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Sensitivity Evaluation of MEPDG Performance Prediction

DETAILS

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SENSITIVITY EVALUATION OF MEPDG PERFORMANCE PREDICTION

This digest summarizes the findings from NCHRP Project 1-47, "Sensitivity Evaluation of MEPDG Performance Prediction." It was prepared by Amir N. Hanna, NCHRP Senior Program Officer, from the contractor's final report authored by Charles W. Schwartz and Rui Li of the University of Maryland, College Park, Maryland, and Sung Hwan Kim, Halil Ceylan, and Kasthurirangan Gopalakrishnan of Iowa State University, Ames, Iowa. Charles W. Schwartz served as principal investigator.

INTRODUCTION

The AASHTO interim edition of the *Mechanistic-Empirical Pavement Design Guide (MEPDG) Manual of Practice* was published in 2008. This Guide and related software provide a methodology for the analysis and performance prediction of flexible and rigid pavements based on mechanistic-empirical principles. For given pavement structure, material properties, environmental conditions, and traffic loading characteristics, the structural responses such as stresses, strains, and deflections are mechanistically calculated using multilayer elastic theory or finite element methods. Thermal and moisture distributions are also mechanistically determined using an Enhanced Integrated Climate Model. These responses are then used as inputs to empirical models for predicting pavement performance in terms of distresses such as cracking, rutting, faulting, and smoothness. These empirical models have been calibrated using data from the Long-Term Pavement Performance (LTPP) database for in-service pavements that are representative of the conditions encountered in the United States.

The performance predicted by these models depends on the values of input parameters that characterize the pavement materials, layers, design features, and condition. However, because these input parameter values are expected to differ from those for the constructed pavement, the predicted performance will also vary to some degree depending on the input parameter values. Earlier studies conducted to relate predicted performance to differences in input parameter values have not addressed this relationship in a systematic manner to identify the relative influence of input parameter values on predicted performance. Also, these studies have not considered the combined effects of variations in two or more input parameter values on predicted performance in a comprehensive manner. Research was needed to determine the degree of sensitivity of the performance predicted by the MEPDG to input parameter values and identify, for specific climatic region and traffic conditions, the input parameters that appear to substantially influence predicted performance. In this manner, users can focus efforts on those input parameters that will greatly influence the pavement design. NCHRP Project 1-47 was conducted to address this need; this digest summarizes the findings of this research.

The original research version of the MEPDG software (Version 0.7) was

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released in July 2004. The software was subsequently updated several times under NCHRP projects. Version 1.0 of the MEPDG was adopted as an interim AASHTO pavement design procedure in 2007. Version 1.1, released in September 2009, included enhancements and improved rehabilitation design analyses; it was used as a basis for the DARWin-ME software that was released by AASHTO in April 2011 (now called Pavement ME). The sensitivity analysis was performed using Version 1.1 of the MEPDG software.

RESEARCH APPROACH

The research addressed five pavement types: new hot-mix asphalt (HMA), HMA over a stiff foundation, new jointed plain concrete pavement (JPCP), JPCP over a stiff foundation, and new continuously reinforced concrete pavement (CRCP). The stiff foundation variants were intended to represent either stabilized base/subgrade layers or an overlay over an existing pavement. Each pavement type was evaluated for five climate conditions (hot-wet, hot-dry, cold-wet, cold-dry, and temperate) and for three traffic levels (low, medium, and high) or a set of 15 base cases for each pavement type. The design inputs evaluated in the analyses included traffic volume, layer thicknesses, material properties (e.g., stiffness, strength, HMA and concrete mixture characteristics, and subgrade type), groundwater depth, geometric parameters (e.g., lane width), and others. Traffic inputs were limited to volume (annual average daily truck traffic [AADTT]) and operating speed. Depending on the base case, approximately 25 to 35 design inputs were evaluated in the analyses. Correlations among design inputs (e.g., between concrete elastic modulus and modulus of rupture) were considered where appropriate.

