Estimation of the Sensitivity of Design Input Variables for the Mechanistic-Empirical Design Guide

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ABSTRACT: Many highway agencies use AASHTO methods for the design of pavement structures. Current AASHTO methods are based on empirical relationships between traffic loading, materials, and pavement performance developed from the AASHO Road Test (1958-1961). The applicability of these methods to modern-day conditions has been questioned; in addition, the lack of realistic inputs regarding environmental and other factors in pavement design has caused concern. Research sponsored by the National Cooperative Highway Research Program has resulted in the development of a mechanistic-empirical design guide (*M-E Design Guide)* for pavement structural analysis. The new *M-E Design Guide* requires over 100 inputs to model traffic, environmental, materials, and pavement performance to provide estimates of pavement distress over the design life of the pavement. Many designers may lack specific knowledge of the data required. A study was performed to assess the relative sensitivity of the models used in the *M-E Design Guide* to inputs relating to construction materials in the analysis of flexible and rigid pavement structures. Inputs were evaluated by analyzing a standard pavement section and changing the value of each input individually, then assessing the change in predicted pavement distress (cracking, faulting, and roughness for rigid pavements; rutting, fatigue, and low-temperature cracking for flexible pavements). The evaluations may aid designers in focusing on those inputs having the most effect on desired pavement performance.

KEYWORDS: Mechanistic-Empirical Design; Pavement Design; M-E Design Guide

1 INTRODUCTION

The structural pavement design procedure currently used by many highway agencies is detailed in the 1993 AASHTO Guide for the Design of Pavement Structures (hereinafter, the *1993 Guide*) (AASHTO, 1993). The procedures specified in the *1993 Guide* (and previous versions) were developed from empirical relationships determined during the AASHO Road Test conducted from 1958 to 1961. The applicability and effectiveness of the *1993 Guide* has been questioned based on current traffic loads, advances in materials design and characterization, and a lack of consideration of the effect of environmental factors on pavement performance (NCHRP, 2000). In response, the National Cooperative Highway Research Program (NCHRP) sponsored research projects 1-37 and 1-37a, resulting in the development of a Mechanistic-Empirical (M-E) pavement analysis system.

In the M-E approach, input design parameters representing materials, traffic, and environmental factors are used in a pavement structural model to estimate pavement responses (stresses, strains, and deflections) from the pavement structure and subgrade. These pavement responses are then used in another series of performance models to estimate pavement distress. Pavement distress predictions are used to assess the performance that could be expected of the pavement structure. Figure 1 shows a flowchart of the design approach contained in the *M-E Design Guide* (ERES, 2002).

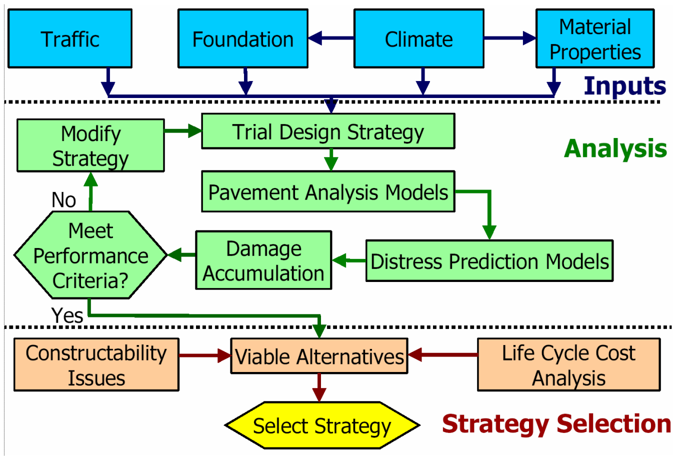

Figure 1. Mechanistic-Empirical Design Approach (ERES, 2002)

The use of stress and strain to estimate pavement distress forms the "engineering mechanics" basis for the design procedure – thus, the "Mechanistic" label given to the process. However, the procedure also uses a series of models to characterize input parameters and to develop pavement distress predictions based on the (mechanistic) outputs – stress and strain – of the pavement structural model. The models must be calibrated to enable the system to produce realistic estimates of pavement distress. Such calibration is performed using field data – observed pavement performance – thus, the "Empirical" label given to the process.

