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Sensitivity Evaluation of MEPDG Performance Prediction

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ABSTRACT

This report documents and presents the results of a study to evaluate the sensitivity of pavement performance predicted by the Mechanistic-Empirical Pavement Design Guide to the values of the design inputs. Global sensitivity analyses were performed for five pavement types under five climate conditions and three traffic levels. Design inputs evaluated in the analyses included traffic volume, layer thicknesses, material properties (e.g., stiffness, strength, HMA and PCC mixture characteristics, subgrade type), groundwater depth, geometric parameters (e.g., lane width), and others. Detailed traffic inputs were not considered. Depending on the base case, approximately 25 to 35 design inputs were evaluated in the analyses. Correlations among design inputs (e.g., between PCC elastic modulus and modulus of rupture) were considered where appropriate. A normalized sensitivity index defined as the percentage change of predicted distress relative to its design limit caused by a given percentage change in the design input. The analyses found that, for all pavement types and distresses, the sensitivities of the design inputs for the bound surface layers were consistently the highest. Additional findings are also reported for each specific pavement type.

EXECUTIVE SUMMARY

The *Mechanistic-Empirical Pavement Design Guide Manual of Practice* (AASHTO, 2008) and related MEPDG software provide a new, more theoretically grounded methodology for the analysis and performance prediction of different types of flexible and rigid pavements. The cracking, rutting, faulting, smoothness, and other distresses predicted by the MEPDG for the anticipated climatic and traffic conditions will depend on the values of the input parameters that characterize the pavement materials, layers, design features, and condition. Knowledge of the sensitivity of predicted performance to the design input values can help identify, for specific climatic region and traffic conditions, the inputs that most influence predicted performance. This will help pavement designers determine where additional effort is justified in developing higher quality and/or more certain input values.

The overall objective of the research described in this report was to determine the sensitivity of the pavement performance predicted by the MEPDG to variability of the design input values for flexible and rigid pavements. This has been evaluated through an initial triage, extensive one-at-a-time (OAT) sensitivity analyses, and comprehensive global sensitivity analyses (GSA). 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 base cases 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 refine the list of sensitive design inputs to be considered in the more computationally intensive GSA. The GSA, in contrast to the OAT analyses, varied all design inputs simultaneously across the entire problem domain for each pavement type. 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.

Five pavement types were evaluated: 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 conditions or HMA/JPCP overlays on 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). This produced 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 PCC mixture characteristics, subgrade type), groundwater depth, geometric parameters (e.g., lane width), and others. Detailed traffic inputs beyond volume (AADTT) and operating speed were not considered. Depending on the base case, approximately 25 to 35 design inputs were evaluated in the analyses. Correlations among design inputs (e.g., between PCC elastic modulus and modulus of rupture) were considered where appropriate.

The key findings from the study are based on the global sensitivity analysis results, as these most thoroughly evaluate the mean and variability of the sensitivities across the problem domain as well as any potential interaction effects among design inputs. Over 41,000 MEPDG runs were performed for the GSA. In addition, over one million evaluations of the neural network response surface models were used to quantify the distribution of design input sensitivities across the entire problem domain.

A normalized sensitivity index (NSI) was adopted as the quantitative metric. The NSI is defined as the percentage change of predicted distress (e.g., total rutting) relative to its design limit (e.g., 0.75 inches) caused by a given percentage change in the design input (e.g., granular base resilient modulus). For example, NSI = -0.25 for the sensitivity of total rutting to granular base layer resilient

modulus implies that a 10% reduction in base resilient modulus will increase total rutting by 2.5% of its design limit of 0.75 inches. 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 percentage change in distress relative to its design limit equals the percentage change in the design input. The “mean plus/minus two standard deviations” value of NSI ($NSI_{\mu \pm 2\sigma}$) was adopted as the best and most robust ranking measure because it incorporates both the mean sensitivity and the variability of sensitivity across the problem domain. Based on this, the following design input sensitivity categories were defined for the GSA results: Hypersensitive, $NSI_{\mu \pm 2\sigma} > 5$; Very Sensitive, $1 < NSI_{\mu \pm 2\sigma} < 5$; Sensitive, $0.1 < NSI_{\mu \pm 2\sigma} < 1$; and Non-Sensitive, $NSI_{\mu \pm 2\sigma} < 0.1$. For practical design purposes, the high sensitivity or critical design inputs can be limited to those in the Hypersensitive and Very Sensitive categories.

The wide range of pavement types, distresses, and design inputs considered in this study made it difficult to extract broad conclusions that apply to all pavements under all conditions. Nonetheless, some important trends consistently observed in the GSA result included:

- Most of the NSI frequency distributions generated from the ANN RSMs for each pavement type-climate zone-distress combination showed very well defined single peaks, indicating that the NSI value did not vary significantly over the problem domain. The few cases in which the NSI distributions were more broad either had NSI values that were all small and not of interest or all large and thus always of interest. No frequency distributions exhibited multi-mode or multiple peak characteristics.
- For all pavement types and distresses, the sensitivities of the design inputs for the bound surface layers (HMA, PCC) were the most important.
- The sensitivity values for each distress-design input combination did not vary substantially or systematically by climate zone. However, the distress magnitudes may vary by climate.

Key findings specific to flexible pavements included:

- Only the HMA properties were most consistently in the highest sensitivity categories: the lower and upper shelves of the HMA dynamic modulus master curve, HMA thickness, surface shortwave absorptivity, and Poisson’s ratio. None of the base, subgrade, or other properties (e.g., traffic volume) was as consistently in the two highest sensitivity categories.
- The magnitudes of the sensitivity values for longitudinal cracking, 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 had very little overlap with the set of sensitive design inputs for thermal cracking.
- Little or no thermal cracking was predicted when using the correct binder grade for the climate. The low temperature binder grade had to be shifted 2 to 3 grades stiffer (warmer) in order to generate sufficient thermal cracking distress for evaluating the sensitivity metrics.

Key findings specific to JPCP rigid pavements included:

- Slab width was consistently the highest sensitivity design input, followed by the PCC layer properties (PCC unit weight, PCC coefficient of thermal expansion, PCC strength and stiffness properties, PCC thickness, surface shortwave absorptivity) and other geometric properties (design lane width, joint spacing).
- The magnitudes of the sensitivity values for faulting, transverse cracking, and IRI were similar. However, the range of sensitivity values for faulting was significantly larger than for transverse cracking and IRI.

Key findings specific to CRCP rigid pavements included:

- Most of the consistently highest sensitivity design inputs were reinforced PCC/steel layer properties (PCC thickness, PCC strength and stiffness properties, reinforcing steel properties, PCC unit weight, PCC coefficient of thermal expansion, surface shortwave absorptivity) followed by the base and subgrade properties. Traffic volume was also an important design input.
- The highest sensitivity values for New CRCP scenarios were substantially larger than those for any of the other pavement types.
- The magnitudes (mean and standard deviation) of the highest sensitivity values for punchouts and crack width were substantially greater than the values for crack load transfer efficiency (LTE) and IRI.
- The PCC Ratio of 20-year to 28-day modulus of rupture was the third-ranked design input for punchouts and thus for IRI. However, the 20-year modulus of rupture cannot be directly measured and thus this design input can only be estimated.

Guidance for the pavement designer on how to address high sensitivity or critical design inputs varies depending upon the specific design input. Some high sensitivity inputs can be specified very precisely, e.g., PCC thickness. Other properties need to be measured or estimated. The high sensitivity of distresses to the HMA dynamic modulus and PCC strength and stiffness properties indicates a need for careful characterization of these properties. Mix-specific laboratory measurement of dynamic modulus or the complete set of PCC strength and stiffness properties may be appropriate for high-value projects. Other properties like the PCC coefficient of thermal expansion are very difficult to measure, and testing protocols are still evolving. The high sensitivity of distresses to surface shortwave absorptivity for both flexible and rigid pavements is more problematic as this property cannot be readily measured and guidance on realistic values for specific paving materials is lacking. For these as well as all other high sensitivity design inputs, the pavement designer should perform project-specific design sensitivity studies to evaluate the consequences of uncertain input values.

1. BACKGROUND

The *Mechanistic-Empirical Pavement Design Guide Manual of Practice* (AASHTO, 2008) and related MEPDG software provide a new, more theoretically grounded methodology for the analysis and performance prediction of different types of flexible and rigid pavements. Structural responses such as stresses, strains and deflections are mechanistically calculated using multilayer elastic theory or finite element methods for given material properties, environmental conditions, and traffic loading characteristics. Thermal and moisture distributions are also mechanistically determined using an Enhanced Integrated Climate Model. These mechanistic responses are used as inputs to empirical distress models for predicting permanent deformation, fatigue cracking (bottom-up and top-down), thermal cracking, and roughness. The MEPDG models have been calibrated using field data from the LTPP database for conditions representative of the entire U.S.

The cracking, rutting, faulting, smoothness, and other distresses predicted by the MEPDG for the anticipated climatic and traffic conditions will depend on the values of the input parameters that characterize the pavement materials, layers, design features, and condition. Knowledge of the sensitivity of predicted performance to the design input values can help identify, for specific climatic region and traffic conditions, the inputs that most influence predicted performance. This will help pavement designers determine where additional effort is justified in developing higher quality and/or more certain input values.

The overall objective of the research described in this report was to determine the sensitivity of the performance predicted by the MEPDG to variability of the design input values for flexible and rigid pavements. This has been evaluated through an initial triage, extensive one-at-a-time (OAT) sensitivity analyses, and comprehensive global sensitivity analyses (GSA). 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 x 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 refine the list of sensitive design inputs to be considered in the more computationally intensive GSA. The GSA, in contrast to the OAT analyses, varied all design inputs simultaneously across the entire problem domain for each pavement type. 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.

This report summarizes the highlights of the methodology and findings of this research. Chapter 2 summarizes the initial triage of design inputs based on the available literature and other considerations. Chapter 3 describes key aspects of the sensitivity analysis methodology, including the base cases considered, the design inputs and outputs evaluated for each pavement type/scenario, the sensitivity metric definitions, and the sampling and response surface approaches used to generate the results. Chapter 4 presents the results from the OAT local sensitivity analyses and Chapter 5 presents the corresponding results from the GSA for each pavement type: New HMA, HMA Over Stiff Foundation, New JPCP, JPCP Over Stiff Foundation, and New CRCP. Chapter 6 summarizes the overall conclusions from the study.

The highlights provided in main report are supplemented by extensive technical appendices that fully document all details of the study. Appendix A describes the initial triage of design inputs. Appendix B provides a complete description of the methodology, inputs, and results for the OAT local sensitivity analyses. Appendix C provides the corresponding descriptions for the GSA. These appendices are provided in electronic form on the CD accompanying this report.

2. INITIAL TRIAGE OF DESIGN INPUTS

2.1. Introduction

An initial triage was developed to categorize the MEPDG design inputs. The term *triage*, from the French verb *trier* meaning to separate, sift or select (Merriam Webster, 2011), is most commonly used in emergency medicine to describe the heuristic process of sorting incoming patients into categories for treatment. It is used here in its more general sense to describe the process of sorting the MEPDG design input sensitivities into three categories defined as very sensitive, sensitive, and non-sensitive. Input factors in the very sensitive and sensitive categories were intended for inclusion in the main global sensitivity analyses; those in the non-sensitive category were to be excluded from further consideration. Another objective of this preliminary work was to identify any potential correlations of inputs. This was accomplished by reviewing the findings from past studies, subjective assessments, and quantitative evaluations via limited OAT sensitivity analyses of other potentially significant input parameters.

Details of the literature review and design inputs triage are documented in Appendix A of this report. The key issues and findings are summarized in the following subsections.

2.2. Literature Review

Since the release of the original research version of the MEPDG software (Version 0.7) in July 2004, the software was updated under other NCHRP projects several times. Version 1.0 of the MEPDG was adopted as an interim AASHTO pavement design procedure in 2007. A detailed discussion of differences among the different MEPDG software versions can be found in the NCHRP Project 1-40D (Darter *et al.*, 2006) project report. The latest update, Version 1.1 released in September 2009, included further enhancements and improved the rehabilitation design analyses. The DARWin-ME v2.0 software released by AASHTO in April 2011 is based on the mechanistic-empirical models incorporated in Version 1.1 of the MEPDG (AASHTO, 2008).

MEPDG sensitivity studies began appearing in the literature immediately after the initial release of the MEPDG in 2004. Early sensitivity studies for rigid pavements include the work by Rao *et al.* (2004), Selezneva *et al.* (2004), Khazanovich *et al.* (2004), Hall and Beam (2005), Guclu (2005), Kannekanti and Harvey (2006), and Khanum *et al.* (2006). Early sensitivity studies for flexible pavements include those by Lee (2004), Masad (2004), Masad and Little (2004), El-Basyouny and Witczak (2005a, 2005b, 2005c), Schwartz (2005), Brown *et al.* (2006), Carvalho and Schwartz (2006), Chehab and Daniel (2006), Graves and Mahboub (2006a, 2006b), Khazanovich *et al.* (2006), Kim *et al.* (2006), Mohammad *et al.* (2006), Yin *et al.* (2006), Zaghoul *et al.* (2006), Hoerner *et al.* (2007), and Kim *et al.* (2007).

All of these studies were conducted using versions of the MEPDG software prior to the Version 1.0 release in 2007. Some sensitivities of MEPDG performance to design inputs changed significantly from one version to the next as software error corrections, model recalibrations, and other changes were implemented. Consequently, the current project focused its literature review on sensitivity analysis studies conducted using Version 1.0/1.1 of the MEPDG software. For rigid pavements, these included the work by Tanesi *et al.* (2007), Ceylan *et al.* (2009), Buch *et al.* (2008), Haider *et al.* (2008), Haider *et al.* (2009), Hiller and Roesler (2009), Kapmann (2008), McCracken *et al.* (2009), Oh and Fernando (2008), Puertas (2008), Tran *et al.* (2008), Moon (2009), Oman (2010), Johanneck and Khazanovich (2010), and Hall *et al.* (2010). For flexible pavements, these included the work by

Buch *et al.* (2008), Khazanovich *et al.* (2008b), Aguiar-Moya *et al.* (2009), Ahn *et al.* (2009), Schwartz (2009), Thyagarajan *et al.* (2010), Velasquez *et al.* (2009), Ayyala *et al.* (2010), Hall *et al.* (2010), Schwartz and Li (2010), and Yin *et al.* (2010). The objectives and findings of all of these studies are summarized in Appendix A.

Previous MEPDG sensitivity studies have been limited in scope, approach, and findings. Several significant issues with relevance to the present study are highlighted:

1. Most of the studies have focused largely on confirming that the trends in predicted pavement performance are consistent with engineering expectations. Nearly all of these past studies have employed a limited one-at-a-time (OAT) methodology. OAT analyses are easy to perform but have serious shortcomings. In the OAT approach, one or more baseline cases are defined and each input (e.g., granular base layer stiffness) is then varied individually for each case to evaluate its effect on the output (e.g., quantity of fatigue cracking). Only the sensitivities around the reference input values for the baseline cases are evaluated—i.e., the evaluation is only for very small regions of the overall solution space. This provides only a “local” as opposed to a “global” sensitivity evaluation, which is useful but not sufficient for complex problems like pavement performance simulation.
2. The studies have typically varied only a small subset of inputs that have been judged *a priori* as being the most “important.” This is understandable, given the very large number of inputs in the MEPDG. However, the selection of “important” inputs has been subjective and *ad hoc*. More careful and systematic screening was required for objective identification of the subsets of inputs to be varied in the study.
3. The studies have largely ignored any correlations and/or interactions among input parameters. Correlations among inputs are present when a change in one input tends to cause change in another input (e.g., PCC modulus of rupture and modulus of elasticity as related to compressive strength). Interactions among inputs are manifested when simultaneous changes in two independent inputs cause changes in outputs that are greater than the sum of the individual effects (e.g., interactions between climate and subgrade support degradation due to excessive moisture). The OAT methodologies employed in most prior MEPDG sensitivity studies are incapable of including input correlations or detecting input interactions.
4. Not all of the studies used the latest version of the MEPDG software. There were significant enhancements and recalibrations from versions 0.7 to 0.8 to 0.9 to 1.0 and 1.1. The input sensitivities will also change from one version to the next, but by an unknown amount.

2.3. Design Inputs Triage

2.3.1. Issues

The project team grappled with several significant issues while developing tables for the design inputs triage:

1. Most previous studies from the literature have employed subjective qualitative assessments or a mixture of objective quantitative sensitivity measures such as normalized and non-normalized partial derivatives, Pearson and Spearman correlation coefficients, qualitative assessments, and others. These subjective qualitative assessments and/or heterogeneous quantitative measures cannot be compared directly.

2. Even the few previous studies that used the same quantitative sensitivity measures (e.g., Pearson correlation coefficients) used different quantitative ranges to categorize high, moderate, and low sensitivity.
3. Some sensitivity results changed significantly between versions 0.7, 0.8, 0.9, and 1.0 of the MEPDG software. (The project team performed a limited comparison study and no differences between versions 1.0 and 1.1.) The project team therefore excluded prior studies that used MEPDG earlier than version 1.0. However, sensitivity findings obtained using version 0.9 were included if more recent results were unavailable.
4. Only one or two previous studies dealt with the issue of correlations among inputs in a qualitative manner. Input correlations must be identified and quantified *a priori* in sensitivity analyses. The project team relied principally upon engineering judgment in identifying potential input correlations and quantifying their expected magnitudes.
5. Some of the inputs to the MEPDG are in terms of fundamental engineering properties while others are in terms of index properties that are used to estimate fundamental engineering properties. An example of this is the Level 1 measured dynamic modulus for HMA vs. the Level 3 estimates of dynamic modulus from mix gradation, volumetrics, and binder characteristics. The philosophy adopted for this study was to concentrate on sensitivity of predicted performance to fundamental engineering properties (e.g., by shifting the entire dynamic modulus master curve). The sensitivity of the MEPDG submodels linking Level 1 fundamental engineering properties to Level 3 index properties can be and have been evaluated separately using much simpler sensitivity analysis techniques (e.g., Schwartz, 2005; Khazanovich *et al.*, 2008a; and Thyagarajan *et al.*, 2010 for the Witczak dynamic modulus model).

Details of traffic inputs such as vehicle class distributions, axle load distributions, seasonal and daily traffic distributions, axle geometric configuration, tire pressure, and traffic growth rates were not considered. Traffic volume (AADTT) is included in the because the computed sensitivities of predicted performance to this design input provides a context or reference point for the interpretation of the sensitivity of performance to other design inputs. Limited OAT analyses found that the details of the traffic distribution (within reasonable practical bounds) have a much lower impact on predicted performance than does AADTT.

2.3.2. Triage Results: Flexible Pavements

The triage process examined the influence of design inputs on longitudinal cracking, alligator cracking, thermal cracking, asphalt rutting, and total rutting for flexible pavements. IRI, which is largely a function of these primary distresses, was not considered explicitly in the initial triage. Reflection cracking and CTB fatigue cracking distresses for flexible pavements were excluded. The reflection cracking model is largely hidden in the MEPDG (e.g., there is no way to specify a design limit for reflection cracking) and the output for reflection cracking distress is minimal. The reflection cracking model in the current MEPDG was implemented during NCHRP Project 1-37A as a placeholder to be replaced by a validated model in the future. CTB cracking was excluded because it is a highly specialized distress that appears only in a small subset of flexible pavements. The CTB model in the current version of the MEPDG is uncalibrated largely because of the lack of CTB sections in the LTPP database.

Appendix A provides detailed documentation of the flexible pavement triage and includes the individual tables listing the sensitivity of each pavement distress to each MEPDG design input. The principal output of the triage is the categorization of design inputs as “very sensitive,” “sensitive,” and “nonsensitive” in terms of their impacts on predicted pavement performance. The triage results are summarized in in Table 2.1.

Table 2.1 for flexible pavements. A total of 19 flexible pavement inputs were classified as “sensitive” or “very sensitive” in Table 2.1.

Table 2.1. Triage summary for MEPDG flexible pavement inputs.

HMA pavement Inputs		Level of Sensitivity for Flexible Pavement Outputs ¹				
Group	Parameters	HMA Rutting	Total Rutting	Alligator Cracking	Long. Cracking	Thermal Cracking
General	Traffic open month	NS	NS	NS	NS	NS
Traffic	Volume	VS	VS	VS	VS	NS
	Speed	VS	VS	S	S	NS
Climate	Location	VS	S	S	S	S
	Depth to groundwater table	NS	S	NS	NS	NS
Layer/General	Surface shortwave absorptivity	VS	VS	S	VS	NS
Layer/HMA	Thickness	VS	VS	VS	S	NS
	Dynamic modulus	S	S	S	S	NS
	Binder grade/stiffness	VS	S	S	S	S
	Poisson's ratio	NS	NS	NS	NS	NS
	Thermal conductivity	NS	NS	NS	NS	S
	Heat capacity	NS	NS	NS	NS	S
	Creep compliance	NS	NS	NS	NS	VS
	Tensile strength at 14°F	NS	NS	NS	NS	VS
	Aggregate coefficient of thermal contraction	NS	NS	NS	NS	VS
Layer/Base (Subbase)	Thickness	S	S	S	S	NS
	Resilient modulus	S	S	S	VS	NS
	Poisson's ratio	NS	NS	NS	NS	NS
	Soil-water characteristic curve	NS	NS	NS	NS	NS
	Permeability	NS	NS	NS	NS	NS
	Compacted/uncompacted	NS	NS	NS	NS	NS
Layer/Subgrade	Resilient modulus	NS	VS	S	S	NS
	Poisson's ratio	NS	NS	NS	NS	NS
	Soil-water characteristic curve	S	S	S	S	NS
	Permeability	NS	NS	NS	NS	NS
	Compacted/uncompacted	NS	NS	NS	NS	NS
HMA/HMA (Rehab)	Milled AC thickness	NS	NS	NS	NS	NS
	Existing AC thickness (after milling)	S	S	S	S	NS
	Existing AC binder grade	S	S	S	S	NS
	Pavement rating	VS	S	VS	VS	NS
	Total rutting	VS	VS	NS	NS	NS
HMA/JPCP (Rehab)	Existing PCC modulus of rupture	NS	NS	NS	NS	NS
	Percent slabs cracked/repared	NS	NS	NS	NS	NS
	Monthly modulus of subgrade reaction	NS	NS	NS	NS	NS
	Month for measuring modulus	NS	NS	NS	NS	NS

¹VS = very sensitive, S = sensitive, NS = nonsensitive.

2.3.3. Triage Results: Rigid Pavements

The triage process examined the influence of design inputs on faulting and transverse cracking for rigid JPCP pavements and punchouts, maximum crack width, and LTE for rigid CRCP pavements. IRI, which is largely a function of these primary distresses, was not considered explicitly in the initial triage. Appendix A provides detailed documentation of the design inputs triage and includes the individual tables developed for each rigid pavement type listing the sensitivity of each pavement distress to each MEPDG design input. These results are summarized in Table 2.2 for JPCP and Table 2.3 for CRCP. The number of design inputs rated as “sensitive” or “very sensitive” totaled 24 for JPCP (Table 2.2) and 16 for CRCP (Table 2.3).

Table 2.2. Triage summary for MEPDG JPCP inputs.

JPCP Inputs		Level of Sensitivity for JPCP Distresses ¹	
Groups	Parameters	Faulting	Cracking
Traffic	Initial two-way AADTT	VS	VS
	Design lane width	NS	S
Climate	Climate	VS	S
Design Feature	Permanent curl/warp effective temp difference	VS	VS
	Joint spacing	VS	VS
	Sealant type	NS	NS
	Dowel diameter	S	NS
	Dowel spacing	NS	NS
	Edge Support	VS	S
	Erodibility index	S	NS
	PCC-Base Interface	NS	NS
Layer/General	Surface shortwave absorptivity	VS	VS
Layer/PCC	PCC layer thickness	VS	VS
	Unit weight	S	S
	Poisson's ratio	S	S
	Coefficient of thermal expansion	VS	VS
	Thermal conductivity	S	VS
	Heat capacity	NS	NS
	Cement type	NS	NS
	Cementitious material content	S	NS
	Water/cement ratio	S	NS
	Aggregate type	NS	NS
	PCC zero-stress temperature	S	NS
	Reversible shrinkage	NS	NS
	Time to develop 50% of ultimate shrinkage	NS	NS
	Curing method	NS	NS
	28-day PCC modulus of rupture	S	VS
	28-day PCC compressive strength	NS	VS
Layer/Subbase (Base)	Granular base material/stiffness	VS	S
	Granular base thickness	S	S
	Poisson's ratio	NS	NS
	Compacted or uncompacted	NS	NS

Layer/Subgrade	Subgrade material/stiffness	S	S
	Poisson's ratio	NS	NS
	Compacted or uncompacted	NS	NS
JPCP/HMA (Rehab)	HMA milled thickness	NS	NS
	Pavement rating	S	S
	Monthly modulus of subgrade reaction measured	S	S
	Month for measuring modulus	S	S

¹VS = very sensitive, S = sensitive, NS = nonsensitive.

Table 2.3. Triage summary for MEPDG CRCP inputs.

CRCP Inputs		Level of Sensitivity for CRCP Distresses ¹		
Groups	Parameters	Punch-out	Maximum Crack Width	Minimum LTE
Traffic	Initial two-way AADTT	VS	S	S
Climate	Climate	S	S	S
Design Feature	Permanent curl/warp effective temperature difference	VS	NS	NS
	Shoulder type	S	NS	S
	Percent steel	VS	VS	VS
	Bar diameter	VS	VS	VS
	Steel depth	NS	S	S
	Base/slab friction coefficient	NS	S	NS
Layer/General	Surface shortwave absorptivity	NS	NS	NS
Layer/PCC	PCC layer thickness	VS	S	VS
	Unit weight	S	NS	NS
	Poisson's ratio	S	NS	NS
	Coefficient of thermal expansion	VS	S	S
	Thermal conductivity	NS	NS	NS
	Heat capacity	NS	NS	NS
	Cement type	NS	NS	NS
	Cementitious material content	S	S	S
	Water/cement ratio	NS	S	S
	Aggregate type	NS	NS	NS
	Reversible shrinkage	NS	NS	NS
	Curing method	NS	NS	NS
	28-day PCC modulus of rupture	VS	VS	VS
Layer/Subbase (Base)	Granular base material/stiffness	S	NS	NS
	Granular base thickness	S	NS	NS
	Poisson's ratio	NS	NS	NS
	Compacted or uncompacted	NS	NS	NS
Layer/Subgrade	Subgrade material/stiffness	S	NS	NS
	Poisson's ratio	NS	NS	NS
	Compacted or uncompacted	NS	NS	NS

¹VS = very sensitive, S = sensitive, NS = nonsensitive.

3. SENSITIVITY ANALYSIS METHODOLOGY

The base cases, design inputs, sampling methodology, analysis execution, response surface modeling, and sensitivity metrics for this study are briefly described in the following subsections. Details are provided in Appendices B and C for the one-at-a-time local sensitivity and global sensitivity analyses, respectively.

3.1. Base Cases

Sensitivity analyses were conducted for the full ranges of all model inputs and outputs. However, not all combinations of model input values are physically plausible. For example, a 4 inch full-depth asphalt pavement on an A-7-6 subgrade subjected to 50M ESALs in a wet-freeze climate does not represent a realistic scenario likely to be encountered in practice. Therefore, a set of base cases that is considered useful from a practical perspective was selected for the sensitivity analyses.

A sufficiently large and diverse number of base cases were selected so that the entire solution domain for the MEPDG is evaluated. These base case conditions are summarized in Table 3.1; they span the ranges of commonly encountered pavement types, climate conditions and traffic levels. The total number of base cases is 75 (5 pavement types x 5 climates x 3 traffic levels).

Table 3.1. Conditions for base cases.

Pavement Type	New HMA/GB/SB New JPCP/GB New CRCP/GB HMA on Stiff Foundation JPCP on Stiff Foundation
Climate	Hot-Wet Hot-Dry Cold-Wet Cold-Dry Temperate
Traffic Level	Low Moderate High

Note: HMA/JPCP on Stiff Foundation is intended to represent both new construction/reconstruction on stabilized foundations or rehabilitation (i.e., overlays) on underlying HMA/PCC layers.

For these base cases, two sets of global inputs were used in the sensitivity analyses for all pavement types: climate conditions and traffic levels. Five climate zones were considered: Hot-Dry, Hot-Wet, Temperate, Cold-Dry and Cold-Wet. The specific locations, the weather station used to generate the climate files, the baseline binder grade recommended by LTPPBind at the 98% reliability level, and the range of binder grades used in the sensitivity analyses for each climate category are summarized in Table 3.2. There were no gaps (i.e., no missing months of data) in the MEPDG climate files for the specified locations.

Table 3.2. Climate categories for base cases.

Climate Category	Location	Weather Station	Months of Data	Binder Grade	
				Baseline	Range
Hot-Wet	Orlando FL	ORLANDO INTERNATIONAL ARPT	116	PG 70-10	PG 64-10 PG 76-10
Hot-Dry	Phoenix AZ	PHOENIX SKY HARBOR INTL AP	116	PG 76-10	PG 70-10 PG 82-10
Cold-Wet	Portland ME	PORTLAND INTL JETPORT ARPT	116	PG 52-28	PG 52-34 PG 52-22
Cold-Dry	International Falls MN	FALLS INTERNATIONAL ARPT	112	PG 58-28	PG 58-34 PG 58-22
Temperate	Los Angeles CA	LOS ANGELES INTL AIRPORT	108	PG 58-10	PG 52-10 PG 64-10

The three traffic levels used in all GSA are summarized in Table 3.3. The baseline AADTT values fall within the low (<5,000), medium (5,000-10,000), and high (>15,000) truck volume categories in the FHWA *FAF² Freight Traffic Analysis Report* (Alam *et al.*, 2007). To put these traffic volumes into a more familiar context, the approximate number of ESALs for flexible and rigid pavements are also included in Table 3.3.

Table 3.3. Traffic ranges for base cases.

Traffic Category	Baseline Inputs				AADTT Range
	AADTT ¹	AADTT in Design Lane	Est. ESALs (Flexible) ⁵	Est. ESALs (Rigid) ⁶	
Low	1,000	375 ²	2M	5M	500-5,000
Medium	7,500	2,063 ³	10M	25M	5,000-10,000
High	25,000	6,250 ⁴	30M	75M	20,000-30,000

¹Based on MEPDG Interstate Highway TTC4 Level 3 default vehicle distribution. Potential correlations between operating speed and AADTT have been ignored.

²50% directional split, 2 lanes per direction, 0.75 lane factor for design lane.

³50% directional split, 3 lanes per direction, 0.55 lane factor for design lane.

⁴50% directional split, 3 lanes per direction, 0.50 lane factor for design lane.

⁵Based on 15 year design life.

⁶Based on 25 year design life.

Details of the traffic input such as vehicle class distributions, axle load distributions, seasonal and daily traffic distributions, axle geometric configuration, tire pressure, and traffic growth rates were not considered.

The five climate zones and three traffic levels give a total of 15 base cases for the sensitivity analyses for each pavement type. These base cases are abbreviated as “XXY” in which “XX” designates the climate (CD/Cold-Dry, CW/Cold-Wet, T/Temperate, HD/Hot-Dry, 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.

3.2. Design Inputs

3.2.1. Special Input Considerations

Some of the design inputs are correlated and/or have other characteristics that warrant special treatment. These include:

Unbound Material Properties. The MEPDG needs unbound material gradation and plasticity as inputs at all three input levels. The only unbound design inputs in the “Hypersensitive,” “Very Sensitive,” or “Sensitive” categories from the one-at-a-time sensitivity analyses (Appendix B) were: the base resilient modulus (M_r) and Poisson’s ratio (ν); the subgrade M_r and ν ; and, for the subgrade, the percent passing the No. 200 sieve (P200), the D_{60} gradation parameter, the plasticity index (PI), and the liquid limit (LL) values via their influence on the soil-water characteristic curve (SWCC) parameters. The P200, D_{60} , PI, and LL subgrade inputs are all highly correlated to M_r , which in turn is primarily a function of soil type. Regression models for relating P200, D_{60} , PI, and LL to M_r are documented in Appendix B.

Note that the parameters a_f , b_f , c_f , and h_r for the Fredlund and Xing (1994) SWCC model employed in the MEPDG could have been varied directly for the GSA simulations. However, it is unlikely that unbound Level 1 SWCC parameters will be measured in practice by agencies. It is therefore appropriate to specify the unbound SWCC parameters as Level 3 inputs as functions of P200, D_{60} , PI, and LL.

HMA Dynamic Modulus and Binder Properties. HMA dynamic modulus E^* is a highly sensitive input in the MEPDG performance predictions. Dynamic modulus is multivalued, varying with temperature and loading rate. It is also highly dependent on the viscosity characteristics of the binder. As documented in Appendix B and further detailed in Appendix C, the approach adopted for the sensitivity analyses was to specify E^* using synthetic Level 1 inputs generated using the general sigmoidal form for the dynamic modulus relationship (AASHTO, 2008):

$$\log(E^*) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma \log t_r}} \quad (1)$$

in which:

- E^* = dynamic modulus (psi)
- t_r = loading time (seconds) at the reference temperature
- δ, α = fitting parameters; δ represents the minimum value (lower shelf) for E^* and $\delta + \alpha$ represents the maximum value (upper shelf)
- β, γ = fitting parameters describing the shape (horizontal location and slope) of the sigmoidal function in the transition region between the lower and upper shelves

The δ and α parameters in Equation (1) were varied directly in the sensitivity analyses. Consistent with concepts underlying the Witczak empirical E^* model (AASHTO, 2008), γ is a constant, β is a function of binder viscosity η at the temperature of interest, and t_r is converted to loading rate in terms of frequency (a function of traffic speed, a design input varied in the sensitivity analyses). The binder viscosity η is determined from the binder grade (another design input varied in the sensitivity analyses) and temperature (a function of climate zone). The binder viscosity and temperature are also used to generate synthetic Level 1 binder dynamic shear stiffness G^* and phase angle values for input to the MEPDG.

The key aspect of this approach is that HMA dynamic modulus and binder dynamic shear stiffness are specified in the sensitivity analyses by varying the synthetic Level 1 design inputs (i.e., by varying δ , α , loading rate, and binder grade) rather than by varying the inputs to the Level 3 empirical relations. The Witczak E^* empirical model incorporated into the MEPDG is just one of many similar models that have been proposed in the literature (e.g., Al-Khateeb *et al.*, 2006; Bari and Witczak, 2006; Christensen *et al.* 2003, Ceylan *et al.*, 2007; Ceylan *et al.*, 2009; Far *et al.*, 2009). The prediction errors and lack of sensitivity to mix parameters of the Witczak dynamic modulus model have been amply documented in the literature (e.g., Schwartz, 2005; Ceylan *et al.*, 2009).

HMA Low Temperature Properties. Significant thermal cracking developed in the OAT local sensitivity analyses only when the low temperature PG grade was set 2 or 3 steps warmer than the recommended grade. Consequently, the low temperature tensile strength and creep compliance properties for the HMA are irrelevant for most of the GSA simulations. Special low temperature cracking simulations using unrealistic binder grades having excessively stiff low temperature characteristics are required to evaluate the sensitivity of thermal cracking to MEPDG design inputs.

The key HMA low temperature properties (tensile strength, creep compliance) are correlated with other HMA and binder properties. The low temperature creep compliance in particular is highly correlated, albeit in a complex way, with dynamic modulus. Conceptually, it is possible to fit a Prony series approximation to the synthetic Level 1 HMA E^* data, convert this to a Prony series approximation to the creep compliance using well-known but complex interconversion relations (Park and Schapery, 1999), use this to generate synthetic creep compliance values at various time intervals and low temperatures, and then fit these synthetic compliance values with a power law creep compliance relation of the form used in the MEPDG. Each one of these steps involves numerical approximations and unknown errors.

Given these problems and the fact that thermal cracking is largely decoupled from other pavement distresses, the correlations between the low temperature HMA properties and other mixture and binder properties were not considered in the GSA. Instead, the low temperature HMA properties were sampled randomly between their likely lower and upper limits. These limits were estimated using the revised Level 3 relations developed by Darter *et al.* (2006) that were subsequently implemented in the MEPDG software. Details of the revised Level 3 correlations for the low temperature creep compliance as functions of binder properties and mixture volumetrics are provided in Appendix C.

PCC Stiffness and Strength. Portland cement concrete (PCC) stiffness and strength properties are highly sensitive inputs in the prediction of MEPDG performance. Level 1 of the MEPDG for JPCP requires measured values of PCC modulus of elasticity (E) and modulus of rupture (MOR) at various ages to characterize stiffness and strength gains over time. In addition to these two parameter values, Level 1 of the MEPDG for CRCP requires measured values of PCC indirect (or split) tensile strength (f_t') at various ages.

In the GSA simulations, synthetic Level 1 concrete strength and stiffness inputs were generated following the concepts in the Level 3 empirical relations. The steps in this procedure were:

1. Assume that aging relationships for MOR and E_c follow similar trends in time equal on average to those in the Level 3 relationship.
2. Randomly sample a reference 28-day MOR in the range of 500 to 800 psi.

3. Randomly perturb the coefficients in the aging relationship within a $\pm 10\%$ range about their Level 3 defaults and estimate a consistent value of the ratio of 20-year to 28-day strength. Use these values to predict *MOR* at 7, 14, and 90 days. The perturbation of the aging coefficients is intended conceptually to reflect different aging potentials for different PCC mixes.
4. Randomly perturb the ratio of E_c to *MOR* within a $\pm 10\%$ range about its Level 3 default. Use this perturbed value and the *MOR* values from step 3 to determine elastic modulus at 7, 14, and 90 days. In CRCP analysis, randomly perturb the ratio of f_t' to *MOR* within a $\pm 10\%$ range about its Level 3 default. Use this perturbed value and the *MOR* values from step 3 to predict indirect tensile strength at 7, 14, and 90 days. The perturbations of the stiffness and tensile strength ratios are intended conceptually to reflect the variation of stiffness-to-strength ratios for different PCC mixes.
5. Input the synthetically generated Level 1 concrete strength and stiffness data from steps 3 and 4 into the MEPDG for the GSA simulations.

Details of this procedure are provided in Appendix C. This procedure for generating synthetic Level 1 PCC strength and stiffness data incorporates the correlations among these properties as embodied in the Level 3 empirical relations but still permits evaluation of the sensitivity of predicted performance caused by deviations from the assumptions in the Level 3 empirical relations.

Water/Cement Ratio of PCC. The water-to-cement (or w/c) ratio of a PCC mixture highly influences PCC strength properties. Although the MEPDG does not incorporate any linkage of the w/c ratio with PCC strength properties, it uses the w/c ratio for estimating PCC ultimate shrinkage. Synthetic Level 1 concrete strength and stiffness data were used for the GSA simulations. To ensure concrete shrinkage properties that are consistent with the synthetic strength and stiffness values, a w/c ratio compatible with strength is estimated using correlations between a w/c ratio and PCC strength reported by Abrams (1919) and Popovics and Ujhelyi (2008). Details are provided in Appendix C.

JPCP Dowel Diameter and CRCP Steel Depth. Both JPCP dowel diameter and CRCP steel depth are correlated with slab thickness. The experience-based correlations between dowel diameter/steel depth and slab thickness that were employed in the GSA simulations are documented in Appendix C.

Edge Support Conditions for Rigid Pavements. Categories for edge support in MEPDG JPCP analysis are: (1) no support, (2) tied PCC, and (3) widened slab. Categories for edge support in MEPDG CRCP analysis are specified in terms of shoulder type: gravel, asphalt, monolithic tied concrete, and separate tied concrete shoulder. In the GSA simulations, these edge support conditions are equivalent to load transfer efficiency (LTE). Details are documented in Appendix B.

3.2.2. Flexible Pavements

Inputs for the flexible pavement sensitivity analyses are summarized in Table 3.4 through Table 3.9. The fixed design inputs for all flexible pavements are listed in Table 3.4. Climate-determined binder grades are summarized in Table 3.5. PGHigh- designates that the high temperature grade is decreased by one 6° step; PGLow+ means that the low temperature grade is increased by one step. PGLowTC and PGLowTC+ are the special binder grades for the thermal cracking analyses only; they represent a 2 and 3 step increase in the low temperature grade, respectively. The traffic-related design inputs for the New HMA and HMA Over Stiff Foundation scenarios are listed in Table 3.6 and Table 3.7,

respectively. The HMA Over Stiff Foundation scenarios have thinner HMA layers and different base thickness ranges because of the elevated base stiffness. Material property and other design inputs are listed in Table 3.8 and Table 3.9. The design inputs in Table 3.8 apply to all flexible pavement scenarios, while the design inputs in Table 3.9 are the additional and/or modified properties for the HMA Over Stiff Foundation scenarios only. In these tables, the Baseline values are the values about which the OAT sensitivity indices are evaluated and the Minimum and Maximum values specify the sampling range for the GSA.

Table 3.4. Fixed design inputs for flexible pavements.

Input Parameter	Value
Design Life	15 years
Reliability	90% for all distresses
Road Functional Class	Principal Arterials – Interstate and Defense Route
Truck Traffic Category (TTC)	4
Number of Lanes in Design Direction	2 for low traffic/3 for medium and high traffic
Truck Direction Factor	50
Truck Lane Factor	75 for low traffic/55 for medium traffic/50 for high traffic
Default Growth Rate	No growth
First Layer Material Type	Asphalt Concrete
Second Layer Material Type	Granular Base
Subgrade Material Type	Soil
HMA Aggregate	Virgin – 19mm*

*This mixture has the following properties: cumulative % retained ¾ inch sieve = 5.5; cumulative % retained 3/8 inch sieve = 33.5; cumulative % retained #4 sieve = 55.5; % passing #200 sieve = 4.9; $V_{\text{beff}} = 10.08\%$; $V_a = 6.47\%$

Table 3.5. Binder grade baseline values and variations for flexible pavements.

Climate	Baseline PG	PGHigh-	PGLow+	PGLowTC	PGLowTC+
Cold-Dry	PG 52-40	NA	PG 58-34	PG 52-28	PG 52-22
Cold-Wet	PG 52-28	NA	PG 52-22	PG 52-16	PG 52-10
Hot-Dry	PG 76-10	PG 70-10	NA	NA	NA
Hot-Wet	PG 70-10	PG 64-10	NA	NA	NA
Temperate	PG 58-10	PG 52-10	NA	NA	NA

Table 3.6. Design inputs related to traffic levels for New HMA.

Input Parameter	Low Traffic			Medium Traffic			High Traffic		
	Baseline	Min	Max	Baseline	Min	Max	Baseline	Min	Max
AADTT-Nominal	1000	500	5000	7500	5000	10000	25000	20000	30000
Design Lane	375	188	1875	2063	1375	2750	6250	5000	7500
HMA Thickness (in)	6.5	5	8	10	8	12	12.5	10	15
Base Thickness (in)	6	1	10	7	1	14	9	1	18

Table 3.7. Design inputs related to traffic levels for HMA Over Stiff Foundation.

Input Parameter \ Traffic Level	Low Traffic			Medium Traffic			High Traffic		
	Baseline	Min	Max	Baseline	Min	Max	Baseline	Min	Max
AADTT-Nominal	1000	500	5000	7500	5000	10000	25000	20000	30000
Design Lane	375	188	1875	2063	1375	2750	6250	5000	7500
HMA Thickness (in)	2	1.5	3	3	2	4	4	2	6
Base Thickness (in)	8	4	12	10	5	14	12	6	16

Table 3.8. Other design inputs for flexible pavements.

Input Parameter	Baseline Value	Minimum	Maximum
Operational Speed (mph)	50	30	70
Groundwater Depth (ft)	10	2	18
Surface Shortwave Absorptivity	0.85	0.80	0.98
HMA Unit Weight (pcf)	149.9	134.9	164.9
HMA Poisson's Ratio	0.35	0.315	0.385
HMA Thermal Conductivity (BTU/hr-ft-°F)	0.67	0.44	0.81
HMA Heat Capacity (BTU/lb-°F)	0.23	0.22	0.40
HMA E* Delta Parameter (log psi)	2.83	2.75 ¹	2.91 ¹
HMA E* Alpha Parameter (log psi)	3.90	3.82 ¹	3.98 ¹
HMA Effective Binder Volume (%)	10	6	14
HMA Air Voids (%)	7	4	10
Base Resilient Modulus (psi)	25000	15000	40000
Base Poisson's Ratio	0.35	0.315	0.385
Subgrade Resilient Modulus (psi)	15000	10000	20000
Subgrade Poisson's Ratio	0.35	0.315	0.385
Subgrade Percent Passing No. 200 (%)	-- ²	24	99
Subgrade Plasticity Index (%)	-- ²	0	62
Subgrade Liquid Limit (%)	-- ²	26	92
HMA Tensile Strength at 14° F ⁴ (psi)	125	475	1600
HMA Creep Compliance D at -4° F ³ (1/psi)	1.43E-08	1.54E-07	4.44E-07
14° F ³	1.54E-07	2.48E-07	6.86E-07
32° F ³	2.48E-07	3.35E-07	9.19E-07
HMA Creep Compliance m at -4° F ³	0.115	0.246	0.181
14° F ³	0.204	0.276	0.351
32° F ³	0.352	0.608	0.475
Aggregate Coef. of Thermal Contraction ³ (in/in-°F)	5E-6	2E-6	7E-6

¹Encompasses two-thirds or more of mixtures in Bari and Witczak (2006) database.

²Function of subgrade resilient modulus (see Section 3.2.1).

³Relevant for special thermal cracking analyses only.

Table 3.9. Input parameter ranges for HMA Over Stiff Foundation cases.

Input Parameter	Baseline Value	Minimum	Maximum
Base Unit Weight (pcf)	150	125	175
Base Poisson's Ratio	0.35	0.315	0.385
Base Resilient Modulus (psi)	400000	10000	3000000
Base Thermal Conductivity (BTU/hr-ft-°F)	0.35	0.315	0.385
Base Heat Capacity (BTU/lb-°F)	0.28	0.224	0.336

3.2.3. JPCP Rigid Pavements

Inputs for the JPCP rigid pavement sensitivity analyses are summarized in Table 3.10 through Table 3.14. Fixed design inputs for all rigid pavements are listed in Table 3.10. Note that these apply for all CRCP as well as all JPCP rigid pavement scenarios. Traffic-related design inputs for the New JPCP and JPCP Over Stiff Foundation scenarios are listed in Table 3.11 and Table 3.12, respectively. The JPCP Over Stiff Foundation scenarios have slightly different PCC and base thickness ranges because of the elevated base stiffness. Material property and other design inputs are detailed in Table 3.13 and Table 3.14. The design inputs in Table 3.13 apply to all JPCP rigid pavement scenarios, while the design inputs in Table 3.14 are the additional and/or modified properties for the JPCP Over Stiff Foundation scenarios only. In these tables, the Baseline values are the values about which the OAT sensitivity indices are evaluated and the Minimum and Maximum values specify the sampling range for the GSA simulations.

Table 3.10. Fixed design inputs for all rigid pavements.

Input Parameter	Value
Design Life	25 years
Reliability	90% for all distresses
Road Functional Class	Principal Arterials – Interstate and Defense Rout
Truck Traffic Category (TTC)	4
Number of Lanes in Design Direction	2 for low traffic/3 for medium and high traffic
Truck Direction Factor	50
Truck Lane Factor	75 for low traffic/55 for medium traffic/50 for high traffic
Default Growth Rate	No growth
First Layer Material Type	Portland Cement Concrete
Second Layer Material Type	Granular Base
Subgrade Material Type	Soil

Table 3.11. Design inputs related to traffic levels for New JPCP.

Input Parameter \ Traffic Level	Low Traffic			Medium Traffic			High Traffic		
	Baseline	Min	Max	Baseline	Min	Max	Baseline	Min	Max
AADTT-Nominal	1000	500	5000	7500	5000	10000	25000	20000	30000
Design Lane	375	188	1875	2063	1375	2750	6250	5000	7500
PCC Thickness (in)	8	6	10	10	8	12	12	10	14
Base Thickness (in)	4	2	6	6	3	9	8	5	12

Table 3.12. Design inputs related to traffic levels for JPCP Over Stiff Foundation.

Input Parameter \ Traffic Level	Low Traffic			Medium Traffic			High Traffic		
	Baseline	Min	Max	Baseline	Min	Max	Baseline	Min	Max
AADTT-Nominal	1000	500	5000	7500	5000	10000	25000	20000	30000
Design Lane	375	188	1875	2063	1375	2750	6250	5000	7500
PCC Thickness (in)	8	7	9	9	8	10	11	9	13
Base Thickness (in)	4	3	6	6	4	8	8	6	10

Table 3.13. Input parameter ranges for JPCP rigid pavements.

Input Parameter	Baseline Value	Minimum	Maximum
Construction Month	July 2006	March 2006	October 2006
Design Lane Width	12	11	12
Joint Spacing (in)	15	10	20
Dowel Diameter (in)	Various	1.00	1.75
Edge Support – Load Transfer Efficiency (%)	5 (no support)	5	80
Edge Support – Widened Slab (in)	12 (no support)	12	14
Erodibility Index	3	1	5
Surface Shortwave Absorption	0.85	0.8	0.98
PCC Unit Weight (pcf)	150	140	160
PCC Poisson's Ratio	0.15	0.10	0.20
PCC Coefficient of Thermal Expansion (in/in-°F)	5.56	2	10
PCC Thermal Conductivity (BTU/hr-ft-°F)	1.25	0.50	2.00
PCC Cement Content (lb/yd ³)	500	400	700
PCC Water-to-Cement Ratio	Various	0.30	0.70
PCC 7-Day Modulus of Rupture ¹ (psi)	572	414	812
PCC 7-Day Elastic Modulus ¹ (psi)	3,650,255	2,144,002	5,700,014
PCC 14-Day Modulus of Rupture ¹ (psi)	597	433	847
PCC 14-Day Elastic Modulus ¹ (psi)	3,809,795	2,242,398	5,945,704
PCC 28-Day Modulus of Rupture (psi)	620	450	880
PCC 28-Day Elastic Modulus (psi)	3,956,571	2,330,437	6,177,355
PCC 90-Day Modulus of Rupture ¹ (psi)	655	475	931
PCC 90-Day Elastic Modulus ¹ (psi)	4,179,925	2,459,906	6,535,361
PCC Ratio of 20-year to 28-day Modulus of Rupture ¹	1.2	1	1.5
Base Resilient Modulus (psi)	25,000	15,000	40,000
Subgrade Resilient Modulus (psi)	15,000	10,000	20,000
Groundwater Depth (ft)	10	2	18

¹7-, 14- and 90-day and 20-year strength and stiffness values not considered explicitly in OAT analyses.

Table 3.14. Input parameters and variations for JPCP Over Stiff Foundation cases.

Input Parameter	Baseline Value	Minimum	Maximum
Stabilized Base Resilient Modulus (psi)	100,000	40,000	3,000,000
Loss of Full Friction (months)	136	0	150

3.2.4. CRCP Rigid Pavements

The fixed design inputs for the CRCP rigid pavement sensitivity analyses are listed in Table 3.10 (same as for JPCP rigid pavements). Traffic-related design inputs are listed in Table 3.15, and material property and other design inputs are listed in Table 3.16. The Baseline values are the values about which the OAT sensitivity indices were evaluated and the Minimum and Maximum values specify the range for the GSA simulations.

Table 3.15. Design inputs related to traffic levels for CRCP rigid pavements.

Input Parameter	Low Traffic			Medium Traffic			High Traffic		
	Baseline	Min	Max	Baseline	Min	Max	Baseline	Min	Max
AADTT-Nominal	1000	500	5000	7500	5000	10000	25000	20000	30000
Design Lane	375	188	1875	2063	1375	2750	6250	5000	7500
PCC Thickness (in)	8	7	9	10	8	12	12	10	14
Base Thickness (in)	4	2	6	6	4	8	8	6	10

Table 3.16. Input parameters and variations for CRCP rigid pavements.

Input Parameter	Baseline Value	Minimum	Maximum
Construction Month	July/2006	March/2006	October/2006
Bar Diameter (in)	0.60	0.50	1.00
Percent Steel (%)	0.75	0.50	1.00
Steel Depth (in)	Various	2.50	7.00
Edge Support – Load Transfer Efficiency (%)	5 for Asphalt or Gravel	N/A	70 for Tied PCC
Base Slab Friction Coefficient	2.5	0.5	4
Surface Shortwave Absorption	0.85	0.80	0.98
PCC Unit Weight (pcf)	150	140	160
PCC Poisson's Ratio	0.15	0.10	0.20
PCC Coef. of Thermal Expansion (in/in-°F)	5.56	2	10
PCC Cement Content (lb/yd ³)	500	400	700
PCC Water-to-Cement Ratio	Various	0.3	0.7
PCC 7-Day Modulus of Rupture ¹ (psi)	572	414	812
PCC 7-Day Elastic Modulus ¹ (psi)	3,650,255	2,144,002	5,700,014
PCC 7-Day Indirect Tensile Strength ¹ (psi)	383	250	598
PCC 14-Day Modulus of Rupture ¹ (psi)	597	433	847
PCC 14-Day Elastic Modulus ¹ (psi)	3,809,795	2,242,398	5,945,704
PCC 14-Day Indirect Tensile Strength ¹ (psi)	400	261	624
PCC 28-Day Modulus of Rupture (psi)	620	450	880
PCC 28-Day Elastic Modulus (psi)	3,956,571	2,330,437	6,177,355
PCC 28-Day Indirect Tensile Strength (psi)	415	271	649
PCC 90-Day Modulus of Rupture ¹ (psi)	655	475	931
PCC 90-Day Elastic Modulus ¹ (psi)	4,179,925	2,459,906	6,535,361
PCC 90-Day Indirect Tensile Strength ¹ (psi)	439	286	686
PCC Ratio of 20-year to 28-day Modulus of Rupture ¹	1.2	1.0	1.5
PCC Ratio of 20-year to 28-day Indirect Tensile Strength ¹	1.2	1.0	1.5
Base Resilient Modulus (psi)	25,000	15,000	40,000
Subgrade Resilient Modulus (psi)	15,000	10,000	20,000
Groundwater Depth (ft)	10	2	18

¹7-, 14- and 90-day and 20-year strength and stiffness values not considered explicitly in OAT analyses.

3.3. Sampling

For sampling for the OAT local sensitivity analyses, small perturbations above and below the baseline values (See Section 3.2) were performed individually for each design input and the corresponding distresses (for baseline values and perturbations) were predicted using the MEPDG. These values were used to compute the sensitivity metrics defined later in Section 3.5.

The GSA required some form of Monte Carlo simulation. As detailed in Section 7 of Appendix C, Latin Hypercube Sampling (LHS) was adopted for generating the GSA simulation inputs. LHS is a widely used variant of the standard or “random” Monte Carlo method. In LHS the range of each of the K model inputs $X_1, X_2, \dots, X_K$ is divided into N intervals in such a way that the probability of the input value falling in any of the intervals is $1/N$. One value is selected at random from each interval. The N values for X_1 are paired randomly with the N values of X_2 ; these sets are then paired randomly with the N values of X_3 and so on. The resulting N K -tuples are the LHS samples for the GSA. This

process can be repeated with a different random seed to generate as many sets of N K -tuples as desired. Further details of the LHS sampling procedure are provided in Appendix C.

The efficiency of the LHS approach reduces by a factor of 5 to 20 the required number of simulations as compared to the conventional Monte Carlo method. There are few guidelines for the number of LHS simulations required for any given problem. Minimum numbers of simulation samples suggested in the literature include: $(4/3)*K$ (Iman and Helton, 1985), $(3/2)*K$ (Simlab, 2009), and $2*K$ (McKay, 1988), where K is the number of model inputs. Suggested upper bounds for the numbers of simulation samples include: $3*K$ (Manache, 2001) and $10*K$ (SimLab, 2009, Saltelli *et al.*, 2004 as reported by Graves and Mahboub, 2006). In reality, both the lower and upper bounds are dependent upon the specific problem and on the intended use of the simulation results.

A limited parametric investigation was performed to determine the required number of simulations to achieve stable results in the GSA simulations. A multi-criteria assessment using various statistic measures was performed using 1000 MEPDG simulation each for new flexible and JPCP rigid pavement scenarios for one base case (TM). The statistic measures evaluated were the linear regression coefficient β , Spearman's rank correlation coefficient ρ , and the standard error of the sample mean $SE_{\bar{y}_j}$ in which $\bar{y}_i$ is the estimated mean of the predicted distresses. The β and ρ statistical measures converged the most quickly, while $SE_{\bar{y}_j}$ converged more slowly. The results from these numerical experiments suggested that sufficiently stable results could be obtained from approximately 400 to 500 simulations per pavement scenario, or approximately $20*K$. This is expected to be conservative, as it substantially exceeds even the highest numbers cited in the literature, e.g., $10*K$ for SimLab (2009).

3.4. Analysis Execution

The local OAT s and global sensitivity analyses required many tens of thousands of MEPDG simulation runs. Scores of computers were used to expedite processing.

The *AutoIt* scripting utility (<http://www.autoitscript.com/autoit3/index.shtml>) was adopted to automate the entry/creation of MEPDG input files, to initiate the MEPDG execution, and to collect the analysis results into a central spreadsheet repository. *AutoIt* is a free, open source, sophisticated BASIC-like scripting language designed for automating Windows program operations via simulated keystrokes and mouse movements. *AutoIt* scripts are compiled into stand-alone executables that can be easily distributed and run on other host computers.

Distribution of MEPDG batch processing to the computers was accomplished using the *LogMeIn* (<https://secure.logmein.com/>) software utility for remote access and file transfer to the analysis computers via a simple web browser interface on a central workstation. This enabled copying of the *AutoIt* scripts to the remote analysis computers, initiation of *AutoIt* script and MEPDG execution, and the transfer of the results back to the central workstation.

3.5. Response Surface Models

The GSA simulations provided predictions of pavement performance at random discrete locations in the problem domain. In order to compute sensitivity indices as defined later in Section 7, it is necessary to evaluate the derivatives of distress with respect to design inputs at specific discrete locations. Fitting a continuous response surface model (RSM) to the randomly located GSA

simulation results make this possible. The derivatives can either be expressed analytically from the RSM or estimated numerically using finite difference approximations in terms of the values of the RSM in the local area around the discrete specified locations.

Two RSM approaches are employed in this study: multivariate linear regressions (MVLR) and artificial neural networks (ANN or NN). MVLR estimates the linear functional trends between model outputs (i.e., individual distresses) and model inputs (i.e., a set of design inputs). ANNs, in contrast, provide a “function-free” numerical approximation of the nonlinear relationship between distresses and design inputs.

The MVLR is defined in normalized terms as follows:

$$\frac{Y}{DL} = a_0 + \sum_{i=1}^n a_i \frac{X_i}{\bar{X}_i} \quad (2)$$

in which Y is distress j (e.g., total rutting, IRI), DL is the design limit or range for distress (e.g., 0.75 in for total rutting, 172-63=109 in/mile for IRI), X_i is design input i , $\bar{X}_i$ is the mean value for X_i , a_0 is the intercept, and the a_i values are regression coefficients. As described in Section 7, the regression coefficients represent the average sensitivity of the normalized distress to the normalized input i .

ANNs are newer techniques than MVLR but have today become standard data fitting tools for problems that are too complex, poorly understood, or resource intensive to tackle using more traditional numerical and/or statistical techniques. They can in one sense be viewed as similar to nonlinear regression except that the functional form of the fitting equation does not need to be specified *a priori*. The basic concepts underlying standard backpropagation ANNs can be found in Ceylan *et al.* (2009). The ANNs in this study were designed, trained, and evaluated using the MATLAB Neural Network toolbox (Beale *et al.*, 2011). All of the ANNs were conventional two-layer (hidden layer and output layer) feed-forward network. Sigmoid transfer functions were used for all hidden layer neurons while linear transfer functions were employed for the output neurons. Training was accomplished using the Levenberg-Marquardt backpropagation algorithm. Separate ANN models were developed for each distress-climate zone combination for each pavement type. Seventy percent of the GSA simulations for each distress-climate zone combination were used for training, 15% were used for validation (to halt training when generalization stops improving), and 15% were used for independent testing of the trained model.

The basic ANN modeling approach was extended in this study by using the averages of an ensemble of ANNs for each pavement type-distress-climate zone combination. Because the ANN models are approximations dependent upon the random initial values assigned to the connection weights and neuron bias terms and upon the training history, any individual ANN may have local biases in particular regions of the problem domain even though it has excellent overall goodness-of-fit statistics. Averaging multiple ANN models tends to minimize any local bias effects. Twenty ANN models passing a minimum goodness-of-fit threshold were averaged to form the RSM for each pavement type-distress-climate zone combination. The goodness-of-fit threshold varied some among the different models but was generally quite high (e.g., $R^2 \geq 0.98$).

3.6. Sensitivity Metrics

There is a wide variety of metrics that can be used to quantify sensitivity of model outputs to model inputs. No individual metric is “perfect” or ideal for all of the variables in this study. The primary

metric selected for the OAT analyses is a point-normalized sensitivity index; the rationale for the selection of this criterion is provided in Appendix B. The primary metrics used for the GSA are regression coefficients from normalized multivariate linear regression and a point-normalized sensitivity index.

MVLR provides estimates of the average sensitivities of distresses to inputs across the solution domain. Specifically, the individual coefficients a_i in the normalized regression equation (see preceding section) represent the average sensitivity of the normalized distress to the normalized input i . In other words, a_i represents the percentage change in a distress relative to its design limit/range caused by a given percentage change in the design input relative to its mean value. Note that since the a_i values are fixed quantities, they cannot capture sensitivity variations at different locations within the problem domain. The a_i values can provide only the average sensitivities over the problem domain.

The nonlinear fitting from the ANN models, on the other hand, can be used to provide point estimates of sensitivities across the problem domain. The point-normalized sensitivity index S_{ijk} is defined as:

$$S_{ijk} = \frac{\partial Y_j}{\partial X_k} \bigg|_i \left(\frac{X_{ki}}{Y_{ji}} \right) \quad (3)$$

in which Y_{ji} , X_{ki} are the values of the model output j and input k all evaluated at location i in the problem domain. The partial derivative can be approximated using a standard central difference approximation:

$$\frac{\partial Y_j}{\partial X_k} \bigg|_i \cong \frac{\Delta Y_j}{\Delta X_k} \bigg|_i = \frac{Y_{j,i+1} - Y_{j,i-1}}{X_{k,i+1} - X_{k,i-1}} \quad (4)$$

The S_{ijk} sensitivity index can be interpreted as the local percentage change in model output Y_j caused by a given percentage change in the model input X_k at location i in the problem domain. For example, $S_{ijk} = 0.5$ implies that a 20% change in the local value of X_{ki} will cause a 10% local change in Y_{ji} . Since S_{ijk} is a local point estimate of sensitivity, it will vary across the problem domain.

Problems were encountered when calculating the point-normalized sensitivity index for some analyses because the predicted distress values Y_{ji} were near zero for some of the input sets, resulting in artificially large sensitivity index values. To circumvent this problem, a “design limit” normalized sensitivity index S_{ijk}^{DL} was defined as:

$$S_{ijk}^{DL} = \frac{\Delta Y_{ji}}{\Delta X_{ki}} \frac{X_{ki}}{DL_j} \quad (5)$$

in which X_{ki} is the value of design input k at point i , ΔX_{ki} is the change in design input k about point i , ΔY_{ji} is the change in predicted distress j corresponding to ΔX_{ki} , and DL_j is the design limit for distress j .

For simplicity, the design limit normalized sensitivity index S_{ijk}^{DL} is termed more simply as the “normalized sensitivity index” or NSI. The NSI always uses the design limit as the normalizing factor

for the predicted distress. For example, consider total rutting as the predicted distress with a design limit of 0.75 inches. An NSI of -0.25 for the sensitivity of total rutting to granular base layer resilient modulus implies that a 10% reduction in base resilient modulus will increase total rutting by

$NSI * \Delta X_k = 2.5\%$ of its design limit DL_j --i.e., it will increase rutting by $(-0.1)*(-0.25)*0.75=0.01875$ inches.

NSI was calculated using Equation (5) for most design inputs. However, in some cases the design input was categorical rather than continuous (e.g., binder grade and construction month). For these design inputs, a modified non-normalized NSI definition is used instead:

$$NSI = \frac{\Delta Y_{ji}}{DL_j} \bigg|_{\Delta X_{ki}=1 \text{ category}} \quad (6)$$

This modified design limit NSI still takes the design limit as reference for predicted distress. It quantifies how the predicted distress changes in normalized terms if the design input is changed by one category.

NSI for IRI was also treated as a special case because it has a nonzero lower bound. The normalized NSI for IRI was defined in terms of the difference between the default terminal (172 in/mile) and initial (63 in/mile) IRI values:

$$NSI = \frac{IRI - 63}{172 - 63} \quad (7)$$

The NSI definitions in Equations (5) through (7) were sufficient for all design inputs that are varied directly in the GSA simulations. However, some of these inputs are Level 1 material properties that in practice may alternatively be specified in the MEPDG in terms of Level 3 empirical relations. Examples of this include the HMA dynamic modulus sigmoidal function constants δ (lower shelf) and α (offset to the upper shelf) and the HMA low temperature strength S_t and creep compliance parameters D and m (see Section 3.2.1 for details). Rather than the direct sensitivity of predicted distress to these Level 1 inputs, the pavement designer may instead be more interested in the sensitivity of predicted distress to the inputs to the Level 3 empirical relations used within the software to derive the Level 1 properties. Fortunately, one can estimate the NSI for any secondary variable z (i.e., a Level 3 empirical relation variable) in terms of the NSI for the primary variable x (i.e., a GSA simulation variable) using:

$$NSI_z = NSI_x \left[\frac{\partial x}{\partial z} \bigg|_i \frac{z_i}{x_i} \right] \quad (8)$$

Appendix C provides additional examples on the application of Equation (8).

4. ONE-AT-A-TIME LOCAL SENSITIVITY ANALYSIS RESULTS

In a one-at-a-time (OAT) analysis, each potentially sensitive design input is varied individually for a given base case or reference condition in order to assess quantitatively the local sensitivity of the predicted output (distress). An extensive set of OAT local sensitivity analyses were performed to confirm the assessments from the initial triage of design inputs and ideally to prune the list of sensitive design inputs further before commencing the computationally-intensive GSA simulations. Over 3800 MEPDG runs were executed for 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 inputs for the OAT analyses are summarized in Chapter 3 and documented in more detail in Appendix B. Appendix B also provides much more extensive documentation of the OAT results, including ranges of computed distress levels, charts of NSI values by base case for each distress, and charts of high-low-average NSI statistics over all base cases for each distress. The OAT local sensitivity analyses were performed to confirm the assessments from the initial triage of design inputs and ideally to prune the list of sensitive design inputs further before commencing the computationally-intensive GSA simulations.

The key outcome of the OAT analyses was the final ranking of the design inputs and the definition of sensitivity categories. The rank ordering is by decreasing maximum absolute NSI over all analyses. The maximum absolute NSI is the largest NSI value (in an absolute value sense) calculated for the design input for any pavement type, base case, or distress. Design inputs with maximum absolute NSI values greater than 5 were rated as hypersensitive, between 1 and 5 very sensitive, between 0.1 and 1 sensitive, and less than 0.1 insensitive.

Table 4.1 and Table 4.2 provide the overall sensitivity values for the design inputs in rank order for the flexible pavement scenarios. Also included in the tables for reference is the preliminary sensitivity assessment from the initial triage, with VS indicating very sensitive, S indicating sensitive, and NS indicating insensitive. The sensitivity ratings based on the OAT results and engineering judgment are categorized as Hypersensitive, $NSI > 5$; Very Sensitive, $1 < NSI < 5$; Sensitive, $0.1 < NSI < 1$; and Insensitive, $NSI < 0.1$. Bold lines in the table indicate the breaks between the OAT sensitivity categories.

The results from the OAT analyses agree with the judgments from the initial triage at about the 65% level. There are some notable exceptions, however, as indicated by the shaded/highlighted entries in the tables. Flexible pavement design inputs judged to be insensitive in the initial triage but found to be sensitive or above in the OAT analyses include: HMA Poisson's Ratio, HMA Unit Weight, Base Poisson's Ratio, Subgrade Plasticity Index, Subgrade Liquid Limit, and Subgrade Percent Passing No. 200 (both pavement scenarios); Subgrade Poisson's Ratio (New HMA only); and Base Unit Weight (HMA Over Stiff Foundation only). Conversely, only the Aggregate Coefficient of Thermal Contraction (both scenarios) and HMA Tensile Strength at 14°F (HMA Over Stiff Foundation only) were judged to be very sensitive or sensitive in the initial triage but found to be insensitive in the OAT analyses.

One special condition to be kept in mind is that the thermal cracking analyses required low temperature binder grades 2 to 3 steps warmer than recommended in order to generate any significant predicted distress. The relatively high sensitivities for the HMA Creep Compliance D Parameter, HMA Creep Compliance m Exponent, and the HMA Tensile Strength at 14°F should be evaluated in this context. Their sensitivities would be much lower if the correct binder grade had been specified, simply because no thermal cracking would then be predicted.

All design inputs ranked as sensitive or above were included in the GSA simulations. For both the New HMA and HMA Over Stiff Foundation scenarios, this totals 26 design inputs each.

Table 4.1. Ranking of design inputs by maximum absolute NSI: New HMA.

New HMA	Sensitivity ¹	
	OAT Analyses	Initial Triage
HMA E* Alpha Parameter²	-24.2	VS ³
HMA E* Delta Parameter²	-23.8	VS ³
HMA Thickness	-7.3	VS
Surface Shortwave Absorptivity	5.0	VS
HMA Creep Compliance m Exponent	-4.5	VS
HMA Poisson's Ratio	-4.1	NS
HMA Air Voids	4.0	S ³
Base Resilient Modulus	-3.6	VS
HMA Tensile Strength at 14°F	-3.4	VS ³
HMA Effective Binder Volume	-3.2	S ³
Base Thickness	-1.7	S
Traffic Volume (AADTT)	1.6	VS
Subgrade Resilient Modulus	1.3	VS
Operational Speed	-1.00	VS
HMA Unit Weight	-0.98	NS
Base Poisson's Ratio	-0.88	NS
HMA Creep Compliance D Parameter	-0.85	VS
Subgrade Poisson's Ratio	0.83	NS
Binder Low Temperature PG	0.74	VS ³
Binder High Temperature PG	0.70	VS ³
HMA Heat Capacity	-0.54	S
Subgrade Plasticity Index	-0.23	NS
Subgrade Liquid Limit	0.23	NS
Groundwater Depth	0.19	S
HMA Thermal Conductivity	0.17	S
Subgrade Percent Passing No. 200	-0.15	NS
Base Percent Passing No. 200	-0.08	NS
HMA Endurance Limit	-0.06	-
Base Plasticity Index	-0.03	NS
Construction Month	0.02	NS
Subgrade D ₆₀ Gradation Parameter	0.00	NS
Base Liquid Limit	0.00	NS
Aggregate Coef. of Thermal Contraction	0.00	VS
Base Coef. of Lateral Pressure	0.00	NS
Base D ₆₀ Gradation Parameter	0.00	NS
Subgrade Coef. of Lateral Pressure	0.00	NS

¹Maximum sensitivity (in absolute value sense) over all baseline cases and distresses. Sensitivity ratings are indicated by font type: **Bold** designates Hypersensitive, NSI > 5; **Bold Italics** designates Very Sensitive, 1 < NSI < 5; *Italics* designates Sensitive, 0.1 < NSI < 1; and Regular font designates Insensitive, NSI < 0.1. Bold lines indicate breaks between sensitivity categories. Shaded entries indicate discrepancies between OAT results and the initial triage.

²See Equation (1) in Section 3.2.1.

³Inputs that were only implicitly evaluated during the initial triage.

Table 4.2. Ranking of design inputs by maximum absolute NSI: HMA Over Stiff Foundation.

HMA Over Stiff Foundation	Sensitivity ¹	
	OAT Analyses	Initial Triage
HMA E* Alpha Parameter ²	-52.0	VS ³
HMA E* Delta Parameter ²	-51.4	VS ³
Surface Shortwave Absorptivity	10.8	VS
HMA Poisson's Ratio	-7.8	NS
Base Thermal Conductivity	-5.3	-
HMA Creep Compliance m Exponent	-4.7	VS
HMA Thickness	3.5	VS
HMA Effective Binder Volume	3.5	S ³
Traffic Volume (AADTT)	3.4	VS
Operational Speed	-2.2	VS
Base Thickness	1.6	S
HMA Air Voids	1.6	S ³
Binder High Temperature PG	1.5	VS ³
HMA Tensile Strength at 14°F	-1.2	VS
HMA Creep Compliance D Parameter	-1.1	VS
HMA Unit Weight	-1.1	NS
HMA Heat Capacity	-0.91	S
Subgrade Resilient Modulus	0.64	VS
Base Thermal Conductivity	-0.62	S
Base Poisson's Ratio	0.52	NS
Base Heat Capacity	-0.48	-
Base Unit Weight	-0.46	NS
Binder Low Temperature PG	-0.41	VS ³
HMA Thermal Conductivity	0.38	S
Base Resilient Modulus	0.26	VS
Groundwater Depth	0.24	S
Subgrade Percent Passing No. 200	-0.12	NS
Subgrade Plasticity Index	-0.12	NS
Subgrade Liquid Limit	0.10	NS
Construction Month	0.06	NS
Subgrade Poisson's Ratio	0.04	NS
Subgrade D ₆₀ Gradation Parameter	0.00	NS
HMA Endurance Limit	0.00	-
Aggregate Coef. of Thermal Contraction	0.00	VS
Base Modulus of Rupture	0.00	-
Subgrade Coef. of Lateral Pressure	0.00	NS

¹Maximum sensitivity (in absolute value sense) over all baseline cases and distresses. Sensitivity ratings are indicated by font type: **Bold** designates Hypersensitive, NSI > 5; **Bold Italics** designates Very Sensitive, 1 < NSI < 5; *Italics* designates Sensitive, 0.1 < NSI < 1; and Regular font designates Insensitive, NSI < 0.1. Bold lines indicate breaks between sensitivity categories. Shaded entries indicate discrepancies between OAT results and the initial triage.

²See Equation (1) in Section 3.2.1.

³Inputs that were only implicitly evaluated during the initial triage.

Table 4.3 and Table 4.4 provide the overall sensitivity values for the design inputs in rank order for the JPCP scenarios. The results from the OAT analyses agree with the preliminary judgments from the initial triage at about the 75% to 85% level. Major discrepancies include Groundwater Depth,

which had been judged to be insensitive in the initial triage but found to be sensitive in the OAT analyses, and Design Lane Width under No Edge Support and 80% LTE conditions (New JPCP) and Stabilized Base Resilient Modulus (JPCP Over Stiff Foundation), which had been judged to be sensitive in the initial triage but found to be insensitive in the OAT analyses. All design inputs ranked as sensitive or above were included in the GSA simulations. For the New JPCP scenario, this totals 21 design inputs; for the JPCP over Stiff Foundation scenario, 23.

Table 4.3. Ranking of design inputs by maximum absolute NSI: New JPCP.

New JPCP	Sensitivity ¹	
	OAT Analyses	Initial Triage
PCC 28-Day Modulus of Rupture	-16.55	VS
PCC Thickness	-15.03	VS
Surface Shortwave Absorptivity	10.99	VS
Joint Spacing	9.91	VS
PCC 28-Day Modulus of Elasticity	9.87	S ²
Design Lane Width (14ft Widened Slab)	-7.20	S
Edge Support - Widened Slab	-6.60	VS
PCC Thermal Conductivity	-5.33	VS
PCC Coef. of Thermal Expansion	4.63	VS
PCC Unit Weight	3.60	S
Dowel Diameter	-2.46	S
PCC Poisson's Ratio	1.53	S
Traffic Volume (AADTT)	1.25	VS
Base Resilient Modulus	1.07	VS
<i>Subgrade Resilient Modulus</i>	-0.86	S
<i>PCC Cement Content</i>	0.83	S
<i>Construction Month</i>	0.67	-
<i>PCC Water-to-Cement Ratio</i>	0.42	S
<i>Groundwater Depth</i>	-0.32	NS
<i>Erodibility Index</i>	0.25	S
<i>Base Thickness</i>	-0.20	S
<i>Design Lane Width (No Edge Support)</i>	-0.08	S
<i>Edge Support - Load Transfer Efficiency</i>	-0.07	-
<i>Design Lane Width (80% LTE)</i>	0.00	S

¹Maximum sensitivity (in absolute value sense) over all baseline cases and distresses. Sensitivity ratings are indicated by font type: **Bold** designates Hypersensitive, NSI > 5; **Bold Italics** designates Very Sensitive, 1 < NSI < 5; *Italics* designates Sensitive, 0.1 < NSI < 1; and Regular font designates Insensitive, NSI < 0.1. Bold lines indicate breaks between sensitivity categories. Shaded entries indicate discrepancies between OAT results and the initial triage.

²Inputs that were only implicitly evaluated during the initial triage.

Table 4.4. Ranking of design inputs by maximum absolute NSI: JPCP Over Stiff Foundation.

JPCP Over Stiff Foundation	Sensitivity ¹	
	OAT Analyses	Initial Triage
PCC Thickness	-25.86	VS
Surface Shortwave Absorptivity	18.45	VS
Design Lane Width (14ft Widened Slab)	-18.32	S
PCC 28-Day Modulus of Rupture	-16.62	VS
Edge Support - Widened Slab	-16.00	VS
PCC 28-Day Modulus of Elasticity	14.82	S ²
Joint Spacing	9.98	VS
PCC Unit Weight	-5.80	S
PCC Thermal Conductivity	-5.35	VS
<i>PCC Coef. of Thermal Expansion</i>	4.63	VS
<i>Construction Month</i>	-3.62	-
<i>PCC Poisson's Ratio</i>	3.56	S
<i>Traffic Volume (AADTT)</i>	3.40	VS
<i>Design Lane Width (No Edge Support)</i>	2.88	S
<i>Dowel Diameter</i>	-2.54	S
<i>Subgrade Resilient Modulus</i>	2.53	S
<i>Base Thickness</i>	-2.34	S
<i>PCC Cement Content</i>	0.63	S
<i>Loss of Friction</i>	0.60	-
<i>PCC Water-to-Cement Ratio</i>	-0.53	S
<i>Groundwater Depth</i>	-0.31	NS
<i>Erodibility Index</i>	0.20	S
<i>Edge Support - Load Transfer Efficiency</i>	-0.18	-
<i>Stabilized Base Resilient Modulus</i>	-0.09	VS
<i>Design Lane Width (80% LTE)</i>	0.00	NS

¹Maximum sensitivity (in absolute value sense) over all baseline cases and distresses. Sensitivity ratings are indicated by font type: **Bold** designates Hypersensitive, NSI > 5; ***Bold Italics*** designates Very Sensitive, 1 < NSI < 5; *Italics* designates Sensitive, 0.1 < NSI < 1; and Regular font designates Insensitive, NSI < 0.1. Bold lines indicate breaks between sensitivity categories. Shaded entries indicate discrepancies between OAT results and the initial triage.

²Inputs that were only implicitly evaluated during the initial triage.

Table 4.5 provides the overall sensitivity values for the design inputs in rank order for the New CRCP scenario. The results from the OAT analyses agree with the preliminary judgments from the initial triage at about the 75% level. Major discrepancies between the initial triage and OAT analyses include Surface Shortwave Absorptivity and Groundwater Depth. All design inputs ranked as sensitive or above were included in the GSA simulations. For the New CRCP scenario, this totals 20 design inputs.

Table 4.5. Ranking of design inputs by maximum absolute NSI: New CRCP.

New CRCP	Sensitivity ¹	
	OAT Analyses	Initial Triage
CRCP Thickness	-37.44	VS
PCC 28-Day Modulus of Rupture	-27.31	VS
Percent Steel	-23.27	VS
Surface Shortwave Absorptivity	-21.43	NS
PCC Unit Weight	-19.91	S
Bar Diameter	13.56	VS
PCC 28-Day Elastic Modulus	10.07	S
Traffic Volume (AADTT)	7.91	VS
PCC Cement Content	6.90	S
Base Slab Friction Coefficient	-6.79	S
PCC Water-to-Cement Ratio	6.08	S
Steel Depth	5.05	S
<i>PCC Coef. of Thermal Expansion</i>	4.48	VS
<i>Base Resilient Modulus</i>	-3.58	S
<i>Subgrade Resilient Modulus</i>	-1.96	S
<i>Construction Month</i>	<i>0.48</i>	-
<i>PCC Poisson's Ratio</i>	<i>0.36</i>	S
<i>Base Thickness</i>	<i>-0.22</i>	S
<i>Edge Support - Load Transfer Efficiency</i>	<i>-0.21</i>	S
<i>Groundwater Depth</i>	<i>0.14</i>	NS
Design Lane Width (40% LTE)	-0.01	-
Design Lane Width (70% LTE)	0.00	-
Design Lane Width (No Edge Support)	0.00	-

¹Maximum sensitivity (in absolute value sense) over all baseline cases and distresses. Sensitivity ratings are indicated by font type: **Bold** designates Hypersensitive, NSI > 5; **Bold Italics** designates Very Sensitive, 1 < NSI < 5; *Italics* designates Sensitive, 0.1 < NSI < 1; and Regular font designates Insensitive, NSI < 0.1. Bold lines indicate breaks between sensitivity categories. Shaded entries indicate discrepancies between OAT results and the initial triage.

5. GLOBAL SENSITIVITY ANALYSIS RESULTS

The overall objective of the GSA is to determine the sensitivity of the performance predicted by the MEPDG to variations of input parameter values for flexible and rigid pavements across the entire problem domain. The key difference between the GSA and OAT analyses (Chapter 4) is that all input parameters are varied simultaneously from their baseline values instead of just one at a time. Over 41,000 MEPDG runs were performed for the GSA. In addition, over one million evaluations of the neural network response surface models were used to quantify the distribution of design input sensitivities across the entire problem domain.

The inputs for the GSA are summarized in Chapter 3 and documented in more detail in Appendix C, which also contains comprehensive evaluations of the GSA results. A principal conclusion from the GSA was that the most severe but arguably most robust measure of sensitivity is the mean plus/minus two standard deviation ($\mu \pm 2\sigma$) NSI values. The mean and standard deviation statistics for each NSI were derived from 10,000 ANN RSM evaluations for each climate zone and distress combination. The $\mu \pm 2\sigma$ NSI metric ($NSI_{\mu \pm 2\sigma}$) captures both the mean value of the sensitivity and the range of this sensitivity across the problem domain. These $NSI_{\mu \pm 2\sigma}$ rankings are summarized in the following subsections by pavement type.

5.1. New HMA

The design inputs for New HMA are listed in Table 5.1 in rank order by the maximum absolute value of $NSI_{\mu \pm 2\sigma}$ across distresses. The plus and minus signs are retained for each individual sensitivity index to indicate whether distress increases (+) or decreases (-) with increasing input value. Usually—and especially for the highest sensitivity inputs—the plus/minus signs for each design input are consistent across all distresses.

The OAT local sensitivity category (Chapter 4) for each design input is also indicated in Table 5.1. Not only is there a there nearly complete congruence between the ranking of inputs from the ANN RSMs and the categorization from the OAT analyses, but the ranges of $NSI_{\mu \pm 2\sigma}$ values in Table 5.1 also line up very closely with the ranges of normalized sensitivity index values used to define the OAT categories. These sensitivity ratings as defined for the OAT analysis results are categorized as Hypersensitive (HS), $NSI_{\mu \pm 2\sigma} > 5$; Very Sensitive (VS), $1 < NSI_{\mu \pm 2\sigma} < 5$; Sensitive (S), $0.1 < NSI_{\mu \pm 2\sigma} < 1$; and Non-Sensitive (NS), $NSI_{\mu \pm 2\sigma} < 0.1$. The heavy lines in the table indicate the break points between sensitivity categories. For added insight, the top three sensitivity values for each distress are indicated by the shaded cells in the table.

Table 5.1. Ranking of New HMA design inputs by maximum $NSI_{\mu+2\sigma}$ values (ANN RSMs).

Design Input	Maximum $NSI_{\mu+2\sigma}$ Values (ANN RSMs) ¹							OAT ²
	Long. Crack	Alligator Crack	Thermal Crack	AC Rut Depth	Total Rut Depth	IRI	Max	
HMA E* Alpha Parameter ³	-29.52	-15.94	-0.58	-24.40	-8.98	-3.58	-29.52	HS
HMA E* Delta Parameter ³	-23.87	-13.18	2.41	-24.43	-8.99	-2.80	-24.43	HS
HMA Thickness	-10.31	-7.46	-0.86	-4.21	-1.58	-1.11	-10.31	HS
HMA Creep Compliance m Exponent	N.A.	N.A.	-4.85	N.A.	N.A.	N.A.	-4.85	VS
Base Resilient Modulus	-4.72	-2.73	-0.17	0.14	-0.15	-0.36	-4.72	VS
Surface Shortwave Absorptivity	4.32	1.28	-0.20	4.65	1.67	0.67	4.65	VS
HMA Air Voids	4.47	3.39	1.33	-0.05	0.03	0.29	4.47	VS
HMA Poisson's Ratio	-2.38	-1.01	0.23	-4.33	-1.46	-0.43	-4.33	VS
Traffic Volume (AADTT)	3.72	3.94	0.02	1.87	0.66	0.51	3.94	VS
HMA Effective Binder Volume	-3.88	-2.93	-0.17	0.05	0.06	-0.24	-3.88	VS
Subgrade Resilient Modulus	-2.07	-3.41	0.15	0.08	-0.28	-0.44	-3.41	VS
Base Thickness	-2.40	-1.02	-0.03	0.22	0.04	-0.09	-2.40	VS
Subgrade Percent Passing No. 200	-1.71	-0.68	0.08	-0.10	-0.10	-0.12	-1.71	S
HMA Tensile Strength at 14°F	N.A.	N.A.	-1.59	N.A.	N.A.	N.A.	-1.59	S
Operational Speed	-1.26	-0.83	-0.04	-1.06	-0.39	-0.15	-1.26	S
HMA Creep Compliance D Parameter	N.A.	N.A.	-1.03	N.A.	N.A.	N.A.	-1.03	S
HMA Unit Weight	-0.88	0.97	-0.76	-0.88	-0.30	-0.08	0.97	S
Base Poisson's Ratio	0.91	0.90	0.18	-0.19	-0.05	0.09	0.91	S
HMA Heat Capacity	-0.76	-0.55	-0.77	-0.81	-0.28	-0.14	-0.81	S
Subgrade Liquid Limit	-0.67	-0.79	-0.10	-0.10	0.07	0.03	-0.79	S
Binder Low Temperature PG	0.56	0.09	-0.74	0.25	0.09	0.02	-0.74	S
HMA Thermal Conductivity	-0.53	-0.40	-0.67	0.20	0.04	0.02	-0.67	S
Binder High Temperature PG	-0.60	-0.48	0.00	-0.66	-0.25	-0.09	-0.66	S
Subgrade Poisson's Ratio	0.44	-0.59	0.16	0.08	0.07	0.04	-0.59	S
Groundwater Depth	0.20	-0.16	0.08	0.01	-0.02	-0.02	0.20	S
Subgrade Plasticity Index	-0.15	0.11	0.03	0.01	0.02	0.00	-0.15	S
Aggregate Coef. Of Thermal Contraction	N.A.	N.A.	-0.07	N.A.	N.A.	N.A.	-0.07	NS

¹Maximum sensitivity (in absolute value sense) over all baseline cases and distresses. Sensitivity ratings are indicated by font type: **Bold** designates Hypersensitive, $NSI_{\mu+2\sigma} > 5$; **Bold Italics** designates Very Sensitive, $1 < NSI_{\mu+2\sigma} < 5$; *Italics* designates Sensitive, $0.1 < NSI_{\mu+2\sigma} < 1$; and Regular font designates Insensitive, $NSI_{\mu+2\sigma} < 0.1$. Bold lines indicate breaks between sensitivity categories. Shaded entries indicate the three most sensitive inputs for each individual distress.

²HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Non-Sensitive.

³See Equation (1) in Section 3.2.1.

Figure 5.1 provides graphical summaries of the input sensitivities by distress (larger versions of these figures are included in Appendix C). Thermal cracking is not included here; the substantially stiffer low temperature binder grades in these cases were substantially different from the other distresses and do not reflect what would be used in practice. The solid bars in the figures indicate the mean NSI values, and the error bars correspond to one standard deviation. All of the figures have the same horizontal axis range so that the differences in sensitivities across distresses can be more clearly evaluated. The sensitivities are also broken down by climate zone for each design input.

Figure 5.1 highlights the difference in sensitivities between the categories. For all distresses there is a very sharp drop in bar lengths moving from Hypersensitive to Very Sensitive and again from Very Sensitive to Sensitive. At $NSI_{\mu+2\sigma} = 1$ corresponding to the upper limit of the Sensitive range in Table 5.1, the percentage change in distress relative to its design limit equals the percentage change in the design input. This is very small in practical terms, especially since it is defined at the $\mu+2\sigma$ level. The focus of the pavement designer should therefore be on the Hypersensitive and Very Sensitive design inputs; these are the values that need to be most carefully determined.

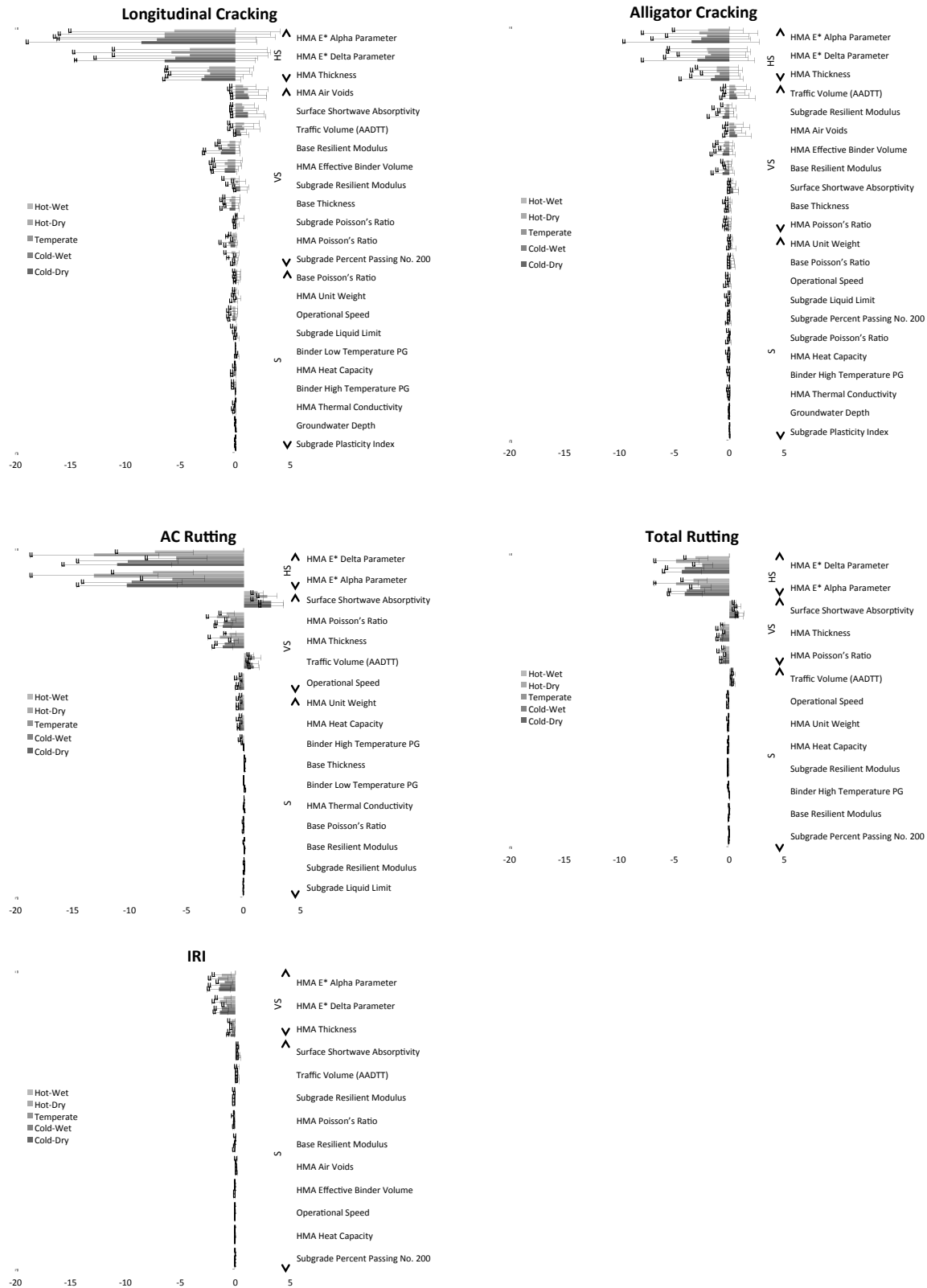


Figure 5.1. Ranking of New HMA design inputs. Solid bars indicate mean NSI, error bars indicate one standard deviation.

These results match engineering judgment and experience in overall terms. Although the details vary by distress type, the HMA layer properties (dynamic modulus parameters and layer thickness in particular) are consistently the highest sensitivity inputs, with subgrade modulus and granular base modulus and thickness following behind at a distance. Traffic volume is also an important design input, as expected. However, there are a few observations from Table 5.1 and Figure 5.1 that merit special note and discussion:

- The magnitudes of the sensitivity values for longitudinal cracking, alligator cracking, AC rutting, and total rutting were consistently and substantially higher than the values for thermal cracking and IRI.
- The most sensitive design inputs for longitudinal cracking, alligator cracking, AC rutting, total rutting, and IRI had very little overlap with the most sensitive design inputs for thermal cracking. Clearly this is because the former are primarily load-related distresses while thermal cracking is exclusively environment-driven.
- The sensitivity index values for each distress-design input combination do not vary substantially or systematically by climate zone.
- When interpreting the very large sensitivity values for the HMA E* Alpha and Delta parameters, it is important to note that the typical ranges for these parameters are very narrow. The standard deviations for α and δ are only 1.6% and 3.5% of their mean values, respectively (see Appendix C). The high sensitivity of most predicted distresses to the HMA E* Alpha and Delta parameters suggests a careful Level 1 characterization of HMA dynamic modulus for important projects.
- Poisson's ratio was an unexpectedly sensitive input for HMA and, to a lesser extent, for the subgrade. Poisson's ratio is conventionally thought to have only minor effect on pavement performance and consequently its value is usually assumed for design. These findings suggest a need for reexamination.
- HMA unit weight was also an unexpectedly sensitive input. The reasons for the high sensitivity are unclear. It may be that HMA unit weight is included in an obscure way in some of the secondary models in the MEPDG. Further investigation is warranted.
- The sensitivity of thermal cracking to the HMA E* Delta Parameter (lower shelf of the dynamic modulus master curve) is larger in absolute value terms than its sensitivity to the HMA E* Alpha Parameter (the offset of the upper shelf above Delta). In addition, the influence of HMA E* Delta on thermal cracking is positive; as the lower shelf stiffness increases (which also increases the upper shelf stiffness, for fixed HMA E* Alpha), thermal cracking also increases. This appears contrary to engineering expectations.
- The high sensitivities for HMA Air Voids and HMA Effective Binder Volume are in addition to any influence they may have on HMA dynamic modulus and/or low temperature strength and creep compliance. The GSA simulations used synthetic Level 1 inputs for the HMA dynamic modulus and low temperature properties. Formulating these properties in terms of the Level 3 empirical relations would increase the sensitivities attributable to HMA Air Voids and Effective Binder Volume.

The extremely high sensitivity values for the HMA E* Alpha and Delta parameters merit further examination. As described previously in Section 3.2, the GSA simulations were based on synthetic Level 1 inputs for HMA dynamic modulus. In practice, these properties will very often be input into the MEPDG in terms of the Level 3 empirical relations. The pavement designer may therefore be more interested in the sensitivity of predicted distress to the inputs to the Level 3 empirical relations

than to the Level 1 inputs. These sensitivities can be evaluated using Equation (8) and the Level 3 empirical relations for HMA dynamic modulus given in Appendix C. These estimates are summarized in Table 5.2. The values in the table are approximations using average HMA mix gradation and volumetric data and the corresponding Level 3 α and δ values in lieu of the true point values. Some practical observations regarding the results in Table 5.2 include the following:

- The NSI values for the secondary variables (i.e., the inputs to the Level 3 empirical HMA dynamic modulus relations) are much lower than the NSI values for the primary variables α and δ .
- All of the NSI values for the secondary variables are in either the Sensitive or lower portion of the Very Sensitive categories.
- If using Level 3 inputs for HMA dynamic modulus, the NSI_z values for V_a and V_{beff} values are in addition to the NSI values in Table 5.1.

It is important to note that the NSI_z values in Table 5.2 and related discussion are all predicated on the validity of the Witczak dynamic modulus model.

Table 5.2. NSI values for HMA Level 3 dynamic modulus inputs.

Primary Variable			Secondary Variable			
Variable	x_i	NSI _x ¹	Variable	z_i	NSI _z	Category
α	3.90	-29.52	ρ_4	55.5%	0.88	S
			ρ_{38}	33.5%	-0.71	S
			ρ_{34}	5.5%	-0.23	S
δ	2.83	-24.43	ρ_{200}	4.9%	-0.51	S
			ρ_4	55.5%	-1.36	VS
			V_a	6.47%	1.60	VS
			V_{beff}	10.08%	1.65	VS

¹Overall maximum from Table 5.1.