These analyses included an initial triage, one-at-a-time (OAT) sensitivity analyses, and global sensitivity analyses (GSAs). The initial triage was largely qualitative based on past studies and experience. In the OAT analyses, each potentially sensitive design input identified in the initial triage was varied individually over the set of 15 base cases (5 climates × 3 traffic levels) for each of 5 pavement types to assess quantitatively the local sensitivity of the MEPDG predicted distresses to the design input. The OAT local sensitivity results were used to refine the list of sensitive design inputs to be considered in the GSA. The GSA, however, varied all design inputs simultaneously across the entire problem domain for each pavement type; the results were used to evaluate the mean and variability of the sensitivities as well as any potential interaction effects among design inputs. Artificial neural network (ANN) response surface models (RSMs) were fit to the GSA results to permit evaluation of design input sensitivities across the entire problem domain. The key findings from the study are based on the GSA results.

A normalized sensitivity index (NSI) was adopted as the quantitative metric. The NSI is defined as the average percent change of predicted distress relative to its design limit caused by a percent change in the design input. For example, considering sensitivity of total rutting to granular base resilient modulus, if a 10% reduction in base resilient modulus increases the total rutting by 0.01875 in. with respect to its design limit of 0.75 in., then $NSI = 0.01875 \times 100/(0.75 \times 10) = 0.25$. In other words, the 10% reduction in base resilient modulus will increase rutting by $(-0.10) * (-0.25) * 0.75 = 0.01875$. At NSI = 1, the percent change in distress relative to its design limit equals the percent change in the design input. The mean plus/minus two standard deviations value of NSI (i.e., $NSI_{\mu\pm2\sigma}$) was adopted as the ranking measure because it incorporates both the mean sensitivity and the variability of sensitivity across the problem domain. The following design input sensitivity categories were defined for the GSA results: Hypersensitive, $NSI_{\mu\pm2\sigma} > 5$; Very Sensitive, $1 < NSI_{\mu\pm2\sigma} < 5$; Sensitive, 0.1 $NSI_{\mu\pm2\sigma} < 1$; and Non-Sensitive, $NSI_{\mu\pm2\sigma} < 0.1$. For practical design purposes, the high sensitivity or critical design inputs are those in the hypersensitive and very sensitive categories.

SENSITIVITY ANALYSIS METHODOLOGY

Design Inputs

An initial triage was developed to divide the identified MEPDG design inputs into three categories—very sensitive, sensitive, and non-sensitive—and to identify any potential correlations of inputs. Input factors in the very sensitive and sensitive categories were intended for inclusion in the GSA and those in the non-sensitive category were to be excluded from further consideration.

For flexible pavements, the triage process examined the influence of design inputs on longitudinal cracking, alligator cracking, thermal cracking, asphalt rutting, and total rutting. International Roughness Index (IRI) was not considered explicitly in the initial triage because it is a function of the other primary distresses. Reflection cracking and fatigue cracking of cement-treated bases (CTB) were not considered.

For rigid pavements, the triage process examined the influence of design inputs on faulting and transverse cracking for JPCP and punchouts, maximum crack width, and load transfer efficiency (LTE) for CRCP; IRI was not considered explicitly in the initial triage.

Some of the design inputs are correlated and/or have other characteristics that warranted special treatment. For HMA pavements, these included unbound material properties, HMA dynamic modulus and binder properties, and HMA low temperature properties. For concrete pavements, these included unbound material properties, concrete stiffness and strength, water/cement ratio, dowel diameter and steel depth, and edge support condition.

Ranges for inputs for the flexible and rigid pavement were identified for use in the sensitivity analyses. The baseline values for these inputs were used to define the OAT sensitivity indices, and the minimum and maximum values provided the range for the GSA simulations.

