

Sensitivity Analysis of Rigid Pavement Systems Using Mechanistic-Empirical Pavement Design Guide

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ABSTRACT

Pavement design procedures available in the literature do not fully take advantage of mechanistic design concepts, and as a result, heavily rely on empirical approaches. Because of their heavy dependence on empirical procedures, the existing rigid pavement design methodologies do not capture the actual behavior of Portland Cement Concrete (PCC) pavements. However, reliance on empirical solutions can be reduced by introducing mechanistic–empirical methods, now adopted in the newly released Mechanistic-Empirical Pavement Design Guide (MEPDG). This new design procedure incorporates a wide range of input parameters associated with the mechanics of rigid pavements. A study was undertaken to compare the sensitivity of these various input parameters on the performance of concrete pavements. Two Jointed Plain Concrete Pavement (JPCP) sites were selected in Iowa. These two sections are also part of the Long Term Pavement Performance (LTPP) program, where a long history of pavement performance data exists. Data obtained from the Iowa Department of Transportation (Iowa DOT) Pavement Management Information System (PMIS) and LTPP database were used to form two standard pavement sections for the comprehensive sensitivity analyses. The sensitivity analyses were conducted using the MEPDG software to study the effects of design input parameters on pavement performance, specifically faulting, transverse cracking, and smoothness. Based on the sensitivity results, the rigid pavement input parameters were ranked and categorized from most sensitive to insensitive to help pavement design engineers to identify the level of importance for each input parameter. The curl/warp effective temperature difference (built-in curling and warping of the slabs) and PCC thermal properties are found to be the most sensitive input parameters. Based on the comprehensive sensitivity analyses, the idea of developing an expert system is introduced to help the designer identify the input parameters that can be modified to satisfy the predetermined pavement performance criteria.

Keywords: jointed plain concrete pavements—mechanistic-empirical pavement design guide (MEPDG)—pavement performance—rigid pavement design—sensitivity analysis

INTRODUCTION

Background

The historical development of Mechanistic-Empirical (M-E) pavement design procedures in the American Association of State Highway and Transportation Officials (AASHTO) guides goes back to the 1986. In the 1986 AASHTO guide for pavement structures, M-E design procedure was firstly defined as the calibration of mechanistic models with observations of performance, i.e., empirical correlations. It was also stated that in a multi-layered pavement system, analytical methods were the numerical calculations of the pavement responses when subjected to external loads or the effects of temperature or moisture. Then, assuming that pavements can be modeled as a multi-layered elastic or visco-elastic structure on an elastic or visco-elastic foundation, the stress, strain, or deflection could be calculated at any point within or below the pavement structure. Mechanistic procedures are referred to for their ability to translate the analytical calculations of the pavement responses to physical distress such as cracking or rutting (pavement performance). However, pavement performance is subject to a number of factors that cannot be exactly modeled by mechanistic methods. It is, therefore, necessary to incorporate empirical pavement performance models with mechanistic models. Thus, in the 1986 AASHTO guide, the procedure is defined conceptually as a mechanistic-empirical pavement design procedure (AASHTO 1972).

The AASHTO pavement design guides (AASHTO 1972, 1986, 1993) used empirical methods, which are valid for specific environmental, material, and loading conditions. In order to develop a design procedure without these limitations, the development of M-E design procedures was promoted by the AASHTO Joint Task Force on Pavements (JTTF). AASHTO JTTF recommended the research should be initiated for the later versions of the AASHTO design guides. The National Cooperative Highway Research Project (NCHRP) Project 1-26 was the first NCHRP project to be sponsored (NCHRP 1990a, 1990b, 1992a, 1992b). Later, the second phase of NCHRP 1-26 was completed in 1992 with its two volumes of final reports detailing the guidelines for the data input stage of the procedures (Masada et al. 2004). Finally, at the conclusion of a workshop held in March 1996 in Irvine, California, JTTF concluded a long-term project for the development of a design guide based as fully as possible on mechanistic principles. This guide is titled *The NCHRP Project 1-37A mechanistic-empirical design guide for design of new and rehabilitated pavement structures* (NCHRP 2004).

Project Scope

The main focus of this paper is to identify the sensitivity of input parameters needed for designing jointed plain concrete pavements used in the mechanistic-empirical pavement design guide. This paper identifies input parameters ranging from “most sensitive” to “insensitive” for three critical rigid pavement performance measures of faulting, transverse cracking, and smoothness.