5.2. HMA Over Stiff Foundation

The HMA Over Stiff Foundation design inputs are listed in Table 5.3 in rank order by the maximum absolute value of NSI _{$\mu \pm 2\sigma$} across distresses. The format of the presentation here is the same as described previously in Section 5.1 for New HMA.

The OAT local sensitivity category (Chapter 4) for each design input is also indicated in Table 5.3. There is a lack of full congruence between the ranking of inputs from the ANN RSMs and the categorization from the OAT analyses. This is likely because the OAT sensitivities are local measures that do not necessarily fully represent the global sensitivity.

Overall, the sensitivities of all of the design inputs evaluated in the HMA Over Stiff Foundation scenarios were quite high, and because of this there is a possibility that some of the MEPDG design inputs not evaluated here might also have higher-than-expected sensitivities.

Table 5.3. Ranking of HMA Over Stiff Foundation design inputs by maximum $NSI_{\mu \pm 2\sigma}$ values (ANN RSMs).

Design Input	Maximum $NSI_{\mu \pm 2\sigma}$ Values (ANN RSMs) ¹							
	Long. Crack	Alligator Crack	Thermal Crack	AC Rut Depth	Total Rut Depth	IRI	Max	OAT ²
HMA E* Delta Parameter ³	-19.60	9.00	3.52	-43.25	-12.76	-3.49	-43.25	HS
HMA E* Alpha Parameter ³	-22.02	-3.91	-2.82	-39.33	-13.12	-3.67	-39.33	HS
HMA Unit Weight	10.77	3.69	-1.02	-1.70	-0.65	-0.38	10.77	VS
HMA Air Voids	-8.12	-2.53	1.84	0.62	-0.26	-0.08	-8.12	VS
Surface Shortwave Absorptivity	-4.90	-1.86	-0.38	7.43	2.50	0.86	7.43	HS
HMA Poisson's Ratio	-6.93	-2.11	-0.30	-5.57	-1.96	-0.61	-6.93	HS
Subgrade Liquid Limit	6.76	2.47	0.18	0.97	0.19	-0.16	6.76	S
HMA Creep Compliance m Exponent	N.A.	N.A.	-6.65	N.A.	N.A.	N.A.	-6.65	VS
Sub Resilient Modulus	5.82	0.94	0.37	1.85	-1.72	-0.29	5.82	S
HMA Effective Binder Volume	-5.61	0.90	-0.70	-1.98	-0.40	-0.16	-5.61	VS
Base Poisson's Ratio	5.55	2.26	-0.46	-2.78	-0.56	-0.16	5.55	S
HMA Heat Capacity	-5.24	-1.88	-0.68	-1.36	-0.38	-0.24	-5.24	S
Base Thermal Conductivity	-5.05	-1.42	-0.84	-1.13	-0.42	-0.18	-5.05	HS
Base Thickness	3.25	1.67	0.22	2.00	0.32	0.10	3.25	VS
HMA Thickness	2.73	1.82	-0.70	3.11	0.87	0.30	3.11	VS
Operational Speed	3.09	0.56	-0.14	-1.62	-0.58	-0.16	3.09	VS
Traffic Volume (AADTT)	0.74	0.56	-0.06	2.94	0.91	0.26	2.94	VS
Subgrade Percent Passing No. 200	2.78	0.53	-0.35	0.57	-0.23	0.10	2.78	S
Base Resilient Modulus	-1.84	0.58	-0.47	-2.23	-0.33	0.22	-2.23	S
Base Heat Capacity	-2.18	-0.50	-0.40	-0.86	-0.45	-0.23	-2.18	S
Subgrade Plasticity Index	1.66	0.49	-0.07	0.70	0.09	0.02	1.66	S
HMA Tensile Strength at 14°F	N.A.	N.A.	-1.65	N.A.	N.A.	N.A.	-1.65	VS
Base Resilient Modulus	-1.63	-0.25	-0.09	0.94	0.30	-0.13	-1.63	S
Groundwater Depth	-1.30	-0.24	0.09	0.34	-0.06	-0.02	-1.30	S
Binder High Temperature PG	-0.68	-0.23	0.00	-1.15	-0.38	-0.11	-1.15	VS
HMA Creep Compliance D Parameter	N.A.	N.A.	-1.10	N.A.	N.A.	N.A.	-1.10	VS
Binder Low Temperature PG	-0.51	-0.09	-0.92	0.38	0.15	0.07	-0.92	S
HMA Thermal Conductivity	0.83	-0.60	-0.56	0.62	0.24	0.15	0.83	S
Aggregate Coef. Of Thermal Contraction	N.A.	N.A.	-0.16	N.A.	N.A.	N.A.	-0.16	NS

¹Maximum sensitivity (in absolute value sense) over all baseline cases and distresses. Sensitivity ratings are indicated by font type: **Bold** designates Hypersensitive, $NSI_{\mu \pm 2\sigma} > 5$; **Bold Italics** designates Very Sensitive, $1 < NSI_{\mu \pm 2\sigma} < 5$; *Italics* designates Sensitive, $0.1 < NSI_{\mu \pm 2\sigma} < 1$; and Regular font designates Insensitive, $NSI_{\mu \pm 2\sigma} < 0.1$. Bold lines indicate breaks between sensitivity categories. Shaded entries indicate the three most sensitive inputs for each individual distress.

²HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Non-Sensitive.

³See Equation (1) in Section 3.2.1.

Figure 5.2 provides graphical summaries of the input sensitivities by distress (larger versions of these figures are included in Appendix C). Thermal cracking is not included here; the substantially stiffer low temperature binder grades in these cases were substantially different from the other distresses and do not reflect what would be used in practice. The solid bars in the figures indicate the mean NSI values, and the error bars correspond to one standard deviation. All of the figures have the same horizontal axis range so that the differences in sensitivities across distresses can be more clearly evaluated. The sensitivities are also broken down by climate zone for each design input.

Figure 5.2 highlights the difference in sensitivities between the categories. For all distresses there is a very sharp drop in bar lengths moving from Hypersensitive to Very Sensitive and again from Very Sensitive to Sensitive. At $NSI_{\mu \pm 2\sigma} = 1$ corresponding to the upper limit of the Sensitive range in Table 5.3, the percentage change in distress relative to its design limit equals the percentage change in the design input. This is very small in practical terms, especially since it is defined at the $\mu \pm 2\sigma$ level. The focus of the pavement designer should therefore be on the Hypersensitive and Very Sensitive design inputs; these are the values that need to be most carefully determined.

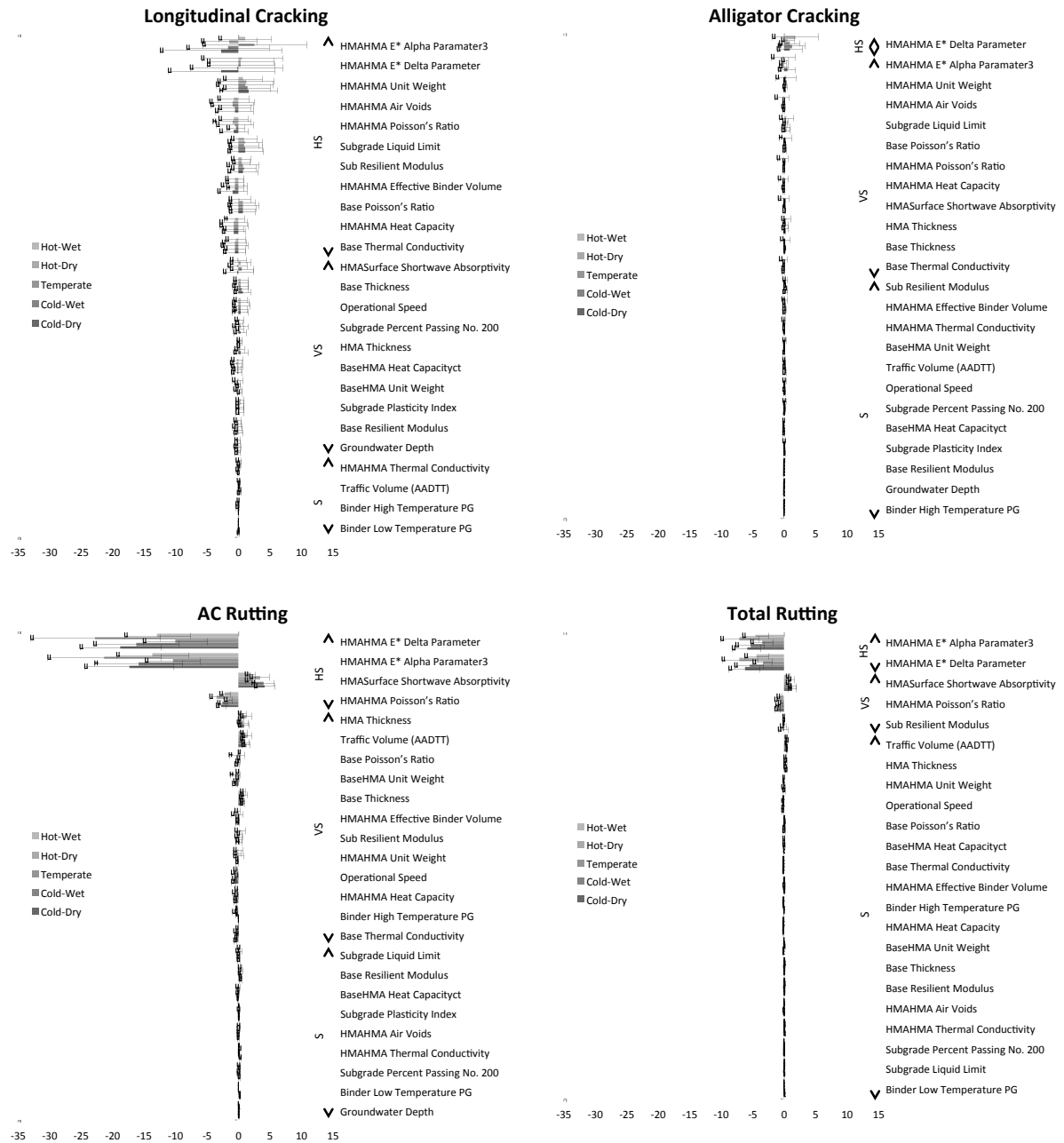


Figure 5.2. Ranking of HMA Over Stiff Foundation design inputs. Solid bars indicate mean NSI, error bars indicate one standard deviation.

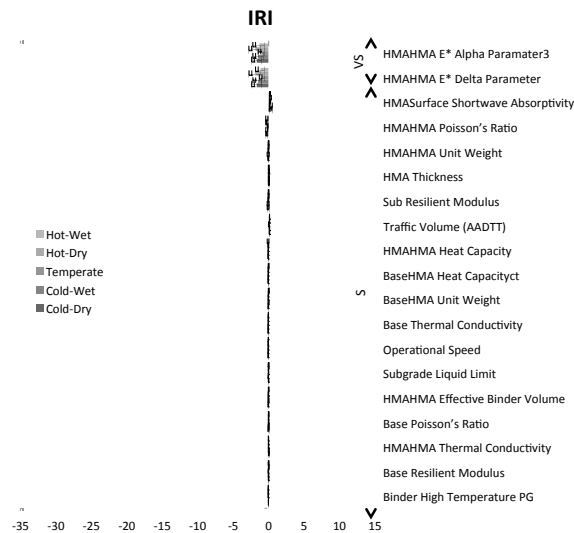


Figure 5.2 continued.

These results largely match engineering expectations and experience in an overall sense. Most of the detailed observations made for the New HMA scenario in the preceding section apply in the HMA Over Stiff Foundation case as well. Notable differences/additions include:

- The magnitudes of the sensitivity values for longitudinal cracking, AC rutting, and to a lesser extent, total rutting were substantially higher than the values for alligator cracking, thermal cracking, and IRI.
- HMA unit weight was found to be a hypersensitive input. Although the high sensitivity of this design input was noted previously in the New HMA scenarios, the very high sensitivity of longitudinal and alligator cracking to HMA unit weight in the HMA Over Stiff Foundation scenario is stark.
- 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. This is problematic in practice, as these properties are very difficult to measure. In addition, these might also be sensitive inputs for conventional granular bases, but the MEPDG does not permit input of these values for nonstabilized base layers.
- A moderately high sensitivity of longitudinal cracking and AC rutting on traffic speed was noted. This is likely due to its influence on the dynamic modulus value used in the pavement structural response calculations.

5.3. New JPCP

The New JPCP design inputs are listed in Table 5.4 in rank order by the maximum absolute value of $NSI_{\mu \pm 2\sigma}$ across distresses. The OAT local sensitivity category (Chapter 4) for each design input is also indicated in Table 5.4. Not only is there good congruence between the ranking of inputs from the ANN RSMs and the categorization from the OAT analyses, but the ranges of $NSI_{\mu \pm 2\sigma}$ in Table 5.4 also line up closely with the ranges of normalized sensitivity index values used to define the OAT categories.

Table 5.4. Ranking of New JPCP design inputs by maximum $NSI_{\mu+2\sigma}$ values (ANN RSMs).

Design Input	Maximum $NSI_{\mu+2\sigma}$ Values (ANN RSMs) ¹				OAT ²
	Faulting	Transverse Cracking	IRI	Maximum	
Slab Width	-17.97	-5.04	-8.81	-17.97	HS
PCC 28-Day Modulus of Rupture	0.92	-4.21	-0.63	-4.21	HS
PCC Thickness	0.51	-3.88	-0.50	-3.88	HS
Design Lane Width	1.58	-3.78	0.65	-3.78	HS/NS ³
PCC Unit Weight	-2.33	3.13	-1.19	3.13	VS
PCC Coef. of Thermal Expansion	2.16	2.81	1.25	2.81	VS
PCC Ratio of 20-year to 28-day Modulus of Rupture	0.50	-2.69	-0.26	-2.69	- ⁴
PCC 28-Day Elastic Modulus	0.21	2.57	0.37	2.57	HS
Surface Shortwave Absorptivity	0.68	2.27	0.55	2.27	HS
Joint Spacing	0.66	1.79	0.36	1.79	HS
PCC Water-to-Cement Ratio	0.62	1.62	0.82	1.62	S
PCC Thermal Conductivity	-0.21	-1.12	-0.21	-1.12	HS
Subgrade Resilient Modulus	-0.20	-0.34	-0.99	-0.99	S
Dowel Diameter	-0.69	0.98	-0.37	0.98	VS
PCC Poisson's Ratio	0.26	-0.75	0.19	-0.75	VS
Traffic Volume (AADTT)	0.63	0.56	0.37	0.63	VS
PCC Cement Content	0.30	0.55	0.18	0.55	S
Base Resilient Modulus	0.33	0.40	0.22	0.40	VS
Groundwater Depth	0.08	-0.37	-0.06	-0.37	S
Base Thickness	-0.12	0.35	-0.08	0.35	S
Edge Support – Load Transfer Efficiency	-0.13	-0.26	-0.07	-0.26	NS
Erodibility Index	0.25	-0.19	0.16	0.25	S
Construction Month	0.11	0.22	0.07	0.22	S

¹Maximum sensitivity (in absolute value sense) over all baseline cases and distresses. Sensitivity ratings are indicated by font type: **Bold** designates Hypersensitive, $NSI_{\mu+2\sigma} > 5$; **Bold Italics** designates Very Sensitive, $1 < NSI_{\mu+2\sigma} < 5$; *Italics* designates Sensitive, $0.1 < NSI_{\mu+2\sigma} < 1$; and Regular font designates Insensitive, $NSI_{\mu+2\sigma} < 0.1$. Bold lines indicate breaks between sensitivity categories. Shaded entries indicate the three most sensitive inputs for each individual distress.

²HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Non-Sensitive.

³Design lane width for widened slab condition was Hyper Sensitive; Design lane width for tied shoulder or no edge support condition was Non Sensitive in OAT analyses.

⁴20-year strength ratio values not considered explicitly in OAT analyses.

Figure 5.3 provides graphical summaries of the input sensitivities by distress (larger versions of these figures are included in Appendix C). The solid bars in the figures indicate the mean NSI values, and the error bars correspond to one standard deviation. All of the figures have the same horizontal axis range so that the differences in sensitivities across distresses can be more clearly evaluated. The sensitivities are also broken down by climate zone for each design input.

Figure 5.3 highlights the difference in sensitivities between the categories. For all distresses there is a very sharp drop in bar lengths moving from Hypersensitive to Very Sensitive and again from Very Sensitive to Sensitive. At $NSI_{\mu+2\sigma} = 1$ corresponding to the upper limit of the Sensitive range in Table 5.4, the percentage change in distress relative to its design limit equals the percentage change in the design input. This is very small in practical terms, especially since it is defined at the $\mu+2\sigma$ level. The focus of the pavement designer should therefore be on the Hypersensitive and Very Sensitive design inputs; these are the values that need to be most carefully determined.

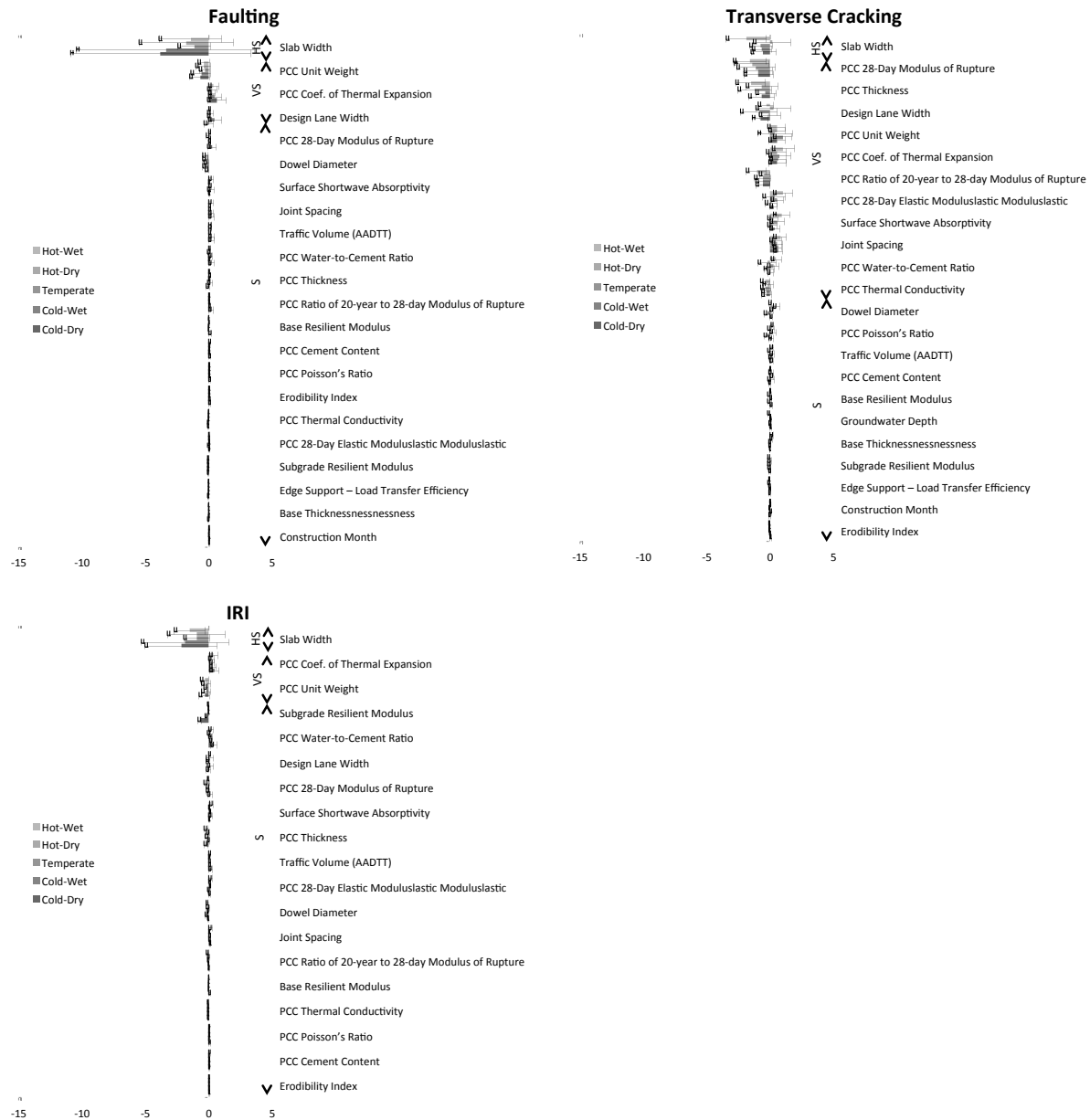


Figure 5.3. Ranking of New JPCP design inputs. Solid bars indicate mean NSI, error bars indicate one standard deviation.

These results match engineering judgment and experience. Although the details vary by distress type, slab width is consistently the highest sensitivity design input, followed by the PCC layer properties (PCC unit weight, PCC coefficient of thermal expansion, PCC strength parameters, surface shortwave absorptivity) and other geometric properties (design lane width, PCC thickness, joint spacing). However, there are a few observations from Table 5.4 and Figure 5.3 that merit special note and discussion:

- The magnitudes of the sensitivity values for faulting, transverse cracking, and IRI are similar. However, the range of faulting sensitivity values (error bars) is significantly larger than for transverse cracking and IRI.

- The sensitivity index values for each distress-design input combination do not vary substantially or systematically by climate zone.
- When interpreting the sensitivity of Design Lane Width, it is important to note that it was evaluated under three different edge support conditions (no edge support, tied shoulder edge support with 80% LTE, and widened slab edge support condition). Design Lane Width under widened slab edge support showed high sensitivity for transverse cracking but Design Lane Width under either no edge support or tied shoulder edge support was not sensitive.
- PCC Unit Weight is an unexpectedly sensitive input. The PCC unit weight is an important factor in the calculation of critical responses in the rigid pavement structural response models employed in MEPDG through its influence on curling deflections (faulting) and curling stresses (transverse cracking).
- PCC Thickness is a relatively less sensitive input than the PCC material properties.
- The JPCP cracking predictions could not be accurately characterized with either the classical MVLN or the more advanced ANN response surface modeling methodologies. This is described more thoroughly in Appendix C. The failure of the response surface models to capture the computed cracking behavior suggests that either better response surface models are needed or that the JPCP cracking model included in the MEPDG deserves more scrutiny.

5.4. JPCP Over Stiff Foundation

The JPCP Over Stiff Foundation design inputs are listed in Table 5.5 in rank order by the maximum absolute value of $NSI_{\mu+2\sigma}$ across distresses. The OAT local sensitivity category (Chapter 4) for each design input is also indicated in Table 5.5. Not only is there good congruence between the ranking of inputs from the ANN RSMs and the categorization from the OAT analyses, but the ranges of $NSI_{\mu+2\sigma}$ in Table 5.5 also line up closely with the ranges of normalized sensitivity index values used to define the OAT categories. These results also match engineering judgment and experience.

Figure 5.4 provides graphical summaries of the input sensitivities by distress (larger versions of these figures are included in Appendix C). The solid bars in the figures indicate the mean values, and the error bars correspond to one standard deviation. All of the figures have the same horizontal axis range so that the differences in sensitivities across distresses can be more clearly evaluated. The sensitivities are also broken down by climate zone for each design input.

Figure 5.4 highlights the difference in sensitivities between the categories. For all distresses there is a very sharp drop in bar lengths moving from Hypersensitive to Very Sensitive and again from Very Sensitive to Sensitive. At $NSI_{\mu+2\sigma} = 1$ corresponding to the upper limit of the Sensitive range in Table 5.5, the percentage change in distress relative to its design limit equals the percentage change in the design input. This is very small in practical terms, especially since it is defined at the $\mu+2\sigma$ level. The focus of the pavement designer should therefore be on the Hypersensitive and Very Sensitive design inputs; these are the values that need to be most carefully determined.

The key observations for the JPCP Over Stiff Foundation scenario match identically those made earlier for the New JPCP case.

Table 5.5. Ranking of JPCP Over Stiff Foundation design inputs by maximum $NSI_{\mu \pm 2\sigma}$ values (ANN RSMs).

Design Input	Maximum $NSI_{\mu \pm 2\sigma}$ Values (ANN RSMs) ¹				OAT ²
	Faulting	Transverse Cracking	IRI	Maximum	
Slab Width	-16.34	-4.74	-9.63	-16.34	HS
PCC 28-Day Modulus of Rupture	0.49	-5.52	-0.62	-5.52	HS
PCC Thickness	0.40	-5.05	-0.51	-5.05	HS
PCC Unit Weight	-4.16	2.68	-2.63	-4.16	HS
Design Lane Width	1.67	-3.23	-0.74	-3.23	HS/NS³
PCC Coef. of Thermal Expansion	2.54	3.10	1.42	3.10	VS
PCC Ratio of 20-year to 28-day Modulus of Rupture	0.31	-3.02	-0.29	-3.02	-⁴
PCC 28-Day Elastic Modulus	0.47	2.40	0.45	2.40	HS
PCC Water-to-Cement Ratio	0.28	2.23	0.78	2.23	S
Joint Spacing	0.70	1.98	0.33	1.98	HS
Surface Shortwave Absorptivity	0.67	1.97	0.58	1.97	HS
PCC Thermal Conductivity	-0.54	-1.29	-0.33	-1.29	HS
Dowel Diameter	-0.44	1.13	-0.36	1.13	VS
Subgrade Resilient Modulus	-0.38	0.24	-1.06	-1.06	VS
PCC Poisson's Ratio	0.26	0.72	0.24	0.72	VS
Traffic Volume (AADTT)	0.47	0.72	0.35	0.72	VS
Base Thickness	-0.32	-0.51	-0.17	-0.51	VS
Edge Support – Load Transfer Efficiency	-0.12	-0.47	-0.10	-0.47	S
Erodibility Index	0.27	-0.12	0.15	0.27	S
Loss of Friction	0.03	-0.26	-0.02	-0.26	S
PCC Cement Content	0.21	0.22	0.12	0.22	S
Groundwater Depth	-0.07	-0.21	-0.05	-0.21	S
Stabilized Base Resilient Modulus	0.06	-0.19	-0.06	-0.19	NS
Construction Month	0.10	0.14	0.06	0.14	VS

¹Maximum sensitivity (in absolute value sense) over all baseline cases and distresses. Sensitivity ratings are indicated by font type: **Bold** designates Hypersensitive, $NSI_{\mu \pm 2\sigma} > 5$; **Bold Italics** designates Very Sensitive, $1 < NSI_{\mu \pm 2\sigma} < 5$; *Italics* designates Sensitive, $0.1 < NSI_{\mu \pm 2\sigma} < 1$; and Regular font designates Insensitive, $NSI_{\mu \pm 2\sigma} < 0.1$. Bold lines indicate breaks between sensitivity categories. Shaded entries indicate the three most sensitive inputs for each individual distress.

²HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Non-Sensitive.

³Design lane width for widened slab condition was Hyper Sensitive; Design lane width for tied shoulder or no edge support condition was Non Sensitive in OAT analyses.

⁴20-year strength ratio values not considered explicitly in OAT analyses.

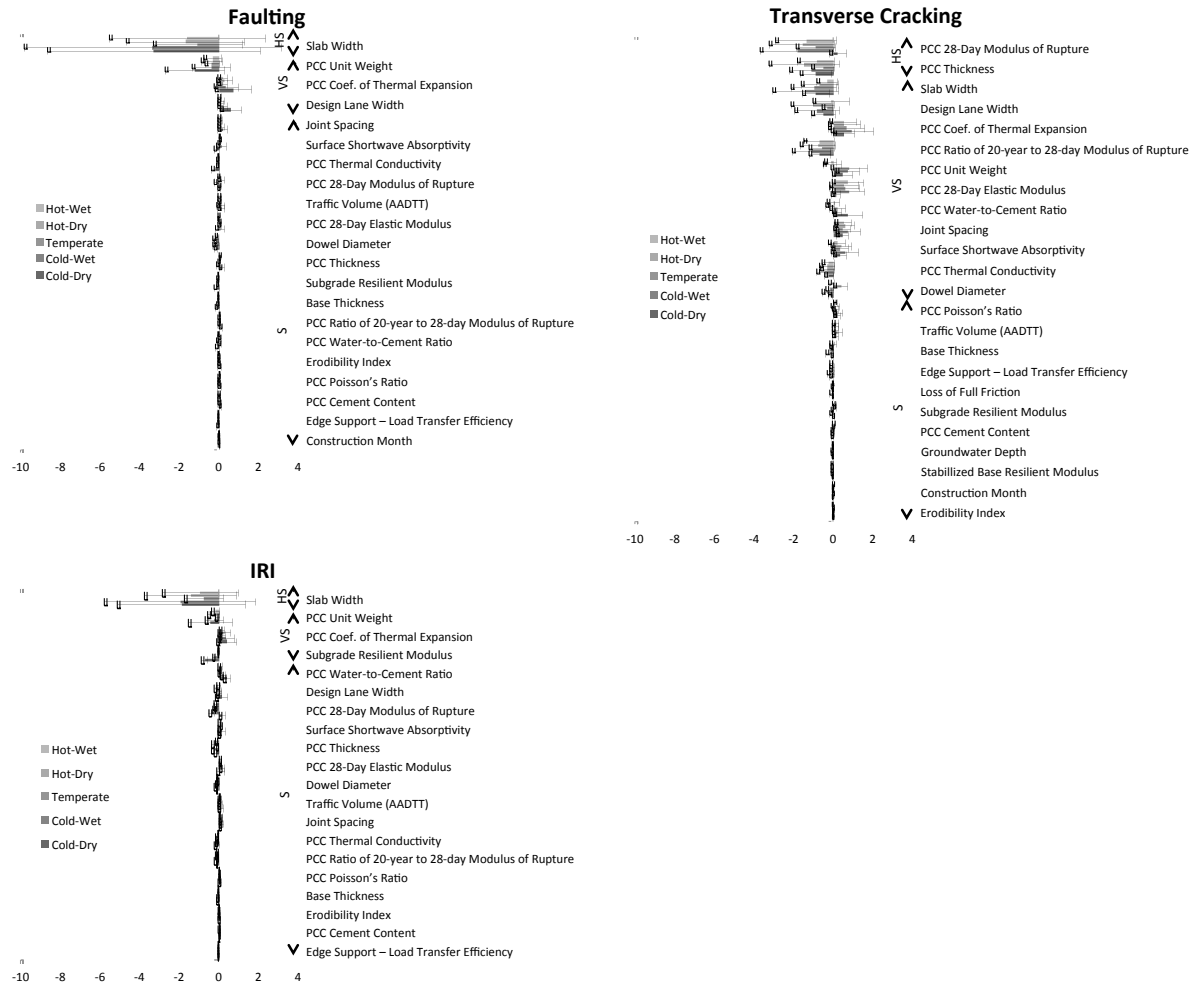


Figure 5.4. Ranking of JPCP Over Stiff Foundation design inputs. Solid bars indicate mean NSI, error bars indicate one standard deviation.

5.5. New CRCP

The New CRCP design inputs are listed in Table 5.6 in rank order by the maximum absolute value of $NSI_{\mu \pm 2\sigma}$ across distresses. The OAT local sensitivity category (Chapter 4) for each design input is also indicated in Table 5.6. Not only is there is a full congruence between the ranking of inputs from the ANN RSMs and the categorization from the OAT analyses, but the ranges of $NSI_{\mu \pm 2\sigma}$ in Table 5.6 also line up closely with the ranges of normalized sensitivity index values used to define the OAT categories.

Figure 5.5 provides graphical summaries of the input sensitivities by distress (larger versions of these figures are included in Appendix C). The solid bars in the figures indicate the mean NSI values, and the error bars correspond to one standard deviation. All of the figures have the same horizontal axis range so that the differences in sensitivities across distresses can be more clearly evaluated. The sensitivities are also broken down by climate zone for each design input.

Figure 5.5 highlights the difference in sensitivities between the categories. For all distresses there is a very sharp drop in bar lengths moving from Hypersensitive to Very Sensitive and again from Very Sensitive to Sensitive. At $NSI_{\mu \pm 2\sigma} = 1$ corresponding to the upper limit of the Sensitive range in Table 5.6, the percentage change in distress relative to its design limit equals the percentage change in the design input. This is very small in practical terms, especially since it is defined at the $\mu \pm 2\sigma$ level. The focus of the pavement designer should therefore be on the Hypersensitive and Very Sensitive design inputs; these are the values that need to be most carefully determined.

Table 5.6. Ranking of New CRCP design inputs by maximum $NSI_{\mu \pm 2\sigma}$ values (ANN RSMs).

Design Input	Maximum $NSI_{\mu \pm 2\sigma}$ Values (ANN RSMs) ¹					OAT ²
	Punchout	Crack Width	Crack LTE	IRI	Max	
PCC 28-Day Indirect Tensile Strength	11.13	61.48	-1.33	2.37	61.48	- ³
PCC 28-Day Modulus of Rupture	-40.29	-47.80	2.35	-7.37	-47.80	HS
PCC Thickness	-44.43	-10.47	1.57	-8.94	-44.43	HS
PCC Water-to-Cement Ratio	8.42	36.09	-0.82	1.88	36.09	HS
PCC Unit Weight	-17.22	-35.27	0.53	-3.22	-35.27	HS
Bar Diameter	11.41	23.29	-1.49	1.93	23.29	HS
Base Slab Friction	-4.17	-21.62	0.35	-0.78	-21.62	HS
PCC Cement Content	7.56	21.55	-0.65	1.38	21.55	HS
PCC Ratio 20-year to 28-day Modulus of Rupture	-18.81	7.88	-0.50	-3.48	-18.81	- ³
Percent Steel	-15.41	-18.00	1.04	-2.99	-18.00	HS
PCC 28-Day Elastic Modulus	10.90	15.97	-0.61	2.13	15.97	HS
Steel Depth	6.43	13.39	-0.61	1.51	13.39	HS
Traffic Volume (AADTT)	8.47	1.03	-0.42	1.61	8.47	HS
Base Resilient Modulus	-6.39	-4.71	0.10	-1.16	-6.39	VS
PCC Coef. of Thermal Expansion	6.19	5.54	-0.06	1.19	6.19	VS
PCC Ratio 20-year to 28-day Indirect Tensile Strength	1.62	-5.81	0.14	-0.29	-5.81	- ³
Surface Shortwave Absorptivity	3.32	-5.44	0.20	0.74	-5.44	HS
Base Thickness	-1.79	4.71	-0.10	-0.42	4.71	S
Subgrade Resilient Modulus	-3.23	-4.64	0.06	-1.17	-4.64	VS
Edge Support – Load Transfer Efficiency	-3.26	2.16	0.30	-0.59	-3.26	S
PCC Poisson's Ratio	1.79	-2.44	0.04	0.34	-2.44	S
Construction Month	1.62	2.33	-0.08	0.25	2.33	S
Groundwater Depth	0.43	-1.19	0.03	-0.09	-1.19	S

¹Maximum sensitivity (in absolute value sense) over all baseline cases and distresses. Sensitivity ratings are indicated by font type: **Bold** designates Hypersensitive, $NSI_{\mu \pm 2\sigma} > 5$; **Bold Italics** designates Very Sensitive, $1 < NSI_{\mu \pm 2\sigma} < 5$; *Italics* designates Sensitive, $0.1 < NSI_{\mu \pm 2\sigma} < 1$; and Regular font designates Insensitive, $NSI_{\mu \pm 2\sigma} < 0.1$. Bold lines indicate breaks between sensitivity categories. Shaded entries indicate the three most sensitive inputs for each individual distress.

²HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Non-Sensitive.

³20-year strength ratio values not considered explicitly in OAT analyses.

- The largest sensitivity values for New CRCP are substantially larger than those for any of the other pavement types.
- The magnitudes (mean and standard deviation) of the highest sensitivity values for punchouts and crack width are substantially greater than the values for crack LTE and IRI.
- The sensitivity index values for each distress-design input combination do not vary substantially or systematically by climate zone.
- The PCC Ratio 20-year to 28-day Modulus of Rupture is the third-ranked design input for punchouts and thus for IRI. This is troubling because the 20-year modulus of rupture cannot be directly measured and thus this design input can only be estimated.

Appendix C provides complete GSA results for each pavement type, including the following:

- Tabular summaries of summary statistics (mean, minimum, maximum, standard deviation) for each predicted distress by climate-traffic level base case.
- Graphs of frequency distributions for all predicted distresses by climate zone and traffic level.
- Goodness-of-fit statistics for the multivariate linear regression (MVLR) and artificial neural network (ANN) response surface models (RSM) for each climate zone-distress combination.
- Scattergrams plotting ANN predicted distress vs. MEPDG predicted distress for all distresses by climate zone.
- Tabular summaries of average sensitivity values from the MVLR RSMs for all design inputs by distress and climate zones.
- Graphical ranked summaries of average sensitivity values from the MVLR RSMs.
- Tabular summaries of NSI statistics (mean, standard deviation) from the ANN RSMs by distress and climate zone. Approximately 10,000 evaluations of the ANN RSMs were performed for each pavement type-climate zone-distress type combination to generate these statistics.
- Frequency distributions of NSI values for each design input-distress combination.
- Ranking of design inputs in terms of the maximum (in an absolute value sense) average sensitivity coefficients from the MVLR RSMs.
- Ranking of design inputs in terms of the maximum (in an absolute value sense) mean NSI value from the ANN RSMs.

6. SUMMARY, CONCLUSIONS, AND RECOMMENDED RESEARCH

The sensitivity of MEPDG predicted pavement performance to design inputs has been evaluated through an initial triage, extensive one-at-a-time (OAT) sensitivity analyses, and comprehensive global sensitivity analyses (GSA). 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 x 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 refine the list of sensitive design inputs for the more computationally intensive GSA. The GSA, in contrast to the OAT analyses, varied all design inputs simultaneously across the entire problem domain for each pavement type. 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 summarized in this chapter are based on the GSA results, as these most thoroughly evaluate the mean and variability of the sensitivities across the problem domain as well as any potential interaction effects among design inputs. The GSA base cases and design inputs were summarized previously in Chapter 3, and the final GSA results are described in Chapter 5. Complete detailed documentation of the GSA is provided in Appendix C. General conclusions regarding the sensitivity analysis methodology, the major conclusions for all pavement types, and the major specific conclusions for flexible and rigid pavements are summarized in the following subsections. Recommendations for future research are also provided.

6.1. General Conclusions: Methodology

General conclusions regarding the GSA methodology include the following:

- There is no sensitivity metric that is uniquely best for all variables and all purposes. The design limit normalized sensitivity index (NSI) adopted for this study has the practical interpretation of relating a given percentage change in a design input to the corresponding percentage change in predicted distress relative to its design limit value. For example, $NSI = -0.25$ for the sensitivity of total rutting to granular base layer resilient modulus implies that a 10% reduction in base resilient modulus will increase total rutting by 2.5% of its design limit of 0.75 inches. In other words, the 10% reduction in base resilient modulus will increase rutting by $(-0.10)*(-0.25)*0.75=0.01875$ inches. At $NSI = 1$, the percentage change in distress relative to its design limit equals the percentage change in the design input. For the purposes of understanding which pavement design inputs are most important, the relative magnitudes of the NSI values are more important than their precise values.
- The OAT local sensitivity analysis results agreed with the initial triage at about the 65-85% level, depending on pavement type. This means that the conventional wisdom incorporated in the initial triage was basically sound, but that it also benefited from the fine-tuning provided by the OAT analyses.
- The multivariate linear regression (MVLRL) RSMs, although widely employed in the sensitivity analysis literature, were insufficient for capturing the complex nonlinearities of pavement performance. The MVLRL RSMs in this study had only poor to fair goodness-of-fit statistics. They are incapable of capturing the variation in sensitivities across the problem domain and thus at best are useful only for determining “first-cut” average sensitivities.

- The artificial neural network (ANN) RSMs provided generally robust and accurate representations of the complex relationships between design inputs and distress outputs. The ANNs achieved excellent goodness-of-fit statistics for most distresses, although cracking was more problematic than rutting, faulting, or IRI. The ANN RSMs capture the variation of sensitivities across the problem domain and thus enabled generation of frequency distributions and summary statistics (minimum, maximum, mean, standard deviation, etc.). Enhanced versions of the ANN RSMs (e.g., to include climate effects more explicitly) could in some cases be adequate replacements for the more rigorous but laborious geomechanics computations in the MEPDG. Ceylan and Gopalakrishnan (2011) demonstrated this approach.
- The “mean plus/minus two standard deviations” ($\mu \pm 2\sigma$) normalized sensitivity metric ($NSI_{\mu \pm 2\sigma}$) derived from ANN RSM statistics was judged to be the best and most robust ranking measure because it incorporates both the mean sensitivity and the variability of sensitivity across the problem domain.
- Sensitivity categories based on the GSA results were defined as follows: Hypersensitive (HS), $NSI_{\mu \pm 2\sigma} > 5$; Very Sensitive (VS), $1 < NSI_{\mu \pm 2\sigma} < 5$; Sensitive (S), $0.1 < NSI_{\mu \pm 2\sigma} < 1$; and Non-Sensitive (NS), $NSI_{\mu \pm 2\sigma} < 0.1$.
- The design input rankings by $NSI_{\mu \pm 2\sigma}$ from the GSA agreed well with the OAT rankings. This should not be interpreted as implying that OAT local sensitivity analyses will be an acceptable substitute for the more demanding GSA. Rather, it is due in large part to the exhaustive nature of the OAT analyses considered in this study. The set of 3800 MEPDG analyses over 5 pavement types, 5 climate zones, 3 traffic levels, and dozens of design inputs sampled a significantly larger subset of the problem domain than in most past studies. The OAT rankings were also based on the very severe metric of the maximum NSI value observed for any distress, pavement type, climate zone, or traffic level. This is similar in concept (although not in detail) to the $NSI_{\mu \pm 2\sigma}$ metric in the GSA.
- The agreement of the GSA and OAT rankings suggests that interactions among design inputs (effects of two variables changing greater than their multiplicative individual effects) were not significant.

6.2. General Conclusions: All Pavements

The wide range of pavement types, distresses, and design inputs considered in this study makes it difficult to extract broad conclusions that apply to all pavements under all conditions. Nonetheless, a few trends were consistently observed in the GSA results:

- Most of the NSI frequency distributions generated from the 10,000 evaluations of the ANN RSMs for each pavement type-climate zone-distress combination showed very well defined single peaks, indicating that the NSI value did not vary significantly over the problem domain. The few cases in which the NSI distributions were more broad either had NSI values that were all small and not of interest or all large and thus always of interest. No frequency distributions exhibited multi-mode, multiple peak characteristics.
- For all pavement types and distresses, the sensitivities of the design inputs for the bound surface layers (HMA, PCC) were the most important.
- The sensitivity values for each distress-design input combination did not vary substantially or systematically by climate zone. However, the distress magnitudes may vary across climate zones;

hot climate zones may still likely produce higher AC rutting than cool climates, for example. Of course, some distresses only occur in certain climate zones (e.g., thermal cracking).

6.3. Conclusions: Flexible Pavements

The specifics of the sensitivities of the design inputs on the predicted performance of flexible pavements vary by distress type (e.g., rutting vs. cracking, load related vs. non-load related) and, to a lesser extent, by pavement type (conventional new HMA vs. HMA over stiff foundation). Nonetheless, the GSA results do suggest some broad conclusions.

As a more practical aid to the pavement designer, Table 6.1 summarizes in rank order the Hypersensitive, Very Sensitive, and Sensitive design inputs by material category (HMA, base, subgrade, other) for each distress for the New HMA pavement type. The companion table for the HMA Over Stiff Foundation scenarios is very similar and is given in Appendix C. The design inputs that fall in the Hypersensitive or Very Sensitive categories for most (4 out of 5) distresses are indicated by bold font in the table. For practical design purposes, the high sensitivity or critical design inputs can be limited to those in the Hypersensitive and Very Sensitive categories. At $NSI_{\mu+2\sigma} = 1$ corresponding to the lower limit of the Very Sensitive/upper limit of the Sensitive ranges, the percentage change in distress relative to its design limit equals the percentage change in the design input. This is usually acceptably small in practical terms, especially since it is defined at the $\mu+2\sigma$ level.

Conclusions applicable to most flexible pavement scenarios based on the GSA results in Sections 5.1 and 5.2 and Table 6.1 include the following:

- 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 properties (e.g., traffic volume) was as consistently in the two highest sensitivity categories.
- The magnitudes of the sensitivity values for longitudinal cracking, 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 had very little overlap with the set of sensitive design inputs for thermal cracking. This is not unexpected because the former are primarily load-related distresses while thermal cracking is exclusively environment-driven.
- Although the lower (δ) and upper ($\delta+\alpha$) shelves of the HMA dynamic modulus master curve were consistently the highest ranked inputs for all distresses except thermal cracking, these high sensitivities are mitigated to some degree because δ and α do not vary over a wide range.
- The computed sensitivities for HMA air voids and effective binder volume are in addition to any influence they may have on HMA dynamic modulus. The GSA simulations used synthetic Level 1 inputs for the HMA dynamic modulus. Formulating these properties in terms of the Level 3 empirical relations would increase the sensitivities attributable to air voids and effective binder volume (see Section 5.1).
- Little or no thermal cracking was predicted when using the correct binder grade recommended by LTPPBind (98% reliability). The low temperature binder grade had to be shifted 2 to 3 grades stiffer (warmer) in order to generate sufficient thermal cracking distress for evaluating the sensitivity metrics.

- The thermal conductivity and heat capacity of the stabilized base in the HMA Over Stiff Foundation scenarios were found to be sensitive design inputs for longitudinal cracking and, to a lesser extent, for alligator cracking and asphalt rutting. This is problematic in practice, as these properties are very difficult to measure. These might also be sensitive inputs for conventional granular bases, but the MEPDG does not permit input of these values for nonstabilized materials.
- A moderately high sensitivity of longitudinal cracking and AC rutting on traffic speed was noted in the HMA Over Stiff Foundation results. This is likely due to its influence on HMA dynamic modulus.

There were also a few unexpected findings. These include the following:

- Poisson's ratio was an unexpectedly sensitive input for HMA and, to a lesser extent, for the subgrade. Poisson's ratio is conventionally thought to have only minor effect on pavement performance and consequently a typical value is usually assumed for design
- HMA unit weight was also an unexpectedly sensitive input. The reasons for the high sensitivity are unclear. Further investigation is warranted.
- The sensitivity of thermal cracking to the HMA dynamic modulus lower shelf (δ) was larger in absolute value terms than its sensitivity to the upper shelf ($\delta + \alpha$). The influence of lower shelf stiffness on thermal cracking was positive; as the lower shelf stiffness δ increases (which also increases the upper shelf stiffness, for fixed α), thermal cracking also increases.

Guidance for the pavement designer on how to address high sensitivity or critical design inputs varies depending upon the specific design input. Some high sensitivity inputs can be specified very precisely, e.g., HMA thickness. Other properties need to be measured or estimated. The high sensitivity to the HMA dynamic modulus indicates a need for careful characterization of this property. Mix-specific laboratory measurement of dynamic modulus may be appropriate for high-value projects. The high sensitivity of Poisson's ratio suggests that more attention should be given to defining this property for the actual materials in the design rather than just using typical values. The high sensitivities to surface shortwave absorptivity for all asphalt surfaces and the thermal conductivity and heat capacity of stabilized bases are more problematic as these properties cannot be readily measured and guidance on realistic values for specific paving materials is lacking. For these as well as all other high sensitivity design inputs, the pavement designer should perform project-specific design sensitivity studies to evaluate the consequences of uncertain input values.

Table 6.1. Hypersensitive, Very Sensitive, and Sensitive design inputs by distress and input category for New HMA flexible pavements.
NSI _{$\mu \pm 2\sigma$} values are given in parentheses. Inputs in bold font are Hypersensitive or Very Sensitive for most (4 out of 5) distresses.

<i>Distress</i>	<i>Input Category</i>	<i>Hypersensitive (>5)</i>	<i>Very Sensitive (1-5)</i>	<i>Sensitive (0.1-1)</i>
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)
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)

<i>Distress</i>	<i>Input Category</i>	<i>Hypersensitive (>5)</i>	<i>Very Sensitive (1-5)</i>	<i>Sensitive (0.1-1)</i>
AC Rutting	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)

6.4. JPCP Rigid Pavements

The specifics of the sensitivities of the design inputs on the predicted performance of JPCP pavements vary by distress type (e.g., faulting vs. cracking vs. IRI) and, to a lesser extent, by pavement type (conventional new JPCP vs. JPCP over stiff foundation). Nonetheless, the GSA results do suggest some broad conclusions.

As a more practical aid to the pavement designer, Table 6.2 summarizes in rank order the Hypersensitive, Very Sensitive, and Sensitive design inputs by material category (PCC, base, subgrade, other) for each distress for the New JPCP pavement type. The companion table for the JPCP Over Stiff Foundation scenarios is very similar and is given in Appendix C. The design inputs that fall in the Hypersensitive or Very Sensitive categories for most (2 out of 3) distresses are indicated by bold font in the table. For practical design purposes, the high sensitivity or critical design inputs can be limited to those in the Hypersensitive and Very Sensitive categories. At $NSI_{\mu \pm 2\sigma} = 1$ corresponding to the lower limit of the Very Sensitive/upper limit of the Sensitive ranges, the percentage change in distress relative to its design limit equals the percentage change in the design input. This is usually acceptably small in practical terms, especially since it is defined at the $\mu \pm 2\sigma$ level.

Conclusions applicable to most JPCP pavement scenarios based on the GSA results in Sections 5.3 and 5.4 and Table 6.2 include the following:

- Slab width was consistently the highest sensitivity design input, followed by the PCC layer properties (PCC unit weight, PCC coefficient of thermal expansion, PCC strength and stiffness properties, PCC thickness, surface shortwave absorptivity) and other geometric properties (design lane width, joint spacing). The high sensitivity of PCC strength and stiffness inputs suggests that care is required to avoid implausible estimates of PCC stiffness and strength gains with time that can cause large errors in predicted rigid pavement distresses.
- The magnitudes of the sensitivity values for faulting, transverse cracking, and IRI were similar. However, the range of sensitivity values for faulting was significantly larger than for transverse cracking and IRI.
- The sensitivity to design lane width was evaluated under three different edge support conditions (no edge support, tied shoulder edge support with 80% LTE, and widened slab edge support condition). Design lane width under widened slab edge support showed high sensitivity for transverse cracking but was not sensitive for either no edge support or tied shoulder edge support conditions.

Guidance for the pavement designer on how to address high sensitivity or critical design inputs varies depending upon the specific design input. Some high sensitivity inputs can be specified very precisely, e.g., PCC thickness or design lane width. Other inputs need to be measured or estimated. The high sensitivity of performance to the PCC strength and stiffness properties indicates a need for careful characterization of these values. Mix-specific laboratory measurement of Level 1 PCC modulus of rupture and modulus of elasticity may be appropriate for high-value projects. Other properties like the PCC coefficient of thermal expansion are very difficult to measure, and testing protocols are still evolving. The high sensitivity to surface shortwave absorptivity is more problematic as this cannot be readily measured and guidance on realistic values for specific PCC surface conditions is lacking. For this as well as all other high sensitivity design inputs, the pavement designer should perform project-specific design sensitivity studies to evaluate the consequences of uncertain input values.

Table 6.2. Hypersensitive, Very Sensitive, and Sensitive design inputs by distress and input category for New JPCP pavements. $NSI_{\mu \pm 2\sigma}$ values are given in parentheses. Inputs in bold font are Hypersensitive or Very Sensitive for most (2 out of 3) distresses.

<i>Distress</i>	<i>Input Category</i>	<i>Hypersensitive (>5)</i>	<i>Very Sensitive (1-5)</i>	<i>Sensitive (0.1-1)</i>
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)

<i>Distress</i>	<i>Input Category</i>	<i>Hypersensitive (>5)</i>	<i>Very Sensitive (1-5)</i>	<i>Sensitive (0.1-1)</i>
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)

6.5. Conclusions: CRCP Rigid Pavements

The specifics of the sensitivities of the design inputs on the predicted performance of CRCP pavements vary by distress type (e.g., faulting vs. crack width vs. crack LTE vs. IRI). Nonetheless, the GSA results do suggest some broad conclusions.

As a more practical aid to the pavement designer, Table 6.3 summarizes in rank order the Hypersensitive, Very Sensitive, and Sensitive design inputs by material category (PCC/steel, base, subgrade, other) for each distress for the New CRCP pavement type. The design inputs that fall in the Hypersensitive or Very Sensitive categories for most (3 out of 4) distresses are indicated by bold font in the table. For practical design purposes, the high sensitivity or critical design inputs can be limited to those in the Hypersensitive and Very Sensitive categories. At $NSI_{\mu \pm 2\sigma} = 1$ corresponding to the lower limit of the Very Sensitive/upper limit of the Sensitive range, the percentage change in distress relative to its design limit equals the percentage change in the design input. This is usually acceptably small in practical terms, especially since it is defined at the $\mu \pm 2\sigma$ level.

Conclusions applicable to most JPCP pavement scenarios based on the GSA results in Section 5.5 and Table 6.3 include the following:

- Most of the consistently highest sensitivity design inputs were reinforced PCC/steel layer properties (PCC thickness, PCC strength and stiffness properties, reinforcing steel properties, PCC unit weight, PCC coefficient of thermal expansion, surface shortwave absorptivity) followed by the base and subgrade properties. Traffic volume was also an important design input.
- The largest sensitivity values for New CRCP scenarios were substantially larger than those for any of the other pavement types.
- 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 PCC Ratio 20-year to 28-day Modulus of Rupture was the third-ranked design input for punchouts and thus for IRI. This is troubling because the 20-year modulus of rupture cannot be directly measured and thus this design input can only be estimated.

Guidance for the pavement designer on how to address high sensitivity or critical design inputs varies depending upon the specific design input. Some high sensitivity inputs can be specified very precisely, e.g., PCC thickness and the steel properties. Other inputs need to be measured or estimated. The high sensitivity of performance to the PCC strength and stiffness properties indicates a need for careful characterization of these values. Mix-specific laboratory measurement of Level 1 PCC modulus of rupture, indirect tensile strength, and modulus of elasticity may be appropriate for high-value projects. Other properties like the PCC coefficient of thermal expansion are very difficult to measure, and testing protocols are still evolving. The high sensitivity to surface shortwave absorptivity is more problematic as this cannot be readily measured and guidance on realistic values for specific PCC surface conditions is lacking. For this as well as all other high sensitivity design inputs, the pavement designer should perform project-specific design sensitivity studies to evaluate the consequences of uncertain input values.

Table 6.3. Hypersensitive, Very Sensitive, and Sensitive design inputs by distress and input category for New CRCP pavements. $NSI_{\mu+2\sigma}$ values are given in parentheses. Inputs in bold font are Hypersensitive or Very Sensitive for most (3 out of 4) distresses.

<i>Distress</i>	<i>Input Category</i>	<i>Hypersensitive (>5)</i>	<i>Very Sensitive (1-5)</i>	<i>Sensitive (0.1-1)</i>
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)	
Crack LTE	PCC/Steel Properties		28-Day Modulus of Rupture (+2.4) Thickness (+1.6) 28-Day Indirect Tensile Strength (-1.3) Percent Steel (+1.0)	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)

<i>Distress</i>	<i>Input Category</i>	<i>Hypersensitive (>5)</i>	<i>Very Sensitive (1-5)</i>	<i>Sensitive (0.1-1)</i>
Crack LTE	Base Properties			Base Slab Friction (+0.4) Resilient Modulus (+0.1) Thickness (-0.1)
	Subgrade Properties			
	Other Properties		Bar Diameter (-1.5)	Steel Depth (-0.6) Traffic Volume (-0.4) Edge Support LTE (+0.3)
IRI	PCC/Steel Properties	Thickness (-9.0) 28-Day Modulus of Rupture (-7.4)	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)	Surface Shortwave Absorptivity (+0.7) Poisson's Ratio (+0.3) 20-year to 28-day Indirect Tensile Strength (-0.3)
	Base Properties		Resilient Modulus (-1.2)	Base Slab Friction (-0.8) Thickness (-0.4)
	Subgrade Properties		Resilient Modulus (-1.2)	
	Other Properties		Bar Diameter (+1.9) Traffic Volume (+1.6) Steel Depth (+1.5)	Edge Support LTE (-0.6) Construction Month (+0.3)

6.6. Recommended Research

While this study produced practically useful findings and conclusions regarding the sensitivity of MEPDG predicted performance on the design inputs, there were other findings that suggested issues needing further investigation in the future. These include the following:

- The design inputs related to the base layer and subgrade showed significant sensitivities in only a small number of cases. It is not clear how well this matches engineering expectations/experience or the behavior of other pavement models (e.g., the 1993 AASHTO empirical equation). There are many routine pavement design scenarios for which the 1993 AASHTO method provides a reasonable relationships between design inputs and pavement performance; the MEPDG relationships should be expected to mirror these. This issue should be investigated.
- The extremely high sensitivity of predicted distress to some inputs is questionable and may warrant future investigations of the various submodels in the MEPDG. Design inputs in this category include:
 - The δ and α parameters defining the lower and upper shelves of HMA dynamic modulus master curve.
 - Poisson's ratio for HMA and, to a lesser extent, for the base and subgrade in flexible pavements.
 - HMA unit weight, especially with respect to longitudinal cracking in flexible pavements on stiff foundations
 - The curling and warping related inputs (PCC coefficient of thermal expansion and unit weight) for rigid pavements.
- The very low sensitivity of predicted performance to many design inputs suggests that reasonable default values can be used in the MEPDG without significant loss of accuracy.
- The sensitivity of thermal cracking to the lower shelf of the dynamic modulus master curve (δ) is larger in absolute value terms than its sensitivity to the offset of the upper shelf (α). This appears contrary to expectations and merits further investigation.

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ABBREVIATIONS AND ACRONYMS

AADTT	Annual average daily truck traffic
AASHTO	American Association of State Highway and Transportation Officials
ANN	Artificial neural network
CRCP	Continuously reinforced concrete pavement
CTB	Cement Treated Base
CTE	Coefficient of thermal expansion
DL	Design limit
E	Elastic modulus
E*	Dynamic modulus
GSA	Global sensitivity analysis
GWD	Groundwater depth
HMA	Hot mix asphalt
HS	Hypersensitive
IRI	International roughness index
JPCP	Jointed plain concrete pavement
LTE	Load transfer efficiency
MEPDG	Mechanistic-Empirical Pavement Design Guide
MOR	Modulus of rupture
Mr	Resilient modulus
MVLR	Multivariate linear regression
NCHRP	National Cooperative Highway Research Program
NN	(Artificial) neural network
NS	Nonsensitive
NSI	Normalized sensitivity index
OAT	One-at-a-time
PCC	Portland cement concrete
PG	Performance grade
RSM	Response surface model
S	Sensitive
SSA	Surface shortwave absorptivity
ST	Indirect tensile strength
VS	Very sensitive
W/C	Water-to-cement ratio

APPENDIX A: INITIAL TRIAGE OF DESIGN INPUTS

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1 INTRODUCTION

The first activity in this study was the identification of a short list of MEPDG design inputs to be investigated further in the subsequent one-at-a-time (OAT) local sensitivity analyses and the main global sensitivity analyses (GSA). An initial triage of design inputs into “Very Sensitive”, “Sensitive”, and “Non Sensitive” categories was based upon information in the literature, some limited one-at-a-time sensitivity analyses, and engineering judgment. The literature review also examined background information on some of the methodological issues in performing global sensitivity analyses of complex models. The findings from the literature review and the results of the design inputs triage are documented in Sections 2 and 3, respectively, of this appendix. In addition, some preliminary investigations into some of the methodological issues for the study are documented in Section 4.

2 LITERATURE REVIEW

Since the release of the original research version of the MEPDG (Version 0.7) in July 2004, the software was updated under NCHRP Project 1-40D several times. Version 1.0 of the MEPDG was adopted as an interim AASHTO pavement design procedure after balloting by the states in 2007. A detailed discussion of differences among the different MEPDG software versions can be found in the NCHRP Project 1-40D (2006) project report. The research version of the MEPDG software continues to be updated. The latest update, Version 1.10 released in September 2009, corrected some program bugs and improved the rehabilitation design analyses (NCHRP 2009). Table 1 summarizes the release dates for each version of the MEPDG software. The DARWin-ME v2.0 software released by AASHTO in April 2011 is based on the mechanistic-empirical models incorporated in Version 1.1 of the MEPDG.

The information relevant to the MEPDG pavement input parameter sensitivity to performance were collected and reviewed. An annotated bibliography drawn from this information is included at the end of this appendix. A brief discussion of this information is presented below.

Table 1. Summary of release dates for each MEPDG software version.

MEPDG Software Version	Release Date
0.700	July 2004
0.800	November 2005
0.900	July 2006
1.000	April 8, 2007
1.100	August 31, 2009

2.1 Rigid Pavements

MEPDG sensitivity studies began appearing in the literature immediately after the initial release of the MEPDG in 2004. Early sensitivity studies for rigid pavements include work by Rao *et al.* (2004), Selezneva *et al.* (2004), Khazanovich *et al.* (2004), Hall and Beam (2005), Guclu (2005), Kannekanti and Harvey (2006), and Khanum *et al.* (2006).

Rao *et al.* (2004) and Selezneva *et al.* (2004) conducted extensive sensitivity analyses to test the reasonableness of the CRCP punch-out model. Based on the study results, they concluded that CRCP punch-out models showed reasonable sensitivities to key inputs such as PCC thickness, percentage of longitudinal reinforcement, and PCC coefficient of thermal expansion.

Khazanovich *et al.* (2004) performed an extensive sensitivity analysis to test the reasonableness of the transverse joint faulting prediction model. They found that the joint faulting model showed reasonable sensitivities to key inputs such as dowel diameter, base erodibility, shoulder type, and slab widening. Hall and Beam (2005) found that the JPCP cracking, faulting, and roughness performance were all sensitive to 6 out of 29 rigid pavement design inputs; one or two of the distress models were sensitive to an additional 6 of the 29 inputs, and all distress models were insensitive to the remaining 17 of the 29 inputs. Since Hall and Beam's study (as most other) performed one-at-a-time (OAT) analyses, no insights were gained regarding the interaction among the inputs.

Guclu (2005) examined the effect of MEPDG input parameters on JPCP and CRCP performance for Iowa conditions. The results indicated that the curl/warp effective temperature difference, the PCC coefficient of thermal expansion, and PCC thermal conductivity had the greatest impact on the JPCP and CRCP distresses. Kannekanti and Harvey (2006) performed about 10,000 MEPDG simulations of JPCP for California conditions. They found that the cracking model was sensitive to the coefficient of thermal expansion, surface absorption, joint spacing, shoulder type, PCC thickness, climate zone, and traffic volume. They also found that faulting was sensitive to dowels, shoulder type, climate zone, PCC thickness, and traffic volume. Kannekanti and Harvey concluded that both the cracking and faulting models showed reasonable trends that were consistent with prevailing pavement engineering knowledge and California experience but that there were some cases where results were counter-intuitive. These included thinner sections performing better than thicker sections and asphalt shoulders performing better than tied and widened lanes.

A study by Khanum *et al.* (2006) focused on the effect of traffic inputs on MEPDG JPCP predicted performance for Kansas condition. This study found that the MEPDG default traffic input data produced more severe JPCP slab cracking than did the Kansas inputs. They also found that the distribution of truck classes did not significantly affect the predicted JPCP distresses.

All of the studies described above were conducted using versions of the MEPDG software prior to the Version 1.0 release in 2007. As will be described later in the discussion subsection, some sensitivities of MEPDG performance to design inputs changed significantly from one version of the next as software error corrections, model recalibrations, and other changes were implemented. Consequently, the current project has focused its literature review on prior sensitivity analysis studies conducted using Version 1.0/1.1 of the MEPDG software. Rigid pavement sensitivity studies meeting this criterion include work by Tanesi *et al.* (2007), Ceylan *et al.* (2009), Buch *et al.* (2008), Haider *et al.* (2008), Haider *et al.* (2009), Hiller and Roesler (2009), Kapmann (2008), McCracken *et al.* (2009), Oh and Fernando (2008), Puertas (2008), Tran *et al.* (2008), Moon (2009), Oman (2010), Johanneck and Khazanovich (2010), and Hall *et al.* (2010).

Ceylan *et al.* (2009) identified curl/warp effective temperature difference and the PCC coefficient of thermal expansion (CTE) as being the most sensitive inputs influencing predicted rigid pavement performance using all three versions (0.7, 0.9, and 1.0) of MEPDG software.

Buch *et al.* (2009) and Haider *et al.* (2008) conducted comprehensive sensitivity analyses for rigid pavements. The approach in these studies included: (1) OAT analyses to investigate the effect of individual input variables on performance (preliminary sensitivity analyses), and (2) full factorial analyses to evaluate the interaction effects of input variables on performance (detailed sensitivity analyses). The preliminary sensitivity results identified 23 sensitive input variables for the three-level full factorial design matrix (total MEPDG runs: $3^{23} = 9.4 \times 10^{10}$); this list was subsequently reduced using various criteria to decrease the number of MEPDG runs. The analysis results revealed that the effect of PCC slab thickness and edge support on performance were most significant among the design inputs and that CTE, modulus of rupture (MOR), base type and subgrade type material inputs also played an important role. In terms of input variable interaction effects, slab thickness-CTE-MOR, CTE-MOR-subgrade soil type-climate, and slab thickness-CTE-subgrade soil type-climate interactions were found to be significant for JPCP cracking, faulting, and roughness (IRI), respectively.

Haider *et al.* (2009) proposed simplified JPCP performance models for use during the initial design stage to quantify the impact of design-related input variables on expected performance. Hall (2009) noted that the spalling equation in the MEPDG report and software does not differentiate among the three scenarios of no sealant, liquid sealant, and silicone sealant for the prediction of joint spalling. The latest version 1.1 of MEPDG reduce options to only two types of sealant methods—preformed and other—as compared to the four options previously available—none, liquid, silicone, preformed. She also noted that the concrete pavement air content should intuitively be an important input in the prediction of JPCP IRI but that the MEPDG software fixes the concrete air content at 6 percent without allowing any user override.

Hiller and Roesler (2009) demonstrated the sensitivity of input parameters such as joint spacing, shoulder type, traffic level, climatic location, and built-in curl level on JPCP fatigue failure mechanisms predicted by MEPDG as well as by several other design methods. It was found that the level of built-in curl significantly affected the required slab thickness in the MEPDG and that the required thickness increased as the built-in curl level became more negative.

In a study evaluating the effect of the MEPDG hierarchical levels on JPCP predicted performance, McCracken *et al.* (2009) concluded that the PCC CTE and MOR were the most sensitive inputs on predicted JPCP performance. The hierarchical level of individual design inputs was also found to be significant in some cases. For example, it was noted that the use of different levels (1, 2, and 3) for CTE input changed the design thickness by up to 51 mm (2 in). On the other hand, they did not find that the slab thickness was significantly influenced by the input levels used in defining the PCC strength and subgrade resilient modulus or the use of different climatic weather stations. (Note: Early findings by the Principal Investigator on another project suggest that the PCC strength input level may have a substantial impact on predicted slab cracking.)

As part of their research on developing thickness design tables based on the MEPDG under Florida conditions, Oh and Fernando (2008) conducted rigid pavement sensitivity studies that identified PCC CTE and compressive strength as the most significant variables impacting projected performance measures. Other sensitive variables identified were joint spacing, dowel diameter, and slab width. However, the moduli of the unbound materials and MOR were found to have minimal effect on the projected JPCP performance measures.

The CTE of concrete has been identified as one of most sensitivity inputs for rigid pavement performance measures in all versions of MEPDG software. Mallela *et al.* (2005) found that the CTE varies widely depending on the predominant aggregate type used in the concrete. MEDPG sensitivity analysis showed that CTE had a significant effect on slab cracking and, to a lesser degree, on joint faulting. Its overall effect on smoothness was also significant.

Tanesi *et al.* (2006, 2007) investigated the effect of MEPDG hierarchical input levels for CTE on predicted JPCP performance. The effect of PCC CTE input on predicted IRI was more pronounced for JPCP with thinner slabs or lower PCC strengths. A combination of high cement factor and higher PCC CTE produced higher JPCP faulting. In general, faulting was very sensitive to this input. PCC CTE also had a very significant effect on slab cracking. However, it did not affect the predicted IRI for a JPCP with widened lane and tied PCC shoulder. Level 2 CTE input may result in more conservative JPCP design than that using Level 1 input. The detrimental effects of high CTE value could be mitigated using higher PCC slab thickness, larger diameter dowel bars or widened lane with tied PCC shoulder. They also recommended (1) not using a single test result as representative of the CTE of a mixture and (2) implementing a specification for the minimum number of tests and the acceptable test variability.

A study by Kampmann (2008) focused exclusively on the effect of CTE on MEPDG predicted JPCP performance measures based on experimental analysis of three typical Florida concrete mixtures. This study found that CTE was least sensitive for JPCP faulting, reasonably sensitive for bottom-up damage for thin PCC layers, and extremely sensitive for top-down damage, cracking, and smoothness. Laboratory test results also revealed that CTE rapidly increases within the first week but stabilizes after 28 days. Tran *et al.* (2008) also focused on characterizing CTE. They found that aggregate type has significant influence on both the laboratory-measured CTE as well as on MEPDG pavement performance predictions. The MEDPG recommended default CTE values were found appropriate for PCC mixtures with limestone and sandstone aggregates but not with gravel.

Puertas (2008) performed several sensitivity analyses in the context of evaluating the MEPDG JPCP cracking model. The study found that anomalies exist in the MEPDG prediction of JPCP top-down fatigue cracking and that the cracking results contradict current engineering understanding of this failure mechanism. This was thought to be due to inadequate treatment of certain newly introduced inputs such as the permanent built-in temperature gradient (or permanent curl-warp effective temperature difference). Recommendations from this study include use of Response Surface Methodology (RSM) to support at more exhaustive sensitivity analyses covering a wider range of input values.

Johanneck and Khazanovich (2010) conducted a comprehensive evaluation of the effect of climate in MEPDG predictions for an asphalt-over-concrete (AC/PCC) composite pavement. As expected, it was found that environment has a significant impact on predicted pavement performance. They also found that some of the weather stations included in the MEPDG database may be of insufficient quality to obtain reliable pavement performance predictions.

Moon (2009) evaluated the Texas DOT rigid pavement database with the MEPDG and found that the zero-stress temperature and built-in curling have substantial effects on CRCP punch-out development and thus on the design slab thickness.

Hall *et al.* (2010) examined HMA overlay designs (HMA over HMA and HMA over PCC) using the MEPDG to assess the relative sensitivity to variations in surface layer thickness. The analyses indicated that overlaid HMA bottom-up fatigue and rutting will not likely be sensitive to variations in existing (underlying) surface layer thickness (existing HMA or PCC). On the other hand, the current

models for top-down cracking and reflection cracking in MEPDG appear to be more sensitive to existing surface layer thickness.

Oman (2010) conducted a MEPDG traffic characterization study using the weigh-in-motion data acquired at the MnRoad research facility. The study results revealed that the MEPDG predicted distresses are sensitive to the axle load spectra and the percentage of vehicles in the design lane. Further, the Monthly Adjustment Factors (MAF) were found to have moderate impact on the predicted distresses, whereas the axle groups per vehicle showed least sensitivity in terms of predicted performance. The hourly distribution factors seem to influence cracking in rigid pavements.

2.2 Flexible Pavements

As for rigid pavements, MEPDG sensitivity studies for flexible pavement systems began appearing in the literature immediately after the initial release of the MEPDG in 2004. Early sensitivity studies for flexible pavements include work by Lee (2004), Masad (2004), Masad and Little (2004), El-Basyouny and Witczak (2005a, 2005b, 2005c), Schwartz (2005), Brown *et al.* (2006), Carvalho and Schwartz (2006), Chehab and Daniel (2006), Graves and Mahboub (2006a, 2006b), Khazanovich (2006), Kim *et al.* (2006) Mohammad *et al.* (2006), Yin *et al.* (2006), Zaghoul *et al.* (2006), Hoerner *et al.* (2007), and Kim *et al.* (2007).

El-Basyouny and Witczak (2005a, 2005b, 2005c) conducted flexible pavement input parameter sensitivity analyses as part of the original development of the MEPDG design methodology. Their studies study focused on the sensitivity of fatigue cracking and permanent deformation performance measures to various input parameters. They found that subgrade stiffness and traffic were consistently influential in the prediction of performance, while the other design inputs had varying degrees of significance.

Lee (2004) evaluated the influence of Poisson's ratio, surface shortwave absorption, heat capacity, thermal conductivity, air voids, binder grade, total unit weight, and effective binder content on the performance of flexible pavements. Two different mixture sizes (12.5 and 25.0 mm) and 4 different gradations were studied. Their results found that only air voids and effective binder content for the 12.5 mm mixes had a significant impact on top-down fatigue cracking performance. Air voids and effective binder content for both mix sizes were found to be significant for top-down fatigue cracking. None of the input variables considered in their study was found to have a significant effect on rutting. Only air voids and effective binder content for the 12.5 mm mixes were found to be significant for IRI. It should be noted that these studies were for a single traffic level, subgrade strength, and climatic location.

A study by Masad and Little (2004) focused on the effect of unbound granular base layer properties on MEPDG predicted performance. They found that base modulus and thickness had a significant influence on the IRI and longitudinal cracking. The influence of these properties on alligator cracking was approximately half that for longitudinal cracking. They also found that the granular base material properties had little influence on total and HMA rutting.

The accuracy and robustness of the Witczak HMA $|E^*|$ model incorporated in the MEPDG was evaluated through a set of sensitivity and validation studies by Schwartz (2005). Although the results suggested that the model may overestimate $|E^*|$, particularly at higher temperatures, the overall findings confirmed that the Witczak model can provide sufficiently accurate and robust estimates of $|E^*|$ for use in mechanistic-empirical pavement performance prediction and design. Because of the strong dominance of temperature influences over other mixture parameters, however, the model may

not be able to make fine distinctions between predicted performances for different mixtures under the same environmental and other conditions.

As part of MEPDG implementation activities in Iowa, Kim *et al.* (2006, 2007) assessed the comparative effects of design input parameters pertaining to material properties, traffic, and climate on performance for two existing flexible pavements in Iowa with relatively thick HMA layers. A total of 20 individual inputs were evaluated on each pavement structure resulting. The study found that the predicted longitudinal cracking and total rutting were influenced to varying degrees by most of input parameters.

Carvalho and Schwartz (2006) compared flexible pavement designs and performance predictions derived from the empirical 1993 AASHTO pavement design methodology and the MEPDG approach for a range of locations within the United States, each with its own climate, subgrade, and other material properties and local design preferences. Particular emphasis was devoted to the influence of traffic and reliability levels. The results suggested that relative to the MEPDG predicted performance, the 1993 AASHTO guide overestimates performance (i.e., underestimates distress) for pavements in warm locations and at high traffic levels. Trends of pavement performance with reliability level were similar for both methodologies. The results suggest that the default design criteria incorporated in the MEPDG software are broadly consistent with what would be observed historically from pavements designed with the 1993 AASHTO guide.

Chehab and Daniel (2006) assessed the sensitivity of binder grade on predicted performance of a recycled asphalt pavement (RAP) surface layer. They found that the binder PG grade, and in particular the high temperature grade, for the RAP mixtures had a significant influence on predicted thermal cracking and rutting for the given structure. An added benefit from this sensitivity study was the identification of issues that should be considered when incorporating RAP mixtures in pavements designed using the MEPDG software.

Graves and Mahboub (2006a, 2006b) conducted a limited global sensitivity analysis using random sampling techniques. Flexible pavement design inputs varied in their study included AADTT, truck classification class (TTC), nominal HMA thickness, subgrade CBR, nominal HMA aggregate size, HMA gradation (coarse/fine), climate zone, and construction month. All other inputs were set at the MEPDG Level 3 default values. Random Monte Carlo sampling assuming uniformly distributed input ranges resulted in a total of 100 sections for simulation. Sensitivity of predicted distresses to the model inputs were quantified using Pearson and Spearman correlation coefficients. AADTT and HMA thickness were found to be sensitive inputs for all distresses; binder grade bump, subgrade CBR, and construction season were found to be somewhat significant for some distresses; and all other inputs were found to have only small influences on predicted performance.

Zaghloul, *et al.* (2006) performed a sensitivity analysis of traffic input level (Level 1 to Level 3). They reported significant differences between Level 1 vs. Level 3 traffic inputs in some cases. They speculated that this behavior might be a consequence of some analysis scenarios being out of range for the performance models.

All of the studies described above were conducted using versions of the MEPDG software prior to the Version 1.0 release in 2007. As will be described later in the discussion subsection, some sensitivities of MEPDG performance to design inputs changed significantly from one version of the next as software error corrections, model recalibrations, and other changes were implemented. Consequently, the current project has focused its literature review on prior sensitivity analysis studies conducted using Version 1.0/1.1 of the MEPDG software. Flexible pavement sensitivity studies meeting this criterion include work by Buch *et al.* (2008), Kazanovich *et al.* (2008), Aguiar-Moya *et al.* (2009),

Ahn *et al.* (2009), Schwartz (2009), Thyagarajan *et al.* (2010), Velasquez *et al.* (2009), Ayyala *et al.* (2010), Hall *et al.* (2010), Schwartz and Li (2010), and Yin *et al.* (2010).

Ahn *et al.* (2009) focused on the effects of input traffic parameters on the MEPDG pavement performance. Traffic inputs studied were annual average daily truck traffic (AADTT), monthly adjustment factors (MAF), and axle load distribution factors. AADTT was found to have a significant effect on predicted performance, especially fatigue cracking; MAF was not found to have a significant influence. The accuracy of pavement prediction increased when using WIM-collected axle load distributions from Arizona as compared to the MEPDG default values.

Aguiar-Moya *et al.* (2009) used Ground Penetrating Radar to determine the thickness distributions of the HMA surface layer, binder course, and granular base layer for LTPP SPS-1 sections in Texas. The vast majority of the analyzed pavement layers were found to have normally distributed thicknesses. The variations in thickness along the lane centerline and under the right wheel-path were also determined. MEPDG sensitivity analyses were performed based on the measured coefficients of variation for the thicknesses of the HMA surface and granular base layers. The results showed considerable changes in distress, especially fatigue cracking, for layer thicknesses variations within ± 3 standard deviations from the mean.

Hall *et al.* (2010) investigated the required accuracy of layer thickness estimates using nondestructive testing (NDT) techniques. HMA overlay designs (HMA over HMA and HMA over PCC) using the mechanistic-empirical procedures in the new MEPDG, were examined to assess the relative sensitivity to variations in surface layer thickness. The study found that bottom-up fatigue and rutting in HMA overlays were not sensitive to variations in the thickness of the underlying existing surface layer (existing HMA or PCC). The current models for top-down cracking and reflection cracking appear to be more sensitive to the thickness of the existing surface layer.

Ayyala *et al.* (2010) evaluated the sensitivity of thirteen MEPDG inputs for base cases consisting of one LTPP section each from NH and CT. MEPDG Version 1.0 was used for all distresses except thermal cracking; Version 0.91 was used for thermal cracking evaluation as no distress was predicted by Version 1.0. Sensitivity was quantified in terms of correlation ratios between inputs and outputs. Design inputs were assigned to quantitative sensitivity categories tabulated by distress.

Schwartz and Li (2010) quantified the sensitivity of predicted pavement distresses to subgrade type, groundwater table depth, saturated hydraulic conductivity, and soil water characteristic curve parameters analyses for three flexible pavement sections in four climate locations. In overall terms, traffic volume and subgrade resilient modulus were the two inputs of those studied that had the largest impact on predicted distresses. The environmental inputs related to groundwater depth, soil water characteristic curve parameters, and saturated hydraulic conductivity all had slight to negligible influence on the predicted distresses. Variations of performance with climate location and subgrade type were sensible. (Note: Additional unpublished analyses found that predicted distresses were moderately to highly sensitive to surface shortwave absorptivity and generally negligibly sensitive to HMA thermal conductivity and heat capacity.)

Sensitivity studies conducted by Thyagarajan *et al.* (2010) focused on influence of the air voids, effective binder content, and gradation inputs to the Witczak $|E^*|$ predictive model on predicted performance. Only one pavement scenario (structural section, binder grade, traffic level) was considered. Sensitivity was characterized via tornado plots of Spearman correlation coefficients and by extreme tail analysis. Air voids were found to be the most sensitive parameter affecting all predicted distress modes. Percent passing the No. 200 sieve and retained above the No. 4 sieve also

had a significant influence on rutting, while effective binder content had a significant influence on fatigue cracking. Khazanovich *et al.* (2008) also performed a very similar study.

Yin *et al.* (2010) compared thermal crack predictions from Level 1 vs. Level 2 vs. Level 3 creep compliance inputs as well as directly measured creep compliance vs. converted-from- E^* values for Level 1/2 inputs. This paper did not evaluate sensitivity *per se*, but significant differences in predicted thermal cracking for the various input options suggest that thermal cracking is sensitive to creep compliance.

2.3 Summary of Problems with Previous MEPDG Sensitivity Studies

As should be clear from the preceding section, previous MEPDG sensitivity studies have been quite disparate in scope, approach, and findings. Several significant issues with relevance to the present study must be highlighted:

1. Most sensitivity studies of the MEPDG to date have been quite primitive and have focused largely on confirming that the trends in predicted pavement performance are consistent with engineering expectations. Nearly all of these past studies have employed limited one-at-a-time (OAT) methodology. OAT analyses are easy to perform but have serious shortcomings. In the OAT approach, one or more baseline cases are defined and each input (e.g., granular base layer stiffness) is then varied individually for each case to evaluate its effect on the output (e.g., quantity of fatigue cracking). Only the sensitivities around the reference input values for the baseline cases are evaluated—i.e., the evaluation is only for very small regions of the overall solution space. This provides only a “local” as opposed to a “global” sensitivity evaluation, which is not sufficient for complex nonlinear problems like pavement performance simulation.
2. Past MEPDG sensitivity studies have typically varied only a small subset of inputs that have been judged *a priori* as being the most “important.” This is understandable, given the very large number of inputs in the MEPDG. However, the selection of “important” inputs has been subjective and *ad hoc* in these past studies. More careful and systematic screening must be required for objective identification of the subsets of inputs to be varied in the study.
3. Past MEPDG sensitivity studies have also largely ignored any correlations and/or interactions among input parameters. Correlations among inputs are present when a change in one input tends to cause change in another input (e.g., PCC modulus of rupture and modulus of elasticity as related to unconfined compressive strength). Interactions among inputs are manifested when simultaneous changes in two independent inputs cause changes in outputs that are greater than the sum of the individual effects (e.g., interactions between climate and subgrade support degradation due to excessive moisture). The OAT methodologies employed in most prior MEPDG sensitivity studies are incapable of including input correlations or detecting input interactions.
4. Not all of the prior studies used the latest version of the MEPDG software. There were significant bug fixes and recalibrations from versions 0.7 to 0.8 to 0.9 to 1.0 and 1.1. One must assume that the input sensitivities will also change from one version to the next, but by an unknown amount. Figure 1 and Figure 2 provide examples of sensitivity trends that changed from one MEPDG version to the next. The recent MEPDG software update from Version 1.0 to Version 1.1 is not expected to have a similar impact on sensitivity, in large part because the major changes were for composite pavement design where there are few prior sensitivity studies. Limited evaluations of Version 1.1 vs. 1.0 conducted by the project team during the project found no differences in predictions for new flexible and rigid pavements.

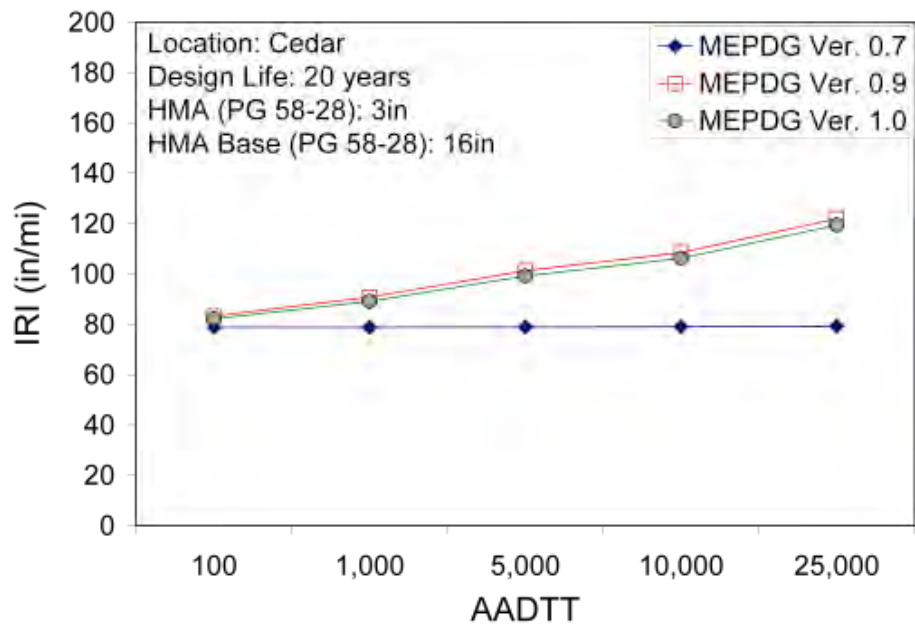


Figure 1. Comparisons of different versions of MEPDG predictions for IRI vs. AADTT for a flexible pavement in Iowa.

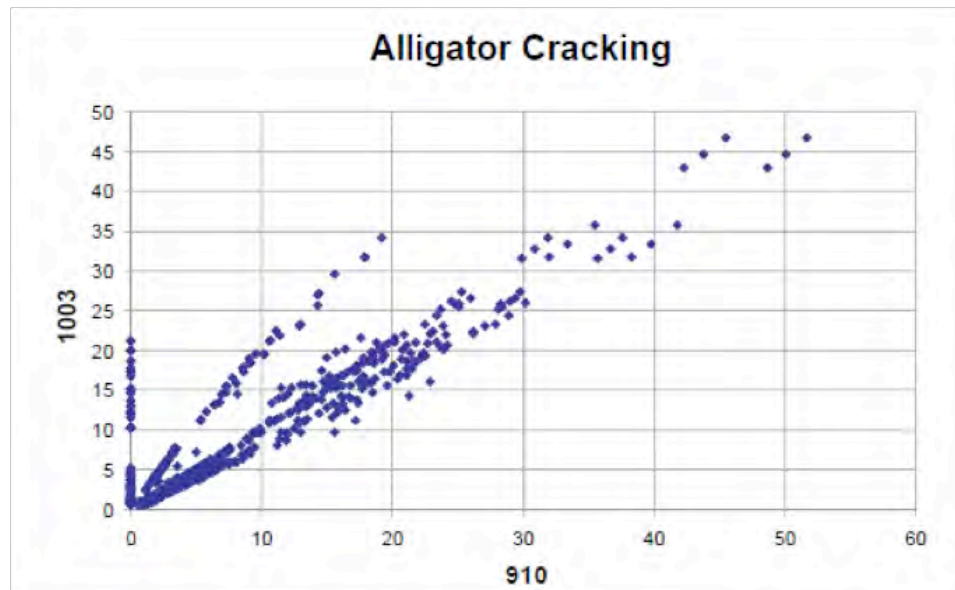


Figure 2. Comparisons of versions 9.1 and 1.003 of MEPDG HMA alligator cracking predictions (Velasquez et al 2009).

A few key studies offering some insights into these problems are listed in Table 2. A brief summary of these studies and their findings were presented previously in Sections 2.1 and 2.2.

Table 2. Studies addressing key issues 1-4.

Type of pavement analysis	Feature	Reference
JPCP	Global sensitivity and correlation	Puertas, J. J. G. (2008). <i>Evaluating the JPCP Cracking Model of the Mechanistic-Empirical Pavement Design Guide</i> , M.S. Thesis, University of Pittsburgh, PA. (http://etd.library.pitt.edu/ETD/available/etd-03142008-140330/unrestricted/GUTIERREZ_JUAN_ETD_04-03-08.pdf)
JPCP	Interaction	Buch, N., Chatti, K., Haider, S. W., and Manik, A. (2008) <i>Evaluation of the 1-37A Design Process for New and Rehabilitated JPCP and HMA Pavements</i> , Research Report RC-1516, Michigan State University, East Lansing, MI; June. (http://www.michigan.gov/mdot/0,1607,7-151-9622_11045_24249-204916-,00.html)
HMA	Global sensitivity	Thyagarajan, S. (2009). <i>Improvements to Strain Computation and Reliability Analysis of Flexible Pavements in the Mechanistic-Empirical Pavement Design Guide</i> , Ph.D. dissertation, Washington State University, May.
HMA	Global sensitivity	Graves, R. C., and Mahboub, K. C. (2006b). "Pilot Study in Sampling-Based Sensitivity Analysis of NCHRP Design Guide for Flexible Pavements," <i>Transportation Research Record 1947</i> , Transportation Research Board, National Research Council, Washington, DC, p. 123-135. (http://trb.metapress.com/content/h284502553h703x1)
Composite	Rehabilitation inputs	Hoerner, T. E., Zimmerman, K. A., Smith, K. D., and Cooley, L. A. (2007). <i>Mechanistic-Empirical Pavement Design Guide Implementation Plan</i> . Report No. SD2005-01, South Dakota Department of Transportation, Pierre, SD. (http://www.state.sd.us/Applications/HR19ResearchProjects/Projects/sd2005-01_Final_Report.pdf)

3 TRIAGE OF DESIGN INPUTS

3.1 Methodology

An initial triage of design inputs was performed to identify: (a) high sensitivity input factors that need to be included in the global sensitivity analyses; (b) non-sensitive factors that can be excluded; and (c) any potential correlations of inputs. This was pursued via a combination of approaches: findings from prior acceptable sensitivity studies; subjective assessments drawing on the project team's experience in pavement engineering and the MEPDG; and quantitative evaluations via limited OAT sensitivity analyses of previously unexplored but potentially significant input parameters. Input factors were triaged qualitatively into three categories based on their expected effects on pavement performance:

1. Very sensitive (VS): those that have very significant effect (highly sensitive) on one or more outputs; roughly corresponds to a mean-normalized sensitivity index > 0.5 . (Mean-normalized sensitivity indices and other sensitivity metrics are described later in Section 4.1)
2. Sensitive (S): those that have a moderate effect on one or more outputs; roughly corresponds to a mean-normalized sensitivity index in the range of $0.1 - 0.5$.
3. Not sensitive (NS): those that have only minor effect (insensitive) on one or more outputs; roughly corresponds to a mean-normalized sensitivity index < 0.1 .

The project team had to grapple with several significant issues while developing tables for detailed triage of input sensitivities. These include:

1. Most previous studies from the literature have employed subjective qualitative assessments or a mixture of objective quantitative sensitivity measures such as normalized and non-normalized partial derivatives, Pearson and Spearman correlation coefficients, qualitative assessments, and others. These subjective qualitative assessments and/or heterogeneous quantitative measures cannot be compared directly.
2. Even the few previous studies that used the same quantitative sensitivity measures—e.g., Pearson correlation coefficients—used different quantitative ranges to categorize high, moderate, and low sensitivity.
3. Some sensitivity results changed significantly between versions 0.7, 0.8, 0.9, and 1.0 of the MEPDG software. (Fortunately, the project team performed a limited comparison study and did not find this problem between versions 1.0 and 1.1.) The project team therefore decided to exclude prior studies that used MEDPG earlier than version 1.0. In a few rare cases, sensitivity findings obtained using version 0.9 were included if no more recent results were available. One practical consequence of this decision is a reduction in the number of qualifying prior studies.
4. Only one or two previous studies grappled with the issue of correlations among inputs, and even then in only a qualitative fashion. Input correlations must be identified and quantified *a priori* in sensitivity analyses. The project team had to rely principally upon engineering judgment in identifying potential input correlations and in quantifying their expected magnitudes.

5. Some of the inputs to the MEPDG are in terms of fundamental engineering properties while others are in terms of index properties that are used to estimate fundamental engineering properties. An example of this is the Level 1 measured dynamic modulus for HMA vs. the Level 3 estimates of dynamic modulus from mix gradation, volumetrics, and binder characteristics. The project team's philosophy was to concentrate on sensitivity of predicted performance to the fundamental engineering properties (e.g. by shifting the entire dynamic modulus master curve). The sensitivity of the MEPDG submodels linking Level 1 fundamental engineering properties to Level 3 index properties can be and have been evaluated separately using much simpler sensitivity analysis techniques—e.g., Schwartz (2005), Khazanovich *et al.* (2008), and Thyagarajan *et al.* (2010) for the Witczak $|E^*|$ model.

As summarized in Table 3, a total of 39 inputs were evaluated for sensitivity with regard to the two JPCP primary distresses of faulting and transverse cracking. Four of the 39 inputs are specifically related to JPCP overlays of flexible pavements. Table 4 summarizes the 29 inputs that were evaluated for sensitivity with regard to the three primary CRCP distresses of punch-out, maximum crack width, and minimum Load Transfer Efficiency (LTE). IRI, which is a function of the primary distresses, was not explicitly considered in this initial triage. Reflection cracking and CTB fatigue cracking distresses for flexible pavements are also excluded. The reflection cracking model is largely hidden in the MEPDG—e.g., there is no way to specify a design limit for reflection cracking, and the output for reflection cracking distress is minimal. The reflection cracking model in the current MEPDG was implemented during NCHRP Project 1-37A as a place-holder to be replaced by a better model in the future (e.g., the products of NCHRP Project 1-41). CTB cracking was excluded because it is a highly specialized distress that appears only in a small subset of flexible pavements. The CTB model in the current version of the MEPDG is uncalibrated largely because of the lack of CTB sections in the LTPP database.

Table 3. Input parameters evaluated for rigid JPCP performance.

Group	Parameters
Traffic	Initial two-way AADTT; design lane width (ft)
Climate	Climate
Design feature	Permanent curl/warp effective temperature difference (°F); joint spacing (ft); sealant type; dowel diameter (in); dowel spacing (in); edge support; erodibility index; PCC-base interface
Layer/General	Surface shortwave absorptivity
Layer/PCC	PCC layer thickness (in); unit weight (pcf); Poisson's ratio; coefficient of thermal expansion (per F° x 10 ⁻⁶); thermal conductivity (BTU/hr-ft-F°); heat capacity (BTU/lb-F°); cement type; cementitious material content (lb/yd ³); water/cement ratio; aggregate type; PCC zero-stress temperature (F°); reversible shrinkage (% of ultimate shrinkage); time to develop 50% of ultimate shrinkage (days); curing method; 28-day PCC modulus of rupture (psi); 28-day PCC compressive strength (psi)
Layer/Subbase (Base)	Granular base material type; granular base thickness (in); Poisson's ratio; compacted or uncompacted
Layer/Subgrade	Subgrade material type; Poisson's ratio; compacted or uncompacted
JPCP/HMA (rehab)	Milled HMA thickness (in); pavement rating; monthly modulus of subgrade reaction measured (pci); and month for measuring modulus of subgrade reaction

Table 4. Input parameters evaluated for sensitivity of CRCP rigid performance.

Group	Parameters
Traffic	Initial two-way AADTT
Climate	Climate
Design feature	Permanent curl/warp effective temperature difference (°F); shoulder type; percent steel (%); bar diameter (in); steel depth (in); base/slab friction coefficient
Layer/General	Surface shortwave absorptivity
Layer/PCC	PCC layer thickness (in); unit weight (pcf); Poisson's ratio; coefficient of thermal expansion (per F° x 10 ⁻⁶); thermal conductivity (BTU/hr-ft-F°); heat capacity (BTU/lb-F°); cement type; cementitious material content (lb/yd ³); water/cement ratio; aggregate type; reversible shrinkage (% of ultimate shrinkage); curing method; 28-day PCC modulus of rupture (psi)
Layer/Subbase (Base)	Granular base material type; granular base thickness (in); Poisson's ratio; compacted or uncompacted
Layer/Subgrade	Subgrade material type; Poisson's ratio; compacted or uncompacted

As summarized in Table 5, a total of 39 inputs were evaluated for sensitivity with regard to the five primary flexible pavement distresses of HMA rutting, total rutting, alligator cracking, longitudinal cracking, and thermal cracking. Nine of these 39 inputs are specifically related to HMA overlays of flexible and rigid (JPCP) pavement systems.

Table 5. Input parameters evaluated for sensitivity of flexible pavement performance.

Group	Parameters
General Info.	Traffic open month
Traffic	Initial two-way AADTT; speed
Climate	Location; depth to groundwater table
Layer/General	Surface shortwave absorptivity
Layer/HMA	Thickness (in.); dynamic modulus (psi); binder grade/stiffness; Poisson's ratio; thermal conductivity (BTU/hr-ft-F°); heat capacity (BTU/lb-F°); creep compliance; tensile strength at 14 deg F; aggregate coefficient of thermal contraction
Layer/Subbase (base)	Granular base material type; granular base thickness (in); Poisson's ratio; compacted or uncompacted; soil-water characteristic curve; permeability
Layer/Subgrade	Subgrade material type; Poisson's ratio; compacted or uncompacted; soil-water characteristic curve; permeability
HMA/HMA (rehab)	Milled HMA thickness; existing HMA thickness (after milling); existing AC binder grade; pavement rating; total rutting
HMA/JPCP (rehab)	Existing PCC modulus of rupture (psi); percent slabs cracked; percent slabs repaired; monthly modulus of subgrade reaction measured (pci); month for measuring modulus

Details of the traffic inputs such as vehicle class distributions, axle load distributions, seasonal and daily traffic distributions, axle geometric configuration, tire pressure, and traffic growth rates are not considered here. The sensitivity of MEPDG distress predictions to detailed traffic inputs is being investigated in studies currently being conducted by others (e.g., LTPP data analysis projects). In addition, a detailed traffic input sensitivity study was beyond the current study's scope to "identify, *for specific climatic region and traffic conditions*, the input parameters that appear to substantially influence predicted performance" [from RFP, emphasis added]. Traffic volume (AADTT) is included in the triage tables (e.g., Table 3, Table 4, and Table 5) because the computed sensitivities of predicted performance to this design input provides a context or reference point for the interpretation of the sensitivity of performance to other design inputs. Limited OAT analyses performed by the project team found that the details of the traffic distribution (within reasonable practical bounds) have a much lower impact on predicted performance than does AADTT.

