix			
Unit Weight	Poisson's Ratio	COTE	Thermal Conductivity	Heat Capacity	Cement content	W/C Ratio	Aggregate
150	0.2	5	1.25	0.28	500	0.40	Limestone

MEPDG Structure - Layer 2 - Base					
Material	Thickness	Strength Properties - Level 3			Notes
		Poisson's	CoLP, Ko	Modulus	
A-1-a	4	0.35	0.5	35640	Values estimate Class 5; modulus from lab tests

MEPDG Structure - Layer 3 - Subbase					
Material	Thickness	Strength Properties - Level 3			Notes
		Poisson's	CoLP, Ko	Modulus	
A-3	12	0.35	0.5	18350	Values estimate Select Granular; modulus from lab tests

MEPDG Structure - Layer 4 - Subgrade				
Material	Thickness	Strength Properties - Level 3		
		Poisson's	CoLP, Ko	Modulus
A-6	Semi-infinite	0.35	0.5	14000

These input values, in addition to selected climate files and/or traffic load spectra files, are used to create a full database of M-E project files. This database represents all projects of interest to the agency for its pavement design table.

In addition, the development of the database is complicated in that the selected projects for the final database must assume values for both thickness that span a range of acceptable thickness for all possible projects that the agency develops. For example, if an agency constructs projects no thinner than 7 inches and no thicker than 13 inches, than values spanning 7 to 13 inches should be selected. The smaller the interval between the values, the more accurate the interpolation for damage or differential energy later in the design tool analysis.

A similar procedure to the exception for thickness must be followed for other parameters that are to be incorporated in a non-discrete manner. One such parameter is the flexural strength of the PCC. Rather than restricting users to limited values, the agency may wish to provide more leeway by developing projects to account for variance in flexural strength. This variance can then be taken into account in the interpolation for damage/differential energy and possible reliability analysis.

Hence, if an agency wishes to develop a database for a design table that accounts for 3 climate files, 2 load spectra files, 7 PCC thickness values, 2 PCC modulus of rupture values, 2 joint spacing values, 2 outer lane width values, then the total factorial of projects to be built and run using the AASHTO M-E software is $3 \times 2 \times 7 \times 2 \times 2 \times 2 = 336$ projects.

Performance criteria and reliability

The design table should provide a thickness estimate that meets the performance criteria determined by the agency. Given that the design tool is based upon the AASHTO M-E procedure, the performance criteria is restricted to those of the AASHTO M-E procedure for JPCP, which fall into three categories: faulting, transverse cracking, and roughness (IRI). The agency determination in this regard controls which intermediate project performance information will be used for the distress calculation and in turn the design thickness estimate.

- If transverse cracking is determined to be the controlling distress, than the design tool will utilize top-down and bottom-up damage calculations from the intermediate project files in the database.
- If joint faulting is determined to be the controlling distress, the design tool will use differential energy calculations from the intermediate project files.
- If roughness (IRI) is the controlling distress, the design tool will require both damage and differential energy calculations from the intermediate project files in the database.

The calculation of distresses from the indicated outputs in the intermediate files should be conducted according to the model equations as specified in AASHTO (2008) and NCHRP (2003). Given that the design tool will calculate distress according to the AASHTO M-E model equations, local calibration coefficients determined by the agency can be incorporated at this point in the transverse cracking and/or joint faulting calculation.

In addition to calculating the controlling distress, the agency may also wish to implement performance criteria based upon project location and anticipated traffic volume. These criteria follow AASHTO recommendations to vary cracking and reliability based upon traffic volume, the rationale being that higher volume roadways should be subject to more stringent design criteria (NCHRP, 2003; AASHTO, 2008). An example of agency-determined criteria for a design table is provided in Table 2.