SENSITIVITY ANALYSIS USING MECHANISTIC-EMPIRICAL PAVEMENT DESIGN GUIDE

Collecting MEPDG data

The very first part of this project involved extensive data collection. Two rigid pavement sections were selected from the Iowa Department of Transportation (Iowa DOT) Pavement Management Information System (PMIS) which were also part of the Long Term Pavement Performance (LTPP) program. A history of pavement deflection testing, material testing, traffic, and other related data were available in the LTPP database. These two sections were named as PCC-1 and PCC-2.

PCC-1, located on US-218 near Johnson County, Iowa, was constructed in 1983. This section of US-218 is located in the wet-freeze environmental region. This area has a freezing index of 466.88 and receives 930.58 mm of rainfall annually. The latitude and longitudes are given as 41.57 degrees and 91.55 degrees, respectively. The pavement is a 9.6-inch JPCP with 15 ft joints and Class II type aggregates. The slab rests on a 4-inch Class A sub-base course. The subgrade for this site consists of AASHTO A-7-6 material and it is noted that there exists silty clay of Loess material with some glacial till treatments.

PCC-2, located on US-20 near Hamilton County, Iowa, was constructed in 1968. The test section was westbound in the north central LTPP SHRP region, and designated between 149.5 and 153.47 miles of US-20. This section of US-20 is also located in the wet-freeze environmental region. This area has a freezing index of 763.69 and receives 861.74 mm (34 in) of rainfall annually. The latitude and longitudes are 42.46 degrees and 93.59 degrees, respectively. The pavement is a 10-inch JPCP with 15 ft joints. The slab rests on a 4-inch granular sub-base course. The subgrade is made of AASHTO A-6 (7) to A-6 (10) material, a glacial till soil.

Generating a Representative Pavement Section for MEPDG

In order to conduct mechanistic-empirical analyses using the MEPRG, a pavement section representative of the Iowa highway system was generated. Sensitivity analyses were carried out on this representative pavement section to examine the effect of each input or inputs groups of two on pavement performance by using the MEPDG software and the design inputs. The standard input parameters for the representative pavement section were determined using the inputs from two PCC sections and were adjusted considering Iowa conditions.

Sensitivity Analysis Using MEPDG

The representative pavement section was analyzed using the MEPDG software by varying one input parameter within its ranges while holding other parameters constant in the model. Several analyses were carried out. Pavement distresses throughout the design life for each input file were plotted. The goal of these analyses was to determine the individual effects of each input parameter on the critical pavement performance using the MEPDG software. It should be noted that the climate input variable in the MEPDG sensitivity analyses reflects Iowa's climate data, in or around Iowa. The chosen weather stations are located in Figure 1.

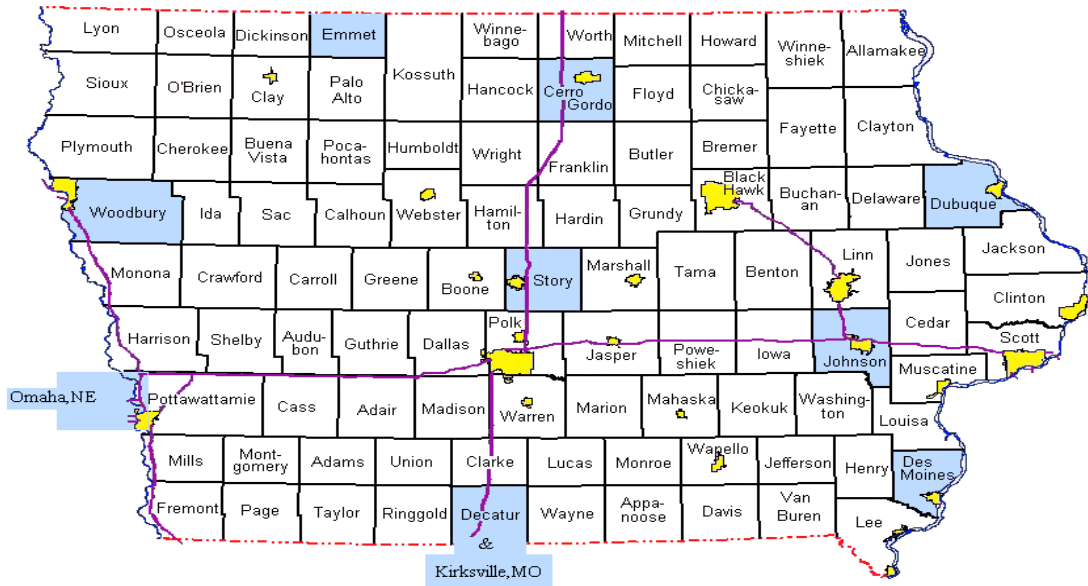


Figure 1. The selected climatic locations for sensitivity analysis

The second step was to find the interaction of input parameters between each other and their interaction with pavement performance values. The results of the first test (varying one variable) revealed that the standard input parameters established for the representative pavement section were corresponding beyond the capacity of pavement performance. Therefore, in some cases the standard input variables were modified to reflect the capacity of pavement performance.