Base Cases

Sensitivity analyses were conducted for the full ranges of all model inputs and outputs that were considered practical. Seventy-five base cases that covered the commonly encountered ranges of pavement types, climate conditions, and traffic levels (5 pavement types × 5 climates × 3 traffic levels) were selected to evaluate the entire solution domain for the MEPDG. For these base cases, sets of climate conditions and traffic levels were used as global inputs in the sensitivity analyses for all pavement types. Five climate zones were considered—hot-dry, hot-wet, temperate, cold-dry and cold-wet—and three traffic levels that were classified based on AADTT values and truck volume as low (<5,000), medium (5,000–10,000), and high (>15,000) were used in all GSAs. The resulting 15 base cases for the sensitivity analyses for each pavement type were abbreviated in the form of "XXY" in which "XX" designates the climate (CD = cold-dry; CW = cold-wet; T = temperate; HD = hot-dry; and HW = hot-wet) and "Y" designates the traffic level (L = low, M =medium, H = high). For example, CDH designates the cold-dry climate at the high traffic level.

Sampling and Analysis Process

For the OAT local sensitivity analyses, small perturbations above and below the baseline values were considered individually for each design input and the corresponding distresses were predicted using the MEPDG software. These values were used to compute the sensitivity metrics.

For the GSA simulation inputs, Latin Hypercube Sampling (LHS), which is a widely used variant of the standard or random Monte Carlo method, was adopted. The LHS approach reduces by a factor of 5 to 20 the required number of simulations as compared with the conventional Monte Carlo method.

The GSA simulations provided predictions of pavement performance at random discrete locations in the problem domain; these were fitted with continuous RSMs that provided a means for computing derivatives for sensitivity indices. The primary metrics selected to quantify sensitivity of model outputs to model inputs were a point-normalized sensitivity index for the OAT analyses and the regression coefficients from normalized multivariate linear regression and a point-normalized sensitivity index for the GSAs.

OAT SENSITIVITY ANALYSIS RESULTS

In an OAT analysis, each potentially sensitive design input was varied individually for a given base case or reference condition to quantify and assess the local sensitivity of the predicted output (distress). The OAT local sensitivity analyses were performed to confirm the assessments from the initial triage of design inputs and to identify sensitive design inputs for use in the GSA simulations. Results of the OAT analyses and the results were used to calculate NSI values for each design input-pavement distress combination for each of the 15 base cases for each pavement type.

The OAT analyses provided the final ranking and sensitivity categories of the design inputs based on the maximum absolute NSI calculated for the design input for any pavement type, base case, or distress. The overall sensitivity values for the design inputs scenarios were categorized as

- Hypersensitive (HS, NSI > 5);
- Very sensitive (VS, 1 < NSI < 5);

- Sensitive (S, 0.1 < NSI < 1); and
- Insensitive (NS, NSI < 0.1).

All design inputs that ranked as sensitive or above were included in the GSA simulations. The results from the OAT analyses agreed with the judgments from the initial triage at about the 65% level for flexible pavements, at about the 75% to 85% level for JPCP, and at about the 75% level for CRCP.

GSA Results

The GSAs determined the sensitivity of the performance predicted by the MEPDG to variations of input parameter values across the entire problem domain for flexible and rigid pavements. In these analyses, all input parameters were varied simultaneously from their baseline values (and not just one at a time as for the OAT analyses). The measure of sensitivity taken is the mean plus/minus two standard deviation ($\mu \pm 2\sigma$) NSI values.

For all pavement types, the design inputs were order-ranked by the maximum absolute value of $NSI_{\mu \pm 2\sigma}$ across distresses. The results were found to vary by distress type and match engineering judgment and experience in overall terms.

For new HMA pavements, HMA layer properties (dynamic modulus parameters, layer thickness, and shortwave absorptivity, in particular) were consistently the highest sensitivity inputs, with subgrade modulus and granular base modulus and thickness following behind at a distance, and traffic volume as an important design input. For HMA over stiff foundation, the sensitivities of all of the design inputs evaluated were quite high with trends similar to those found for HMA pavements.

For the new JPCP, slab width was consistently the highest sensitivity design input, followed by the concrete layer properties (concrete unit weight, coefficient of thermal expansion, strength parameters, and surface shortwave absorptivity) and other geometric properties (lane width, slab thickness, and joint spacing). The sensitivity of the design inputs for JPCP over stiff foundation were identical to those found for the new JPCP.