3.2 Triage Results

3.2.1 Rigid Pavements

Limited OAT sensitivity evaluations of inputs not investigated in prior studies were performed to supplement the sensitivity findings from prior studies. Two typical rigid pavement structures, shown in Figure 3, were modeled as base cases. The initial two-way AADTT for both sections was 12,000 with a 5% compound growth rate over a 25 year design life. The climate corresponded to a wet-freeze condition (Ames, IA). Design reliability was set at 50% for all distresses. All other inputs were set to Level 3 default values. Selected inputs were varied about their reference values to evaluate their influence on predicted pavement distresses.

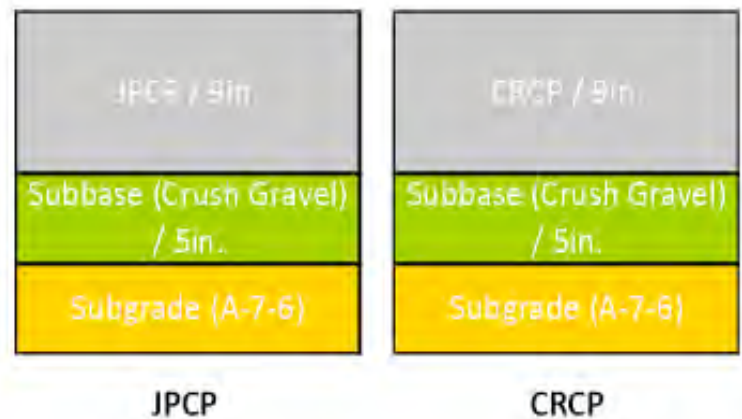


Figure 3. Base cases for rigid pavement structures (not to scale).

An additional OAT analysis was performed to evaluate the impact of existing pavement condition inputs for a JPCP overlay on flexible pavement rehabilitation scenario. The composite pavement structure used as the base case is shown in Figure 4. Traffic, climate, and other design inputs were similar to those for the rigid pavement base cases described previously. Selected inputs were varied about their reference values to evaluate their influence on predicted pavement distresses.

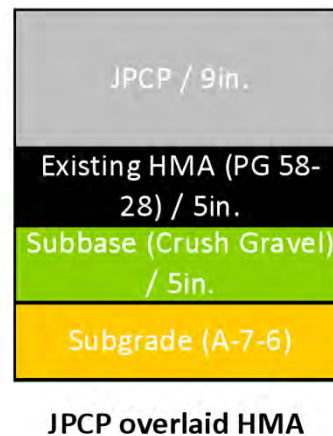


Figure 4. Base case for JPCP over flexible pavement rehabilitation scenario (not to scale).

Individual tables were developed for each rigid pavement type to detail the sensitivity of each pavement distress to each MEPDG design input. Table 6 provides detailed triage of input sensitivities for JPCP faulting; Table 7 provides the corresponding references to previous studies. Table 8 and Table 9 provide detailed triage of input sensitivities for JPCP cracking and the associated references; Table 10 and Table 11 for CRCP punch-outs; and Table 12 and Table 13 for CRCP maximum crack width and minimum LTE.

In addition to columns describing the sensitivity findings from prior studies, there are additional columns in the detailed triage tables that document: (a) the results of the limited OAT sensitivity analyses described above—i.e., the design inputs that were varied OAT and their influence on the individual predicted distresses, (b) the expert judgment of the project team for entries where no other guidance is available, and (c) a consensus judgment of the sensitivity of the distress to each MEPDG design input. The consensus column is a qualitatively weighted average of all of the other columns in the table. These consensus columns are then combined into summary tables for each pavement type, as shown in Table 14 for JPCP and Table 15 for CRCP. The number of design inputs rated as “sensitive” or “very sensitive” totaled 24 for JPCP (Table 14) and 16 for CRCP (Table 15).

Note that the consensus sensitivity assessments documented in the tables are intended to be conservative—i.e., in case of doubt, the higher sensitivity category is assigned.

Table 6. Detailed triage of input sensitivities for JPCP faulting.

JPCP Inputs		Level of Sensitivity for MEPDG JPCP Faulting Prediction										
		NCHRP 1-47 Preliminary			Prior Studies							
Group	Parameters	Consensus	Engineering Judgment	OAT Analyses	Original ISU Study	1	2	3	4	5	6	7
Traffic	Initial two-way AADTT	VS	VS				VS		VS			VS
	Design lane width (ft)	NS	NS				NS		NS			
Climate	Climate	VS	VS/S			VS						
Design feature	Permanent curl/warp effective temperature difference (°F)	VS	VS		VS		VS		VS	VS		
	Joint spacing (ft)	VS	VS/S		S	VS	S		S			VS
	Sealant type	NS	NS		NS							
	Dowel diameter (in)	S	S		S							
	Dowel spacing (in)	NS	NS		NS							
	Edge Support	VS	S	S	S	VS		VS				
	Erodibility index	S	S		S							
	PCC-Base Interface	NS	NS		NS							
Layer/General	Surface shortwave absorptivity	VS	S	VS								
Layer/PCC	PCC layer thickness (in)	VS	VS		NS	VS	S	VS	S			
	Unit weight (pcf)	S	S		S							
	Poisson's ratio	S	S		S							
	Coefficient of thermal expansion ($/F^{\circ} \times 10^{-6}$)	VS	VS		VS	VS	VS	VS	VS	VS	VS	VS
	Thermal conductivity (BTU/hr-ft-F°)	S	S		S							
	Heat capacity (BTU/lb-F°)	NS	NS		NS							
	Cement type	NS	NS		NS							
	Cementitious material content (lb/yd ³)	S	S		S							
	Water/cement ratio	S	S		S							
	Aggregate type	NS	NS		NS							
	PCC zero-stress temperature (F°)	S	S		S							
	Reversible shrinkage (% of ultimate shrinkage)	NS	NS		NS							
	Time to 50% of ultimate shrinkage (days)	NS	NS		NS							
	Curing method	NS	NS		NS							
	28-day PCC modulus of rupture (psi)	S	NS		NS	S	NS	VS	NS			

	28-day PCC compressive strength (psi)	NS	NS		NS							
Layer/Subbase (Base)	Granular base material/stiffness	VS	VS/S			VS	S	VS	S			VS
	Granular base thickness (in)	S	S	S								
	Poisson's ratio	NS	NS	NS								
	Compacted/uncompacted	NS	NS	NS								
Layer/Subgrade	Subgrade material/stiffness	S	VS/S			VS	NS		NS			
	Poisson's ratio	NS	NS	NS								
	Compacted/uncompacted	NS	NS	NS								
JCPC/HMA (Rehab)	HMA milled thickness	NS	NS	NS								
	Pavement rating	S	S	NS								
	Monthly modulus of subgrade reaction measured	S	NS	S								
	Month for measuring modulus	S	NS	S								

Table 7. References for Table 6.

Num.	Reference
1	Buch, N., Chatti, K., Haider, S. W., and Manik, A. (2008) "Evaluation of the 1-37A Design Process for New and Rehabilitated JPCP and HMA Pavements," <i>Research Report RC-1516</i> , Michigan State University, East Lansing, MI; June.(http://www.michigan.gov/mdot/0,1607,7-151-9622_11045_24249-204916--,00.html)
2	FHWA, "Development of Simplified Rigid Pavement Performance Models Using M-E PDG for HERS/NAPCOM," Office of Policy, Federal Highway Administration, Washington, D.C. Technical Memorandum, May 15 2007.
3	Haider, S. W., Buch, N., and Chatti, K. (2008). "Evaluation of ME PDG for Rigid Pavements—Incorporating the State-of-the-Practice in Michigan," <i>Proceedings of 9th International Conference on Concrete Pavement</i> , Vol. 1, p. 111-133, International Society for Concrete Pavement, San Francisco, California, August 17-21.
4	Haider, S. W., Buch, N., and Chatti, K. (2009). "Simplified Approach for Quantifying Effect of Significant Input Variables and Designing Rigid Pavements using M-E PDG," Annual Meeting CD-ROM, Transportation Research Board, National Research Council, Washington, DC. (http://pubsindex.trb.org/view.aspx?id=881418)
5	Kampmann, R. (2008). "Engineering Properties of Florida Concrete Mixes for Implementing the AASHTO Recommended Mechanistic-Empirical Rigid Pavement Design Guide," M.S. Thesis, Florida State University, FL. (http://etd.lib.fsu.edu/theses/available/etd-07212008-173629/)
6	Tanesi, J., Kutay, M. E., Abbas, A. R., and Meininger, R. C. (2007). "Effect of Coefficient of Thermal Expansion Test Variability on Concrete Pavement Performance as Predicted by Mechanistic-Empirical Pavement Design Guide," <i>Transportation Research Record 2020</i> , Transportation Research Board, National Research Council, Washington, DC, p. 40-44. (http://cat.inist.fr/?aModele=afficheN&cpsidt=20123310)

7	Velasquez, R., Hoegh, K., Yut, I., Funk, N., Cochran, G., Marasteanu, M. O., and Khazanovich, L. (2009). "Implementation of the MEPDG for New and Rehabilitated Pavement Structures for Design of Concrete and Asphalt Pavements in Minnesota," <i>Research Report Mn/DOT 2009-06</i>, University of Minnesota, Minneapolis, Minnesota; January. (http://www.cts.umn.edu/Publications/ResearchReports/reportdetail.html?id=1734)

Table 8. Detailed triage of input sensitivities for JPCP cracking.

JPCP Inputs		Level of Sensitivity for MEPDG JPCP Cracking Prediction											
		NCHRP 1-47 Preliminary			Prior Studies								
Group	Parameters	Consensus	Engineering Judgment	OAT Analyses	Original ISU Study	1	2	3	4	5	6	7	8
Traffic	Initial two-way AADTT	VS	VS				VS	VS					VS
	Design lane width (ft)	S	S/NS				NS		S		S		
Climate	Climate	S	S			NS	S	NS	S				
Design feature	Permanent curl/warp effective temperature difference (°F)	VS	VS		VS		VS		VS				
	Joint spacing (ft)	VS	VS		VS	VS	VS	VS	VS				VS
	Sealant type	NS	NS		NS								
	Dowel diameter (in)	NS	NS		NS								
	Dowel spacing (in)	NS	NS		NS								
	Edge Support	S	S	S	NS	NS		S					
	Erodibility index	NS	NS		NS								
	PCC-Base Interface	NS	NS		NS								
Layer/General	Surface shortwave absorptivity	VS	VS	VS									
Layer/PCC	PCC layer thickness (in)	VS	VS/S		VS	VS	VS	VS	VS				VS
	Unit weight (pcf)	S	S		S								
	Poisson's ratio	S	S		S								
	Coef of thermal expansion ($F^{\circ} \times 10^{-6}$)	VS	VS		VS	VS	VS	VS	VS	VS	VS	VS	VS
	Thermal conductivity (BTU/hr-ft-F°)	VS	VS		VS								
	Heat capacity (BTU/lb-F°)	NS	NS		NS								
	Cement type	NS	NS		NS								
	Cementitious material content (lb/yd ³)	NS	NS		NS								
	Water/cement ratio	NS	NS		NS								
	Aggregate type	NS	NS		NS								
	PCC zero-stress temperature (F°)	NS	NS		NS								
	Reversible shrinkage (% of ultimate shrinkage)	NS	NS		NS								
	Time to 50% of ultimate shrinkage (days)	NS	NS		NS								

	Curing method	NS	NS		NS								
	28-day PCC modulus of rupture (psi)	VS	VS		VS	VS	VS	VS	VS				VS
	28-day PCC compressive strength (psi)	VS	VS		VS						VS		
Layer/ Subbase (Base)	Granular base material/stiffness	S	VS/S/NS			NS	S	NS	S				VS
	Granular base thickness (in)	S	S	S									
	Poisson's ratio	NS	NS	NS									
	Compacted/uncompacted	NS	NS	NS									
Layer/ Subgrade	Subgrade material/stiffness	S	NS		NS								
	Poisson's ratio	NS	NS	NS									
	Compacted/uncompacted	NS	NS	NS									
JCPC/HMA (Rehab)	HMA milled thickness	NS	NS	NS									
	Pavement rating	S	S	S									
	Monthly modulus of subgrade reaction measured	S	NS	S									
	Month for measuring modulus	S	NS	S									

Table 9. References for Table 8.

Num.	Reference
1	Buch, N., Chatti, K., Haider, S. W., and Manik, A. (2008) "Evaluation of the 1-37A Design Process for New and Rehabilitated JPCP and HMA Pavements," <i>Research Report RC-1516</i> , Michigan State University, East Lansing, MI; June. (http://www.michigan.gov/mdot/0,1607,7-151-9622_11045_24249-204916--,00.html)
2	FHWA, "Development of Simplified Rigid Pavement Performance Models Using M-E PDG for HERS/NAPCOM," Office of Policy, Federal Highway Administration, Washington, D.C. Technical Memorandum, May 15 2007.
3	Haider, S. W., Buch, N., and Chatti, K. (2008). "Evaluation of ME PDG for Rigid Pavements—Incorporating the State-of-the-Practice in Michigan," <i>Proceedings of 9th International Conference on Concrete Pavement</i> , Vol. 1, p. 111-133, International Society for Concrete Pavement, San Francisco, California, August 17-21.
4	Haider, S. W., Buch, N., and Chatti, K. (2009). "Simplified Approach for Quantifying Effect of Significant Input Variables and Designing Rigid Pavements using M-E PDG," Annual Meeting CD-ROM, Transportation Research Board, National Research Council, Washington, DC. (http://pubsindex.trb.org/view.aspx?id=881418)
5	Kampmann, R. (2008). "Engineering Properties of Florida Concrete Mixes for Implementing the AASHTO Recommended Mechanistic-Empirical Rigid Pavement Design Guide," M.S. Thesis, Florida State University, FL. (http://etd.lib.fsu.edu/theses/available/etd-07212008-173629/)

6	Oh, J., and Fernando, E. G. (2008). "Development of Thickness Design Tables Based on the M-E PDG," <i>Research Report BDH10-1</i> , Texas Transportation Institute, College Station, TX; June. (http://www.dot.state.fl.us/research-Center/Completed_Proj/Summary_RD/FDOT_BDH10_rpt.pdf)
7	Tanesi, J., Kutay, M. E., Abbas, A. R., and Meininger, R. C. (2007). "Effect of Coefficient of Thermal Expansion Test Variability on Concrete Pavement Performance as Predicted by Mechanistic-Empirical Pavement Design Guide," <i>Transportation Research Record 2020</i> , Transportation Research Board, National Research Council, Washington, DC, p. 40-44. (http://cat.inist.fr/?aModele=afficheN&cpsidt=20123310)
8	Velasquez, R., Hoegh, K., Yut, I., Funk, N., Cochran, G., Marasteanu, M. O., and Khazanovich, L. (2009). "Implementation of the MEPDG for New and Rehabilitated Pavement Structures for Design of Concrete and Asphalt Pavements in Minnesota," <i>Research Report Mn/DOT 2009-06</i> , University of Minnesota, Minneapolis, Minnesota; January. (http://www.cts.umn.edu/Publications/ResearchReports/reportdetail.html?id=1734)

Table 10. Detailed triage of input sensitivities for CRCP punch-out.

CRCP Inputs		Level of Sensitivity for MEPDG CRCP Punch-out Prediction					
		NCHRP 1-47 Preliminary			Prior Studies		
Group	Parameters	Consensus	Engineering Judgment	OAT Analyses	Original ISU Study	1	2
Traffic	Initial two-way AADTT	VS	VS	VS			
Climate	Climate	S	S				
Design feature	Permanent curl/warp effective temperature difference (°F)	VS	VS		VS	VS	
	Shoulder type	S	S	S			
	Percent steel (%)	VS	VS		VS	VS	
	Bar diameter (in)	VS	VS	VS			
	Steel depth (in)	NS	NS	NS			
	Base/slab friction coefficient	NS	NS		NS		
Layer/General	Surface shortwave absorptivity	NS	NS		NS		
Layer/PCC	PCC layer thickness (in)	VS	VS		VS	VS	VS
	Unit weight (pcf)	S	S		S		
	Poisson's ratio	S	S		S		
	Coefficient of thermal expansion (per F° x 10 ⁶)	VS	VS		VS	VS	VS
	Thermal conductivity (BTU/hr-ft-F°)	NS	NS		NS		
	Heat capacity (BTU/lb-F°)	NS	NS		NS		
	Cement type	NS	NS	NS			
	Cementitious material content (lb/yd ³)	S	S	S			
	Water/cement ratio	NS	NS	NS			
	Aggregate type	NS	NS		NS	NS	
	Reversible shrinkage (% of ultimate shrinkage)	NS	NS	NS			
	Curing method	NS	NS	NS		VS	
	28-day PCC modulus of rupture (psi)	VS	VS		VS		

Layer/ Subbase (base)	Granular base material/stiffness	S	S	S			
	Granular base thickness (in)	S	S	S			
	Poisson's ratio	NS	NS	NS			
	Compacted or uncompacted	NS	NS	NS			
Layer/ Subgrade	Subgrade material/stiffness	S	S	S			
	Poisson's ratio	NS	NS	NS			
	Compacted or uncompacted	NS	NS	NS			

Table 11. References for Table 10.

Num.	Reference
1	Brown, S. F., Thompson, M., and Barenberg, E. (2006). NCHRP Research Results Digest 307: Independent Review of the Mechanistic-Empirical Pavement Design Guide and Software, Transportation Research Board, National Research Council, Washington, DC. (http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rrd_307.pdf)
2	Selezneva, O., Rao, C., Darter, M. I., Zollinger, D., and Khazanovich, L. (2004). "Development of a Mechanistic-Empirical Structural Design Procedure for Continuously Reinforced Concrete Pavements," Transportation Research Record 1896, Transportation Research Board, National Research Council, Washington, DC, p. 46—56. (http://pubsindex.trb.org/view.aspx?id=749597)

Table 12. Detailed triage of input sensitivities for CRCP maximum crack width.

CRCP Inputs		Level of Sensitivity for MEPDG CRCP Maximum Crack Width Prediction			
		NCHRP 1-47 Preliminary			Prior Studies
Group	Parameters	Consensus	Engineering Judgment	OAT Analyses	Original ISU Study
Traffic	Initial two-way AADTT	S	S	NS	
Climate	Climate	S	S		
Design feature	Permanent curl/warp effective temperature difference (°F)	NS	NS		NS
	Shoulder type	NS	NS	NS	
	Percent steel (%)	VS	VS		VS
	Bar diameter (in)	VS	VS	VS	
	Steel depth (in)	S	S	S	
	Base/slab friction coefficient	S	S		S
Layer/General	Surface shortwave absorptivity	NS	NS		NS
Layer/PCC	PCC layer thickness (in)	S	S		S
	Unit weight (pcf)	NS	NS		NS
	Poisson's ratio	NS	NS		NS
	Coefficient of thermal expansion (per F° x 10 ⁶)	S	S		S
	Thermal conductivity (BTU/hr-ft-F°)	NS	NS		NS
	Heat capacity (BTU/lb-F°)	NS	NS		NS
	Cement type	NS	NS	NS	
	Cementitious material content (lb/yd ³)	S	S	S	
	Water/cement ratio	S	S	S	
	Aggregate type	NS	NS		NS
	Reversible shrinkage (% of ultimate shrinkage)	NS	NS	NS	
	Curing method	NS	NS	NS	
	28-day PCC modulus of rupture (psi)	VS	VS		VS
Layer/Subbase (Base)	Granular base material/stiffness	NS	NS	NS	
	Granular base thickness (in)	NS	NS	NS	
	Poisson's ratio	NS	NS	NS	
	Compacted or uncompacted	NS	NS	NS	
Layer/Subgrade	Subgrade material/stiffness	NS	NS	NS	
	Poisson's ratio	NS	NS	NS	
	Compacted or uncompacted	NS	NS	NS	

Table 13. Detailed triage of input sensitivities for CRCP minimum LTE.

CRCP Inputs		Level of Sensitivity for MEPDG CRCP Minimum LTE Prediction			
		NCHRP 1-47 Preliminary			Prior Studies
Group	Parameters	Consensus	Engineering Judgment	OAT Analyses	Original ISU Study
Traffic	Initial two-way AADTT	S	S	S	
Climate	Climate	S	S		
Design feature	Permanent curl/warp effective temperature difference (°F)	NS	NS		NS
	Shoulder type	S	S	S	
	Percent steel (%)	VS	VS		VS
	Bar diameter (in)	VS	VS	VS	
	Steel depth (in)	S	S	S	
	Base/slab friction coefficient	NS	NS		NS
Layer/General	Surface shortwave absorptivity	NS	NS		NS
Layer/PCC	PCC layer thickness (in)	VS	VS		VS
	Unit weight (pcf)	NS	NS		NS
	Poisson's ratio	NS	NS		NS
	Coefficient of thermal expansion (per F° x 10 ⁶)	S	S		S
	Thermal conductivity (BTU/hr-ft-F°)	NS	NS		NS
	Heat capacity (BTU/lb-F°)	NS	NS		NS
	Cement type	NS	NS	NS	
	Cementitious material content (lb/yd ³)	S	S	S	
	Water/cement ratio	S	S	S	
	Aggregate type	NS	NS		NS
	Reversible shrinkage (% of ultimate shrinkage)	NS	NS	NS	
	Curing method	NS	NS	NS	
	28-day PCC modulus of rupture (psi)	VS	VS		VS
Layer/Subbase (Base)	Granular base material/stiffness	NS	NS	NS	
	Granular base thickness (in)	NS	NS	NS	
	Poisson's ratio	NS	NS	NS	
	Compacted or uncompacted	NS	NS	NS	
Layer/Subgrade	Subgrade material/stiffness	NS	NS	NS	
	Poisson's ratio	NS	NS	NS	
	Compacted or uncompacted	NS	NS	NS	

Table 14. Summary of input sensitivity triage for MEPDG JPCP performance predictions.

JPCP Inputs		Level of Sensitivity for JPCP Distresses	
Groups	Parameters	Faulting	Cracking
Traffic	Initial two-way AADTT	VS	VS
	Design lane width (ft)	NS	S
Climate	Climate	VS	S
Design Feature	Permanent curl/warp effective temp difference (°F)	VS	VS
	Joint spacing (ft)	VS	VS
	Sealant type	NS	NS
	Dowel diameter (in)	S	NS
	Dowel spacing (in)	NS	NS
	Edge Support	VS	S
	Erodibility index	S	NS
	PCC-Base Interface	NS	NS
Layer/General	Surface shortwave absorptivity	VS	VS
Layer/PCC	PCC layer thickness (in)	VS	VS
	Unit weight (pcf)	S	S
	Poisson's ratio	S	S
	Coefficient of thermal expansion (per F° x 10 ⁻⁶)	VS	VS
	Thermal conductivity (BTU/hr-ft-F°)	S	VS
	Heat capacity (BTU/lb-F°)	NS	NS
	Cement type	NS	NS
	Cementitious material content (lb/yd ³)	S	NS
	Water/cement ratio	S	NS
	Aggregate type	NS	NS
	PCC zero-stress temperature (F°)	S	NS
	Reversible shrinkage (% of ultimate shrinkage)	NS	NS
	Time to develop 50% of ultimate shrinkage (days)	NS	NS
	Curing method	NS	NS
	28-day PCC modulus of rupture (psi)	S	VS
	28-day PCC compressive strength (psi)	NS	VS
Layer/Subbase (Base)	Granular base material/stiffness	VS	S
	Granular base thickness (in)	S	S
	Poisson's ratio	NS	NS
	Compacted or uncompacted	NS	NS
Layer/Subgrade	Subgrade material/stiffness	S	S
	Poisson's ratio	NS	NS
	Compacted or uncompacted	NS	NS
JPCP/HMA (Rehab)	HMA milled thickness	NS	NS
	Pavement rating	S	S
	Monthly modulus of subgrade reaction measured	S	S
	Month for measuring modulus	S	S

Table 15. Summary of input sensitivity triage for MEPDG CRCP performance predictions.

CRCP Inputs		Level of Sensitivity for CRCP Distresses		
Groups	Parameters	Punch-out	Maximum Crack Width	Minimum LTE
Traffic	Initial two-way AADTT	VS	S	S
Climate	Climate	S	S	S
Design Feature	Permanent curl/warp effective temperature difference (°F)	VS	NS	NS
	Shoulder type	S	NS	S
	Percent steel (%)	VS	VS	VS
	Bar diameter (in)	VS	VS	VS
	Steel depth (in)	NS	S	S
	Base/slab friction coefficient	NS	S	NS
Layer/General	Surface shortwave absorptivity	NS	NS	NS
Layer/PCC	PCC layer thickness (in)	VS	S	VS
	Unit weight (pcf)	S	NS	NS
	Poisson's ratio	S	NS	NS
	Coefficient of thermal expansion (per F° x 10 ⁻⁶)	VS	S	S
	Thermal conductivity (BTU/hr-ft-F°)	NS	NS	NS
	Heat capacity (BTU/lb-F°)	NS	NS	NS
	Cement type	NS	NS	NS
	Cementitious material content (lb/yd ³)	S	S	S
	Water/cement ratio	NS	S	S
	Aggregate type	NS	NS	NS
	Reversible shrinkage (% of ultimate shrinkage)	NS	NS	NS
	Curing method	NS	NS	NS
	28-day PCC modulus of rupture (psi)	VS	VS	VS
Layer/Subbase (Base)	Granular base material/stiffness	S	NS	NS
	Granular base thickness (in)	S	NS	NS
	Poisson's ratio	NS	NS	NS
	Compacted or uncompacted	NS	NS	NS
Layer/Subgrade	Subgrade material/stiffness	S	NS	NS
	Poisson's ratio	NS	NS	NS
	Compacted or uncompacted	NS	NS	NS

3.2.2 Flexible Pavements

Limited OAT sensitivity analyses were performed to evaluate flexible pavement inputs not examined in prior studies. Separate series of analyses were performed to evaluate the influences of (a) unbound and HMA thermo-hydraulic properties; (b) subgrade type; and (c) existing pavement condition (for rehabilitation scenarios). For the first analysis series, three pavement sections at each of four sites with different climate extremes were selected as base cases. Pavement sections consisted of 2 inches, 4 inches, or 6 inches of HMA over 12 inches of A-1-a base over a reference A-4 subgrade. Four sites representing different climate extremes were considered: Seattle WA (wet-no freeze; PG 52-16), Caribou ME (wet-freeze; PG 52-34), Phoenix AZ (dry-no freeze; PG 76-10); and College Park MD (temperate; PG 64-22). Traffic levels were adjusted to give a service life of approximately 15 years for the reference conditions at a 50% reliability level. HMA material properties were typical for a 19 mm dense graded Superpave mixture. All other reference inputs were set equal to the Level 3 defaults. Input parameters considered in OAT sensitivity analyses included subgrade type (A-2-4, A-4, and A-7-6), groundwater table (GWT) depth (2, 7, and 12 feet), soil water characteristic curve (SWCC, weighted plasticity index wPI varied by $\pm 50\%$ from reference), unbound saturated hydraulic conductivity k_s ($\log k_s$ varied by $\pm 50\%$ from reference), traffic ($\pm 50\%$ from reference), and subgrade resilient modulus M_R ($+50\%$ from reference). Additional analysis details can be found in Schwartz and Li (2010).

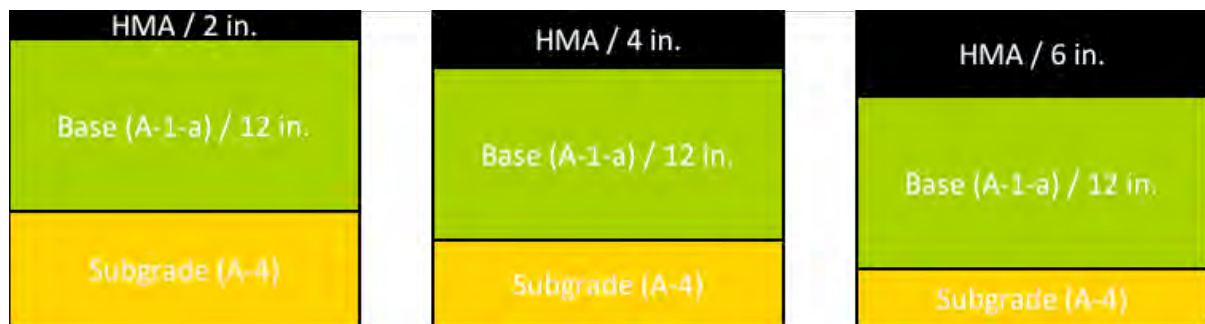


Figure 5. Base cases for flexible pavement environmental inputs sensitivity studies (not to scale).

Although the results from these OAT analyses are summarized in the triage tables described later, some of the findings were surprising and merit more extended discussion. Table 16 summarizes for all predicted distresses the mean-normalized sensitivity index S_{jk} values for each input parameter varied in this study (S_{jk} is defined and discussed in more detail in Section 4.1). In order to provide more insight, the cells in Table 16 are categorized by sensitivity value: cells with $S_{jk} > 0.5$ are rated the highest sensitivity (red), 0.35-0.5 are medium sensitivity (yellow), 0.2-0.35 are low sensitivity (green), and cells with $S_{jk} < 0.2$ are rated as negligible sensitivity (uncolored). Close examination of Table 16 leads to the following observations: (a) longitudinal/top-down and alligator/bottom-up cracking distresses tend to show the highest sensitivities to the inputs, followed by subgrade/HMA/total rutting; (b) granular base rutting and roughness/IRI had negligible sensitivities to all of the input parameters considered; (c) traffic and subgrade M_R are the two inputs that tend to have the largest impact on predicted distresses; and (d) the environmental inputs of GWT depth, SWCC parameters, and $\log k_s$ all tend to have slight to negligible influence on the predicted distresses. Figure 6 and Figure 7 highlight the last two observations by plotting the average absolute sensitivity index for each variable input considered in the study—i.e., the average of the rows in

Table 16 in absolute value terms. Note that the vertical axis scale in Figure 6 is much exaggerated compared to Figure 7—i.e., the sensitivity index values for the environmental inputs are approximately an order of magnitude smaller than those for traffic and subgrade modulus. Figure 6 and Figure 7 also illustrate the influence of climate conditions on the computed sensitivity values. The average sensitivity of predicted distress to traffic (Figure 6) is relatively uniform at all four sites but more variable—but in a sensible way—with respect to subgrade modulus (Figure 7). The highest sensitivity in Seattle is probably due to the fact that the moisture-adjusted moduli there are the lowest of the four sites. Conversely, the relatively low sensitivity of average performance to subgrade modulus for Caribou may be attributed to the frozen stiff state of the subgrade for part of the year. Subgrade conditions in Phoenix and College park are arguably intermediate between these two extremes, which is consistent with their intermediate sensitivity values. The variations in average absolute sensitivities to environmental inputs (Figure 7) are more difficult to rationalize. However, all of the sensitivity values are negligibly small, so the variations may be as much due to numerical noise as to any real physical cause.

Subsequent follow-up analyses evaluated the sensitivity of pavement performance to the HMA environmental variables. HMA environmental inputs considered were surface shortwave absorptivity (SSA; $\pm 50\%$ from reference), HMA thermal conductivity ($\pm 50\%$ from reference), and HMA specific heat ($\pm 50\%$ from reference). Results from these additional analyses are summarized in Figure 8 and Figure 9. In general terms, the sensitivity of pavement performance to SSA was high and comparable to that for traffic and subgrade stiffness (Figure 8), while the sensitivity of performance to HMA thermal conductivity and heat capacity was much lower and comparable to that for the unbound material environmental inputs (Figure 9). Overall, the influence of all environment-related design inputs (unbound and HMA) except SSA is quite low; this finding is more than a bit surprising, given the sophisticated environmental modeling incorporated in the MEPDG.

Table 16. Mean-normalized sensitivity indices for all cases analyzed.

Location	Variable	Subfactor	LT Cracking	Alligator Cracking	SG Rutting	Base Rutting	HMA Rutting	Total Rutting	IRI
Seattle	Traffic	2" HMA	1.503	1.782	0.120	0.099	0.500	0.194	0.045
		4" HMA	1.496	1.152	0.104	0.091	0.497	0.243	0.077
		6" HMA	1.496	1.076	0.099	0.085	0.492	0.271	0.064
	GWT Depth	2" HMA	0.149	0.018	0.055	0.001	0.007	0.024	0.005
		4" HMA	0.032	0.026	0.000	0.000	0.025	0.010	0.006
		6" HMA	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	SWCC	A- 7- 6	0.163	0.025	0.168	0.004	0.006	0.072	0.003
		A- 4	0.364	0.082	0.046	0.008	0.006	0.019	0.015
		A- 2- 4	0.138	0.107	0.130	0.004	0.017	0.033	0.000
	log k _s	A- 7- 6	0.000	0.005	0.001	0.000	0.000	0.000	0.000
		A- 4	0.489	0.224	0.180	0.016	0.030	0.070	0.020
		A- 2- 4	0.401	0.168	0.213	0.009	0.028	0.052	0.013
	Subgrade M _r	A- 7- 6	1.924	0.370	0.846	0.072	0.030	0.365	0.076
		A- 4	1.608	0.386	0.860	0.058	0.036	0.380	0.081
		A- 2- 4	1.116	0.401	0.940	0.004	0.034	0.293	0.057
Caribou	Traffic	2" HMA	1.504	1.781	0.139	0.119	0.494	0.214	0.064
		4" HMA	1.486	1.115	0.119	0.103	0.497	0.271	0.111
		6" HMA	1.496	1.058	0.114	0.098	0.499	0.310	0.099
	GWT Depth	2" HMA	0.021	0.032	0.084	0.014	0.000	0.037	0.009
		4" HMA	0.041	0.008	0.048	0.004	0.005	0.020	0.005
		6" HMA	0.004	0.018	0.032	0.006	0.007	0.014	0.003
	SWCC	A- 7- 6	0.043	0.004	0.120	0.000	0.003	0.044	0.006
		A- 4	0.232	0.039	0.014	0.004	0.008	0.003	0.006
		A- 2- 4	0.158	0.066	0.030	0.006	0.020	0.000	0.006
	log k _s	A- 7- 6	0.005	0.001	0.001	0.001	0.000	0.001	0.000
		A- 4	0.210	0.046	0.042	0.005	0.015	0.012	0.005
		A- 2- 4	0.107	0.030	0.058	0.002	0.011	0.010	0.004
	Subgrade M _r	A- 7- 6	0.114	0.012	0.241	0.002	0.015	0.091	0.007
		A- 4	0.840	0.157	0.417	0.029	0.025	0.164	0.047
		A- 2- 4	0.580	0.153	0.455	0.001	0.020	0.118	0.031
Phoenix	Traffic	2" HMA	1.501	1.779	0.114	0.091	0.498	0.255	0.061
		4" HMA	1.498	1.164	0.099	0.071	0.499	0.330	0.111
		6" HMA	1.498	1.082	0.093	0.065	0.496	0.367	0.114
	GWT Depth	2" HMA	0.315	0.013	0.128	0.005	0.024	0.039	0.008
		4" HMA	0.452	0.059	0.131	0.009	0.024	0.023	0.007
		6" HMA	0.387	0.092	0.151	0.013	0.024	0.018	0.006
	SWCC	A- 7- 6	0.142	0.015	0.077	0.004	0.005	0.024	0.001
		A- 4	0.341	0.032	0.038	0.004	0.005	0.007	0.007
		A- 2- 4	0.112	0.039	0.058	0.001	0.009	0.006	0.001
	log k _s	A- 7- 6	0.008	0.008	0.006	0.001	0.000	0.001	0.000
		A- 4	0.111	0.016	0.026	0.002	0.006	0.004	0.001
		A- 2- 4	0.073	0.022	0.038	0.000	0.006	0.004	0.001
	Subgrade M _r	A- 7- 6	1.270	0.124	0.420	0.038	0.013	0.117	0.032
		A- 4	1.069	0.134	0.445	0.026	0.015	0.118	0.033
		A- 2- 4	0.721	0.140	0.463	0.008	0.011	0.093	0.026
College Par	Traffic	2" HMA	1.506	1.782	0.121	0.106	0.496	0.214	0.052
		4" HMA	1.496	1.140	0.104	0.081	0.496	0.268	0.090
		6" HMA	1.497	1.074	0.099	0.074	0.498	0.302	0.077
	GWT Depth	2" HMA	0.122	0.011	0.036	0.003	0.007	0.013	0.003
		4" HMA	0.136	0.023	0.037	0.003	0.006	0.013	0.003
		6" HMA	0.122	0.040	0.053	0.005	0.009	0.014	0.004
	SWCC	A- 7- 6	0.085	0.013	0.083	0.003	0.002	0.032	0.002
		A- 4	0.181	0.037	0.023	0.004	0.004	0.007	0.006
		A- 2- 4	0.077	0.051	0.068	0.004	0.008	0.014	0.000
	log k _s	A- 7- 6	0.008	0.003	0.001	0.000	0.002	0.000	0.000
		A- 4	0.102	0.043	0.038	0.004	0.009	0.012	0.004
		A- 2- 4	0.120	0.045	0.064	0.004	0.008	0.013	0.003
	Subgrade M _r	A- 7- 6	0.964	0.170	0.423	0.037	0.013	0.161	0.037
		A- 4	0.801	0.179	0.430	0.029	0.015	0.167	0.039
		A- 2- 4	0.566	0.185	0.470	0.001	0.016	0.123	0.028

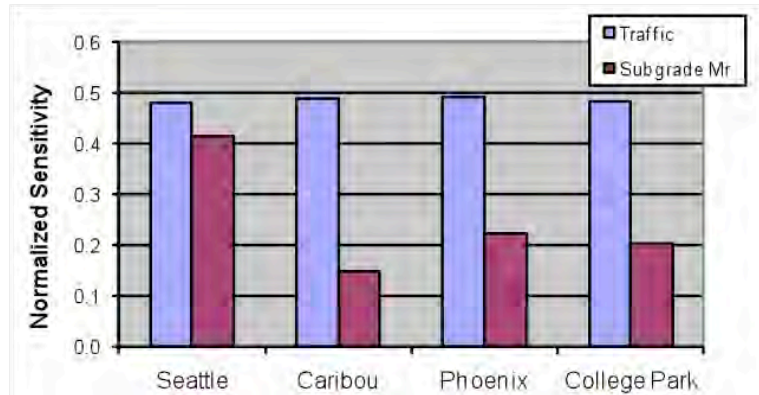


Figure 6. Average absolute sensitivity by input: non-environmental variables traffic and subgrade M_R .

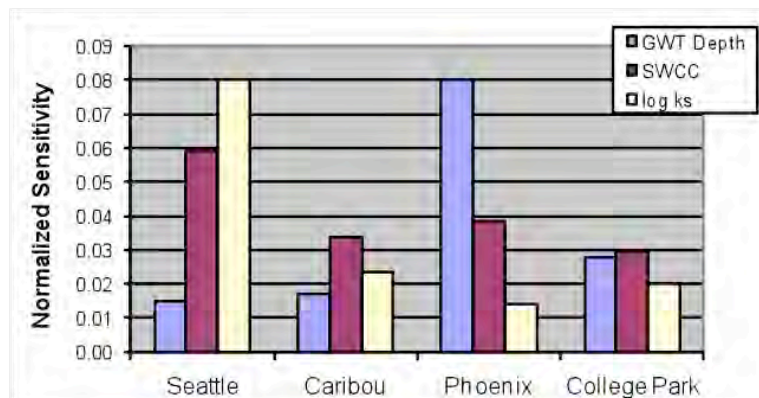


Figure 7. Average absolute sensitivity by input: environmental variables GWT depth, SWCC, and log k_s .

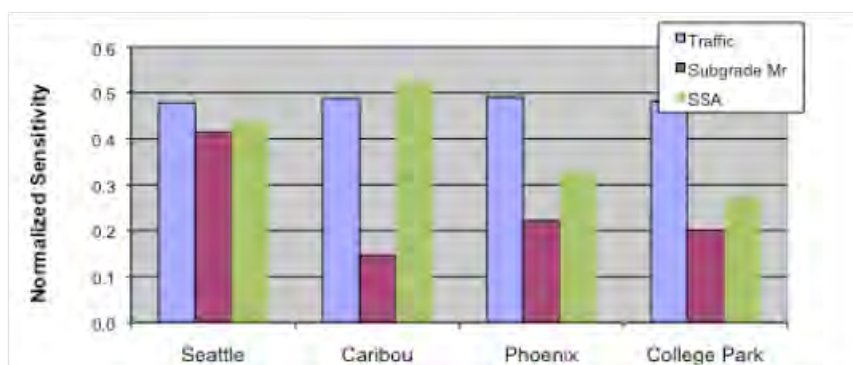


Figure 8. Average absolute sensitivity to surface shortwave absorptivity SSA; sensitivities to traffic and subgrade M_R included for comparison.

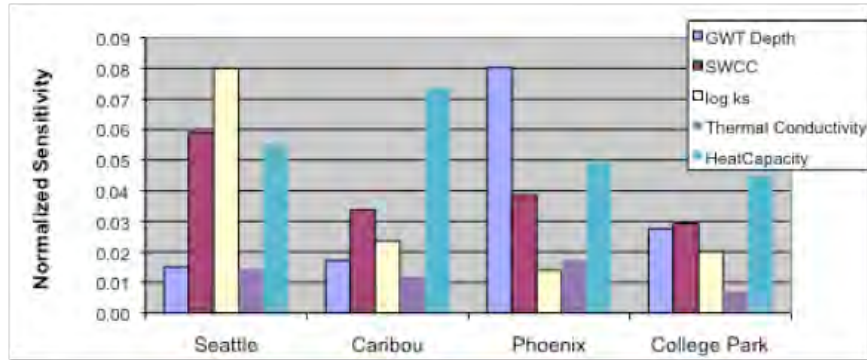


Figure 9. Average absolute sensitivity to HMA thermal conductivity and heat capacity; sensitivities to unbound material environmental inputs included for comparison.

The second major OAT sensitivity analysis for flexible pavements focused on the influence of subgrade type on predicted performance. Subgrade characteristics are arguably more important for flexible pavements than for rigid. A single base case was analyzed. The pavement section consisted of 6 inches of HMA over 12 inches of an A-1-a granular base over subgrade. Level 3 default input values were assumed for the granular base and each subgrade type. Traffic volume corresponded to approximately 2.5M ESALs over 15 years. Climate conditions were temperate (mid-Atlantic region). Predicted total rutting, longitudinal cracking, and alligator cracking were evaluated for all realistic AASHTO subgrade soil types. (No transverse thermal cracking was predicted for any of the cases, as would be expected for a temperate climate; however, thermal cracking should be relatively insensitive to the subgrade characteristics.) The results for each distress are summarized in Figure 10, Figure 11, and Figure 12, respectively. The trends in these results are remarkably consistent. Although there are clear and logical differences in performance as a function of subgrade type, the dominant influence appears to be the subgrade modulus as opposed to other subgrade characteristics. The predicted total rutting, longitudinal cracking, and alligator cracking all fall closely along linear trends with subgrade modulus. (The magnitude of predicted alligator cracking was quite small, but the trends are nonetheless similar to those for the other distresses.) These results suggest that it is not subgrade type that is the important design input but rather the subgrade modulus.

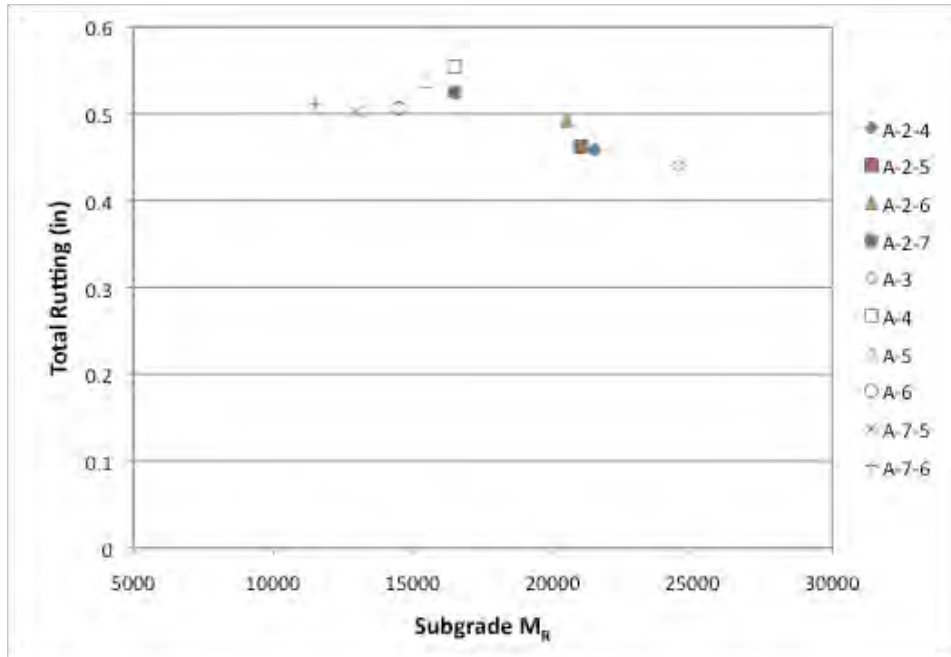


Figure 10. Predicted total rutting as a function of subgrade type and M_R .

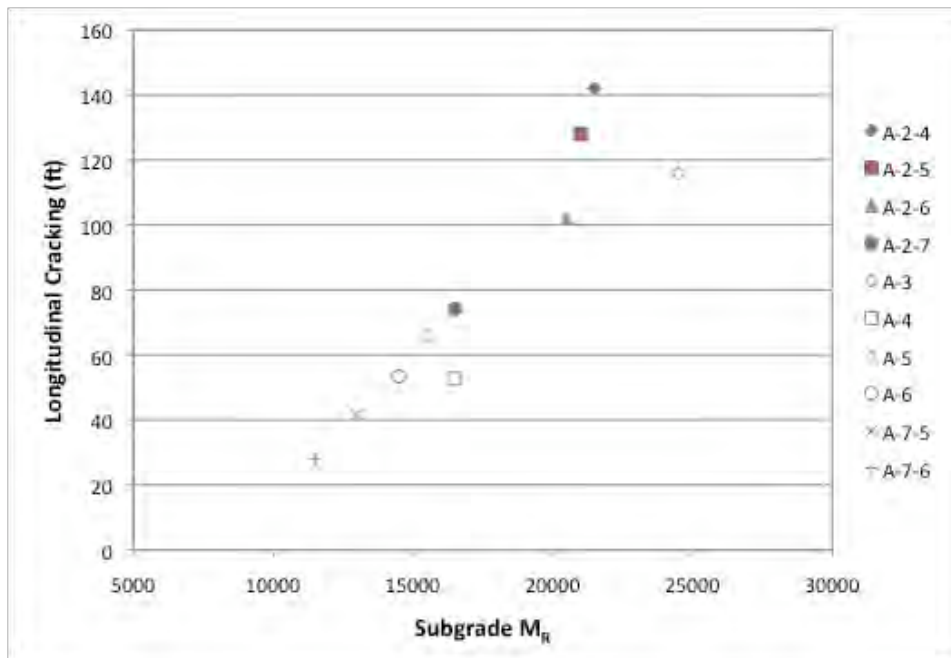


Figure 11. Predicted longitudinal cracking as a function of subgrade type and M_R .

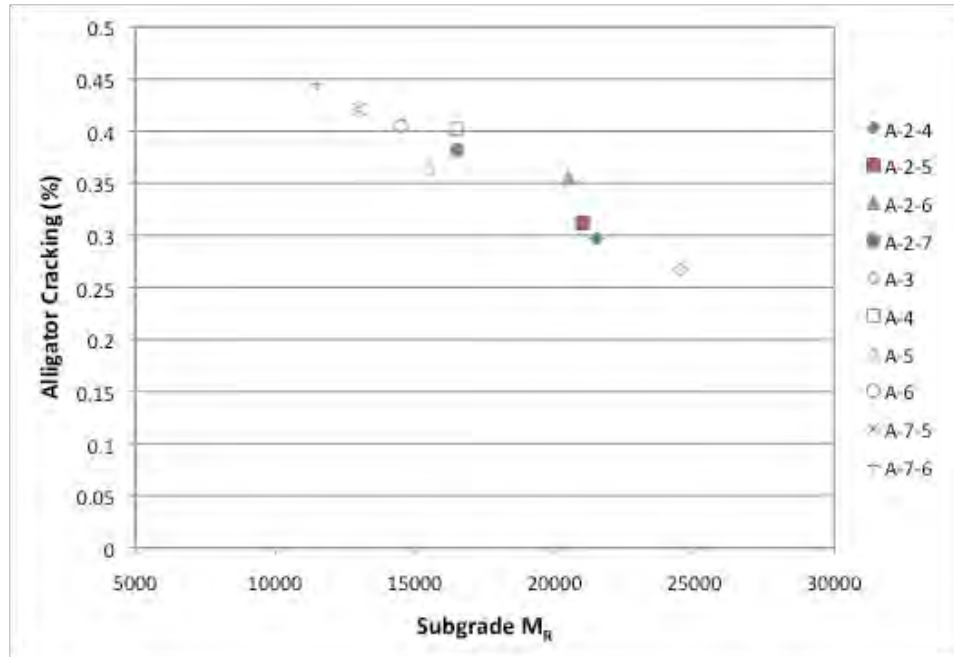


Figure 12. Predicted alligator cracking as a function of subgrade type and M_R .

The final OAT analysis series evaluated the influence of existing pavement condition inputs for an HMA overlay on JPCP rigid pavement rehabilitation scenario. The composite pavement structure used as the base case is shown in Figure 13. The initial two-way AADTT for both sections was 12,000 with a 5% compound growth rate over a 15 year design life. The climate was a wet-freeze condition (Ames, IA). Design reliability was set at 50% for all distresses. All other design inputs were set equal to the Level 3 defaults. Selected inputs were varied about their reference values to evaluate their influence on predicted pavement distresses.

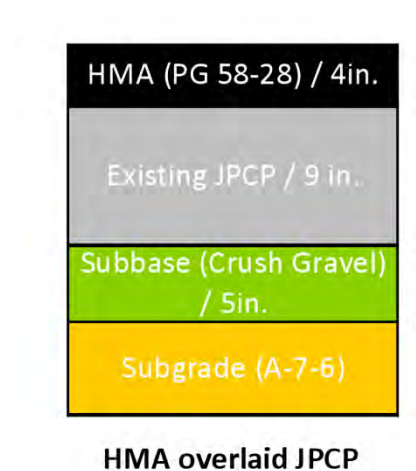


Figure 13. Base case for HMA overlay on JPCP rigid pavement rehabilitation scenario (not to scale).

Similar to the procedure followed for rigid pavements, individual tables were developed that detail the sensitivity of each flexible pavement distress to each MEPDG design input. Table 17 to Table 21 provide the detailed triage of input sensitivities for HMA rutting, total rutting, alligator cracking, longitudinal cracking, and thermal cracking. Table 22 lists the corresponding references to previous studies for HMA rutting, total rutting, alligator cracking, and longitudinal cracking sensitivities, while Table 23 provides similar references for thermal cracking.

In addition to columns describing the sensitivity findings from prior studies, there are additional columns in Table 17 to Table 21 that document: (a) the results of the OAT sensitivity analyses described above—i.e., the design inputs that were varied OAT and their influence on the individual predicted distresses; (b) the expert judgment of the project team for entries where no other guidance is available; and (c) a consensus judgment of the sensitivity of the distress to each MEPDG design input. The consensus column is a qualitative weighted average of all of the other columns in the table. These consensus columns are then combined into the summary Figure 18 for flexible pavements. As for the rigid pavement triage, the consensus estimates of sensitivities are deliberately conservative. A total of 19 flexible pavement inputs were classified as “sensitive” or “very sensitive” in Figure 18

Table 17. Detailed triage of input sensitivities for HMA rutting.

Flexible Pavement Inputs		Level of Sensitivity for MEPDG HMA Rutting Prediction				
		NCHRP 1-47 Preliminary			Prior Studies	
Group	Parameters	Consensus	Engineering Judgment	OAT Analyses	1	2
General Information	Traffic open month	NS	NS			
Traffic	Volume	VS	S	S	VS	S
	Speed	VS	S			VS
Climate	Location	VS	VS	S	VS	
	Depth to groundwater table	NS	NS	NS	NS	NS
Layer/General	Surface shortwave absorptivity	VS	S	VS		
Layer/HMA	Thickness	VS	S		VS	
	Dynamic modulus	S	S			
	Binder grade/stiffness	VS	VS		VS	VS
	Poisson's ratio	NS	NS			
	Thermal conductivity	NS	NS	NS		
	Heat capacity	NS	NS	S/NS		
	Creep compliance	NS	NS		NS	
	Tensile strength at 14°F	NS	NS			
	Aggregate coefficient of thermal contraction	NS	NS		NS	
Layer/Base (Subbase)	Thickness	S	NS		NS	S/NS
	Resilient modulus	S	S		NS	S/NS
	Poisson's ratio	NS	NS			
	Soil-water characteristic curve	NS	NS			
	Permeability	NS	NS			
	Compacted/uncompacted	NS	NS			
Layer/Subgrade	Resilient modulus	NS	NS	NS	NS	NS
	Poisson's ratio	NS	NS			
	Soil-water characteristic curve	S	S	NS		
	Permeability	NS	NS	NS		
	Compacted/uncompacted	NS	NS			
HMA/HMA (Rehab)*	Milled AC thickness	NS	NS		NS	
	Existing AC thickness (after milling)	S	NS		S	
	Existing AC binder grade	S	NS		S	
	Pavement rating	VS	S		VS	
	Total rutting	VS	S		VS	
HMA/JPCP (Rehab)	Existing PCC modulus of rupture	NS	NS	NS		
	Percent slabs cracked and percent slabs repaired	NS	NS	NS		
	Monthly modulus of subgrade reaction measured	NS	NS	NS		
	Month for measuring modulus	NS	NS	NS		

*HMA/HMA rehabilitation scenario only (Version 0.9 of MEPDG)

Table 18. Detailed triage of input sensitivities for total rutting.

Flexible Pavement Inputs		Level of Sensitivity for MEPDG Total Rutting Prediction				
		NCHRP 1-47 Preliminary			Prior Studies	
Group	Parameters	Consensus	Engineering Judgment	OAT Analyses	1	2
General Information	Traffic open month	NS	NS			
Traffic	Volume	VS	S	S	VS	S
	Speed	VS	S			VS
Climate	Location	S	S	S	S	
	Depth to groundwater table	S	S	NS	S	NS
Layer/General	Surface shortwave absorptivity	VS	S	VS		
Layer/HMA	Thickness	VS	S		VS	S
	Dynamic modulus	S	S			S/NS
	Binder grade/stiffness	S	S		S	S
	Poisson's ratio	NS	NS			
	Thermal conductivity	NS	NS	NS		
	Heat capacity	NS	NS	NS		
	Creep compliance	NS	NS		NS	
	Tensile strength at 14°F	NS	NS			
	Aggregate coefficient of thermal contraction	NS	NS		NS	
Layer/Base (Subbase)	Thickness	S	S	S/NS	NS	
	Resilient modulus	S	S	S	S	
	Poisson's ratio	NS	NS			
	Soil-water characteristic curve	NS	NS			
	Permeability	NS	NS			
	Compacted/uncompacted	NS	NS			
Layer/Subgrade	Resilient modulus	VS	S	VS/S/NS	S	S/NS
	Poisson's ratio	NS	NS			
	Soil-water characteristic curve	S	S	NS		
	Permeability	NS	NS	NS		
	Compacted/uncompacted	NS	NS			
HMA/HMA (Rehab)*	Milled AC thickness	NS	NS		NS	
	Existing AC thickness (after milling)	S	NS		S	
	Existing AC binder grade	S	NS		S	
	Pavement rating	S	S		S	
	Total rutting	VS	S		VS	
HMA/JPCP (Rehab)	Existing PCC modulus of rupture	NS	NS	NS		
	Percent slabs cracked and percent slabs repaired	NS	NS	NS		
	Monthly modulus of subgrade reaction measured	NS	NS	NS		
	Month for measuring modulus	NS	NS	NS		

*HMA/HMA rehabilitation scenario only (Version 0.9 of MEPDG)

Table 19. Detailed triage of input sensitivities for alligator cracking.

Flexible Pavement Inputs		Level of Sensitivity for MEPDG Alligator Cracking Prediction				
		NCHRP 1-47 Preliminary			Prior Studies	
Group	Parameters	Consensus	Engineering Judgment	OAT Analyses	1	2
General Information	Traffic open month	NS	NS			
Traffic	Volume	VS	S	VS	NS	S
	Speed	S	S			S
Climate	Location	S	S	S	NS	
	Depth to groundwater table	NS	NS	NS	NS	NS
Layer/General	Surface shortwave absorptivity	S	S	S		
Layer/HMA	Thickness	VS	VS		NS	VS
	Dynamic modulus	S	S			S
	Binder grade/stiffness	S	S		NS	
	Poisson's ratio	NS	NS			
	Thermal conductivity	NS	NS	NS		
	Heat capacity	NS	NS	NS		
	Creep compliance	NS	NS		NS	
	Tensile strength at 14°F	NS	NS			
	Aggregate coefficient of thermal contraction	NS	NS		NS	
Layer/Base (Subbase)	Thickness	S	S		NS	
	Resilient modulus	S	S		NS	
	Poisson's ratio	NS	NS			
	Soil-water characteristic curve	NS	NS			
	Permeability	NS	NS			
	Compacted/uncompacted	NS	NS			
Layer/Subgrade	Resilient modulus	S	S	S/NS	NS	S/NS
	Poisson's ratio	NS	NS			
	Soil-water characteristic curve	S	S	S/NS		
	Permeability	NS	NS	S/NS		
	Compacted/uncompacted	NS	NS			
HMA/HMA (Rehab)*	Milled AC thickness	NS	NS		NS	
	Existing AC thickness (after milling)	S	S		NS	
	Existing AC binder grade	S	S		S	
	Pavement rating	VS	S		VS	
	Total rutting	NS	NS		NS	
HMA/JPCP (Rehab)	Existing PCC modulus of rupture	NS	NS	NS		
	Percent slabs cracked and percent slabs repaired	NS	NS	NS		
	Monthly modulus of subgrade reaction measured	NS	NS	NS		
	Month for measuring modulus	NS	NS	NS		

*HMA/HMA rehabilitation scenario only (Version 0.9 of MEPDG)

Table 20. Detailed triage of input sensitivities for longitudinal cracking.

Flexible Pavement Inputs		Level of Sensitivity for MEPDG Longitudinal Cracking Prediction				
		NCHRP 1-47 Preliminary			Prior Studies	
Group	Parameters	Consensus	Engineering Judgment	OAT Analyses	1	2
General Information	Traffic open month	NS	NS			
Traffic	Volume	VS	S	VS	VS	VS/S
	Speed	S	S			VS/S
Climate	Location	S	S	NS	S	
	Depth to groundwater table	NS	NS	NS	NS	NS
Layer/General	Surface shortwave absorptivity	VS	S	VS/S		
Layer/HMA	Thickness	S	S		S	VS/S
	Dynamic modulus	S	S			S
	Binder grade/stiffness	S	S		VS	S/NS
	Poisson's ratio	NS	NS			
	Thermal conductivity	NS	NS	NS		
	Heat capacity	NS	NS	NS		
	Creep compliance	NS	NS		NS	
	Tensile strength at 14°F	NS	NS			
	Aggregate coefficient of thermal contraction	NS	NS		NS	
Layer/Base (Subbase)	Thickness	S	S		S	
	Resilient modulus	VS	S		VS	
	Poisson's ratio	NS	NS			
	Soil-water characteristic curve	NS	NS			
	Permeability	NS	NS			
	Compacted/uncompacted	NS	NS			
Layer/Subgrade	Resilient modulus	S	S	VS	S	S
	Poisson's ratio	NS	NS			
	Soil-water characteristic curve	S	S	S/NS		
	Permeability	NS	NS	S/NS		
	Compacted/uncompacted	NS	NS			
HMA/HMA (Rehab)*	Milled AC thickness	NS	NS		NS	
	Existing AC thickness (after milling)	S	S		S	
	Existing AC binder grade	S	S		S	
	Pavement rating	VS	S		VS	
	Total rutting	NS	NS		NS	
HMA/JPCP (Rehab)	Existing PCC modulus of rupture	NS	NS	NS		
	Percent slabs cracked and percent slabs repaired	NS	NS	NS		
	Monthly modulus of subgrade reaction measured	NS	NS	NS		
	Month for measuring modulus	NS	NS	NS		

*HMA/HMA rehabilitation scenario only (Version 0.9 of MEPDG)

Table 21. Detailed triage of input sensitivities for thermal cracking.

Flexible Pavement Inputs		Level of Sensitivity for MEPDG Thermal Cracking Prediction			
		NCHRP 1-47 Preliminary			Prior Studies
Group	Parameters	Consensus	Engineering Judgment	OAT Analyses	1
General Information	Traffic open month	NS	NS		
Traffic	Volume	NS	NS		
	Speed	NS	NS		
Climate	Location	S	S		
	Depth to groundwater table	NS	NS		
Layer/General	Surface shortwave absorptivity	NS	NS		
Layer/HMA	Thickness	NS	NS		S
	Dynamic modulus	NS	NS		
	Binder grade/stiffness	S	S		
	Poisson's ratio	NS	NS		
	Thermal conductivity	S	S		
	Heat capacity	S	S		
	Creep compliance	VS	VS		
	Tensile strength at 14°F	VS	VS		
Layer/Base (Subbase)	Aggregate coefficient of thermal contraction	VS	VS		
	Thickness	NS	NS		
	Resilient modulus	NS	NS		
	Poisson's ratio	NS	NS		
	Soil-water characteristic curve	NS	NS		
	Permeability	NS	NS		
	Compacted/uncompacted	NS	NS		
Layer/Subgrade	Resilient modulus	NS	NS		
	Poisson's ratio	NS	NS		
	Soil-water characteristic curve	NS	NS		
	Permeability	NS	NS		
	Compacted/uncompacted	NS	NS		
HMA/HMA (Rehab)*	Milled AC thickness	NS	NS		
	Existing AC thickness (after milling)	NS	NS		
	Existing AC binder grade	NS	NS		
	Pavement rating	NS	NS		
	Total rutting	NS	NS		
HMA/JPCP (Rehab)	Existing PCC modulus of rupture	NS	NS	NS	
	Percent slabs cracked and percent slabs repaired	NS	NS	NS	
	Monthly modulus of subgrade reaction measured	NS	NS	NS	
	Month for measuring modulus	NS	NS	NS	

*HMA/HMA rehabilitation scenario only (Version 0.9 of MEPDG)

**Table 22. References for Table 17, Table 18, Table 19, and
Table 20.**

Num.	Reference
1	Hoerner, T. E., Zimmerman, K. A., Smith, K. D., and Cooley, L. A. (2007). "Mechanistic-Empirical Pavement Design Guide Implementation Plan," <i>Report No. SD2005-01</i> , South Dakota Department of Transportation, Pierre, SD. (http://www.state.sd.us/Applications/HR19ResearchProjects/Projects/sd2005-01_Final_Report.pdf) [Version 0.9; one of few studies to consider rehabilitation inputs]
2	Ayyala, D., Chehab, G. R., and Daniel, J. S. (2010). "Sensitivity of MEPDG Level 2 and 3 Inputs using Statistical Analysis Techniques for New England States," Annual Meetings CD-ROM, Transportation Research Board, National Research Council, Washington, DC. [Version 1.0, except Version 0.91 for thermal cracking]

Table 23. Reference for Table 21.

Num.	Reference
1	Yin, H., Chehab, G. R., Stoffels, S. M., Kumar, T., and Premkumar, L. (2010). "Use of Creep Compliance Interconverted from Complex Modulus for Thermal Cracking Prediction Using the M-E Pavement Design Guide." <i>International Journal of Pavement Engineering</i> , Vol. 11, No. 2, April, p. 95-105. [Not stated, but presumably Version 1.0]

Table 24. Summary of input sensitivity triage for MEPDG flexible pavements.

HMA pavement Inputs		Level of Sensitivity for Flexible Pavement Outputs				
Group	Parameters	HMA Rutting	Total Rutting	Alligator Cracking	Long. Cracking	Thermal Cracking
General Information	Traffic open month	NS	NS	NS	NS	NS
Traffic	Volume	VS	VS	VS	VS	NS
	Speed	VS	VS	S	S	NS
Climate	Location	VS	S	S	S	S
	Depth to groundwater table	NS	S	NS	NS	NS
Layer/General	Surface shortwave absorptivity	VS	VS	S	VS	NS
Layer/HMA	Thickness	VS	VS	VS	S	NS
	Dynamic modulus	S	S	S	S	NS
	Binder grade/stiffness	VS	S	S	S	S
	Poisson's ratio	NS	NS	NS	NS	NS
	Thermal conductivity	NS	NS	NS	NS	S
	Heat capacity	NS	NS	NS	NS	S
	Creep compliance	NS	NS	NS	NS	VS
	Tensile strength at 14°F	NS	NS	NS	NS	VS
	Aggregate coefficient of thermal contraction	NS	NS	NS	NS	VS
Layer/Base (Subbase)	Thickness	S	S	S	S	NS
	Resilient modulus	S	S	S	VS	NS
	Poisson's ratio	NS	NS	NS	NS	NS
	Soil-water characteristic curve	NS	NS	NS	NS	NS
	Permeability	NS	NS	NS	NS	NS
	Compacted/uncompacted	NS	NS	NS	NS	NS
Layer/Subgrade	Resilient modulus	NS	VS	S	S	NS
	Poisson's ratio	NS	NS	NS	NS	NS
	Soil-water characteristic curve	S	S	S	S	NS
	Permeability	NS	NS	NS	NS	NS
	Compacted/uncompacted	NS	NS	NS	NS	NS
HMA/HMA (Rehab)	Milled AC thickness	NS	NS	NS	NS	NS
	Existing AC thickness (after milling)	S	S	S	S	NS
	Existing AC binder grade	S	S	S	S	NS
	Pavement rating	VS	S	VS	VS	NS
	Total rutting	VS	VS	NS	NS	NS
HMA/JPCP (Rehab)	Existing PCC modulus of rupture	NS	NS	NS	NS	NS
	Percent slabs cracked/repared	NS	NS	NS	NS	NS
	Monthly modulus of subgrade reaction	NS	NS	NS	NS	NS
	Month for measuring modulus	NS	NS	NS	NS	NS

3.3 Potential Correlations of Inputs

Correlations of design inputs must be considered whenever two or more inputs tend to change in related ways. Examples of correlated inputs judged in the initial triage to have high sensitivities include:

- resilient modulus, gradation, and plasticity parameters for unbound materials;
- binder grade and viscosity inputs;
- individual Level 1 input values for HMA dynamic modulus;
- individual Level 1 input values for HMA low temperature creep compliance;
- PCC elastic modulus, modulus of rupture, and compressive strength;
- individual Level 1 input values for PCC elastic modulus, modulus of rupture, and compressive strength at 7, 14, 28, and 90 days;
- PCC compressive strength and water-to-cement ratio;
- JPCP dowel diameter/CRCR steel depth and slab thickness.

Changing the value of one correlated variable—e.g., while doing Monte Carlo simulations—requires consistent changes of the values of all other variables to which it is correlated. Failing to account for correlations between variables may lead to unrealistic results (Puertas 2008).

Correlations among model inputs must be identified and quantified *a priori*—i.e., they cannot be determined *post facto* from the results of the sensitivity analyses. Unfortunately, little guidance other than engineering judgment exists at present for identifying or quantifying possible correlations among inputs. In general, it will be easier to identify potentially correlated inputs than to quantify the strength of their correlations.

Some limited information on potential correlations among MEPDG design inputs was gleaned from the NCHRP 1-37A project report (2003) and other relevant literature such as the work of Puertas (2008). However, in the end the project team had to make educated assumptions about the form and magnitude of most correlations. These are described in the detailed methodology documentation in Appendices B and C.

4 METHODOLOGICAL ISSUES

Several methodological issues were also explored in the literature review: sensitivity metrics, sampling methodology, and response surface modeling. Each of these are critical components of the global sensitivity analyses.

4.1 Sensitivity Metrics

It is important to choose the most insightful tool to quantify the impact of model inputs on model outputs. Quantitative sensitivity metrics considered here include:

- *Pearson correlation coefficient.* Also termed the Pearson product-moment correlation coefficient, is a measure of the linear dependence between model output Y and model input X . The Pearson correlation coefficient r for a data samples $X_i, Y_i, i=1...n$ is computed as:

$$r = \frac{\sum_{i=1}^n (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^n (X_i - \bar{X})^2} \sqrt{\sum_{i=1}^n (Y_i - \bar{Y})^2}} \quad (1)$$

The correlation coefficient r ranges from -1 (perfect inverse linear correlation) to +1 (perfect linear correlation), with $r = 0$ indicating zero correlation.

- *Spearman rank correlation coefficient.* The Spearman correlation coefficient is a non-parametric measure of statistical dependence between two variables that assesses how well the two variables agree in terms of a monotonic ranking. Model input and output samples X_i, Y_i are converted to ranks x_i, y_i and the differences $d_i = x_i - y_i$ between the ranks of each sample of the two variables are calculated. If there are no tied ranks, the Spearman correlation coefficient ρ is given by:

$$\rho = 1 - \frac{6 \sum_{i=1}^n d_i^2}{n(n^2 - 1)} \quad (2)$$

The correlation coefficient ρ ranges from -1 (perfect inverse ranking of X_i and Y_i) to +1 (identical ranking of X_i and Y_i), with $\rho = 0$ indicating no agreement in ranking.

- *Non-normalized sensitivity index.* Sensitivity indices are computed as partial derivatives of model outputs to model inputs. Considering the general case where there are multiple model outputs and model inputs, the sensitivity index S_{jk} describing the influence of input X_k on output Y_j is given as:

$$S_{jk} = \frac{\partial Y_j}{\partial X_k} \quad (3)$$

This non-normalized sensitivity index is not dimensionally homogeneous and thus will give different values for different systems of units. As a consequence, normalized sensitivity indices are the preferred alternative.

- *Mean-normalized sensitivity index.* The mean-normalized sensitivity index S_{jk}^μ is defined as:

$$S_{jk}^\mu = \frac{\partial Y_j}{\partial X_k} \bigg|_i \left(\frac{\bar{X}_k}{\bar{Y}_j} \right) \quad (4)$$

This sensitivity index can be interpreted as the percentage change in model output Y_j relative to its mean value caused by a given percentage change in model input X_k relative to its mean value. For example, $S_{jk}^\mu = 0.5$ implies that a 20% change in X_k (relative to its mean value of $\bar{X}_k$) will cause a 10% change in Y_j (relative to its mean value $\bar{Y}_j$). Note that S_{jk}^μ will equal S_{jk}^i in OAT analyses if the model input variations are taken about the mean values (i.e., the mean is the local point).

- *Sigma-normalized sensitivity index.* The sigma-normalized sensitivity index S_{jk}^σ is defined as:

$$S_{jk}^\sigma = \frac{\partial Y_j}{\partial X_k} \bigg|_i \left(\frac{\sigma_{X_k}}{\sigma_{Y_j}} \right) \quad (5)$$

This sensitivity index can be interpreted as the fractional change in model output Y_j relative to its standard deviation σ_{Y_j} caused by a given fractional change in model input X_k relative to its standard deviation σ_{X_k} . For example, $S_{jk}^\sigma = 0.5$ implies that a changing X_k by one standard deviation σ_{X_k} will cause a change in Y_j equal to one-half of its standard deviation σ_{Y_j} . Note that for linear models S_{jk}^σ is equivalent to the standardized regression coefficient (SRC) used in Simlab and elsewhere in the literature (Saltelli *et al.*, 2000).

- *Point-normalized sensitivity index.* The point-normalized sensitivity index S_{ik}^i is defined as:

$$S_{jk}^i = \frac{\partial Y_j}{\partial X_k} \bigg|_i \left(\frac{X_{ki}}{Y_{ji}} \right) \quad (6)$$

in which $\frac{\partial Y_j}{\partial X_k} \bigg|_i$ is the partial derivative and Y_{ji} , X_{ki} are the model output and input values all evaluated at location i . This sensitivity index can be interpreted as the local percentage change in model output Y_j caused by a given percentage change in the model input X_k . For example, $S_{jk}^i = 0.5$ implies that a 20% local change in X_{ki} will cause a 10% change in Y_{ji} .

Correlation coefficients have been employed as the sensitivity metric in many prior studies, in large part because they are easy to compute. Unfortunately, correlation coefficients are limited in that they can identify sensitivities but cannot quantify their relative strengths robustly. Figure 14 illustrates an example in which calculated observations of model output Y_j versus samples of three model inputs X_k , $k=1\dots3$ all lie along respective lines:

$$Y_j = a_k + b_k X_k \quad (7)$$

Since each set of data follows a linear trend and are perfectly ranked, both the Pearson and Spearman correlation coefficients will equal 1 for all three data sets. The mean-normalized sensitivity index for each line can be calculated as:

$$S_{jk}^{\mu} = \frac{\partial Y_j}{\partial X_k} \left(\frac{\bar{X}_k}{\bar{Y}_j} \right) = b_k \left(\frac{\frac{1}{n} \sum_{i=1}^n X_{ki}}{\frac{1}{n} \sum_{i=1}^n (a_k + b_k X_{ki})} \right) = b_k \left(\frac{\sum_{i=1}^n X_{ki}}{a_k + b_k \sum_{i=1}^n X_{ki}} \right) \quad (8)$$

The intercept a_k equals zero for $k=1,2$ and therefore $S_{jk}^{\mu} = 1$; in other words, the mean-normalized sensitivity index is identical in value to the Pearson and Spearman correlation coefficients for these cases. However, for $k=3$ the intercept term a_3 does not equal zero—the condition to be expected in general—and therefore $S_{jk}^{\mu} \neq 1$ in contrast to the Pearson and Spearman coefficients, which remain equal to unity. The mean-normalized sensitivity index S_{jk}^{μ} more consistently captures the true influence of the model inputs; a given percentage change in X_3 causes a lower percentage increase in Y_j than does the same percentage change in X_1 even though the degree of linearity and the slope coefficients are the same in both cases. Clearly, the correlation coefficients are incapable of robustly distinguishing *how much* model output Y_j increases for a given increase in model input X_k in all three cases. Correlation coefficients are best suited for triage—i.e., for determining which inputs are likely to have little sensitivity on outputs because of low correlation coefficients—but not for quantifying these sensitivities.

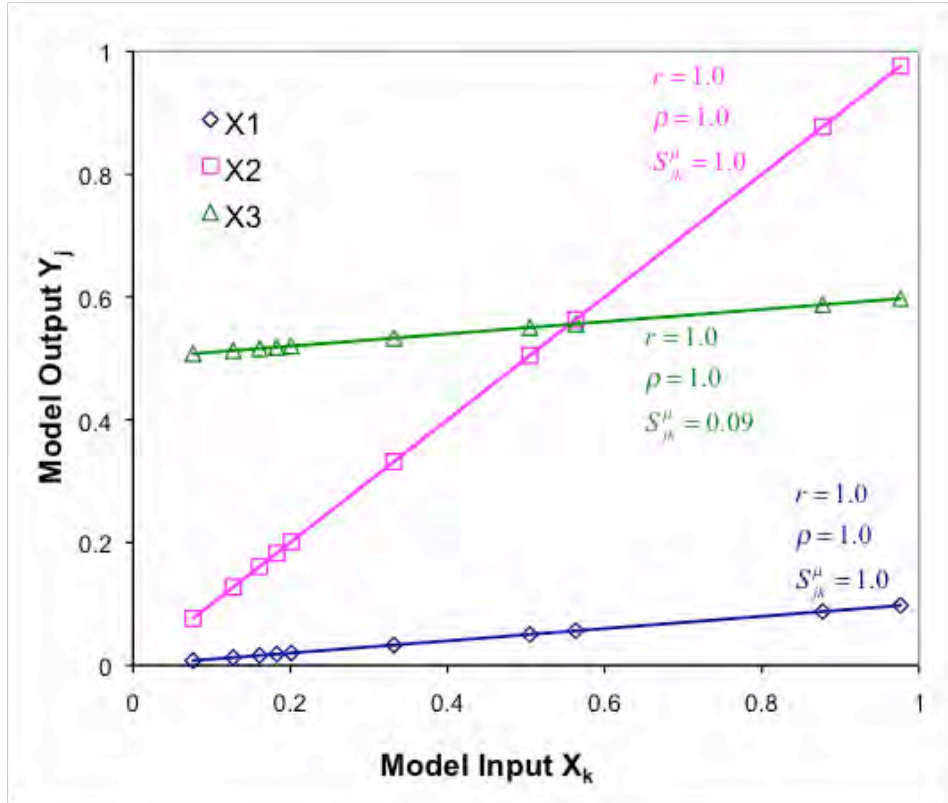


Figure 14. Example of differences between correlation coefficients and sensitivity indices (r = Pearson linear correlation coefficient, ρ = Spearman rank correlation coefficient, S_{jk}^{μ} = mean-normalized sensitivity index).

A simple example based on the 1993 AASHTO rigid pavement design equation effectively illustrates the differences among the various sensitivity metrics. The pavement consists of a 10 inch thick JPCP over a fair subgrade in a temperate environment. The analysis scenario is the simplest case of an OAT partial factorial simulation analysis. Parameters for the simulation are summarized in Table 25.

Table 25. Parameters for 1993 AASHTO rigid pavement OAT sensitivity analysis.

Parameter	Type	Mean Value	Spec Limits	Std Dev	Comments
W_{18}	Natural	1.078E7	N.A.	4.312E6	Mean value consistent with other input mean values; COV=40%.
D	Specification	10 in.	0.5 in.	0.25 in.	Assume Spec Limit = $\pm 2*(\text{Std Dev})$.
ΔPSI	User-Controlled	1.9	$\pm 0.4^1$	0.2	Assume Spec Limit = $\pm 2*(\text{Std Dev})$.
Reliability	User-Controlled	85%	$\pm 10^1$	5	Must convert to Z_R . Assume Spec Limit = $\pm 2*(\text{Std Dev})$.
S_0	User-Controlled	0.35	$\pm 0.05^1$	0.025	Assume Spec Limit = $\pm 2*(\text{Std Dev})$.
p_t	User-Controlled	2.6	0.4	0.2	Assume Spec Limit = $\pm 2*(\text{Std Dev})$.
E_c	Natural	4.0E6 psi	N.A.	4.0E5 psi	Based on $f'_c=5000$ psi; COV=10%.
S_c	Natural	600 psi	N.A.	60 psi	Based on $f'_c=5000$ psi; COV=10%.
J	Natural	2.8	± 0.3	0.15	Dowell bars w/ tied PCC shoulders. Assume Spec Limit = $\pm 2*(\text{Std Dev})$.
k	Natural	25 pci	N.A.	10 pci	COV=40%.
C_d	Natural	1.05	0.05	0.025	Good drainage with 5-25% saturation time. Assume Spec Limit = $\pm 2*(\text{Std Dev})$.

Figure 15 compares several different metrics for the sensitivity of predicted design traffic W_{18} to model inputs. The four sensitivity metrics compared are the Pearson linear and Spearman rank correlation coefficients and the mean-normalized and sigma-normalized sensitivity indices. Note that since this is an OAT sensitivity analysis centered on the mean inputs, the mean- and point-normalized sensitivity indices are identical. It is clear that although all of the metrics are consistent in sense (i.e., positive vs. negative), the magnitudes of the metrics vary enormously for any given model input. The mean/point-normalized sensitivity index exhibits the largest range of values, suggesting that it may be the most powerful metric for drawing practical insights.

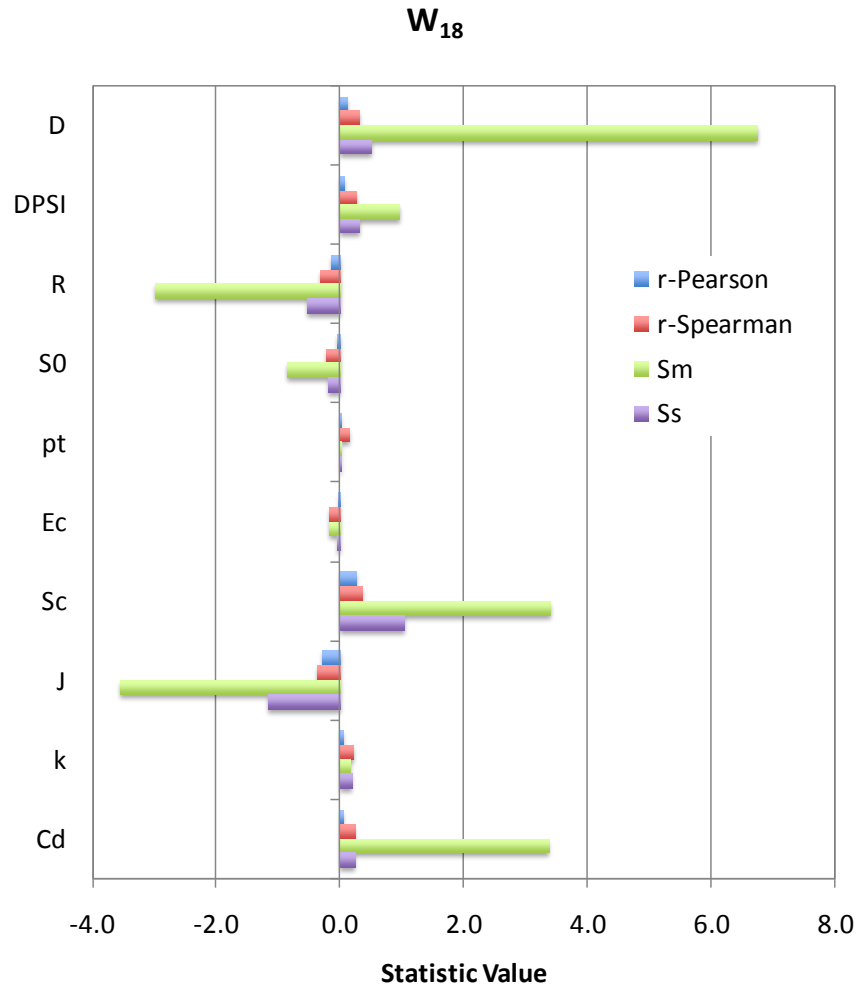


Figure 15. Comparison of input sensitivity metrics for W_{18} model output—1993 AASHTO rigid pavement model.

Given the limited differentiation capabilities of the Pearson and Spearman correlation coefficients and the poorly defined standard deviation values for most MEPDG model inputs, the mean- and point-normalized sensitivity indices are judged the most useful for this study. The advantages of the mean- and point-normalized sensitivity indices are that they can distinguish quantitatively among different levels of sensitivity, they have a clear physical interpretation, and they can be computed using the available information. The mean-normalized index is best suited for giving an overall view of sensitivity while the point-normalized index provides insights on the distribution of sensitivity values over the entire problem domain.

4.2 Sampling Methodology

Global sensitivity analysis (GSA) inevitably requires some form of Monte Carlo simulation. Latin hypercube sampling (LHS) is a widely used variant of the standard or “random” Monte Carlo method. In LHS the range of each of the K model inputs $X_1, X_2, \dots, X_K$ is divided into N intervals in such a way that the probability of the input value falling in any of the intervals is $1/N$. One value is selected at random from each interval. The N values for X_1 are paired randomly with the N values of X_2 ; these

sets are then paired randomly with the N values of X_3 and so on. The resulting N K -tuples are the LHS samples for the GSA. This process can be repeated with a different random seed to generate additional sets of N K -tuples. Correlations among model inputs can also be incorporated in the LHS procedure (Stein, 1987).

For example, consider a model having $K=5$ inputs $X_1, X_2, \dots, X_5$ with each input subdivided into $N=3$ intervals defined for convenience as integers 0, 1, and 2. The set of 3 LHS random samples generated by this procedure might then look as follows:

X_1	X_2	X_3	X_4	X_5
0	2	2	0	2
2	1	0	1	1
1	0	1	2	0

The stratification level N can be increased to generate larger numbers of simulation samples. Alternatively, the LHS procedure can be repeated at the same N using a different random seed:

X_1	X_2	X_3	X_4	X_5
0	2	2	0	2
2	1	0	1	1
1	0	1	2	0
1	1	1	2	1
2	0	0	1	0
0	2	2	0	2

This can be repeated r times to generate a sufficiently large set of $n=r*N$ random samples to achieve stable output statistics and sensitivities and to identify any and all factor interactions.

The efficiency of the LHS approach reduces by a factor of 5 to 20 the required number of simulations as compared to the conventional Monte Carlo method. Unfortunately, there are few good guidelines for how many LHS simulations are required for any given problem. Minimum numbers of simulation samples suggested in the literature include: $(4/3)*K$ (Iman and Helton, 1985); $(3/2)*K$ (Simlab, 2009); $2*K$ (McKay, 1988). Suggested upper bounds for the numbers of simulation samples include: $3*K$ (Manache, 2001); $10*K$ (SimLab, 2009; Saltelli *et al.*, 2004 as reported by Graves and Mahboub, 2006). In reality, both the lower and upper bounds are likely dependent upon the specific problem and on the intended use of the simulation results.

Schuyler (1997) proposed a dynamic “stopping rule” for determining whether a sufficient number of trials have been performed by evaluating $SE_{\bar{y}_j}$, the standard error of the sample mean $\bar{y}_j$ of the predicted model output Y_j :

$$SE_{\bar{y}_j} = \frac{s_{\bar{y}_j}}{\sqrt{n}}$$

in which $s_{\bar{y}_j}$ is the sample standard deviation of Y_j and n is the total number of trials. Schuyler suggests $SE_{\bar{y}_j} < \alpha \bar{y}_j$ as the stopping criteria and recommends $\alpha = 0.01$. Saltelli *et al.* (2008) propose a similar approach.

Since the required number of simulations is a critical quantity for estimating the computational burden for a GSA, the project team evaluated this further by examining the number of simulations required to satisfy the stopping criterion $SE_{\bar{y}_j} < \alpha \bar{y}_j$ using the 1993 AASHTO rigid pavement design models. The simulations were based on the rigid pavement scenario given previously in Table 25. The model was run separately for each of the three possible model outputs W_{18} , D , and ΔPSI . LHS simulation trials were repeated until the slowest converging model output met the stopping criterion. An example of the convergence characteristics of the rigid pavement model is provided in Figure 16; the pavement structure model output D converged the most quickly, while the distress ΔPSI and service life W_{18} converged more slowly but in a similar way.

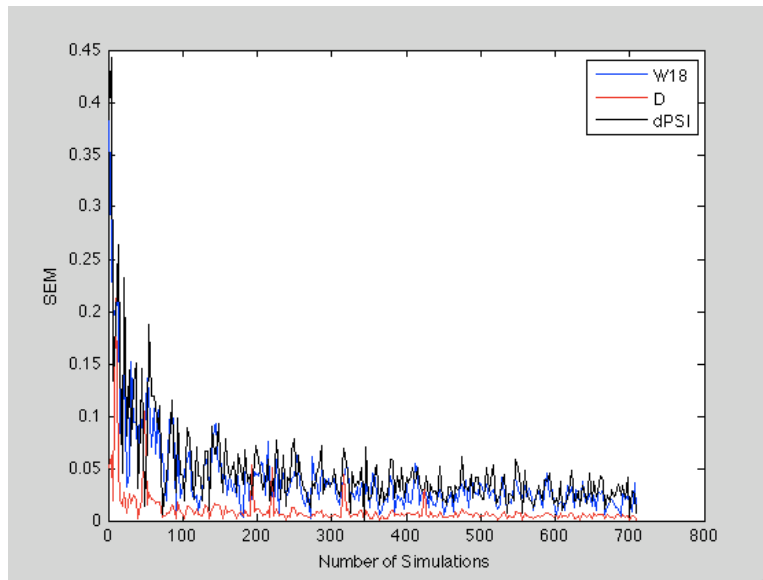


Figure 16. Convergence of 1993 AASHTO rigid pavement model. Stratification level $N=3$, inputs range= $\pm 1.5\sigma$, simulations to convergence=711 ($\alpha=0.01$).

A similar example simulation exercise was performed for the 1993 AASHTO flexible pavement design model. The flexible pavement simulations were based on the pavement scenario given in Table 26. Similar to the rigid pavement simulation, the model was run separately for each of the three possible model outputs W_{18} , SN , and ΔPSI . LHS simulation trials were repeated until the slowest converging model output met the stopping criterion. An example of the convergence characteristics of the flexible pavement model is provided in Figure 17; the pavement structure model output SN converged the most quickly, while the distress ΔPSI and service life W_{18} converged more slowly but in a similar way. The flexible pavement model, which has only $K=5$ inputs for each output,

paradoxically converged more slowly than the rigid pavement model, which has $K=10$ inputs for each output. This may be because many of the rigid pavement design inputs have relatively little effect on predicted performance.

A small parametric study was performed to evaluate the influence of stratification level and input variable range on the LHS convergence characteristics of the 1993 AASHTO rigid and flexible pavement models. Because of the random nature of the LHS sampling, 5 trials were run for each combination of parameters. The results are summarized in Table 27. Key observations from these results include:

- The number of simulations required to achieve convergence was quite variable, as would be expected in a random sampling process.
- The number of simulations to convergence, both in terms of total number of simulations and number of simulations per model input, was consistently and significantly higher for the flexible pavement model than for the rigid.
- As expected, the number of simulations to convergence increased with increasing range of the input values.
- The number of simulations to convergence increased with stratification level N .
- The overall upper bound on the number of simulations per model input required for convergence is approximately 500 for $\alpha=0.01$.

Table 26. Parameters for 1993 AASHTO flexible pavement OAT sensitivity analysis.

Parameter	Type	Mean Value	Spec Limits	Std Dev	Comments
W_{18}	Natural	1.063E6	N.A.	0.425E6	Mean value consistent with other input mean values; COV=40%
SN	Natural	4.08	N.A.	0.82	COV=20% (approx; based on weighted average of a_1 and a_2 COV bumped up slightly to include variability in D_1 , D_2 , and m_2)
ΔPSI	User-Controlled	1.6	$\pm 0.4^1$	0.2	Assume Spec Limit = $\pm 2*(\text{Std Dev})$
Reliability	User-Controlled	85%	$\pm 10^1$	5	Must convert to Z_R . Assume Spec Limit = $\pm 2*(\text{Std Dev})$
S_0	User-Controlled	0.45	$\pm 0.05^1$	0.025	Assume Spec Limit = $\pm 2*(\text{Std Dev})$
M_R	Natural	5000 psi	N.A.	1500 psi	COV=30%

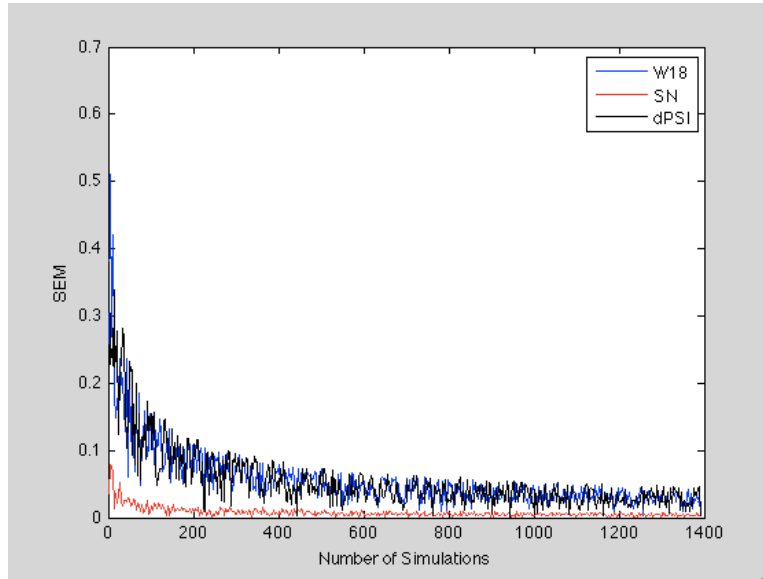


Figure 17. Convergence of 1993 AASHTO flexible pavement model. Stratification level $N=3$, inputs range= $\pm 1.5\sigma$, simulations to convergence=1395 ($\alpha=0.01$).

Table 27. Simulations to satisfy stopping criterion with $\alpha=0.01$ —1993 AASHTO design models.

Input Range	Stratification (<i>N</i>)	Number of Simulations		
		Range (5 trials)	Average (5 trials)	Simulations per Input (<i>n/K</i>)
Rigid Pavement Equation				
+1.0σ	3	231-432	346	35
+1.5σ	3	693-861	788	79
+1.0σ	5	320-650	490	49
+1.5σ	5	880-1415	1131	113
Flexible Pavement Equation				
+1.0σ	3	438-771	550	110
+1.5σ	3	999-1620	1324	265
+1.0σ	5	1350-1835	1609	322
+1.5σ	5	1730-3495	2806	561

The estimates for the required number of simulations in Table 27 are very conservative. They greatly exceed the numbers typically cited in the literature, e.g., $n/K=10$ for SimLab (2009). Schuyler (1997) himself notes that $\alpha=0.01$ is a very severe tolerance. Figure 18 shows the variation in the required number of simulations per input vs. α for the 1995 AASHTO rigid and flexible models. The model inputs vary over a range of $\pm 1.5\sigma$ in $N=5$ stratifications. As before, convergence is defined by the most slowly-converging model output. The trends in Figure 18 show a steep decline in the required number of simulations as α increases.

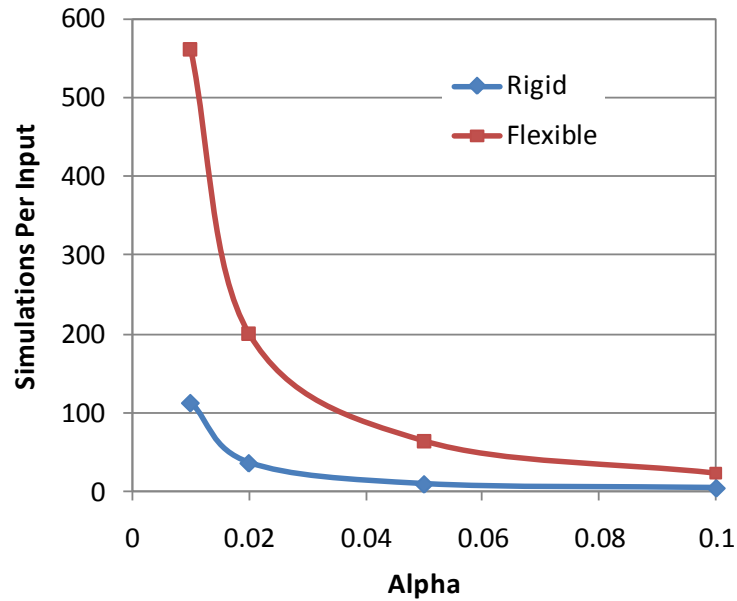
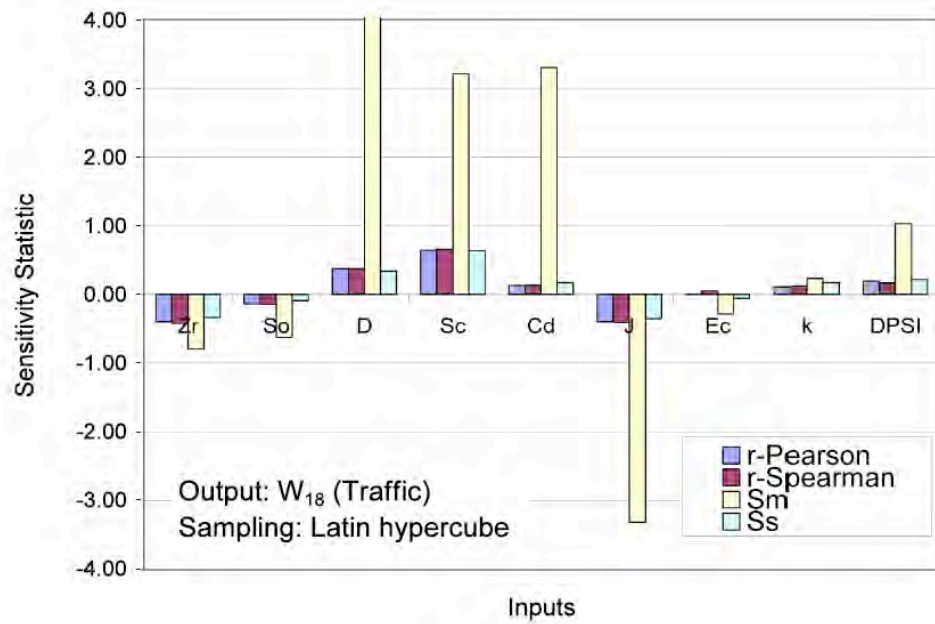


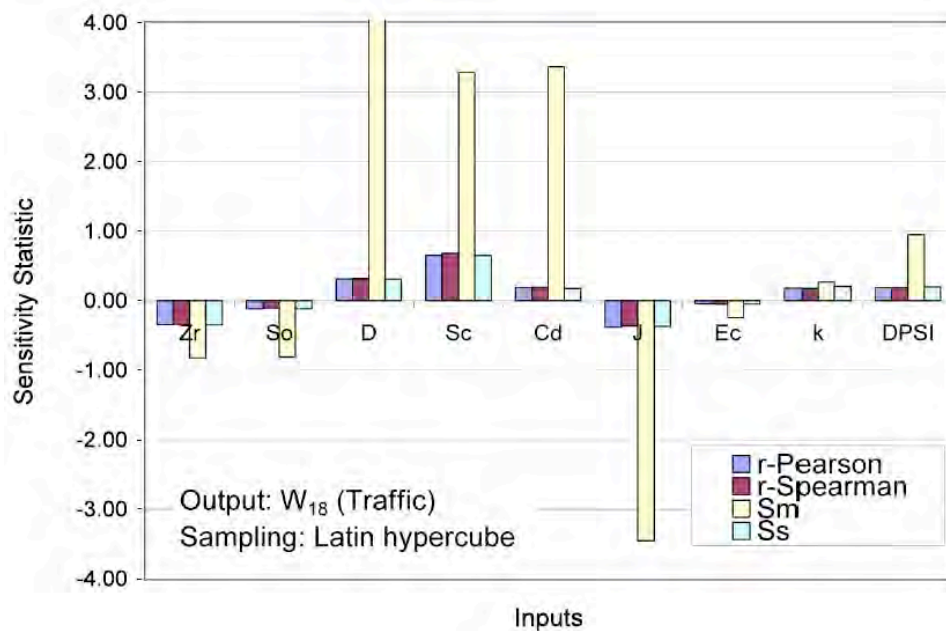
Figure 18. Effect of stopping criterion on number of simulations required per input.