The *M-E Design Guide* is, comparatively speaking, much more complex than current AASHTO pavement design procedures. As such, it requires significantly more input values from the designer. Many of these inputs will be unfamiliar to most pavement design professionals. This paper reports on a study to estimate the sensitivity of the *M-E Design Guide* pavement performance predictions to changes in design inputs, for Jointed Plain Concrete Pavement (JPCP) and hot-mix asphalt (HMA) pavement. Such information will be useful to pavement designers in terms of recognizing which inputs will require the most scrutiny (for obtaining reasonable estimates of pavement performance) and which inputs do not have a large effect on predicted pavement performance – thus are satisfied by using a default-type value.

2 M-E DESIGN GUIDE OVERVIEW

One feature contained in the *M-E Design Guide* new to pavement design is the option to use hierarchal input levels. This allows the designer to input project specific information for some aspects of the pavement design (Level 1), where that information is available, or to accept nationally-averaged default values for inputs where no information is available (Level 3). There is also a middle level of input, Level 2, where the designer may be able to input a different parameter than what is required; the *M-E Guide* software provides the required input based on embedded correlations. This hierarchal input system allows for greater flexibility in application of the software, letting the designer determine the suitability of design input level. Theoretically, a design with Level 1 inputs should have higher design reliability than a design with Level 3 inputs.

2.1 Rigid Pavement

The structural pavement model used to generate stresses and strains in a rigid pavement structure and subgrade is based on the ISLAB2000 finite element program. However, unacceptable time and computational requirements for running the ISLAB2000 program "behind" the guide software led to the use of a neural network which was trained using thousand of results from the ISLAB2000 program. Once pavement responses are determined with the analysis, transfer functions relate the responses to pavement damage. Such an analysis is performed incrementally (i.e. monthly) over the design life and damage is accumulated to produce pavement performance predictions. For JPCP pavements, three primary damage prediction models are used: cracking (percent slabs cracked), faulting at joints (inches), and smoothness (expressed as the International Roughness Index (IRI)). The designer can assess the predicted damage at any point during the design life of the pavement and make changes to the design (materials, layer thicknesses, etc.) to bring predicted pavement performance into compliance with pre-determined performance criteria.

2.2 Flexible Pavement

The structural pavement model used in flexible pavement analyses is intended to be a function of the input level(s) used to characterize paving materials. For Level 2 and 3 inputs, pavement responses are generated using the JULEA layered elastic analysis system. For Level 1 inputs, a finite-element approach is planned; currently, the finite element model is not implemented for routine use. As with rigid pavements, pavement responses and subsequent corresponding damage assessments are performed incrementally; damage is accumulated to produce pavement performance predictions. For flexible pavements, three primary damage prediction models are used: fatigue cracking (top-down and bottom-up), rutting, and thermal (low temperature) cracking. Pavement smoothness, as expressed by IRI, is also included.

3 PROJECT OBJECTIVES

Current AASHTO procedures require eleven inputs for rigid pavement thickness design and five primary inputs for flexible pavement design; the *M-E Design Guide* software requires over one hundred inputs to characterize the pavement section materials, traffic loading, and environment. In addition, the *M-E Design Guide* allows for three different levels of input for most required values. The large number of inputs and the hierarchical nature of the software raise several questions relating to the relative effect of changing input values on predicted pavement performance. The overall objective of this project relates to answering these questions. Ideally, this can be accomplished by documenting all of the design inputs pertaining to structural pavement analysis in the *M-E Design Guide* and perform a sensitivity analysis relative to those inputs. However, this project focuses only on PCC and HMA *material* inputs; additional, concurrent projects relate to base/subbase material inputs, traffic inputs, and the climatic module.

4 RESEARCH APPROACH

To satisfy project objectives, two primary tasks were accomplished: in Task 1 a "standard" pavement structure was analyzed by varying one design input per trial to show the sensitivity of the system to that particular input; in Task 2 inputs were evaluated regarding the significance of impact on the overall performance of the pavement. A comprehensive description of the research approach is given by Beam (2003) and Lee (2004) for rigid and flexible pavements, respectively. For brevity, only summaries and highlights are given here.