For each input variable, range was defined according to their maximum and minimum values. Moreover, additional values in between minimum and maximum values were considered in order to observe the trend of their impact on pavement performance. Several hundreds of graphs were created using the results of MEPDG software (Guclu 2005). The different curl/warp effective temperature difference input vs. pavement responses graphs are shown as examples of those graphs in Figures 2 through 4.

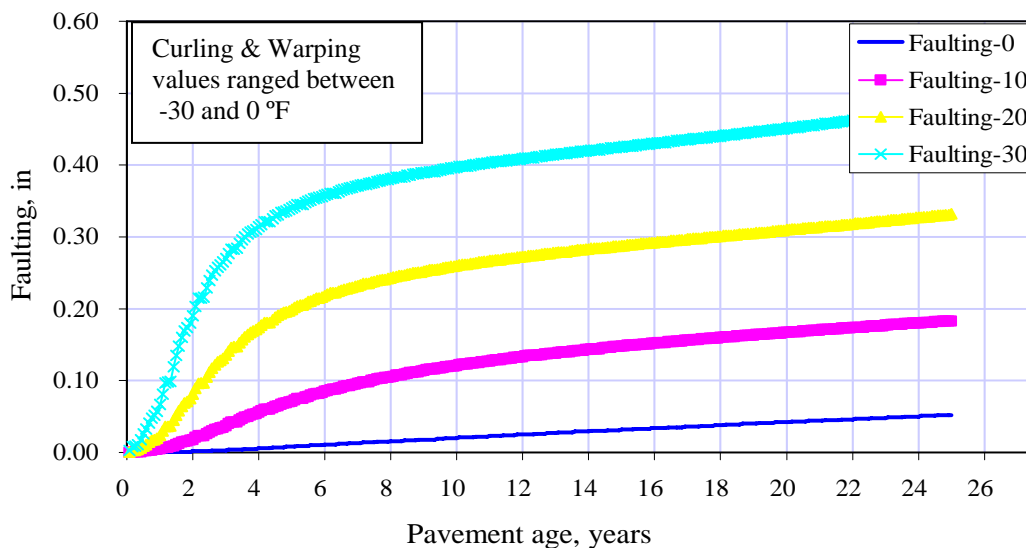


Figure 2. Faulting for different curl/warp effective temperature difference (built-in)

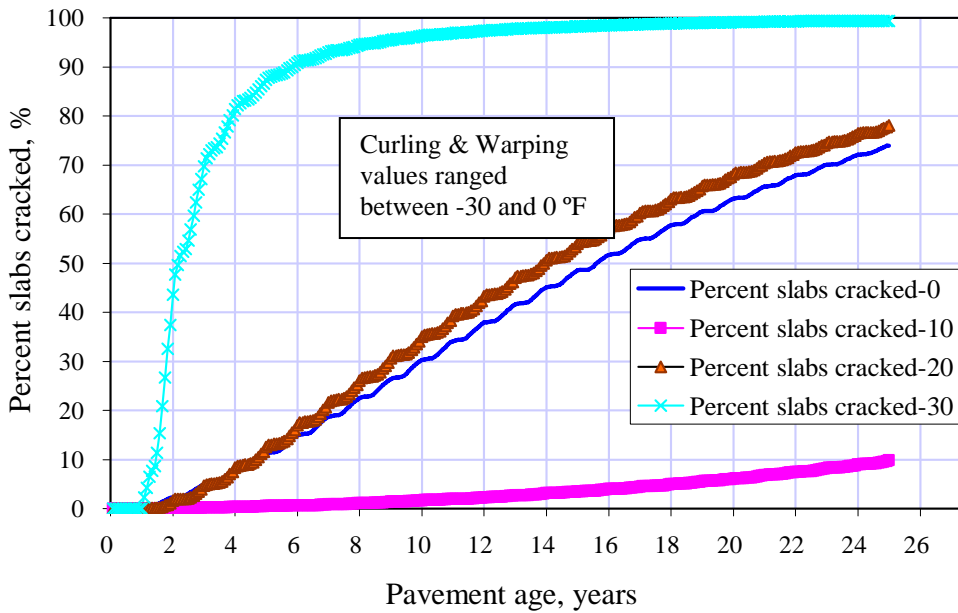


Figure 3. Cracking for different curl/warp effective temperature difference (built-in)