The parametric study summarized in Table 27 and illustrated in Figure 16 through Figure 18 focused on convergence of the standard error of the sample means of the predicted model outputs. A second limited analysis was performed on the 1993 AASHTO rigid pavement model to evaluate the stability of the computed sensitivities of the W_{18} model output as a function of the number of LHS simulations. As shown in Figure 19, the sensitivity metrics after 200 LHS simulations (Figure 19a) were nearly identical to those after 2000 runs (Figure 19b). This suggests that sensitivity metrics may converge more quickly than the standard error of the sample mean of the model output. Figure 20 compares sensitivity metrics after 200 LHS simulations against those after 200 random Monte Carlo samples. Most metrics were in close agreement.

Based on all of the above considerations, Latin hypercube sampling methodology is recommended for the MEPDG global sensitivity analyses. A limited parametric investigation will be performed at the outset to evaluate the impacts of model input value ranges and stratification levels on convergence characteristics of the MEPDG simulations, similar to the study summarized in Table 27 for the 1993 AASHTO models.

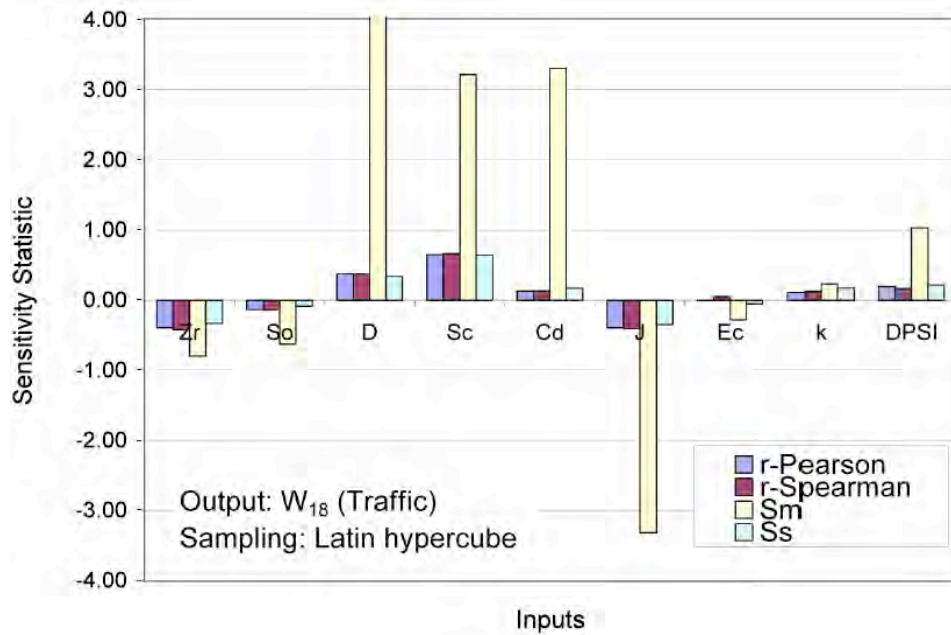


(a) $n=200$

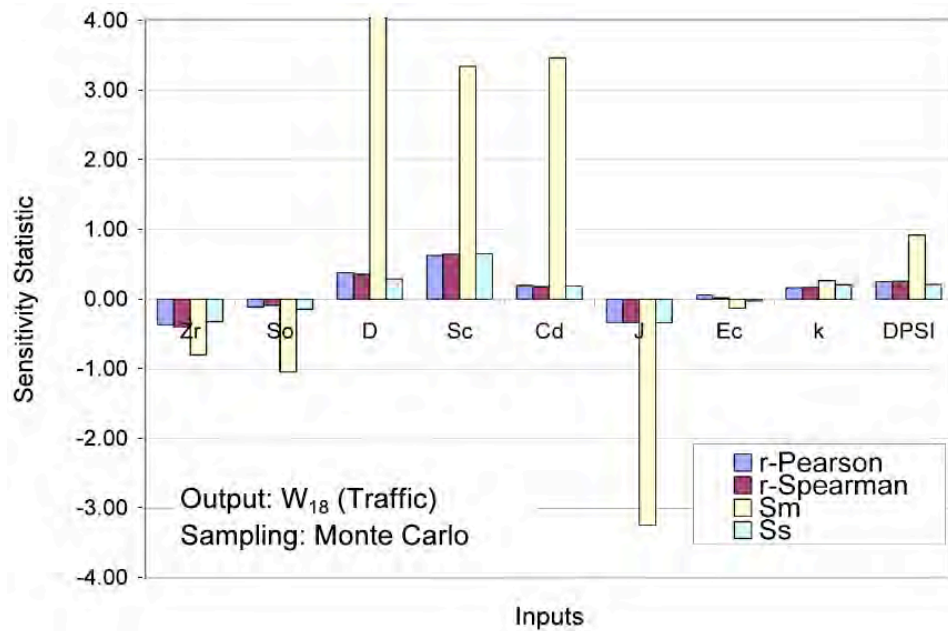


(b) $n=2000$

Figure 19. Comparison of sensitivity metrics to number of Latin hypercube simulations: (a) $n=200$; (b) $n=2000$. 1993 AASHTO rigid pavement design model, output=service life (W_{18}).



(a) Latin hypercube sampling.



(b) Monte Carlo random sampling.

Figure 20. Comparison of sensitivity metrics to sampling scheme: (a) Latin hypercube; (b) random Monte Carlo. 1993 AASHTO rigid pavement design, model output=service life (W_{18}), $n=200$.

4.3 Response Surface Modeling

The Latin hypercube sampling proposed for the GSA will produce a set of model outputs at irregular quasi-random locations within the problem domain—i.e., the overall ranges of the model inputs and outputs. These irregular data can be summarized using simple statistics such as the means and standards deviation of the model outputs and the correlations of model outputs with the model inputs. Response surface modeling enables computation of sensitivity index values throughout the problem domain, which provides more powerful characterization and insights.

The concept and usefulness of response surface modeling is most clearly illustrated in terms of a simple simple analytical model:

$$z = ax^b + cy^d = 0.00090909x^4 + y \quad (9)$$

in which x and y are the model inputs, z is the model output, and a , b , c , and d are the model parameters (generally unknown in a “black box” sense). Sensitivity indices can be defined as usual; for simplicity in this example, they are defined in non-normalized form as:

$$S_x = \frac{\partial z}{\partial x}$$
$$S_y = \frac{\partial z}{\partial y} \quad (10)$$

in which S_x is the sensitivity of the model output z to input x and S_y is the sensitivity of the model output to y .

The analytical model in Eq. (9) can be evaluated at regularly spaced x and y grid points over the problem domain $0 \leq x \leq 10$, $0 \leq y \leq 10$ to produce the contour plot for the model output z shown in Figure 21. This contour plot represents the *true* response surface for the model. The sensitivities defined in Eq. (10) can also be computed at each of the grid points; in this simple example these can be computed analytically, but in the general case they could be computed using finite difference approximations since the grid points in Figure 21 are uniformly spaced. Contour plots of the sensitivities of the model output z to the inputs x and y are shown in Figure 22 and Figure 23.

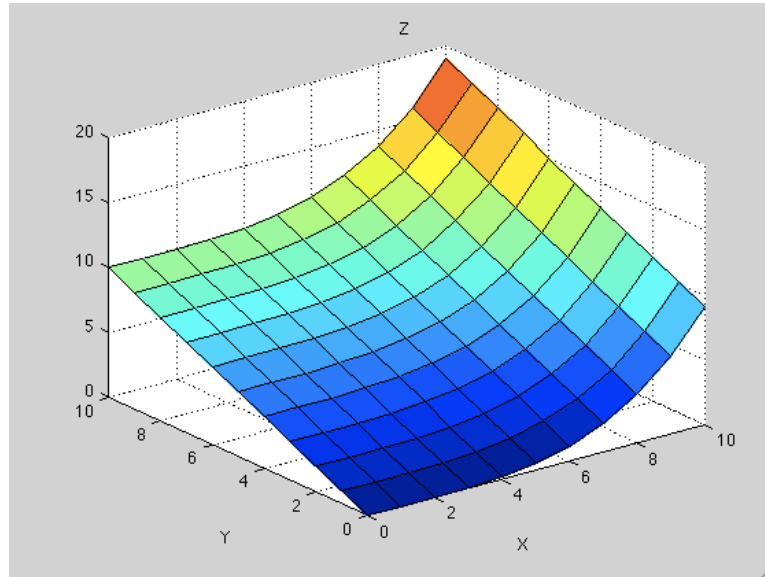


Figure 21. Contour plot of model output for Eq. (9).

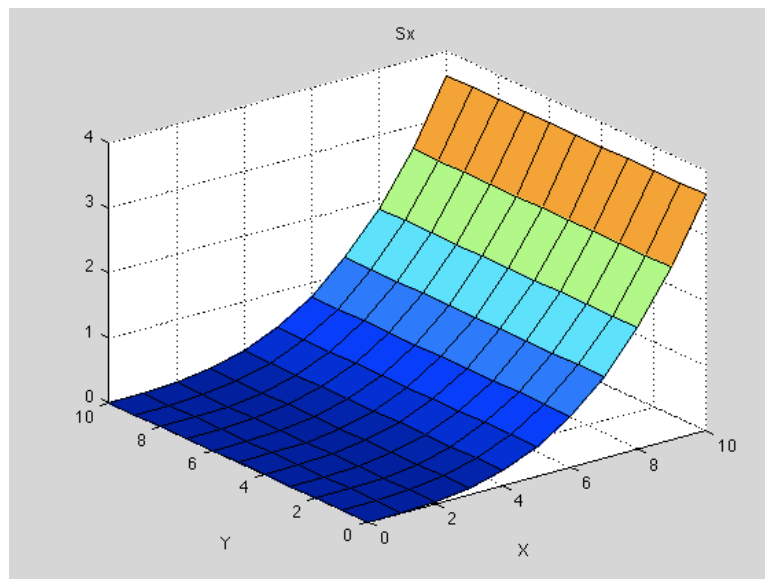


Figure 22. Contour plot of S_x computed from Eqs. (9) and (10).

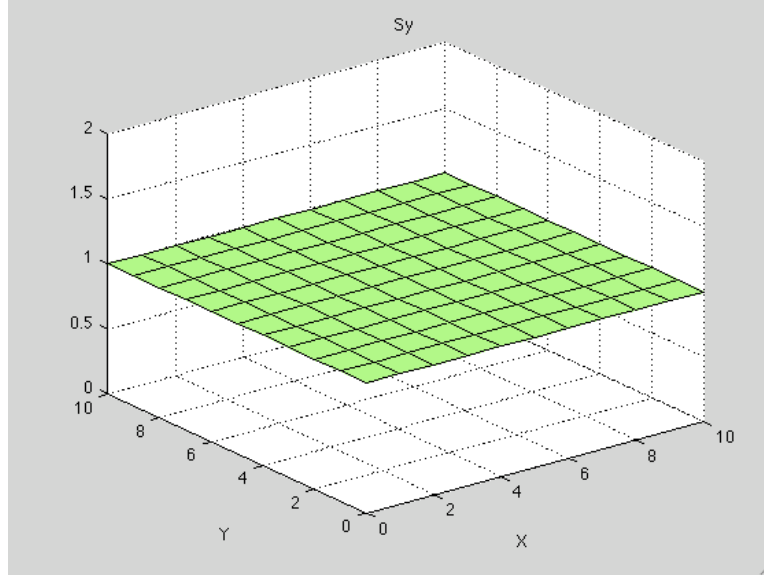


Figure 23. Contour plot of S_y from Eqs. (9) and (10).

It is clear from Figure 22 that the sensitivities of the model outputs to the inputs are not necessarily constant across the input domain. This is the principal reason why local sensitivity analysis is inadequate for complex nonlinear models (this is clear even for the very simple model considered here). Figure 24 and Figure 25 show the distributions of S_x and S_y as computed at each of the regular grid points across the input domain similar to what might be computed in a GSA. Both distributions have the same mean sensitivity value of 1.0. But, while all values of S_y equal a moderate value of 1.0 (Figure 25), the values for S_x vary from 0 to nearly 4 (Figure 24). In other words, the model output is insensitive to input x at some locations in the problem domain but is extremely sensitive to x at others. Clearly, the means of the sensitivity index values are insufficient to fully capture these qualitative differences in model sensitivity.

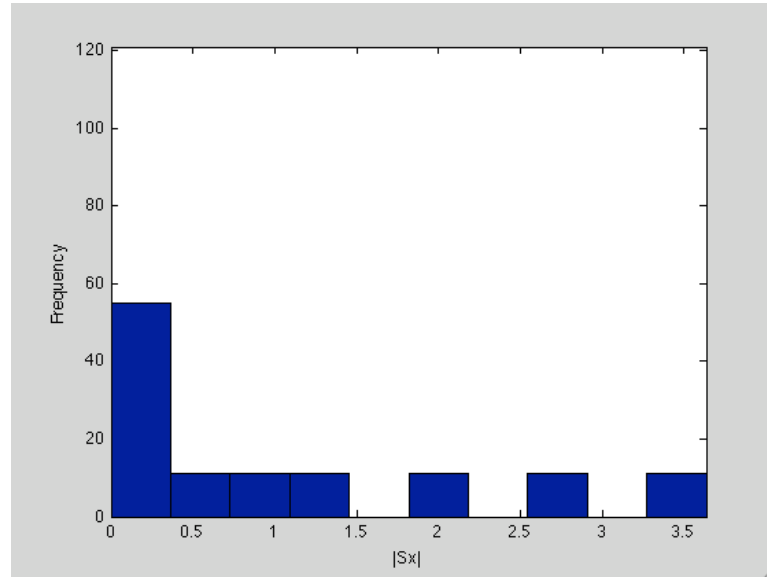


Figure 24. S_x distribution. Minimum=0, maximum=3.63, mean=1.0.

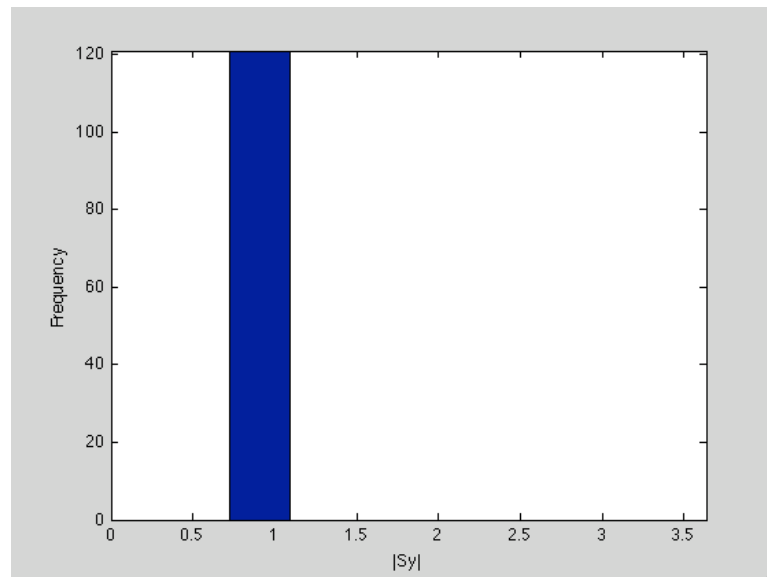


Figure 25. S_y distribution. Minimum=1.0, maximum=1.0, mean=1.0.

The analytical equivalent of Eq. (9) is generally unknown for realistically complicated models. In addition, the set of model results from a GSA will be generated by a Monte Carlo-type simulation and thus will not be available at regularly spaced input grid points as in Figure 21. This makes it impossible to calculate the partial derivatives in Eq. (10) either analytically using calculus or numerically (at least directly) using finite difference approximations. These limitations are a primary motivation for developing an approximate response surface for the model outputs. Derivatives can then be estimated from this approximate response surface—either analytically from regression-based approaches or numerically with neural network techniques—to permit evaluation of sensitivity indices at any location in the problem domain.

The simplest response surface model is a multivariate linear regression equation. This, for example, is the approach implemented in SimLab (2009). The linear response surface for the model given in Eq. (9) can be obtained from a conventional least-squares regression analysis of the set of model results:

$$z = -1.7973 + 0.7782x + 1.0000y \quad R^2 = 0.8813 \quad (11)$$

The sensitivity indices can then be evaluated analytically by taking the partial derivatives of Eq. (3):

$$S_x = \frac{\partial z}{\partial x} = 0.7782 \quad (12)$$

$$S_y = \frac{\partial z}{\partial y} = 1.0000$$

The obvious limitation of this approach is that the sensitivity indices in Eq. (12) obtained from the linear response surface do not vary over the problem domain. The sensitivity indices calculated from a linear response surface approximate of the mean values of the indices but cannot capture the distributional details as in Figure 24 and Figure 25. (Note that the sensitivity indices computed from the linear multivariate regression analysis are mean values in a least squares sense and will in general be slightly different from the arithmetic means.)

Higher order response surface models are required to capture, at least in an approximate way, the variation of sensitivities over the problem domain. These higher order models could be either nonlinear multivariate regression equations or neural network models. A quadratic multivariate regression equation is an example of the first approach:

$$z = a_0 + a_1x + a_2y + a_3xy + a_4x^2 + a_5y^2 \quad (13)$$

Fitting this model to the simulated output from Eq. (9) and Figure 21 using conventional least squares regression techniques gives the model coefficients shown in Table 28.

Table 28. Regression coefficients for quadratic response surface model ($R^2=0.9896$).

Coefficient	Term	Value	t-statistic
a_0	Intercept	0.5891	3.4255
a_1	x	-0.8127	-15.7031
a_2	y	1.0000	19.3216
a_3	xy	0.0000	0.0000
a_4	x^2	0.1592	34.6818
a_5	y^2	0.0000	0.0000

The sensitivity indices computed from this approximate response surface at the same equally spaced grid points as before are summarized in Figure 26 and Figure 27. The quadratic response surface better captures the variation of the sensitivity indices over the problem domain than does the linear surface, although with less fidelity than the true distributions (Figure 22 and Figure 23).

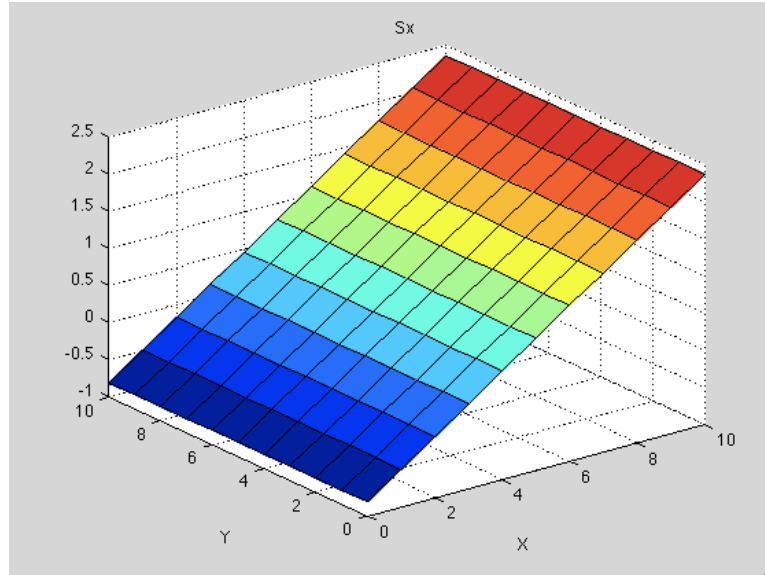


Figure 26. Contour plot of S_x computed from quadratic response surface—Eq. (13).

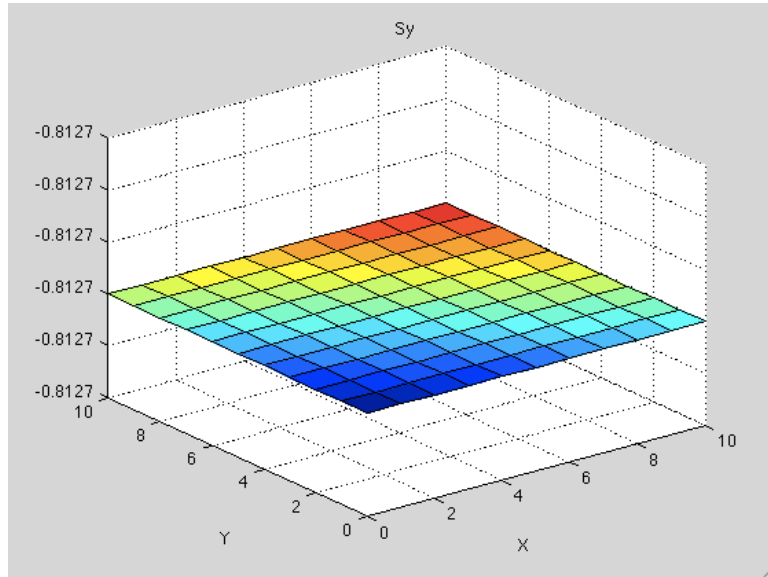


Figure 27. Contour plot of S_y computed from quadratic response surface—Eq. (13).

Frequency distributions and summary statistics for the sensitivity indices computed from the quadratic response surface are summarized in Figure 28 and Figure 29. The comparison with the “true” distributions in Figure 24 and Figure 25 are reasonable. This applies also to the range and mean summary statistics of the sensitivity indices.

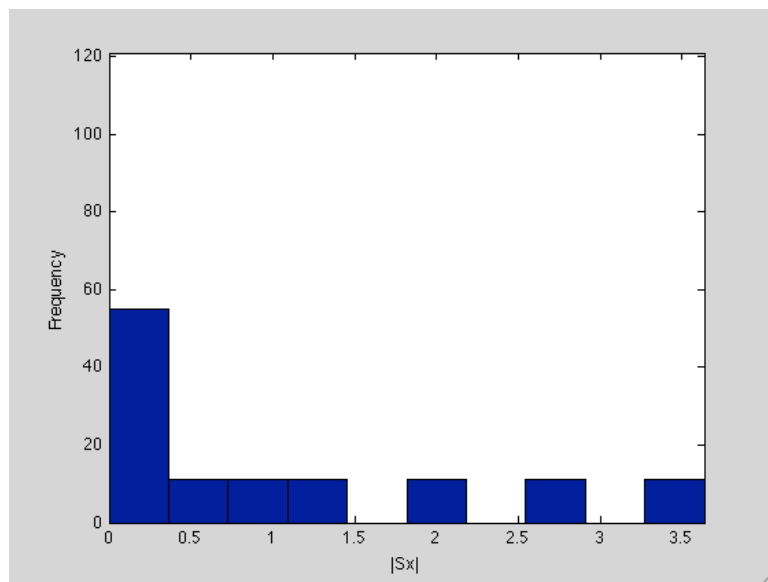


Figure 28. S_x distribution from quadratic response surface—Eq. (13). Minimum=0.1418, maximum=2.3691, mean=1.0479.

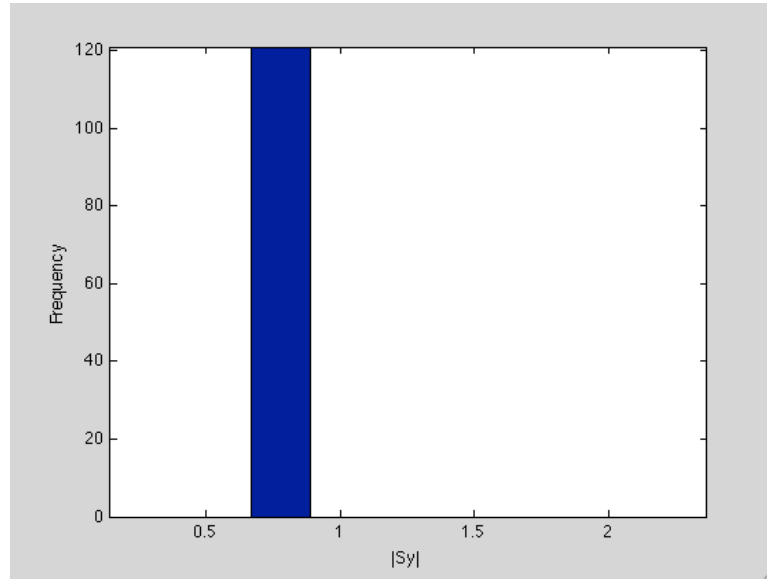


Figure 29. S_x distribution from quadratic response surface—Eq. (13). Minimum=0.8127, maximum=0.8127, mean=0.8127.

In addition to enabling a more robust description of the distribution of sensitivity index values over the entire problem domain, response surface modeling also enables the evaluation of interactions among model inputs. For example, the term a_3xy in the response surface Eq. (13) captures the interactions between model inputs x and y . Since there is no interaction between these inputs in the true underlying process as defined by Eq. (9), the coefficient a_3 sensibly has a value of zero (Table 28).

The simple example described above highlights the power of response surface modeling for capturing the distribution of sensitivity index values over the problem domain and for evaluating interactions among model inputs. Instead of multivariate nonlinear regression (e.g., Eq. (13) or equivalent), however, artificial neural networks (ANN) will be used to generate the response surfaces. ANN modeling is similar to multivariate nonlinear regression but does not require an *a priori* definition of a functional form for the model. Sensitivity index values can be computed from the ANN model numerically using standard finite difference techniques. Interactions among model inputs can also be evaluated numerical via sampling.

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APPENDIX B: ONE-AT-A-TIME LOCAL SENSITIVITY ANALYSES

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1 INTRODUCTION

Some preliminary one-at-a-time (OAT) local sensitivity analyses were performed during the preliminary triage as part of the effort to categorize the importance of the various MEPDG inputs. More comprehensive OAT local sensitivity analyses were subsequently conducted for each base case as a complement to the global sensitivity analysis (GSA). The two primary objectives of the OAT sensitivity analyses are:

- (1) To confirm the “sensitive” and “very sensitive” design inputs identified in the preliminary triage; and
- (2) To narrow the sets of inputs needed for the computationally intensive GSA simulations.

Over 3800 MEPDG runs were performed for the OAT analyses. This appendix documents the OAT analysis methodology, design input values, results, and findings.

2 GLOBAL INPUTS

There are two sets of global inputs used in all OAT analyses: climate conditions and traffic levels. There are 5 climate zones: Hot-Dry, Hot-Wet, Temperate, Cold-Dry, and Cold-Wet. The specific locations, the weather station used to generate the climate files, the baseline binder grade recommended by LTPPBinder, and the range of binder grades considered in the OAT analysis for each climate category are summarized in Table 2.1.

Table 2.1. Climate categories for base cases.

Climate Category	Location	Weather Station	Binder Grade	
			Baseline	Range
Hot-Wet	Orlando FL	ORLANDO INTERNATIONAL ARPT	PG 70-10	PG 64-10 PG 76-10
Hot-Dry	Phoenix AZ	PHOENIX SKY HARBOR INTL AP	PG 76-10	PG 70-10 PG 82-10
Cold-Wet	Portland ME	PORTLAND INTL JETPORT ARPT	PG 52-28	PG 52-34 PG 52-22
Cold-Dry	Spokane WA*	SPOKANE INTERNATIONAL ARPT	PG 58-28	PG 58-34 PG 58-22
Temperate	Los Angeles CA	LOS ANGELES INTL AIRPORT	PG 58-10	PG 52-10 PG 64-10

*During the OAT analyses it was determined that Spokane WA was not sufficiently cold to generate significant thermal cracking. Consequently, International Falls MN is proposed as a replacement to represent Cold-Dry climate for GSA. See the transverse cracking discussion in Section 6.2 and Section 7.2 for detail.

The three traffic levels used in all OAT analyses are summarized in Table 2.2. The baseline AADTT values are designed to fall within the low (<5,000), medium (5,000-10,000), and high (>15,000) truck volume categories in Table 6.4 of the FHWA *FAF² Freight Traffic Analysis Report*.¹ To put these traffic volumes into a more familiar context, the approximate number of ESALs for flexible and rigid pavements are also included in Table 2.2. The AADTT ranges in the last column of Table 2.2 are designed to be continuous in log(AADTT) space.

Table 2.2. Traffic ranges for base cases.

Traffic Category	Baseline Inputs			AADTT Range
	AADTT ¹	Est. ESALs (Flexible) ²	Est. ESALs (Rigid) ³	
Low	1,000	2M	5M	500-5,000
Medium	7,500	10M	25M	5,000-10,000
High	25,000	30M	75M	20,000-30,000

¹Based on MEPDG Interstate Highway TTC4 Level 3 default vehicle distribution.

²Based on 15 year design life.

³Based on 25 year design life.

The five climate zones and three traffic levels give a total of 15 base cases for the sensitivity analyses. The combinations and abbreviations for each are as follows:

¹ http://ops.fhwa.dot.gov/freight/freight_analysis/faf/faf2_reports/reports7/

CDL	Cold-Dry-Low-Traffic
CDM	Cold-Dry-Medium-Traffic
CDH	Cold-Dry-High-Traffic
CWL	Cold-Wet-Low-Traffic
CWM	Cold-Wet-Medium-Traffic
CWH	Cold-Wet-High-Traffic
TL	Temperate-Low-Traffic
TM	Temperate-Medium-Traffic
TH	Temperate-High-Traffic
HDL	Hot-Dry-Low-Traffic
HDM	Hot-Dry-Medium-Traffic
HDH	Hot-Dry-High-Traffic
HWL	Hot-Wet-Low-Traffic
HWM	Hot-Wet-Medium-Traffic
HWH	Hot-Wet-High-Traffic

3 SPECIAL INPUT CONSIDERATIONS

3.1 Unbound Material Properties

The MEPDG needs unbound material gradation as inputs at all three input levels. The only unbound design inputs in the “Very Sensitive” or “Sensitive” categories from the preliminary triage were the base M_r and the subgrade M_r and SWCC. The SWCC curve parameters as they are expected to be determined in practice (i.e., as Level 3 inputs) are functions of the percent passing the No. 200 sieve (P_{200}), the D_{60} gradation parameter, and the plasticity index (PI). The P_{200} , D_{60} and PI parameters will be highly correlated to M_r , which in turn is primarily a function of soil type. Therefore, the recommended procedure for the sensitivity analyses is to first select a design input value for M_r and then use correlation relations to determine compatible values of P_{200} , D_{60} , and PI.

Although only the P_{200} and D_{60} gradation parameters are required for the OAT sensitivity analyses, D_{60} is not a direct user input but rather is derived internally within the MEPDG from the gradation curve. The MEPDG requires a minimum of five gradation inputs including the percentages passing the No. 4, No. 40, and No. 200 sieves. In actuality, the Level 3 default gradation data includes twelve sieves; Table 3.1 shows the Level 3 default gradation information for all AASHTO soil types as defined in the MEPDG. The input gradation data must be consistent with the P_{200} and D_{60} values that in turn must be compatible with the design M_r . A short study was conducted to determine whether synthetic gradation data could be generated to satisfy these requirements.

Table 3.1. Gradation information of all the soil types built in the MEPDG.

Sieve #	Opening (mm)	A-1-a	A-1-b	A-2-4	A-2-5	A-2-6	A-2-7	A-3	A-4	A-5	A-6	A-7-5	A-7-6
#200	0.075	8.7	13.4	22.4	30	24.8	27.4	5.2	60.6	54.3	63.2	70.5	79.1
#80	0.18	12.9	20.8	42.3	46	32.4	32.0	33.0	73.9	66.2	73.5	77.7	84.9
#40	0.425	20.0	37.6	67.2	61	43.5	37.1	76.8	82.7	74.3	82.4	83.3	88.8
#10	2	33.8	64.0	82.5	75	59.4	47.6	93.4	89.9	82.6	90.2	90.8	93.0
#4	4.75	44.7	74.2	87.2	81	67.2	55.4	95.3	93.0	86.9	93.5	94.0	94.9
3/8"	9.52	57.2	82.3	91.6	88	78.8	72.4	96.6	95.6	90.2	96.4	95.7	96.9
1/2"	12.5	63.1	85.8	93.5	90	83.3	78.1	97.1	96.7	91.9	97.4	96.3	97.5
3/4"	19	72.7	90.8	95.9	94	90.4	85.3	98.0	98.0	94.1	98.4	97.3	98.3
1"	25.4	78.8	93.6	97.2	98	94.5	89.1	98.6	98.7	95.9	99.0	97.9	98.8
1 1/2"	38.1	85.8	96.7	98.5	100	97.7	94.6	99.2	99.4	97.5	99.5	98.4	99.3
2"	50.8	91.6	98.4	99.0	100	99.4	97.0	99.7	99.6	98.5	99.8	98.8	99.6
3 1/2"	88.9	97.6	99.4	99.6	100	99.9	100	99.9	99.8	99.5	100	99.3	99.9

A general soil gradation curve can be modeled as a sigmoidal function having a maximum value of 100% passing and a minimum value of 0%:

$$Y = 0 + \frac{100}{1 + e^{\beta + \gamma \log_{10}(X)}} \quad (3.1)$$

in which X represent the opening size (mm) and Y represents the percentage passing the opening size. The fitting parameters β and γ in Eq. (3.1) could be determined for each soil type via regression analysis on the data in Table 3.1. However, since P_{200} and D_{60} will be determined from correlations with M_r , it is preferable to determine the β and γ parameters from P_{200} and D_{60} instead. This can be easily done by evaluating Eq. (3.1) at the D_{60} and P_{200} data values. Taking an A-3 soil type as an example, D_{60} is 0.3255 mm and P_{200} is 5.2%. Equation (3.1) then can be written as:

$$\begin{aligned}
D_{60} = 60 &= 0 + \frac{100}{1 + e^{\beta + \gamma \log_{10}(0.3255)}} \\
P_{200} = 5.2 &= 0 + \frac{100}{1 + e^{\beta + \gamma \log_{10}(0.075)}}
\end{aligned}
\tag{3.2}$$

Solving simultaneously:

$$\begin{aligned}
\beta &= -2.93533 \\
\gamma &= -5.19001
\end{aligned}
\tag{3.3}$$

The full gradation curve is then:

$$Y = 0 + \frac{100}{1 + e^{-2.93533 - 5.19001 \log_{10}(X)}}
\tag{3.4}$$

Table 3.2 compares the predicted gradations from Eq. (3.4) with the Level 3 default values for the A-3 soil example. The R^2 is 0.9894, confirming excellent agreement.

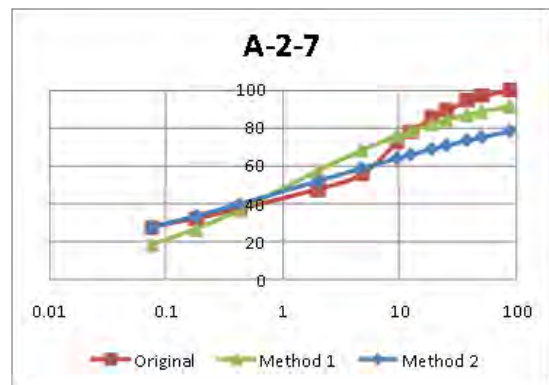
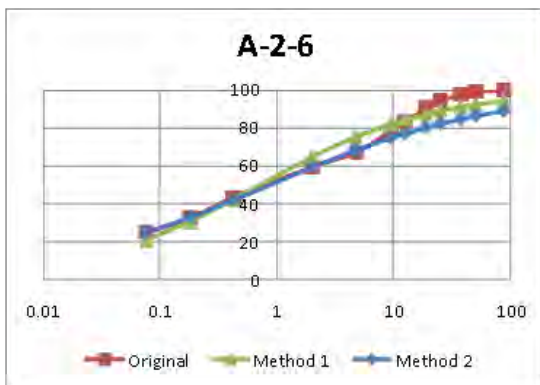
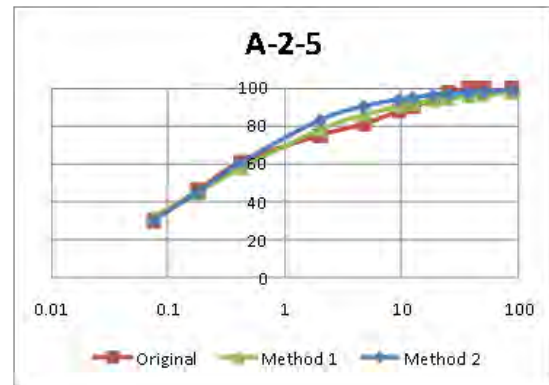
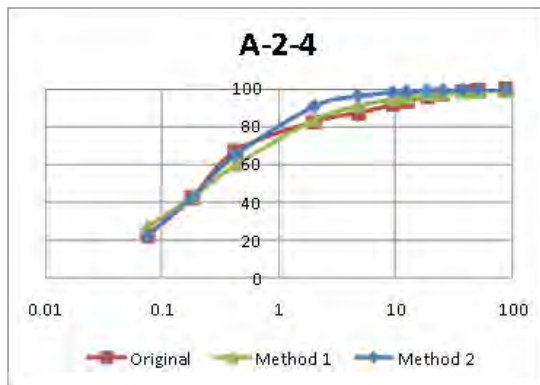
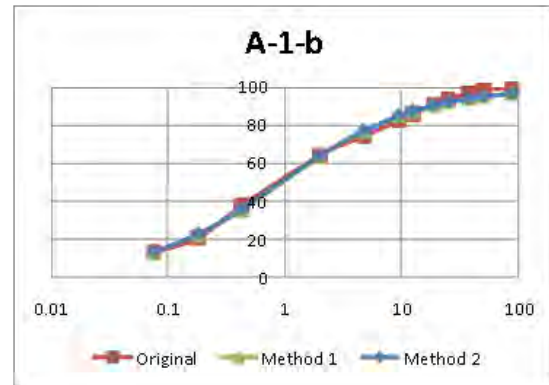
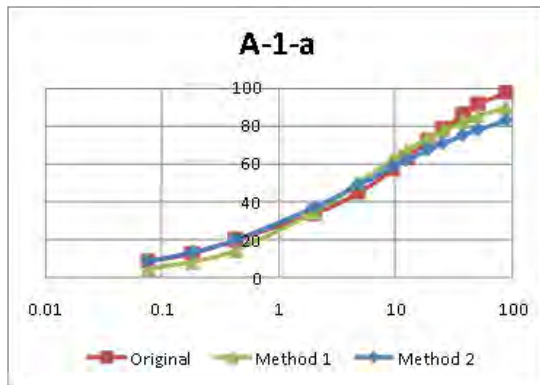
Table 3.2. Example soil gradation.

Sieve #	Opening (mm)	A-3	
		Level 3 Defaults (Table 3.1)	Predicted (Eq. 3.4)
#200	0.075	5.2	5.2
#80	0.18	33.0	28.3
#40	0.425	76.8	73.2
#10	2	93.4	98.9
#4	4.75	95.3	99.8
3/8"	9.52	96.6	100.0
1/2"	12.5	97.1	100.0
3/4"	19	98.0	100.0
1"	25.4	98.6	100.0
1 1/2"	38.1	99.2	100.0
2"	50.8	99.7	100.0
3 1/2"	88.9	99.9	100.0

The R^2 values for the fitted soil gradations for all soil classifications are summarized in Table 3.3. Two fitting methods are included: Method 1, a conventional least squares regression fit of Eq. (3.1) to the full gradation data in Table 3.1; and Method 2, the two-point direct determination of the fitting parameters using D_{60} and P_{200} as in Eq. (3.2). Figure 3.1 provides a visual comparison between the default Level 3 soil gradation data in the MEPDG and the fitted sigmoidal curves using these two methods. The two-point method gives R^2 values greater than 0.9 for all soils other than A-2-7 ($R^2=0.71$), A-4 ($R^2=0.82$) and A-6 ($R^2=0.895$). These results suggest that the two-point method is suitable for generating synthetic gradation information.

Table 3.3. R^2 values of fitted gradation curves.

Soil Type	A-1-a	A-1-b	A-2-4	A-2-5	A-2-6	A-2-7	A-3	A-4	A-5	A-6	A-7-5	A-7-6
Method 1	0.9755	0.9952	0.9841	0.9816	0.9647	0.9218	0.9924	0.9919	0.9842	0.9936	0.9962	0.9867
Method 2	0.9399	0.9950	0.9654	0.9613	0.9022	0.7108	0.9894	0.8153	0.9836	0.8954	0.9952	0.9393



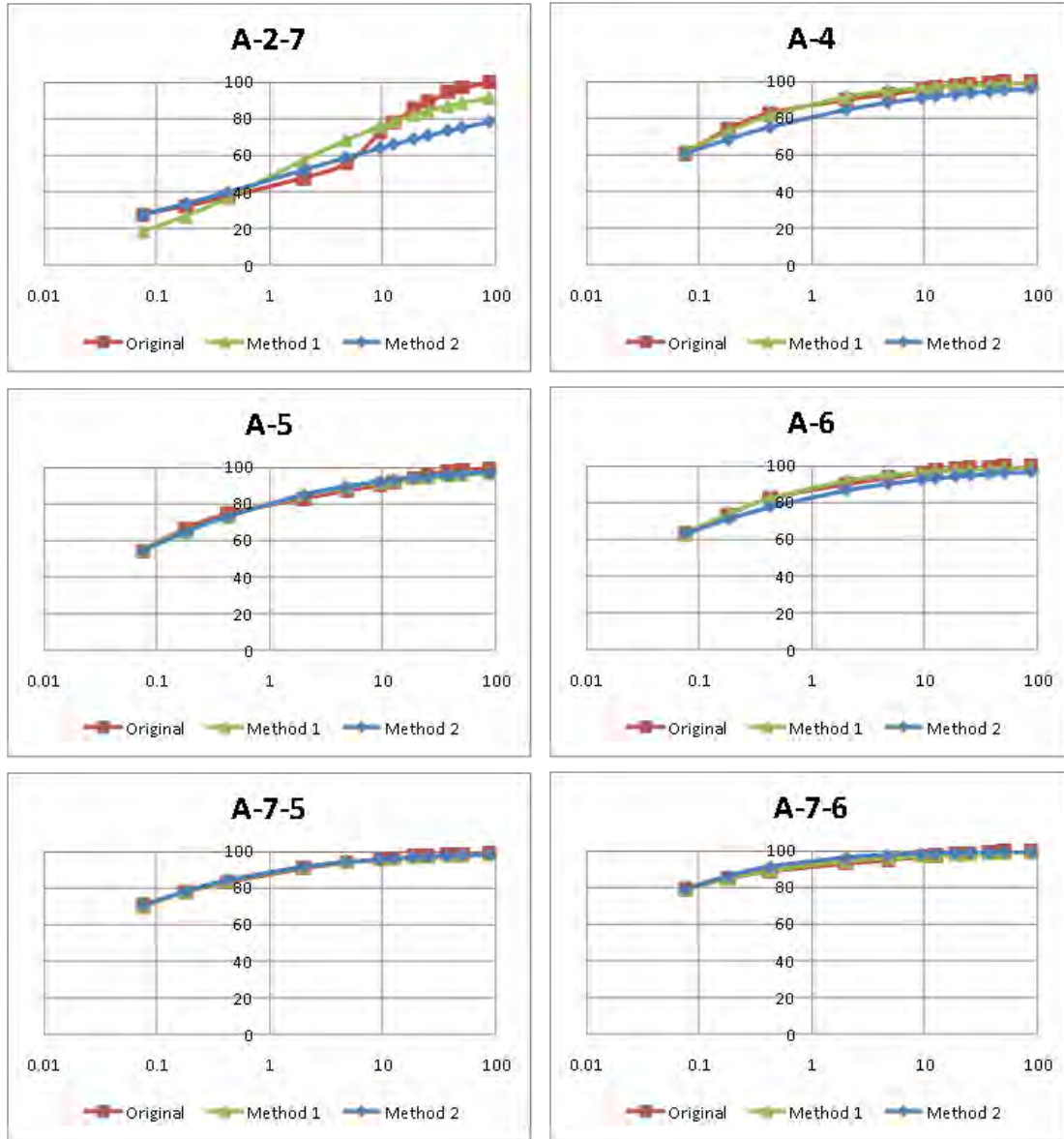


Figure 3.1. Comparisons between predicted gradation curves and original data.

The relationships between D_{60} and M_r and between P_{200} and M_r can be captured by the following nonlinear and/or composite models:²

P_{200} vs. M_r :

$$P_{200} = \frac{100}{1 + \exp(-42.2678 + 10.0223 \cdot \log(M_r))} \quad (3.5)$$

² The A-2-6 and A-2-7 soil classes are excluded as outliers.

D_{60} vs. M_r :

$$\begin{aligned}
 D_{60} &= \frac{100}{1 + \exp(42.8844 - 8.45632 \log(M_r))} & M_r < 17000 \\
 D_{60} &= 0.00003M_r - 0.3846 & M_r \geq 17000 \\
 D_{60} &= 100 & D_{60} > 100
 \end{aligned} \tag{3.6}$$

A visual verification of the quality of the models is shown in Figure 3.2. The figure on the right is plotted with a logarithmic vertical scale in order to better illustrate the D_{60} vs. M_r relationship. All the data points are close to the model curves, indicating a good model fit.

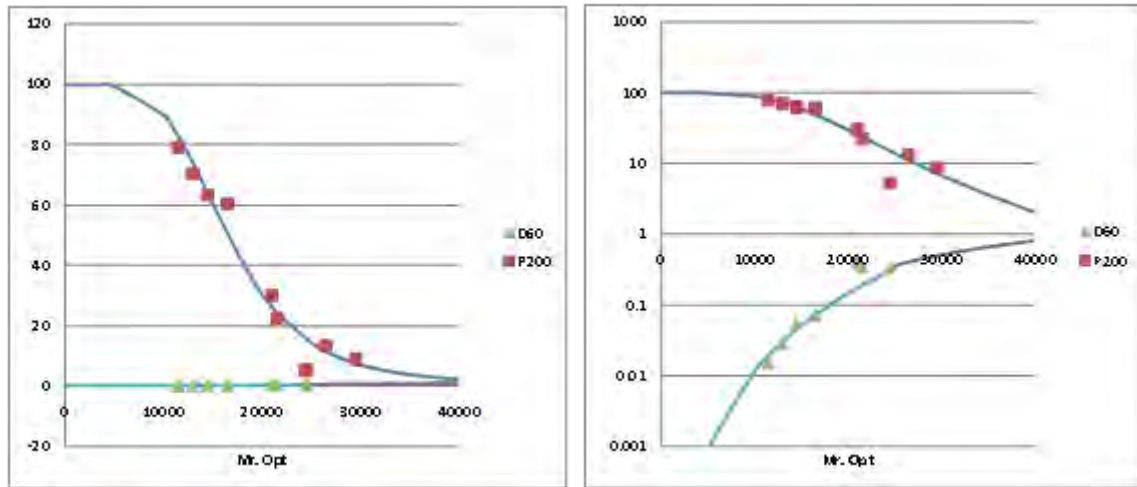


Figure 3.2. P200 and D_{60} vs. unbound resilient modulus.

In summary, the process for generating gradation and plasticity data for unbound materials in the OAT sensitivity analyses is as follows:

- 1) The design input value for M_r is established.
- 2) Baseline values for P_{200} and D_{60} that are compatible with the M_r design input value are determined using Eqs. (3.5) and (3.6). The effect of less-than-perfect correlations between P_{200} and M_r and between D_{60} and M_r are incorporated by independently varying P_{200} and D_{60} about their baseline values in the OAT sensitivity analyses.
- 3) The baseline P_{200} and D_{60} values are used to compute the β and γ parameters (Eq. 3.2), which in turn are used to generate the full gradation curve (Eq. 3.1).
- 4) The baseline value for PI that is compatible with the M_r design input is determined from:³

$$PI = 283.45 - 27.84 \ln(M_r), PI \geq 0 \quad (R^2 = 0.69) \tag{3.7}$$

³ Excludes A-2-7 soil class.

The goodness-of-fit of this improved relation is illustrated in Figure 3.3.3.

- 5) A liquid limit (LL) value must also be input into the MEPDG. The only requirement on the LL is that it be larger than the PI. However, following techniques similar to those for Eq. (3.7) the following relation was derived to determine LL values compatible with the design M_r input:

$$LL = 218.44e^{-M_r/10000}, LL \geq 0 \quad (R^2 = 0.74) \quad (3.8)$$

The goodness of fit of this relation is illustrated in Figure 3.3.4.

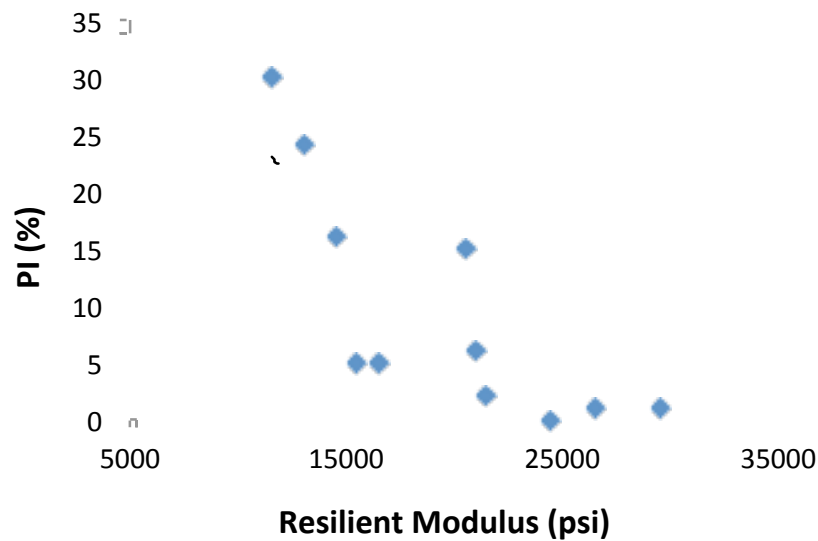


Figure 3.3.3. Relationship between MEPDG Level 3 default values for PI and M_r .

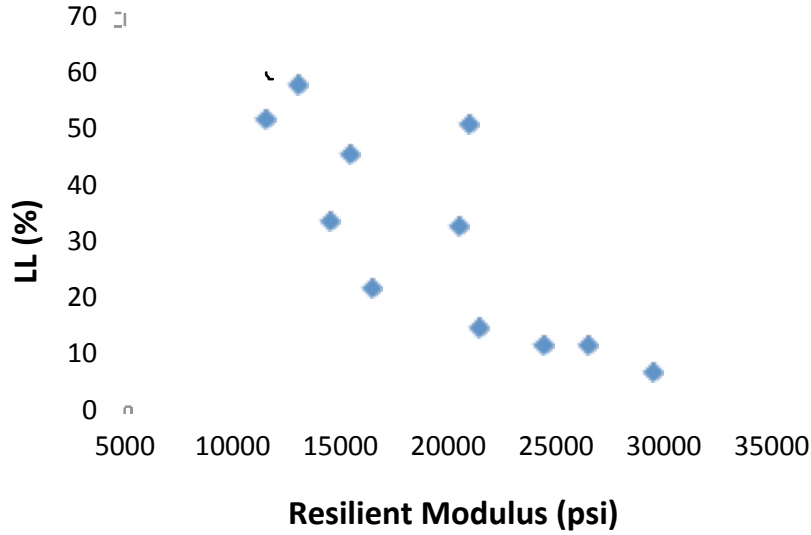


Figure 3.3.4. Relationship between MEPDG Level 3 default values for LL and M_r .

3.2 HMA Dynamic Modulus

HMA dynamic modulus E^* is a highly sensitive input in the MEPDG performance predictions. However, varying E^* in a systematic way must be done with care. Dynamic modulus is multivalued—i.e., it varies with temperature and loading rate as a function of the viscosity characteristics of the binder. The E^* design inputs for the OAT analyses are specified via synthetic Level 1 E^* vs. temperature vs. frequency data generated using the sigmoidal master curve function:

$$\log(E^*) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma \log t_r}} \quad (3.8)$$

in which:

- E^* = dynamic modulus
- t_r = loading time at the reference temperature
- δ, α = fitting parameters; δ represents the minimum value (lower shelf) for E^* and $\delta + \alpha$ represents the maximum value (upper shelf)
- β, γ = fitting parameters describing the shape (horizontal location and slope) of the sigmoidal function in the transition region between the lower and upper shelves

Equation (3.8) is the basis for the Witczak E^* predictive model:

$$\log(E^*) = \delta + \frac{\alpha}{1 + e^{(-0.603313 - 0.313351 \log f - 0.393532 \log \eta)}} \quad (3.9)$$

in which:

- E^* = dynamic modulus, psi
- η = binder viscosity, 10^6 Poise

$$\begin{aligned}
f &= \text{loading frequency, Hz} \\
\delta &= 3.750063 + 0.02932\rho_{200} - 0.001767(\rho_{200})^2 - 0.002841\rho_4 \\
&\quad - 0.058097V_a - 0.802208\left(\frac{V_{beff}}{V_{beff} + V_a}\right)
\end{aligned} \tag{3.10}$$

$$\alpha = 3.871977 - 0.0021\rho_4 + 0.003958\rho_{38} - 0.000017(\rho_{38})^2 + 0.005470\rho_{34} \tag{3.11}$$

$$\beta = -0.603313 - 0.393532\log\eta \tag{3.12}$$

V_a = air void content, %

V_{beff} = effective bitumen content, % by volume

ρ_{34} = cumulative % retained on the 3/4 in sieve

ρ_{38} = cumulative % retained on the 3/8 in sieve

ρ_4 = cumulative % retained on the No.4 in sieve

ρ_{200} = % passing the No. 200 sieve

The following observations can be drawn from Witczak model regarding the four fitting parameters in the sigmoidal master curve function (Eq. 3.9): (a) the lower and upper shelves (δ and $\delta+\alpha$) are functions only of mixture gradation and volumetrics; (b) the shape parameter β is a function only of the binder viscosity, which in turn is a function of temperature; (c) the shape parameter γ is a constant; and (d) loading time t_r is replaced by its inverse, frequency f . Therefore, in order to generate synthetic Level 1 E^* data at various temperatures and frequencies f , it is necessary to establish the appropriate constant values for δ , α , and γ and the temperature-specific binder viscosity η . The OAT sensitivity analyses can then vary δ , α , and η about their baseline values.

The baseline values for δ and α were determined for a typical 19.0 mm Superpave dense graded mixture having the following gradation and volumetric properties:

$$\begin{aligned}
V_a &= 6.47\% \\
V_{beff} &= 10.08\% \\
\rho_{34} &= 5.5\% \\
\rho_{38} &= 33.5\% \\
\rho_4 &= 55.5\% \\
\rho_{200} &= 4.9\%
\end{aligned}$$

These values when substituted into the Witczak E^* predictive model produce values of $\delta = 2.8291$ and $\alpha = 3.8990$. These values lie close the means for the 346 mixtures included in the enhanced Bari and Witczak (2006) database, as shown in Table 3.4. It is important to note that the ranges of δ and α (Table 3.4) are very narrow; the total spreads between the maximum and minimum values for the 346 mixtures are only 28% and 7% of their respective means. This is consistent with the finding by Ceylan *et al.* (2010) and others that the Witczak predictive model is dominated by binder influences and is relatively insensitive to mixture factors such as gradation and volumetrics.

Table 3.4. Statistics for δ and α from Bari and Witczak (2006) database.

	δ	α
Mean	2.8249	3.8864
Standard Deviation	0.0999	0.0628
Coef. of Variation	3.5%	1.6%
Minimum	2.2144	3.7838
Maximum	3.0121	4.0610
Range	0.7977	0.2772

In the MEPDG, the binder viscosity η used to determine β is a function only of binder grade and temperature. Each climate category has an appropriate baseline PG binder grade, as summarized in Table 2.1. Binder grade was judged as highly sensitive input in the preliminary triage. Initial attempts to evaluate the influence of binder grade focused on the viscosity parameters A and VTS for the binder temperature susceptibility curve. Note that the MEPDG does not allow direct user input of A or VTS ; at Level 3, the MEPDG uses default A and VTS values based on the PG grade. The binder viscosity η for a given binder grade and temperature is determined from (MEPDG, 2004):

$$\begin{aligned} \log \log \eta &= A + VTS \log T_R \quad (A + VTS \log T_R < 2.7 \times 10^{12}) \\ \eta &= 2.7 \times 10^{12} \quad (A + VTS \log T_R \geq 2.7 \times 10^{12}) \end{aligned} \quad (3.13)$$

in which:

- η = viscosity, cP
- T_R = temperature of interest, Rankine (°R)
- A = intercept of viscosity temperature susceptibility line for given binder grade
- VTS = slope of viscosity temperature susceptibility line for given binder grade

Note that the asphalt binder viscosity has a maximum value of 2.7×10^{10} Poise at low temperature and/or high rates of loading.

As described above, HMA stiffness for the OAT sensitivity analyses is entered into the MEPDG as synthetic Level 1 data. The MEDPG then requires complementary Level 1 binder stiffness data for use in the global aging model. The steps in generating synthetic Level 1 G^* and phase angle data from A and VTS are as follows (Bari and Witczak, 2007):

1. Determine the Level 3 default A and VTS values for the binder grade of interest.
2. Calculate the frequency adjusted A' and VTS' values:

$$A' = c_0 f_s^{c_1} \times A \quad (3.14)$$

$$VTS' = d_0 f_s^{d_1} \times VTS \quad (3.15)$$

in which:

A = regression intercept
 VTS = regression slope of viscosity temperature susceptibility
 f_s = loading frequency in the G_b^* testing (Hz)
 c_0, c_1, d_0, d_1 = frequency adjustment factors = 0.9699, -0.0527, 0.9668 and -0.0575

3. Calculate the asphalt binder viscosity η (cP):

$$\log \log \eta = A' + VTS' \log T_R \quad (3.16)$$

in which:

A' = adjusted A (adjusted for loading frequency)
 VTS' = adjusted VTS (adjusted for loading frequency)
 T_R = temperature in Rankine ($^{\circ}R$)

4. Calculate the dynamic shear modulus G^* (Pa) and phase angle δ_b ($^{\circ}$):

$$|G_b^*| = a_1 f_s \eta (\sin \delta)^{a_2 + a_3 f_s + a_4 f_s^2} \quad (3.17)$$

$$\delta_b = 90 + (b_1 + b_2 VTS') \times \log(f_s \times \eta) + (b_3 + b_4 VTS') \times \{\log(f_s \times \eta)\}^2 \quad (3.18)$$

in which:

f_s = loading frequency (Hz)
 η = viscosity of asphalt binder as a function of both loading frequency and temperature (cP)
 A' = adjusted A (adjusted for loading frequency)
 VTS' = adjusted VTS (adjusted for loading frequency)
 a_1, a_2, a_3, a_4 = fitting parameters = 0.0051, 7.1542, -0.4929 and 0.0211
 b_1, b_2, b_3, b_4 = fitting parameters = -7.3146, -2.6162, 0.1124 and 0.2029

At first A and VTS were varied independently (i.e. A kept constant while VTS varied by a given percentage) in order to investigate the sensitivity of predicted pavement distresses to each parameter separately. However, the correlation coefficient between A and VTS is 0.9996 for the MEPDG default values over all PG grades. This high correlation suggested that A and VTS should not be varied independently.

The next attempt varied A and VTS by the same percentage from their baseline values, but this method gave unreasonable binder viscosities. For example, Figure 3.1 shows the viscosity susceptibility curves for PG 70-10 and PG 64-10 binders. The values for A and VTS change by 6.94% and 7.77% respectively moving from the PG 70-10 to the PG 64-10 binder grade. Shifting A and VTS by the average value of 7.46% from the PG 70-10 produces a viscosity curve slightly different from the PG 64-10. Even though this difference is slight, it had a substantial influence on performance because of the high sensitivity to binder viscosity.

The final decision was to incorporate binder sensitivity directly via comparisons of adjacent PG grades rather than via A and VTS . The disadvantage of this approach is that the input parameter is no longer a continuous variable. However, it eliminates some of the irrational performance predictions

that sometimes occur when varying A and VTS directly. It also makes more practical sense because the PG grade of binder is the actual input, not A and VTS .

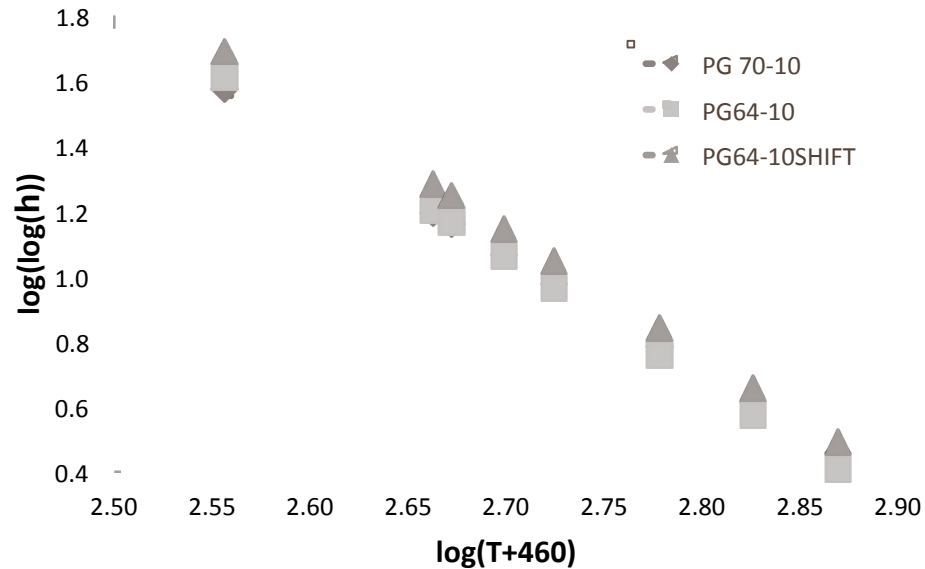


Figure 3.5. Binder viscosity comparison between different PG grades.

The last set of required HMA material inputs consists of the low temperature tensile strength, creep compliance, and aggregate coefficient of thermal contraction properties used in the thermal cracking model. The MEPDG Level 3 default relations are used to specify these inputs. The Level 3 default relations for low temperature tensile strength and creep compliance are functions of mixture volumetrics (V_a and VFA) and binder viscosity; these properties are all included as design inputs in the OAT analyses.

3.3 PCC Stiffness and Strength

Portland cement concrete (PCC) stiffness and strength properties are highly sensitive inputs in the prediction of MEPDG performance. The MEPDG needs PCC stiffness and strength design inputs at all three input levels. Level 1 of the MEDPG requires measured values of PCC modulus of elasticity (E) and modulus of rupture (MOR) at various ages to characterize stiffness and strength gains over time. The required stiffness and strength values at Level 2 are estimated from unconfined compressive strength (f'_c) results at various ages. Corresponding values of E and MOR are estimated from f'_c using standard empirical relations (Mallela *et al.* 2001). The required stiffness and strength values at Level 3 are estimated from a single point measurement of MOR (or f'_c) and optionally the corresponding measured E at 28 days. The four options for specifying level 3 PCC stiffness and strength design inputs are (1) the 28-day MOR only; (2) the 28-day f'_c only; (3) the 28-day MOR and the corresponding 28-day E ; and (4) the 28-day f'_c and the corresponding 28-day E . Using these inputs, the MEPDG estimates stiffness and strength gains over time.

A total of six design input options (Level 1, Level 2, and the four Level 3 alternatives) are available in the MEPDG for PCC stiffness and strength. This leads to two questions for the OAT analyses. The first is “Do all of the MEPDG alternatives for PCC stiffness and strength design inputs yield comparable predictions of rigid pavement performance predictions?” If the answer to this question is “no,” then the follow-on question is: “When Level 1 design inputs are not available, which other PCC stiffness and strength design inputs provide the most comparable and reliable rigid pavement performance predictions?”

To answer these questions, the research team evaluated the effect of design input level for PCC strength and stiffness properties on MEPDG performance predictions for jointed plain concrete pavements (JPCP) using eight different PCC mixtures in several different JPCP design scenarios (Schwartz *et al.*, 2011). Figure 3.6 summarizes the predicted JPCP distresses after normalization by their respective Level 1 results. All of the MEPDG PCC input levels provided comparable predictions for faulting and to a lesser extent for IRI but different predictions for transverse slab cracking. Figure 3.7 presents the ranges and averages for the normalized slab cracking predictions for all input levels. It is clear that the Level 3 inputs of measured 28-day MOR and E agree best with the Level 1 results in terms of having the smallest range and a mean value closest to 1. These results suggest that the use of Level 3 inputs of measured 28-day MOR and E is a suitable alternative to Level 1 for MEPDG rigid pavement predictions.

The influence of PCC input option was further investigated in the OAT simulations. PCC strength and stiffness options were specified using two Level 3 options: (a) 28-day MOR and 28-day E ; and (b) 28-day MOR only. The effect of the different input options on the ranking of design input sensitivities can then be evaluated.

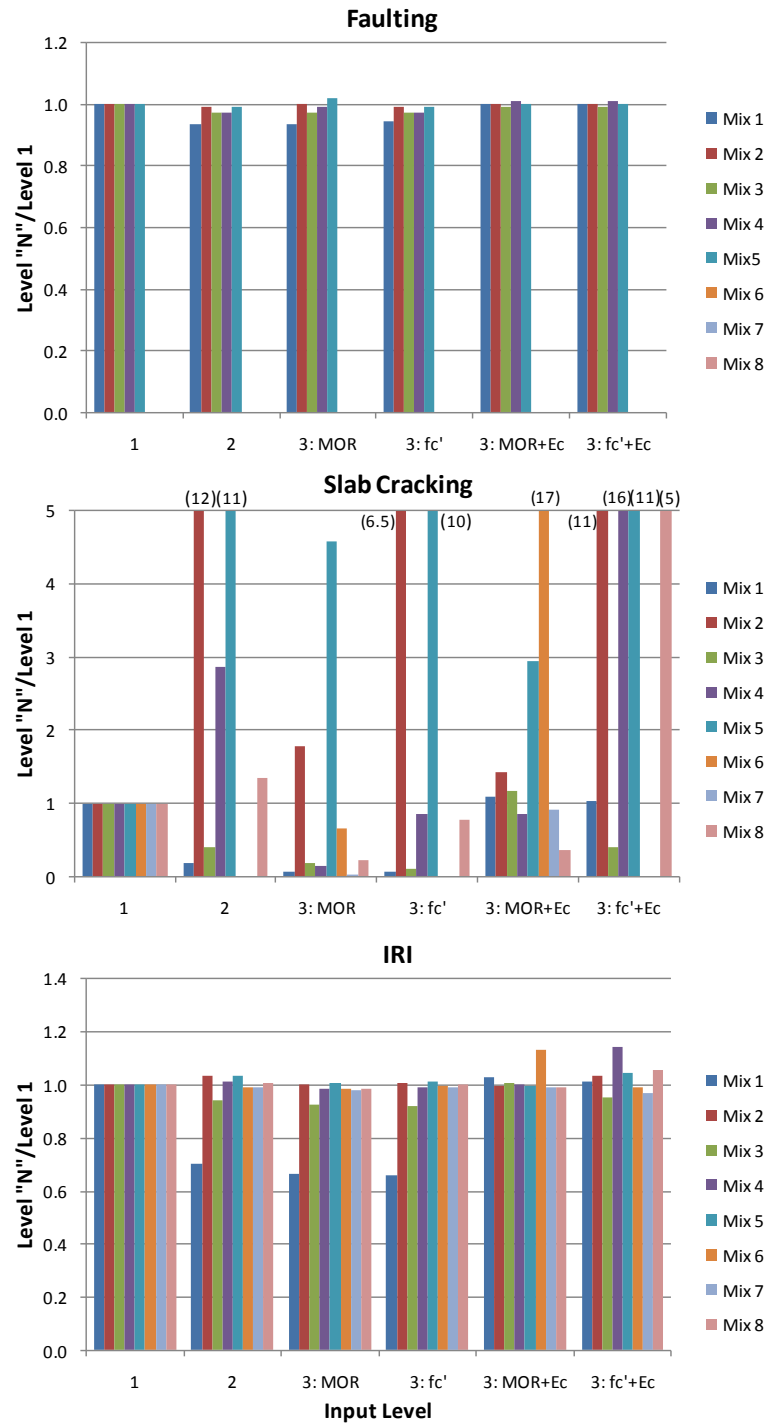


Figure 3.6. Normalized predicted distresses.

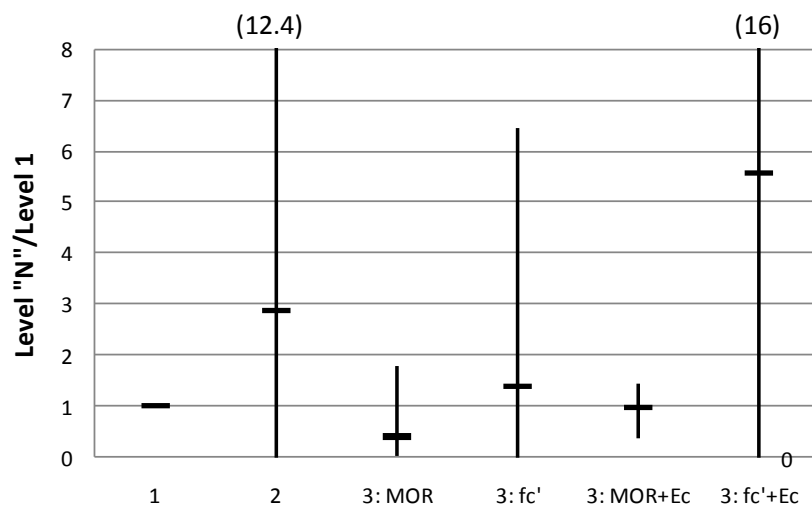


Figure 3.7. Ranges and mean values for normalized slab cracking predictions at each PCC design input level.

3.4 Edge Support Conditions for Rigid Pavements

Categories for edge support in MEPDG JPCP analysis are given as: (1) no support, (2) tied PCC, and (3) widened slab. Categories for edge support in MEPDG CRCP analysis are specified in terms of shoulder type: gravel, asphalt, monolithic tied concrete, and separate tied concrete shoulder. It is difficult to calculate sensitivity indices using category input values. Consequently, for the OAT sensitivity analyses these category input values are specified in terms of equivalent load transfer efficiency (LTE) and/or slab width values as documented in Table 3.5.

Table 3.5. Scaled MEPDG edge support input values.

JPCP			CRCP
No Support	Tied PCC	Widened Slab	Type of Shoulder
5% LTE and 12ft slab width	50% to 80% LTE	13ft to 14ft of slab width	Asphalt or gravel (5% LTE), Monolithic tied concrete (40% LTE), Separate tied concrete (70% LTE)

4 SENSITIVITY METRICS

As described in Appendix A, there is a wide variety of metrics that can be used to quantify sensitivity of model outputs to model inputs. Unfortunately, no individual metric is “perfect” or ideal for all of the variables in this study. The recommendation approach was to summarize the OAT analysis results in terms of a point-normalized sensitivity index S_{jk}^i :

$$S_{jk}^i = \frac{\partial Y_j}{\partial X_k} \bigg|_i \left(\frac{X_{ki}}{Y_{ji}} \right) \quad (3.19)$$

in which $\frac{\partial Y_j}{\partial X_k} \bigg|_i \equiv \frac{\Delta Y_j}{\Delta X_k} \bigg|_i$ is the partial derivative and Y_{ji} , X_{ki} are the model output and input values all evaluated at location i in the problem domain. This sensitivity index can be interpreted as the local percentage change in model output Y_j caused by a given percentage change in the model input X_k at location i in the problem domain. For example, $S_{jk}^i = 0.5$ implies that a 20% local change in X_{ki} will cause a 10% local change in Y_{ji} .

However, problems were encountered when calculating the point-normalized sensitivity index for the OAT analyses because the predicted distress values Y_{ji} were near zero for some of the baseline conditions, resulting in artificially large sensitivity index values. To circumvent this problem, a “design limit” normalized sensitivity index S_{jk}^{DL} was defined:

$$S_{jk}^{DL} = \frac{\Delta Y_j}{\Delta X_k} \frac{X_k}{DL_j} \quad (3.20)$$

in which

- X_k = baseline value of design input k
- ΔX_k = change in design input k about the baseline
- ΔY_j = change in predicted distress j corresponding to ΔX_k
- DL_j = the design limit for distress j

For the remainder of this report, the design limit normalized sensitivity index S_{jk}^{DL} will be notated more simply as NSI. The NSI always uses the design limit as the normalizing factor for the predicted distress. For example, consider total rutting as the predicted distress with a design limit of 0.75 inches. An NSI of -0.25 for the sensitivity of total rutting to granular base layer resilient modulus implies that a 10% reduction in base resilient modulus will increase total rutting by $NSI * \Delta X_k = 25\%$ its design limit DL_j --i.e., it will increase rutting by $0.1 * 0.25 * 0.75 = 0.01875$ inches.

NSI can be calculated using Eq. 3.20 for most design inputs. However, in some cases the design input is categorical rather than continuous—e.g., binder grade and construction month. For these design inputs, a modified non-normalized NSI definition is used instead:

$$NSI = \frac{\Delta Y_j}{D_j} \quad (3.21)$$

This modified design limit NSI also takes the design limit as reference for predicted distress. It shows how the predicted distress changes in normalized terms if the design input is changed by one category.

5 AUTOIT TOOL

The current version of the MEPDG is research grade software requires manual input of all input data. Manual input of the thousands of analyses for the OAT sensitivity analyses and the even larger set of analyses required for the GSA is clearly not feasible. Consequently, AutoIt scripts were developed to generate all MEPDG input files. AutoIt (<http://www.autoitscript.com/>) is a Windows-based scripting language that simulates keyboard, mouse inputs, and file I/O in an automated mode.

Thousands of lines of AutoIt code were developed to conduct the OAT analyses. It automatically generated the MEPDG input files for the OAT analyses, and then set the MEPDG to run, and harvested output data at the end. *AutoIt* is small, self-contained, and runs on all versions of Windows. It incorporates powerful programming capabilities that support complex expressions, user functions, loops, file I/O, and other sophisticated scripting features. *AutoIt* is a stand-alone application requiring no external .dll files or modifications to the Windows registry. Scripts can be compiled into stand-alone executables that can be easily distributed and run on other host computers.

6 NEW HMA

6.1 Analysis Inputs

The baseline values and variations for all inputs investigated in the OAT sensitivity analyses are documented in this section. Project-specific parameters that are fixed for all analyses are summarized in the Table 6.1.

Table 6.1. Fixed design inputs for New HMA cases.

Input Parameter	Baseline Value
Design Life	15 years
Reliability	90% for all distresses
AADTT Category	Principal Arterials – Interstate and Defense Route
TTC	4
Number of Lanes in Design Direction	2
Truck Direction Factor	50
Truck Lane Factor	95
Default Growth Rate	0
First Layer Material Type	Asphalt Concrete
Second Layer Material Type	Granular Base
Subgrade Material Type	Soil
HMA Aggregate	Virgin – 19mm*

*This mixture has the following properties: cumulative % retained $\frac{3}{4}$ inch sieve = 5.5; cumulative % retained $\frac{3}{8}$ inch sieve = 33.5; cumulative % retained #4 sieve = 55.5; % passing #200 sieve = 4.9; V_{beff} = 10.08%; V_a = 6.47%

As stated in Section 3.2 binder properties are specified in terms of discrete binder grade rather than in terms of continuous inputs like A and VTS . Table 6.2 summarizes the binder grade baseline value and the grade variations for each climate zone. PGHigh- means that the high temperature grade decreases one step; PGLow+ means that the low temperature grade increases one step.

Table 6.2. Binder grade baseline values and variations for New HMA cases.

Climate	Baseline PG Grade	PGHigh-	PGLow+
Cold-Dry*	PG 58-28	NA	PG 58-22
Cold-Wet	PG 52-28	NA	PG 52-22
Hot-Dry	PG 76-10	PG 70-10	NA
Hot-Wet	PG 70-10	PG 64-10	NA
Temperate	PG 58-10	PG 52-10	NA

*The location for this climate zone and the corresponding binder grade will be changed in the GSA.

Table 6.3 summarizes the design inputs that are related to traffic level. Higher traffic levels require correspondingly thicker asphalt and base layers. The baseline value, reduced value (“-value”), and increased value (“+value”) for the HMA and granular base layers are listed under each traffic level category.

Table 6.3. Design inputs related to traffic levels in New HMA cases.

Input Parameter \ Traffic Level	Low Traffic			Medium Traffic			High Traffic		
	Baseline	-	+	Baseline	-	+	Baseline	-	+
AADTT	1000	500	5000	7500	5000	10000	25000	20000	30000
HMA Thickness	6.5	5	8	10	8	12	12.5	10	15
Base Thickness	6	1*	10	7	1*	14	9	1*	18

*The minimum base thickness is 1(inch).

The remaining design inputs that are varied in the OAT sensitivity analyses are summarized in Table 6.4. These inputs correspond to the “Very Sensitive” and “Sensitive” design inputs as identified during the preliminary triage. Some additional design inputs were also included in the OAT analyses to confirm their low sensitivity. The baseline value, reduced value (“-value”), and increased value (“+value”) are summarized for each design input. Some of the decreases/increases from the baseline values are stated in absolute terms, such as “30” and “70” for Operational Speed; others are represented by a multiplicative factor, such as “x0.9” and “x1.1” for Delta in HMA Sigmoidal Curve. A multiplicative factor is used rather than absolute values for design inputs having values that change between base cases (i.e., with climate zone and/or traffic level). For example, the baseline value of Subgrade Percent Passing #200 Sieve is different for different Subgrade Resilient Modulus values.

Table 6.4. Input parameters and variations in New HMA cases.

Input Parameter	Baseline Value ¹	-value	+value
Construction Month ²	August 2006	July 06	Sept 06
Operational Speed	50	30	70
Ground Water Depth	10	2	18
Surface Shortwave Absorption	0.85	0.80	0.98
Endurance Limit ³	100	50	250
HMA Unit Weight ²	149.9	134.9	164.9
HMA Poisson's Ratio ²	0.35	0.315	0.385
HMA Thermal Conductivity	0.67	0.44	0.81
HMA Heat Capacity	0.23	0.22	0.4
Delta in HMA Sigmoidal Curve	2.83 ⁴	x0.99	x1.01
Alpha in HMA Sigmoidal Curve	3.90 ⁴	x0.99	x1.01
Effective Binder Content in HMA ⁵	10.1 ⁴	x0.9	x1.1
Air Voids in HMA ⁵	6.5 ⁴	x0.9	x1.1
Tensile Strength at 14° F	500	100	2000
Aggregate Coefficient of Contraction in HMA	5e-6	2e-6	7e-6
Base Resilient Modulus	25000	15000	40000
Base Poisson's Ratio ²	0.35	x0.9	x1.1
Base Lateral Stress Coefficient ²	0.5	x0.9	x1.1
Base Percent Passing #200 Sieve	x1 ⁶	x0.9	x1.1
Base D ₆₀	x1 ⁶	x0.9	x1.1
Base Plasticity Index	x1 ⁶	x0.9	x1.1
Base Liquid Limit ²	x1 ⁶	x0.9	x1.1
Subgrade Resilient Modulus	15000	10000	20000
Subgrade Poisson's Ratio ²	0.35	x0.9	x1.1
Subgrade Lateral Stress Coefficient ²	0.5	x0.9	x1.1
Subgrade Percent Passing #200 Sieve	x1 ⁶	x0.9	x1.1

Subgrade D ₆₀	x1 ⁶	x0.9	x1.1
Subgrade Plasticity Index	x1 ⁶	x0.9	x1.1
Subgrade Liquid Limit ²	x1 ⁶	x0.9	x1.1

¹All values are in same units as MEPDG inputs.

²Added input for OAT sensitivity analyses.

³No endurance limit was considered for baseline cases. The baseline value listed here is only for the purpose of evaluating performance sensitivity to endurance limit.

⁴Based on gradation and volumetric properties of a typical Superpave 19 mm mix; see Section 3.2.

⁵To evaluate the influence on the global aging model. The effects of air voids and effective binder content on dynamic modulus are implicitly included in the variations of Delta for HMA Sigmoidal Curve.

⁶These parameters are correlated with M_r , as described in Section 3.1; the OAT variations are about the correlated mean values.

6.2 Results

The 33 design inputs in Table 6.2 through Table 6.4 are varied over 3 input levels for 15 base cases (5 climate zones and 3 traffic levels) in the OAT sensitivity analyses. This required a total of 1005 MEPDG runs⁴ for the New HMA scenarios. The predicted distresses at the 50% reliability level for the New HMA baseline scenarios are summarized in Table 6.5. The predictions span a wide range of magnitudes (including some exceeding the design limits) for longitudinal cracking, AC rutting, and total rutting, a more modest span for IRI, and only a very small amount of alligator cracking. No significant transverse thermal cracking was predicted for even the coldest climates; this will be discussed more fully later. When interpreting Table 6.5, it is important to keep in mind the objectives of the OAT sensitivity analyses: the precise magnitudes of the predicted distresses are not the focus but rather how these predicted distresses vary as each design input is varied about its baseline value.

Table 6.5. Predicted distress levels for New HMA baseline scenarios.

Traffic	Climate	HMA (in)	Base (in)	Longitudinal	Alligator	Transverse	AC Rut (in)	Total Rut (in)	IRI (in/mi)
				Cracking (ft/mi)	Cracking (%)	Cracking (ft/mi)			
Low	Hot-Wet	6.5	6	1060	2.55	0	0.172	0.501	101.2
Low	Hot-Dry	6.5	6	1910	2.59	0	0.295	0.613	102.1
Low	Cold-Wet	6.5	6	3130	3.57	0.3	0.233	0.594	110.5
Low	Cold-Dry	6.5	6	1140	1.97	0	0.174	0.499	103.9
Low	Temperate	6.5	6	598	1.82	0	0.123	0.433	95.8
Medium	Hot-Wet	10	7	2.5	1.88	0	0.371	0.691	108.3
Medium	Hot-Dry	10	7	36.1	1.94	0	0.635	0.948	115
Medium	Cold-Wet	10	7	168	2.51	0.2	0.513	0.862	120.5
Medium	Cold-Dry	10	7	25.3	1.42	0	0.384	0.699	111.5
Medium	Temperate	10	7	1.45	1.34	0	0.264	0.564	100.7
High	Hot-Wet	12.5	9	0.07	1.8	0	0.502	0.808	113
High	Hot-Dry	12.5	9	0.33	1.78	0	0.838	1.14	122.6
High	Cold-Wet	12.5	9	1.5	2.22	0.1	0.675	1.007	126.2
High	Cold-Dry	12.5	9	0.25	1.27	0	0.508	0.808	115.8
High	Temperate	12.5	9	0.03	1.3	0	0.358	0.646	104
Design Limits:				2000	25	1000	0.25	0.75	172

A Normalized Sensitivity Index (NSI) value is calculated for each design input-pavement distress combination for each of the base cases. The NSI values calculated over all design inputs and base cases are summarized in two charts for each distress. One chart details the NSI values by base case

⁴ When trial runs, error corrections, and other re-runs are considered, the total number of MEPDG runs executed is substantially greater.

while the other summarizes the high-low-average NSI statistics over all base cases for each design parameter for the distress of interest.

This section summarizes the design input NSI values on a distress-by-distress basis for the New HMA scenarios only. Section 11 compiles key NSI values across all distresses and across all flexible pavement scenarios in order to identify which design inputs have sufficiently high sensitivities for inclusion in the GSA simulations.

The NSI values for longitudinal cracking are summarized in Figure 6.1 and Figure 6.2. Figure 6.1 plots the individual NSI values for all of the base cases. As shown in the chart legend, the diamond markers represent the cases with low (L) traffic volume, the circle markers represent the cases with medium (M) traffic volume, and the triangle markers represent the cases with high (H) traffic volume. The climate conditions are designated by the colors of the markers. As shown in the legend, red represents the hot-dry (HD) climate, orange represents the hot-wet (HW) climate, green represents the temperate (T) climate, blue represents the cold-dry (CD) climate, and purple represents the cold-wet (CW) climate. The design inputs are listed along the horizontal axis; Table 6.6 provides the key to the design input labels. All of the design inputs varied in the OAT analyses are plotted in Figure 6.2, but not all of the very low sensitivity inputs are included in Figure 6.1 in order to keep the plot readable.

Table 6.6. Definitions of design input labels for New HMA cases.

Name of Design Input	Description
Construction Month	Base/Subgrade construction time, usually one month ahead of pavement construction month
AADTT	Average Annual Daily Truck Traffic
Operational Speed	Average vehicle travel speed
GWD	Ground Water Depth
SSA	Surface Shortwave Absorption
Limit Strain	Fatigue analysis endurance limit (only applies to bottom up alligator cracking)
HMA Thickness	Thickness of asphalt concrete layer
HMA Unit Weight	Unit weight of asphalt concrete
HMA Poisson's Ratio	Poisson's Ratio of asphalt concrete
HMA Thermal Conductivity	Thermal conductivity of asphalt concrete
HMA Heat Capacity	Heat capacity of asphalt concrete
HMA Δ	The lower limit of the sigmoidal function for $\log(E^*)$
HMA α	The upper limit of the sigmoidal function for $\log(E^*)$
HMA V _{beff}	Volume of effective binder
HMA V _a	Air voids
PGHigh-	High temperature binder grade. The NSI was calculated by decreasing the high temperature grade by one step from baseline
PGLow+	Low temperature binder grade. The NSI was calculated by increasing the low temperature grade by one step from baseline.
Tensile Strength at 14F	Average tensile strength at 14 °F
Aggregate CTC	Coefficient of Thermal Contraction of asphalt concrete aggregate
Base Thickness	Thickness of granular base layer

Base Mr	Resilient modulus of granular base layer material
Base PR	Poisson's ratio of granular base layer material
Base Ko	Coefficient of lateral earth pressure of granular base layer
Base N200	Percentage passing #200 sieve of granular base layer material
Base D60	Granular base layer aggregate diameter at 60% passing
Base PI	Plasticity Index of granular base layer material
Base LL	Liquid Limit of granular base layer material
Subgrade Mr	Resilient modulus of subgrade material
Subgrade PR	Poisson's ratio of subgrade material
Subgrade Ko	Coefficient of lateral earth pressure of subgrade material
SubgradeN200	Percentage passing #200 sieve of subgrade material
SubgradeD60	Subgrade aggregate diameter at 60% passing
SubgradePI	Plasticity Index of subgrade material
SubgradeLL	Liquid Limit of subgrade material

Because of the wide range of NSI values, the detailed results in Figure 6.1 are plotted at two different vertical axis scales. The HMA dynamic modulus parameters HMAAlpha and HMADelta rank as the two most sensitive design inputs for longitudinal cracking. This was especially true for the low traffic volume cases. The negative sign of the NSI values means longitudinal cracking decreases as HMAAlpha or HMADelta increases (i.e., as HMA stiffness increases).

When interpreting the NSI values for HMAAlpha and HMADelta, however, one must remember that the typical ranges for these parameters are very narrow. As detailed in Table 3.4, the standard deviations (σ) are only 1.6% and 3.5% of the mean values, respectively. A sigma-normalized sensitivity index (see Appendix A) would be more appropriate for HMAAlpha and HMADelta. Unfortunately, this would make the sensitivity evaluation for these two parameters inconsistent with those for most of the other design inputs for which standard deviations cannot be easily determined.

Recall that the HMAAlpha and HMADelta inputs at Level 3 in the MEPDG are determined using the Witczak E^* predictive model as functions of gradation and volumetric properties. The sensitivity of dynamic modulus and thus performance to these gradation and volumetric inputs has not been evaluated directly in the OAT analyses. The principle reason for this is evidence from the literature (e.g., Ceylan *et al.*, 2009) that the Witczak predictive model is driven primarily by binder viscosity and underestimates the influence of the other mixture characteristics—in other words, the Witczak model may not correctly capture the sensitivity of dynamic modulus and thus performance to mixture gradation and volumetric property inputs. Nonetheless, one can separately evaluate these sensitivities using the NSI values for HMAAlpha and HMADelta and the relationships in Eqs. 3.10 and 3.11. For example, following Eq. 3.20 the design-limit normalized sensitivity of predicted performance to air voids NSI_{V_a} can be defined as:

$$NSI_{V_a} = \frac{\Delta Y}{\Delta V_a} \frac{V_a}{DL} \quad (3.21)$$

in which ΔY is the change in distress magnitude caused by the change in air voids ΔV_a , V_a is the baseline air voids value, and DL is the design limit for the given distress. Equation 3.21 can then be expressed in terms of the NSI for HMA Δ using:

$$NSI_{V_a} = \frac{\Delta Y}{\Delta \delta} \frac{\Delta \delta}{\Delta V_a} \frac{V_a}{DL} = \left(\frac{\Delta Y}{\Delta \delta} \frac{\delta}{DL} \right) \frac{\Delta \delta}{\Delta V_a} \frac{V_a}{DL} \left(\frac{DL}{\delta} \right) = NSI_{\delta} \frac{\Delta \delta}{\Delta V_a} \left(\frac{V_a}{\delta} \right) \quad (3.22)$$

in which δ is the baseline value for HMA Δ and $\frac{\Delta \delta}{\Delta V_a}$ can be evaluated for the Witczak E^* predictive model using Eq. 3.10. For the reference 19mm Superpave dense graded mix properties in Section 3.2, $\frac{\Delta \delta}{\Delta V_a} \left(\frac{V_a}{\delta} \right) = -0.068$, implying that the sensitivity of distress to air voids is only about 7% of the sensitivity of distress to HMA Δ and of opposite sign according to the Witczak E^* predictive model.

HMA Thickness ranks as the third most sensitive design input for longitudinal cracking. The NSI values range from -5 to -8 for the low traffic cases and approach zero for high traffic. The negative sign of the NSI values means that longitudinal cracking decreases as HMA thickness increases. The most sensitive NSI value is -7.26, which means that 10% decrease in HMA layer thickness will cause an increase in cracking equal to 72.6% of the design limit. However, since this is an OAT sensitivity analysis, only linear inferences near the base case conditions are appropriate—i.e., one should not extrapolate these results to conclude that a 50% increase in HMA thickness will decrease longitudinal cracking by 313% of its design limit.

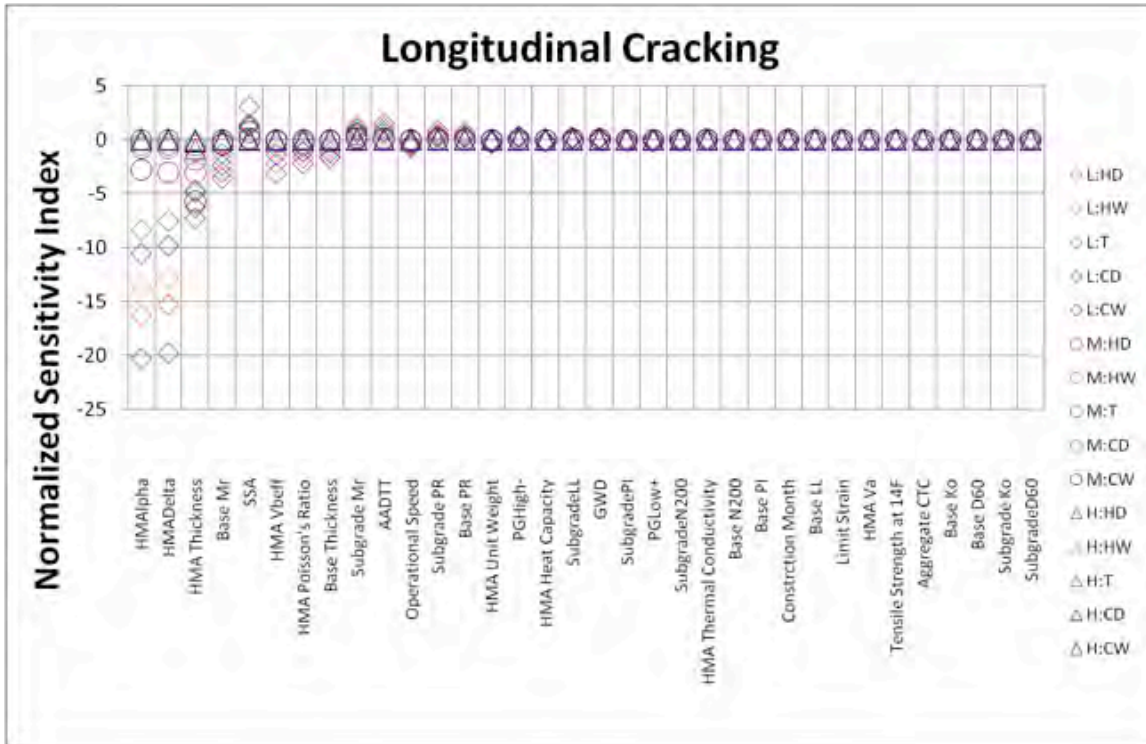
Note that the sensitivity of longitudinal cracking to HMA stiffness and thickness does not necessarily conform to conventional wisdom. Top-down cracking is usually thought to be a problem primarily for very thick and stiff (at least at the surface) HMA layers, but the NSI values indicate that increasing stiffness and/or thickness results in a decrease in cracking. This may be attributable to the immaturity of the longitudinal cracking model in the MEPDG, which was always intended to be a placeholder until a better model could be developed (e.g., NCHRP Project 1-42A and follow-on projects).

Base Mr ranks as the fourth most sensitive design input for longitudinal cracking, with values ranging up to -3.6. The negative NSI values mean that predicted longitudinal cracking decreases as Base Mr increases. SSA ranks fifth with a maximum NSI of about 3; all NSI values are positive, implying that the more heat the asphalt concrete surface absorbs from sun light, the more longitudinal cracking it will exhibit.

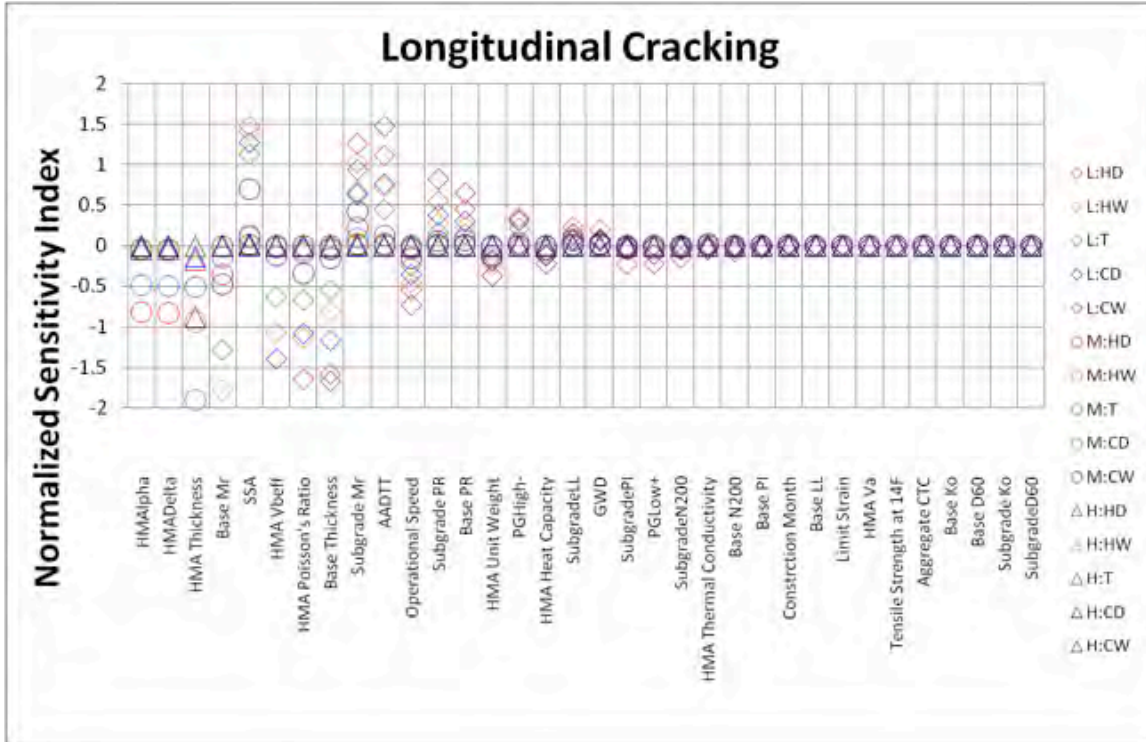
It can be seen in Figure 6.1 that the low traffic volume cases (diamond markers) always had the highest NSI absolute values. The thinner HMA designs for low traffic exhibit large amounts of longitudinal cracking, up to 3100 feet per mile for the cold-wet low traffic baseline case with 6.5 inches of HMA. In comparison, only 1.5 feet per mile of longitudinal cracking is predicted for the cold-wet high traffic baseline case with a 12.5-inch HMA layer. Recall that the NSI in this study is normalized by the longitudinal cracking design limit of 2000 feet per mile and not by the predicted cracking for the baseline conditions.