The structure for jointed plain concrete pavement consisted of a PCC slab over 12 inches of unbound granular (crushed stone) base placed on an AASHTO class A-6 subgrade. For flexible pavements, the structure consisted of a total of 10 inches of asphalt – including 4 inches of 12.5 mm surface mix and 6 inches of 25 mm binder mix – and 12 inches of unbound granular (crushed stone) base over an AASHTO class A-6 subgrade.

4.1 Task 1

Tables 1 and 2 list design inputs that were varied and analyzed for rigid and flexible pavements, respectively; the "baseline" data for the study is shown to the right of the input descriptions. In most cases, the "baseline" value is the default value included in the M-E Design Guide software, particularly for Level 3 inputs. Using the baseline data as the "standard" pavement, each of the inputs listed was varied over a typical range of values to determine how each affects each of the performance prediction models.

It must be noted here that, at the time of the research, significant difficulties were experienced in using the flexible pavement portions of the M-E Design Guide software; consequently, comparatively fewer input variables were addressed for flexible pavement than for rigid pavement. In addition, at the time of the research providing a direct value for the dynamic modulus (E*) of hot-mix asphalt was not possible – thus, the sensitivity of performance predictions to changes in E* is not reported here. Finally, it is acknowledged that the research approach taken is limited regarding the interaction among design variables. Each variable used in the analysis is changed individually – no interaction is included – therefore the sensitivity results reported here are not globally applicable.

4.2 Task 2

Each trial run performed using the data shown in Tables 1 and 2 yields a series of tables and associated graphs showing predicted pavement distress (damage) over time. Evaluation related to the significance of differences in predicted damage resulting from changing a given variable is primarily based on a visual inspection of the graphs. Two items were particularly noted on each distress graph. One is the difference between lines representing different values of the variable being analyzed. The other is the relative scale of the "Y" axis (the damage axis). This was to ensure that apparent differences in damage estimates due to the variable in question are indeed significant from a practical viewpoint. For example, lines on a graph of PCC faulting may appear significantly different; however the damage axis scale may range from only zero inches (zero mm) to 0.1 inches (2.5 mm). In such a case, differences due to the variable may not be reported as "significant".

It is noted that only results stemming from a "deterministic" analysis are used in this paper – that is, results corresponding to a nominal 50 percent design reliability. The reliability approach used in the M-E Design Guide has been questioned regarding its applicability and appropriateness. The trial runs performed for the study contained distress predictions for both 50 percent and 90 percent design reliability. In all cases, results representing 90 percent design reliability are simply reflections of the 50 percent design reliability results adjusted by a constant multiplication factor. Assessments of relative sensitivity are not significantly affected between the design reliability levels.

Table 1. PCC Design Inputs Analyzed

Project Information	**Baseline Value**
Structure	
Design Features	
Permanent curl/warp effective temperature difference (^oF)	-10
Joint Design	
Joint Spacing (ft)	15
Sealant type (None, Liquid, Silicone, Preformed)	Liquid
Doweled Transverse Joints(None, diameter / spacing)	1.25”/12”
Optional – Random joint spacing (Enter four different spacings)	
Edge Support (Nothing or Tied PCC shoulder and/or Widened slab)	
Tied PCC shoulder – Long-term LTE (%)	40
Widened slab – Slab width (ft)	12
Base Properties	
Base Type – edited under “Layers”	
PCC-Base Interface (Bonded or Unbonded)	Unbonded
Erodibility index (“Extremely Resistant” to “Very Erodable”)	Very Erosion Resistant (2)
For “Bonded” only – Loss of bond age (mo)	60
Drainage and Surface Properties	
Surface shortwave absorptivity	0.85
Infiltration (0, 10, 50, or 100%)	10
Drainage path length (ft)	12
Pavement cross slope (%)	2
Layer 1 – PCC	
Unit Weight (pcf)	150
Poisson’s ratio	0.20
Thermal Properties	
Coefficient of thermal expansion (per $^oFx10^{-6}$)	6
Thermal conductivity (BTU/hr-ft-^oF)	1.25
Heat capacity (BTU/lb-^oF)	0.28
Mix	
Cement type (Type I –III)	Type I
Cement content (lb/yd^3)	600
Water/cement ratio	0.42
Aggregate type (Quartzite, Limestone, Dolomite, Granite, Rhyolite, Basalt, Synetite, Gabbro, Chert)	Limestone
Optional – PCC set temperature (^oF)	120
Optional – Ultimate shrinkage at 40% R.H. (microstrain)	700
Reversible shrinkage (% of ultimate shrinkage)	50
Time to develop 50% of ultimate shrinkage (days)	35
Curing Method (Curing compound, Wet curing)	Curing comp.
PCC Strength	
Level 1 – the following parameters at 7, 14, 28, and 90 days, plus the ratio at 20 years to 28 days	
Compressive Strength (psi)	1500/2000/3000/3500/1.2
E (psi)	2/2.5/3/3.5 $x10^6$/1.2
Modulus of Rupture (psi)	300/400/600/600/1.2
S.T. (psi)	300/400/600/600/1.2
Level 2 – the following parameters at 7, 14, 28, and 90 days, plus the ratio at 20 years to 28 days	
Compressive Strength (psi)	1500/2000/3000/3500/1.2
Level 3 – choose one of the following	
28-day PCC modulus of rupture (psi) (or)	650
28-day PCC compressive strength (psi)	4000