Table 2. Example performance criteria selected for a rigid pavement design tool [from Tompkins and Khazanovich (2014)]

<i>Total trucks over service life</i>	Metro district (Minneapolis-St. Paul)		All other districts	
	<i>Reliability</i>	<i>Cracking</i>	<i>Reliability</i>	<i>Cracking</i>
6.5M or less	75%	6.5%	50%	15%
6.5M to 13M	90%	6.5%	75%	15%
13M or more	97.5%	6.5%	90%	15%

Finally, alternatives to the default AASHTO reliability analysis can also be included in the determination of the design thickness: one example is the use of known variation of as-constructed pavements in a Monte Carlo simulation, which allowed the reliability analysis to account for variation in PCC modulus of rupture and PCC thickness (Tompkins and Khazanovich, 2014).

Distress calculation and design table thickness result

The last stage in the use of the database and intermediate values associated with the controlling distress(es) is to calculate the distress for the level of damage/differential energy associated with

the user's project of interest. Finding the damage/differential energy is a simple "look-up" action in the design table, where the input values are all associated with a multidimensional table consisting of intermediate results. The calculation of the final distress requires the use of:

- The AASHTO M-E JPCP performance models as detailed in either NCHRP (2003), AASHTO (2008), or, ideally, the documentation (e.g. help files) associated with the AASHTO M-E software used to build the database. These equations are not reproduced here.
- AASHTO default or agency-specific calibration coefficients for the model(s) of interest. As alluded to previously, the distress calculation and calibration coefficients are another opportunity for the agency to "localize" the AASHTO M-E procedure.
- Bicubic interpolation methods detailed in NCHRP (2003) describing the damage calculation. Similar methods would be applied to the differential energy if faulting and/or IRI were controlling distresses. Again, the interpolation may be applied to more parameters than thickness if those additional parameters are of close interest to the agency

The use of the above, along with the look-up damage/differential energy, will be used alongside the agency-selected reliability method to determine the final design thickness.

IMPLEMENT DESIGN TOOL IN ACCESSIBLE SOFTWARE

The final thickness design tool can be implemented in many forms of software. The final software, to promote adoption, should limit user interaction to changing pavement design inputs and obtaining a design thickness. The different forms the software can take include:

- Microsoft Excel macro-enabled worksheet
- HTML/CSS table online
- Java (or similar simple scripting language) program

Whatever the form of the software, the software will be used to take the important inputs – as specified by the agency – and identify the project in the agency database of AASHTO M-E projects with those inputs. The software then uses the project intermediate information (i.e. damage and/or differential energy) for that project to calculate distress levels and consequently design thickness. The final software should be tested extensively to ensure that the design process clearly indicates design inputs and outputs.

Example of software implementation of agency design tool

The authors used the method described above to develop a design tool for the Minnesota Department of Transportation (MnDOT). This design tool was known at the time of its completion as "MnPCC-ME" (Tompkins and Khazanovich, 2014). The software implementation of the design tool is illustrated in Figure 1, where the Main tab (Figure 1a) contains all intended design parameters for a given project. The software was designed so that it can be used without the need to "learn" the program, but rather picked up and put to use immediately. One feature particular to this implementation is that MnDOT decided to include specific project inputs that

were restricted for use by only research engineers (Figure 1b). This includes the use of an alternative reliability method (which accounts for coefficients of variation for both slab thickness and flexural strength), AASHTO M-E model calibration coefficients, and additional performance criteria.