The only surprising results in Figure 6.1 and Figure 6.2 are the high sensitivities associated with Poisson's ratios for the HMA, granular base, and subgrade layers. Pavement critical distresses are

often thought to be relatively insensitive to Poisson's ratio. The results here suggest that this thinking may be incorrect.



(a) Full vertical axis scale.



(b) Reduced vertical axis scale.

Figure 6.1. NSI values for longitudinal cracking in New HMA (details).

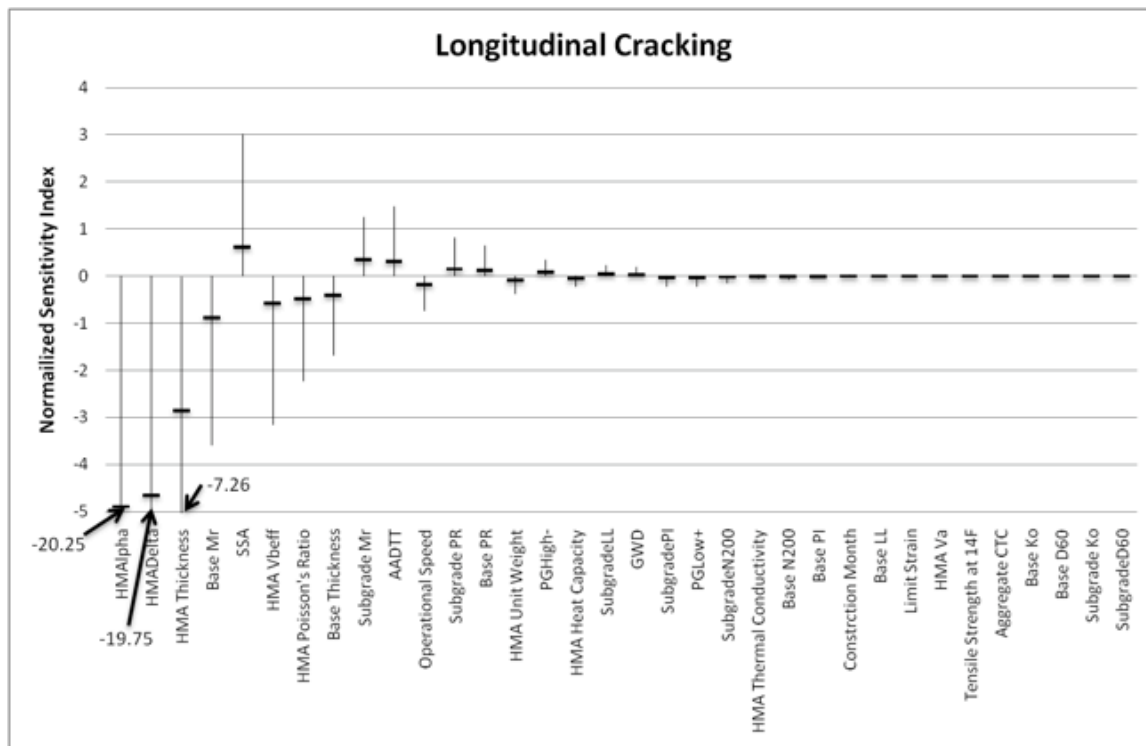


Figure 6.2. NSI values for longitudinal cracking in New HMA (high-low-average).

The NSI values for alligator cracking are summarized in Figure 6.3 and Figure 6.4. The HMA dynamic modulus parameters HMAAlpha and HMA Delta again rank as the two most sensitive design inputs, with NSI values varying from -0.3 to -1.4 (recall again that HMAAlpha and HMA Delta vary only over a narrow range). The negative signs indicate that increases in E^* (at least the lower and upper shelves of the master curve) cause decreases in alligator cracking, arguably contrary to conventional wisdom. HMA Thickness ranks as the third most sensitive design input for alligator cracking with NSI values ranging from about -0.4 to -0.9, sensibly implying decreasing cracking with increasing thickness. Alligator cracking was only modestly sensitive to HMA Vbeff, Base Mr, SSA, and AADT; maximum NSI values for these design inputs were all below 0.2 in absolute value terms.

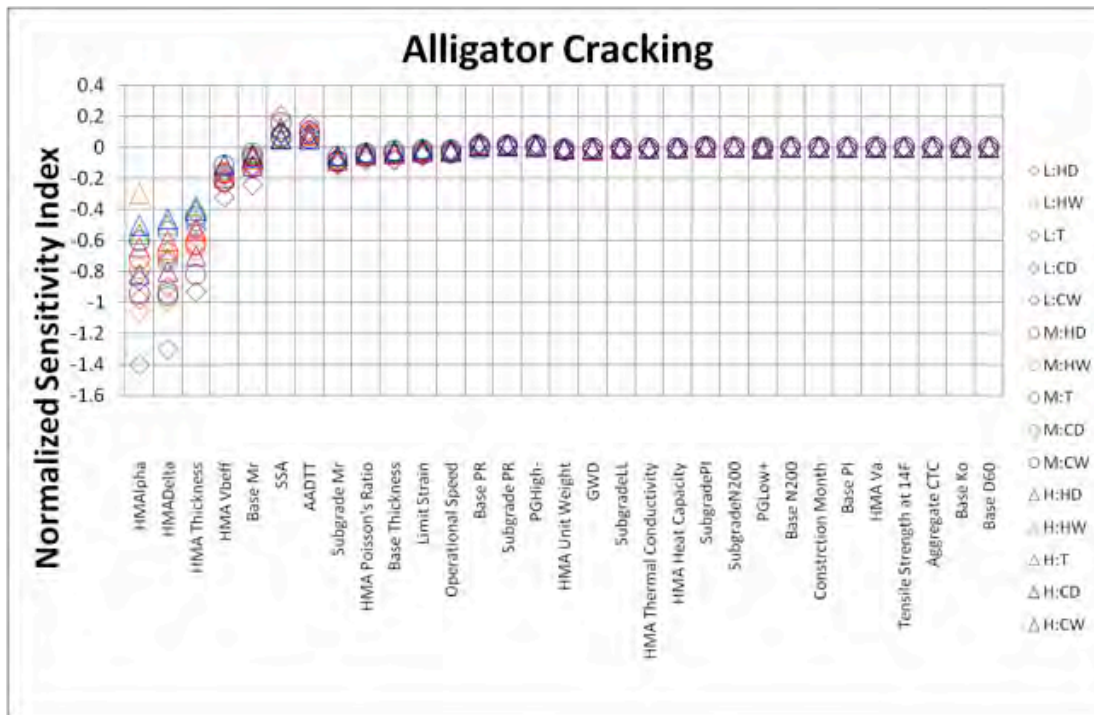


Figure 6.3. NSI values for alligator cracking in New HMA (details).

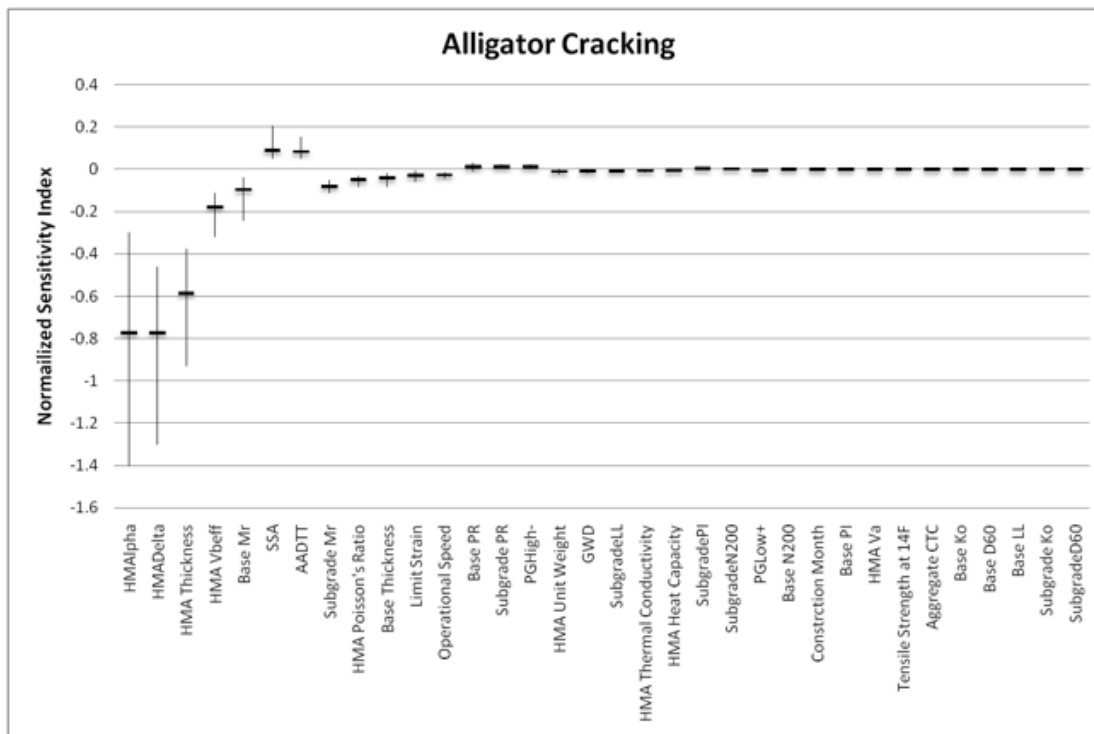


Figure 6.4. NSI values for alligator cracking in New HMA (high-low-average).

The NSI values for transverse thermal cracking are summarized in Figure 6.5 and Figure 6.6. Only the cold-wet climate is presented because no transverse cracking was predicted for the other climate zones. Even for the cold-wet climate, the maximum predicted transverse cracking was only 2.8 feet per mile, a very small amount compared to the design limit of 1000 feet per mile.

HMA Vbeff, HMA Thermal Conductivity, and Tensile Strength at 14F are the three most sensitive design inputs for thermal cracking. All three have negative NSI values, meaning that an increase in the design input value will produce a decrease in predicted thermal cracking. However, even the highest NSI values for these design inputs are near zero. In addition, although engineering experience would suggest that PGLow+ should have a major impact on thermal cracking, the OAT analyses found it to be one of the least sensitive inputs.

The fact that no thermal cracking was predicted for the cold-dry climate zone suggests that the selected city of Spokane WA may not be sufficiently cold. After careful examination of several other northern tier cities, International Falls MN was selected as better representing cold-dry climate conditions. The base binder grade for International Falls is a PG 52-40. However, even for this case insignificant amounts of thermal cracking were predicted. Significant thermal cracking was predicted only when the low temperature binder grade was set two or three steps too stiff. Consequently, as special set of OAT analyses were performed for the International Falls cold-dry climate using out-of-spec low temperature binder grades in order to generate more significant thermal cracking from which to estimate sensitivity indices. The parameter variations considered in these special OAT analyses are summarized in Table 6.7. Note that only predicted thermal cracking is examined in these analyses.

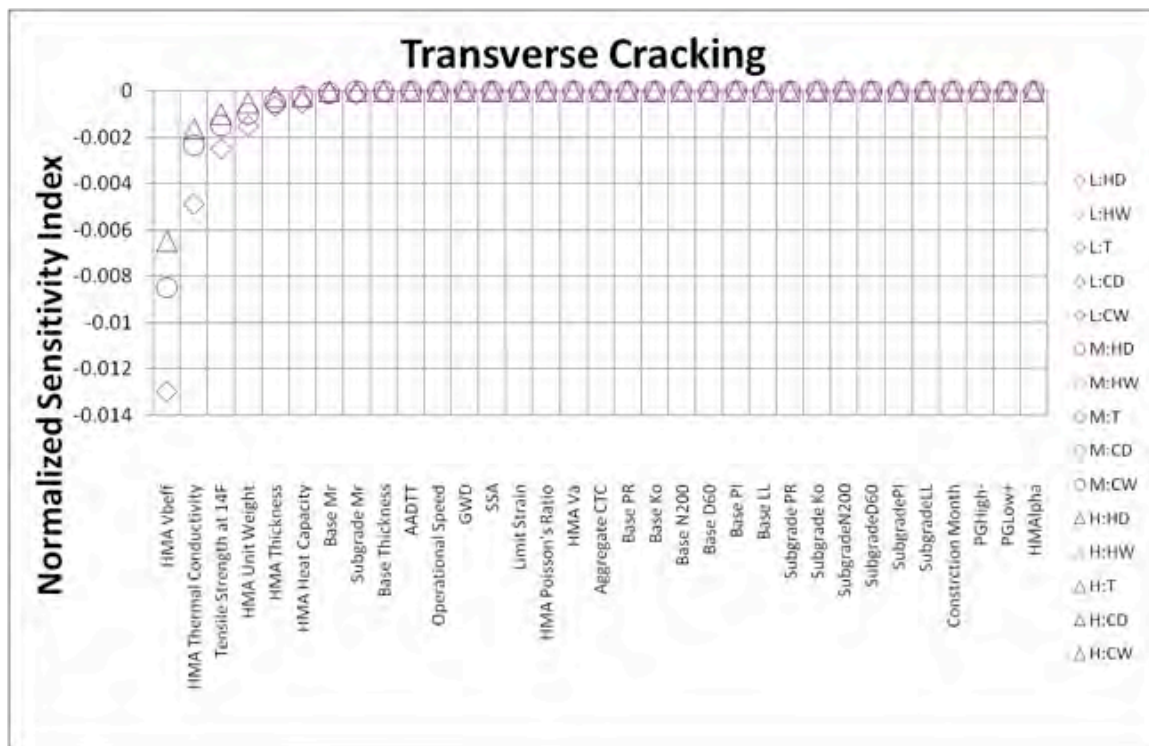


Figure 6.5. NSI values for transverse cracking in New HMA (details).

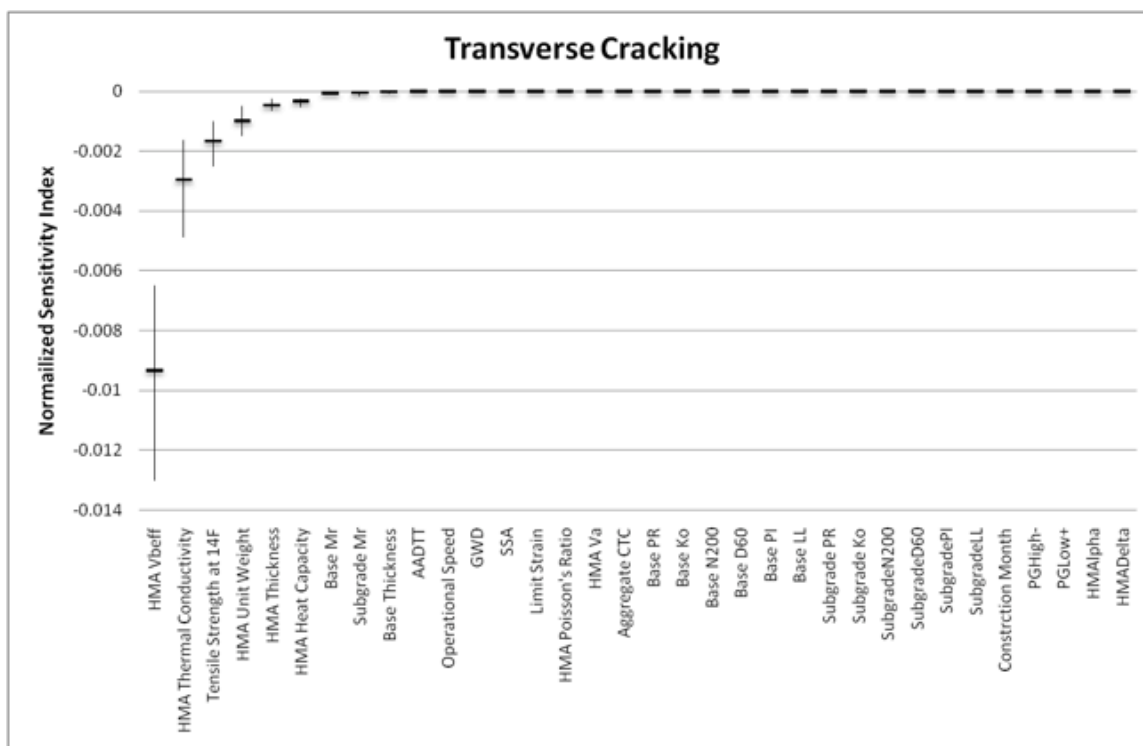


Figure 6.6. NSI values for transverse cracking in New HMA (high-low-average).

Table 6.7. Varied input parameters for special thermal cracking OAT analyses – New HMA.

Input Parameter	Baseline Value ¹	-value	+value
HMA Thickness	See Table 7.1	See Table 7.1	See Table 7.1
PGLow ²	-28	-34	-22
HMA Thermal Conductivity	See Table 6.4	See Table 6.4	See Table 6.4
HMA Heat Capacity	See Table 6.4	See Table 6.4	See Table 6.4
Tensile Strength at 14°F	464 ⁴	372	558
Creep compliance D at 32°F ³	4.35E-07 ⁴	2.48E-07	5.22E-07
14°F ³	3.12E-07 ⁴	2.50E-07	3.12E-07
-4°F ³	1.76E-07 ⁴	1.41E-07	2.11E-07
Creep compliance m at 32°F ³	0.485 ⁴	0.388	0.581
14°F ³	0.284 ⁴	0.228	0.341
-4°F ³	0.191 ⁴	0.153	0.229
Aggregate Coefficient of Contraction in HMA	See Table 6.4	See Table 6.4	See Table 6.4

¹All values are in same units as MEPDG inputs.

²Default binder grade recommended by LTPPBind is PG 52-40.

³Used to generate synthetic creep compliance data for direct input to MEPDG.

⁴Based on MEDPG Level 3 empirical relations (v0.900 updates), volumetric properties for a typical 19 mm Superpave mixture, and A and VTS values corresponding to binder grade.

The special low temperature OAT analyses using the International Falls climate data and low temperature binder grades up to 3 steps too stiff successfully generated thermal cracking ranging from near zero to over 2000 ft or approximately twice the design limit. The NSI values for transverse

thermal cracking for the special binder analyses are summarized in Figure 6.7. The low temperature creep compliance parameters D and m and the Tensile Strength at 14F are the three most sensitive design inputs for thermal cracking, followed by PGLow and the HMA Heat Capacity. Note that the sensitivities to D and m are in addition to the influence of the low temperature binder grade; the reference values for D and m are based on the binder grade used in the analysis.

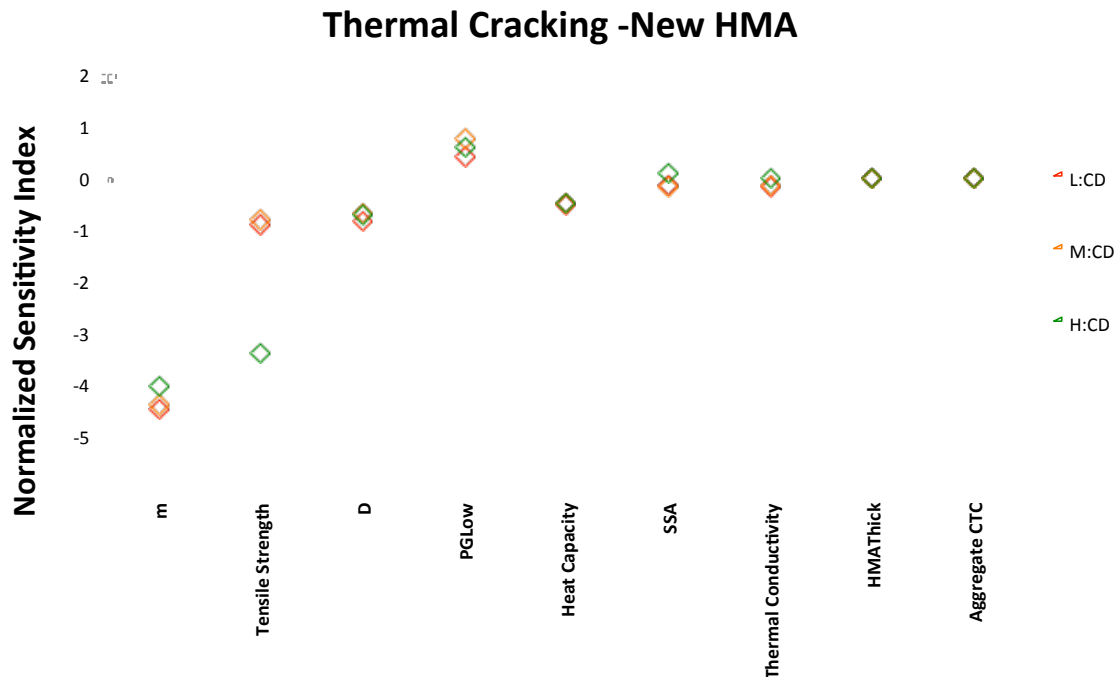


Figure 6.7. NSI values for transverse cracking in New HMA – special binder analyses.

The NSI values for AC rutting are summarized in Figure 6.8 and Figure 6.9. As expected, the dynamic modulus parameters HMA Delta and HMA Alpha are the two most sensitive design inputs. The NSI range from about -4 to about -24 with average value about -11; the highest values occur in the high traffic cases. The negative values mean that increasing either HMA Delta or HMA Alpha—i.e., increasing mix stiffness—will decrease AC rutting, as would be expected. Although the NSI values for HMA Delta and HMA Alpha are high, the ranges of typical input values for these two parameters are quite small.

SSA, HMA Poisson's Ratio and HMA Thickness were ranked as next three most sensitive design inputs. Their absolute values of NSI range from 0.5 to 5. The NSI for SSA is positive; this is sensible because the pavement absorbs more solar radiation and thus softens more as SSA increases. The NSI values for HMA Thickness are negative, implying that rutting decreases as thickness increases. The large negative NSI values for HMA Poisson's Ratio are surprising in that pavement response is conventionally thought to depend only slightly on this material property. However, the high sensitivity of HMA Poisson's Ratio is sensible; the resilient strain in the MEPDG rutting model is the total vertical strain due to the vertical direct compression from the tire load and the vertical Poisson compression/expansion from the high horizontal tensile/compressive bending strains.

The NSI values for HMA Vbeff and AADTT average around +0.8, implying that higher Vbeff and AADTT will produce more AC rutting. The NSI values for Operational Speed average around -0.5,

implying that slower vehicles will cause more rutting. These trends all agree with engineering experience.

The NSI for HMA Unit Weight is surprisingly high, averaging approximately -0.5 NSI. Lower unit weight will therefore produce more predicted AC rutting. The reason for this is not yet fully understood.

As described in Section 4, the sensitivity metric for binder grade is different from the other NSI values, so the fact that PGHigh- with an average NSI of 0.8 was ranked as the 10th most sensitive design input does not necessarily mean that it is less significant than the first 9. The correct interpretation of the binder grade NSI is that lowering the high temperature grade by one step will produce additional predicted AC rutting equal to 80% of the design limit.

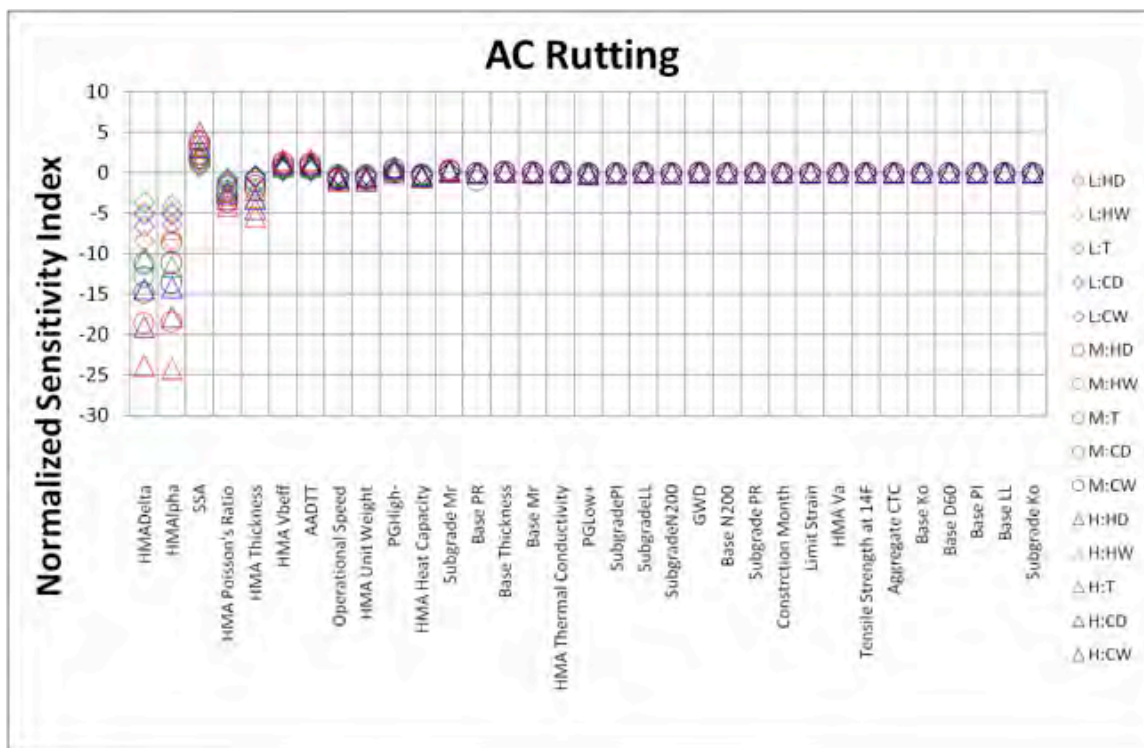


Figure 6.8. NSI values for AC rutting in New HMA (details).

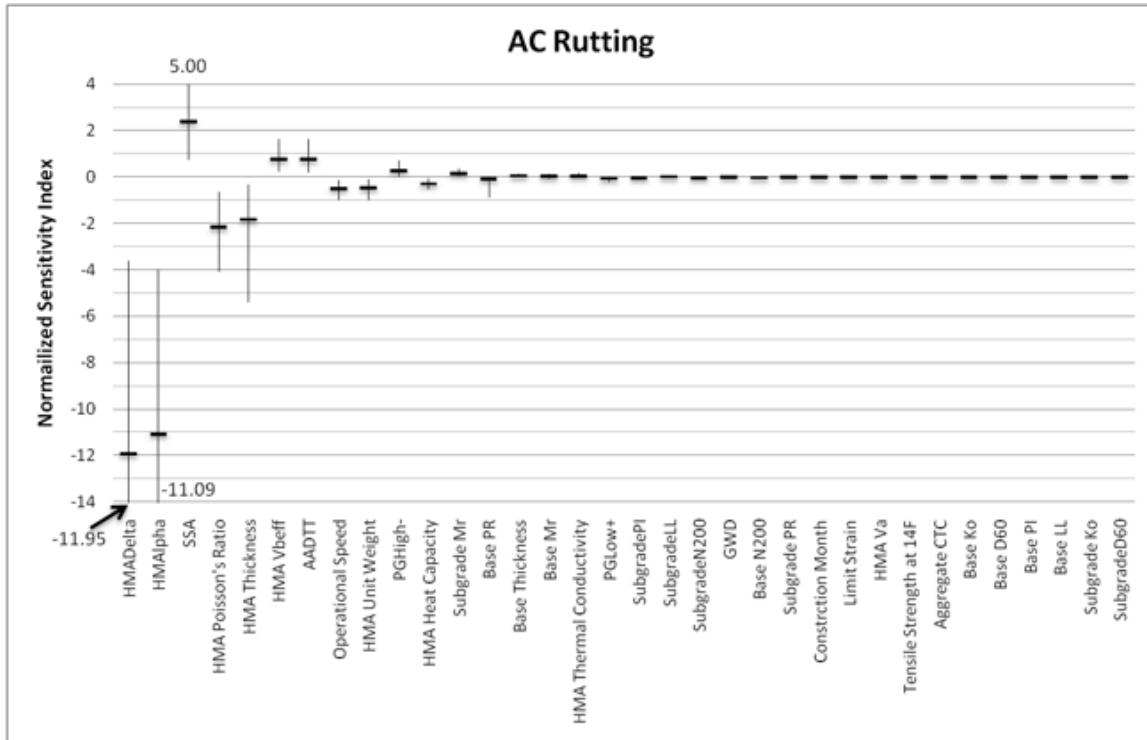


Figure 6.9. NSI values for AC rutting in New HMA (high-low-average).

The NSI values for total rutting are summarized in Figure 6.10 and Figure 6.11. The sensitivity results for total rutting are qualitatively identical to those for AC rutting. The HMA Delta and HMA Alpha are two most sensitive design inputs, with NSI values ranging between -1.8 to -9 and an average value about -5. These are followed by HMA Thickness, SSA, HMA Poisson's Ratio, AADTT, HMA Vbeff, Operational Speed, and HMA Unit Weight; the order is only slightly rearranged from the AC rutting results. The most sensitive design input for the unbound materials is Subgrade Mr, ranked 10th with NSI values in a relatively narrow range of -0.13 to -0.17. This means that a 10% decrease in subgrade resilient modulus will cause additional total rutting equal to about 1.5% of the design limit.

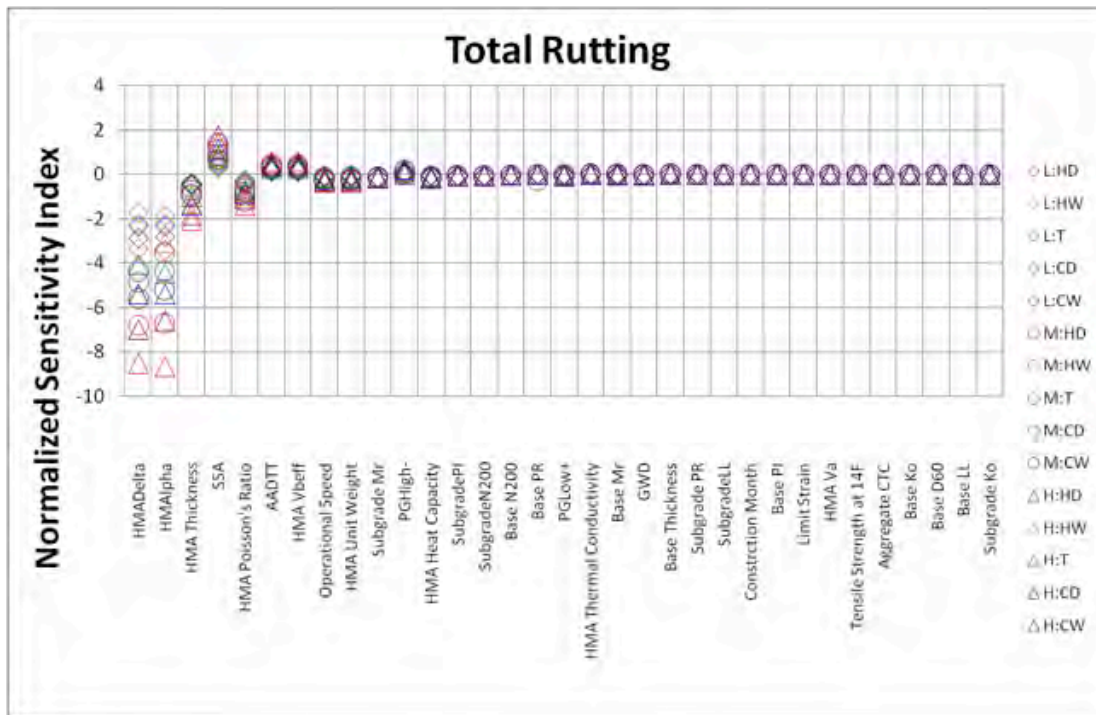


Figure 6.10. NSI values for total rutting in New HMA (details).

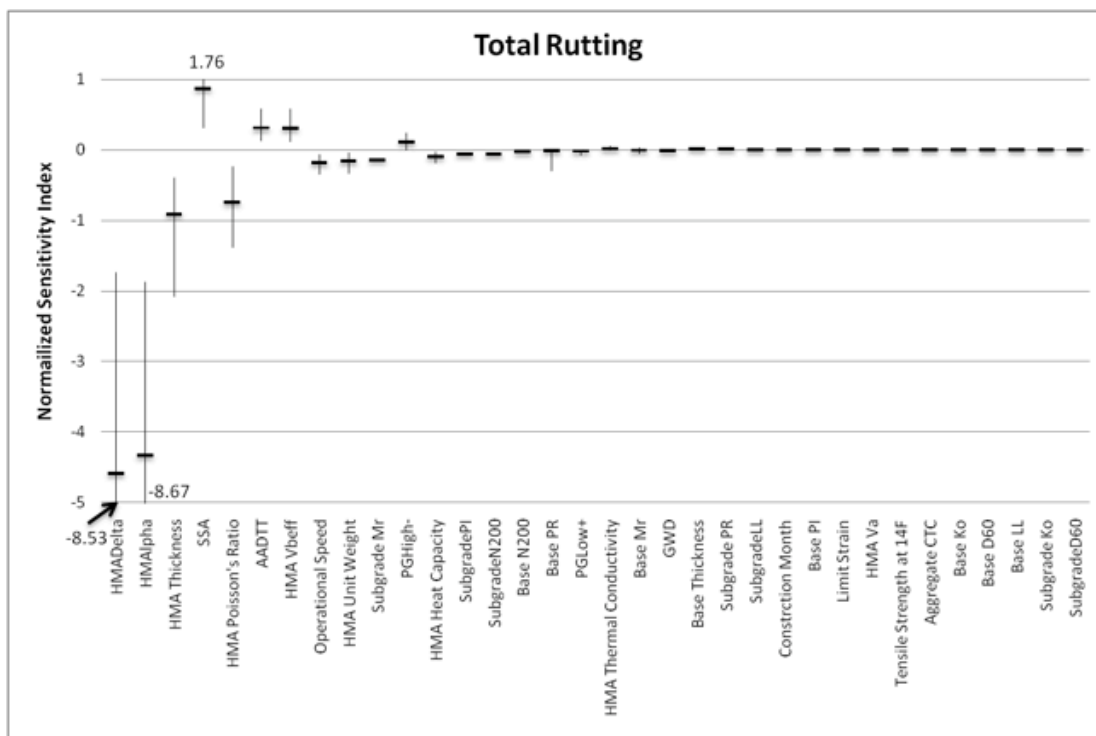


Figure 6.11. NSI values for total rutting in New HMA (high-low-average).

The NSI values for IRI are summarized in Figure 6.12 and Figure 6.13. As would be expected given that IRI is based in part on the primary distresses, the sensitivity trends for IRI mirror those for the individual distresses. The dynamic modulus parameters HMA Delta and HMA Alpha are the two most sensitive parameters, with NSI values ranging between about -0.3 to about -1.6 and averaging about -0.7. HMA Thickness has an average NSI of -0.2 while SSA has positive NSI value averaging about 0.2. Other design inputs with non-negligible NSI values include HMA Poisson's Ratio, AADTT, HMA Vbeff, Subgrade MR, and Operational Speed. Surprisingly, HMA Unit Weight has almost the same sensitivity on IRI as Operational Speed.

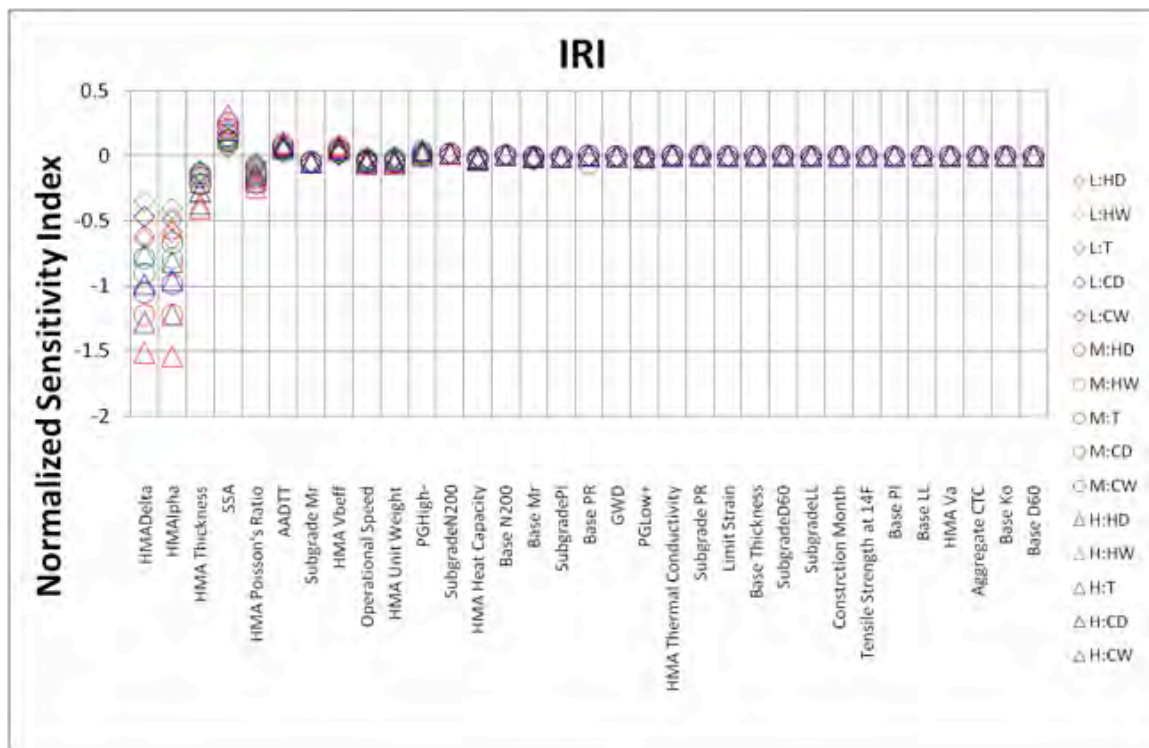


Figure 6.12. NSI values for IRI in New HMA (details).

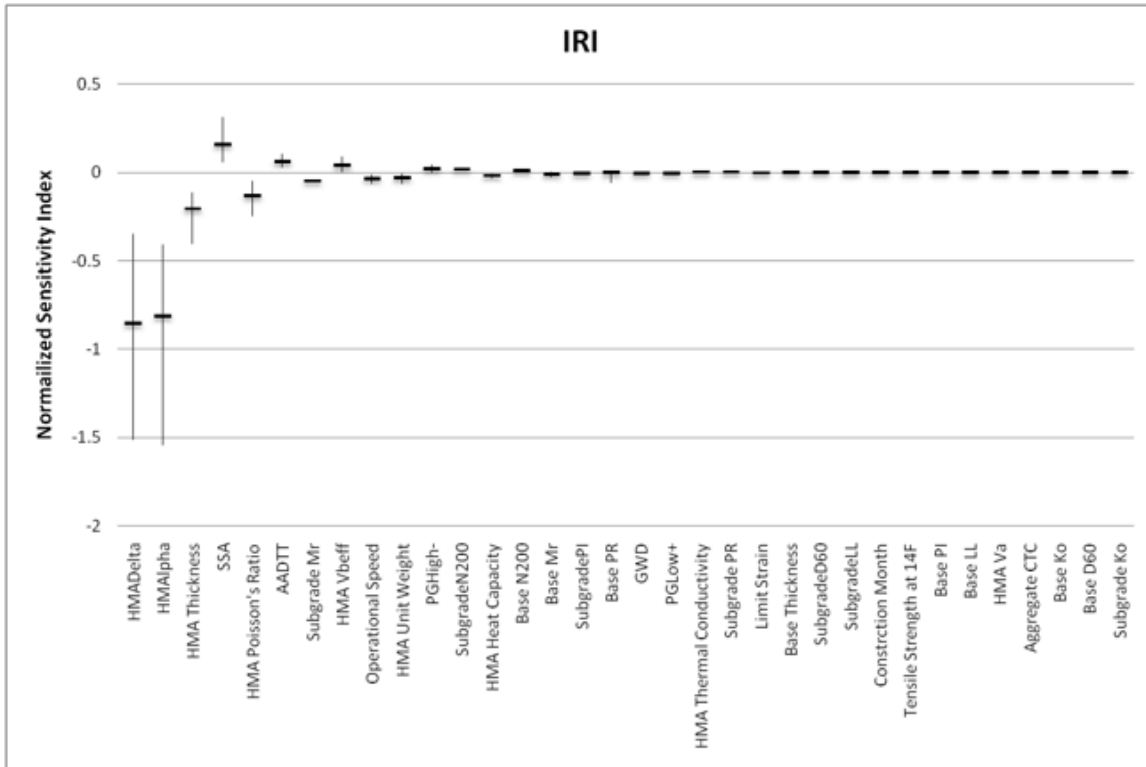


Figure 6.13. NSI values for IRI in New HMA (high-low-average).

7 HMA OVER STIFF FOUNDATION

7.1 Analysis Inputs

The project-specific design inputs that are fixed for all HMA Over Stiff Foundation analyses are generally the same as those given previously in Table 6.1 for the New HMA scenarios. The only exception is that the second layer material type may be granular base, a stabilized base, or existing pavement (rehabilitation/overlay scenarios). The baseline binder grades and variations for the HMA Over Stiff Foundation are also the same as those given previously in Table 6.2.

Table 7.1 summarizes the design inputs that are related to traffic level. Higher traffic levels require correspondingly thicker asphalt and base layers.

Table 7.1. Input Parameter related to traffic levels in HMA Over Stiff Foundation cases.

Input Parameter \ Traffic Level	Low Traffic			Medium Traffic			High Traffic		
	Baseline	-	+	Baseline	-	+	Baseline	-	+
AADTT	1000	500	5000	7500	5000	10000	250000	20000	30000
HMA Thickness	2	1.5	3	3	2	4	4	10	15
Stiff Layer Thickness	8	4	12	10	5	14	12	6	16

The remaining design inputs that are varied in the OAT sensitivity analyses are mostly the same as listed previously in Table 6.4. Design inputs from the New HMA scenarios that have been deleted in the HMA Over Stiff Foundation cases include: Construction Month; Base Lateral Stress Coefficient; Base Percent Passing #200 Sieve; Base D₆₀; Base Plasticity Index, Base Liquid Limit. New and/or modified design inputs for the HMA Over Stiff Foundation cases are summarized in Table 7.2.

Table 7.2. Input parameters and variations in HMA Over Stiff Foundation cases.

Input Parameter	Baseline Value	- value	+ value
Base Unit Weight	150	125	175
Base Resilient Modulus	400000	100000	3000000
Base Modulus of Rupture	500	300	700
Base Thermal Conductivity	1.25	1	1.5
Base Heat Capacity	0.28	0.224	0.336

7.2 Results

The 31 design inputs in Table 6.2, Table 6.4, Table 7.1, and Table 7.2 are varied over 3 input levels for 15 base cases (5 climate zones and 3 traffic levels) in the OAT sensitivity analyses. This required a total of 945 MEPDG runs⁵ for the HMA Over Stiff Foundation scenarios. The predicted distresses at the 50% reliability level for the HMA Over Stiff Foundation baseline scenarios are summarized in Table 7.3. The predictions span a wide range of magnitudes (including values beyond the design limits) for AC rutting and total rutting and a more modest range for IRI. Very little longitudinal and

⁵ In actuality, when trial runs, error corrections, and other re-runs are included the total number of MEPDG runs executed is substantially greater.

alligator cracking was predicted, which is sensible for the stiff foundation conditions in these cases. No significant transverse thermal cracking was predicted for even the coldest climates; as previously described, this is likely because the locations chosen for the cold climates, and the cold dry climate in particular, do not have sufficiently severely cold weather histories. When interpreting Table 7.3, it is important to keep in mind the objectives of the OAT sensitivity analyses: the precise magnitudes of the predicted distresses are not the focus but rather how these predicted distresses vary as each design input is varied about its baseline value.

Table 7.3. Predicted distress levels for HMA Over Stiff Foundation baseline scenarios.

Traffic	Climate	HMA (in)	Base (in)	Longitudinal Cracking (ft/mi)	Alligator Cracking (%)	Transverse Cracking (ft/mi)	AC Rut (in)	Total Rut (in)	IRI (in/mi)
Low	Hot-Wet	2	8	0	0	0	0.099	0.369	94.5
Low	Hot-Dry	2	8	0.01	0	0	0.173	0.387	91.6
Low	Cold-Wet	2	8	0	0	0.5	0.126	0.406	101
Low	Cold-Dry	2	8	0	0	0	0.097	0.356	97.1
Low	Temperate	2	8	0	0	0	0.077	0.318	90.2
Medium	Hot-Wet	3	10	0.01	0	0	0.462	0.75	109.7
Medium	Hot-Dry	3	10	0.04	0.0001	0	0.813	1.045	117.9
Medium	Cold-Wet	3	10	0.02	0	0.4	0.625	0.922	121.6
Medium	Cold-Dry	3	10	0.01	0	0	0.47	0.746	112.7
Medium	Temperate	3	10	0.01	0.0001	0	0.348	0.608	101.7
High	Hot-Wet	4	12	0	0.0347	0	1.001	1.281	131
High	Hot-Dry	4	12	0.36	0.0422	0	1.764	1.994	156
High	Cold-Wet	4	12	1.73	0.0367	0.4	1.383	1.671	151.7
High	Cold-Dry	4	12	0.34	0.032	0	1.034	1.303	135
High	Temperate	4	12	0	0.0388	0	0.745	0.999	117.5
Design Limi				2000	25	1000	0.25	0.75	172

An NSI value is calculated for each design input-pavement distress combination for each of the base cases. The NSI values calculated over all design inputs and base cases are summarized in two charts for each distress. One chart details the NSI values by base cases while the other summarizes the high-low-average NSI statistics over all base cases for each design parameter for the distress of interest.

This summarizes the design input NSI values on a distress-by-distress for the HMA Over Stiff Foundation scenarios only. Section 11 compiles key NSI values across all distresses and across all flexible pavement scenarios in order to identify which design inputs have sufficiently high sensitivities for inclusion in the GSA simulations.

The NSI values for longitudinal cracking are summarized in Figure 7.1 and Figure 7.2. The formats for these charts are similar to those described previously for the New HMA scenario. Most of the design input labels along the horizontal axes are defined in Table 6.6; Table 7.4 defines the new labels added for the HMA Over Stiff Foundation charts.

Table 7.4. Definitions of design input labels added for the HMA Over Stiff Foundation cases.

Name of Design Input	Description
Base Unit Weight	Unit Weight of base layer material
Base MOR	Modulus of Rupture of base layer material
Base Thermal Conduct	Thermal Conductivity of base layer material
Base Heat Capacity	Heat Capacity of base layer material

From Figure 7.1 it is seen that Base Thickness was ranked as the most sensitive parameter for longitudinal cracking, ranging up to nearly -1.3 for the hot-dry medium traffic base case. Base Mr was ranked second, but its maximum NSI value of about -0.05 is much less than for Base Thickness. Most of the design inputs having a large influence on longitudinal cracking for the New HMA scenarios—e.g., HMAAlpha, HMADelta, HMA Thickness, SSA—have negligible NSI values in the HMA Over Stiff Foundation cases.

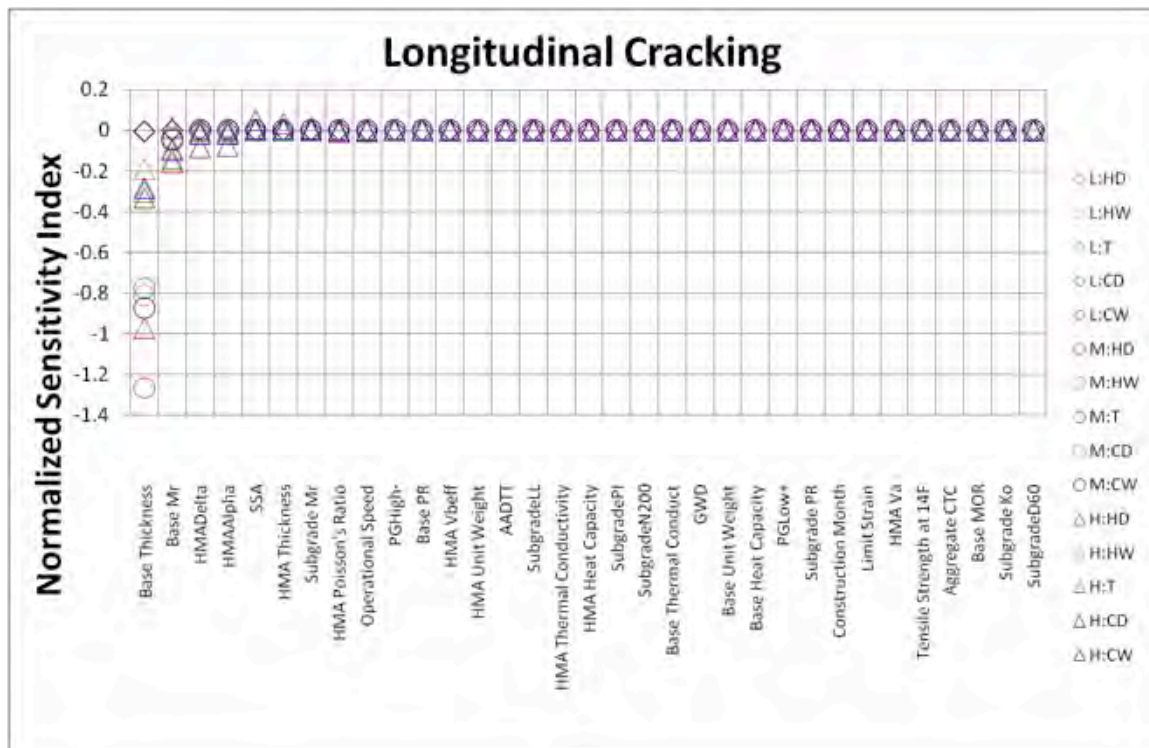


Figure 7.1. NSI values for longitudinal cracking in HMA Over Stiff Foundation (details).

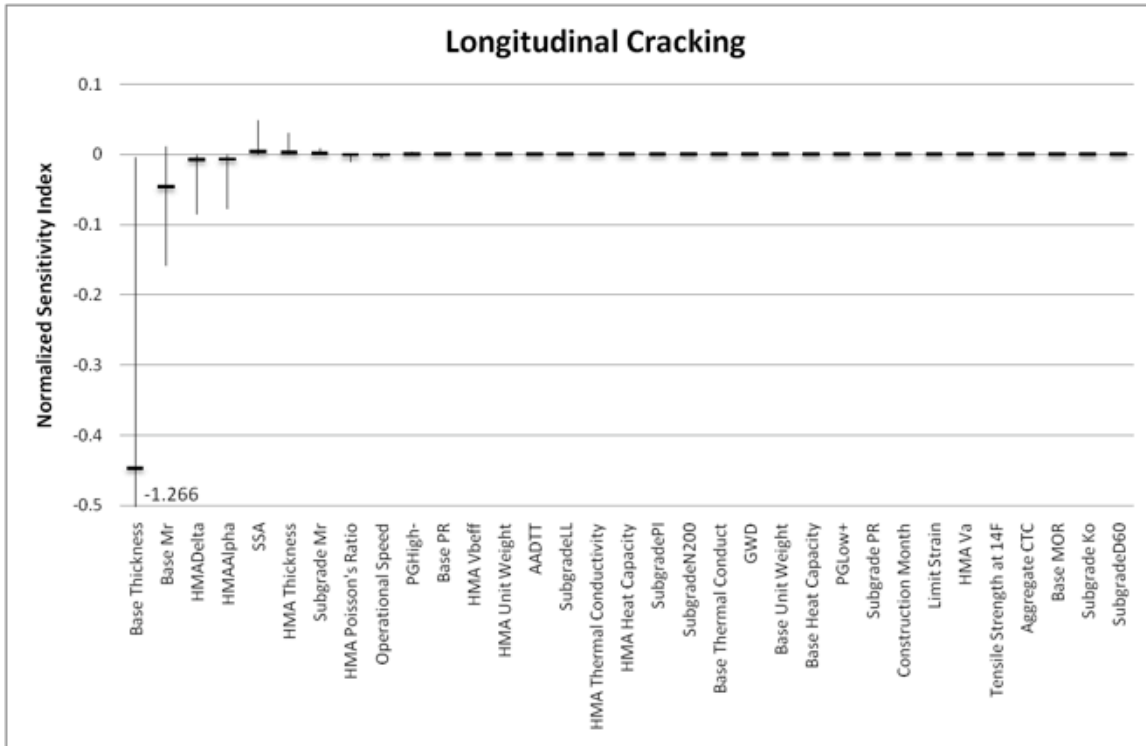


Figure 7.2. NSI values for longitudinal cracking in HMA Over Stiff Foundation (high-low-average).

The NSI values for alligator cracking are summarized in Figure 7.3 and Figure 7.4. Base Mr ranks as the most sensitive design input, but its maximum NSI value is only about -0.02, indicating very low sensitivity. The NSI values for all other design inputs are near zero. This is simply a consequence of negligible predicted alligator cracking in all of the HMA Over Stiff Foundation scenarios.

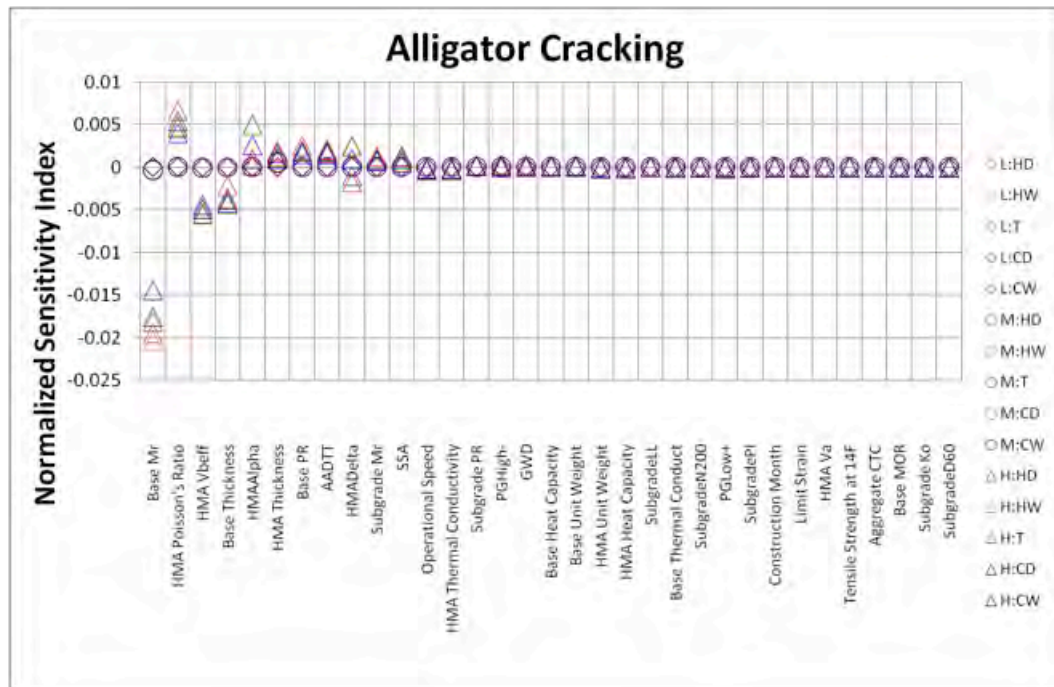


Figure 7.3. NSI values for alligator cracking in HMA Over Stiff Foundation (details).

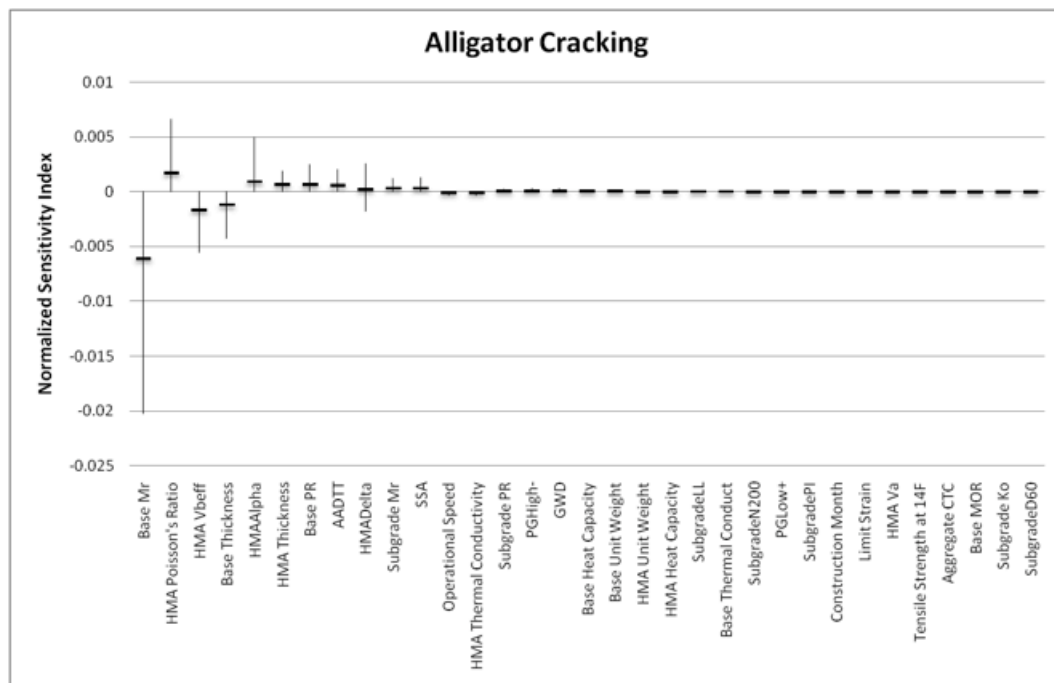


Figure 7.4. NSI values for alligator cracking in HMA Over Stiff Foundation (high-low-average).

The NSI values for transverse thermal cracking are summarized in Figure 7.5 and Figure 7.6. Only the cold-wet climate is presented because no transverse cracking was predicted for the other climate zones. Even for the cold-wet climate, the maximum magnitude of transverse cracking was only 6.8 feet per mile as compared to the design limit of 1000 feet per mile.

HMA Vbeff, Tensile Strength at 14F, HMA Thickness, Base Thermal Conductivity, and HMA Thermal Conductivity are the three most sensitive design inputs for transverse thermal cracking. All have negative NSI values, meaning that an increase in the design input value will produce a decrease in predicted thermal cracking. However, even the highest NSI values for these design inputs are near zero. In addition, although engineering experience would suggest that PGLow+ should have a major impact on thermal cracking, the OAT analyses found it to be one of the least sensitive inputs.

As described previously for the New HMA scenarios, the fact that no thermal cracking was predicted for the cold-dry climate zone suggests that the selected city of Spokane WA may not be sufficiently cold. Consequently, as special set of OAT analyses were performed for the International Falls cold-dry climate using out-of-spec low temperature binder grades in order to generate more significant thermal cracking from which to estimate sensitivity indices. The parameter variations considered in these special OAT analyses are summarized in Table 7.5. Note that only predicted thermal cracking is examined in these analyses.

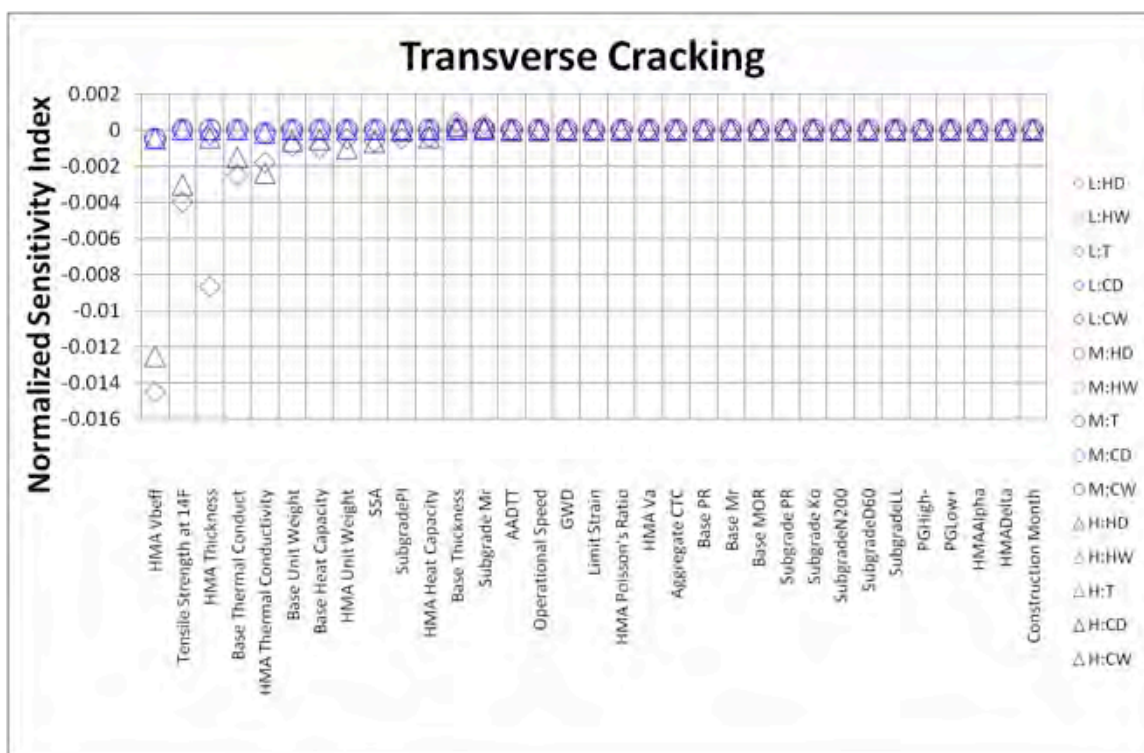


Figure 7.5. NSI values for transverse thermal cracking in HMA Over Stiff Foundation (detail).

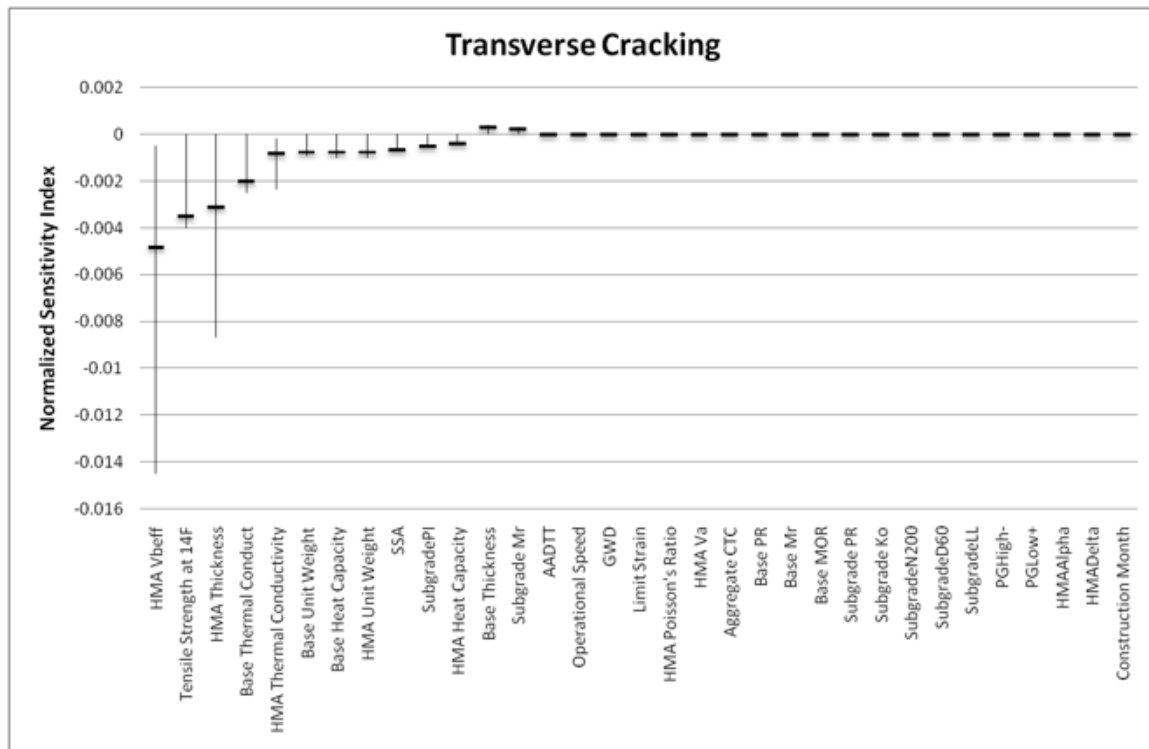


Figure 7.6. NSI values for transverse thermal cracking in HMA Over Stiff Foundation (high-low-average).

Table 7.5. Varied input parameters for special thermal cracking OAT analyses – HMA Over Stiff Foundation.

Input Parameter	Baseline Value ¹	-value	+value
HMA Thickness	See Table 7.1	See Table 7.1	See Table 7.1
PGLow ²	-28	-34	-22
HMA Thermal Conductivity	See Table 6.4	See Table 6.4	See Table 6.4
HMA Heat Capacity	See Table 6.4	See Table 6.4	See Table 6.4
Tensile Strength at 14°F	464 ⁴	372	558
Creep compliance D at 32°F ³	4.35E-07 ⁴	2.48E-07	5.22E-07
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Creep compliance m at 32°F ³	0.485 ⁴	0.388	0.581
14°F ³	0.284 ⁴	0.228	0.341
-4°F ³	0.191 ⁴	0.153	0.229
Aggregate Coefficient of Contraction in HMA	See Table 6.4	See Table 6.4	See Table 6.4
Base Thermal Conductivity	See Table 7.2	See Table 7.2	See Table 7.2
Base Heat Capacity	See Table 7.2	See Table 7.2	See Table 7.2

¹All values are in same units as MEPDG inputs.

²Default binder grade recommended by LTPPBind is PG 52-40.

³Used to generate synthetic creep compliance data for direct input to MEPDG.

⁴Based on MEDPG Level 3 empirical relations (v0.900 updates), volumetric properties for a typical 19 mm Superpave mixture, and A and VTS values corresponding to binder grade.

The special low temperature OAT analyses using the International Falls climate data and low temperature binder grades up to 3 steps too stiff successfully generated thermal cracking ranging from near zero to over 2000 ft or approximately twice the design limit. The NSI values for transverse thermal cracking for the special binder analyses are summarized in Figure 7.7. Surprisingly, the thermal conductivity of the stabilized base is the most sensitive design input; this is probably because this parameter governs the rate of heat transfer from the bottom of the HMA layer. (Note that for nonstabilized bases—i.e., the New HMA scenarios—thermal conductivity is not a design input in the MEPDG). The low temperature creep compliance parameters D and m and the Tensile Strength at 14F are the three next most sensitive design inputs for thermal cracking, followed by the HMA thickness. Note that the sensitivities to D and m are in addition to the influence of the low temperature binder grade; the reference values for D and m are based on the binder grade used in the analysis.

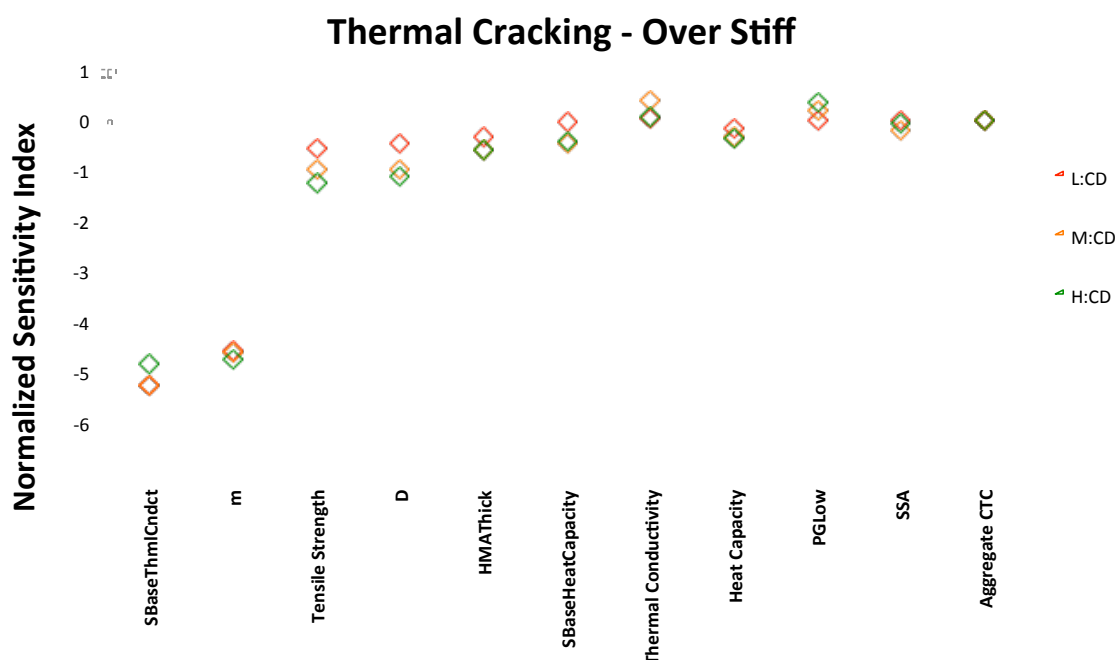


Figure 7.7. NSI values for transverse cracking in New HMA – special binder analyses.

The NSI values for AC rutting are summarized in Figure 7.8 and Figure 7.9. Similar to the New HMA scenarios, the dynamic modulus parameters HMA Δ and HMA α are the two most sensitive design inputs. The NSI range from about -4 to over -50 with average value about -18; the highest values occur in the high traffic cases. The negative values mean that increasing either HMA Δ or HMA α —i.e., increasing mix stiffness—will decrease AC rutting, as would be expected. Although the NSI values for HMA Δ and HMA α are high, the ranges of typical input values for these two parameters are quite small.

The SSA ranks as the third sensitive parameter, with NSI values ranging from 0.5 to 10.8 and an average of about 3.5. This means that the additional pavement heating accompanying a 10% increase in SSA will on average increase the predicted AC rutting by 35% of its design limit.

HMA Poisson's Ratio is the fourth most sensitive design input for AC rutting, with NSI values ranging from -0.5 to -8 and an average of about -3. As described previously in relation to the New HMA scenarios, the large negative NSI values for HMA Poisson's Ratio appear to contradict

conventional wisdom but are sensible because the Poisson strains contribute to the total vertical strains in the MEPDG AC rutting model.

Other highly sensitive design inputs for AC rutting include HMA Thickness, HMA Vbeff, AADTT, Operational Speed, Base Thickness, and PGHigh-. The NSI signs (positive/negative) for all of these inputs agree generally with engineering experience.

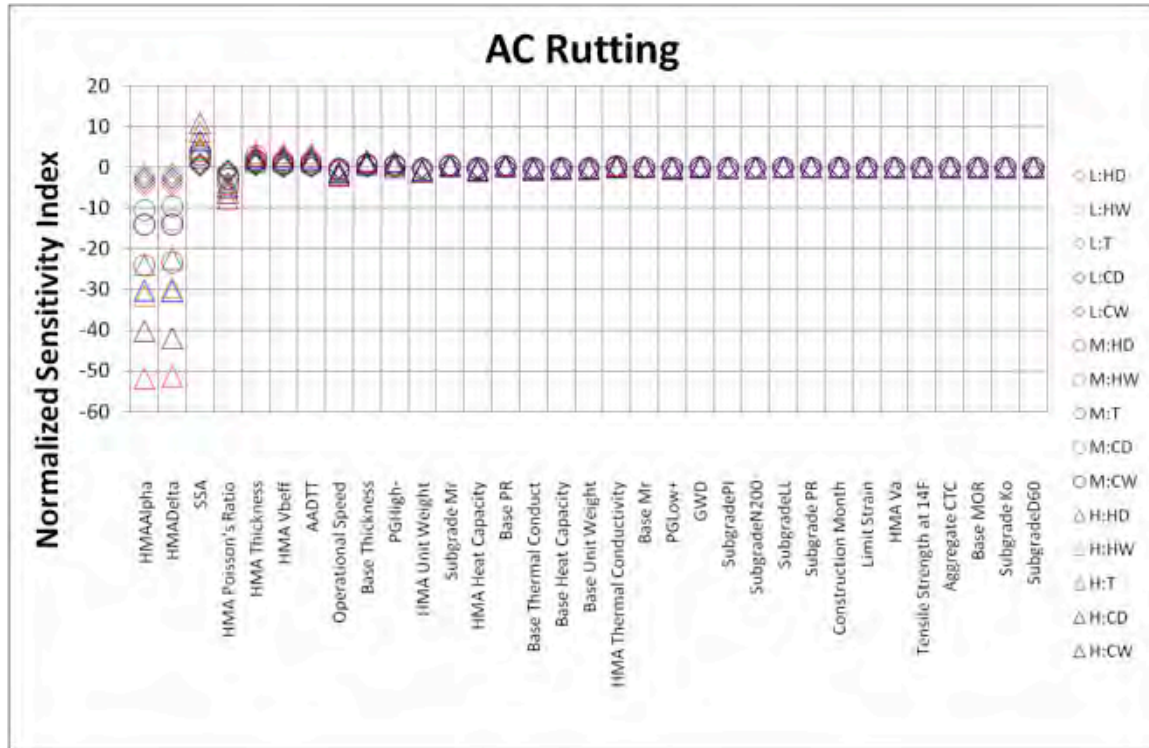


Figure 7.8. NSI values for AC rutting (details) – HMA Over Stiff Foundation scenarios.

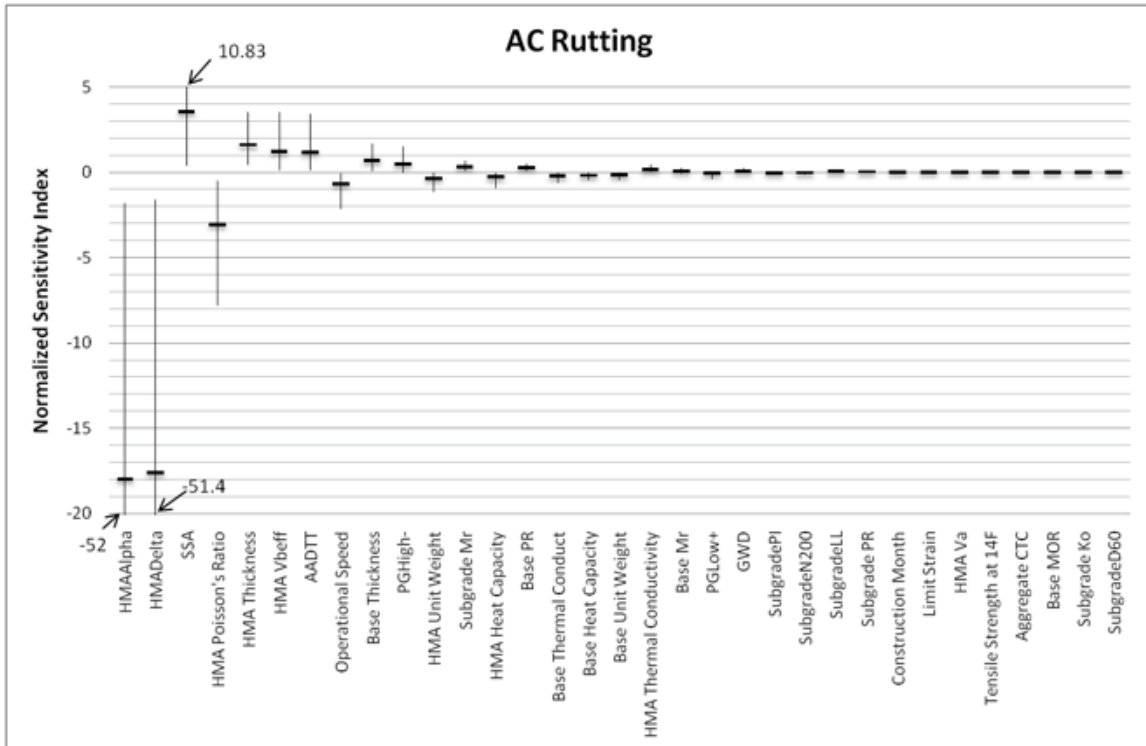


Figure 7.9. NSI values for AC rutting in HMA Over Stiff Foundation (high-low-average).

The NSI values for total rutting are summarized in Figure 7.10 and Figure 7.11. The sensitivity results for total rutting are qualitatively identical to those for AC rutting. The HMA Delta and HMA Alpha are two most sensitive design inputs, with NSI values ranging between about -1 to -17 and an average value about -7. These are followed by SSA, HMA Poisson's Ratio, HMA Thickness, AADTT, HMA Vbeff, Operational Speed, and PGHigh-; the order is only slightly rearranged from the AC rutting results.

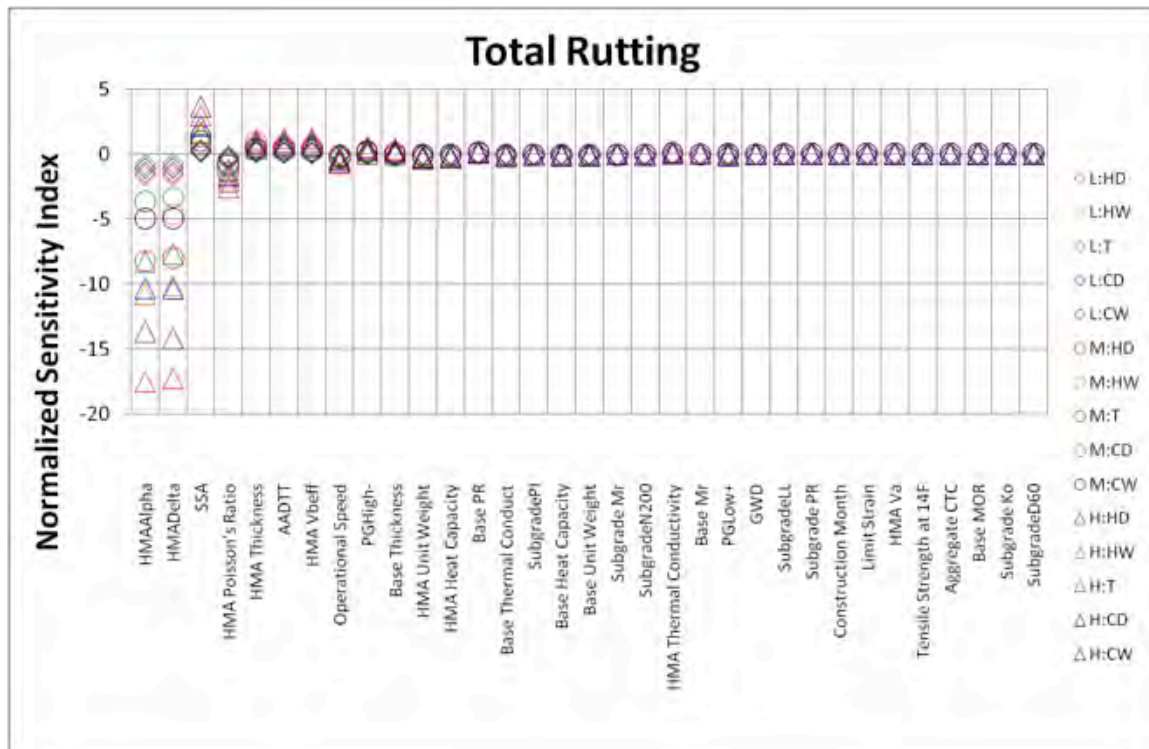


Figure 7.10. NSI values for total rutting in HMA Over Stiff Foundation (details).

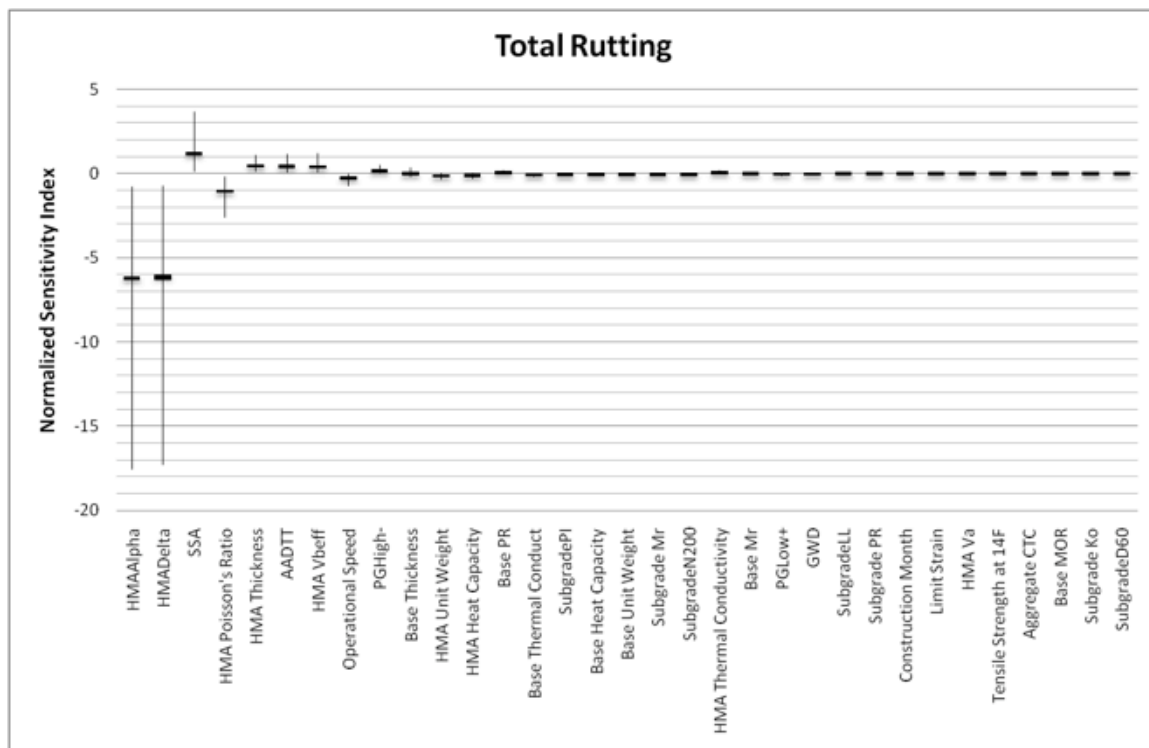


Figure 7.11. NSI values for total rutting in HMA Over Stiff Foundation (high-low-average).

The NSI values for IRI are summarized in Figure 7.12 and Figure 7.13. As would be expected given that IRI is based in part on the primary distresses, the sensitivity trends for IRI mirror those for the individual distresses. The dynamic modulus parameters HMA Delta and HMA Alpha are the two most sensitive parameters, with NSI values ranging between about -0.1 to about -3 and averaging about -1. SSA and HMA Poisson's Ratio are the only other design inputs that have any significant sensitivity for predicted IRI.

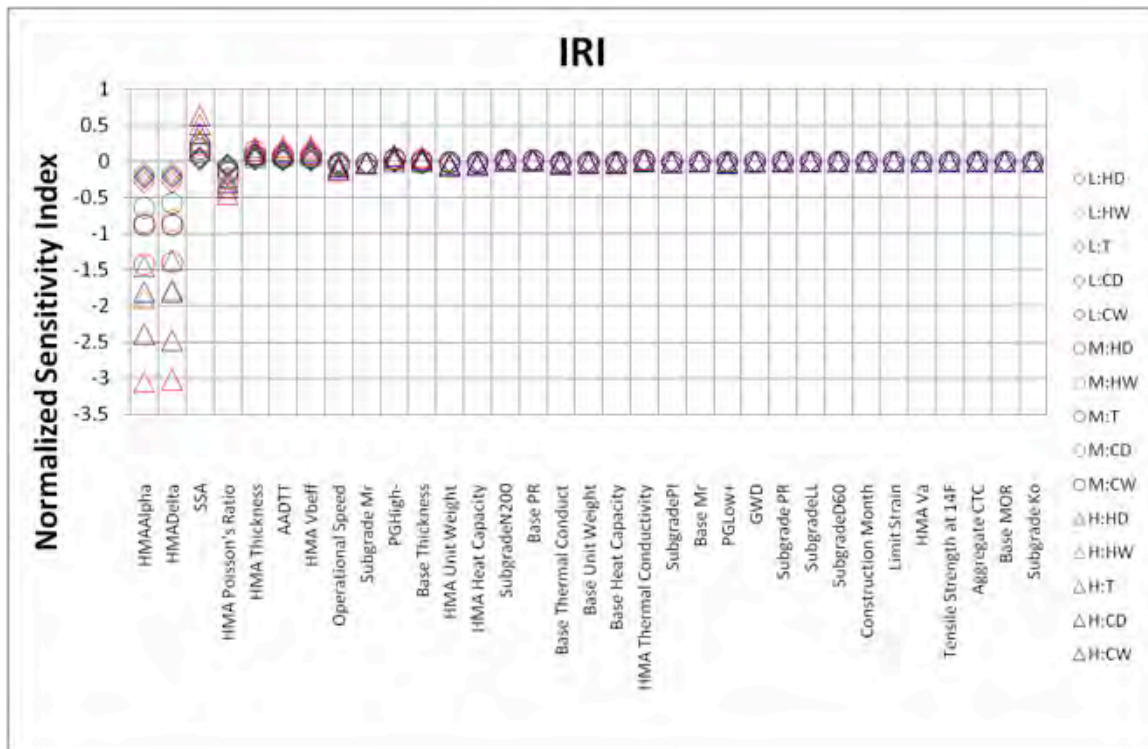


Figure 7.12. NSI values for IRI in HMA Over Stiff Foundation (details).

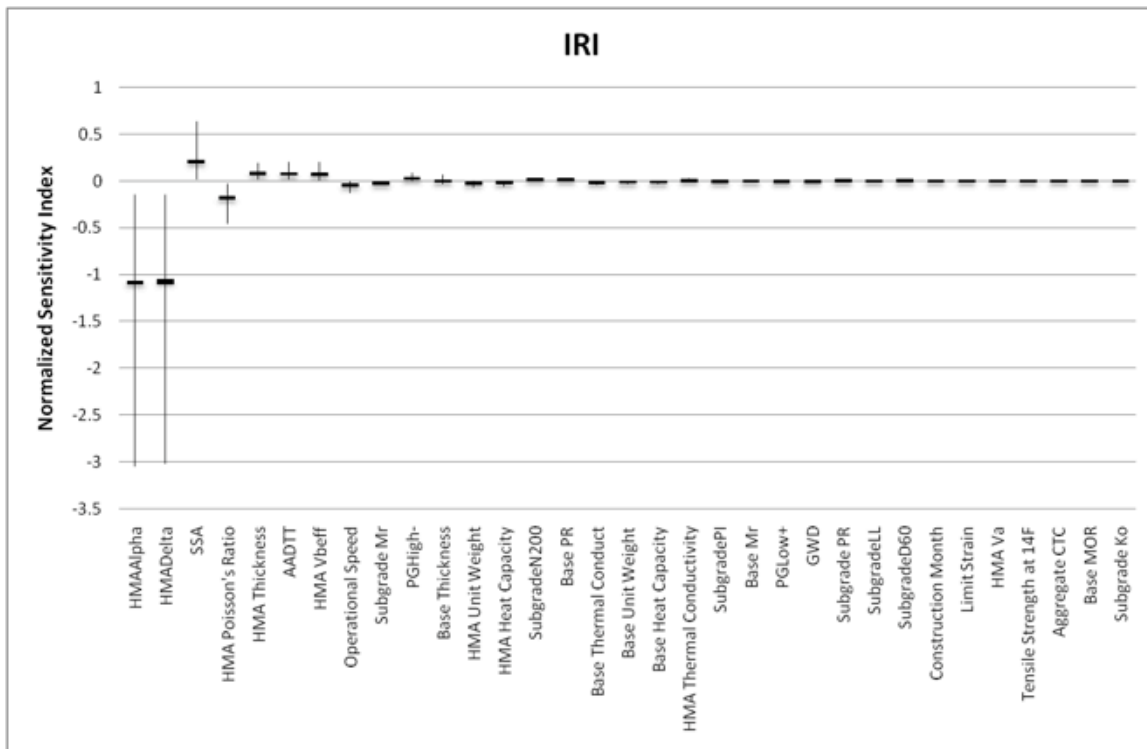


Figure 7.13. NSI values for IRI in HMA Over Stiff Foundation (high-low-average).

8 NEW JPCP

8.1 Analysis Inputs

Similar to OAT analyses of flexible pavements, the OAT analyses of rigid pavements encompassed a total of 15 base cases consisting of five climate zones and three traffic levels. Table 8.1 presents project-specific parameters that were fixed for all New JPCP analyses.

Table 8.1. Fixed design inputs for New JPCP cases.

Input Parameter	Value
Design Life	25 years
Reliability	90% for all distresses
AADTT Category	Principal Arterials – Interstate and Defense Route
TTC	4
Number of Lanes in Design Direction	2 for low traffic/ 3 for medium and high traffic
Truck Direction Factor	50
Truck Lane Factor	75 for low traffic /55 for medium traffic /50 for high traffic
Default Growth Rate	No Growth
First Layer Material Type	Portland Cement Concrete
Second Layer Material Type	Granular Base
Subgrade Material Type	Soil

Table 8.2 summarizes the design inputs that are related to traffic level. Higher traffic levels require correspondingly thicker PCC and base layers. The baseline value, reduced value (“-value”), and increased value (“+value”) for the PCC and granular base layers are listed under each traffic level category.

Table 8.2. Design inputs related to traffic levels in New JPCP cases.

Traffic Level Input Parameter	Low Traffic			Medium Traffic			High Traffic		
	Baseline	-	+	Baseline	-	+	Baseline	-	+
Nominal AADTT	1000	500	5000	7500	5000	10000	25000	20000	30000
Design Lane	375	188	1875	2063	1375	2750	6250	5000	7500
PCC Thickness	8	6	10	10	8	12	12	10	14
Base Thickness	4	2	6	6	3	9	8	5	12

The remaining design inputs varied in the OAT sensitivity analyses are summarized in Table 8.3. These inputs correspond to the “Highly Sensitive” and “Sensitive” design inputs as identified during the preliminary triage process. The baseline value, reduced value (“-value”), and increased value (“+value”) are listed for each design input. Similar to the OAT sensitivity analyses for flexible pavements, absolute terms and multiplicative factors were utilized to describe the decreases/increases from the baseline values. As stated in Section 3.4, edge support inputs in MEPDG JPCP analyses are specified as one of three options: no support, tied PCC, and widened slab. The no support condition represented as a 5% LTE and 12-ft slab width was selected as the base condition. The distress

predictions under the no support condition were compared to those for two other LTE values (50% and 80%) for the tied PCC option or two slab widths (13ft and 14ft) for the widened slab option.

Table 8.3. Input parameters and variations in new JPCP cases.

Input Parameter	Baseline Value¹	- value	+ value
Construction Month	July 2006	March 2006	October 2006
Design Lane Width	12	11	12
Joint Spacing	15	10	20
Dowel Diameter	1.2	1.0	1.5
Edge Support – LTE	5 (no support)	5	50, 80
Edge Support – Widened Slab	12 (no support)	12	13, 14
Erodibility Index	3	1	5
Surface Shortwave Absorption	0.85	0.80	0.98
PCC Unit Weight	150	140	160
PCC Poisson's Ratio	0.15	0.10	0.20
PCC Coef. of Thermal Expansion	5.56	2	10
PCC Thermal Conductivity	1.25	0.5	2
Cement Content	500	400	700
Water/Cement Ratio	0.4	0.3	0.7
PCC Modulus of Rupture at 28 days	620	× 0.8 (496)	× 1.2 (744)
PCC Elastic Modulus at 28 days	3,956,571	× 0.8 (3,165,257)	× 1.2 (4,747,885)
Base Resilient Modulus	25,000	15,000	40,000
Subgrade Resilient Modulus	15,000	10,000	20,000
GWD	10	2	18

¹All values are in same units as MEPDG inputs.

8.2 Results

The 21 design inputs in Table 8.2 and Table 8.3 are varied over 3 input levels for 15 base cases (5 climate zones and 3 traffic levels) in the OAT sensitivity analyses. This required a total of 645 MEPDG runs⁶ for the New JPCP scenarios. The predicted distresses at the 50% reliability level for the New JPCP baseline scenarios are summarized in Table 8.4. The predictions span a wide range of magnitudes (including values beyond the design limits) for all distresses. When interpreting Table 8.4, it is important to keep in mind the objectives of the OAT sensitivity analyses: the precise magnitudes of the predicted distresses are not the focus but rather how these predicted distresses vary as each design input is varied about its baseline value.

⁶ When trial runs, error corrections, and other re-runs are included, the total number of MEPDG runs executed is substantially greater.

Table 8.4. Predicted distress levels for New JPCP baseline scenarios.

Traffic	Climate	PCC (in.)	Base (in)	Faulting (in)	Trans. Crack (%)	IRI (in/mile)
Low	Hot-Wet	8	4	0.008	4.8	72.5
Low	Hot-Dry	8	4	0.009	13.7	80.0
Low	Cold-Wet	8	4	0.018	9.7	105.2
Low	Cold-Dry	8	4	0.009	14.6	142.4
Low	Temperate	8	4	0.005	1.5	68.1
Medium	Hot-Wet	10	6	0.046	2.0	89.9
Medium	Hot-Dry	10	6	0.052	7.2	96.9
Medium	Cold-Wet	10	6	0.089	2.4	134.0
Medium	Cold-Dry	10	6	0.045	5.0	151.1
Medium	Temperate	10	6	0.032	0.4	80.9
High	Hot-Wet	12	8	0.131	0.5	132.8
High	Hot-Dry	12	8	0.156	2.1	147.1
High	Cold-Wet	12	8	0.167	0.6	171.6
High	Cold-Dry	12	8	0.107	1.5	179.0
High	Temperate	12	8	0.102	0.1	117.2
Design Limit				0.120	15	172

A Normalized Sensitivity Index (NSI) value is calculated for each design input-pavement distress combination for each of the base cases. The NSI values calculated over all design inputs and base cases are summarized in two charts for each distress. One chart details the NSI values by base case while the other summarizes the high-low-average NSI statistics over all base cases for each design parameter for the distress of interest.

This section summarizes the design input NSI values on a distress-by-distress for the New JPCP scenarios only. Section 11 compiles key NSI values across all distresses and across all rigid pavement scenarios in order to identify which design inputs have sufficiently high sensitivities for inclusion in the GSA simulations.

The NSI values for all distresses of the New JPCP cases are summarized through Figure 8.1 to Figure 8.6. The formats for these figures are the same as for the flexible pavement scenarios presented previously. The key to the design input labels along the horizontal axes in these figures is provided in Table 8.5.

Table 8.5. Definition of design input labels for New JPCP cases.

Name of Design Input	Description
AADTT	Average Annual Daily Truck Traffic
Construction Month	Base/Subgrade construction time, usually one month ahead of pavement construction month
GWD	Ground Water Depth
Design Lane Width @ No Edge Support	Distance between the lane markings on either side of the design lane (not the “slab width”) under no edge support condition
Design Lane Width @ LTE = 80	Distance between the lane markings on either side of the design lane (not the “slab width”) under tied shoulder with LTE = 80
Design Lane Width @ 14 -ft.	Distance between the lane markings on either side of the design lane (not the “slab width”) under 14 -ft. Widened Slab

Widened Slab	
Dowel Diameter	Diameter of dowel bar
Joint Spacing	Transverse joint spacing of Jointed Plain Concrete Pavement
Edge Support - Widened Slab	Widened slab widths for edge support
Edge Support - LTE	Load Transfer Efficiency of tied shoulder for edge support
Erodibility Index	Erodibility condition of base material layer
SSA	Surface Shortwave Absorption
JPCP Layer Thickness	Thickness of Portland Cement Concrete layer
PCC Unit Weight	Unit weight of Portland Cement Concrete
PCC CTE	Coefficient of Thermal Contraction of Portland Cement Concrete
PCC 28-day E	28-day elastic modulus of Portland Cement Concrete
PCC 28-day MOR	28-day Modulus of Rupture of Portland Cement Concrete
PCC Poisson's Ratio	Poisson's ratio of Portland Cement Concrete
Cement Content	Cement content of Portland Cement Concrete
Thermal Conductivity	Thermal conductivity of Portland Cement Concrete
W/C ratio	Ratio of water to cement of Portland Cement Concrete
Base Thickness	Thickness of base material layer
Base Mr	Resilient modulus of base material
Subgrade Mr	Resilient modulus of subgrade material

Figure 8.1 and Figure 8.2 present the NSI values for faulting of New JPCP. PCC unit weight, dowel diameter, and edge support with widened slab rank as the three most sensitive design inputs with NSI values ranging from -0.2 to -3.4. The negative sign of the NSI values means that faulting decreases with increases in values of these design inputs. The decrease in faulting values using these design inputs is more prominent at higher traffic volumes. The PCC unit weight is a critical factor in the calculation of critical responses in the rigid pavement structural response models employed in MEPDG. An increase in unit weight can decrease curling deflections, which can reduce faulting. The increases in dowel diameter are highly effective for reducing faulting by increasing the transverse joint LTE. The use of a wider slab reduces deflections by keeping the vehicles axles well away from the free edge and corners where they can cause large stresses and strains in the pavement slabs.