Table 2. HMA Design Inputs Analyzed

Project Information	Baseline Value
Poisson's Ratio	0.35
Surface Shortwave Absorptivity	0.85
Heat Capacity (BTU/lb/deg F)	0.23
Thermal Conductivity (Btu/(ft)(hr)(°F))	0.67
Air Voids (%)	8
Binder Grade (PG System)	70-22
Total Unit Weight (lb/ft^3)	135
Percent Binder Effective (%)	Mix design dependent (8 mix designs were used in the analyses)

5 RESULTS

For this project, well over 200 graphs representing predictions of pavement performance were generated. Obviously, results can only be summarized here; complete results are available elsewhere (Beam, 2003; Lee, 2004). One example is given for illustrative purposes. Figure 2 shows the prediction of joint faulting for varying levels of PCC compressive strength. It is apparent from both the magnitude of the predicted faulting and the relative difference in curves representing strength levels that the faulting prediction model is sensitive to PCC compressive strength.

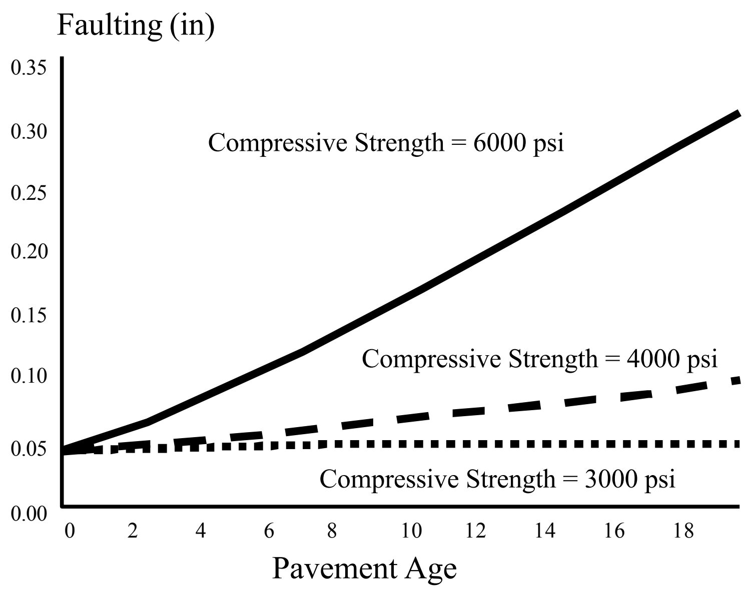

Figure 2. Example of PCC Distress Prediction Curve

5.1 Rigid Pavements

Table 3 summarizes the results of the sensitivity analysis for jointed plain concrete pavement. An assessment is shown regarding the relative sensitivity of each major predicted distress for each input analyzed. In all, 29 variables were considered in the sensitivity analysis. Due to the nature of the IRI model, sensitivity shown by only one of the physical distress models does not necessary equate to sensitivity of the IRI prediction. Interestingly, only 7 of 29 variables were listed as sensitive for the faulting model; 11 of 29 were listed as sensitive for the cracking model; and 9 of 29 were listed as sensitive for the IRI model. All three performance prediction models are shown as sensitive to a total of only six (6) variables out of 29. All three performance models are shown as not sensitive to 17 variables out of 29, suggesting that default values may be used with relative confidence.