For the new CRCP, the highest sensitivity design inputs were concrete layer properties (concrete thickness, strength parameters, reinforcing steel properties, unit weight, coefficient of thermal expansion, and surface shortwave absorptivity) followed by the base and subgrade properties. Traffic volume is also an important design input.

SUMMARY OF FINDINGS

The sensitivity of MEPDG predicted pavement performance to design inputs has been evaluated through an initial triage, OAT sensitivity analyses, and GSAs. The initial triage was largely qualitative based on past studies and experience. In the OAT analyses, each potentially sensitive design input identified in the initial triage was varied individually over a set of 15 base cases (5 climates × 3 traffic levels) for each of 5 pavement types in order to assess quantitatively the local sensitivity of the MEPDG predicted distresses to the design input. The OAT local sensitivity results were used to identify the more sensitive design inputs for the GSA. The GSAs, however, varied all design inputs simultaneously across the entire problem domain for each pavement type. RSMs were fit to the GSA results to permit evaluation of design input sensitivities across the entire problem domain. Because the GSAs evaluated the mean and variability of the sensitivities across the problem domain as well as potential interaction effects among design inputs, the key findings of this research were derived from the GSA results.

Methodology

General findings regarding the GSA methodology include the following:

- There is no sensitivity metric that is uniquely suited for all variables and all purposes. The design limit NSI was adopted for this study. This index related the percentage change in a design input to the corresponding percentage change in predicted distress relative to its design limit value.
- The OAT local sensitivity analysis results agreed with the initial triage at about the 65–85% level, depending on pavement type, indicating that the judgment incorporated in the initial triage was appropriate.
- The "mean plus/minus two standard deviations" ($\mu \pm 2\sigma$) normalized sensitivity metric ($NSI_{\mu \pm 2\sigma}$) was used as the ranking measure because it incorporated both the mean sensitivity and the variability of sensitivity across the problem domain.
- Sensitivity categories based on the GSA results were defined as hypersensitive (HS, NSI > 5); very sensitive (VS, 1 < NSI < 5);

sensitive (S, $0.1 < NSI < 1$); and insensitive (NS, $NSI < 0.1$).
- The design input rankings by $NSI_{\mu \pm 2\sigma}$ from the GSAs agreed well with the OAT rankings. This agreement suggests that interactions among design inputs (effects of two variables changing greater than their multiplicative individual effects) were not significant.

Findings for All Pavements

The following trends were consistently observed for all pavement types:

- All distress predictions were most sensitive to variability of the design inputs for the bound surface layers (HMA and portland cement concrete [PCC]).
- The sensitivity values for each distress-design input combination did not vary substantially or systematically by climate zone.

Findings for Flexible Pavements

The sensitivity of the predicted performance to variations in the design inputs of flexible pavements varied by distress type (e.g., rutting vs. cracking or load related vs. non-load related) and to a lesser extent by pavement type (new HMA vs. HMA over stiff foundation) but the results suggest some broad conclusions. Table 1 summarizes the sensitivity level of the design inputs by material category (HMA, base, subgrade, other) for each distress for the new HMA pavements (similar trends were found for HMA pavements on stiff foundation). The findings were as follows:

- Only the HMA properties were most consistently in the highest sensitivity categories: the E* master curve δ and α parameters (i.e., the lower and upper shelves of the master curve), thickness, surface shortwave absorptivity, and Poisson's ratio. None of the base, subgrade, or other inputs design (e.g., traffic volume) was as consistently in the two highest sensitivity categories.
- The magnitudes of the sensitivity values for longitudinal cracking, asphalt concrete (AC) rutting, and alligator cracking were consistently and substantially higher than the values for IRI and thermal cracking.
- The sets of sensitive design inputs for longitudinal cracking, alligator cracking, AC rutting, total rutting, and IRI were generally different from the set of sensitive design inputs for thermal cracking.
- The computed sensitivities for HMA air voids and effective binder volume do not consider the influence of these inputs on HMA dynamic modulus. The GSA simulations used synthetic Level 1 inputs for the HMA dynamic modulus; estimating these properties based on Level 3 empirical relations would increase the sensitivities attributable to air voids and effective binder volume.
- For HMA over stiff foundation, the thermal conductivity and heat capacity of the stabilized base were found to be sensitive design inputs for longitudinal cracking and, to a lesser extent, for alligator cracking and asphalt rutting.
- A moderately high sensitivity of longitudinal cracking and AC rutting to traffic speed was noted in the HMA over stiff foundation results, likely due to its influence on HMA dynamic modulus.