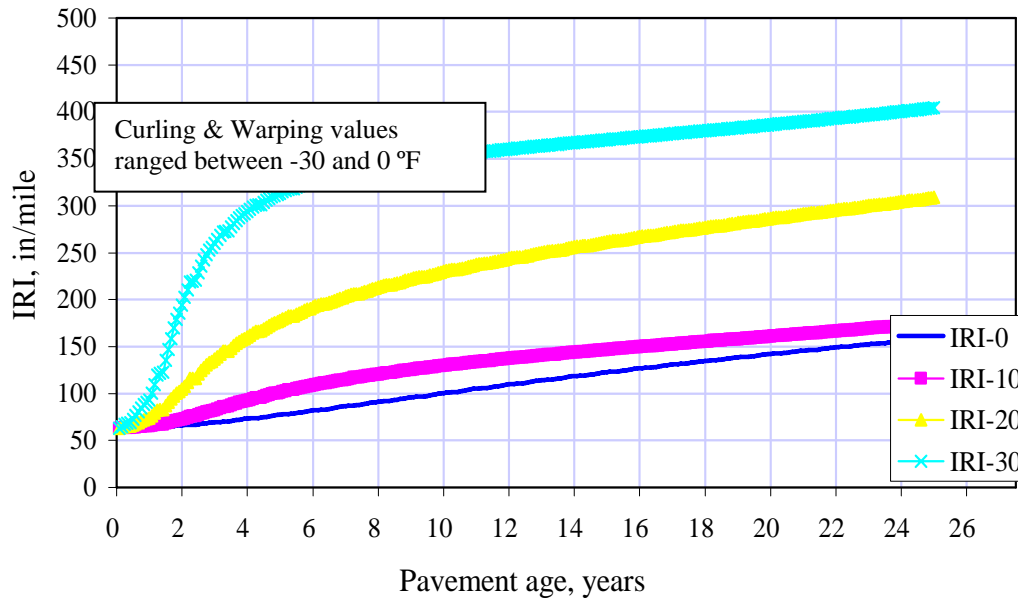


Figure 4. IRI for different curl/warp effective temperature difference (built-in)

The obtained sensitivity graphs were visually inspected. The evaluation was made according to the pavement performance value and the amount of change in the pavement performance value due to changing input variable. The results obtained were sensitive in different scales, so the scales from insensitive to the most sensitive were developed for a better understanding of the effects of each input parameters.

The sensitivity values extracted from all of the sensitivity analyses are summarized according to their sensitivities for each pavement response and presented in Tables 1-3. In the tables, the sensitivities of inputs are given under three columns—extreme sensitivity, sensitive to very sensitive, and low sensitive to insensitive for each pavement performance models of faulting, transverse cracking, and smoothness.

Table 1. Summary of sensitivity level of input parameters for faulting of JPCP

Performance Models	Inputs		
	Extreme Sensitivity	Sensitive to Very Sensitive	Low Sensitive to Insensitive
Faulting	<ul style="list-style-type: none"> • Curl/Warp Effective Temperature Difference • Doweled Transverse Joints 	<ul style="list-style-type: none"> • AADTT • Mean Wheel Location • Unbound Layer Modulus • Cement Content • Water/Cement Ratio • Coefficient of Thermal Expansion • Thermal Conductivity 	<ul style="list-style-type: none"> • Sealant Type • Dowel Diameter • Dowel Spacing • PCC-Base Interface • Erodibility Index • Traffic Wander • Design Lane Width • Infiltration of Surface Water • Drainage Path Length • Pavement Cross Slope • Cement Type • Aggregate Type • PCC Set (Zero Stress) Temperature • Ultimate Shrinkage at 40% R.H. • Reversible Shrinkage • Time to Develop 50% of Ultimate Shrinkage • Curing Method • Edge Support • Surface Shortwave Absortivity • Unit Weight • Poisson’s Ratio • Climate • PCC Strength • Joint Spacing

Table 2. Summary of sensitivity level of input parameters for transverse cracking of JPCP