The next three most sensitive design inputs are PCC CTE with NSI values varying up to 1.9, joint spacing with NSI values ranging varying up to 1.6, and the PCC slab thickness with NSI values ranging from -1.7 to 0.8 . The positive signs of the NSI values for these inputs mean that faulting increases with increases in values of these design inputs. A larger PCC CTE can cause higher curling deflections resulting in increased faulting. The increase in predicted faulting with increased joint spacing. Although it has been recognized that slab thickness affects slab cracking very significantly and faulting to a lesser extent, it was unexpected that faulting would increase as slab thickness increased in some cases in this analysis. This can be explained by the reduction of dowel shear effectiveness. An increase in PCC thickness leads to a decrease in the ratio of dowel cross-section to PCC cross-section (NCHRP 2004). Thus, an increase in PCC thickness may require a correlated increase in dowel diameter to avoid an increase in faulting. Note that the OAT analysis for PCC thickness varied only PCC thickness design inputs with fixed values of the other design inputs including dowel diameter.

SSA, AADTT, and cement content are the next most sensitive design inputs. Higher cement content and SSA may increase the drying shrinkage at the surface of the PCC slab, which may increase faulting due to increased warping deflection. AADTT agrees with engineering experience

The other design inputs have less than 0.5 of average NSI values (see Figure 8.2). The low NSI values for these inputs indicate that they have only minor influence on the faulting predictions for New JPCP.

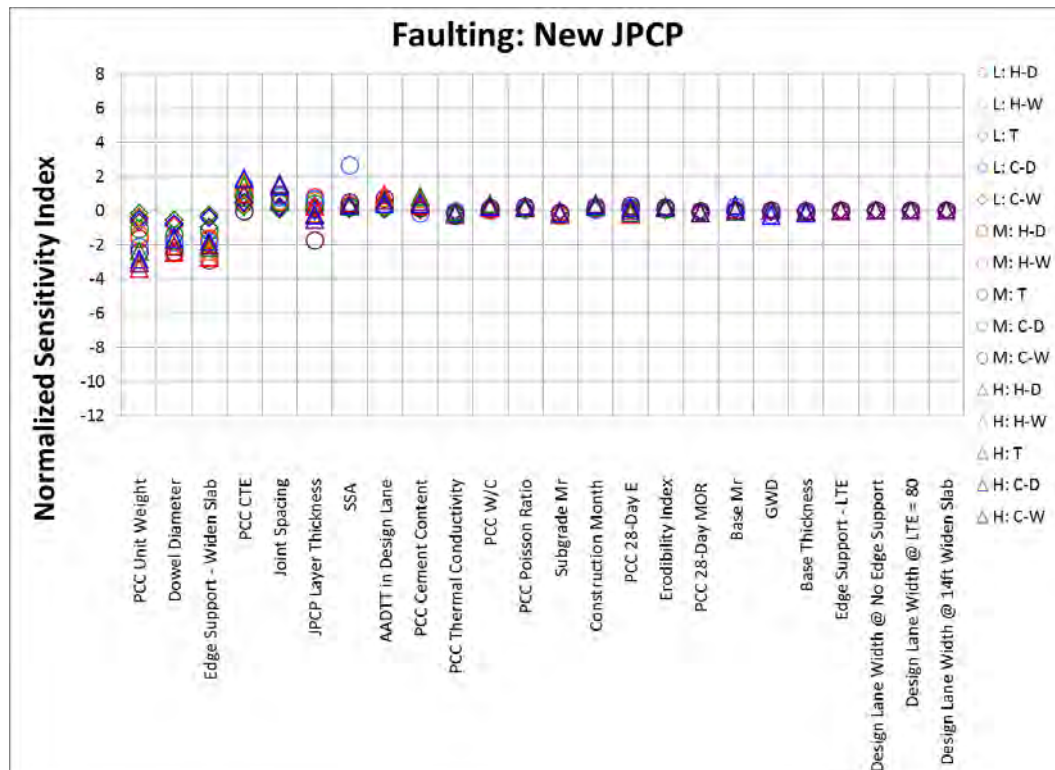


Figure 8.1. NSI values for faulting in New JPCP (details).

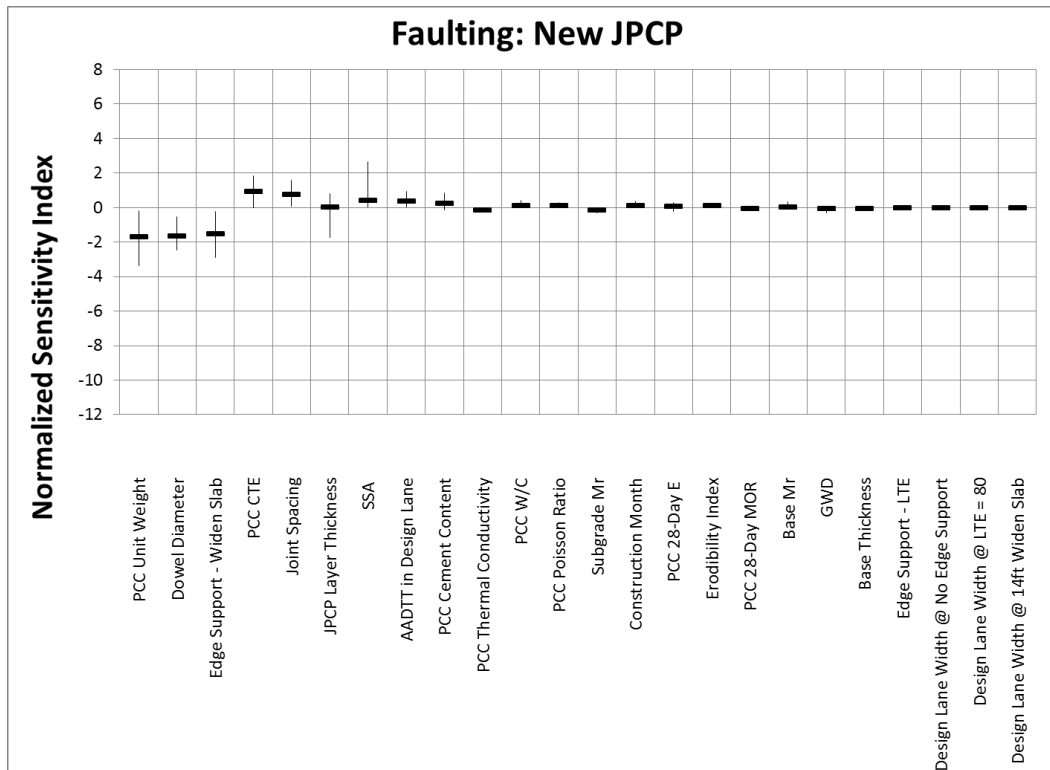


Figure 8.2. NSI values for faulting in New JPCP (high-low-average).

The NSI values for transverse cracking of New JPCP cases are summarized in Figure 8.3 and Figure 8.4. The most sensitive design inputs in decreasing order are PCC 28-day MOR with NSI values ranging from -9.6 to -16.6, PCC thickness with NSI values ranging from -0.6 to -15, joint spacing with NSI values ranging from 2.5 to 9.9 and PCC 28-days *E* with NSI values ranging from 0.4 to 9.8. Reduced transverse cracking with higher PCC strength and increased PCC thickness agrees with engineering experience. Increased transverse cracking with increasing joint spacing also agrees with engineering experience. Increases in PCC *E* lead to increases in bending stresses that may produce increased transverse cracking. Although in reality PCC MOR also increases with increasing PCC *E*, this was not reflected in the OAT analyses that by definition vary only one design input at a time.

The next most sensitive design inputs are PCC CTE with NSI values varying up to 4.6, thermal conductivity with NSI values ranging from -1.4 to -5.3, SSA with NSI values varying up to 11, edge support with widened slab with NSI values varying down to -6.6, and design lane width under widened slab condition with NSI values varying down to -7.2. Higher PCC CTE increases curling stresses resulting in increased transverse cracking. Higher thermal conductivity can decrease curling stress by reducing temperature differences between the top and bottom of PCC slabs, which in turn decreases curling stresses and transverse cracking. As SSA increases, the pavement surface absorbs more heat from solar radiation, which can make PCC slab surface drier. More drying shrinkage at the top of the slab can result in increased transverse cracking due to warping stress. Wider slabs can greatly reduce tensile bending stresses and transverse cracking by keeping the vehicles axles well away from the free edge and corners of the slabs.

Significant but lower sensitivity design inputs include PCC unit weight, PCC Poisson's ratio, and AADTT in design lane. PCC unit weight is an important input in the calculation of critical responses

in rigid pavement structural response model employed in the MEPDG. An increase in unit weight can increase curling and warping stresses by restraining slabs from expanding and contracting due to temperature and moisture gradients. PCC Poisson's ratio is a required input to the structural response computation models employed in MEPDG. Although its effect on computed pavement responses is not great, the OAT analyses show that higher PCC Poisson's ratio may increase transverse cracking predictions by increasing the influence of lateral stresses. Increased transverse cracking with increasing AADTT agrees with engineering experience.

The other design inputs have average NSI values of less than 0.5 (see Figure 8.4). The low NSI values of these inputs indicate that they have only minor influence on the transverse cracking of New JPCP.

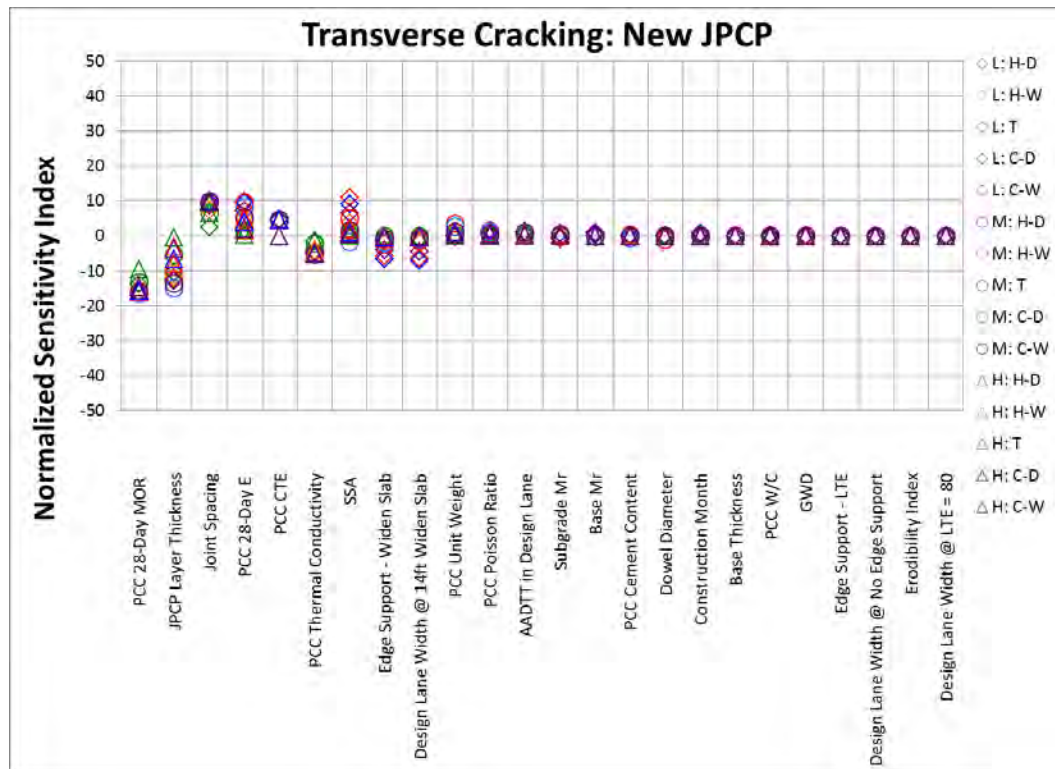


Figure 8.3. NSI values for transverse cracking in New JPCP (details).

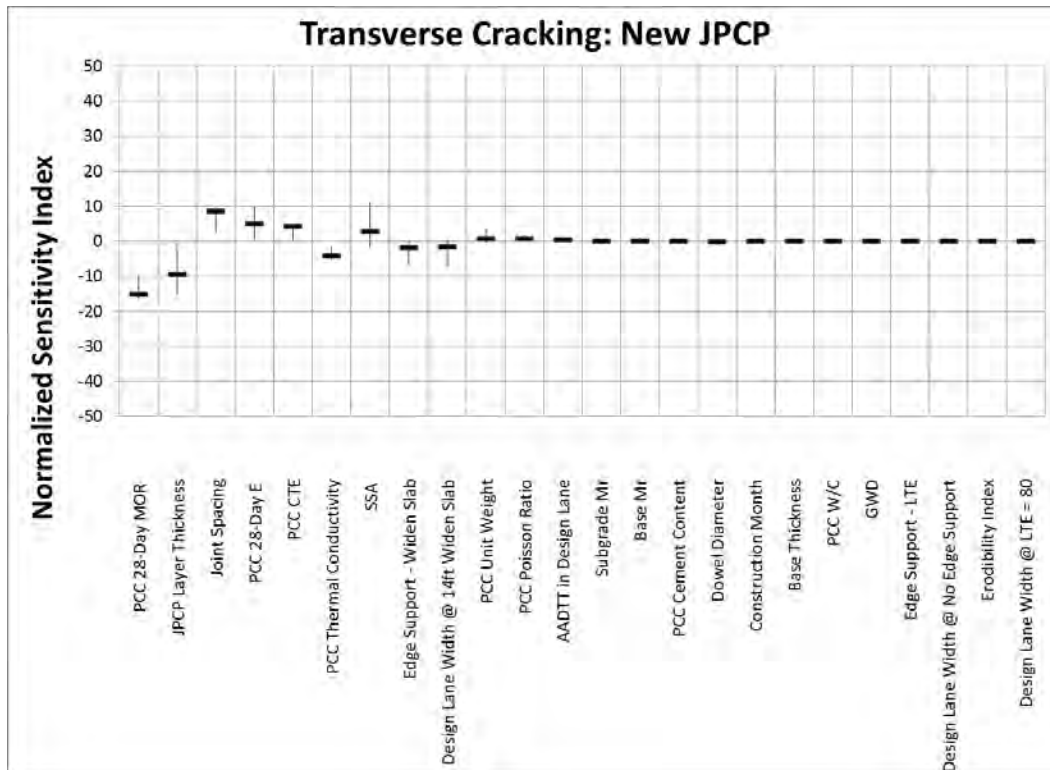


Figure 8.4 NSI values for transverse cracking in new JPCP (high-low-average).

The NSI values for predicted IRI of the New JPCP cases are summarized in Figure 8.5 and Figure 8.6. IRI predictions in MEPDG are calculated from regression equations that have as principal inputs the primary distresses (e.g., faulting, transverse cracking) along with a site factor. This means that the highly sensitive design inputs for faulting and /or transverse cracking will also be sensitive design inputs for IRI predictions.

The most sensitive design inputs for IRI predictions include PCC 28-day MOR, PCC thickness, edge support with widened slab, joint spacing, PCC CTE, dowel diameter, and PCC unit weight. Among these, the sensitive design inputs for both faulting and transverse cracking predictions are PCC thickness, edge support with widened slab, joint spacing, PCC CTE, and PCC unit weight. Increased PCC thickness in these OAT analyses resulted in a decrease in predicted faulting and predicted transverse cracking. A widened slab can also improve IRI by reducing faulting and transverse cracking. Higher PCC CTE and increased joint spacing increase predicted IRI by increasing both faulting and transverse cracking predictions. Increased PCC unit weight in these OAT analyses resulted in a decrease in predicted faulting and an increase in predicted transverse cracking. The net effect is that increased PCC unit weight causes a decrease in predicted IRI.

Among the sensitive design inputs for predicted IRI, those that are also sensitive design inputs for predicted transverse cracking alone are PCC 28-day MOR. The sensitive design input for predicted faulting alone is dowel diameter. As stated previously, these design inputs are the most sensitive for individual distress prediction. Thus, it is reasonable that these design inputs are also sensitive for predicted IRI. A higher PCC 28-day MOR can improve IRI by reducing transverse cracking. Increased dowel diameter can also improve IRI by reducing faulting.

The other design inputs have average NSI values of less than 0.5 (see Figure 8.6). These low NSI values indicate that these inputs have only minor influences on IRI predictions for New JPCP.

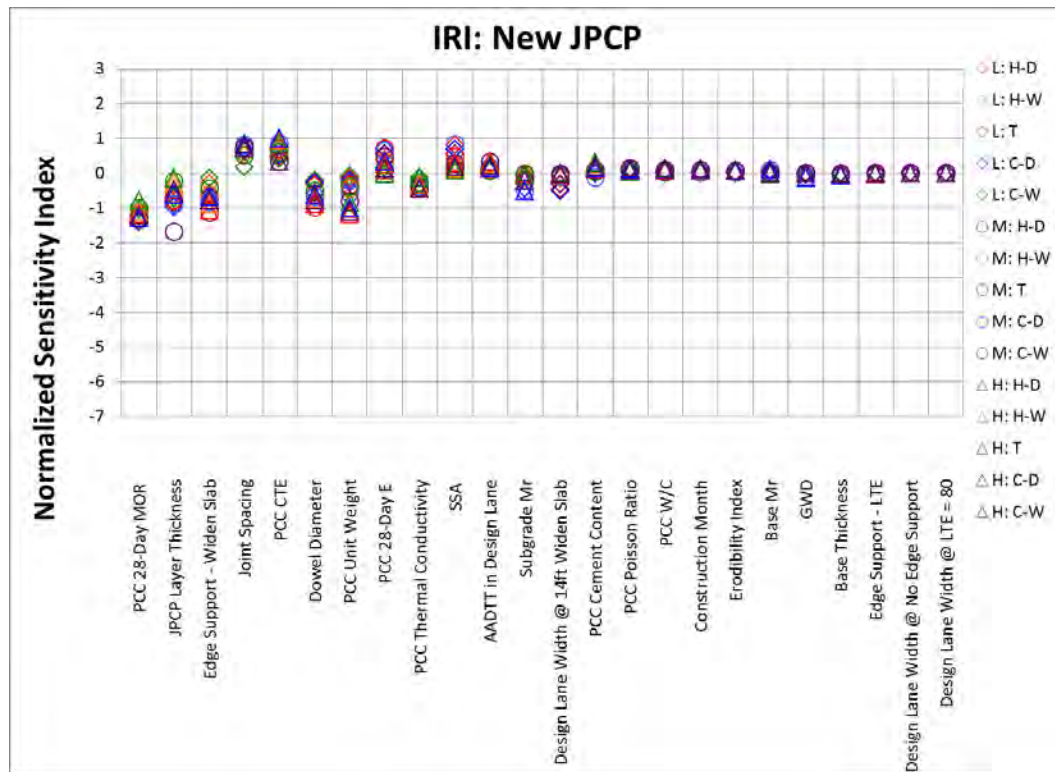


Figure 8.5. NSI values for IRI in New JPCP (details).

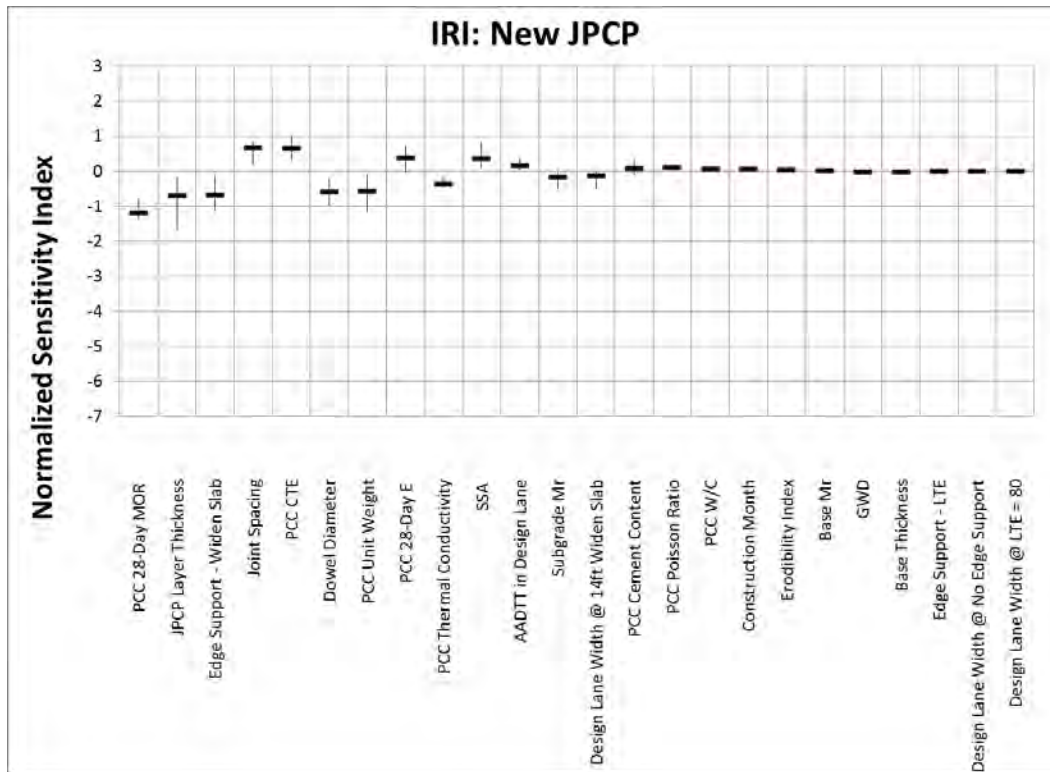


Figure 8.6. NSI values for IRI in New JPCP (high-low-average).

As described in Section 3.3, the method by which PCC strength and stiffness properties are specified can have a significant effect on predicted performance in the MEPDG. Table 8.6 summarizes the five most sensitive design inputs for the level 3 input option of measured 28-day MOR and *E* and the level 3 input option of measured 28-day MOR only. As seen in Table 8.6, these two input options result in some differences for transverse cracking predictions and IRI predictions but not for faulting and. The PCC MOR rank as the first most sensitive design inputs for the level 3 option of measured 28-day MOR and *E*. However, PCC thickness ranks as first most sensitive design inputs for the level 3 option of measured 28-day MOR.

Table 8.6. Five most sensitive design inputs at level 3 PCC material properties for New JPCP cases.

Ranking	Level 3 Input of Measured 28-day MOR and 28-day E			Level 3 Input of Measured 28-day MOR		
	Faulting	Cracking	IRI	Faulting	Cracking	IRI
1	PCC Unit Weight	PCC 28-Day MOR	PCC 28-Day MOR	PCC Unit Weight	JPCP Layer Thickness	JPCP Layer Thickness
2	Dowel Diameter	JPCP Layer Thickness	JPCP Layer Thickness	Dowel Diameter	Joint Spacing	Edge Support - Widen Slab
3	Edge Support - Widen Slab	Joint Spacing	Edge Support - Widen Slab	Edge Support - Widen Slab	PCC 28-Day MOR	Joint Spacing
4	PCC CTE	PCC 28-Day E	Joint Spacing	PCC CTE	PCC 28-Day E	PCC CTE
5	Joint Spacing	PCC CTE	PCC CTE	Joint Spacing	PCC CTE	PCC 28-Day MOR

9 JPCP OVER STIFF FOUNDATION

9.1 Analysis Inputs

This pavement type is intended to encompass JPCP on stiff stabilized base/subgrade layers. The project-specific parameters for all OAT analyses of JPCP Over Stiff Foundation cases are the same as the ones for the New JPCP cases (see Table 8.1) except for the second layer material type. The JPCP Over Stiff Foundation cases utilize stabilized unbound materials as the second layer material type instead of the granular materials used in the New JPCP scenarios. Stabilized unbound materials are characterized in terms of their resilient modulus values.

Table 9.1 summarizes the design inputs that are related to traffic level. The 5-in. baseline JPCP slab thickness with variations ranging from 3 in. to 7 in. was initially suggested for the low traffic level. However, the MEPDG requires a minimum PCC slab thickness of 6 inches. Therefore, an 8-in. baseline PCC slab thickness (with values ranging from 7 to 9 in.) was selected to evaluate the sensitivity of MEPDG distress predictions to PCC thickness under low traffic condition. The design inputs varied in the OAT sensitivity analyses for JPCP Over Stiff Foundation are summarized in Table 9.2. Except for the base resilient modulus, these are all similar to the New JPCP cases.

Table 9.1. Design inputs related to traffic levels in JPCP Over Stiff Foundation cases.

Input Parameter \ Traffic Level	Low Traffic			Medium Traffic			High Traffic		
	Baseline	-	+	Baseline	-	+	Baseline	-	+
Nominal AADTT	1000	500	5000	7500	5000	10000	25000	20000	30000
Design Lane	375	188	1875	2063	1375	2750	6250	5000	7500
PCC Thickness	8	7	9	9	8	10	11	9	13
Base Thickness	4	3	6	6	4	8	8	6	10

Table 9.2. Input parameters and variations in JPCP Over Stiff Foundation cases.

Input Parameter	Baseline Value ¹	- value	+ value
Construction Month	July 2006	March 2006	October 2006
Design Lane Width	12	11	12
Joint Spacing	15	10	20
Dowel Diameter	1.2	1.0	1.5
Edge Support – LTE	5 (no support)	5	50, 80
Edge Support – Widened Slab	12 (no support)	12	13, 14
Erodibility Index	3	1	5
Surface Shortwave Absorption	0.85	0.80	0.98
PCC Unit Weight	150	140	160
PCC Poisson's Ratio	0.15	0.10	0.20
PCC Coef. of Thermal Expansion	5.56	2	10
PCC Thermal Conductivity	1.25	0.5	2
Cement Content	500	400	700
Water/Cement Ratio	0.4	0.3	0.7
PCC Modulus of Rupture at 28 days	620	× 0.8 (496)	× 1.2 (744)

PCC Elastic Modulus at 28 days	3,956,571	× 0.8 (3,165,257)	× 1.2 (4,747,885)
Stabilized Base Resilient Modulus	100,000	40,000	3,000,000
Subgrade Resilient Modulus	15,000	10,000	20,000
Loss of Full Friction	136	0	150
GWD	10	2	18

¹All values are in same units as MEPDG inputs.

9.2 Results

The 21 design inputs in Table 9.1 and Table 9.2 are varied over 3 input levels for 15 base cases (5 climate zones and 3 traffic levels) in the OAT sensitivity analyses. This required a total of 645 MEPDG runs⁷ for the JPCP Over Stiff Foundation scenarios.

The predicted distress levels for each of the JPCP over stiff foundation baseline scenarios are summarized in Table 9.4. The predictions span a wide range of magnitudes for transverse cracking and IRI and a more modest range for faulting.

Table 9.3. Predicted distress levels for JPCP Over Stiff Foundation baseline scenarios.

Traffic	Climate	PCC (in.)	Base (in)	Faulting (in)	Trans. Crack (%)	IRI (in/mile)
Low	Hot-Wet	8	4	0.005	7.3	73.0
Low	Hot-Dry	8	4	0.005	22.7	85.6
Low	Cold-Wet	8	4	0.012	21.9	112.2
Low	Cold-Dry	8	4	0.006	30.9	154.5
Low	Temperate	8	4	0.002	1.6	66.9
Medium	Hot-Wet	9	6	0.030	7.6	86.3
Medium	Hot-Dry	9	6	0.037	30.9	109.0
Medium	Cold-Wet	9	6	0.066	21.6	138.6
Medium	Cold-Dry	9	6	0.034	41.2	176.0
Medium	Temperate	9	6	0.018	1.6	74.7
High	Hot-Wet	11	8	0.070	1.0	101.1
High	Hot-Dry	11	8	0.096	5.8	118.8
High	Cold-Wet	11	8	0.120	1.1	148.5
High	Cold-Dry	11	8	0.084	3.9	170.1
High	Temperate	11	8	0.045	0.1	87.4
Design Limit				0.120	15	172

An NSI value is calculated for each design input-pavement distress combination for each of the base cases. The NSI values calculated over all design inputs and base cases are summarized in two charts for each distress. One chart details the NSI values by base cases while the other summarizes the high-low-average NSI statistics over all base cases for each design parameter for the distress of interest.

⁷ When trial runs, error corrections, and other re-runs are included, the total number of MEPDG runs executed is substantially greater.

This section summarizes the design input NSI values on a distress-by-distress for the JPCP Over Stiff Foundation scenarios only. Section 11 compiles key NSI values across all distresses and across all rigid pavement scenarios in order to identify which design inputs have sufficiently high sensitivities for inclusion in the GSA simulations.

The NSI values for all distresses in the JPCP Over Stiff Foundation cases are summarized in Figure 9.1 through Figure 9.6. The formats for these charts are similar to those described previously. The design input labels along the horizontal axes can be found in Table 8.5. Overall, the OAT results for JPCP Over Stiff Foundation cases are very similar to the ones for the New JPCP scenarios, although small differences are observed in the magnitudes of individual NSI values.

Figure 9.1 and Figure 9.2 summarize the NSI values for faulting of JPCP Over Stiff Foundation Cases. Edge support with widened slab and dowel diameter rank as the two most sensitive design inputs, with NSI values varying from -0.1 to -3. The decrease in faulting values with these design inputs is greater under higher traffic volume. The next most sensitive design inputs are PCC unit weight with NSI values ranging from -0.1 to -28 and PCC CTE with NSI values ranging from 0.2 to 2.7. The joint spacing is also sensitive design inputs. All other design inputs have average NSI values less than 0.5 (see Figure 9.2). These low NSI values indicate that these inputs have only minor influence on faulting predictions in the JPCP Over Stiff Foundation cases.

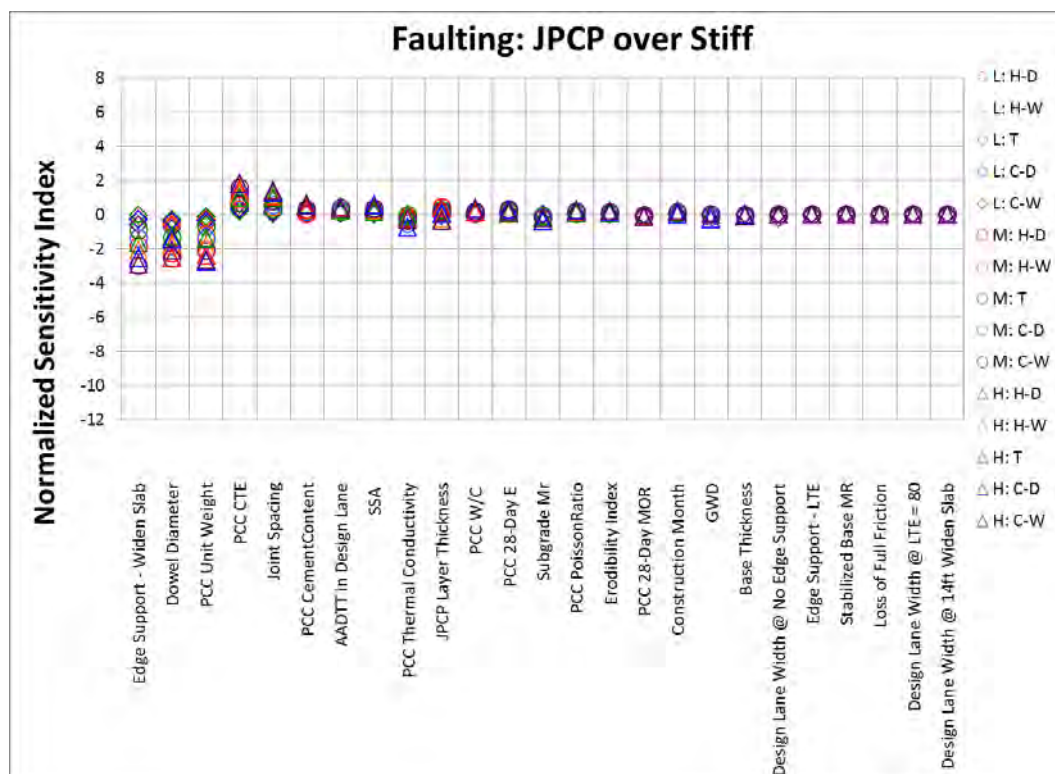


Figure 9.1. NSI values for faulting in JPCP Over Stiff Foundation (details).

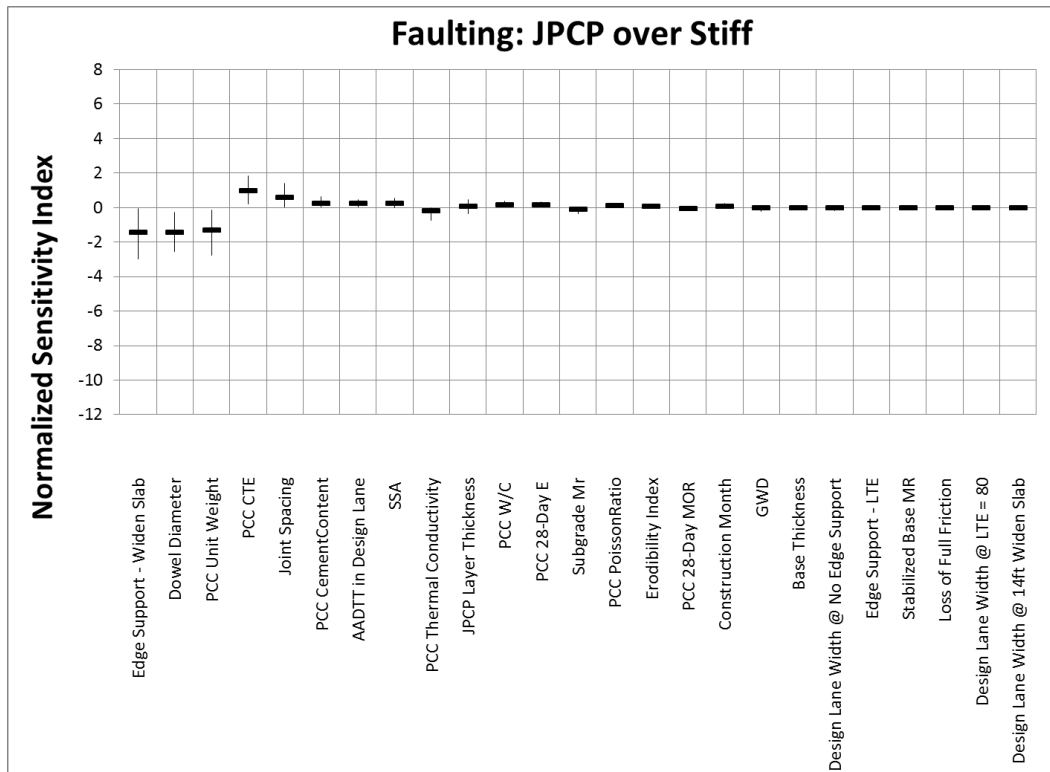


Figure 9.2. NSI values for faulting in JPCP Over Stiff Foundation (high-low-average).

The NSI values for transverse cracking are summarized in Figure 9.3 and Figure 9.4. The most sensitive design inputs in decreasing order are PCC 28-day MOR with NSI values ranging from -12 to -16, PCC thickness with NSI values varying up to -26, joint spacing with NSI values ranging from 1.4 to 10, PCC 28-days *E* with NSI values ranging from 0.9 to 15, SSA with NSI values ranging varying down to -26, design lane width under widen slab varying down to -18, and edge support with widened slab with NSI values varying down to -16.

The next most sensitive design inputs are PCC CTE with NSI values of about 4.5 and PCC thermal conductivity with NSI values ranges from -0.8 to -5.4, followed PCC unit weight, PCC Poisson's ratio, AADTT, and base thickness. All other design inputs have average NSI values less than 0.5 (see Figure 9.4). The low NSI values for these inputs indicate that they have only minor influence on transverse cracking predictions in the JPCP Over Stiff Foundation cases.

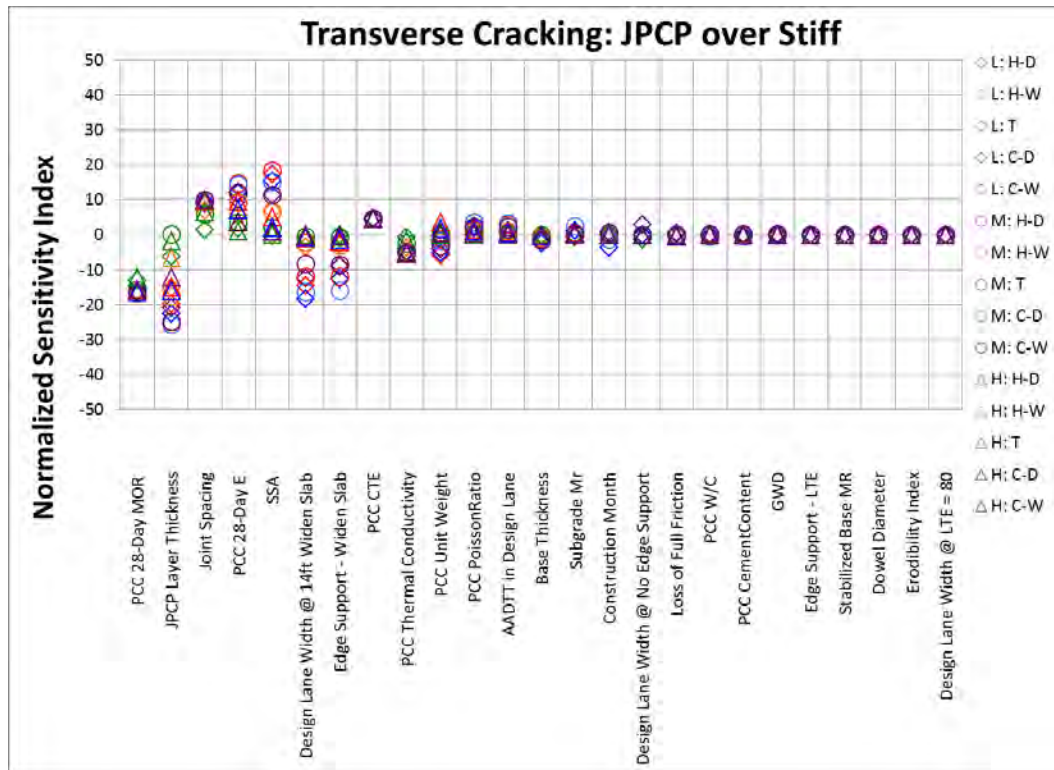


Figure 9.3. NSI values for transverse cracking in JPCP Over Stiff Foundation (detail).

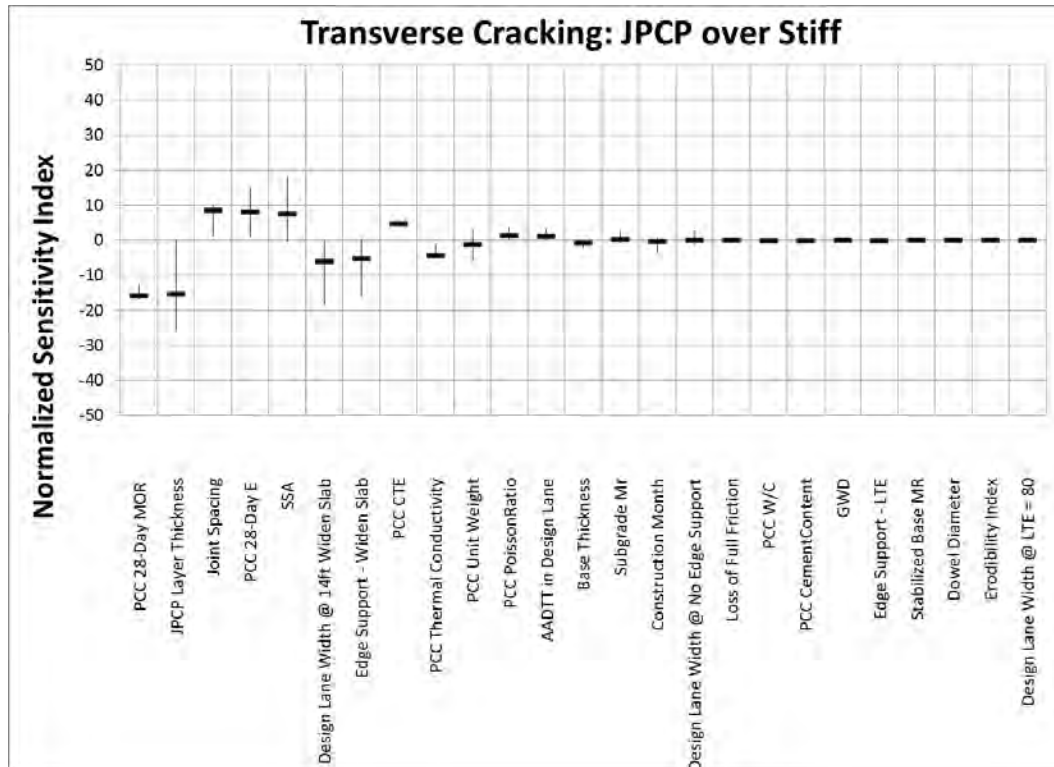


Figure 9.4. NSI values for transverse cracking in JPCP Over Stiff Foundation (high-low-average).

The NSI values for IRI are summarized in Figure 9.5 and Figure 9.6. The most sensitive design inputs for IRI predictions include PCC 28-day MOR, PCC thickness, edge support with widened slab, joint spacing, PCC CTE, SSA, PCC 28-day E, PCC unit weight, and dowel diameter. These design inputs are also highly sensitive for faulting and/or transverse cracking predictions.

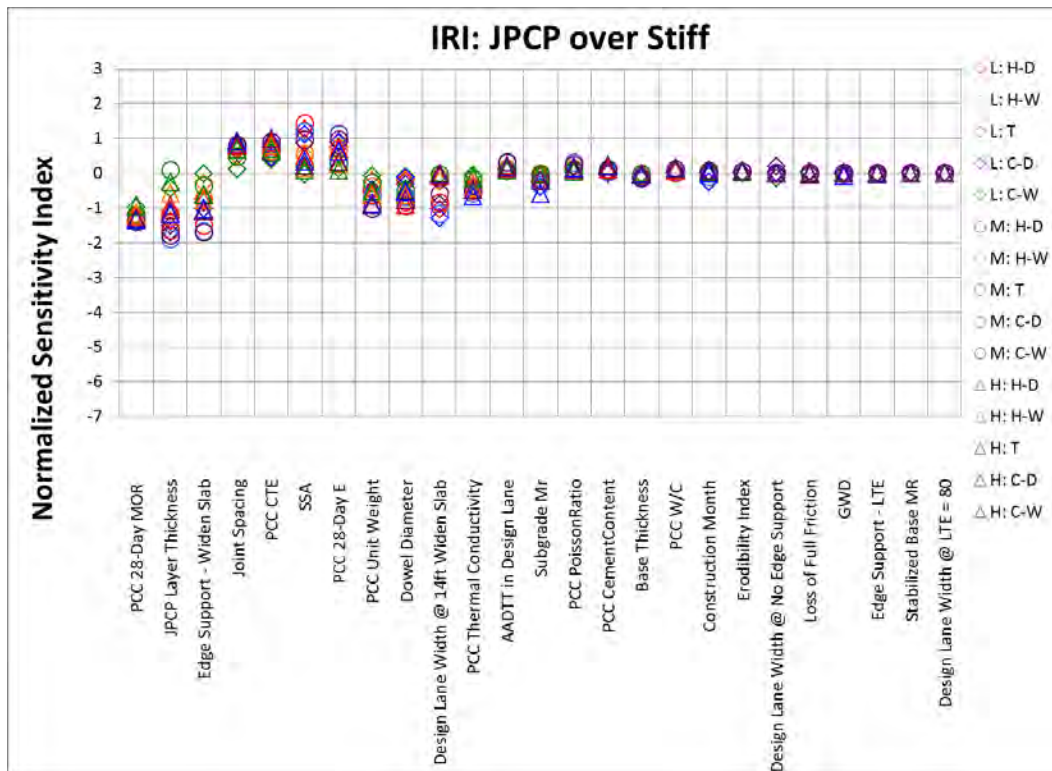


Figure 9.5. NSI values for IRI in JPCP Over Stiff Foundation (details).

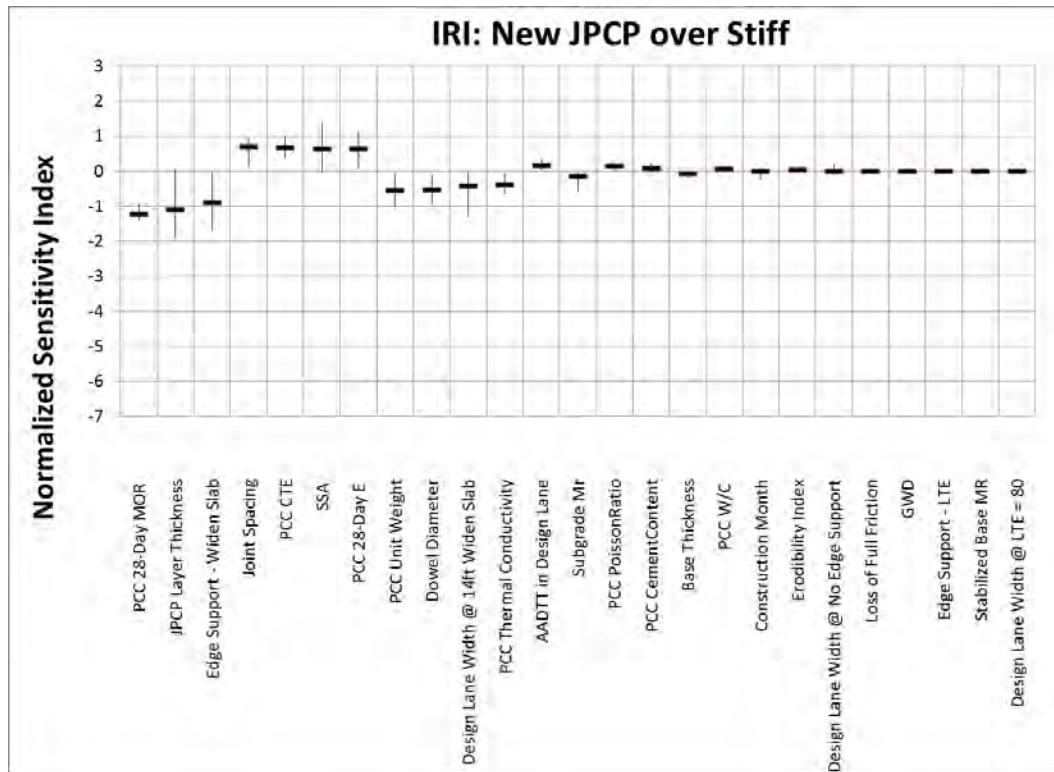


Figure 9.6. NSI values for IRI in JPCP Over Stiff Foundation (high-low-average).

Table 9.4 summarizes the five most sensitive design inputs for level 3 PCC stiffness and strength inputs specified as 28-day MOR and 28-day *E* versus 28-day MOR alone. Similar to the New JPCP cases, the PCC MOR rank as the first most sensitive design inputs for the level 3 option of measured 28-day MOR and *E* while PCC thickness ranks as first most sensitive design inputs for the level 3 option of measured 28-day MOR.

Table 9.4. Five most sensitive design inputs at level 3 PCC material properties for JPCP over stiff foundation cases.

Ranking	Level 3 Input of Measured 28-day MOR and E			Level 3 Input of Measured 28-day MOR		
	Faulting	Cracking	IRI	Faulting	Cracking	IRI
1	Edge Support - Widen Slab	PCC 28-Day MOR	PCC 28-Day MOR	Edge Support - Widen Slab	JPCP Layer Thickness	JPCP Layer Thickness
2	Dowel Diameter	JPCP Layer Thickness	JPCP Layer Thickness	Dowel Diameter	PCC 28-Day MOR	Edge Support - Widen Slab
3	PCC Unit Weight	Joint Spacing	Edge Support - Widen Slab	PCC Unit Weight	PCC 28-Day E	PCC 28-Day MOR
4	PCC CTE	PCC 28-Day E	Joint Spacing	PCC CTE	Joint Spacing	PCC 28-Day E
5	Joint Spacing	SSA	PCC CTE	Joint Spacing	SSA	Joint Spacing

10 NEW CRCP

10.1 Analysis Inputs

Similar to the preceding OAT scenarios, the OAT analyses of the New CRCP cases encompassed a total of 15 base cases associated with five climatic conditions at three traffic levels. The project-specific parameters for all OAT analyses of New CRCP cases are the same as the ones for the New JPCP cases shown previously in Table 8.1.

Table 10.1 summarizes the design inputs that are related to traffic level. A 6-in. reduced PCC thickness for the low traffic level was initially proposed. However, the MEPDG requires a minimum CRCP slab thickness of 7 inches. Therefore, an 8-in. baseline PCC slab thickness (with values ranging from 7 to 9 in.) was selected to evaluate the sensitivity of MEPDG distress predictions to PCC thickness under low traffic condition.

The design inputs varied in the OAT sensitivity analyses for New CRCP are summarized in Table 10.2. As described previously in Section 3.4, the edge support input in MEPDG CRCP analyses are given as four shoulder types including asphalt, gravel, monolithic tied concrete, and separate tied concrete. Each shoulder type is represented here in terms of its equivalent LTE value (see Table 3.5). These LTE values were used in the calculations of NSI for all distresses. The MEPDG requires a maximum steel depth should be mid-depth of PCC slab. Therefore, the baseline and ranges of steel depth values were changed in accordance to PCC slab thickness under each traffic level.

Table 10.1. Design inputs related to traffic levels in New CRCP cases.

Input Parameter \ Traffic Level	Low Traffic			Medium Traffic			High Traffic		
	Baseline	-	+	Baseline	-	+	Baseline	-	+
Nominal AADTT	1,000	500	5000	7500	5000	10000	25000	20000	30000
Design Lane	375	188	1875	2063	1375	2750	6250	5000	7500
PCC Thickness	8	7*	9	10	8	12	12	10	14
Base Thickness	4	2	6	6	4	8	8	6	10

*The minimum CRCP slab thickness in MEPDG.

Table 10.2. Input parameters and variations in New CRCP cases.

Input Parameter	Baseline Value ¹	- value	+ value
Construction Month	July/2006	March/2006	October/2006
Design Lane Width	12	11	12
Bar Diameter	0.60	0.50	1.00
Percent Steel	0.75	0.50	1.00
Steel Depth	3.3/4.0/5.0 ²	× 0.9 (3/3.6/4.5)	× 1.1(3.67/4.4/5.5)
Edge Support – Shoulder Type	Asphalt or Gravel	N/A	Tied PCC
Base Slab Friction Coef.	2.5	0.5	4
Surface Shortwave Absorption	0.85	0.80	0.98
PCC Unit Weight	150	140	160

PCC Poisson's Ratio	0.15	0.10	0.20
PCC Coef. of Thermal Expansion	5.56	2	10
Cement Content	500	400	700
Water/Cement Ratio	0.4	0.3	0.7
PCC Modulus of Rupture at 28 days	620	× 0.8 (496)	× 1.2 (744)
PCC Elastic Modulus at 28 days	3,956,571	× 0.8 (3,165,257)	× 1.2 (4,747,885)
Base Resilient Modulus	100,000	40,000	300,0000
Subgrade Resilient Modulus	15,000	12,000	24,000
GWD	S	10	2

¹All values are in same units as MEPDG inputs.

² Low traffic/Medium traffic/Higher traffic conditions.

10.2 Results

The 19 design inputs in Table 10.1 and Table 10.2 are varied over 3 input levels for 15 base cases (5 climate zones and 3 traffic levels) in the OAT sensitivity analyses. This requires a total of 585 MEPDG runs⁸ for the New CRCP scenarios. The predicted distress levels for each of the CRCP baseline scenarios are summarized in Table 10.3. The predictions span a wide range of magnitudes for all distress predictions except IRI having a more modest range.

Table 10.3. Predicted distress levels for New CRCP baseline scenarios.

Traffic	Climate	PCC (in.)	Base (in)	Crack	Punchout		IRI
				Width (mils)	Crack LTE (%)	(per mile)	(in/mile)
Low	Hot-Wet	8	4	16.6	93.2	2.8	68.7
Low	Hot-Dry	8	4	22.8	83.3	2.9	69.1
Low	Cold-Wet	8	4	20.8	88.1	3.2	88.2
Low	Cold-Dry	8	4	18.7	90.8	7.0	139.4
Low	Temperate	8	4	18.9	90.3	1.9	66.9
Medium	Hot-Wet	10	6	16.7	93.3	0.4	63.8
Medium	Hot-Dry	10	6	23.0	59.7	3.1	69.1
Medium	Cold-Wet	10	6	20.9	82.2	0.6	83.0
Medium	Cold-Dry	10	6	18.2	89.6	1.1	127.7
Medium	Temperate	10	6	19.1	86.9	0.3	63.6
High	Hot-Wet	12	8	17.9	87.8	0.2	63.4
High	Hot-Dry	12	8	24.4	44.0	20.1	102.5
High	Cold-Wet	12	8	22.4	49.6	7.5	96.5
High	Cold-Dry	12	8	19.7	69.3	1.4	128.3
High	Temperate	12	8	20.2	71.1	0.8	64.5
Design Limit				20	75	10	172.0

An NSI value is calculated for each design input-pavement distress combination for each of the base cases. The NSI values calculated over all design inputs and base cases are summarized in two charts

⁸ When trial runs, error corrections, and other re-runs are included, the total number of MEPDG runs executed is substantially greater.

for each distress. One chart details the NSI values by base cases while the other summarizes the high-low-average NSI statistics over all base cases for each design parameter for the distress of interest.

This section summarizes the design input NSI values on a distress-by-distress for the New CRCP scenarios only. Section 11 compiles key NSI values across all distresses and across all rigid pavement scenarios in order to identify which design inputs have sufficiently high sensitivities for inclusion in the GSA simulations.

The NSI values for all distresses of New CRCP are summarized in Figure 10.1 through Figure 10.8. The definitions of most of the design input labels along the horizontal axes in these figures is the same as for New JPCP and can be found in Table 8.5. Labels for the additional design inputs for New CRCP are given in Table 10.4.

Table 10.4 Definitions of design input labels for New CRCP cases.

Name of Design Input	Description
Bar Diameter	Diameter of the reinforcing bar
Percent Steel	Steel content expressed as a percentage of steel cross sectional area of the PCC cross section
Edge Support – Shoulder Type	Types of shoulder used for edge support of CRCP
Base/slab friction coefficient	The coefficient of friction of base material

The two distresses predicted by the MEPDG for CRCP are punchouts and IRI. In the punchout model implemented in the MEPDG, an increase in crack width along with loss of support in the base leads to a degradation of LTE that facilitates the development of punchouts. Therefore, predicted crack width and crack LTE are calculated as part of punchout prediction procedure and reported in MEPDG output.

Figure 10.1 and Figure 10.2 present the NSI values for punchouts. PCC slab thickness and PCC MOR ranks as the two most sensitive design inputs, with NSI values ranging from -6 to -37. This is in good agreement with engineering experience that an increase in structural capacity via increased slab thickness and strength will reduce punchout distress.

The next most sensitive design inputs include percent steel with NSI values varying from -10 to -23 and bar diameter with NSI values varying up to about 14. The increase in percent steel is highly effective in reducing punchout due to tightly closed cracks and reduced loss of LTE. In general, as the bar diameter increases, the percent steel increases with consequent reduction in punchout distress. However, an increase in bar diameter under fixed steel percentage as in this OAT analysis leads to increase in crack width with loss of crack LTE and consequent increase in punchout predictions.

Other sensitive design inputs include PCC unit weight, PCC 28-day E, base/slab friction coefficient, PCC cement content, AADTT, PCC W/C, PCC CTE, SSA, steel depth, base and subgrade MR. The PCC unit weight is an important input in the calculation of critical responses in rigid pavement structural response model employed in MEPDG. Increased unit weight decreases deflections which in turn reduce punchouts. The increases in PCC E lead to increased predicted punchouts due to higher bending stress. The use of bases with high friction coefficients could reduce punchout distress by reducing mean crack spacing and providing tighter cracks. Higher cement content and CTE values

produce more drying shrinkage and curling; punchout distress is directly proportional to slab curling and drying shrinkage. It is reasonable that higher AADTT produces more punchouts. Higher PCC W/C ratio leads to increase of crack width and consequent increase in punchout predictions. Increase in steel depth produce a decrease in resistance to bending stress on the bottom of PCC slab. A strong base and subgrade is beneficial in minimizing punchouts by reducing potential loss of support, but this effect is not strong in these OAT analyses.

All other design inputs have average NSI values less than 0.5 (see Figure 10.2). The low NSI values of these inputs means they have minor influence on predicted faulting for New CRCP.

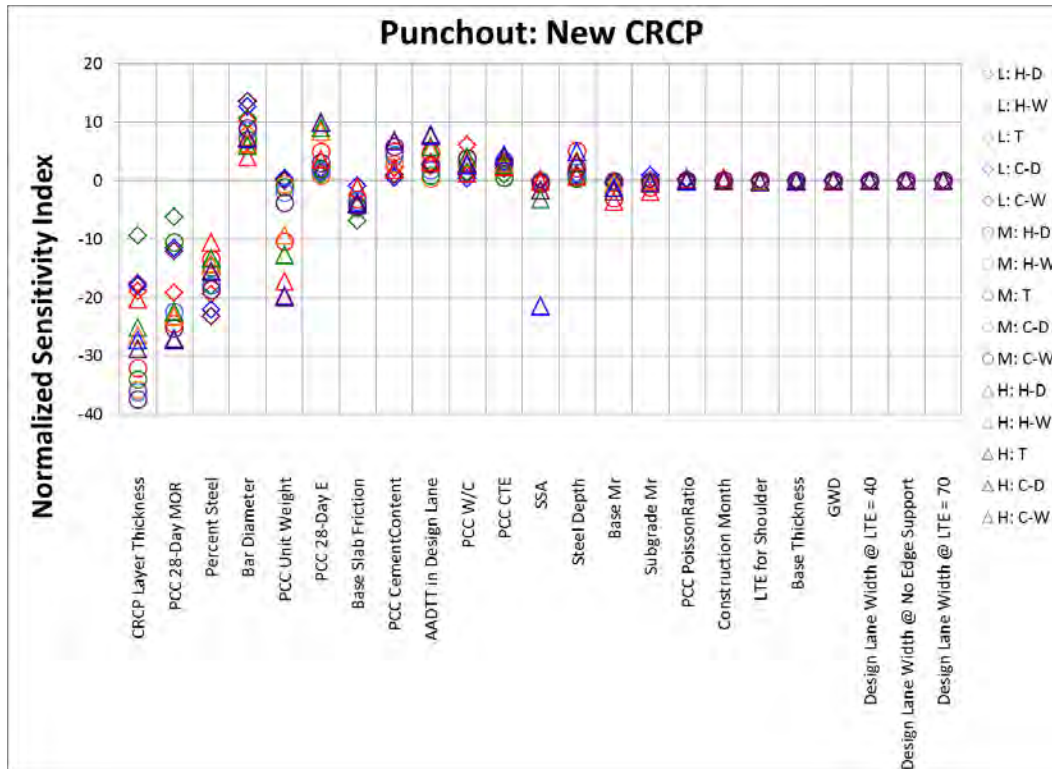


Figure 10.1. NSI values for punchouts in New CRCP (details).

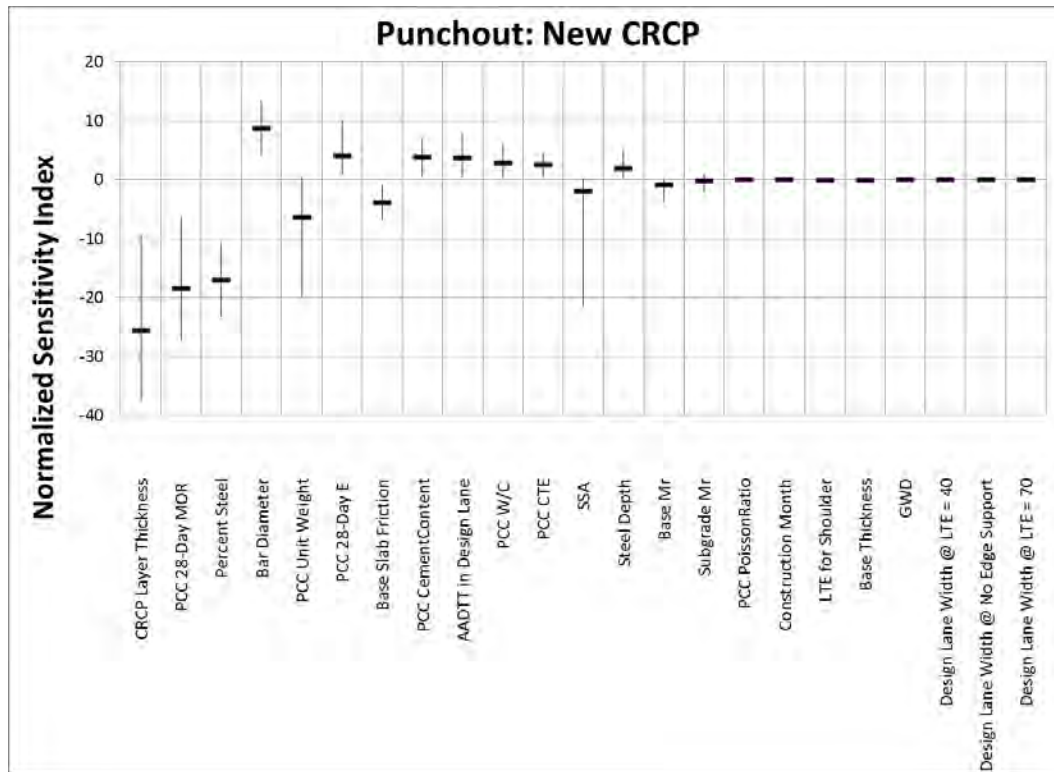


Figure 10.2. NSI values for punchouts in New CRCP (high-low-average).

The NSI values for crack width are summarized in Figure 10.3 and Figure 10.4. The most sensitive design inputs are percent steel, bar diameter, PCC 28-day MOR, base/slab friction coefficient, PCC 28-day E, steel depth, W/C ratio, and cement content. These are directly or indirectly related to the input parameters for the crack width predictive equations employed in MEPDG. Cement content and W/C ratio are used in calculating the PCC zero stress temperature and ultimate shrinkage strain input parameters for the crack width predictive equations. Increased bar diameter, cement content, steel depth, W/C ratio, and PCC 28-day *E* lead to increases in crack width predictions while increases in base/slab friction coefficient, percent steel, and PCC 28-day MOR lead to decreases in crack width predictions.

All other design inputs have average NSI values less than 0.5 (see Figure 10.4). These low NSI values indicate that these design inputs have only minor influence on predicted crack width in New CRCP.

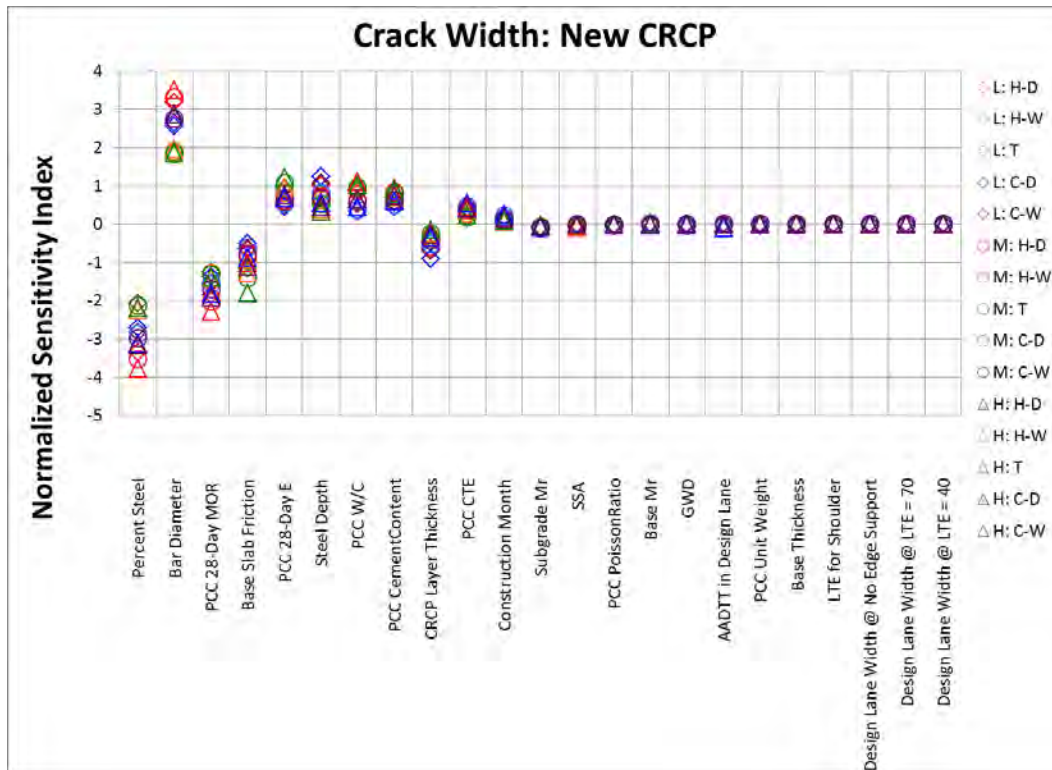


Figure 10.3. NSI values for crack width in New CRCP (details).

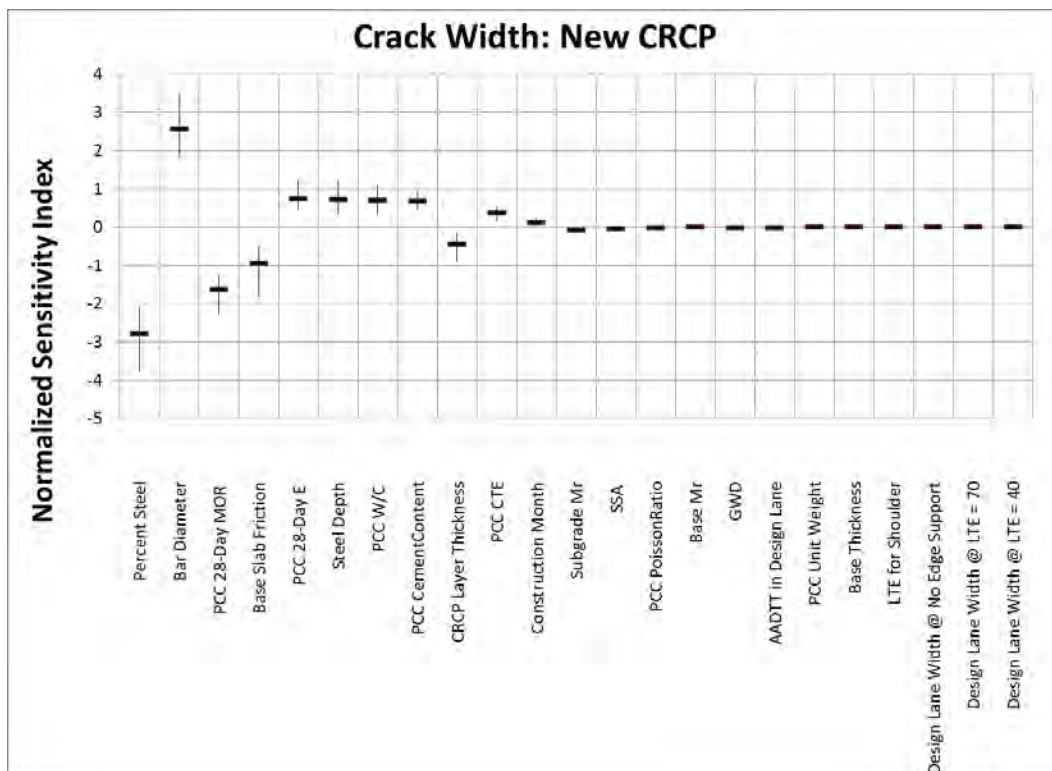


Figure 10.4. NSI values for crack width in New CRCP (high-low-average).

The NSI values for crack LTE cases are summarized in Figure 10.5 and Figure 10.6. The most sensitive design inputs are PCC thickness and percent steel. As expected, thicker PCC slabs and higher percent steel improve LTE. The next most sensitive design inputs include PCC 28-day MOR, bar diameter, PCC 28-day E, cement content, steel depth, AADTT, and PCC unit weight. All other design inputs have average NSI values less than 0.5 (see Figure 10.6). The low NSI values of these inputs imply that they have only minor influence on predicted crack LTE in New CRCP.

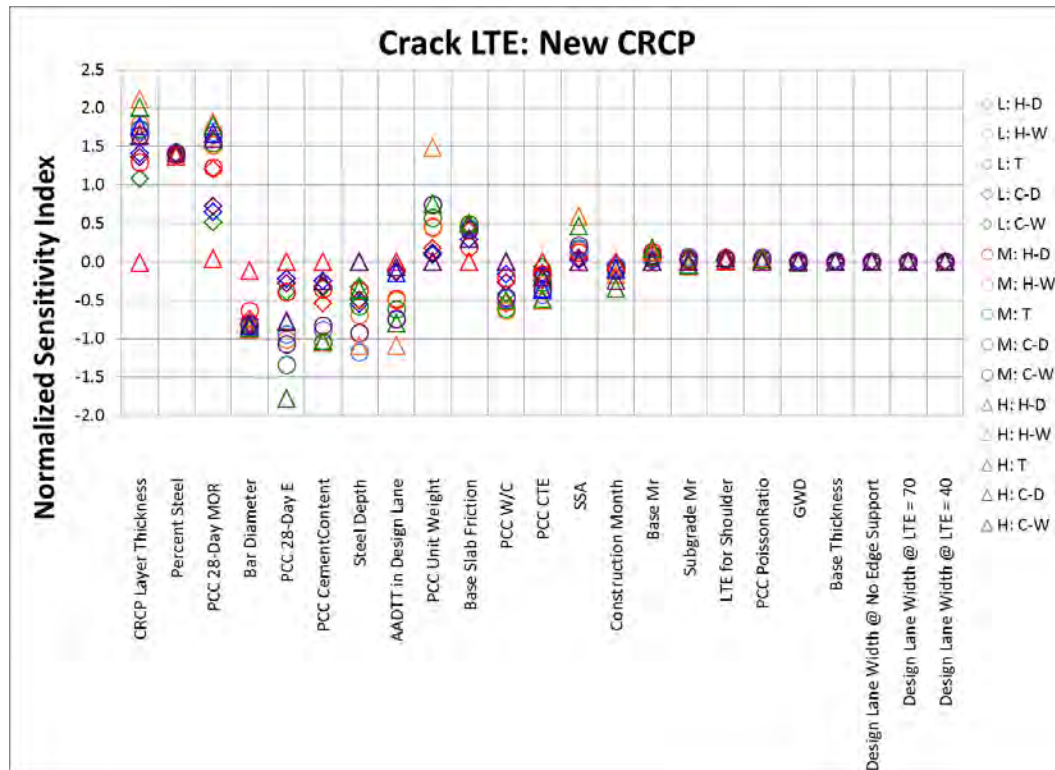


Figure 10.5. NSI values for crack LTE in New CRCP (details).

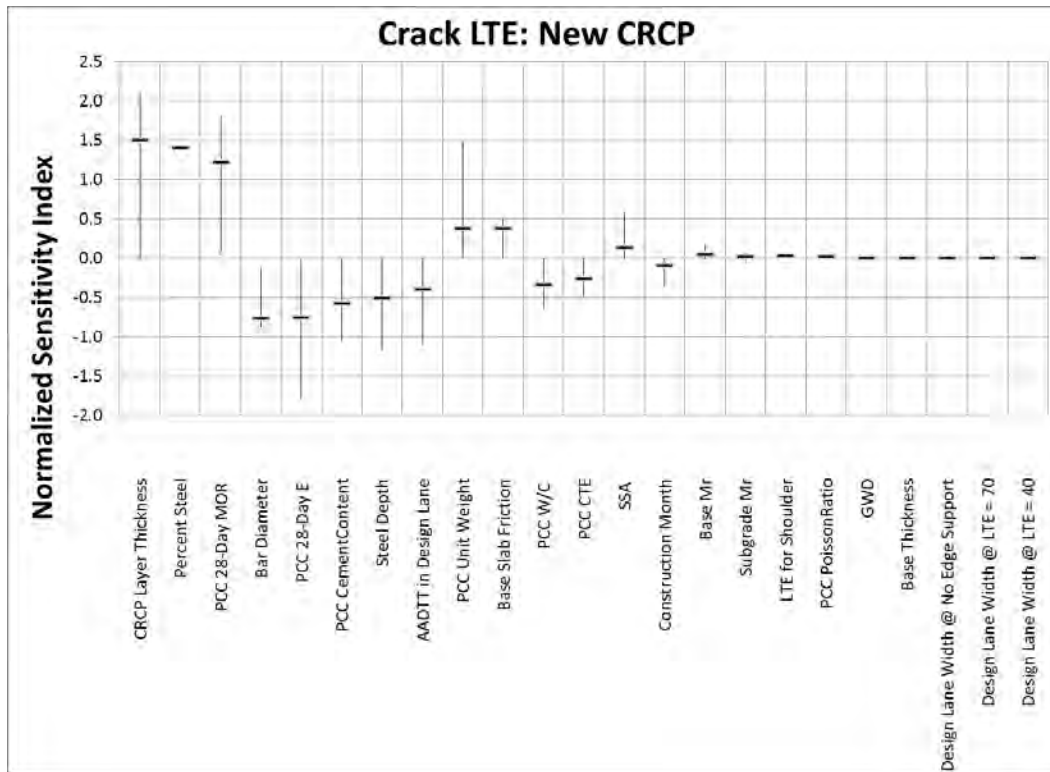


Figure 10.6. NSI values for crack LTE in New CRCP (high-low-average).

The NSI values for IRI are summarized in Figure 10.7 and Figure 10.8. Similar to IRI predictions in the other pavement types, IRI predictions in the New CRCP cases are calculated from regression equations using primary distresses—punchouts, in the case of CRCP—as primary inputs along with a site factor and initial smoothness. The most sensitive design inputs for CRCP IRI predictions include PCC thickness, PCC 28-day MOR, percent steel, bar diameter, PCC unit weight, PCC 28-day E, base/slab friction coefficient, PCC cement content, AADTT, PCC W/C, PCC CTE, SSA, steel depth, base and subgrade MR. These are also sensitive design inputs for CRCP punchout predictions.

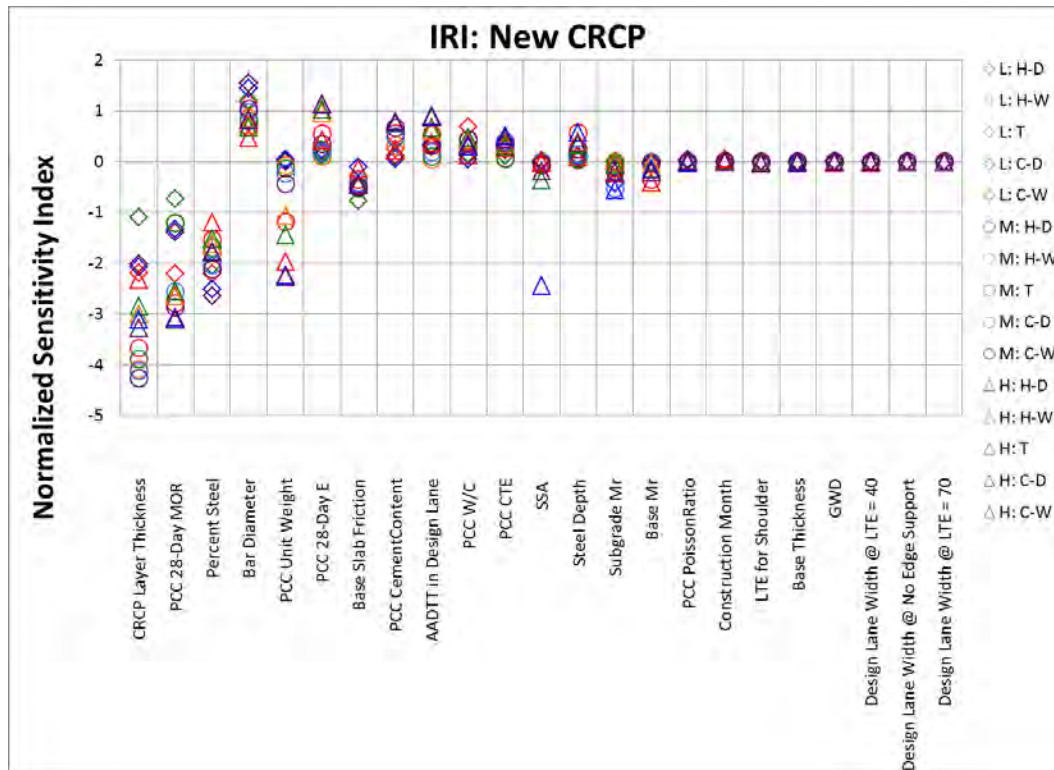


Figure 10.7. NSI values for IRI in New CRCP (details).

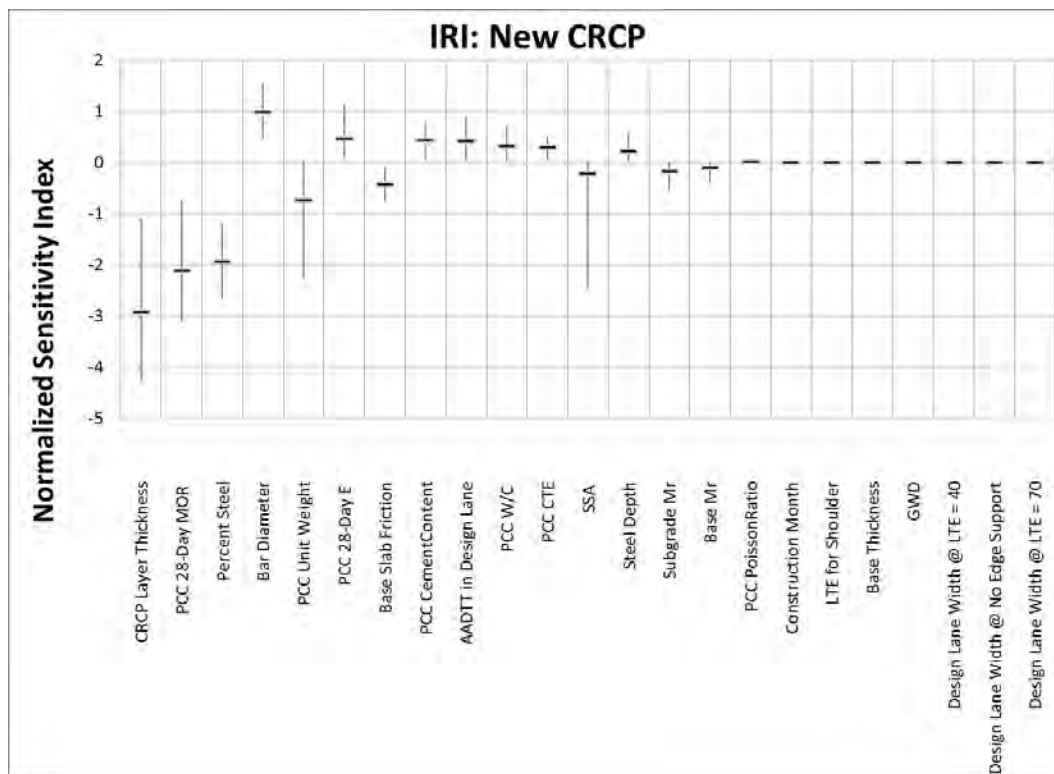


Figure 10.8. NSI values for IRI in New CRCP (high-low-average).

11 CATEGORIZATION OF DESIGN INPUTS

A total of 3825 MEPDG runs were required for the OAT local sensitivity analyses across all base cases and pavement types. Interpreting the enormous quantity of results from these analyses is daunting. Useful observations can be made regarding sensitivities of specific distresses to individual design inputs for particular pavement scenarios, and many of these have already been listed in Section 6 through Section 10. However, the two primary objectives of the OAT local sensitivity analyses as stated in the Introduction section are:

- (1) To confirm the “sensitive” and “very sensitive” design inputs identified in the preliminary triage; and
- (2) To narrow the sets of inputs needed for the computationally intensive GSA scenarios.

In support of these objectives, the most sensitive design inputs over all distresses and base cases for all flexible and rigid pavement types considered in this study have been compiled in rank order and summarized in Table 11.2 through Table 11.6 (definitions of the design input labels can be found in Table 6.6, Table 7.4, Table 8.5, and Table 10.4). The rank ordering is by decreasing maximum absolute NSI over all analyses—i.e., the largest absolute NSI value calculated for the design input from any design scenario, base case, or distress. Also included in the tables for ready reference is the preliminary sensitivity assessment from the preliminary triage process, with VS indicating very sensitive, S indicating sensitive, and NS indicating insensitive.

The quantitative NSI values from the OAT analyses in Table 11.2 through Table 11.6 can be used to refine the definitions of the various sensitivity categories. Based on the rank ordering and engineering judgment, the sensitivity categories listed in Table 11.1 have been defined for use in the remainder of this study. Design inputs with maximum absolute NSI values greater than 5 are deemed to be hypersensitive, between 1 and 5 very sensitive, between 0.1 and 1 sensitive, and less than 0.1 insensitive. These categories are inevitably arbitrary. However, the primary purpose of the OAT local sensitivity analyses is to confirm those sensitive design inputs that need to be included in the GSA simulations, not to establish precise relative rankings among the sensitive design inputs. Note that the maximum absolute NSI value is a very severe criterion and the threshold of 0.1 between the insensitive and sensitive categories is very generous (i.e., low).

Table 11.1. NSI ranges for sensitivity categories.

Max(NSI)	Category	Color
>5	Hypersensitive (HS)	
1 to 5	Very Sensitive (VS)	
0.1 to 1	Sensitive (S)	
<0.1	Insensitive (NS)	

Table 11.2 and Table 11.3 provide the overall sensitivity rankings for the design inputs in the flexible pavement scenarios. For the vast majority of design inputs, the results from the OAT analyses agree with the judgments from the preliminary triage. There are exceptions, however. Flexible pavement design inputs judged to be insensitive in the preliminary triage but found to be sensitive or above in the OAT analyses include: HMA Poisson’s Ratio (VS in OAT analyses), HMA Unit Weight; Base PR; Subgrade PR, SubgradePI, SubgradeLL, and SubgradeN200 (all S). Conversely, only the

Aggregate CTC was judged to be very sensitive or sensitive in the preliminary triage but found to be insensitive in the OAT analyses.

All design inputs ranked as sensitive or above (green/yellow/red cells in table) will be included in the GSA simulations. For both the New HMA and HMA Over Stiff Foundation scenarios, this totals 26 design inputs each.

Table 11.2. Ranking of design inputs by maximum absolute NSI: New HMA.

New HMA	DESIGN INPUT SENSITIVITIES						
	OAT Analyses	Phase I Triage					
	Maximum (All Cases)	HMA rutting	Total Rutting	Alligator Cracking	Long Cracking	Thermal Cracking	MAX
HMAAlpha	-24.2	-	-	-	-	-	VS*
HMADelta	-23.8	-	-	-	-	-	VS*
HMA Thickness	-7.3	VS	VS	VS	S	NS	VS
SSA	5.0	VS	VS	S	VS	NS	VS
m	-4.5	NS	NS	NS	NS	VS	VS
HMA Poisson's Ratio	-4.1	NS	NS	NS	NS	NS	NS
HMA Va	4.0	-	-	-	-	-	S*
Base Mr	-3.6	S	S	S	VS	NS	VS
Tensile Strength at 14F	-3.4	NS	NS	NS	NS	VS	VS*
HMA Vbeff	-3.2	-	-	-	-	-	S*
Base Thickness	-1.7	S	S	S	S	NS	S
AADTT	1.6	VS	VS	VS	VS	NS	VS
Subgrade Mr	1.3	NS	VS	S	VS	NS	VS
Operational Speed	-1.00	VS	VS	S	S	NS	VS
HMA Unit Weight	-0.98	NS	NS	NS	NS	NS	NS
Base PR	-0.88	NS	NS	NS	NS	NS	NS
D	-0.85	NS	NS	NS	NS	VS	VS
Subgrade PR	0.83	NS	NS	NS	NS	NS	NS
PGLow+	0.74	-	-	-	-	-	VS*
PGHigh-	0.70	-	-	-	-	-	VS*
HMA Heat Capacity	-0.54	NS	NS	NS	NS	S	S
SubgradePI	-0.23	NS	NS	NS	NS	NS	NS
SubgradeLL	0.23	NS	NS	NS	NS	NS	NS
GWD	0.19	NS	S	NS	NS	NS	S
HMA Thermal Conductivity	0.17	NS	NS	NS	NS	S	S
SubgradeN200	-0.15	NS	NS	NS	NS	NS	NS
Base N200	-0.08	NS	NS	NS	NS	NS	NS
Limit Strain	-0.06	-	-	-	-	-	-
Base PI	-0.03	NS	NS	NS	NS	NS	NS
Construction Month	0.02	NS	NS	NS	NS	NS	NS
SubgradeD60	0.00	NS	NS	NS	NS	NS	NS
Base LL	0.00	NS	NS	NS	NS	NS	NS
Aggregate CTC	0.00	NS	NS	NS	NS	VS	VS
Base Ko	0.00	NS	NS	NS	NS	NS	NS
Base D60	0.00	NS	NS	NS	NS	NS	NS
Subgrade Ko	0.00	NS	NS	NS	NS	NS	NS

Notes:

- designates design input/distress combination not considered in preliminary triage.

* designates inputs that were implicitly evaluated during the preliminary triage in terms of effect on HMA stiffness.

Table 11.3. Ranking of design inputs by maximum absolute NSI: HMA Over Stiff Foundation.

HMA Over Stiff Foundation	DESIGN INPUT SENSITIVITIES						
	OAT Analyses	Phase I Triage					
	Maximum (All Cases)	HMA rutting	Total Rutting	Alligator Cracking	Long Cracking	Thermal Cracking	MAX
HMAAlpha	-52.0	-	-	-	-	-	VS*
HMADelta	-51.4	-	-	-	-	-	VS*
SSA	10.8	VS	VS	S	VS	NS	VS
HMA Poisson's Ratio	-7.8	NS	NS	NS	NS	NS	NS
Base Thermal Conduct	-5.3	-	-	-	-	-	-
m	-4.7	NS	NS	NS	NS	VS	VS
HMA Thickness	3.5	VS	VS	VS	S	NS	VS
HMA Vbeff	3.5	-	-	-	-	-	S*
AADTT	3.4	VS	VS	VS	VS	NS	VS
Operational Speed	-2.2	VS	VS	S	S	NS	VS
Base Thickness	1.6	S	S	S	S	NS	S
HMA Va	1.6	-	-	-	-	-	S*
PGHigh-	1.5	-	-	-	-	-	VS*
Tensile Strength at 14F	-1.2	NS	NS	NS	NS	VS	VS
D	-1.1	NS	NS	NS	NS	VS	VS
HMA Unit Weight	-1.1	NS	NS	NS	NS	NS	NS
HMA Heat Capacity	-0.91	NS	NS	NS	NS	S	S
Subgrade Mr	0.64	NS	VS	S	VS	NS	VS
Base Thermal Conduct	-0.62	NS	NS	NS	NS	S	S
Base PR	0.52	NS	NS	NS	NS	NS	NS
Base Heat Capacity	-0.48	-	-	-	-	-	-
Base Unit Weight	-0.46	NS	NS	NS	NS	NS	NS
PGLow+	-0.41	-	-	-	-	-	VS*
HMA Thermal Conductivity	0.38	NS	NS	NS	NS	S	S
Base Mr	0.26	S	S	S	VS	NS	VS
GWD	0.24	NS	S	NS	NS	NS	S
SubgradeN200	-0.12	NS	NS	NS	NS	NS	NS
SubgradePI	-0.12	NS	NS	NS	NS	NS	NS
SubgradeLL	0.10	NS	NS	NS	NS	NS	NS
Construction Month	0.06	NS	NS	NS	NS	NS	NS
Subgrade PR	0.04	NS	NS	NS	NS	NS	NS
Tensile Strength at 14F	0.00	NS	NS	NS	NS	VS	VS
SubgradeD60	0.00	NS	NS	NS	NS	NS	NS
Limit Strain	0.00	-	-	-	-	-	-
Aggregate CTC	0.00	NS	NS	NS	NS	VS	VS
Base MOR	0.00	-	-	-	-	-	-
Subgrade Ko	0.00	NS	NS	NS	NS	NS	NS

Notes:

- designates design input/distress combination not considered in preliminary triage.

* designates inputs that were implicitly evaluated during the preliminary triage in terms of effect on HMA stiffness.

Table 11.4 and Table 11.5 provide the overall sensitivity rankings for the design inputs in the JPCP scenarios. For all but two of the design inputs considered, the results from the OAT analyses agree with the preliminary judgments from the preliminary triage. The only exception is Design Lane Width under no edge support and tied shoulder condition, which was judged in the preliminary triage to be a sensitive input for cracking but found to be insensitive for both New JPCP and the JPCP Over Stiff Foundation scenarios in the OAT analyses.

All design inputs ranked as sensitive or above (green/yellow/red cells in table) were included in the GSA simulations. For the New JPCP scenario, this totals 21 design inputs; for the JPCP over Stiff Foundation scenario, 23

Table 11.4. Ranking of design inputs by maximum absolute NSI: New JPCP.

New JPCP	DESIGN INPUT SENSITIVITIES			
	OAT Analyses	Phase I Triage		
	Maximum (All Cases)	Faulting	Transverse Cracking	MAX
PCC 28-Day MOR	-16.55	S	VS	VS
JPCP Layer Thickness	-15.03	VS	VS	VS
SSA	10.99	VS	VS	VS
Joint Spacing	9.91	VS	VS	VS
PCC 28-Day E	9.87	-	-	*S
Design Lane Width @ 14ft Widen Slab	-7.20	NS	S	S
Edge Support - Widen Slab	-6.60	VS	S	VS
PCC Thermal Conductivity	-5.33	S	VS	VS
PCC CTE	4.63	VS	VS	VS
PCC Unit Weight	3.60	S	S	S
Dowel Diameter	-2.46	S	NS	S
PCC Poisson Ratio	1.53	S	S	S
AADTT in Design Lane	1.25	VS	VS	VS
Base Mr	1.07	VS	S	VS
Subgrade Mr	-0.86	S	S	S
PCC Cement Content	0.83	S	NS	S
Construction Month	0.67	-	-	-
PCC W/C	0.42	S	NS	S
GWD	-0.32	NS	NS	NS
Erodibility Index	0.25	S	NS	S
Base Thickness	-0.20	S	S	S
Design Lane Width @ No Edge Support	-0.08	NS	S	S
Edge Support - LTE	-0.07	-	-	-
Design Lane Width @ LTE = 80	0.00	NS	S	S

Notes:

- designates design input/distress combination not considered in preliminary triage

* designates inputs that were implicitly evaluated during preliminary triage in terms of effect on PCC stiffness/strength

Table 11.5. Ranking of design inputs by maximum absolute NSI: JPCP Over Stiff Foundation.

JPCP Over Stiff Foundation	DESIGN INPUT SENSITIVITIES			
	OAT Analyses	Phase I Triage		
	Maximum (All Cases)	Faulting	Transverse Cracking	MAX
JPCP Layer Thickness	-25.86	VS	VS	VS
SSA	18.45	VS	VS	VS
Design Lane Width @ 14ft Widen Slab	-18.32	NS	S	S
PCC 28-Day MOR	-16.62	S	VS	VS
Edge Support - Widen Slab	-16.00	VS	S	VS
PCC 28-Day E	14.82	-	-	*S
Joint Spacing	9.98	VS	VS	VS
PCC Unit Weight	-5.80	S	S	S
PCC Thermal Conductivity	-5.35	S	VS	VS
PCC CTE	4.63	VS	VS	VS
Construction Month	-3.62	-	-	-
PCC PoissonRatio	3.56	S	S	S
AADTT in Design Lane	3.40	VS	VS	VS
Design Lane Width @ No Edge Support	2.88	NS	S	S
Dowel Diameter	-2.54	S	NS	S
Subgrade Mr	2.53	S	S	S
Base Thickness	-2.34	S	S	S
PCC CementContent	0.63	S	NS	S
Loss of Full Friction	0.60	-	-	-
PCC W/C	-0.53	S	NS	S
GWD	-0.31	NS	NS	NS
Erodibility Index	0.20	S	NS	S
Edge Support - LTE	-0.18	-	-	-
Stabilized Base MR	-0.09	VS	S	NS
Design Lane Width @ LTE = 80	0.00	NS	NS	NS

Notes:

- designates design input/distress combination not considered in preliminary triage

* designates inputs that were implicitly evaluated during preliminary triage in terms of effect on PCC stiffness/strength

Table 11.6 provides the overall sensitivity rankings for the design inputs in the New CRCP scenario. For the majority of the design inputs, the results from the OAT analyses agree with the preliminary judgments from the preliminary triage. There are exceptions. SSA and GWD were judged to be insensitive in the preliminary triage but found to be sensitive in the OAT analyses. Design inputs judged to be very sensitive or sensitive in the preliminary triage but found to be insensitive in the OAT analyses are Design Lane Width under no edge support, tied shoulder and widen slab condition.

All design inputs ranked as sensitive or above (green/yellow/red cells in table) will be included in the GSA simulations. For the New CRCP scenario, this totals 20 design inputs.

Table 11.6. Ranking of design inputs by maximum absolute NSI: New CRCP.

New CRCP	DESIGN INPUT SENSITIVITIES				
	OAT Analyses	Phase I Triage			
	Maximum (All Cases)	Punchout	Crack Width	Crack LTE	MAX
CRCP Layer Thickness	-37.44	VS	S	VS	VS
PCC 28-Day MOR	-27.31	VS	VS	VS	VS
Percent Steel	-23.27	VS	VS	VS	VS
SSA	-21.43	NS	NS	NS	NS
PCC Unit Weight	-19.91	S	NS	NS	S
Bar Diameter	13.56	VS	VS	VS	VS
PCC 28-Day E	10.07	-	-	-	S
AADTT in Design Lane	7.91	VS	S	S	VS
PCC CementContent	6.90	S	S	S	S
Base Slab Friction	-6.79	NS	S	NS	S
PCC W/C	6.08	NS	S	S	S
Steel Depth	5.05	NS	S	S	S
PCC CTE	4.48	VS	S	S	VS
Base Mr	-3.58	S	NS	NS	S
Subgrade Mr	-1.96	S	NS	NS	S
Construction Month	0.48	-	-	-	-
PCC PoissonRatio	0.36	S	NS	NS	S
Base Thickness	-0.22	S	NS	NS	S
LTE for Shoulder	-0.21	S	NS	S	S
GWD	0.14	NS	NS	NS	NS
Design Lane Width @ LTE = 40	-0.01	-	-	-	-
Design Lane Width @ LTE = 70	0.00	-	-	-	-
Design Lane Width @ No Edge Support	0.00	-	-	-	-

Notes:

- designates design input/distress combination not considered in preliminary triage

* designates inputs that were implicitly evaluated during preliminary triage in terms of effect on PCC stiffness/strength

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APPENDIX C: GLOBAL SENSITIVITY ANALYSES

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1 INTRODUCTION

The overall objective of the GSA is to determine the sensitivity of the performance predicted by the MEPDG to variations of input parameter values for flexible and rigid pavements across the entire problem domain. The key difference between the GSA and OAT analyses (Chapter 4) is that all input parameters are varied simultaneously from their baseline values instead of just one at a time. Over 41,000 MEPDG runs were performed for the GSA. In addition, over one million evaluations of the neural network response surface models were used to quantify the distribution of design input sensitivities across the entire problem domain.

This appendix documents the GSA methodology, design input values, results, and findings. These include:

- The pavement scenarios and base cases for the GSA simulations;
- Treatment of correlated and other design inputs requiring special consideration;
- The Latin Hypercube sampling scheme used to develop the input data sets for the simulations;
- The AutoIt tool used to automate the input data entry, execution, and results harvesting for the MEPDG runs;
- The multivariate linear regression and nonlinear artificial neural network response surface modeling used to fit the GSA simulation data;
- The normalized metrics used to quantify the sensitivities of predicted distresses to design inputs;
- The specific analysis inputs, predicted distresses, response surface model parameters and statistics, sensitivity index values, and conclusions for each pavement scenario.

2 BASE CASES

The GSA must be organized around a set of base cases to avoid potential distortion of the findings by results from physically unrealistic pavement scenarios—e.g., a 2 inch HMA layer on top of an A-7-6 subgrade subjected to 30M trucks in a Cold-Wet climate. A sufficiently large and diverse number of base cases must be selected so that the entire solution domain for the MEPDG is evaluated. The selected base case conditions are summarized in Table 2.1. These span the ranges of commonly encountered pavement types, climate conditions and traffic levels. A total number of 75 base cases (5 pavement types x 5 climates x 3 traffic levels) were analyzed.