There were also a few unexpected findings, including the sensitivity of predicted distress to HMA Poisson's ratio and unit weight and the higher sensitivity of thermal cracking to the HMA dynamic modulus lower shelf (δ) in absolute value terms than to the upper shelf ($\delta+\alpha$).

Findings for JPCP

The sensitivities of the predicted performance to variations in the design inputs of JPCP varied by distress type (e.g., faulting vs. cracking vs. IRI) and to a lesser extent by type of foundation but the results suggest some broad conclusions. Table 2 summarizes the sensitivity level of design inputs by material category (e.g., concrete slab, base, and subgrade) for each distress for the new JPCP (similar trends were found for JPCP on stiff foundation). The findings were as follows:

- Slab width was consistently the highest sensitivity design input, followed by the concrete layer properties (concrete unit weight, coefficient of thermal expansion, strength and stiffness properties, thickness, and surface shortwave absorptivity) and other geometric properties (e.g., design lane width and joint spacing). The high sensitivity to strength and stiffness inputs suggests that inaccurate

(*text continues on page 10*)

Table 1 Sensitivity of design inputs by distress type for new HMA pavements.

Distress	Input Category	Hypersensitive (NSI > 5)	Very Sensitive (1 < NSI < 5)	Sensitive (0.1 < NSI < 1)
Longitudinal Cracking	HMA Properties	E* Alpha (–29.5) E* Delta (–23.9) Thickness (–10.3)	Air Voids (+4.5) Surface Shortwave Absorptivity (+4.3) Effective Binder Volume (–3.9) Poisson's Ratio (–2.4)	Unit Weight (–0.9) Heat Capacity (–0.8) Low Temperature PG (+0.6) High Temperature PG (+0.6) Thermal Conductivity (–0.5)
	Base Properties		Resilient Modulus (–4.7) Thickness (–2.4)	Poisson's Ratio (+0.9)
	Subgrade Properties		Resilient Modulus (–2.1) Percent Passing No. 200 (–1.7)	Liquid Limit (–0.7) Poisson's Ratio (+0.4) Plasticity Index (–0.2) Groundwater Depth (+0.2)
	Other Properties		Traffic Volume (+3.7) Operating Speed (–1.3)	
Alligator Cracking	HMA Properties	E* Alpha (–15.9) E* Delta (–13.2) Thickness (–7.5)	Air Voids (+3.4) Effective Binder Volume (–2.9) Surface Shortwave Absorptivity (+1.3) Poisson's Ratio (–1.0)	Unit Weight (+1.0) Heat Capacity (–0.6) High Temperature PG (–0.5) Thermal Conductivity (–0.4)
	Base Properties		Resilient Modulus (–2.7) Thickness (–1.0)	Poisson's Ratio (+0.9)
	Subgrade Properties		Resilient Modulus (–3.4)	Liquid Limit (–0.8) Percent Passing No. 200 (–0.7) Poisson's Ratio (–0.6) Groundwater Depth (–0.2) Plasticity Index (+0.1)
	Other Properties		Traffic Volume (+3.9)	Operating Speed (–0.8)