Performance Models	Inputs		
	Extreme Sensitivity	Sensitive to Very Sensitive	Low Sensitive to Insensitive
Transverse Cracking	<ul style="list-style-type: none"> • Curl/Warp Effective Temperature Difference • PCC Thermal Properties (Coefficient of Thermal Expansion, Thermal Conductivity) • PCC Layer Thickness • PCC Strength Properties • Joint Spacing 	<ul style="list-style-type: none"> • Edge Support • Mean Wheel Location • Unit Weight • Poisson's Ratio • Climate • Surface Shortwave Absorptivity • AADTT 	<ul style="list-style-type: none"> • Sealant Type • Dowel Diameter • Doweled Transverse Joints • Dowel Spacing • PCC-Base Interface • Erodibility Index • Traffic Wander • Design Lane Width • Infiltration of Surface Water • Drainage Path Length • Pavement Cross Slope • Cement Type • Cement Content • Water/Cement Ratio • Aggregate Type • PCC Set (Zero Stress) Temperature • Ultimate Shrinkage at 40% R.H. • Reversible Shrinkage • Time to Develop 50% of Ultimate Shrinkage • Curing Method • Unbound Layer Modulus • Heat Capacity

Table 3. Summary of sensitivity level of input parameters for smoothness of JPCP

Performance Models	Inputs		
	Extreme Sensitivity	Sensitive to Very Sensitive	Low Sensitive to Insensitive
Smoothness	<ul style="list-style-type: none"> • Curl/Warp Effective Temperature Difference • PCC Thermal Properties (Coefficient of Thermal Expansion, Thermal Conductivity) 	<ul style="list-style-type: none"> • Doweled Transverse Joints • AADTT • Mean Wheel Location • Joint Spacing • PCC Layer Thickness • PCC Strength Properties • Poisson's Ratio • Surface Shortwave Absortivity • Unbound Layer Modulus • Cement Content • Water/Cement Ratio 	<ul style="list-style-type: none"> • Sealant Type • Dowel Diameter • Dowel Spacing • PCC-Base Interface • Erodibility Index • Traffic Wander • Design Lane Width • Infiltration of Surface Water • Drainage Path Length • Pavement Cross Slope • Cement Type • Aggregate Type • PCC Set (Zero Stress) Temperature • Ultimate Shrinkage at 40% R.H. • Reversible Shrinkage • Time to Develop 50% of Ultimate Shrinkage • Curing Method • Edge Support • Climate • Unit Weight

SUMMARY AND CONCLUSIONS

A number of conclusions were drawn as a result of the sensitivity analyses.

Transverse cracking

- The extremely sensitive input parameters for transverse cracking are the following:
 - Curl/warp effective temperature difference (built-in)
 - Coefficient of thermal expansion
 - Thermal conductivity
 - PCC layer thickness
 - PCC strength properties
 - Joint spacing
- The sensitive to very sensitive input parameters for transverse cracking are the following:
 - Edge support
 - Mean wheel location (traffic wander)
 - Unit weight
 - Poisson's ratio
 - Climate
 - Surface shortwave absorptivity
 - Annual average daily truck traffic (AADTT)
- Other examined parameters are found as less sensitive to insensitive.

Faulting

- The extremely sensitive input parameters for faulting are the following:
 - Curl/warp effective temperature difference (built-in)
 - Doweled transverse joints (load transfer mechanism, doweled or un-doweled)
- The sensitive to very sensitive input parameters for faulting are the following:
 - Coefficient of thermal expansion
 - Thermal conductivity
 - Annual average daily truck traffic (AADTT)
 - Mean wheel location (traffic wander)
 - Unbound layer modulus
 - Cement content
 - Water to cement ratio
- Other examined parameters are found as less sensitive to insensitive.

Smoothness

- The extremely sensitive input parameters for smoothness are the following:
 - Curl/warp effective temperature difference
 - Coefficient of thermal expansion
 - Thermal conductivity
- The sensitive to very sensitive input parameters for smoothness are the following:
 - Annual average daily truck traffic (AADTT)
 - Doweled transverse joints (load transfer mechanism, doweled or un-doweled)
 - Mean wheel location (traffic wander)
 - Joint spacing

- PCC layer thickness
- PCC strength properties
- Poisson's ratio
- Surface shortwave absorptivity
- Unbound layer modulus
- Cement content
- Water to cement ratio
- Other examined parameters are found as less sensitive to insensitive.

Among the extremely sensitive and sensitive to very sensitive parameters, the pavement design engineer can only modify PCC layer thickness, doweled transverse joints, and joint spacing. PCC strength properties are also modifiable provided that pavement design specifications are met.

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