Table 2.1. Conditions for base cases.

Pavement Type	New HMA/GB/SB New JPCP/GB New CRCP/GB HMA on Stiff Foundation JPCP on Stiff Foundation
Climate	Hot-Wet Hot-Dry Cold-Wet Cold-Dry Temperate
Traffic Level	Low Moderate High

Note: HMA/JPCP on Stiff Foundation is intended to represent both new construction/reconstruction on stabilized foundations or rehabilitation (i.e., overlays) on underlying HMA/PCC layers.

The values for the input parameters for each base case must balance the need to explore as much of the problem domain as possible while not creating physically unrealistic pavement scenarios. Note that since this is a sensitivity study and not a reliability analysis, the requirements for the input parameter values are not as severe. Specifically, a GSA does not require specification of the correct distributional forms (frequency distributions) for the input parameters because only the sensitivity of the outputs to the inputs is being evaluated, not the statistical distribution of the outputs (e.g., normal vs. lognormal distribution, means, standard deviations, etc.). Therefore, uniform distributions will be assumed for all input parameters within their ranges of variation.

Two sets of global inputs were used in all global sensitivity analyses: climate conditions and traffic levels. There are 5 climate zones: Hot-Dry, Hot-Wet, Temperate, Cold-Dry and Cold-Wet. The specific locations, the weather station used to generate the climate files, the baseline binder grade recommended by LTPPBind at the 98% reliability level, and the range of binder grades considered in the GSA for each climate category are summarized in Table 2.2. There were no gaps (i.e., no missing months of data) in the MEPDG climate files for the specified locations.

Table 2.2. Climate categories for base cases.

Climate Category	Location	Weather Station	Months of Data	Binder Grade	
				Baseline	Range
Hot-Wet	Orlando FL	ORLANDO INTERNATIONAL ARPT	116	PG 70-10	PG 64-10 PG 76-10
Hot-Dry	Phoenix AZ	PHOENIX SKY HARBOR INTL AP	116	PG 76-10	PG 70-10 PG 82-10
Cold-Wet	Portland ME	PORTLAND INTL JETPORT ARPT	116	PG 52-28	PG 52-34 PG 52-22
Cold-Dry	International Falls MN	FALLS INTERNATIONAL ARPT	112	PG 58-28	PG 58-34 PG 58-22
Temperate	Los Angeles CA	LOS ANGELES INTL AIRPORT	108	PG 58-10	PG 52-10 PG 64-10

Note that the weather station for the cold-dry climate is different from that used in the one-at-a-time (OAT) sensitivity analyses (Appendix B). The Spokane WA location used originally was found to be insufficiently cold to generate significant levels of thermal cracking. The International Falls MN location provides more severe cold weather conditions.

The three traffic levels used in all GSA are summarized in Table 2.3. The baseline AADTT values are designed to fall within the low (<5,000), medium (5,000-10,000), and high (>15,000) truck volume categories in the FHWA *FAF² Freight Traffic Analysis Report* (Alam *et al.*, 2007). To put these traffic volumes into a more familiar context, the approximate number of ESALs for flexible and rigid pavements are also included in Table 2.3.

Table 2.3. Traffic ranges for base cases.

Traffic Category	Baseline Inputs				AADTT Range
	AADTT ¹	AADTT in Design Lane	Est. ESALs (Flexible) ⁵	Est. ESALs (Rigid) ⁶	
Low	1,000	375 ²	2M	5M	500-5,000
Medium	7,500	2,063 ³	10M	25M	5,000-10,000
High	25,000	6,250 ⁴	30M	75M	20,000-30,000

¹Based on MEPDG Interstate Highway TTC4 Level 3 default vehicle distribution.

²50% directional split, 2 lanes per direction, 0.75 lane factor for design lane.

³50% directional split, 3 lanes per direction, 0.55 lane factor for design lane.

⁴50% directional split, 3 lanes per direction, 0.50 lane factor for design lane.

⁵Based on 15 year design life.

⁶Based on 25 year design life.

The five climate zones and three traffic levels give a total of 15 base cases for the sensitivity analyses. The combinations and abbreviations for each are as follows:

CDL Cold-Dry-Low-Traffic
 CDM Cold-Dry-Medium-Traffic
 CDH Cold-Dry-High-Traffic
 CWL Cold-Wet-Low-Traffic
 CWM Cold-Wet-Medium-Traffic
 CWH Cold-Wet-High-Traffic
 TL Temperate-Low-Traffic

TM	Temperate-Medium-Traffic
TH	Temperate-High-Traffic
HDL	Hot-Dry-Low-Traffic
HDM	Hot-Dry-Medium-Traffic
HDH	Hot-Dry-High-Traffic
HWL	Hot-Wet-Low-Traffic
HWM	Hot-Wet-Medium-Traffic
HWH	Hot-Wet-High-Traffic

3 SPECIAL INPUT CONSIDERATIONS

Some of the design inputs are correlated and/or have other characteristics that warrant special treatment. These special input considerations are documented in the following subsections.

3.1 Unbound Material Properties

The MEPDG needs unbound material gradation and plasticity as inputs at all three input levels. The only unbound design inputs in the “Hypersensitive,” “Very Sensitive,” or “Sensitive” categories from the one-at-a-time sensitivity analyses (Appendix B) were: the base resilient modulus (M_r) and Poisson’s ratio (ν); the subgrade M_r and ν ; and, for the subgrade, the percent passing the No. 200 sieve (P200), the D_{60} gradation parameter, the plasticity index (PI), and the liquid limit (LL) values via their influence on the soil-water characteristic curve (SWCC) parameters. The P200, D_{60} , PI, LL subgrade inputs are all highly correlated to M_r , which in turn is primarily a function of soil type. As for the OAT sensitivity analyses, the procedure adopted for the GSA is to first select a design input value for M_r and then use correlation relations described in Section 3.1 of Appendix B to determine compatible values of P200, D_{60} , PI, and LL. For the subgrade where gradation and Atterburg limits are sensitive inputs, a $\pm 10\%$ random variation is applied to the generated P200, D_{60} , PI, and LL values for the GSA to enforce a less-than-perfect correlation.

Note that the parameters a_f , b_f , c_f , and h_r for the Fredlund and Xing (1994) SWCC model employed in the MEDPG could have been varied directly for the GSA simulations, similar to the way that the HMA E^* sigmoidal parameters and cold temperature properties are treated (see following two subsections). However, it is far less likely that unbound Level 1 SWCC parameters will be measured in practice than will the HMA Level 1 E^* and low temperature properties. It is therefore appropriate to specify the unbound SWCC parameters in terms of the Level 3 functions of P200, D_{60} , PI, and LL while formulating the HMA E^* and low temperature properties in terms of Level 1 properties.

3.2 HMA Dynamic Modulus and Binder Properties

HMA dynamic modulus E^* is a highly sensitive input in the MEPDG performance predictions. However, varying E^* in a systematic way must be done with care. Dynamic modulus is multivalued—i.e., it varies with temperature and loading rate. It is also highly dependent on the viscosity characteristics of the binder. The approach for varying E^* adopted in the GSA analyses was the same as that used for the OAT sensitivity analyses as described in Section 3.2 of Appendix B. The E^* design input is specified via synthetic Level 1 E^* vs. temperature vs. frequency data generated using the sigmoidal master curve function:

$$\log(E^*) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma \log t_r}} \quad (3.1)$$

in which:

- E^* = dynamic modulus (psi)
- t_r = loading time (seconds) at the reference temperature
- δ, α = fitting parameters; δ represents the minimum value (lower shelf) for E^* and $\delta + \alpha$ represents the maximum value (upper shelf)
- β, γ = fitting parameters describing the shape (horizontal location and slope) of the sigmoidal function in the transition region between the lower and upper shelves

Equation 3.1 is the basic form for several E^* predictive models. The MEDPG employs the Witczak E^* predictive model (NCHRP, 2004):

$$\log(E^*) = \delta + \frac{\alpha}{1 + e^{[-(0.603313 + 0.393532 \log \eta) - 0.313351 \log f]}} \quad (3.2)$$

in which:

$$\begin{aligned} E^* &= \text{dynamic modulus, psi} \\ \eta &= \text{binder viscosity, } 10^6 \text{ Poise} \\ f &= \text{loading frequency, Hz} \\ \delta &= 3.750063 + 0.02932\rho_{200} - 0.001767(\rho_{200})^2 - 0.002841\rho_4 \\ &\quad - 0.058097V_a - 0.802208\left(\frac{V_{beff}}{V_{beff} + V_a}\right) \end{aligned} \quad (3.3)$$

$$\alpha = 3.871977 - 0.0021\rho_4 + 0.003958\rho_{38} - 0.000017(\rho_{38})^2 + 0.005470\rho_{34} \quad (3.4)$$

$$\begin{aligned} V_a &= \text{air void content, \%} \\ V_{beff} &= \text{effective bitumen content, \% by volume} \\ \rho_{34} &= \text{cumulative \% retained on the 3/4 in sieve} \\ \rho_{38} &= \text{cumulative \% retained on the 3/8 in sieve} \\ \rho_4 &= \text{cumulative \% retained on the No.4 in sieve} \\ \rho_{200} &= \text{\% passing the No. 200 sieve} \end{aligned}$$

Gradation and volumetric properties typical of a 19.0 mm Superpave dense graded mixture are:

$$\begin{aligned} V_a &= 6.47\% \\ V_{beff} &= 10.08\% \\ \rho_{34} &= 5.5\% \\ \rho_{38} &= 33.5\% \\ \rho_4 &= 55.5\% \\ \rho_{200} &= 4.9\% \end{aligned}$$

These values were used to determine the baseline values of $\delta = 2.8291$ and $\alpha = 3.8990$ in the OAT local sensitivity analyses.

Note that in the Witczak model the lower and upper shelves (δ and $\delta + \alpha$) are functions only of mixture gradation and volumetrics, the shape parameter γ is a constant, the loading time t_r is replaced by its frequency inverse f , and the shape parameter β is a function only of the temperature-dependent binder viscosity:

$$\beta = -(0.603313 + 0.393532 \log \eta) \quad (3.5)$$

Therefore, in order to generate synthetic level 1 E^* input data at various temperatures and frequencies f , it is necessary to establish the appropriate constant values for δ , α , and γ and the temperature-specific binder viscosity η . The GSA simulations can then vary δ , α , and η about their baseline values.

Statistics for δ and α determined for the 346 mixtures included in the enhanced Bari and Witczak (2006) database are shown in Table 3.1. It is important to note that the ranges of δ and α in Table 3.1 are very narrow; the total spreads between the maximum and minimum values for the 346 mixtures are only 28% and 7% of their respective means.

Table 3.1. Statistics for δ and α from Bari and Witczak (2006) database.

	δ	α
Mean	2.8249	3.8864
Standard Deviation	0.0999	0.0628
Coef. of Variation	3.5%	1.6%
Minimum	2.2144	3.7838
Maximum	3.0121	4.0610
Range	0.7977	0.2772

In the MEPDG, the binder viscosity η used to determine β in Eq. 3.5 is a function only of binder grade and temperature. Each climate category has an appropriate baseline PG binder grade, as summarized in Table 2.2. Binder viscosity η for a given binder grade and temperature and the corresponding synthetic Level 1 binder shear stiffness G^* and phase angle values for a given binder grade, temperature, and frequency are determined using the methodology documented in Section 3.2 of Appendix B.

3.3 HMA Low Temperature Properties

Significant thermal cracking developed in the OAT local sensitivity analyses only when the low temperature PG grade was set 2 or 3 steps warmer than the recommended grade. This was also the case with the GSA simulations, as will be shown later. Consequently, the low temperature tensile strength and creep compliance properties for the HMA will be irrelevant for most of the GSA simulations. Special low temperature cracking simulations using unrealistic binder grades having excessively stiff low temperature characteristics were required to evaluate the sensitivity of thermal cracking to MEPDG design inputs.

The low temperature properties are correlated with other HMA and binder properties. The low temperature creep compliance in particular is highly correlated, albeit in a complex way, with dynamic modulus. Conceptually, it is possible to fit a Prony series approximation to the synthetic Level 1 HMA E^* data (Section 3.2), convert this to a Prony series approximation to the creep compliance using well-known but complex interconversion relations (Park and Schapery, 1999), use this to generate synthetic creep compliance values at various time intervals and low temperatures, and then fit these synthetic compliance values with a power law creep compliance relation of the form used in the MEDPG. Each one of these steps involves numerical approximations and unknown errors.

Given these problems and the fact that the special GSA simulations for thermal cracking will focus only on thermal cracking distress, the correlations between the low temperature HMA properties and other mixture and binder properties are neglected. Instead, the low temperature HMA properties are sampled randomly between their likely lower and upper limits. These limits are estimated using the revised Level 3 relations developed in NCHRP Project 1-40D (Darter *et al.*, 2006) and implemented in the MEDPG software beginning with version 0.900.

The revised relation for the low temperature HMA tensile strength S_t at 14°F from NCHRP 1-40D is given as:

$$S_t = 4976.34 - 42.49 * V_a - 2.73 * V_a^2 - 80.61 * VFA + 0.465 * VFA^2 + 174.35 * \log(Pen_{77}) - 1217.54 * \log(A_{RTFO}) \quad (3.6)$$

in which the voids filled with asphalt VFA is defined as:

$$VFA = \frac{V_{beff}}{V_{beff} + V_a} \times 100 \quad (3.7)$$

and the penetration at 77°F Pen_{77} can be estimated using (NCHRP, 2004):

$$Pen_{77} = 10^{290.5013 - \sqrt{81177.288 + 257.0694 * 10^{(A_{RTFO} * 2.72973 * VTS_{RTFO})}}} \quad (3.8)$$

in which A_{RTFO} and VTS_{RTFO} are the intercept and slope of the viscosity temperature susceptibility curve for the specified binder grade in the short-term RTFO aged condition.

A power law form is assumed for the low-temperature creep compliance $D(t)$:

$$D(t) = D_1 * t^m \quad (3.9)$$

The revised relations from NCHRP 1-40D define the creep compliance parameters D_1 and m at -20, -10, and 0°C are:

$$\begin{aligned} \log(D_1)_{-20^\circ C} &= -11.92540 + 1.52206 * \log(V_a) + 4.49876 * \log(VFA) - 3.81320 * \log(A_{RTFO}) \\ \log(D_1)_{-10^\circ C} &= -10.76560 + 1.51960 * \log(V_a) + 3.49983 * \log(VFA) - 2.99870 * \log(A_{RTFO}) \\ \log(D_1)_{0^\circ C} &= -9.80627 + 1.50845 * \log(V_a) + 2.99000 * \log(VFA) - 2.90157 * \log(A_{RTFO}) \\ m_{-20^\circ C} &= -1.75987 + 1.78187 * V_a^{0.02030} + 0.00089 * Pen_{77}^{0.96970} \\ m_{-10^\circ C} &= -1.82690 + 1.94218 * V_a^{0.01600} + 0.00098 * Pen_{77}^{0.96857} \\ m_{0^\circ C} &= -2.41043 + 2.59093 * V_a^{0.01547} + 0.00199 * Pen_{77}^{0.97247} \end{aligned} \quad (3.10)$$

3.4 PCC Stiffness and Strength

Portland cement concrete (PCC) stiffness and strength properties are highly sensitive inputs in the prediction of MEPDG performance. The MEPDG needs PCC stiffness and strength design inputs at all three input levels. Level 1 of the MEDPG for JPCP requires measured values of PCC modulus of elasticity (E) and modulus of rupture (MOR) at various ages to characterize stiffness and strength gains over time. In addition to these two parameter values, Level 1 of the MEDPG for CRCP requires measured values of PCC indirect (or split) tensile strength (f_t') at various ages.

For level 1 PCC inputs, the strength and stiffness gain over time f is based on the 7-, 14-, and 90-day laboratory test data and the estimated 20-year values using the following regression equations:

$$\frac{MOR}{MOR_{28day}} = \alpha_1 + \alpha_2 \log_{10}(AGE) + \alpha_3 [\log_{10}(AGE)]^2 \quad (3.11)$$

$$\frac{E_c}{E_{c-28day}} = \beta_1 + \beta_2 \log_{10}(AGE) + \beta_3 [\log_{10}(AGE)]^2 \quad (3.12)$$

in which:

$$\begin{aligned} MOR &= \text{modulus of rupture at given times (psi)} \\ MOR_{28day} &= 28 \text{ day modulus of rupture (psi)} \\ E_c &= \text{elastic modulus at given times (psi)} \\ E_{c-28day} &= \text{elastic modulus (psi)} \\ \alpha_1, \alpha_2, \alpha_3, \beta_1, \beta_2, \beta_3 &= \text{regression coefficients} \end{aligned}$$

The MEPDG at level 3 provides an “averaged” version of Eqs. 3.11 and 3.12 representing typical PCC mixtures:

$$\frac{MOR}{MOR_{28day}} = \frac{E_c}{E_{c-28day}} = \frac{f'_t}{f'_{t-28day}} = 1.0 + 0.12 \log_{10}(AGE / 0.0767) - 0.01566 [\log_{10}(AGE / 0.0767)]^2 \quad (3.13)$$

Of course, MOR , E_c , and compressive strength (f'_c) and indirect (or split) tensile strength (f'_t) are not independent. The standard relations among these properties are:

$$\begin{aligned} MOR &= 9.5 \sqrt{f'_c} \\ E_c &= 33 \rho^{3/2} \sqrt{f'_c} = 33 \rho^{3/2} \left(\frac{MOR}{9.5} \right) = \gamma(MOR) \\ f'_t &= 0.67(MOR) = \delta(MOR) \end{aligned} \quad (3.14)$$

in which:

$$\begin{aligned} f'_c &= \text{compressive strength (psi)} \\ \rho &= \text{unit weight (pcf)} \\ f'_t &= \text{indirect tensile strength (psi)} \end{aligned}$$

In the GSA simulations, synthetic Level 1 concrete strength data were generated for input into the MEPDG using the following procedure:

1. Assume that aging relationships for MOR and E_c follow the same trends in time (i.e., $\alpha_i = \beta_i$ in Eq. 3.11 and 3.12) and equal on average to those in the Level 3 relationship (Eq. 3.13).

2. Randomly sample a reference 28-day *MOR* in the range of 500 to 800 psi.
3. Randomly perturb the aging coefficients (Eq. 3.11) within a $\pm 10\%$ range about their Level 3 defaults and determine a consistent value of the 20-year to 28-day strength. Use these values to predict *MOR* at 7, 14, and 90 days. The perturbation of the aging coefficients is intended conceptually to reflect different aging potentials for different PCC mixes.
4. Randomly perturb the γ coefficient in Eq. 3.14 within a $\pm 10\%$ range about its Level 3 default. Use this perturbed value of γ and the *MOR* values from step 3 in the Level 3 E_c vs. *MOR* relation (Eq. 3.13) to predict elastic modulus at 7, 14, and 90 days. In CRCP analysis, randomly perturb the δ coefficient in Eq. 3.14 within a $\pm 10\%$ range about its Level 3 default. Use this perturbed value of δ and the *MOR* values from step 3 in the Level 3 f_t' vs. *MOR* relation (Eq. 3.13) to predict indirect tensile strength at 7, 14, and 90 days. The perturbations of γ and δ are intended conceptually to reflect the variation of stiffness-to-strength ratios for different PCC mixes.
5. Input the synthetically generated Level 1 concrete strength and stiffness data from steps 3 and 4 into the MEPDG for the GSA simulations.

The important benefit of this procedure for generating synthetic Level 1 PCC strength and stiffness data is that it incorporates the correlations among these properties.

3.5 Water/Cement Ratio of PCC

Water/cement (or w/c) ratio of PCC mixture highly influences on PCC strength properties. Since synthetic Level 1 concrete strength data were utilized for input into the MEPDG in the GSA simulations, a reasonable w/c ratio corresponding to this input PCC strength must be determined. A common correlation of w/c ratio and PCC strength is given by Abrams' formula (1918):

$$f'_c = \frac{A}{B^{w/c}} \quad (3.15)$$

in which:

f'_c	= compressive strength (psi)
w/c	= water/cement (or w/c) ratio
A	= Empirical constant = 21,473 psi
B	= Empirical constant = 20 psi

3.6 JPCP Dowel Diameter and CRCP Steel Depth

The OAT sensitivity analysis results found that an increase in PCC thickness may require a correlated increase in dowel diameter to avoid an increase in faulting. This can be explained by the reduction of dowel shear effectiveness. An increase in PCC thickness leads to a decrease in the ratio of dowel cross-section to PCC cross-section (NCHRP 2004). The relationship between the baseline dowel diameter and JPCP thickness shown in Table 3.2 was developed to establish the correlation of these parameters. In the GSA simulations, the JPCP thickness varied from 6 inch to 14 inch, which corresponded to dowel diameters varying from 1.0 to 1.75 inch.

Table 3.2. Synthetic data between dowel diameter and JPCP thickness

JPCP Thickness (in.)	Dowel Diameter (in.)		
	Baseline	Min (Base × 0.9)	Max (Base × 1.1)
6	1.12	1.01	1.23
7	1.18	1.06	1.30
8	1.24	1.11	1.36
9	1.30	1.17	1.43
10	1.36	1.22	1.49
11	1.41	1.27	1.56
12	1.47	1.33	1.62
13	1.53	1.38	1.68
14	1.59	1.43	1.75

Figure 3.1 illustrates the correlation chart of dowel diameter and PCC thickness made from synthetic data. The linear regression equation was used to specify the baseline dowel diameter for a given PCC thickness input.

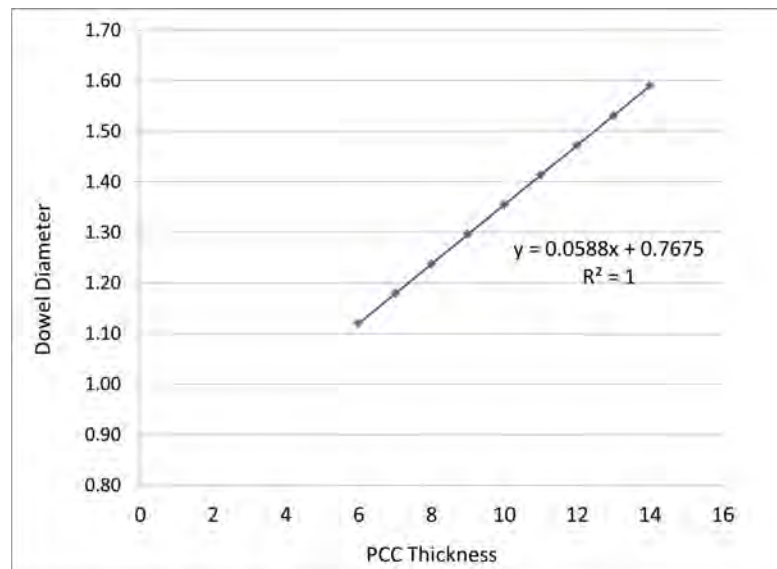


Figure 3.1. Correlation chart of dowel diameter and PCC thickness in JPCP.

In CRCP design, MEPDG requires that the steel location should not be higher than half of PCC thickness. Therefore, the steel height values were varied only within the lower half of the input PCC thickness.

3.7 Edge Support Conditions for Rigid Pavements

Categories for edge support in MEPDG JPCP analysis are given as: (1) no support, (2) tied PCC, and (3) widened slab. Categories for edge support in MEPDG CRCP analysis are specified in terms of shoulder type: gravel, asphalt, monolithic tied concrete, and separate tied concrete shoulder. In the GSA simulations, these edge support conditions are equivalenced to load transfer efficiency (LTE) in the same manner as for the OAT sensitivity analyses documented in Section 3.4 of Appendix B.

4 LATIN HYPERCUBE SAMPLING SCHEME

Latin Hypercube Sampling (LHS) is a widely used variant of the standard or “random” Monte Carlo simulation method. In LHS the range of each of the K model inputs $X_1, X_2, \dots, X_K$ is divided into N intervals in such a way that the probability of the input value falling in any of the intervals is $1/N$. One value is selected at random from each interval. The N values for X_1 are paired randomly with the N values of X_2 ; these sets are then paired randomly with the N values of X_3 and so on. The resulting N K -tuples are the LHS samples for the GSA. This process can be repeated with a different random seed to generate additional sets of N K -tuples.

For example, consider a model having $K=5$ inputs $X_1, X_2, \dots, X_5$ with each input subdivided into $N=3$ intervals defined for convenience as integers 0, 1, and 2. The set of 3 LHS random samples generated by this procedure might then look as follows:

X_1	X_2	X_3	X_4	X_5
0	2	2	0	2
2	1	0	1	1
1	0	1	2	0

The stratification level N can be increased to generate larger numbers of simulation samples. Alternatively, the LHS procedure can be repeated at the same N using a different random seed:

X_1	X_2	X_3	X_4	X_5
0	2	2	0	2
2	1	0	1	1
1	0	1	2	0
1	1	1	2	1
2	0	0	1	0
0	2	2	0	2

The efficiency of the LHS approach reduces by a factor of 5 to 20 the required number of simulations as compared to the conventional Monte Carlo method. Unfortunately, there are few good guidelines for how many LHS simulations are required for any given problem. Minimum numbers of simulation samples suggested in the literature include: $(4/3)*K$ (Iman and Helton, 1985); $(3/2)*K$ (Simlab, 2009); $2*K$ (McKay, 1988). Suggested upper bounds for the numbers of simulation samples include: $3*K$ (Manache, 2001); $10*K$ (SimLab, 2009; Saltelli *et al.*, 2004 as reported by Graves and Mahboub, 2006). In reality, both the lower and upper bounds are likely dependent upon the specific problem and on the intended use of the simulation results.

The LHS methodology was employed for generating the GSA simulation inputs. A limited parametric investigation was performed to determine the required number of simulations in order to get stable results. A multi-criteria assessment using various statistic measures was performed using 1000 MEPDG simulation results for one base case (TM). The statistic measures employed were: the linear regression coefficient β , Spearman's rank correlation coefficient ρ , and the standard error of the sample mean $SE_{\bar{y}_j}$ in which $\bar{y}_i$ is the estimated mean of the predicted distresses.

The β value is the slope of the linear regression line between the predicted distress and the model input, while the ρ coefficient is non-parametric measure of correlation between the ranks of two variables. The estimated values for β and ρ should stabilize when a sufficient number of simulations have been performed. The standard error of the sample mean $SE_{\bar{y}_j}$ can be used to determine the sufficient number of simulations using the criterion $SE_{\bar{y}_j} < \alpha \bar{y}_j$ (Schuyler , 1997). A value of $\alpha=0.01$ is recommended as a very conservative (severe) tolerance.

Examples of the convergence characteristics of the MEPDG rigid pavement models are provided in Figure 4.1, Figure 4.2 and Figure 4.3. The β and ρ statistical measures converged the most quickly, while $SE_{\bar{y}_j}$ converged more slowly. Similar results were obtained for the MEPDG flexible pavement design models.

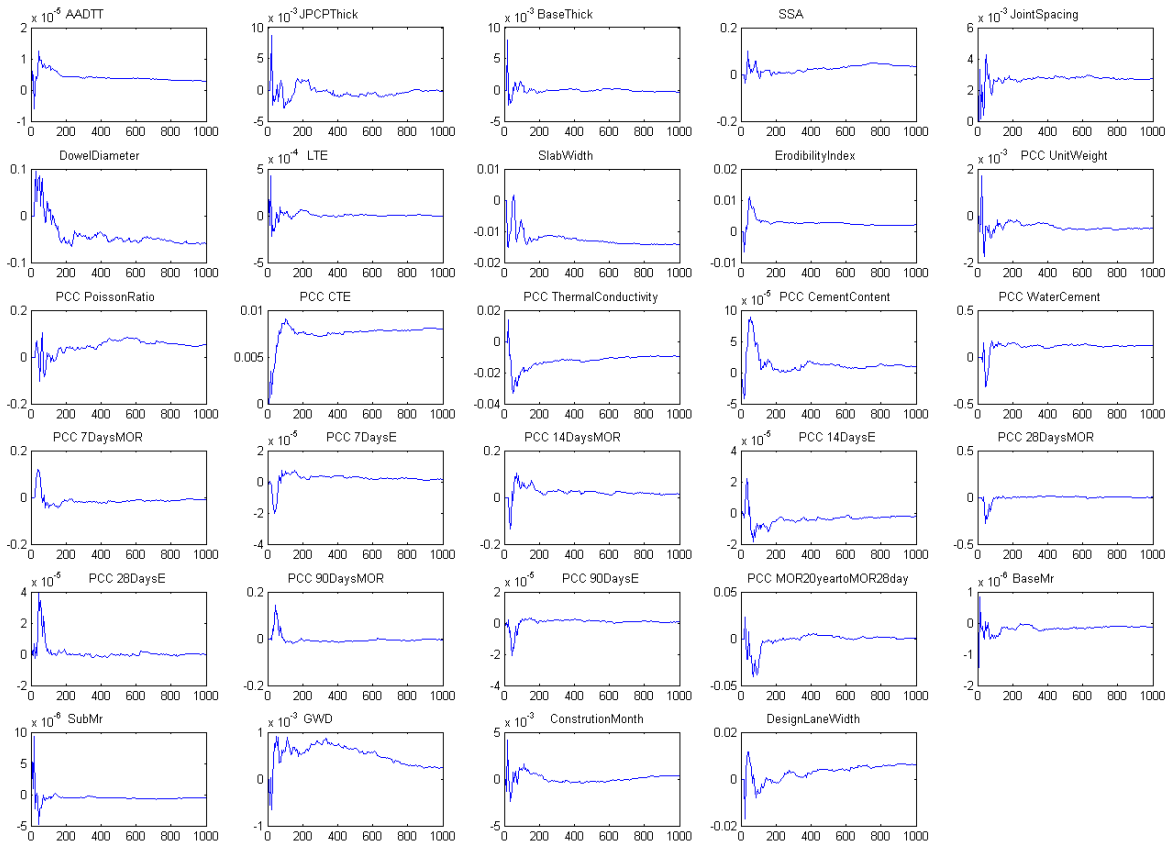


Figure 4.1. Convergence of β for JPCP faulting prediction.

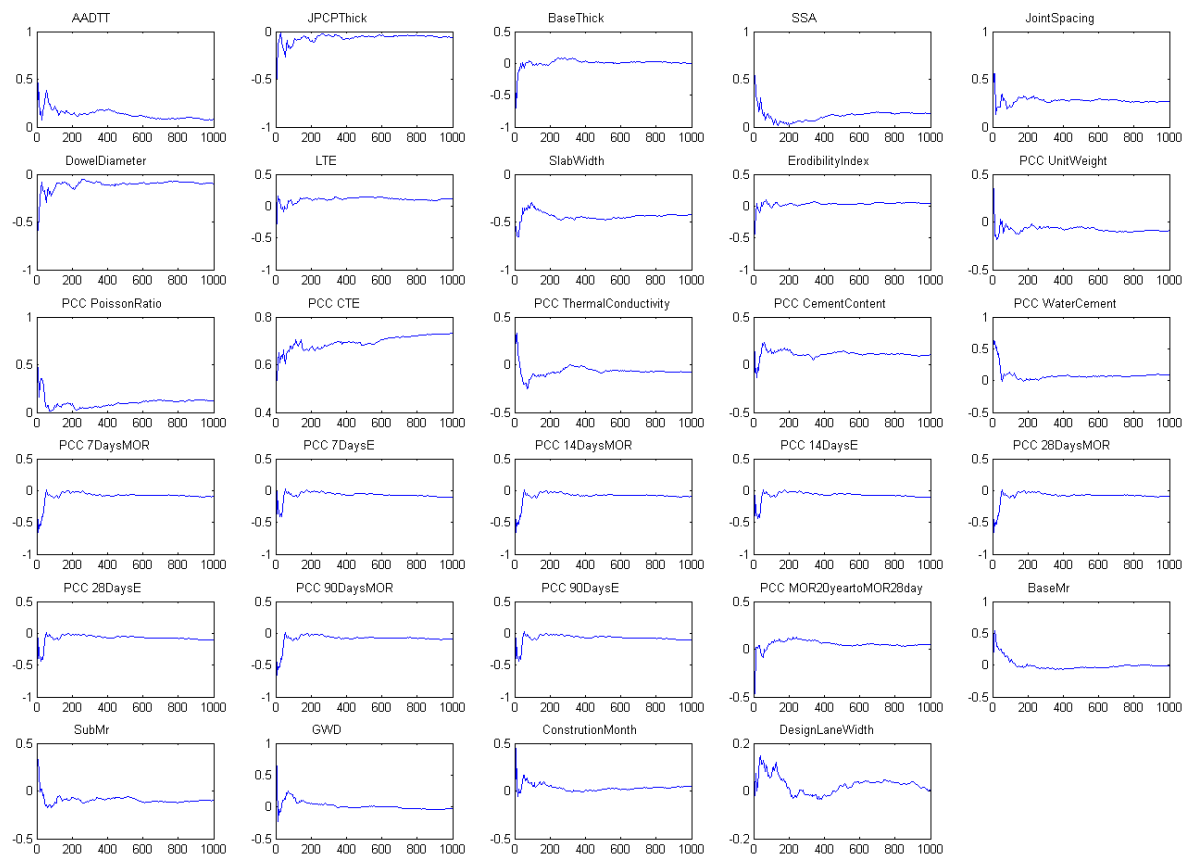


Figure 4.2. Convergence of ρ for JPCP faulting prediction.

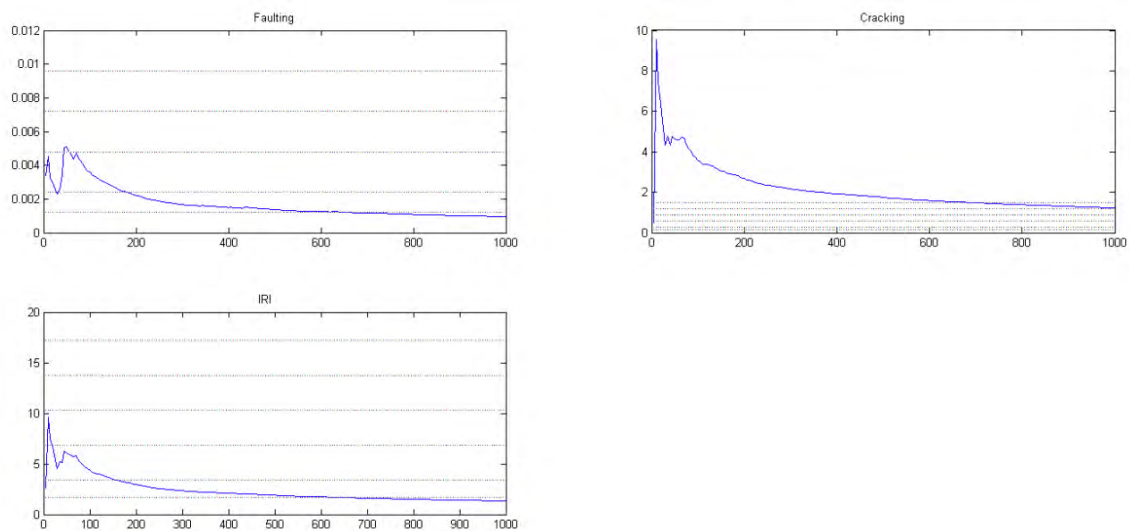


Figure 4.3. Convergence of SE_{y_j} for JPCP performance predictions.

The results from these numerical experiments suggest that sufficiently stable results can be obtained from approximately 400 to 500 simulations per pavement scenario, or approximately $20 \cdot K$. This is expected to be conservative, as it substantially exceeds even the highest numbers cited in the literature, e.g., $10 \cdot K$ for SimLab (2009).

5 AUTOIT TOOL

The GSA required many tens of thousands of MEDPG simulation runs. For flexible pavements, in particular, this is problematic because each run may require on the order of 20 minutes of execution time. The solution to this problem is to distribute the processing over scores of computers in the University of Maryland and Iowa State University laboratories. Three IT components are required to implement this solution: (1) a way to generate efficiently the MEPDG input file required for each simulation run; (2) a way to distribute the processing of these input files to the computers in the laboratories for overnight batch processing; and (3) a way to harvest the results from the simulations the next morning and collect into a central database for subsequent analysis.

The first component is the most problematic of the three. The MEDPG input (*.dgp) files are binary rather than text and there is no documentation for the file structure. It is therefore impossible to write an application to generate these files directly. (This will be much easier to accomplish in DARWin-ME, which will store all input parameters in a database structure.) It clearly is unfeasible to create the MEPDG *.dgp files manually given the number of files required. Some type of automated utility is therefore required to expedite the creation of these files.

The *AutoIt* scripting utility was adopted to automate the entry/creation of MEPDG input files (the first IT component) and to harvest the analysis results into a central spreadsheet repository (the third IT component). *AutoIt*¹ is a free, open source BASIC-like scripting language designed for automating the Windows graphical user interface and for general scripting of Windows program operation. It uses a combination of simulated keystrokes, mouse movements, and window/control manipulations to automate tasks in Windows programs. *AutoIt* is small, self-contained, and runs on all versions of Windows. It incorporates powerful programming capabilities that support complex expressions, user functions, loops, file I/O, and other sophisticated scripting features. *AutoIt* is a stand-alone application requiring no external .dll files or modifications to the Windows registry. Scripts can be compiled into stand-alone executables that can be easily distributed and run on other host computers. Thousands of lines of *AutoIt* code were developed to generate the MEPDG input files for the GSA simulations.

Distribution of MEDPG batch processing to the computers in the laboratories (second IT component) was relatively straightforward. The software utility *LogMeIn*² was used for remote access and file transfer to all of the analysis computers via a simple web browser interface on a central workstation. This enabled copying of the *AutoIt* scripts to the remote analysis computers, initiation of *AutoIt* script execution, and the transfer of the harvested results back to the central workstation.

¹ <http://www.autoitscript.com/autoit3/index.shtml>

² <https://secure.logmein.com/>

6 RESPONSE SURFACE MODELS

The GSA simulations provided predictions of pavement performance at random discrete locations in the problem domain. In order to compute sensitivity indices as defined in Section 7, it is necessary to evaluate the derivatives of distress with respect to design inputs at specific discrete locations. Fitting a continuous response surface model (RSM) to the randomly located GSA simulation results make this possible. The derivatives can either be expressed analytically from the RSM or estimated numerically using finite difference approximations in terms of the values of the RSM in the local area around the discrete specified locations.

Two RSM approaches were employed in this study: multivariate linear regressions (MVLRL) and artificial neural networks (ANN). MVLRL estimates the linear functional trends between model outputs (i.e., individual distresses) and model inputs (i.e., a set of design inputs). ANNs, in contrast, provide a “function-free” numerical approximation of the nonlinear relationship between distresses and design inputs.

The MVLRL is defined in normalized terms as follows:

$$\frac{Y}{DL} = a_0 + \sum_{i=1}^n a_i \frac{X_i}{\bar{X}_i} \quad (3.16)$$

in which Y is distress j (e.g., total rutting, IRI), DL is the design limit or range for distress (e.g., 0.75 in for total rutting, 172-63=109 in/mile for IRI), X_i is design input i , $\bar{X}_i$ is the mean value for X_i , a_0 is the intercept, and the a_i values are regression coefficients. As described in Section 7, the regression coefficients represent the average sensitivity of the normalized distress to the normalized input i .

ANNs are newer techniques than MVLRL but have today become standard data fitting tools for problems that are too complex, poorly understood, or resource intensive to tackle using more traditional numerical and/or statistical techniques. They can in one sense be viewed as similar to nonlinear regression except that the functional form of the fitting equation does not need to be specified *a priori*. The basic concepts underlying standard backpropagation ANNs can be found in Ceylan *et al.* (2009). The ANNs in this study were designed, trained, and evaluated using the MATLAB Neural Network toolbox.³ All of the ANNs were conventional two-layer (hidden layer and output layer) feed-forward network. Sigmoid transfer functions were used for all hidden layer neurons while linear transfer functions were employed for the output neurons. Training was accomplished using the Levenberg-Marquardt backpropagation algorithm. Separate ANN models were developed for each distress-climate zone combination for each pavement type. Seventy percent of the GSA simulations for each distress-climate zone combination were used for training, 15% were used for validation (to halt training when generalization stops improving), and 15% were use for independent testing of the trained model.

The basic ANN modeling approach was extended in this study by using the averages of an ensemble of ANNs for each pavement type-distress-climate zone combination. Because the ANN models are approximations dependent upon the random initial values assigned to the connection weights and neuron bias terms and upon the training history, any individual ANN may have local biases in particular regions of the problem domain even though it has excellent overall goodness-of-fit statistics. Averaging multiple ANN models tends to minimize any local bias effects. Twenty ANN models

³ <http://www.mathworks.com/products/neuralnet/>

passing a minimum goodness-of-fit threshold were averaged to form the RSM for each pavement type-distress-climate zone combination. The goodness-of-fit threshold varied some among the different models but was generally quite high (e.g., $R^2 \geq 0.98$).

7 SENSITIVITY METRICS

As described in Appendix B in the context of the OAT analyses, there is a wide variety of metrics that can be used to quantify sensitivity of model outputs to model inputs. No individual metric is “perfect” or ideal for all of the variables in this study. The primary methods used here were regression coefficients from normalized multivariate linear regression and a point-normalized sensitivity index.

MVLR provides estimates of the average sensitivities of distresses to inputs across the solution domain. Specifically, the individual coefficients a_i in the normalized regression equation (see preceding section) represent the average sensitivity of the normalized distress to the normalized input i . In other words, a_i represents the percentage change in a distress relative to its design limit/range caused by a given percentage change in the design input relative to its mean value. Note that since the a_i values are fixed quantities, they cannot capture sensitivity variations at different locations within the problem domain. The a_i values can provide only the average sensitivities over the problem domain.

The nonlinear fitting from the ANN models, on the other hand, can be used to provide point estimates of sensitivities across the problem domain. As described in Appendix B, the point-normalized sensitivity index S_{ijk} is defined as:

$$S_{ijk} = \frac{\partial Y_j}{\partial X_k} \bigg|_i \left(\frac{X_{ki}}{Y_{ji}} \right) \quad (3.17)$$

in which Y_{ji} , X_{ki} are the values of the model output j and input k all evaluated at location i in the problem domain. The partial derivative can be approximated using a standard central difference approximation:

$$\frac{\partial Y_j}{\partial X_k} \bigg|_i \cong \frac{\Delta Y_j}{\Delta X_k} \bigg|_i = \frac{Y_{j,i+1} - Y_{j,i-1}}{X_{k,i+1} - X_{k,i-1}} \quad (3.18)$$

The S_{ijk} sensitivity index can be interpreted as the local percentage change in model output Y_j caused by a given percentage change in the model input X_k at location i in the problem domain. For example, $S_{ijk} = 0.5$ implies that a 20% change in the local value of X_{ki} will cause a 10% local change in Y_{ji} . Since S_{ijk} is a local point estimate of sensitivity, it will vary across the problem domain.

However, problems were encountered when calculating the point-normalized sensitivity index for the OAT analyses because the predicted distress values Y_{ji} were near zero for some of the baseline conditions, resulting in artificially large sensitivity index values. To circumvent this problem, a “design limit” normalized sensitivity index S_{ijk}^{DL} is defined:

$$S_{ijk}^{DL} = \frac{\Delta Y_{ji}}{\Delta X_{ki}} \frac{X_{ki}}{DL_j} \quad (3.19)$$

in which

- X_{ki} = value of design input k at point i
- ΔX_{ki} = change in design input k about point i
- ΔY_{ji} = change in predicted distress j corresponding to ΔX_{ki}

DL_j = the design limit for distress j

The design limit normalized sensitivity index S_{ijk}^{DL} can be more simply termed as the “normalized sensitivity index” or NSI. The NSI always uses the design limit as the normalizing factor for the predicted distress. For example, consider total rutting as the predicted distress with a design limit of 0.75 inches. An NSI of -0.25 for the sensitivity of total rutting to granular base layer resilient modulus implies that a 10% reduction in base resilient modulus will increase total rutting by $NSI * \Delta X_k = 2.5\%$ of its design limit DL_j --i.e., it will increase rutting by $(-0.1)*(-0.25)*0.75=0.01875$ inches.

NSI can be calculated using Eq. 3.19 for most design inputs. However, in some cases the design input is categorical rather than continuous—e.g., binder grade and construction month. For these design inputs, a modified non-normalized NSI definition is used instead:

$$NSI = \frac{\Delta Y_{ji}}{DL_j} \bigg|_{\Delta X_{ki}=1 \text{ category}} \quad (3.20)$$

This modified design limit NSI also takes the design limit as reference for predicted distress. It quantifies how the predicted distress changes in normalized terms if the design input is changed by one category.

NSI for IRI is also treated as a special case because it has a nonzero lower bound. The normalized NSI for IRI is defined in terms of the difference between the default terminal (172 in/mile) and initial (63 in/mile) IRI values:

$$NSI = \frac{IRI - 63}{172 - 63} \quad (3.21)$$

The NSI definitions in Eqs. 3.19 through 3.21 were sufficient for all design inputs that are varied directly in the GSA simulations. However, some of these inputs are Level 1 material properties that in practice may alternatively be specified in the MEPDG in terms of Level 3 empirical relations. Examples of this include the HMA dynamic modulus sigmoidal function constants δ (lower shelf) and α (offset to the upper shelf—see Section 3.2) and the HMA low temperature strength S_t and creep compliance parameters D and m (see Section 3.3). Rather than the direct sensitivity of predicted distress to these Level 1 inputs, the pavement designer may instead be more interested in the sensitivity of predicted distress to the inputs to the Level 3 empirical relations used within the software to derive the Level 1 properties. Fortunately, one can estimate these sensitivities to the Level 3 inputs using the NSI values for the primary Level 1 input parameters and the derivatives of the Level 3 empirical relations. For example, consider the Level 3 relationship between δ and HMA gradation and volumetric properties given in Eq. 3.3. Following Eq. 3.17, the design-limit normalized sensitivity NSI_{V_a} of predicted performance Y_j to air voids V_a at point i in the problem domain can be defined as:

$$NSI_{V_a} = \frac{\partial Y_j}{\partial V_a} \bigg|_i \frac{(V_a)_i}{DL_j} \quad (3.22)$$

Equation 3.22 can then be expressed in terms of the normalized sensitivity index NSI_{δ} for δ using the chain rule as follows:

$$NSI_{V_a} = \frac{\partial Y_j}{\partial \delta} \left| \frac{\partial \delta}{\partial V_a} \right| \frac{(V_a)_i}{DL_j} = \left(\frac{\partial Y_j}{\partial \delta} \right| \frac{\delta_i}{DL_j} \right) \frac{\partial \delta}{\partial V_a} \left| \frac{(V_a)_i}{DL_j} \frac{DL_j}{\delta_i} \right| = NSI_{\delta} \left[\frac{\partial \delta}{\partial V_a} \left| \frac{(V_a)_i}{\delta_i} \right| \right] \quad (3.23)$$

in which the last term in square brackets can be evaluated from the Level 3 empirical relationship—Eq. 3.3 in this example. Generalizing, the NSI for any secondary variable z (i.e., a Level 3 empirical relation variable) can be expressed in terms of the NSI for the primary variable x (i.e., a GSA simulation variable) using:

$$NSI_z = NSI_x \left[\frac{\partial x}{\partial z} \left| \frac{z_i}{x_i} \right| \right] \quad (3.24)$$

Eq. 3.24 can be further approximated using finite difference estimates for the partial derivative and/or mean values in place of the point values for x and z .

8 NEW HMA

8.1 Analysis Inputs

The GSA analyses of New HMA flexible pavements encompassed a total of 15 base cases spanning five climate zones with three traffic levels each. Table 8.1 summarizes the project-specific parameters that were fixed for all New HMA analyses.

Table 8.1. Fixed design inputs for New HMA cases.

Input Parameter	Value
Design Life	15 years
Reliability	90% for all distresses
AADTT Category	Principal Arterials – Interstate and Defense Route
TTC	4
Number of Lanes in Design Direction	2 for low traffic/3 for medium and high traffic
Truck Direction Factor	50
Truck Lane Factor	75 for low traffic/55 for medium traffic/50 for high traffic
Default Growth Rate	No growth
First Layer Material Type	Asphalt Concrete
Second Layer Material Type	Granular Base
Subgrade Material Type	Soil
HMA Aggregate	Virgin – 19mm*

*This mixture has the following properties: cumulative % retained $\frac{3}{4}$ inch sieve = 5.5; cumulative % retained $\frac{3}{8}$ inch sieve = 33.5; cumulative % retained #4 sieve = 55.5; % passing #200 sieve = 4.9; V_{beff} = 10.08%; V_a = 6.47%

As stated in Section 3.2, binder properties were specified in terms of discrete binder grade rather than in terms of continuous inputs like A and VTS . Binder grade was determined in the OAT local sensitivity analyses to be a sensitive design input (see Appendix B). Table 8.2 summarizes the binder grade baseline values and the grade variations for each climate zone. PGHigh- means that the high temperature grade decreases one step; PGLow+ means that the low temperature grade increases one step. Since binder grade is not a continuous variable, the Latin Hypercube sampling had to be modified for this input. For all “regular” GSA runs, 80% of the simulations used the baseline PG and the remaining 20% used the PGHigh- (Hot-Dry, Hot-Wet, Temperate) or PGLow+ (Cold-Dry, Cold-Wet) grades. However, little or no thermal cracking was predicted using these appropriate or near-appropriate binder grades; as learned during the OAT analyses, the low temperature stiffness must be increased by at least 2 grades above the recommended value in order to generate significant thermal cracking. Consequently a second subset of GSA runs targeted specifically at thermal cracking was performed with one third of the simulations using the PGLow+ (low temperature grade 1 step above baseline), PGLowTC grade (low temperature grade 2 steps above baseline), and PGLowTC+ (low temperature grade 3 steps above baseline). The corresponding binder grades for these special thermal cracking analyses are summarized in Table 8.2. These special scenarios for low temperature thermal cracking are CD1 (Cold-Dry climate, low temperature binder grade 1 step stiffer than baseline), CD2, CD3, CW1, CW2, and CW3. Only the cold climate zones were considered for the special thermal cracking analyses.

Table 8.2. Binder grade baseline values and variations for New HMA cases.

Climate	Baseline PG	PGHigh-	PGLow+	PGLowTC	PGLowTC+
Cold-Dry	PG 52-40	NA	PG 52-34	PG 52-28	PG 52-22
Cold-Wet	PG 52-28	NA	PG 52-22	PG 52-16	PG 52-10
Hot-Dry	PG 76-10	PG 70-10	NA	NA	NA
Hot-Wet	PG 70-10	PG 64-10	NA	NA	NA
Temperate	PG 58-10	PG 52-10	NA	NA	NA

Table 8.3 summarizes the design inputs that are strongly correlated to traffic level. Higher traffic levels require correspondingly thicker asphalt and base layers. AADTT, HMA thickness, and base thickness were all determined in the OAT local sensitivity analyses to be hypersensitive or very sensitive inputs (see Appendix B). The GSA simulations used random input values for the AADTT and the HMA and base thicknesses ranging between the minimum and maximum limits for each traffic level category as determined by the Latin Hypercube algorithm.

Table 8.3. Design inputs related to traffic levels in New HMA cases.

Input Parameter \ Traffic Level	Low Traffic			Medium Traffic			High Traffic		
	Baseline	Min	Max	Baseline	Min	Max	Baseline	Min	Max
AADTT-Nominal	1000	500	5000	7500	5000	10000	25000	20000	30000
Design Lane	375	188	1875	2063	1375	2750	6250	5000	7500
HMA Thickness	6.5	5	8	10	8	12	12.5	10	15
Base Thickness	6	1	10	7	1	14	9	1	18

The remaining design inputs that were varied in the GSA simulations are summarized in Table 8.4. These inputs correspond to the “Hypersensitive,” “Very Sensitive,” and “Sensitive” design inputs as identified in Phase I and confirmed by the OAT local sensitivity analysis findings in Appendix B. The baseline, minimum and maximum values are listed for each design input. The Latin Hypercube algorithm used for generating the GSA simulations randomly sampled each design input uniformly over each sampling interval between the minimum and maximum limits.

The baseline values for the correlated unbound material properties P_{200} , D_{60} , PI, and LL were determined from the sampled M_r values using the procedures described in Section 3.1. The sampled values for P_{200} , D_{60} , PI, and LL were varied by $\pm 10\%$ about the baseline values to reflect less-than-perfect correlation with M_r . All HMA and binder properties were determined using the procedures described in Sections 3.2 and 3.3.

Note that the only differences in the special GSA simulations for thermal cracking are the stiffer low temperature binder grades given in Table 8.2. All other design input ranges were the same as for the regular New HMA GSA simulations—i.e., as given in Table 8.3 and Table 8.4.

Table 8.4. Input parameter ranges for New HMA cases.

Input Parameter	OAT Sensitivity ¹	Baseline Value ²	Minimum ²	Maximum ²
Operational Speed	S	50	30	70
Ground Water Depth	S	10	2	18
Surface Shortwave Absorption	VS	0.85	0.80	0.98
HMA Unit Weight	S	149.9	134.9	164.9
HMA Poisson's Ratio	VS	0.35	0.315	0.385
HMA Thermal Conductivity	S	0.67	0.44	0.81
HMA Heat Capacity	S	0.23	0.22	0.40
Delta in HMA Sigmoidal Curve	HS	2.83	2.75 ³	2.91 ³
Alpha in HMA Sigmoidal Curve	HS	3.90	3.82 ³	3.98 ³
Effective Binder Content in HMA	VS	10	6	14
Air Void in HMA	VS	7	4	10
Base Resilient Modulus	VS	25000	15000	40000
Base Poisson's Ratio	S	0.35	0.315	0.385
Subgrade Resilient Modulus	VS	15000	10000	20000
Subgrade Poisson's Ratio	S	0.35	0.315	0.385
Subgrade Percent Passing #200 Sieve	S	-- ⁴	24	99
Subgrade Plasticity Index	S	-- ⁴	0	62
Subgrade Liquid Limit	S	-- ⁴	26	92
Tensile Strength at 14° F	S	125	475	1600
HMA Creep Compliance D at -4°F	S	1.43E-08	1.54E-07	4.44E-07
14°F	S	1.54E-07	2.48E-07	6.86E-07
32°F	S	2.48E-07	3.35E-07	9.19E-07
HMA Creep Compliance m at -4°F	VS	0.115	0.246	0.181
14°F	VS	0.204	0.276	0.351
32°F	VS	0.352	0.608	0.475
Aggregate Coefficient of Contraction	NS	5E-6	2E-6	7E-6

¹HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Not Sensitive

²All values are in same units as MEPDG inputs.

³Encompasses two-thirds or more of mixtures in Bari and Witczak (2006) database.

⁴Function of subgrade resilient modulus; see Section 3.1.

8.2 Predicted Distresses

Over 9600 MEPDG runs were performed for the New HMA GSA. Table 8.5 through Table 8.10 provide summary statistics for predicted longitudinal cracking, alligator cracking, thermal cracking, AC rut depth, total rut depth, and IRI, respectively, for the GSA simulations for each base case combination of climate zone and traffic level. Recall that the thermal cracking simulations had low temperature binder grades that were up to 3 grades higher than the value recommended by LTPPBind in order to generate significant levels of thermal cracking distress. Overall, the Latin hypercube sampling scheme generated input data sets that produced a wide range for each of the predicted distresses. The range of predicted distresses in most cases is from zero or near zero to values several times the default design limit. The exception to this is IRI (Table 8.10), where none of the predicted values exceed the default design limit of 172 inches/mile. Average values for longitudinal and alligator cracking were larger for the lower traffic categories (probably because of the thinner AC layers, on average) and, to a lesser extent, for the colder climate zones. The average values for AC rutting, total rutting, and IRI tended to increase slightly with traffic level but were relatively insensitive climate zone.

Figure 8.1 through Figure 8.5 provide frequency distributions of predicted distresses by climate zone and traffic level. The distributions of predicted distresses were quite robust in all cases, with the possible exception of IRI. These results confirm that the GSA simulations for the New HMA cases span a wide range of the model output (distress) space as well as the model inputs domain.

Table 8.5. Summary statistics for predicted longitudinal cracking – New HMA.

Scenario	Mean	Minimum	Maximum	Std Dev
CDL	3193	0	10200	3219
CDM	536	0	7140	1223
CDH	105	0	8130	544
CWL	2714	0	10100	2996
CWM	342	0	5770	859
CWH	57	0	6310	375
TL	1287	0	9390	1999
TM	60	0	1930	211
TH	2	0	516	26
HDL	2141	0	10100	2585
HDM	178	0	3680	480
HDH	26	0	4260	227
HWL	1775	0	9790	2486
HWM	52	0	2560	203
HWH	2	0	578	29
Overall	831	0	10200	1617

Table 8.6. Summary statistics for predicted alligator cracking – New HMA.

Scenario	Mean	Minimum	Maximum	Std Dev
CDL	4.6	0.1	37.9	6.0
CDM	1.3	0.1	10.2	1.5
CDH	1.1	0.1	11.2	1.3
CWL	3.9	0.1	31.2	5.1
CWM	1.0	0.1	7.6	1.1
CWH	0.9	0.0	8.5	1.0
TL	2.2	0.1	21.3	2.7
TM	0.7	0.0	4.6	0.7
TH	0.5	0.0	3.6	0.5
HDL	3.0	0.1	31.1	3.6
HDM	0.8	0.1	5.8	0.8
HDH	0.7	0.0	5.4	0.7
HWL	3.0	0.1	26.4	3.7
HWM	0.8	0.1	5.5	0.8
HWH	0.7	0.0	5.5	0.7
Overall	1.7	0.0	37.9	2.7

Table 8.7. Summary statistics for predicted thermal cracking – New HMA.

Scenario	Mean	Minimum	Maximum	Std Dev
CD1	66.0	0.0	1110.0	154.0
CD2	1139.1	59.7	2110.0	442.9
CD3	1797.0	1050.0	2110.0	265.4
CW1	68.8	0.0	1110.0	161.3
CW2	322.1	0.3	1450.0	349.2
CW3	424.1	0.3	1600.0	397.6
Overall	636.2	0.0	2110.0	315.3

Table 8.8. Summary statistics for predicted AC rutting – New HMA.

Scenario	Mean	Minimum	Maximum	Std Dev
CDL	0.23	0.07	0.46	0.08
CDM	0.31	0.16	0.54	0.08
CDH	0.41	0.15	0.76	0.12
CWL	0.20	0.06	0.42	0.07
CWM	0.28	0.14	0.49	0.07
CWH	0.37	0.14	0.70	0.11
TL	0.12	0.04	0.26	0.04
TM	0.17	0.08	0.31	0.04
TH	0.21	0.09	0.41	0.06
HDL	0.26	0.10	0.59	0.09
HDM	0.35	0.17	0.72	0.09
HDH	0.47	0.22	0.88	0.13
HWL	0.16	0.06	0.35	0.05
HWM	0.21	0.10	0.40	0.05
HWH	0.28	0.12	0.53	0.08
Overall	0.27	0.04	0.88	0.08

Table 8.9. Summary statistics for predicted total rutting – New HMA.

Scenario	Mean	Minimum	Maximum	Std Dev
CDL	0.59	0.33	0.96	0.12
CDM	0.62	0.39	0.94	0.10
CDH	0.72	0.41	1.16	0.15
CWL	0.53	0.30	0.86	0.11
CWM	0.56	0.35	0.85	0.09
CWH	0.65	0.37	1.05	0.14
TL	0.41	0.24	0.71	0.07
TM	0.43	0.28	0.65	0.07
TH	0.46	0.29	0.72	0.08
HDL	0.57	0.29	1.02	0.12
HDM	0.62	0.37	1.01	0.11
HDH	0.73	0.41	1.20	0.15
HWL	0.47	0.30	0.82	0.09
HWM	0.48	0.29	0.76	0.07
HWH	0.55	0.35	0.86	0.10
Overall	0.56	0.24	1.20	0.11

Table 8.10. Summary statistics for predicted IRI – New HMA.

Scenario	Mean	Minimum	Maximum	Std Dev
CDL	111.8	99.0	148.0	7.7
CDM	111.0	100.7	126.5	4.7
CDH	114.7	102.1	134.6	6.5
CWL	108.7	97.1	137.0	6.7
CWM	108.1	98.9	121.1	4.2
CWH	111.6	100.1	129.2	5.9
TL	95.4	87.5	119.6	4.3
TM	95.3	88.6	104.7	3.0
TH	96.3	88.9	108.7	3.6
HDL	100.9	88.1	137.9	6.4
HDM	101.6	91.2	117.4	4.7
HDH	106.2	92.9	127.2	6.5
HWL	100.5	91.6	129.8	5.4
HWM	99.5	91.6	111.5	3.4
HWH	102.3	93.3	117.0	4.4
Overall	104.3	87.5	148.0	5.3

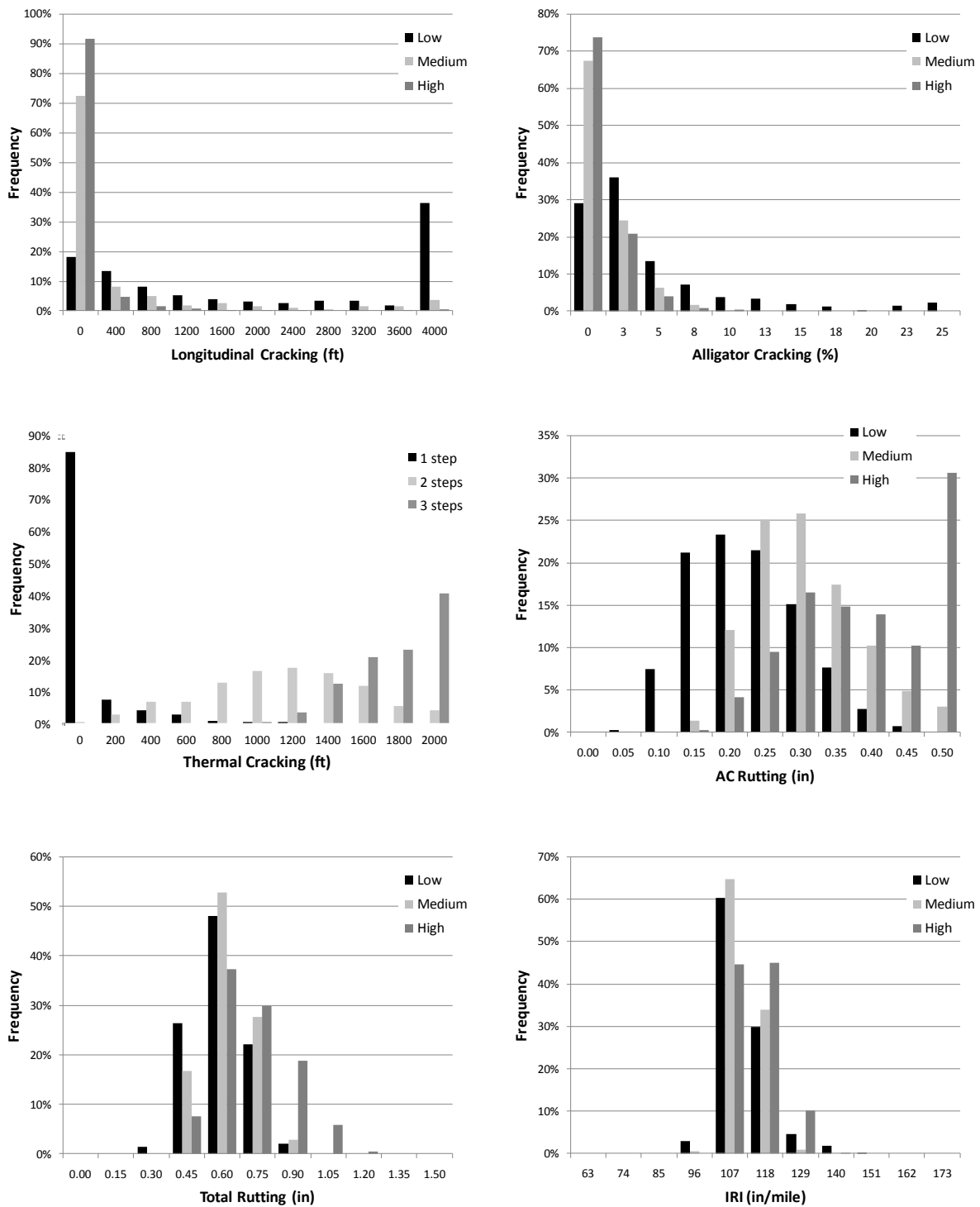


Figure 8.1. Distribution of predicted distresses – New HMA/Cold-Dry climate.

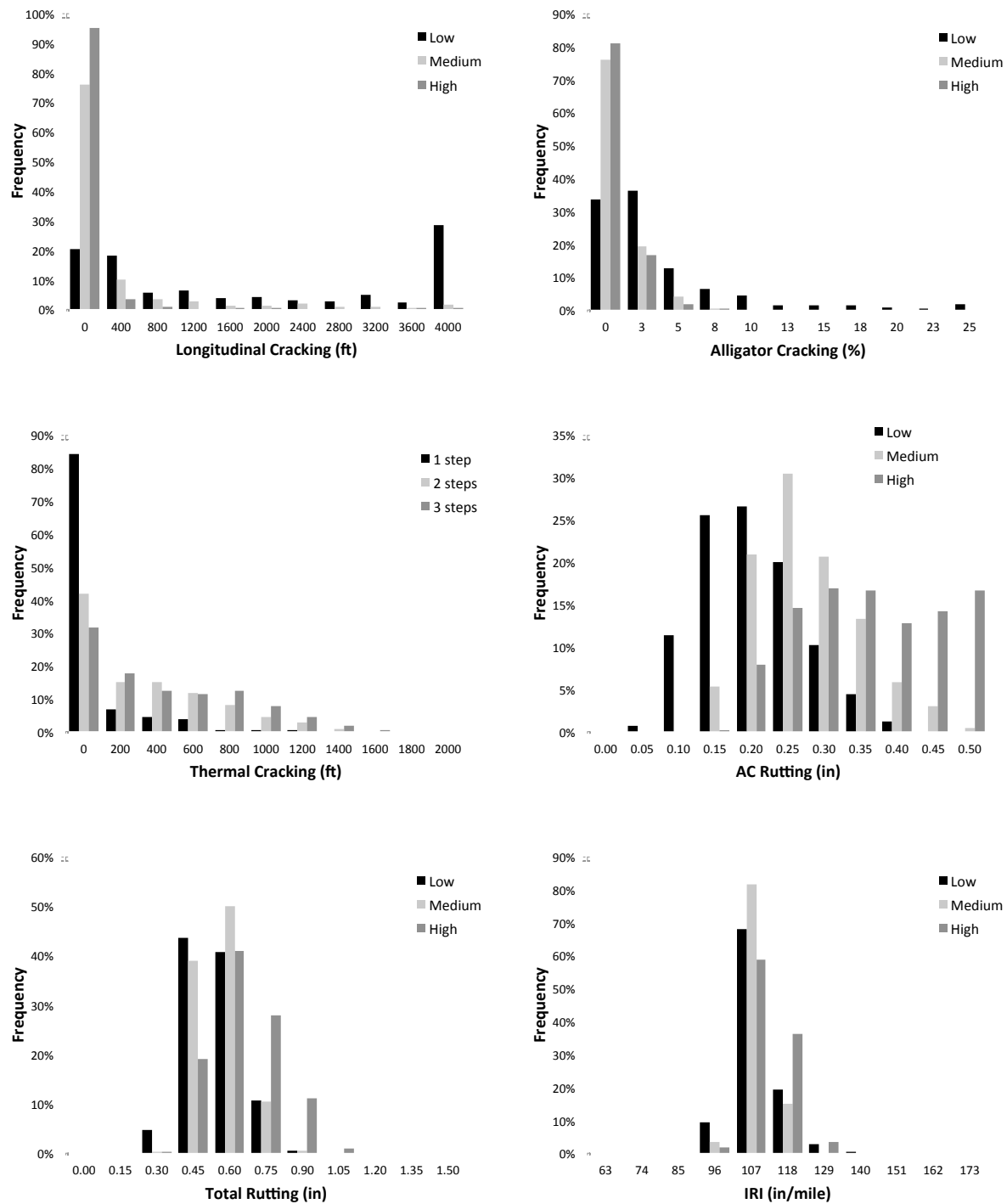


Figure 8.2. Distribution of predicted distresses – New HMA/Cold-Wet climate.

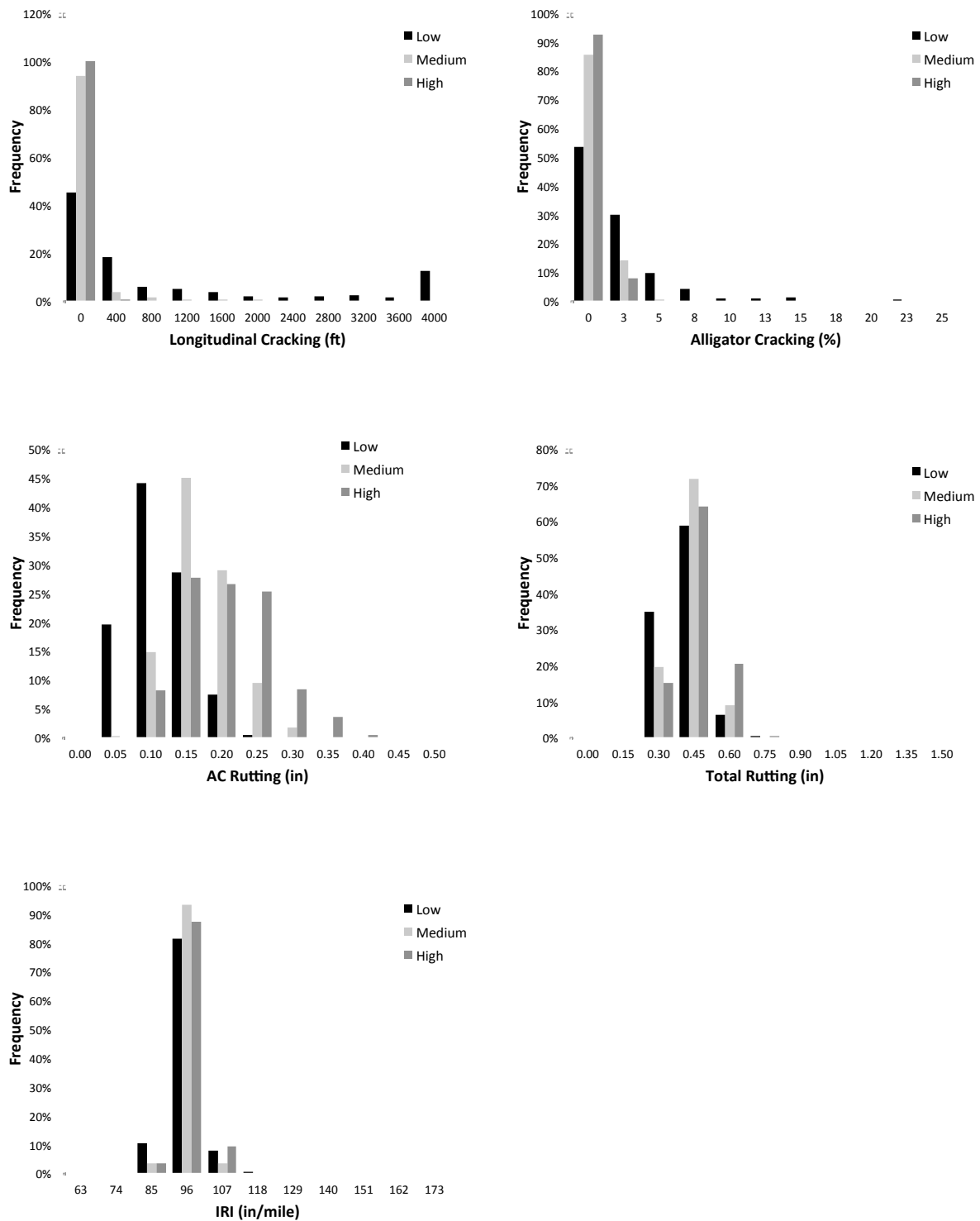


Figure 8.3. Distribution of predicted distresses – New HMA/Temperate climate.

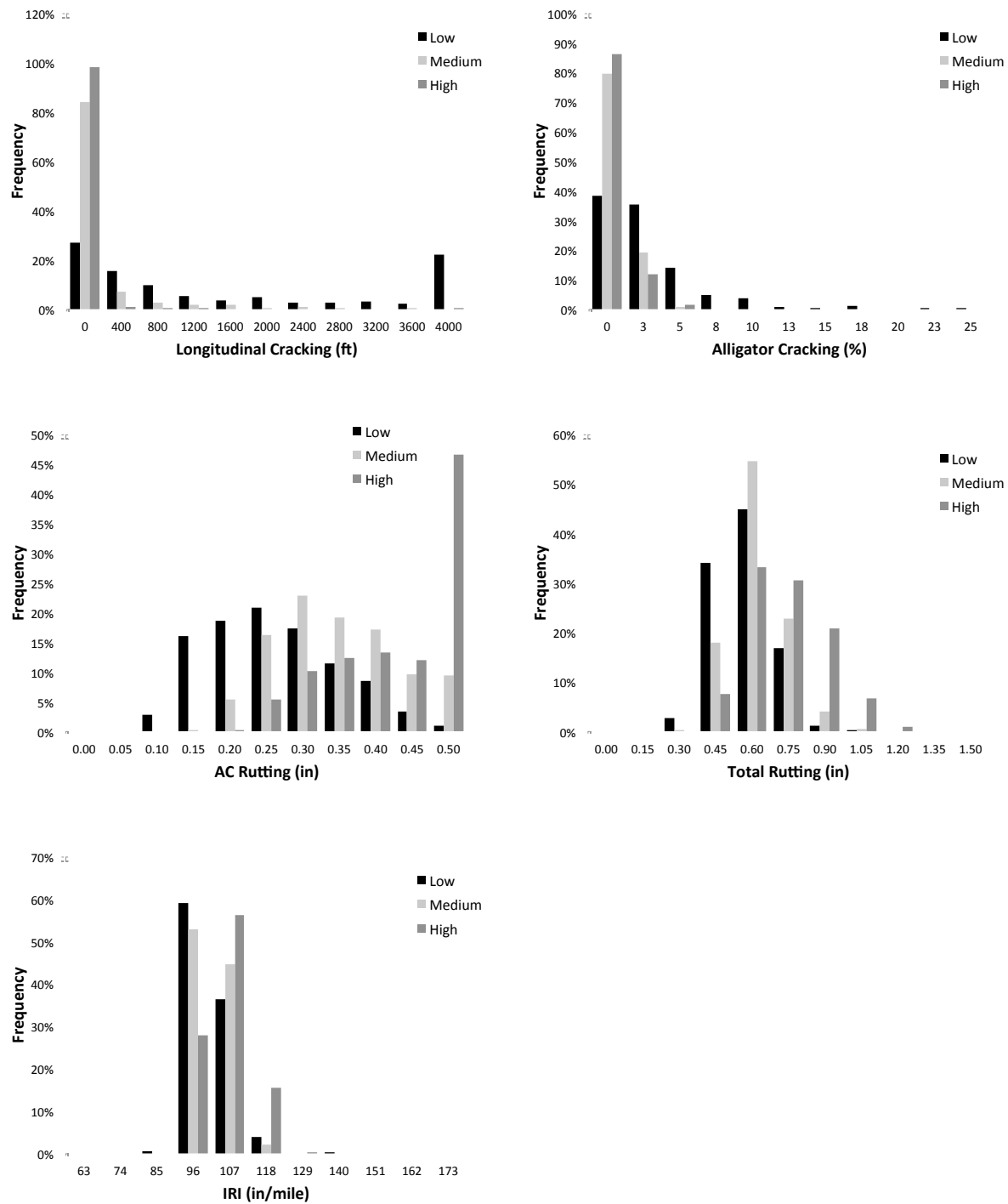


Figure 8.4. Distribution of predicted distresses – New HMA/Hot-Dry climate.

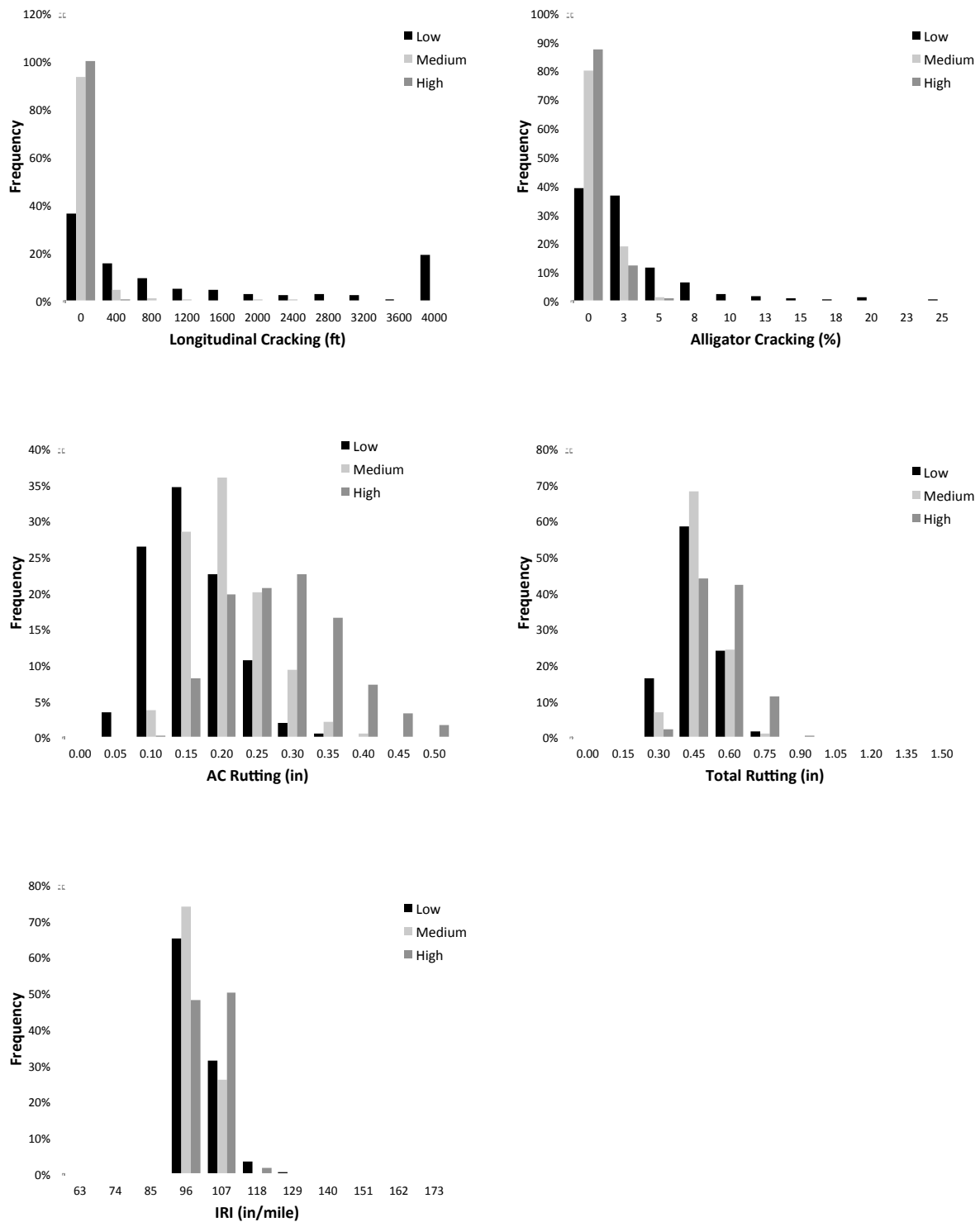


Figure 8.5. Distribution of predicted distresses – New HMA/Hot-Wet climate.

8.3 Response Surface Modeling

Table 8.11 defines the inputs used for the RSMs. These design inputs are the same as those given previously in Table 8.2, Table 8.3, and Table 8.4. The outputs from the RSMs are the predicted distresses: longitudinal cracking, alligator cracking, thermal cracking, AC rutting, total rutting, and IRI. Separate RSMs were developed for each distress. As described previously in Section 6, each input for the MVLR RSMs was normalized by its mean value from the GSA simulations and each output distress was normalized by its default design limit. As described previously in Section 7, IRI was treated as a special case because it has a nonzero lower bound.

The regression coefficients in the normalized MVLR RSMs can be interpreted as average sensitivity indices quantifying the percentage change in distress relative to design limit caused by a given percentage change in the design input relative to its mean value. These average sensitivity indices are constant across the problem domain—i.e., the MVLR RSMs do not capture any variations of sensitivity with location in the problem domain.

The ANN RSMs do not use normalized design inputs or distress outputs. Instead, the ANN RSMs used the actual values for the inputs and outputs. Normalization occurs in the calculation of the point normalized sensitivity indices as described previously in Section 6 (Eq. 3.19).

Table 8.11. Definition of inputs for response surface modeling - New HMA scenarios.

Input No.	Name of Design Input	Description
1	AADTTperLane	Average Annual Daily Truck Traffic in design lane
2	HMAThickness	HMA layer thickness
3	BaseThickness	Base layer thickness
4	OpSpd	Average vehicle travel speed
5	PGHigh	High temperature binder grade. The NSI was calculated by decreasing the high temperature grade by one step from baseline.
6	PGLow	Low temperature binder grade. The NSI was calculated by increasing the low temperature grade by one step from baseline.
7	GWD	Ground Water Depth
8	SSA	Surface Shortwave Absorption
9	UnitW	Unit weight of HMA
10	Pratio	Poisson's ratio of HMA
11	ThmlCn	Thermal conductivity of HMA
12	HtCp	Heat capacity of HMA
13	Delta	The lower limit of the sigmoidal function for $\log(E^*)$
14	Alpha	The upper limit of the sigmoidal function for $\log(E^*)$
15	Vbeff	HMA volume of effective binder
16	Va	HMA air voids
17	BaseMr	Resilient modulus of base material
18	BasePR	Poisson's ratio of granular base layer material
19	SubMr	Resilient modulus of subgrade material
20	SubPR	Poisson's ratio of subgrade material
21	SubN200	Percentage passing #200 sieve of subgrade material
22	SubPI	Plasticity Index of subgrade material
23	SubLL	Liquid Limit of subgrade material

24	TenStr14 ¹	HMA tensile strength at 14°F
25	D ¹	HMA creep compliance constant (averaged over 3 temperatures)
26	m ¹	HMA creep compliance exponent (averaged over 3 temperatures)
27	AggCoefContr ¹	Aggregate coefficient of thermal contraction

¹For thermal cracking RSMs only.

Goodness-of-fit statistics R^2 , root mean squared error (RMSE), and normalized standard error (Se/Sy) for the MVL RSMs are summarized in Table 8.12 by climate zone and distress. Note that RMSE is in the units of the predicted distress while R^2 and Se/Sy are dimensionless. The R^2 values ranged from mediocre values around 0.3 to respectable values of about 0.8, with the cracking distresses tending to have smaller R^2 values and the rutting and IRI distresses tending to have better goodness-of-fit statistics. The low R^2 values for many of the MVL RSMs were not unexpected. The relationships between design inputs and distress outputs was expected to be complexly nonlinear; the multivariate linear regressions were intended only as a rough “first cut” assessment of sensitivities.

Goodness-of-fit statistics for the ANN RSMs are summarized in Table 8.13 by climate zone and distress. The ‘NN’ column describes the ANN network architecture; all ANN RSMs for the New HMA scenarios employed 23 input neurons, 5 hidden neurons in one layer, and one output neuron. There were 4 additional input neurons in the thermal cracking ANN RSMs to allow for the HMA low temperature material inputs. The ‘n’ column gives the combined number of GSA simulations used for training/validating/testing the model. Overall, the ANN RSM model fits were very good. The R^2 values approached 1.00 for rutting and IRI and were only slightly smaller for the cracking distresses; the lowest R^2 value was a very respectable 0.88 (alligator cracking, hot-wet climate).

Scatter plots for ANN predicted vs. MEPDG predicted distresses are provided in Figure 8.6 for longitudinal cracking, alligator cracking, AC rutting, total rutting, and IRI by climate zone and in Figure 8.7 for thermal cracking for the two cold climate zones. These scatter plots graphically confirm the conclusions from the goodness-of-fit statistics that the ANN RSM models provide excellent fits for rutting and IRI and very good fits for the cracking distresses. The high quality of the fits for these ANN RSMs suggest the possibility that enhanced versions of the RMS might be adequate substitutes in some cases for the more rigorous but laborious geomechanics computations in the MEPDG.

Table 8.12. Goodness-of-fit statistics for MVLR RSMs – New HMA.

Climate	Distress	R²	RMSE	Se/Sy
CD	Longitudinal Cracking	0.514	0.846	0.703
	Alligator Cracking	0.431	0.121	0.761
	Thermal Cracking	0.929	0.209	0.270
	AC Rutting	0.725	0.250	0.529
	Total Rutting	0.703	0.099	0.550
	IRI	0.662	0.035	0.586
CW	Longitudinal Cracking	0.470	0.788	0.734
	Alligator Cracking	0.424	0.101	0.766
	Thermal Cracking	0.656	0.206	0.592
	AC Rutting	0.735	0.224	0.519
	Total Rutting	0.712	0.088	0.541
	IRI	0.679	0.030	0.572
T	Longitudinal Cracking	0.291	0.464	0.847
	Alligator Cracking	0.439	0.047	0.754
	AC Rutting	0.793	0.103	0.458
	Total Rutting	0.760	0.047	0.493
	IRI	0.749	0.016	0.504
HD	Longitudinal Cracking	0.394	0.606	0.784
	Alligator Cracking	0.443	0.063	0.751
	AC Rutting	0.735	0.255	0.518
	Total Rutting	0.719	0.096	0.534
	IRI	0.713	0.029	0.539
HW	Longitudinal Cracking	0.356	0.658	0.810
	Alligator Cracking	0.430	0.073	0.762
	AC Rutting	0.755	0.159	0.500
	Total Rutting	0.715	0.068	0.539
	IRI	0.687	0.024	0.565

Table 8.13. Goodness-of-fit statistics for ANN RSMs – New HMA.

Climate	Distress	NN	n	R²	RMSE	Se/Sy
CD	Alligator Cracking	23-5-1	1290	0.92	700	0.291
	Longitudinal Cracking	23-5-1	1290	0.95	0.92	0.231
	Thermal Cracking	27-5-3	1405	0.98	99.0	0.128
	AC Rutting	23-5-1	1290	0.99	0.012	0.097
	Total Rutting	23-5-1	1290	0.98	0.019	0.140
	IRI	23-5-1	1290	0.97	1.07	0.164
CW	Alligator Cracking	23-5-1	1291	0.93	558	0.260
	Longitudinal Cracking	23-5-1	1291	0.94	0.83	0.251
	Thermal Cracking	27-5-1	1404	0.94	87.7	0.251
	AC Rutting	23-5-1	1291	0.99	0.010	0.095
	Total Rutting	23-5-1	1291	0.98	0.016	0.134
	IRI	23-5-1	1291	0.98	0.907	0.156
T	Alligator Cracking	23-5-1	1543	0.89	389	0.327
	Longitudinal Cracking	23-5-1	1543	0.93	0.43	0.258
	AC Rutting	23-5-1	1543	0.99	0.0053	0.091
	Total Rutting	23-5-1	1543	0.98	0.011	0.145
	IRI	23-5-1	1543	0.97	0.58	0.163
HD	Alligator Cracking	23-5-1	1449	0.93	440	0.261
	Longitudinal Cracking	23-5-1	1449	0.95	0.52	0.230
	AC Rutting	23-5-1	1449	0.99	0.013	0.102
	Total Rutting	23-5-1	1449	0.99	0.017	0.122
	IRI	23-5-1	1449	0.98	0.90	0.148
HW	Alligator Cracking	23-5-1	1272	0.88	556	0.342
	Longitudinal Cracking	23-5-1	1272	0.92	0.67	0.277
	AC Rutting	23-5-1	1272	0.99	0.0093	0.116
	Total Rutting	23-5-1	1272	0.98	0.014	0.148
	IRI	23-5-1	1272	0.97	0.78	0.170

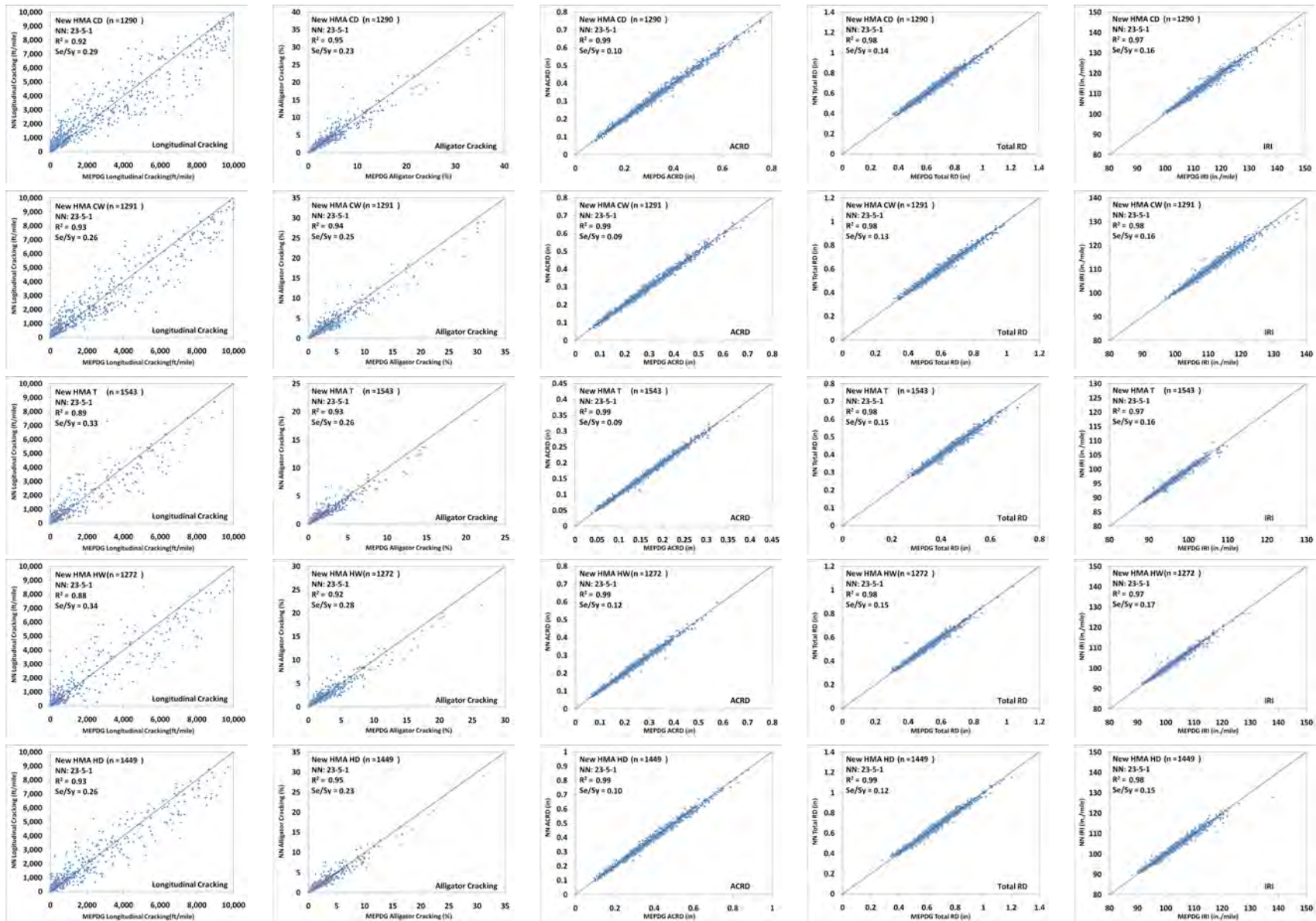


Figure 8.6. ANN predicted vs. MEDPG predicted distresses by climate zone – New HMA.

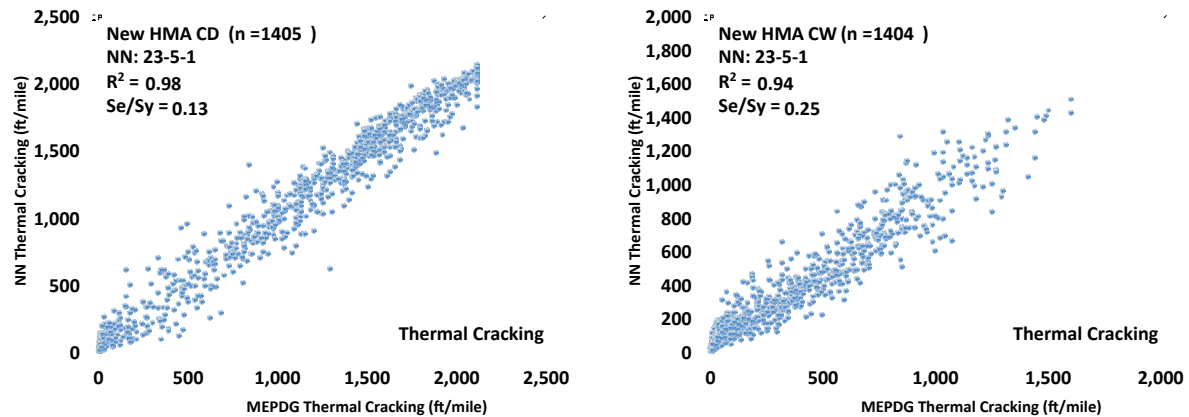


Figure 8.7. ANN predicted vs. MEDPG predicted distresses by climate zone – New HMA/Thermal Cracking.

8.4 Sensitivity Metrics

The average sensitivity indices from the MVL RSMs are summarized in Table 8.14 through Table 8.19. Recall that these average sensitivity indices quantify the percentage change in predicted distress relative to its design limit caused by a given percentage change in each design input relative to its mean value. The average sensitivities are just the regression coefficients from the normalized MVL RSMs, many of which had relatively poor goodness-of-fit statistics (Table 8.12). The values for the average sensitivity indices were all much smaller than the corresponding sensitivity indices computed in the OAT analyses, but this is because the OAT values represented the maximum across all of the base cases, not average values. The values in Table 8.14 through Table 8.19 are just very rough indicators of average sensitivities and do not account for variations in sensitivities across the problem domain.

Figure 8.8 and Figure 8.9 provide graphical summaries by distress and climate zone of the average sensitivities calculated using the MVL RSMs. The high-low-average plots in Figure 8.9 are additionally sorted by maximum average sensitivity (in an absolute value sense) to indicate more clearly the most important design inputs. The most sensitive inputs according to the MVL RSMs in rank order in terms of maximum absolute sensitivity across climate zones (sensitivity values equal to 0.50 or greater) by distress type were (Table 8.11 has definitions for those abbreviations):

- Longitudinal Cracking: Alpha, Delta, HMAThickness, PGHigh, BaseMr, SSA, Va, Vbeff, BasePR
- Alligator Cracking: Alpha, Delta
- Thermal Cracking: AggCoefContr, Alpha, Vbeff, HMAThickness
- AC Rutting: Alpha, Delta, Pratio, SSA, PGHigh, HMAThickness, AADTTperLane
- Total Rutting: Alpha, Delta, PGHigh, SSA, Pratio, HMAThickness
- IRI: Alpha, Delta

Most of these rankings are consistent with engineering judgment. However, there are a few surprises. Poisson's ratios for the HMA and/or base layers (Pratio and Base PR) have surprising high sensitivities for longitudinal cracking and rutting. Poisson's ratio is conventionally thought to have only a minor influence on pavement performance; the results here suggest that this conventional wisdom may need to be re-examined. Another surprise is that most of the low temperature HMA

properties are not on the thermal cracking list, although the creep compliance parameters D and m were slightly below the cut-off with maximum absolute sensitivities of 0.46 and 0.42, respectively.

Table 8.14. Average sensitivities from MVLR RSMs – New HMA/Longitudinal Cracking.

Design Input	Climate Zone				
	CD	CW	T	HD	HW
Constant	3.98	4.83	2.77	10.38	11.91
AADTTperLane	0.39	0.36	0.16	0.26	0.29
HMAThickness	-3.20	-2.82	-1.29	-2.19	-2.04
BaseThickness	-0.38	-0.31	-0.12	-0.23	-0.18
OpSpd	-0.31	-0.26	-0.09	-0.15	-0.15
PGHigh ¹	N.A.	N.A.	0.03	-0.08	-0.07
PGLow ¹	-0.11	-0.09	N.A.	N.A.	N.A.
GWD	0.03	0.01	0.01	0.02	0.00
SSA	1.31	1.21	0.54	0.55	0.81
UnitW	-0.11	-0.15	-0.05	-0.11	-0.24
Pratio	-0.47	-0.42	-0.15	-0.16	-0.21
ThmlCn	-0.05	-0.05	-0.03	-0.02	0.04
HtCp	-0.14	-0.12	0.07	-0.07	-0.04
Delta	-6.18	-5.18	-1.92	-3.11	-3.68
Alpha	-8.43	-7.11	-2.59	-3.93	-4.94
Vbeff	-0.88	-0.77	-0.26	-0.46	-0.45
Va	1.05	0.87	0.30	0.59	0.46
BaseMr	-1.33	-1.08	-0.34	-0.53	-0.60
BasePR	0.50	0.50	0.30	0.41	0.39
SubMr	0.03	-0.02	-0.10	-0.06	-0.20
SubPR	0.25	0.24	0.06	0.22	0.14
SubN200	-0.40	-0.32	-0.24	-0.20	-0.36
SubPI	0.01	0.01	0.01	0.00	0.01
SubLL	0.15	0.11	0.09	0.02	0.10

¹Sensitivity per one grade increase in binder stiffness.