Distress	Input Category	Hypersensitive (NSI > 5)	Very Sensitive (1 < NSI < 5)	Sensitive (0.1 < NSI < 1)
AC Rutting	HMA Properties	E* Alpha (–24.4) E* Delta (–24.4)	Surface Shortwave Absorptivity (+4.6) Poisson's Ratio (–4.3) Thickness (–4.2)	Unit Weight (–0.9) Heat Capacity (–0.8) High Temperature PG (–0.7) Low Temperature PG (+0.2) Thermal Conductivity (+0.2)
	Base Properties			Thickness (+0.2) Poisson's Ratio (–0.2) Resilient Modulus (+0.1)
	Subgrade Properties			Percent Passing No. 200 (–0.1) Liquid Limit (–0.1)
	Other Properties		Traffic Volume (+1.9) Operating Speed (–1.1)	
Total Rutting	HMA Properties	E* Alpha (–9.0) E* Delta (–9.0)	Surface Shortwave Absorptivity (+1.7) Thickness (–1.6) Poisson's Ratio (–1.5)	Unit Weight (–0.3) Heat Capacity (–0.3) High Temperature PG (–0.2)
	Base Properties			Resilient Modulus (–0.2)
	Subgrade Properties			Resilient Modulus (–0.3) Percent Passing No. 200 (–0.1)
	Other Properties			Traffic Volume (+0.7) Operating Speed (–0.4)
IRI	HMA Properties		E* Alpha (–3.6) E* Delta (–2.8) Thickness (–1.1)	Surface Shortwave Absorptivity (+0.7) Poisson's Ratio (–0.4) Air Voids (+0.3) Effective Binder Volume (–0.2)
	Base Properties			Resilient Modulus (–0.4)
	Subgrade Properties			Resilient Modulus (–0.4) Percent Passing No. 200 (–0.1)
	Other Properties			Traffic Volume (+0.5) Operating Speed (–0.2)

$NSI_{\mu\pm2\sigma}$ values are given in parentheses.

Table 2 Sensitivity of design inputs by distress type for new JPCP.

Distress	Input Category	Hypersensitive (NSI > 5)	Very Sensitive (1 < NSI < 5)	Sensitive (0.1 < NSI < 1)
Faulting	PCC Properties		Unit Weight (–2.3) Coefficient of Thermal Expansion (+2.2)	28-Day Modulus of Rupture (+0.9) Surface Shortwave Absorptivity (+0.7) Water-to-Cement Ratio (+0.6) Thickness (+0.5) 20-year to 28-day Modulus of Rupture (+0.5) Cement Content (+0.3) Poisson's Ratio (+0.3) 28-Day Elastic Modulus (+0.2) Thermal Conductivity (–0.2)
	Base Properties			Resilient Modulus (+0.3) Erodibility Index (+0.3) Thickness (–0.1) Edge Support LTE (–0.1)
	Subgrade Properties			Resilient Modulus (–0.2)
	Other Properties	Slab Width (–18.0)	Design Lane Width (+1.6)	Joint Spacing (+0.7) Dowel Diameter (–0.7) Traffic Volume (+0.6) Construction Month (+0.1)
Transverse Cracking	PCC Properties		28-Day Modulus of Rupture (–4.2) Thickness (–3.9) Unit Weight (+3.1) Coefficient of Thermal Expansion (+2.8) 20-year to 28-day Modulus of Rupture (–2.7) 28-Day Elastic Modulus (+2.6) Surface Shortwave Absorptivity (+2.3) Water-to-Cement Ratio (+1.6) Thermal Conductivity (–1.1)	Poisson's Ratio (–0.8) Cement Content (+0.6)
	Base Properties			Thickness (+0.4) Resilient Modulus (+0.4) Erodibility Index (–0.2) Loss of Friction (–0.2)
	Subgrade Properties			Groundwater Depth (–0.4) Resilient Modulus (–0.3)

Distress	Input Category	Hypersensitive (NSI > 5)	Very Sensitive (1 < NSI < 5)	Sensitive (0.1 < NSI < 1)
Transverse Cracking	Other Properties	Slab Width (–5.0)	Design Lane Width (–3.8) Joint Spacing (+1.8)	Dowel Diameter (+0.9) Traffic Volume (+0.6) Edge Support LTE (–0.3) Construction Month (+0.2)
IRI	PCC Properties		Coefficient of Thermal Expansion (+1.3) Unit Weight (–1.2)	Water-to-Cement Ratio (+0.8) PCC 28-Day Modulus of Rupture (–0.6) Surface Shortwave Absorptivity (+0.6) Thickness (–0.5) 28-Day Elastic Modulus (+0.4) 20-year to 28-day Modulus of Rupture (–0.3) Thermal Conductivity (–0.2) Poisson's Ratio (+0.2) Cement Content (+0.2)
	Base Properties			Resilient Modulus (+0.2) Erodibility Index (+0.2)
	Subgrade Properties			Resilient Modulus (–0.9)
	Other Properties	Slab Width (–8.8)		Design Lane Width (+0.7) Joint Spacing (+0.4) Dowel Diameter (–0.4) Traffic Volume (+0.4)

$NSI_{\mu\pm2\sigma}$ values are given in parentheses.