Table 3. Summary of Results: JPCP

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

5.2 Flexible Pavements

Table 4 summarizes the results of the sensitivity analysis for flexible pavement. An assessment is shown regarding the relative sensitivity of each major predicted distress for each input analyzed. In all, 8 variables were considered in the sensitivity analysis. Due to the nature of the IRI model, sensitivity shown by only one of the physical distress models does not necessary equate to sensitivity of the IRI prediction. Interestingly, none of the variables were listed as sensitive for the rutting model; 2 of 8 were listed as sensitive for the surface-down cracking model; and 2 of 8 were listed as sensitive for the bottom-up cracking model. In addition, nominal maximum aggregate size appears to be a factor in the analysis. In no case are all three performance prediction models are shown as sensitive to a given variable. All three performance models are shown as not sensitive to 6 variables out of 8, suggesting that default values may be used with relative confidence.

Table 4. Summary of Results: Flexible Pavement

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

6 CONCLUSIONS AND RECOMMENDATIONS

Particularly compared to current methods, the M-E Design Guide is a rather complex system of interrelated materials and performance prediction models combined to analyze a pavement structure. Observations related to a study of the sensitivity of the analysis and prediction system to required input values follow.

- In general, results of the performance prediction models agree with "conventional wisdom" concerning the performance of concrete pavements and the relative effect of PCC-materials-related and pavement structure-related variables. This statement cannot, however, be applied to performance models for flexible pavements – particularly the rutting model.
- Based on the data generated in this study, few design inputs affect all performance prediction models, for either rigid or flexible pavements. This should allow designers significant flexibility; changes to design parameters may be made to affect only one or two pavement distress modes without negatively affecting other modes.

- Many variables introduced by the M-E Design Guide that were not explicitly considered in previous pavement design procedures do not appear to significantly affect the prediction of pavement performance in the M-E Design Guide. In such cases, the use of the default value included in the software provides adequate results.
- Some variables introduced by the M-E Design Guide that were not explicitly considered in previous PCC pavement design procedures do appear to significantly affect the prediction of pavement performance in the M-E Design Guide. In such cases, the use of the default value included in the software may not provide adequate results; designers are encouraged to determine a reasonable value for such variables consistent with the local situation.
- In some cases, only one or two pavement performance measures may show sensitivity to a particular design input variable. In such cases, designers may be able to affect the performance prediction in a particular area by altering the input without degrading the predicted performance in another area.

As with any study such as this, limitations exist. Potentially significant limitations for this study follow.

- In this study, only one variable was adjusted for each trial run. Therefore, no information is obtained concerning the interaction among variables. In other words, predicted distress may show sensitivity to variable A; however, it is not known whether the distress prediction would continue to show sensitivity to variable A for all values of variable B (or even variables C and D). One major unaccounted-for potential interaction concerns climatic effects – all trial runs were performed using only one climate data file.
- Similar to the previous bullet, changing only one variable at a time ignores natural interactions among variables. For example, the water/cement ratio of the PCC was changed while holding all strength parameters constant – a situation that is unlikely to happen in the field.
- The M-E Design Guide software used for this study is not in its final form. While no significant changes to the models contained in the software are planned, it must be recognized that the software used is considered to be a “draft” of the final product.
- The models used in the M-E Design Guide software have been calibrated using pavement performance measurements obtained primarily from data gathered in the Long-Term Pavement Performance (LTPP) effort. As such, the calibration is considered to be a “national” calibration. States and other agencies are encouraged to provide local and/or regional calibration factors for the models to better represent local conditions. While it is not likely that relative sensitivity to design inputs will change with local calibration, this aspect of the study is noted.

7 ACKNOWLEDGMENTS

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