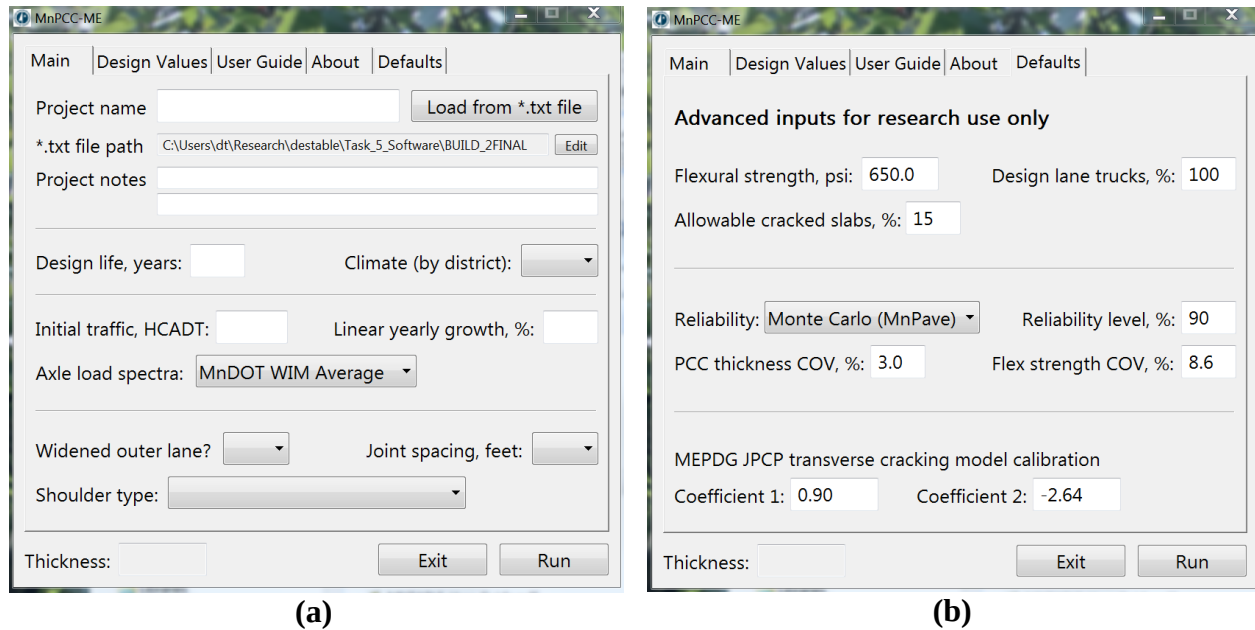


Figure 1. MnPCC-ME software interface

Finally, all projects created in the MnDOT design tool result in the creation of a simple project summary file upon clicking “Run.” The created summary file is in rich-text format and able to be read by any word processing program or simple text editing program, including the built-in text editor in Microsoft Windows. An illustration of a project summary file is provided in Figure 2.

MnPCC-ME 1.0
Design Summary

PROJECT: UMN_Test_1
 DATE: 4/15/2014

CALCULATED THICKNESS: 8.30 inches

Main Inputs

Design Life: 20 years
 Climate (MnDOT District): D4

Initial 2-way traffic volume: 10000 HCA DT
 Linear traffic growth: 2%

Axle load spectra: MnDOT WIM Average
 Joint spacing: 15 feet

Widened outer lane? Yes
 Shoulder type: Tied PCC

Defaults

Trucks in design lane: 100%
 Allowable cracked slabs: 15.0%

Total trucks over service life: 85680000
 Reliability Level: 90.0%

Reliability Analysis: Monte Carlo (MnPave)
 Flexural strength COV: 8.6%

Flexural strength: 650.0 psi
 MEPDG Coefficient 1: 0.90

PCC thickness COV: 3.0%
 MEPDG Coefficient 2: -2.64

Project Notes

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Figure 2. Screenshot of an example MnPCC-ME project summary file

CONCLUSIONS AND DISCUSSION

The agency-led development of a local rigid pavement design thickness tool is a viable “first step” to the full adoption of an AASHTO M-E procedure. In addition to providing the agency with access to the AASHTO M-E performance models without the forcing engineers to master the associated AASHTO software, the design tool provides a number of benefits to the agency.

- The design tool user only needs to modify inputs that have been identified by the agency as being critical to the design. Other inputs/designs are selected and controlled by the agency.
- The agency to review the results of a modernized design process without adopting the complications that accompany full adoption of the accompanying software (e.g. license costs, lack of documentation, and design input parameters that can intimidate inexperienced engineers).
- The final design tool software is fully within the control of the agency.
- Given that it is built upon a database of projects that have already been simulated, the use of the tool is straightforward and provides results almost instantaneously.

Finally, the process described in this paper can be easily adopted for flexible pavements, overlays, or CRCP projects instead of only JPCP projects.

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