(*text continued from page 5*)

estimates of concrete stiffness and strength gains with time can cause large errors in predicted pavement distresses.

- The sensitivity values for faulting, transverse cracking, and IRI were similar in magnitude, but the range for faulting was significantly larger than that for transverse cracking and IRI.
- Transverse cracking is highly sensitive to the widened slab edge support condition but not other edge support conditions (i.e., no edge support and tied shoulder edge support with 80% LTE).

Findings for CRCP

The sensitivity of predicted performance to variations in design inputs of CRCP varied by distress type (e.g., faulting vs. crack width vs. crack LTE vs. IRI) but the results suggest some broad conclusions. Table 3 summarizes the level of sensitivity by material category (e.g., concrete/steel, base, and subgrade) for each distress. The findings were as follows:

- Concrete and steel layer properties (concrete thickness, strength and stiffness properties, reinforcing steel properties, concrete unit weight, coefficient of thermal expansion, surface shortwave absorptivity) were most consistently the highest sensitivity design inputs followed by the base and subgrade properties; traffic volume was also an important design input.
- The largest sensitivity values for CRCP were substantially larger than those for JPCP.
- The magnitudes (mean and standard deviation) of the highest sensitivity values for punchouts and crack width were substantially greater than the values for crack LTE and IRI.
- The 20-year to 28-day ratio for modulus of rupture was the third-ranked sensitive design input for punchouts (and thus for IRI). This is of concern because the 20-year modulus of rupture can only be estimated.

General Remarks

Consideration of the high sensitivity or critical design inputs will depend on the specific design input. While some high sensitivity inputs can be specified with a small tolerance (e.g., HMA thickness, concrete thickness, lane width, and steel properties), other properties need to be measured or estimated. For example, mix-specific laboratory measurement of HMA dynamic modulus and Poisson's ratio and concrete modulus of rupture and modulus of elasticity may be appropriate for high-value projects. However, simple methods for defining surface shortwave absorptivity for asphalt and concrete surfaces and thermal conductivity and heat capacity of stabilized bases are not readily available and realistic values for specific paving materials have not been established. For these reasons, project-specific sensitivity studies to evaluate the consequences of uncertain input values may be appropriate for some situations.

FINAL REPORT

The contract agency's final report, "Sensitivity Evaluation of MEPDG Performance Prediction," gives a detailed account of the project, findings, and conclusions and includes further information on the sensitivity analysis methodology and the results of the different analyses. The report is available online at trb.org by searching NCHRP01-47_FR.pdf-.

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Table 3 Sensitivity of design inputs by distress type for new CRCP.

Distress	Input Category	Hypersensitive (NSI > 5)	Very Sensitive (1 < NSI < 5)	Sensitive (0.1< NSI < 1)
Punchout	PCC/Steel Properties	Thickness (–44.4) 28-Day Modulus of Rupture (–40.3) 20-year to 28-day Modulus of Rupture (–18.8) Unit Weight (–17.2) Percent Steel (–15.4) 28-Day Indirect Tensile Strength (+11.1) 28-Day Elastic Modulus (+10.9) Water-to-Cement Ratio (+8.4) Cement Content (+7.6) Coefficient of Thermal Expansion (+6.2)	Surface Shortwave Absorptivity (+3.3) Poisson's Ratio (+1.8) 20-year to 28-day Indirect Tensile Strength (+1.6)	
	Base Properties	Resilient Modulus (–6.4)	Base Slab Friction (–4.2) Thickness (–1.8)	
	Subgrade Properties		Resilient Modulus (–3.2)	Groundwater Depth (+0.4)
	Other Properties	Bar Diameter (+11.4) Traffic Volume (+8.5) Steel Depth (+6.4)	Edge Support LTE (–3.3) Construction Month (+1.6)	
Crack Width	PCC/Steel Properties	28-Day Indirect Tensile Strength (+61.5) 28-Day Modulus of Rupture (–47.8) Unit Weight (–35.3) Water-to-Cement Ratio (+31.1) Cement Content (+21.6) Percent Steel (–18.0) 28-Day Elastic Modulus (+16.0) Thickness (–10.5) 20-year to 28-day Modulus of Rupture (+7.9) 20-year to 28-day Indirect Tensile Strength (–5.8) Coefficient of Thermal Expansion (+5.5) Surface Shortwave Absorptivity (–5.5)	Poisson Ratio's (–2.4)	
	Base Properties	Base Slab Friction (–21.6)	Resilient Modulus (–4.7) Thickness (+4.7)	
	Subgrade Properties		Resilient Modulus (–4.6) Groundwater Depth (–1.2)	
	Other Properties	Bar Diameter (+23.3) Steel Depth (+13.4)	Construction Month (+2.3) Edge Support LTE (+2.2) Traffic Volume (+1.0)	

(continued on next page)

Table 3 (Continued)

<table>
<tr><th>Distress</th><th>Input Category</th><th>Hypersensitive (NSI > 5)</th><th>Very Sensitive (1 < NSI < 5)</th><th>Sensitive (0.1< NSI < 1)</th></tr>
<tr><td>Crack LTE</td><td>PCC/Steel Properties</td><td></td><td>28-Day Modulus of Rupture (+2.4)
Thickness (+1.6)
28-Day Indirect Tensile Strength (–1.3)
Percent Steel (+1.0)</td><td>Water-to-Cement Ratio (–0.8)
Cement Content (–0.7)
28-Day Elastic Modulus (–0.6)
Unit Weight (+0.5)
20-year to 28-day Modulus of Rupture (–0.5)
Surface Shortwave Absorptivity (+0.2)
20-year to 28-day Indirect Tensile Strength (+0.1)</td></tr>
<tr><td rowspan="3">Crack LTE</td><td>Base Properties</td><td></td><td></td><td>Base Slab Friction (+0.4)
Resilient Modulus (+0.1)
Thickness (–0.1)</td></tr>
<tr><td>Subgrade Properties</td><td></td><td></td><td></td></tr>
<tr><td>Other Properties</td><td></td><td>Bar Diameter (–1.5)</td><td>Steel Depth (–0.6)
Traffic Volume (–0.4)
Edge Support LTE (+0.3)</td></tr>
<tr><td rowspan="4">IRI</td><td>PCC/Steel Properties</td><td>Thickness (–9.0)
28-Day Modulus of Rupture (–7.4)</td><td>20-year to 28-day Modulus of Rupture (–3.5)
Unit Weight (–3.2)
Percent Steel (–3.0)
28-Day Indirect Tensile Strength (+2.4)
28-Day Elastic Modulus (+2.1)
Water-to-Cement Ratio (+1.9)
Cement Content (+1.4)
Coefficient of Thermal Expansion (+1.2)</td><td>Surface Shortwave Absorptivity (+0.7)
Poisson’s Ratio (+0.3)
20-year to 28-day Indirect Tensile Strength (–0.3)</td></tr>
<tr><td>Base Properties</td><td></td><td>Resilient Modulus (–1.2)</td><td>Base Slab Friction (–0.8)
Thickness (–0.4)</td></tr>
<tr><td>Subgrade Properties</td><td></td><td>Resilient Modulus (–1.2)</td><td></td></tr>
<tr><td>Other Properties</td><td></td><td>Bar Diameter (+1.9)
Traffic Volume (+1.6)
Steel Depth (+1.5)</td><td>Edge Support LTE (–0.6)
Construction Month (+0.3)</td></tr>
</table>

$NSI_{\mu\pm2\sigma}$ values are given in parentheses.

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