Table 8.15. Average sensitivities from MVL RSMs – New HMA/Alligator Cracking.

Design Input	Climate Zone				
	CD	CW	T	HD	HW
Constant	1.50	1.31	1.05	1.48	1.88
AADTTperLane	0.08	0.07	0.03	0.04	0.05
HMAThickness	-0.43	-0.36	-0.20	-0.26	-0.28
BaseThickness	-0.04	-0.03	-0.02	-0.03	-0.02
OpSpd	-0.03	-0.02	-0.01	-0.02	-0.02
PGHigh ¹	N.A.	N.A.	-0.01	-0.01	-0.01
PGLow ¹	-0.02	-0.01	N.A.	N.A.	N.A.
GWD	-0.01	0.00	0.00	-0.01	0.00
SSA	0.18	0.15	0.07	0.07	0.09
UnitW	-0.04	-0.04	-0.01	-0.02	-0.02
Pratio	-0.08	-0.08	-0.03	-0.03	-0.06
ThmlCn	-0.01	-0.01	-0.01	0.00	0.00
HtCp	-0.02	-0.02	0.00	-0.01	-0.01
Delta	-0.77	-0.66	-0.34	-0.40	-0.54
Alpha	-1.14	-0.97	-0.46	-0.53	-0.73
Vbeff	-0.23	-0.20	-0.11	-0.14	-0.16
Va	0.19	0.16	0.10	0.12	0.13
BaseMr	-0.19	-0.14	-0.04	-0.06	-0.08
BasePR	0.08	0.07	0.02	0.03	0.05
SubMr	-0.16	-0.13	-0.05	-0.08	-0.09
SubPR	0.01	0.01	0.01	0.01	0.01
SubN200	-0.07	-0.05	-0.02	-0.03	-0.04
SubPI	0.00	0.00	0.00	0.00	0.00

¹Sensitivity per one grade increase in binder stiffness.

Table 8.16. Average sensitivities from MVL RSMs – New HMA/Thermal Cracking.

Design Input	Climate Zone	
	CD	CW
Constant	6.77	4.12
AADTTperLane	0.00	0.00
HMAThickness	-0.51	-0.21
BaseThickness	0.02	0.00
OpSpd	-0.04	-0.02
PGHigh ¹	0.00	0.00
PGLow ¹	0.46	0.04
GWD	0.04	0.00
SSA	0.07	-0.20
UnitW	-0.36	-0.38
Pratio	0.03	-0.04
ThmlCn	-0.11	-0.42
HtCp	-0.06	-0.04
Delta	-0.33	-0.42
Alpha	0.82	1.42
Vbeff	-0.78	-0.70
Va	0.09	0.06
BaseMr	0.49	0.66
BasePR	-0.08	-0.03
SubMr	0.04	-0.02
SubPR	-0.04	-0.01
SubN200	0.07	0.05
SubPI	-0.04	0.02
SubLL	0.00	0.00
TenStr14	0.02	-0.05
D	-0.40	-0.46
m	-0.33	-0.42
AggCoefContr	-2.25	-2.56

Table 8.17. Average sensitivities from MVL RSMs – New HMA/AC Rutting.

Design Input	Climate Zone				
	CD	CW	T	HD	HW
Constant	10.73	10.49	12.07	25.39	14.97
AADTTperLane	0.55	0.50	0.26	0.52	0.39
HMAThickness	-0.74	-0.66	-0.42	-0.73	-0.54
BaseThickness	0.08	0.07	0.04	0.10	0.05
OpSpd	-0.38	-0.34	-0.18	-0.42	-0.23
PGHigh ¹	N.A.	N.A.	-0.22	-0.28	-0.15
PGLow ¹	-0.12	-0.09	N.A.	N.A.	N.A.
GWD	0.01	0.01	0.00	0.01	0.00
SSA	1.87	1.84	0.97	1.58	0.94
UnitW	-0.27	-0.25	-0.14	-0.26	-0.16
Pratio	-1.56	-1.47	-1.00	-1.90	-1.27
ThmlCn	0.01	-0.06	-0.03	-0.01	-0.01
HtCp	-0.31	-0.31	-0.15	-0.35	-0.20
Delta	-7.99	-7.34	-4.53	-9.47	-5.67
Alpha	-7.96	-7.59	-5.07	-10.14	-6.22
Vbeff	0.13	0.11	0.04	0.06	0.06
Va	0.02	0.01	-0.02	-0.01	-0.01
BaseMr	0.03	0.05	0.03	-0.05	0.04
BasePR	0.05	0.06	-0.02	0.02	0.05
SubMr	-0.15	-0.11	0.00	-0.07	-0.05
SubPR	0.09	0.06	0.04	0.05	0.06
SubN200	-0.07	-0.06	-0.03	-0.07	-0.06
SubPI	0.00	0.00	0.00	0.00	0.00
SubLL	-0.09	-0.08	-0.02	-0.06	-0.03

¹Sensitivity per one grade increase in binder stiffness.

Table 8.18. Average sensitivities from MLVR RSMs – New HMA/Total Rutting.

Design Input	Climate Zone				
	CD	CW	T	HD	HW
Constant	1.38	1.59	5.33	9.61	6.40
AADTTperLane	0.24	0.21	0.13	0.21	0.17
HMAThickness	-0.52	-0.46	-0.36	-0.45	-0.40
BaseThickness	0.02	0.01	0.00	0.02	0.01
OpSpd	-0.16	-0.14	-0.08	-0.16	-0.10
PGHigh ¹	N.A.	N.A.	-0.09	-0.10	-0.06
PGLow ¹	-0.05	-0.04	N.A.	N.A.	N.A.
GWD	0.00	0.00	-0.01	-0.01	0.00
SSA	0.71	0.70	0.39	0.57	0.36
UnitW	-0.08	-0.07	-0.05	-0.09	-0.04
Pratio	-0.56	-0.53	-0.36	-0.65	-0.46
ThmlCn	-0.01	-0.03	-0.02	-0.01	-0.01
HtCp	-0.11	-0.11	-0.05	-0.12	-0.06
Delta	-3.24	-2.98	-1.95	-3.55	-2.39
Alpha	-3.40	-3.22	-2.27	-3.91	-2.68
Vbeff	0.05	0.04	0.02	0.02	0.02
Va	0.01	0.00	-0.01	0.00	0.00
BaseMr	-0.08	-0.05	0.00	0.01	-0.02
BasePR	0.02	0.02	0.00	0.01	0.02
SubMr	-0.24	-0.24	-0.18	-0.20	-0.20
SubPR	0.02	0.03	0.03	0.03	0.04
SubN200	-0.08	-0.06	-0.04	-0.05	-0.05
SubPI	0.00	0.00	0.00	0.00	0.00
SubLL	-0.02	-0.03	0.00	-0.01	0.00

¹Sensitivity per one grade increase in binder stiffness.

Table 8.19. Average sensitivities from MVLR RSMs – New HMA/IRI.

Design Input	Climate Zone				
	CD	CW	T	HD	HW
Constant	-0.97	-0.92	1.54	2.75	1.90
AADTTperLane	0.08	0.07	0.04	0.06	0.05
HMAThickness	-0.20	-0.18	-0.13	-0.16	-0.15
BaseThickness	0.00	0.00	0.00	0.00	0.00
OpSpd	-0.05	-0.04	-0.02	-0.05	-0.03
PGHigh ¹	N.A.	N.A.	-0.03	-0.03	-0.02
PGLow ¹	-0.01	-0.01	N.A.	N.A.	N.A.
GWD	0.00	0.00	0.00	0.00	0.00
SSA	0.22	0.21	0.11	0.17	0.11
UnitW	-0.03	-0.03	-0.02	-0.03	-0.01
Pratio	-0.17	-0.16	-0.10	-0.18	-0.13
ThmlCn	0.00	-0.01	-0.01	0.00	0.00
HtCp	-0.03	-0.03	-0.01	-0.03	-0.02
Delta	-0.99	-0.90	-0.58	-1.03	-0.73
Alpha	-1.08	-1.00	-0.68	-1.14	-0.83
Vbeff	-0.02	-0.01	-0.01	-0.01	-0.02
Va	0.03	0.02	0.01	0.01	0.01
BaseMr	-0.05	-0.03	0.00	0.00	-0.02
BasePR	0.02	0.02	0.00	0.01	0.01
SubMr	-0.11	-0.10	-0.08	-0.09	-0.09
SubPR	0.01	0.01	0.01	0.01	0.01
SubN200	-0.02	-0.02	-0.01	-0.01	-0.01
SubPI	0.00	0.00	0.00	0.00	0.00
SubLL	0.00	-0.01	0.00	0.00	0.00

¹Sensitivity per one grade increase in binder stiffness.

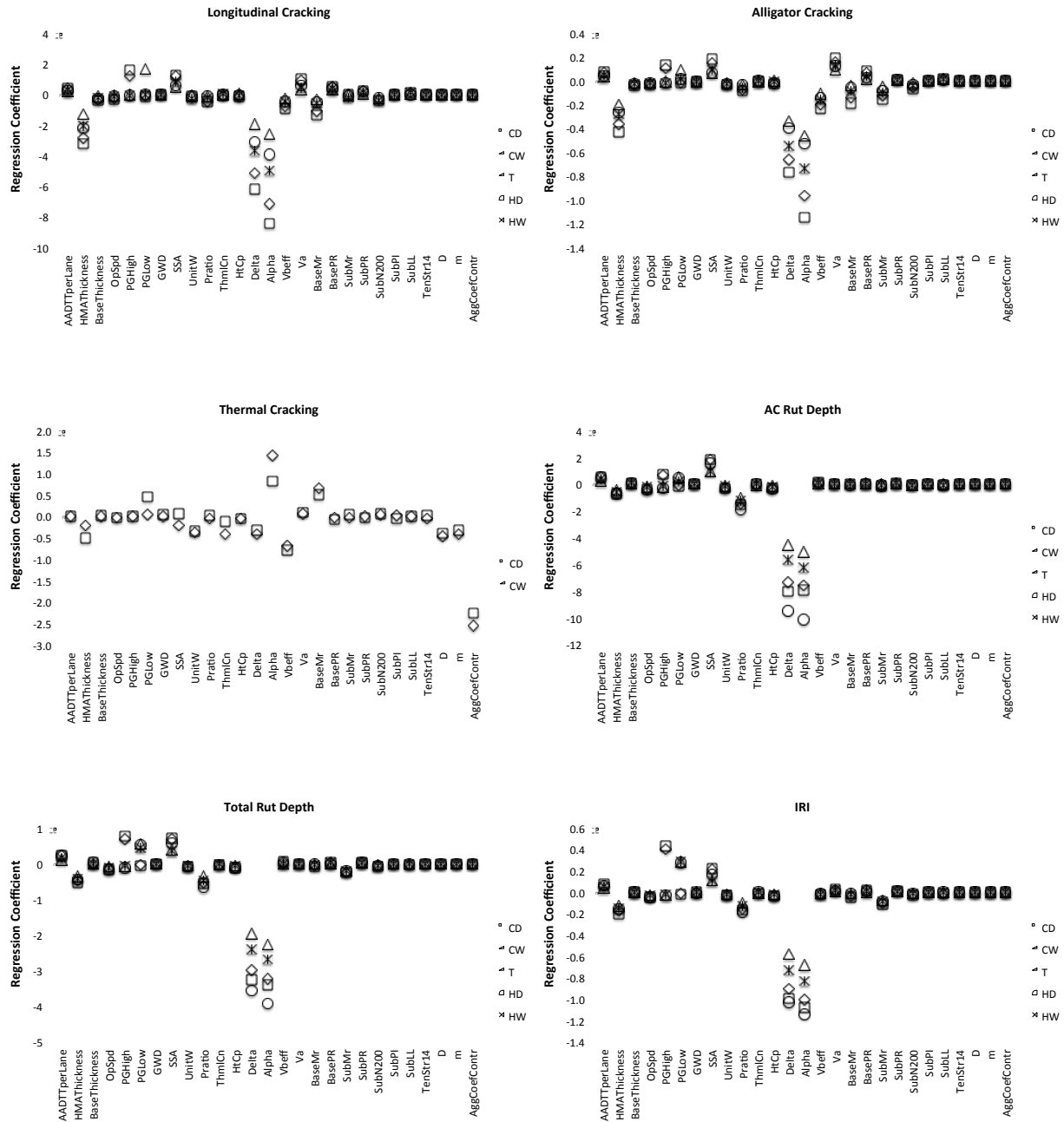


Figure 8.8. Average sensitivities from MVLR RSMs – New HMA.

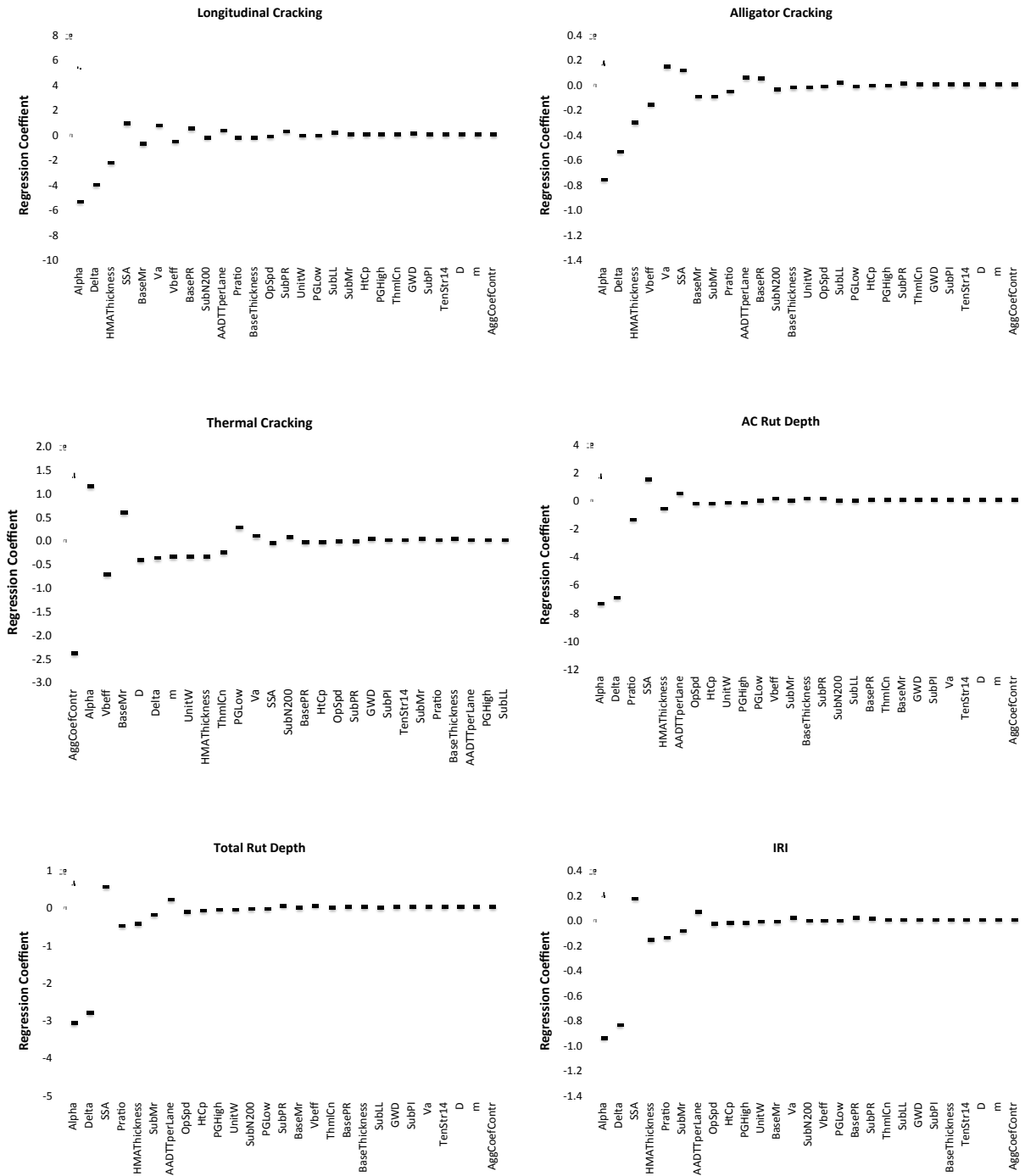


Figure 8.9. Ranking of average sensitivities from MVL RSMs – New HMA.

The ANN RSMs permit a more in-depth evaluation of sensitivities than does the MVLR approach. Ten thousand ANN RSM evaluations were performed for each climate zone and distress combination using random sampling of all design inputs across the problem domain. The random sampling for these simulations was not by traffic level but rather spanned the full range of AADTT, HMA thickness, and base thickness values. Some of the random samples inevitably gave unrealistic pavement sections that produced excessively large predicted distresses—e.g., very high AADTT values combined with thin HMA and base layers. Consequently, any simulation for which any predicted distress exceeded three times its design limit was censored from the database. In general, fewer than 20% of the simulations for each climate zone-distress combination were censored.

Normalized sensitivity index (NSI) values were calculated using Eq. 3.19 or Eq. 3.20 for each of the 10,000 simulations for each climate zone-distress combination. The mean and standard deviations of the NSI values are summarized by climate zone in Table 8.20 through Table 8.25 for each respective distress. Full frequency distributions of the computed NSI values by design input and climate zone are depicted in Figure 8.10 through Figure 8.15 for each distress. An important feature to note in the frequency distributions is that most have well-defined peaks: This implies that the NSI values are close to the mode at nearly all locations in the problem domain—i.e., NSI does not vary significantly over the problem domain. There are some exceptions where the NSI distributions are broader, but in these instances all of the NSI values are either very low and not of interest or all very high and thus always of interest regardless of value. In no cases are there multiple peaks in the distributions. The influence of climate zone on the frequency distributions is also negligible in most cases. Where there are climate zone differences, they are nonsystematic and insignificant.

Table 8.20. NSI statistics from ANN RSMs – New HMA/Longitudinal Cracking.

Design Input	Climate Zone									
	CD		CW		T		HD		HW	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
AADTTperLane	0.53	0.69	0.43	0.59	0.78	1.50	0.63	1.05	0.76	1.48
HMAThickness	-3.06	3.58	-2.84	3.54	-2.27	3.81	-2.55	3.85	-2.34	3.99
BaseThickness	-0.52	0.88	-0.39	0.68	-0.36	0.78	-0.51	0.95	-0.38	0.79
OpSpd	-0.31	0.43	-0.31	0.46	-0.22	0.39	-0.30	0.48	-0.23	0.40
PGHigh	0.00	0.00	0.00	0.00	-0.14	0.21	-0.15	0.22	-0.13	0.22
PGLow	0.15	0.21	0.11	0.15	0.00	0.00	0.00	0.00	0.00	0.00
GWD	0.05	0.08	0.00	0.03	-0.02	0.05	0.02	0.05	-0.02	0.05
SSA	1.14	1.59	1.10	1.58	0.71	1.21	0.80	1.30	0.62	1.10
UnitW	-0.18	0.35	0.18	0.33	-0.15	0.24	-0.01	0.28	-0.04	0.19
Pratio	-0.47	0.62	-0.66	0.86	-0.17	0.24	-0.36	0.51	-0.25	0.37
ThmlCn	-0.09	0.14	-0.13	0.20	-0.05	0.08	-0.11	0.15	0.01	0.06
HtCp	-0.19	0.28	-0.16	0.28	-0.01	0.06	-0.07	0.15	-0.04	0.05
Delta	-6.42	8.25	-5.43	7.42	-4.13	7.11	-5.84	9.01	-4.15	7.07
Alpha	-8.56	10.48	-7.17	9.09	-6.45	10.10	-6.46	9.65	-5.55	9.61
Vbeff	-1.01	1.16	-0.99	1.27	-0.72	1.31	-0.95	1.47	-0.74	1.37
Va	1.20	1.63	1.17	1.64	0.79	1.33	1.11	1.85	0.71	1.20
BaseMr	-1.31	1.71	-1.20	1.67	-0.55	0.92	-0.74	1.09	-0.57	1.06
BasePR	0.01	0.23	0.15	0.28	0.16	0.39	0.16	0.30	0.15	0.38
SubMr	0.45	0.62	0.47	0.74	-0.26	0.64	0.29	0.64	-0.43	0.82
SubPR	0.01	0.22	0.07	0.29	-0.07	0.21	0.30	0.53	0.07	0.11
SubN200	-0.16	0.31	-0.05	0.24	-0.25	0.51	-0.04	0.18	-0.36	0.68
SubPI	0.02	0.03	-0.01	0.04	0.00	0.02	-0.03	0.06	0.02	0.04
SubLL	0.09	0.24	0.06	0.16	-0.08	0.19	-0.01	0.10	-0.14	0.27

Table 8.21. NSI statistics from ANN RSMs – New HMA/Alligator Cracking.

Design Input	Climate Zone									
	CD		CW		T		HD		HW	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
AADTTperLane	0.74	1.60	0.57	1.19	0.42	0.95	0.59	1.39	0.52	1.09
HMAThickness	-1.67	2.90	-1.32	2.29	-0.90	1.72	-1.18	2.39	-1.13	1.98
BaseThickness	-0.15	0.31	-0.11	0.23	-0.10	0.22	-0.18	0.42	-0.10	0.21
OpSpd	-0.17	0.33	-0.11	0.21	-0.07	0.15	-0.11	0.23	-0.11	0.22
PGHigh	0.00	0.00	0.00	0.00	-0.06	0.12	-0.09	0.19	-0.08	0.14
PGLow	0.02	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
GWD	-0.02	0.04	-0.01	0.03	-0.02	0.05	-0.03	0.06	-0.01	0.03
SSA	0.31	0.48	0.31	0.51	0.18	0.32	0.21	0.39	0.13	0.20
UnitW	0.17	0.40	0.09	0.20	0.03	0.10	0.09	0.23	0.08	0.18
Pratio	-0.14	0.26	-0.21	0.40	-0.13	0.26	-0.17	0.36	-0.17	0.31
ThmlCn	-0.02	0.05	-0.05	0.12	-0.05	0.12	-0.07	0.16	-0.07	0.15
HtCp	-0.04	0.08	-0.05	0.09	-0.05	0.13	-0.10	0.22	-0.02	0.05
Delta	-2.88	5.15	-2.17	3.84	-1.64	3.14	-1.91	3.82	-2.01	3.65
Alpha	-3.48	6.23	-2.60	4.55	-2.00	3.80	-2.70	5.29	-1.95	3.22
Vbeff	-0.65	1.14	-0.53	0.91	-0.35	0.65	-0.51	0.95	-0.46	0.79
Va	0.74	1.33	0.56	0.97	0.41	0.76	0.62	1.22	0.47	0.80
BaseMr	-0.58	1.07	-0.44	0.80	-0.17	0.35	-0.22	0.43	-0.27	0.50
BasePR	0.17	0.37	0.16	0.31	0.14	0.31	0.12	0.28	0.12	0.24
SubMr	-0.65	1.38	-0.41	0.83	-0.33	0.72	-0.47	1.10	-0.26	0.54
SubPR	-0.07	0.26	-0.02	0.12	-0.01	0.05	0.03	0.07	-0.09	0.20
SubN200	-0.12	0.28	-0.07	0.15	-0.05	0.12	-0.04	0.15	-0.01	0.06
SubPI	0.02	0.05	0.01	0.03	0.01	0.02	0.01	0.03	0.01	0.03
SubLL	-0.09	0.23	-0.05	0.12	-0.06	0.16	-0.13	0.33	-0.03	0.09

Table 8.22. NSI statistics from ANN RSMs – New HMA/Thermal Cracking.

Design Input	Climate Zone			
	CD		CW	
	Mean	Std Dev	Mean	Std Dev
AADTTperLane	0.00	0.01	0.00	0.01
HMAThickness	-0.29	0.28	-0.07	0.14
BaseThickness	0.00	0.01	0.00	0.01
OpSpd	-0.01	0.02	0.00	0.01
PGHigh	0.00	0.00	0.00	0.00
PGLow	-0.26	0.24	-0.01	0.03
GWD	0.02	0.03	0.00	0.01
SSA	-0.05	0.08	-0.02	0.07
UnitW	-0.26	0.25	-0.15	0.21
Pratio	0.04	0.09	0.00	0.05
ThmlCn	-0.14	0.17	-0.16	0.25
HtCp	-0.26	0.25	-0.16	0.26
Delta	0.76	0.82	0.07	0.40
Alpha	-0.13	0.19	-0.06	0.26
Vbeff	-0.01	0.04	-0.04	0.06
Va	0.43	0.45	0.30	0.46
BaseMr	-0.05	0.06	-0.02	0.03
BasePR	0.04	0.07	0.02	0.06
SubMr	0.01	0.07	0.01	0.04
SubPR	0.04	0.06	0.03	0.06
SubN200	0.00	0.03	0.01	0.04
SubPI	0.00	0.01	0.01	0.01
SubLL	0.00	0.03	-0.01	0.04
TenStr14	-0.47	0.56	-0.24	0.38
D	-0.32	0.36	-0.20	0.32
m	-1.63	1.61	-1.01	1.58
AggCoefContr	-0.01	0.03	-0.01	0.02

Table 8.23. NSI statistics from ANN RSMs – New HMA/AC Rutting.

Design Input	Climate Zone									
	CD		CW		T		HD		HW	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
AADTTperLane	0.88	0.50	0.80	0.47	0.43	0.24	0.98	0.55	0.57	0.30
HMAThickness	-1.86	0.91	-1.68	0.84	-0.90	0.44	-2.09	1.06	-1.20	0.57
BaseThickness	0.09	0.07	0.08	0.05	0.05	0.04	0.12	0.09	0.06	0.04
OpSpd	-0.48	0.24	-0.43	0.21	-0.21	0.11	-0.53	0.26	-0.28	0.14
PGHigh	0.00	0.00	0.00	0.00	-0.16	0.07	-0.36	0.15	-0.19	0.08
PGLow	0.13	0.06	0.11	0.05	0.00	0.00	0.00	0.00	0.00	0.00
GWD	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.00
SSA	2.43	1.11	2.44	1.09	1.19	0.56	2.06	0.90	1.21	0.56
UnitW	-0.45	0.22	-0.42	0.22	-0.19	0.09	-0.43	0.22	-0.24	0.12
Pratio	-1.85	0.80	-1.73	0.77	-1.12	0.51	-2.30	1.01	-1.50	0.66
ThmlCn	0.10	0.05	-0.01	0.01	0.00	0.01	0.04	0.02	0.03	0.02
HtCp	-0.40	0.19	-0.38	0.19	-0.20	0.10	-0.42	0.19	-0.24	0.12
Delta	-11.13	4.81	-10.20	4.47	-5.92	2.71	-13.11	5.66	-7.82	3.44
Alpha	-10.24	4.41	-9.80	4.40	-6.24	2.84	-13.13	5.64	-7.99	3.60
Vbeff	0.01	0.02	0.03	0.03	0.01	0.02	0.03	0.03	0.02	0.02
Va	-0.01	0.02	0.00	0.02	-0.01	0.01	0.01	0.01	-0.01	0.02
BaseMr	0.06	0.04	0.08	0.05	0.03	0.02	-0.04	0.02	0.06	0.04
BasePR	-0.04	0.06	-0.02	0.03	0.00	0.02	-0.06	0.06	-0.03	0.04
SubMr	0.00	0.04	0.05	0.05	0.04	0.04	0.03	0.07	0.03	0.03
SubPR	0.02	0.03	0.02	0.03	0.01	0.02	0.03	0.03	0.03	0.03
SubN200	-0.02	0.02	-0.01	0.02	-0.01	0.02	-0.03	0.03	-0.02	0.02
SubPI	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00
SubLL	-0.04	0.03	-0.03	0.02	-0.01	0.01	-0.04	0.02	-0.01	0.02

Table 8.24. NSI statistics from ANN RSMs – New HMA/Total Rutting.

Design Input	Climate Zone									
	CD		CW		T		HD		HW	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
AADTTperLane	0.34	0.16	0.32	0.15	0.19	0.09	0.37	0.18	0.23	0.10
HMAThickness	-0.90	0.31	-0.81	0.30	-0.50	0.14	-0.90	0.34	-0.62	0.20
BaseThickness	0.02	0.01	0.02	0.01	0.00	0.01	0.02	0.02	0.01	0.01
OpSpd	-0.19	0.09	-0.17	0.09	-0.09	0.04	-0.20	0.10	-0.11	0.05
PGHigh	0.00	0.00	0.00	0.00	-0.07	0.02	-0.13	0.06	-0.07	0.03
PGLow	0.05	0.02	0.04	0.02	0.00	0.00	0.00	0.00	0.00	0.00
GWD	0.00	0.00	0.00	0.00	-0.01	0.00	-0.01	0.01	0.00	0.00
SSA	0.89	0.39	0.92	0.42	0.46	0.20	0.75	0.35	0.43	0.19
UnitW	-0.13	0.06	-0.12	0.06	-0.07	0.03	-0.15	0.08	-0.06	0.03
Pratio	-0.64	0.27	-0.61	0.27	-0.40	0.16	-0.77	0.34	-0.52	0.19
ThmlCn	0.02	0.01	-0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01
HtCp	-0.14	0.06	-0.14	0.07	-0.07	0.03	-0.14	0.07	-0.08	0.04
Delta	-4.33	1.76	-4.08	1.78	-2.44	0.91	-4.83	2.08	-3.07	1.10
Alpha	-4.08	1.61	-3.92	1.67	-2.63	1.00	-4.86	2.06	-3.23	1.23
Vbeff	0.02	0.02	0.02	0.02	0.01	0.02	0.01	0.01	0.00	0.02
Va	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.01
BaseMr	-0.08	0.03	-0.05	0.02	-0.01	0.01	0.00	0.00	-0.03	0.02
BasePR	0.00	0.02	-0.01	0.02	0.01	0.01	0.00	0.01	0.00	0.02
SubMr	-0.17	0.05	-0.16	0.05	-0.15	0.05	-0.15	0.05	-0.16	0.06
SubPR	0.01	0.02	0.02	0.02	0.00	0.01	0.01	0.01	0.01	0.03
SubN200	-0.05	0.03	-0.04	0.02	-0.02	0.01	-0.03	0.02	-0.04	0.02
SubPI	0.01	0.00	0.01	0.00	0.00	0.00	0.01	0.01	0.01	0.00
SubLL	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02

Table 8.25. NSI statistics from ANN RSMs – New HMA/IRI.

Design Input	Climate Zone									
	CD		CW		T		HD		HW	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
AADTTperLane	0.16	0.18	0.15	0.17	0.10	0.14	0.13	0.10	0.13	0.18
HMAThickness	-0.44	0.34	-0.39	0.31	-0.26	0.24	-0.33	0.16	-0.35	0.35
BaseThickness	-0.01	0.02	-0.01	0.02	-0.01	0.03	-0.01	0.02	-0.01	0.04
OpSpd	-0.06	0.04	-0.06	0.04	-0.03	0.02	-0.06	0.04	-0.04	0.04
PGHigh	0.00	0.00	0.00	0.00	-0.02	0.01	-0.04	0.02	-0.03	0.03
PGLow	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GWD	0.00	0.01	0.00	0.01	0.00	0.01	-0.01	0.01	0.00	0.00
SSA	0.30	0.18	0.30	0.18	0.15	0.08	0.23	0.12	0.15	0.10
UnitW	-0.04	0.02	-0.03	0.02	-0.01	0.02	-0.04	0.02	-0.02	0.01
Pratio	-0.19	0.07	-0.16	0.06	-0.11	0.03	-0.22	0.10	-0.15	0.05
ThmlCn	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.01
HtCp	-0.05	0.05	-0.05	0.04	-0.03	0.02	-0.05	0.04	-0.03	0.04
Delta	-1.37	0.68	-1.26	0.68	-0.81	0.45	-1.44	0.68	-1.09	0.72
Alpha	-1.51	1.03	-1.43	1.05	-0.99	0.75	-1.57	0.89	-1.21	0.88
Vbeff	-0.06	0.09	-0.05	0.09	-0.03	0.06	-0.03	0.04	-0.05	0.08
Va	0.07	0.11	0.06	0.09	0.05	0.09	0.03	0.05	0.06	0.11
BaseMr	-0.09	0.13	-0.07	0.11	-0.02	0.04	-0.01	0.02	-0.05	0.10
BasePR	0.01	0.03	0.01	0.02	0.01	0.02	0.01	0.03	0.01	0.04
SubMr	-0.13	0.14	-0.12	0.13	-0.11	0.12	-0.08	0.07	-0.12	0.16
SubPR	0.01	0.02	0.01	0.02	0.00	0.00	0.01	0.00	0.00	0.01
SubN200	-0.02	0.04	-0.02	0.05	-0.01	0.04	-0.01	0.02	-0.02	0.05
SubPI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SubLL	0.00	0.01	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.01

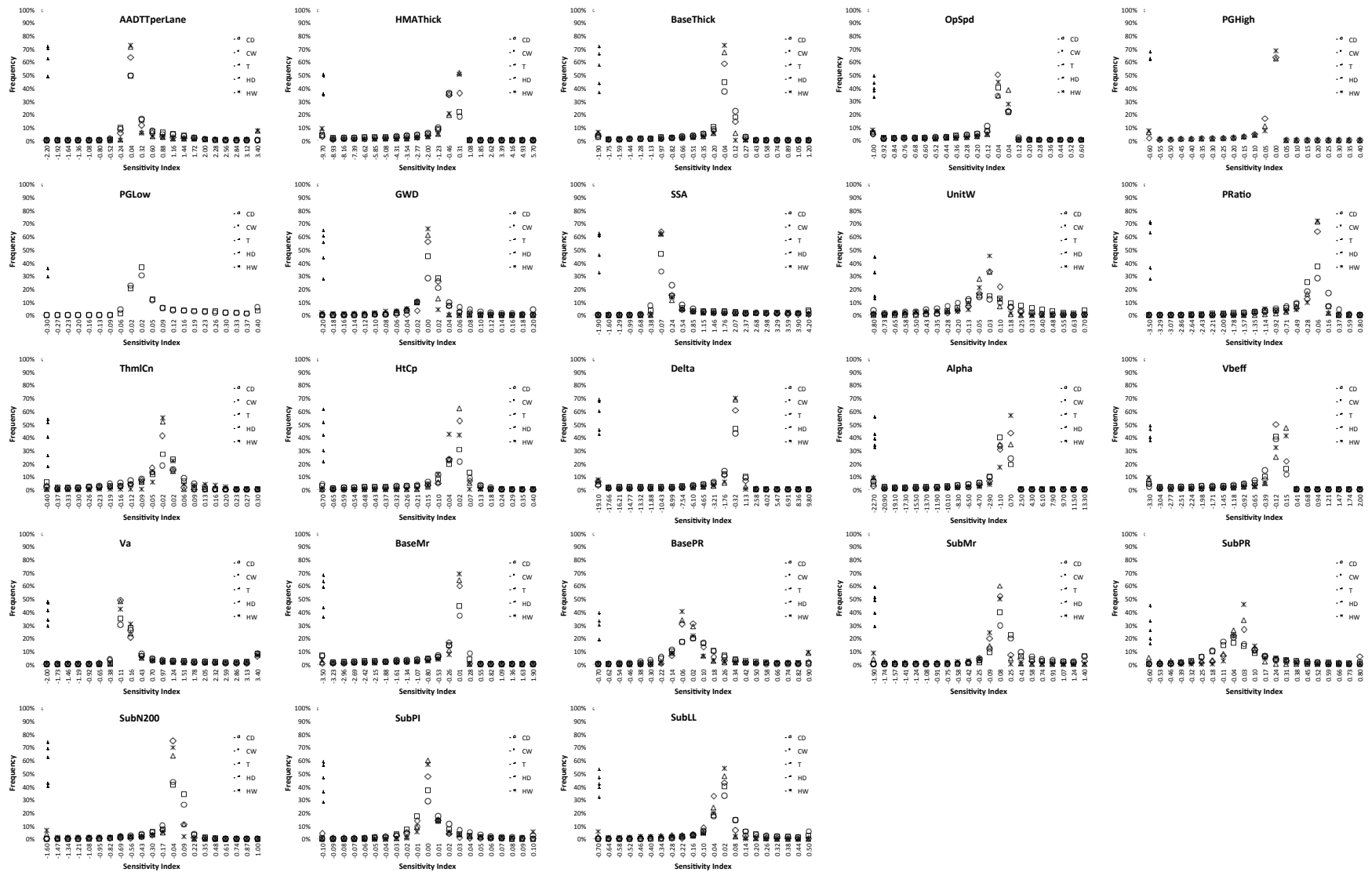


Figure 8.10. Distributions of NSI values – New HMA/Longitudinal Cracking.

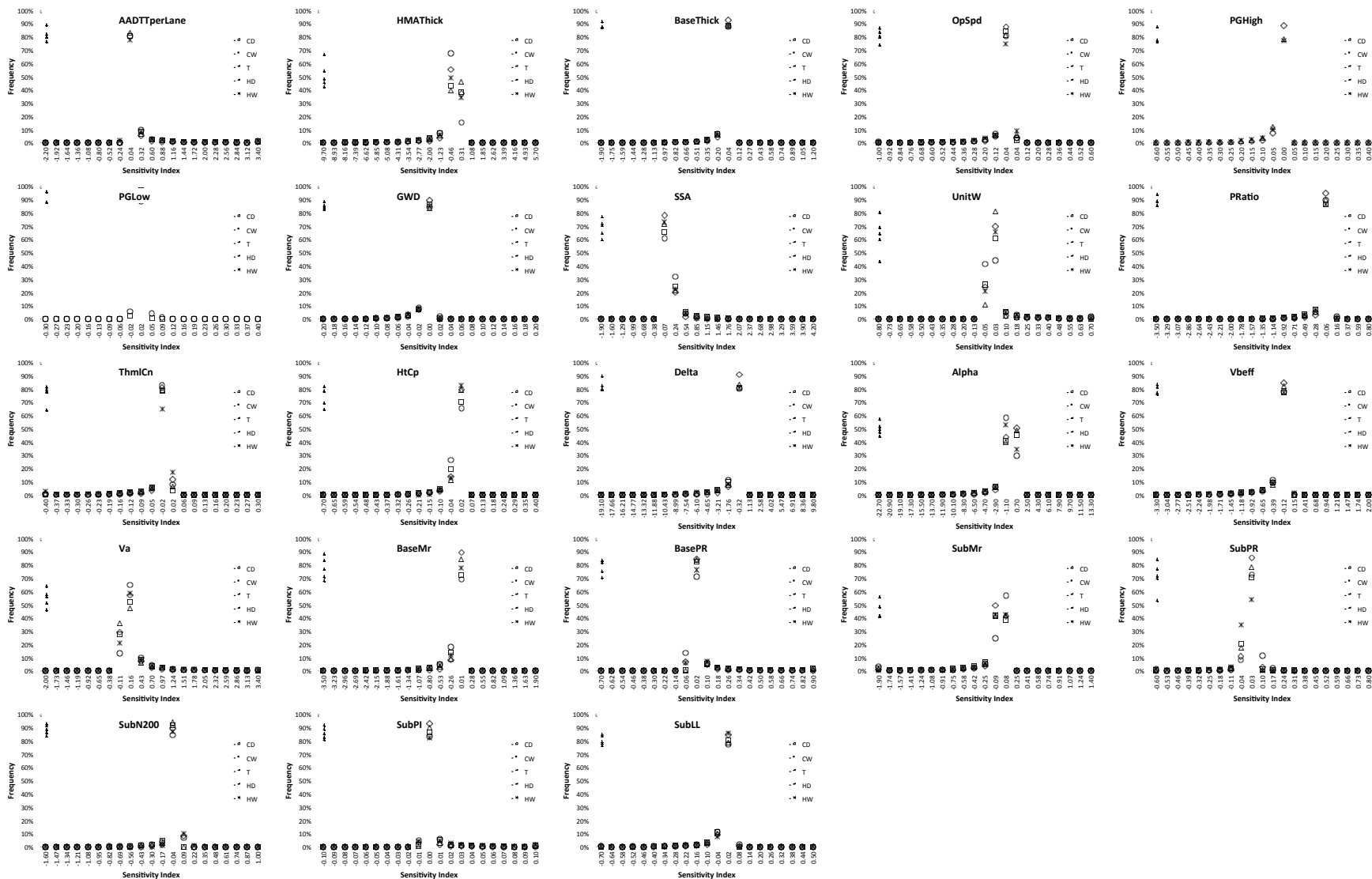


Figure 8.11. Distributions of NSI values – New HMA/Alligator Cracking.

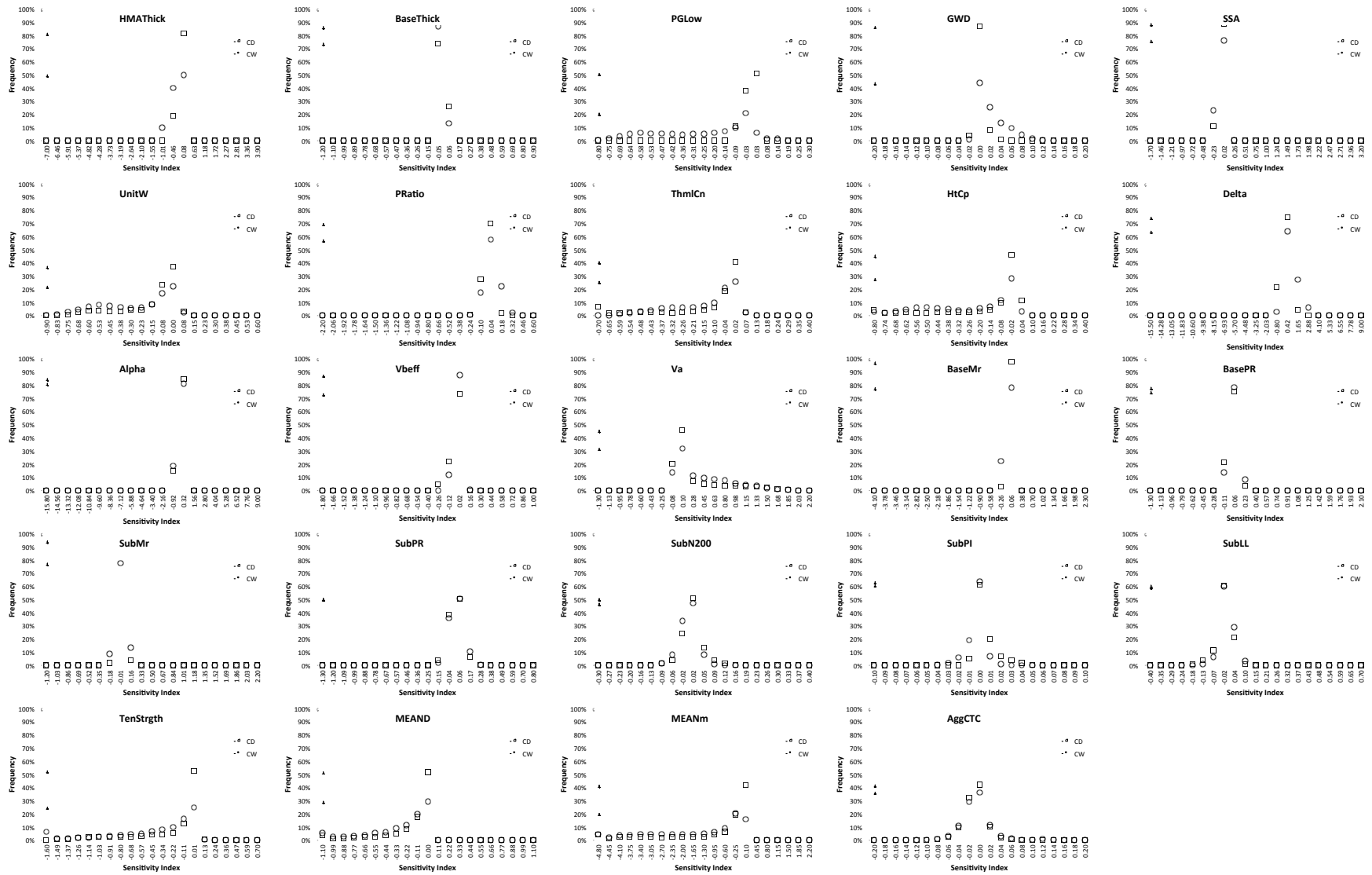


Figure 8.12. Distributions of NSI values – New HMA/Thermal Cracking.

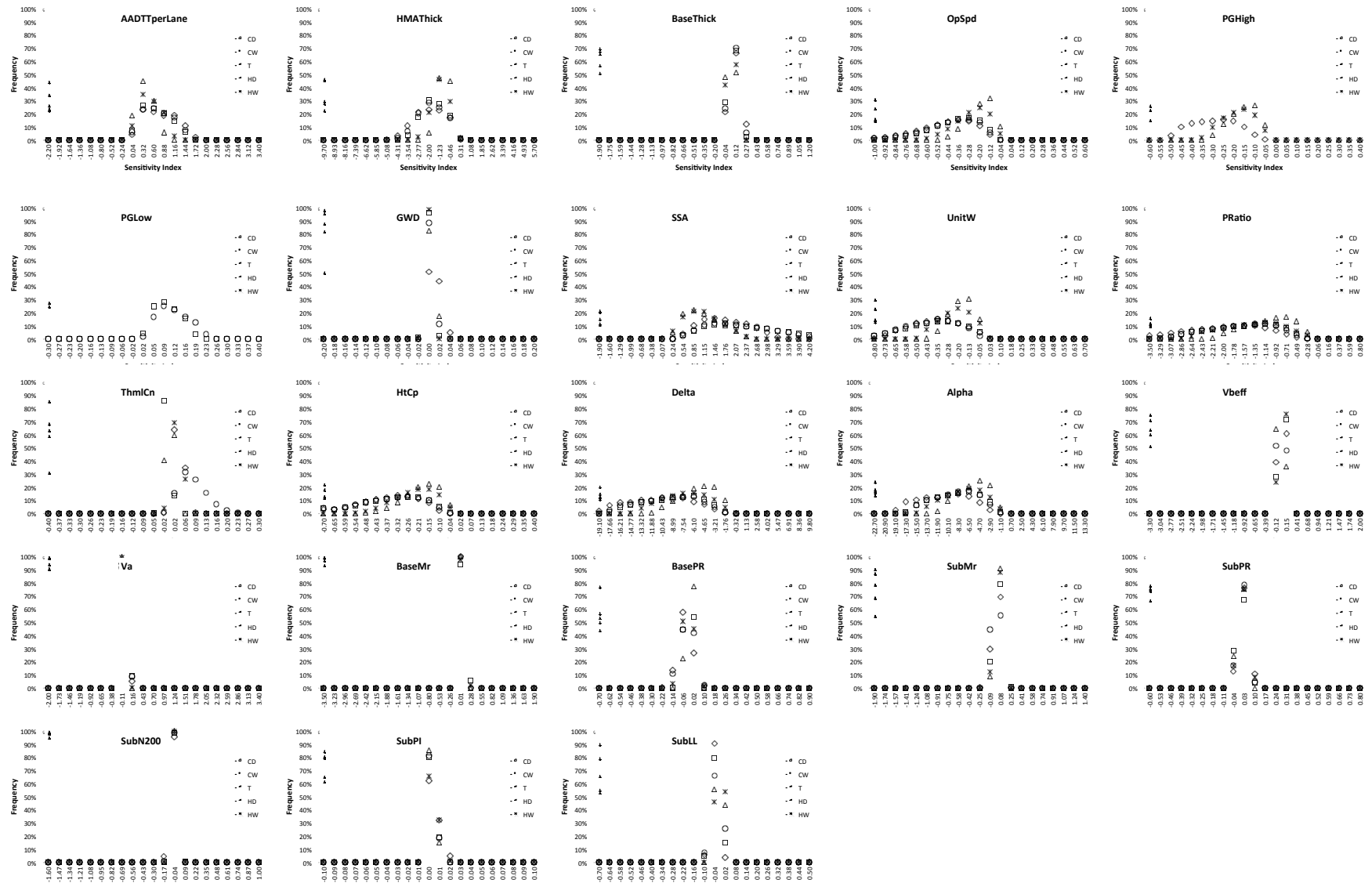


Figure 8.13. Distributions of NSI values – New HMA/AC Rutting.

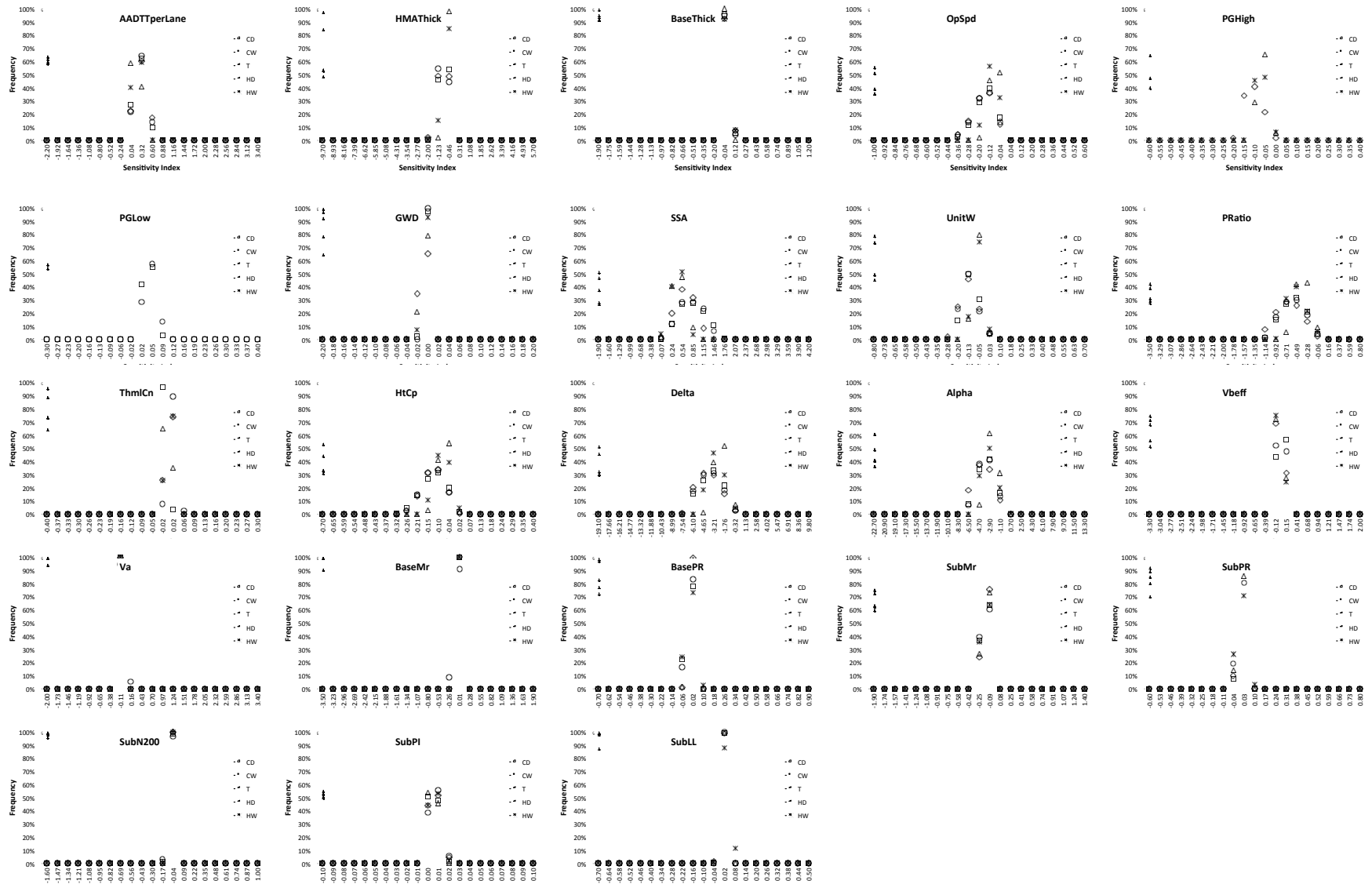


Figure 8.14. Distributions of NSI values – New HMA/Total Rutting.

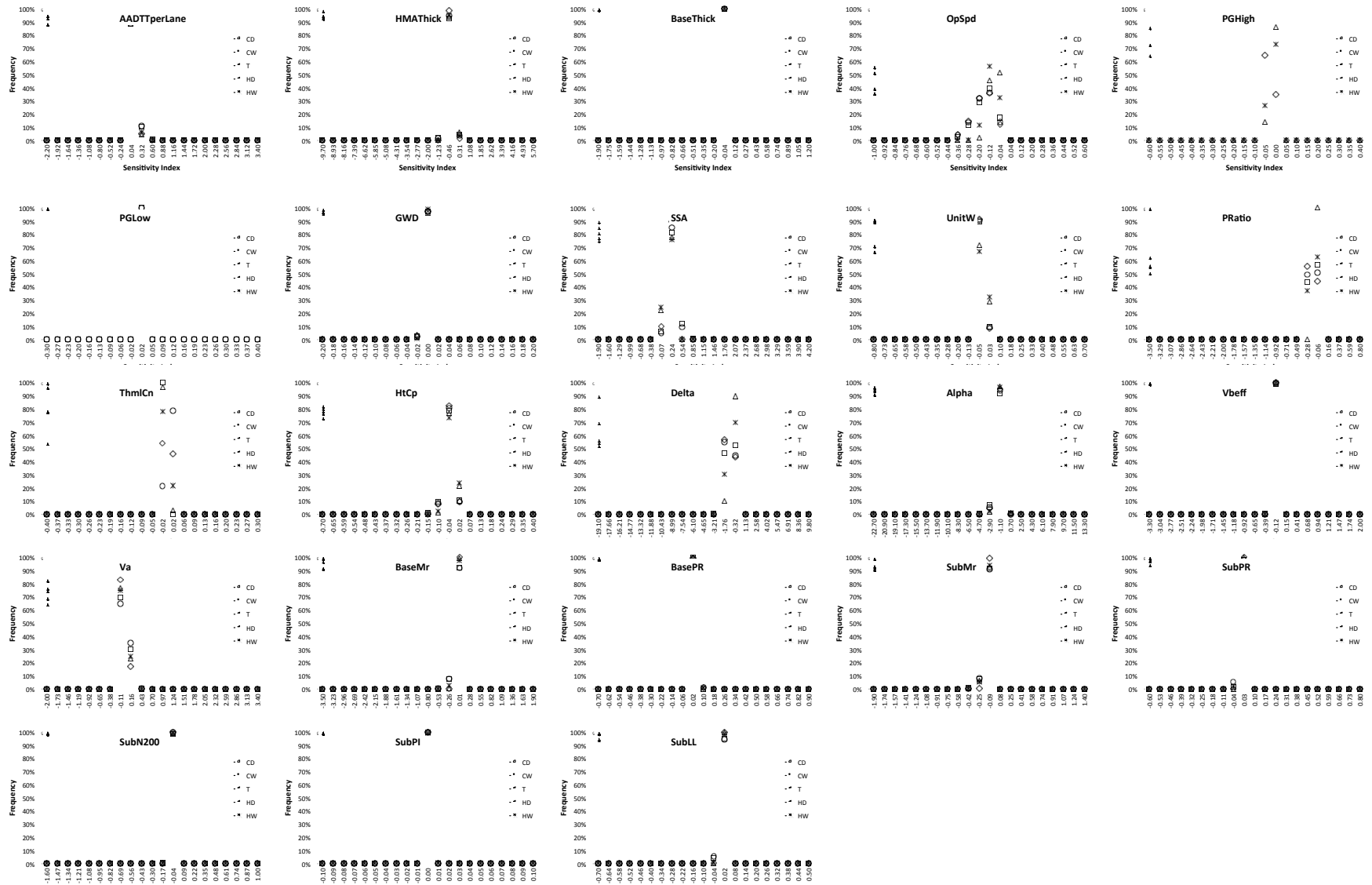


Figure 8.15. Distributions of NSI values – New HMA/IRI.

8.5 Conclusions – New HMA

The maximum average sensitivity coefficients from the MVLR RSMs across climate zones for all distress and design input combinations are ranked in Table 8.26 in terms of the maximum absolute sensitivity across distresses. The plus and minus signs are retained for each individual sensitivity coefficient to indicate whether distress increases (+) or decreases (-) with increasing input value. Usually—and especially for the highest sensitivity inputs—the plus/minus signs for each design input are consistent across all distresses.

The OAT local sensitivity category (Appendix B) for each design input is also indicated in Table 8.26. There was a lack of full congruence between the ranking of inputs from the MVLR RSMs and the categorization from the OAT analyses. The three design inputs categorized as HS in the OAT analyses are also the highest-ranked design inputs in Table 8.26, and most of the inputs categorized as VS in the OAT analyses also appear high in the ranked list. However, there is some mixing of the VS and S inputs in the middle and lower portion of the rankings. Recall, however, that the goodness-of-fit statistics for many of the MVLR RSMs were quite low and that the computed sensitivity coefficients are averages across the problem domain and not maximum values as in the OAT analyses.

Table 8.26. Ranking of New HMA design inputs by maximum |Average Sensitivity Coefficient| (MVLR RSMs).

Design Input	Maximum Average Sensitivity Coefficient (MVLR RSM)							OAT Category ¹
	Long Crk	AllCrk	ThermCrk	ACRD	TotRD	IRI	Maximum	
Alpha	-8.43	-1.14	0.82	-10.14	-3.91	-1.14	-10.14	HS
Delta	-6.18	-0.77	-0.42	-9.47	-3.55	-1.03	-9.47	HS
HMAThickness	-3.20	-0.43	-0.51	-0.74	-0.52	-0.20	-3.20	HS
AggCoefContr	N.A.	N.A.	-2.56	N.A.	N.A.	N.A.	-2.56	NS
Pratio	-0.47	-0.08	-0.04	-1.90	-0.65	-0.18	-1.90	VS
SSA	1.31	0.18	-0.20	1.87	0.71	0.22	1.87	VS
PGHigh	1.62	0.13	0.00	0.75	0.76	0.43	1.62	S
BaseMr	-1.33	-0.19	0.49	-0.05	-0.08	-0.05	-1.33	VS
Va	1.05	0.19	0.09	0.02	0.01	0.03	1.05	VS
Vbeff	-0.88	-0.23	-0.78	0.13	0.05	-0.02	-0.88	VS
AADTTperLane	0.39	0.08	0.00	0.55	0.24	0.08	0.55	VS
BasePR	0.50	0.08	-0.08	0.05	0.02	0.02	0.50	S
PGLow	-0.11	0.02	0.46	0.26	0.45	0.29	0.46	S
D	N.A.	N.A.	-0.46	N.A.	N.A.	N.A.	-0.46	S
OpSpd	-0.31	-0.03	-0.04	-0.42	-0.16	-0.05	-0.42	S
ThmlCn	-0.05	-0.01	-0.42	-0.06	-0.03	-0.01	-0.42	S
m	N.A.	N.A.	-0.42	N.A.	N.A.	N.A.	-0.42	VS
SubN200	-0.40	-0.07	0.07	-0.07	-0.08	-0.02	-0.40	S
BaseThickness	-0.38	-0.04	0.02	0.08	0.02	0.00	-0.38	VS
UnitW	-0.24	-0.04	-0.38	-0.27	-0.09	-0.03	-0.38	S
HtCp	-0.14	-0.02	-0.06	-0.35	-0.12	-0.03	-0.35	S
SubPR	0.25	0.01	-0.04	0.09	0.04	0.01	0.25	S
SubMr	-0.20	-0.16	0.04	-0.15	-0.24	-0.11	-0.24	VS
SubLL	0.15	0.02	0.00	-0.09	-0.03	-0.01	0.15	S
TenStr14	N.A.	N.A.	-0.05	N.A.	N.A.	N.A.	-0.05	S
GWD	0.03	-0.01	0.04	0.01	-0.01	0.00	0.04	S
SubPI	0.01	0.00	-0.04	0.00	0.00	0.00	-0.04	S

¹HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Non-Sensitive

The maximum Mean NSI values across climate zones for all distress and design input combinations are ranked in Table 8.27 in terms of the maximum absolute sensitivity across distresses. The Mean NSI values were computed from the 10,000 ANN RSM evaluations for each climate zone and distress combination (Table 8.20 through Table 8.25). The plus and minus signs are again retained for each individual sensitivity index to indicate whether distress increases (+) or decreases (-) with increasing input value. Usually—and especially for the highest sensitivity inputs—the plus/minus signs for each design input are consistent across all distresses.

The OAT local sensitivity category (Appendix B) for each design input is also indicated in Table 8.27. There was full congruence between the ranking of inputs from the ANN RSMs and the categorization from the OAT analyses.

Table 8.27. Ranking of New HMA design inputs by maximum |Mean| NSI values (ANN RSMs).

Design Input	Maximum Mean NSI Values (ANN RSMs)							OAT Category
	Long Crk	AllCrk	ThermCrk	ACRD	TotRD	IRI	Maximum	
Alpha	-8.56	-1.95	-0.13	-7.99	-3.23	-1.21	-8.56	HS
Delta	-6.42	-2.01	0.76	-7.82	-3.07	-1.09	-7.82	HS
HMAThick	-3.06	-1.13	-0.29	-1.20	-0.62	-0.35	-3.06	HS
m	N.A.	N.A.	-1.63	N.A.	N.A.	N.A.	-1.63	VS
PRatio	-0.66	-0.17	0.04	-1.50	-0.52	-0.15	1.21	VS
BaseMr	-1.31	-0.27	-0.05	0.06	-0.03	-0.05	-1.50	VS
SSA	1.14	0.13	-0.05	1.21	0.43	0.15	-1.31	VS
Va	1.20	0.47	0.43	-0.01	0.00	0.06	1.20	VS
Vbeff	-1.01	-0.46	-0.04	0.02	0.00	-0.05	-1.01	VS
AADTTperLane	0.76	0.52	0.00	0.57	0.23	0.13	0.76	VS
BaseThick	-0.52	-0.10	0.00	0.06	0.01	-0.01	0.45	VS
SubMr	0.45	-0.26	0.01	0.03	-0.16	-0.12	-0.31	VS
SubN200	-0.36	-0.01	0.01	-0.02	-0.04	-0.02	-0.52	S
TenStr14	N.A.	N.A.	-0.47	N.A.	N.A.	N.A.	-0.47	S
PGHigh	-0.15	-0.08	0.00	-0.19	-0.07	-0.03	-0.36	S
D	N.A.	N.A.	-0.32	N.A.	N.A.	N.A.	-0.32	S
HtCp	-0.19	-0.02	-0.26	-0.24	-0.08	-0.03	-0.26	S
UnitW	-0.18	0.08	-0.26	-0.24	-0.06	-0.02	-0.26	S
PGLow	0.15	0.00	-0.26	0.00	0.00	0.00	-0.26	S
OpSpd	-0.31	-0.11	-0.01	-0.28	-0.11	-0.04	-0.24	S
BasePR	0.15	0.12	0.04	-0.03	0.00	0.01	-0.09	S
ThmlCn	-0.13	-0.07	-0.16	0.03	0.01	0.00	-0.16	S
SubLL	-0.14	-0.03	-0.01	-0.01	0.02	0.01	0.15	S
SubPR	0.07	-0.09	0.04	0.03	0.01	0.00	-0.13	S
GWD	0.05	-0.01	0.02	0.00	0.00	0.00	0.05	S
SubPI	-0.03	0.01	0.01	0.00	0.01	0.00	-0.03	S
AggCoefContr	N.A.	N.A.	-0.01	N.A.	N.A.	N.A.	-0.01	NS

¹HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Non-Sensitive

As a more severe measure of sensitivity, the mean plus/minus two standard deviation ($\mu \pm 2\sigma$) NSI values were computed using the statistics in Table 8.20 through Table 8.25 derived from the 10,000 ANN RSM evaluations for each climate zone and distress combination. These sensitivity limits are ranked in Table 8.28 in terms of the maximum absolute value across distresses. The plus and minus signs are again retained for each individual sensitivity index to indicate whether distress increases (+) or decreases (-) with increasing input value. Usually—and especially for the highest sensitivity inputs—the plus/minus signs for each design input are consistent across all distresses. There is very good agreement between the input rankings in Table 8.28 and those based on the mean NSI values in Table 8.27

The OAT local sensitivity category (Appendix B) for each design input is also indicated in Table 8.28. Not only was there full congruence between the ranking of inputs from the ANN RSMs and the categorization from the OAT analyses, but the ranges of $\mu \pm 2\sigma$ values in Table 8.28 also line up perfectly with the ranges of normalized sensitivity index values used to define the OAT categories. These sensitivity categories are highlighted by the fonts in Table 8.28: **Bold** = Hypersensitive (HS), $\mu \pm 2\sigma > 5$; ***Bold Italic*** = Very Sensitive (VS), $1 < \mu \pm 2\sigma < 5$; *Italic* = Sensitive (S), $0.1 < \mu \pm 2\sigma < 1$; and Regular = Non-Sensitive (NS), $\mu \pm 2\sigma < 0.1$. The rankings and $\mu \pm 2\sigma$ values in Table 8.28 are judged to be the best overall measures of the design input sensitivities in the MEPDG.

Figure 8.16 through Figure 8.20 provide graphical summaries of the input sensitivities by distress. These figures highlight the difference in sensitivities between Hypersensitive and Very Sensitive and between Very Sensitive and Sensitive. All of the figures have the same horizontal axis range so that the differences in sensitivities across distresses can be more clearly evaluated. The solid bars in the figures indicate the mean NSI values, and the error bars correspond to one standard deviation. The sensitivities are also broken down by climate zone for each design input. No systematic or substantial effect of climate zone on the design input sensitivity statistics is observed.

Table 8.28. Ranking of New HMA design inputs by maximum $|\mu+2\sigma|$ NSI values (ANN RSMs).

Design Input	Maximum $\mu+2\sigma$ NSI Values (ANN RSMs)							OAT Category
	Long Crk	AllCrk	ThermCrk	ACRD	TotRD	IRI	Maximum	
Alpha	-29.52	-15.94	-0.58	-24.40	-8.98	-3.58	-29.52	HS
Delta	-23.87	-13.18	2.41	-24.43	-8.99	-2.80	-24.43	HS
HMAThick	-10.31	-7.46	-0.86	-4.21	-1.58	-1.11	-10.31	HS
<i>m</i>	N.A.	N.A.	-4.85	N.A.	N.A.	N.A.	-4.85	VS
<i>BaseMr</i>	-4.72	-2.73	-0.17	0.14	-0.15	-0.36	-4.72	VS
<i>SSA</i>	4.32	1.28	-0.20	4.65	1.67	0.67	4.65	VS
<i>Va</i>	4.47	3.39	1.33	-0.05	0.03	0.29	4.47	VS
<i>PRatio</i>	-2.38	-1.01	0.23	-4.33	-1.46	-0.43	-4.33	VS
<i>AADTTperLane</i>	3.72	3.94	0.02	1.87	0.66	0.51	3.94	VS
<i>Vbeff</i>	-3.88	-2.93	-0.17	0.05	0.06	-0.24	-3.88	VS
<i>SubMr</i>	-2.07	-3.41	0.15	0.08	-0.28	-0.44	-3.41	VS
<i>BaseThick</i>	-2.40	-1.02	-0.03	0.22	0.04	-0.09	-2.40	VS
<i>SubN200</i>	-1.71	-0.68	0.08	-0.10	-0.10	-0.12	-1.71	S
<i>TenStr14</i>	N.A.	N.A.	-1.59	N.A.	N.A.	N.A.	-1.59	S
<i>OpSpd</i>	-1.26	-0.83	-0.04	-1.06	-0.39	-0.15	-1.26	S
<i>D</i>	N.A.	N.A.	-1.03	N.A.	N.A.	N.A.	-1.03	S
<i>UnitW</i>	-0.88	0.97	-0.76	-0.88	-0.30	-0.08	0.97	S
<i>BasePR</i>	0.91	0.90	0.18	-0.19	-0.05	0.09	0.91	S
<i>HtCp</i>	-0.76	-0.55	-0.77	-0.81	-0.28	-0.14	-0.81	S
<i>SubLL</i>	-0.67	-0.79	-0.10	-0.10	0.07	0.03	-0.79	S
<i>PGLow</i>	0.56	0.09	-0.74	0.25	0.09	0.02	-0.74	S
<i>ThmlCn</i>	-0.53	-0.40	-0.67	0.20	0.04	0.02	-0.67	S
<i>PGHigh</i>	-0.60	-0.48	0.00	-0.66	-0.25	-0.09	-0.66	S
<i>SubPR</i>	0.44	-0.59	0.16	0.08	0.07	0.04	-0.59	S
<i>GWD</i>	0.20	-0.16	0.08	0.01	-0.02	-0.02	0.20	S
<i>SubPI</i>	-0.15	0.11	0.03	0.01	0.02	0.00	-0.15	S
<i>AggCoefContr</i>	N.A.	N.A.	-0.07	N.A.	N.A.	N.A.	-0.07	NS

¹HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Non-Sensitive

Figure 8.16. Ranking of New HMA design inputs by $|\mu \pm 2\sigma|$ NSI values: longitudinal cracking.

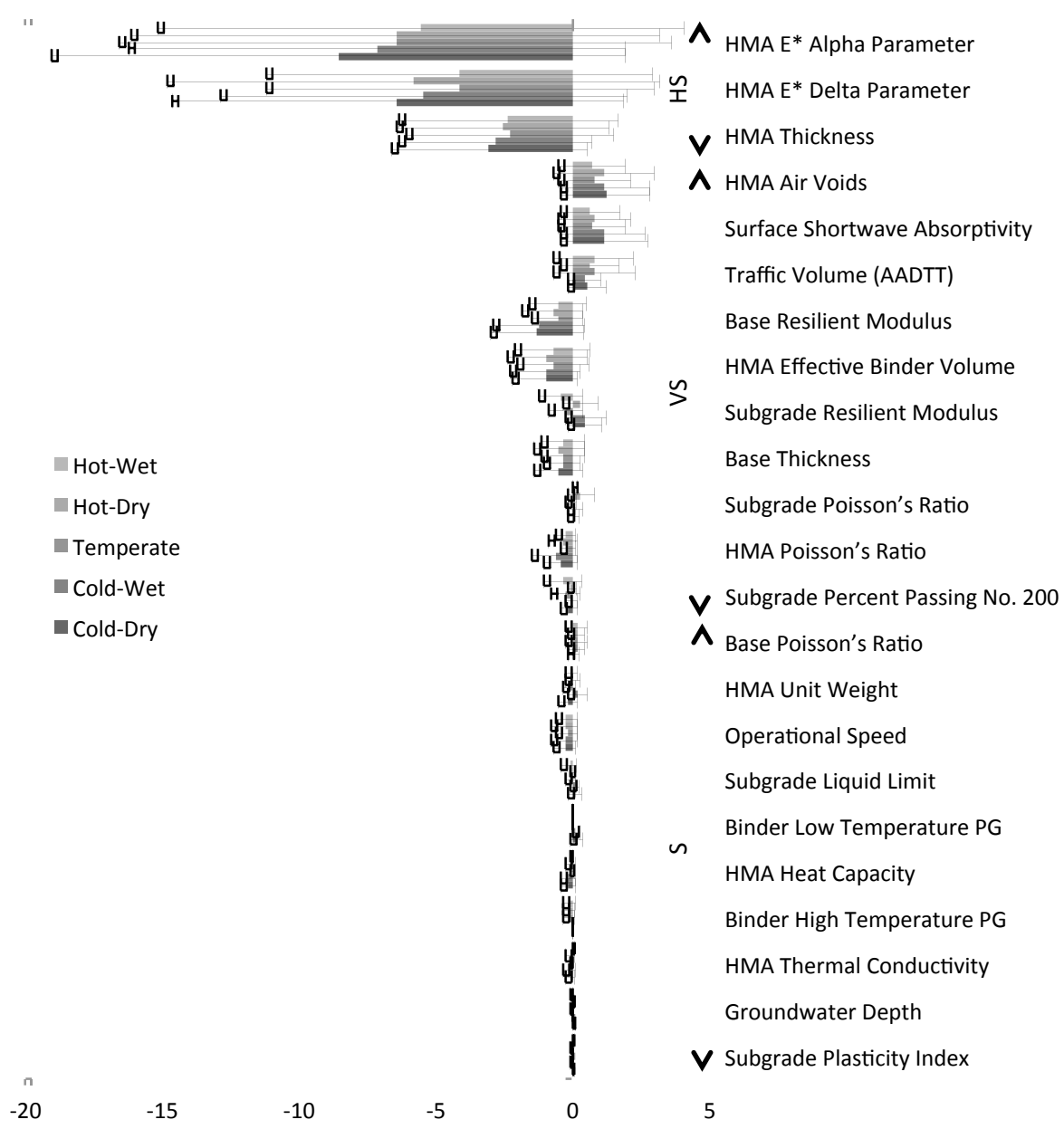


Figure 8.17. Ranking of New HMA design inputs by $|\mu \pm 2\sigma|$ NSI values: alligator cracking.

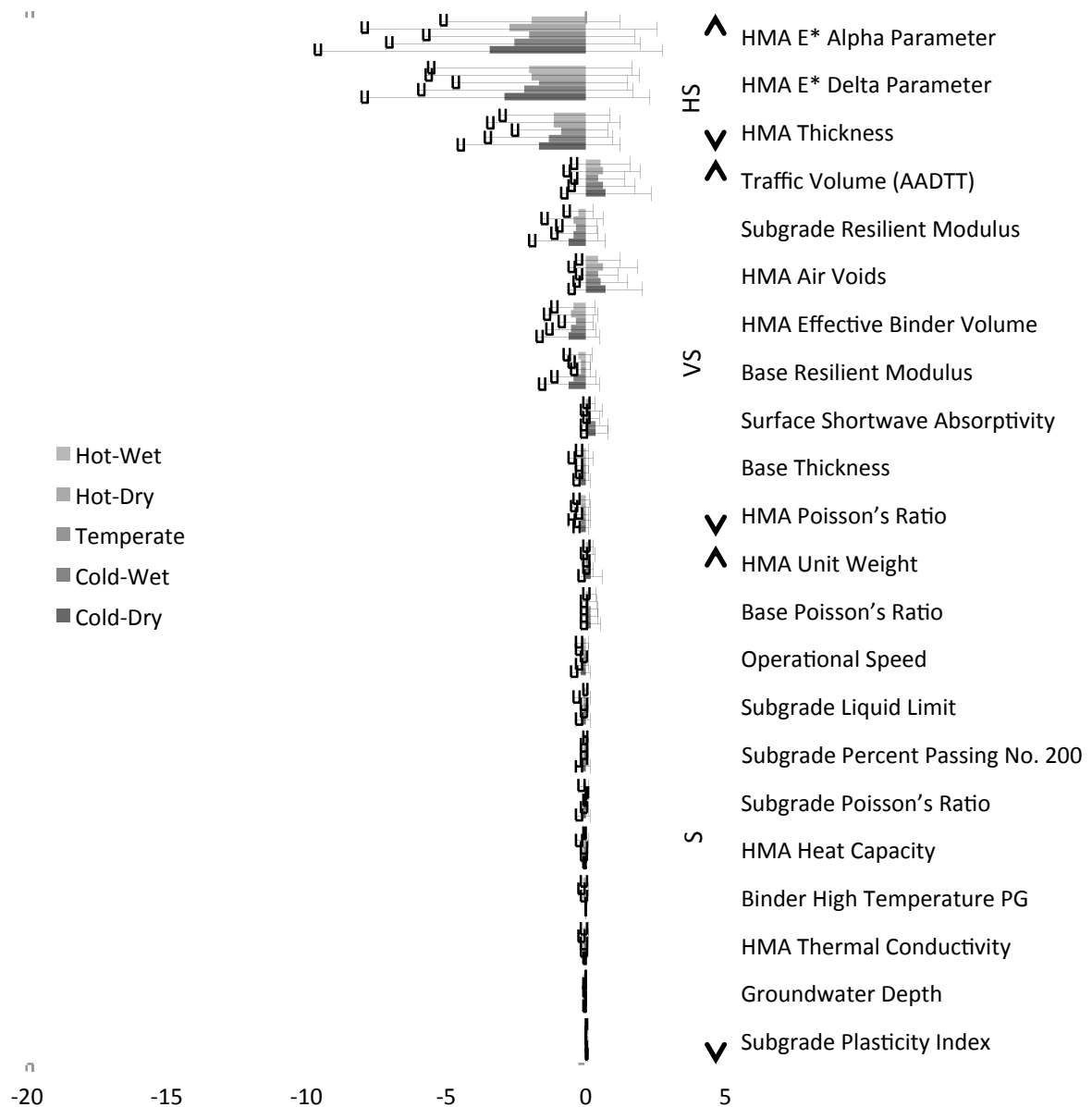


Figure 8.18. Ranking of New HMA design inputs by $|\mu \pm 2\sigma|$ NSI values: AC rutting.

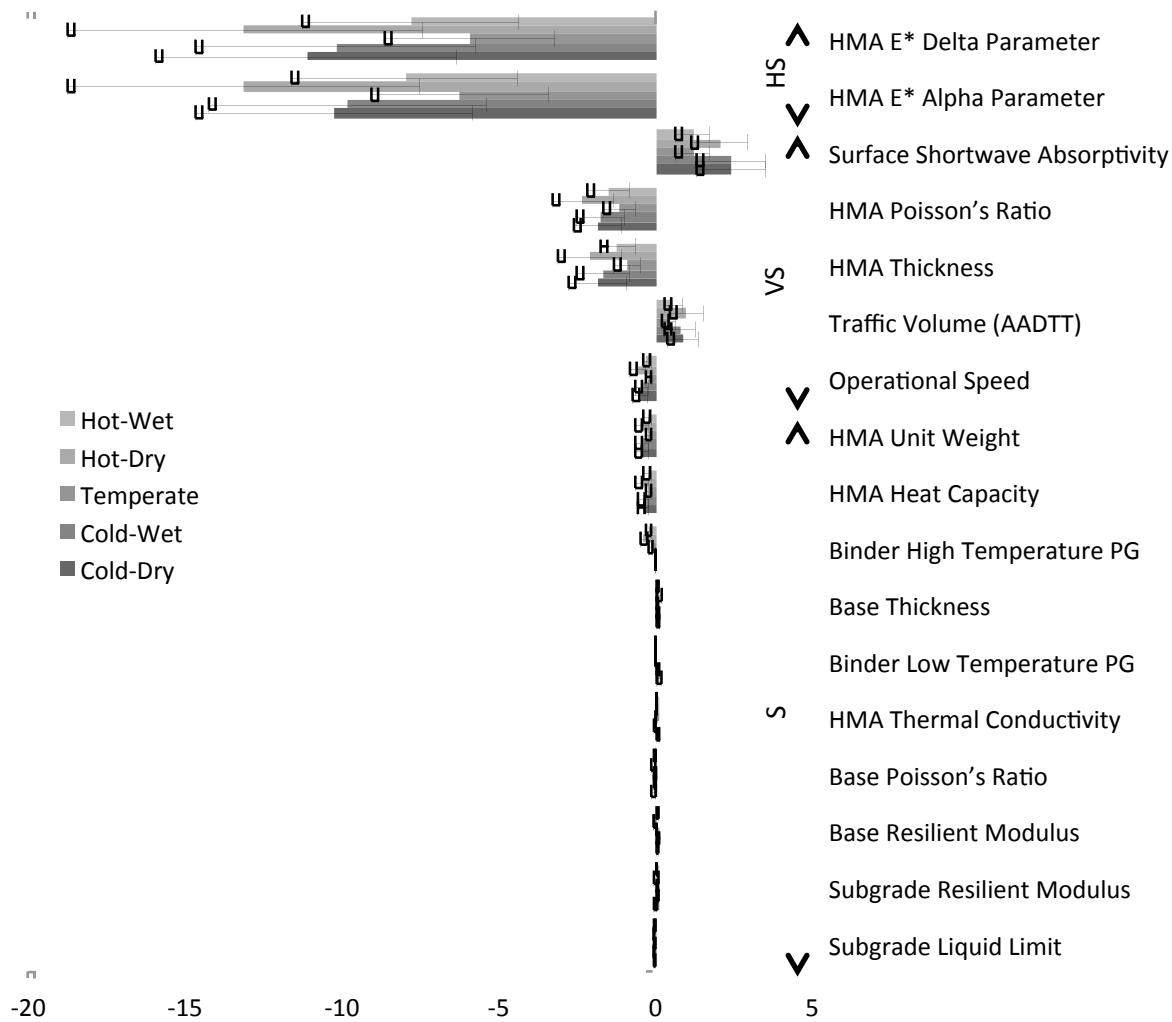


Figure 8.19. Ranking of New HMA design inputs by $|\mu+2\sigma|$ NSI values: total rutting.

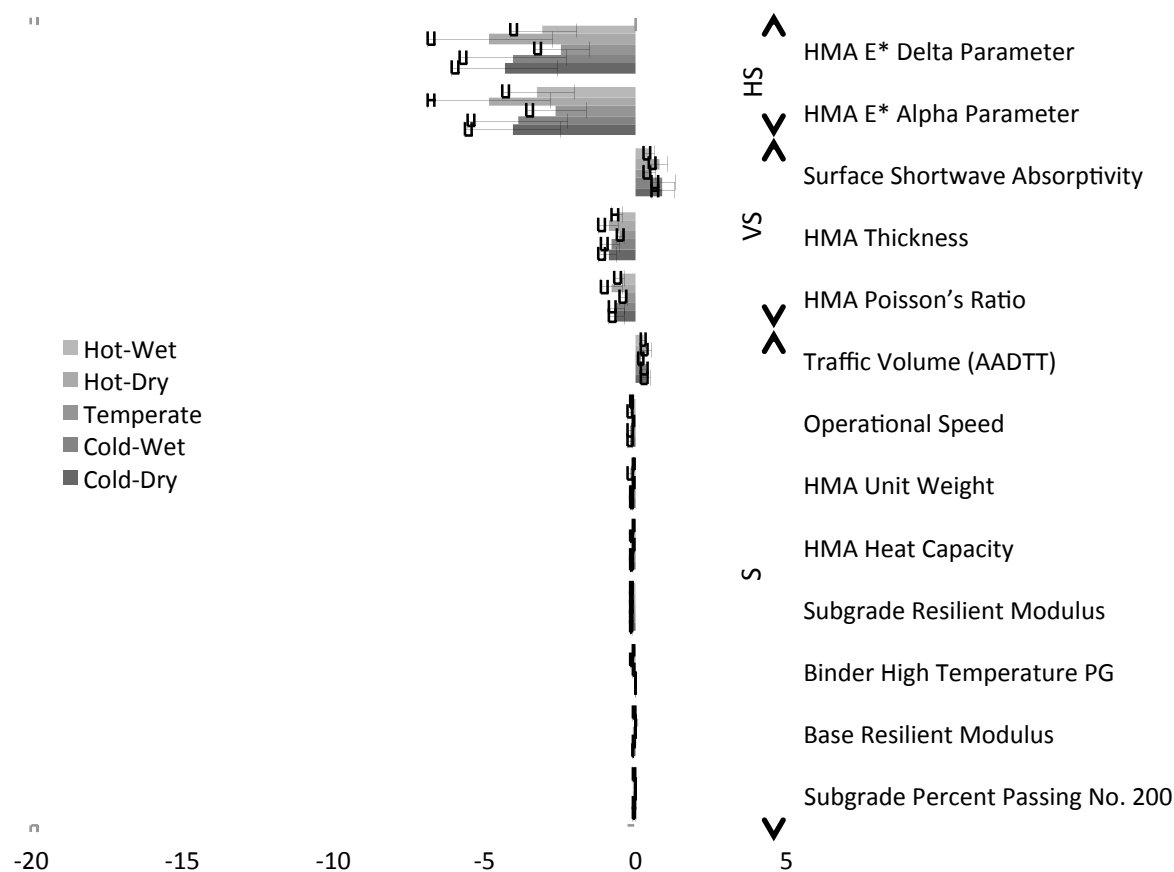
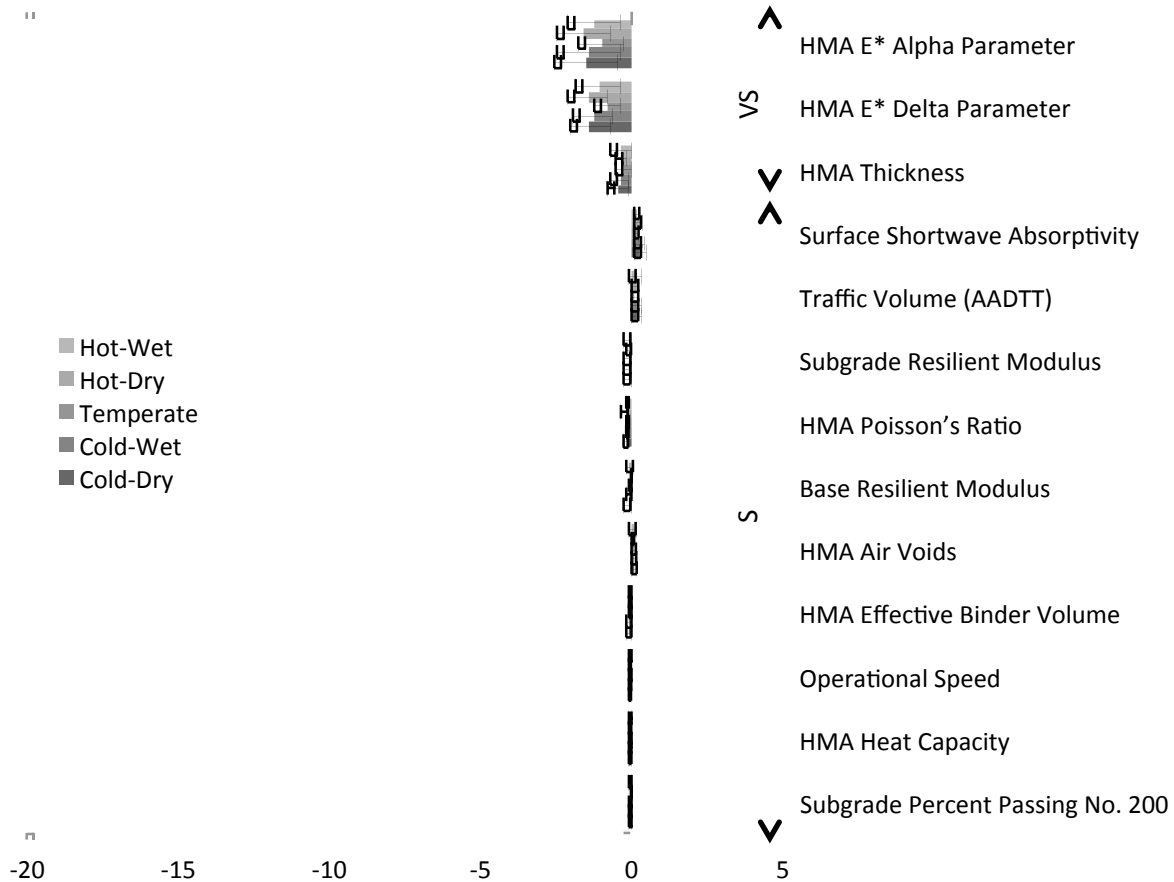


Figure 8.20. Ranking of New HMA design inputs by $|\mu \pm 2\sigma|$ NSI values: IRI.



As a more practical aid to the pavement designer, Table 8.29 summarizes in rank order the Hypersensitive, Very Sensitive, and Sensitive design inputs by material category (HMA, base, subgrade, other) for each distress. The design inputs that fall in the Hypersensitive or Very Sensitive categories for most (4 out of 5) distresses are indicated by bold font in the table. For the New HMA scenarios, these are all HMA properties: 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 properties (e.g., traffic volume) was as consistently in the two highest sensitivity categories.

When interpreting the very large NSI values for E* Alpha and D* Delta, it is important to remember that the typical ranges for these parameters are very narrow. As detailed in Table 3.1, the standard deviations for α and δ are only 1.6% and 3.5% of their mean values, respectively.

The high sensitivity of most distresses to Poisson's ratio for the HMA and, to a lesser extent, for the subgrade, is surprising. Poisson's ratio is conventionally thought to have only minor effect on pavement performance, and thus its value is usually assumed in pavement analyses. The findings here suggest that this conventional wisdom may need to be re-examined.

Table 8.29. Hypersensitive, Very Sensitive, and Sensitive design inputs by distress and input category for New HMA flexible pavements.
NSI_{μ+2σ} values are given in parentheses. Inputs in bold font are Hypersensitive or Very Sensitive for most (4 out of 5) distresses.

<i>Distress</i>	<i>Input Category</i>	<i>Hypersensitive (>5)</i>	<i>Very Sensitive (1-5)</i>	<i>Sensitive (0.1-1)</i>
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)
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)

<i>Distress</i>	<i>Input Category</i>	<i>Hypersensitive (>5)</i>	<i>Very Sensitive (1-5)</i>	<i>Sensitive (0.1-1)</i>
AC Rutting	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)

The hypersensitive NSI values for E* Alpha and Delta merit further examination. As described previously in Section 3.2, the GSA simulations were based on synthetic Level 1 inputs for HMA dynamic modulus. In practice, these properties will very often be input into the MEPDG in terms of the Level 3 empirical relations. The pavement designer may therefore be more interested in the sensitivity of predicted distress to the inputs to the Level 3 empirical relations than to the Level 1 direct inputs. These sensitivities can be evaluated using Eq. 3.24 and the Level 3 empirical relations for HMA dynamic modulus given in Section 3.2. These estimates are summarized in Table 8.30. Note that the values in the table are not true point estimates but rather approximations using the average HMA mix gradation and volumetric data in Section 3.2 and the corresponding Level 3 α and δ values in lieu of the point values. Some practical observations regarding the results in Table 8.30 include the following:

- The NSI values for the secondary variables—i.e., the inputs to the Level 3 empirical HMA dynamic modulus relations—are much lower than the NSI values for the primary variables α and δ .
- All of the NSI values for the secondary variables are in either the Sensitive or lower portion of the Very Sensitive categories.
- If using Level 3 inputs for HMA dynamic modulus, the NSI_z values for V_a and V_{beff} values are in addition to the NSI values in Table 8.28.

It is important to keep in mind that the NSI_z values in Table 8.30 and related discussion are all predicated on the validity of the Witczak dynamic modulus model. Although this is the model currently implemented in the MEPDG, there are several other alternatives that have been proposed in the literature (e.g., Al-Khateeb *et al.*, 2006; Witczak and Bari, 2006; Christensen *et al.*, 2003; Ceylan *et al.*, 2007; Ceylan *et al.*, 2009; Far *et al.*, 2009). The limitations of the Witczak dynamic modulus model have been amply documented in the literature (e.g., Schwartz, 2005; Ceylan *et al.*, 2009).

Table 8.30. NSI values for HMA Level 3 dynamic modulus inputs.

Primary Variable			Secondary Variable			
Variable	x_i	NSI _x ¹	Variable	z_i	NSI _z	Category
α	3.90	-29.52	ρ_4	55.5%	0.88	S
			ρ_{38}	33.5%	-0.71	S
			ρ_{34}	5.5%	-0.23	S
δ	2.83	-24.43	ρ_{200}	4.9%	-0.51	S
			ρ_4	55.5%	-1.36	VS
			V _a	6.47%	1.60	VS
			V _{beff}	10.08%	1.65	VS

¹Overall maximum from Table 8.28.

9 HMA OVER STIFF FOUNDATION

9.1 Analysis Inputs

The HMA Over Stiff Foundation scenarios represent both new HMA over stabilized base/subgrade or an HMA overlay on an existing flexible pavement. The GSA analyses of HMA over stiff foundation flexible pavements encompassed a total of 15 base cases spanning five climate zones with three traffic levels each. The fixed design parameters for the stiff foundation analyses are the same as those in Table 8.1 for the New HMA scenarios with the exception that the material type for the second layer is now cement stabilized base. The binder grades used in the stiff foundation analyses are also the same as those in Table 8.2 for the New HMA scenarios.

Table 9.1 summarizes the design inputs that are strongly correlated to traffic level. Higher traffic levels require correspondingly thicker asphalt and base layers; however, the asphalt layers are thinner in the stiff foundation analyses than in the corresponding New HMA scenarios. AADTT, HMA thickness, and base thickness were all determined in the OAT local sensitivity analyses to be hypersensitive or very sensitive inputs (see Appendix B). The GSA simulations for each traffic category used random input values for the AADTT and the HMA and base thicknesses ranging between the minimum and maximum limits as determined by the Latin Hypercube algorithm.

Table 9.1. Design inputs related to traffic levels for HMA Over Stiff Foundation.

Input Parameter \ Traffic Level	Low Traffic			Medium Traffic			High Traffic		
	Baseline	Min	Max	Baseline	Min	Max	Baseline	Min	Max
AADTT-Nominal	1000	500	5000	7500	5000	10000	25000	20000	30000
Design Lane	375	188	1875	2063	1375	2750	6250	5000	7500
HMA Thickness	2	1.5	3	3	2	4	4	2	6
Base Thickness	8	4	12	10	5	14	12	6	16

Most of the remaining design inputs in the stiff foundation simulations were varied over the same ranges as shown in Table 8.4 for the New HMA scenarios. Changed or added design inputs for the HMA Over Stiff Foundation cases are summarized in Table 9.2.

Table 9.2. Input parameter ranges for HMA Over Stiff Foundation cases.

Input Parameter	OAT Sensitivity ¹	Baseline Value ²	Minimum ²	Maximum ²
Base Unit Weight	S	150	125	175
Base Poisson's Ratio	S	0.35	0.315	0.385
Base Resilient Modulus	S	400000	10000	3000000
Base Thermal Conductivity	S	0.35	0.315	0.385
Base Heat Capacity	S	0.28	0.224	0.336

¹HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Not Sensitive

²All values are in same units as MEPDG inputs.

9.2 Predicted Distresses

Over 9200 MEPDG runs were performed for the HMA Over Stiff GSA. Table 9.3 through Table 9.8 provide summary statistics for predicted longitudinal cracking, alligator cracking, thermal cracking, AC rut depth, total rut depth, and IRI, respectively, for the GSA simulations for each base case combination of climate zone and traffic level. Recall that the binder grades in the thermal cracking simulations were up to 3 grades higher than the value recommended by LTPPBind (see Table 8.2) in order to generate significant levels of thermal cracking distress. Overall, the Latin hypercube sampling scheme generated input data sets that produced a wide range for each of the predicted distresses. The range of predicted distresses in most cases is from zero or near zero to values several times the default design limit. Average values for alligator cracking and, to a lesser extent, longitudinal cracking are very small; this is expected with a stiff foundation. The average values for AC rutting, total rutting, and IRI were relatively insensitive to climate zone but more sensitive to traffic level.

Figure 9.1 through Figure 9.5 provide frequency distributions of predicted distresses by climate zone and traffic level. The distributions of predicted distresses are quite robust for thermal cracking, rutting and IRI but skewed toward the low ends for longitudinal and alligator cracking because of the stiff foundation. These results confirm that the GSA simulations for the HMA over stiff foundation cases span a wide range of the model output (distress) space for the relevant distresses.

Table 9.3. Summary statistics for predicted longitudinal cracking – HMA Over Stiff Foundation.

Scenario	Mean	Minimum	Maximum	Std Dev
CDL	33	0	5610	308
CDM	94	0	9940	730
CDH	622	0	10500	1479
CWL	37	0	5980	336
CWM	98	0	9890	773
CWH	443	0	10500	1296
TL	30	0	5510	297
TM	96	0	9850	794
TH	184	0	10500	1091
HDL	31	0	4390	254
HDM	99	0	9850	795
HDH	287	0	10500	1209
HWL	35	0	6410	351
HWM	99	0	10100	835
HWH	184	0	10500	1109
Overall	158	0	10500	885

Table 9.4. Summary statistics for predicted alligator cracking – HMA Over Stiff Foundation.

Scenario	Mean	Minimum	Maximum	Std Dev
CDL	0.001	0	0.3	0.01
CDM	0.061	0	18.6	0.90
CDH	0.154	0	28.6	1.54
CWL	0.001	0	0.3	0.01
CWM	0.059	0	17.8	0.87
CWH	0.138	0	23.0	1.31
TL	0.001	0	0.2	0.01
TM	0.048	0	13.3	0.65
TH	0.116	0	14.6	0.99
HDL	0.001	0	0.3	0.01
HDM	0.060	0	17.5	0.86
HDH	0.157	0	24.6	1.47
HWL	0.001	0	0.3	0.01
HWM	0.060	0	17.3	0.84
HWH	0.144	0	20.8	1.30
Overall	0.067	0	28.6	0.91

Table 9.5. Summary statistics for predicted thermal cracking – HMA Over Stiff Foundation.

Scenario	Mean	Minimum	Maximum	Std Dev
CD1	106	0.1	1630	240
CD2	1439	94.8	2100	454
CD3	1963	1550	2100	112
CW1	109	0	2090	260
CW2	523	0.9	2090	560
CW3	639	0.7	2090	578
Overall	583	0	2100	690

Table 9.6. Summary statistics for predicted AC rutting – HMA Over Stiff Foundation.

Scenario	Mean	Minimum	Maximum	Std Dev
CDL	0.19	0.02	0.56	0.10
CDM	0.44	0.11	0.96	0.14
CDH	0.89	0.26	1.67	0.24
CWL	0.17	0.01	0.51	0.09
CWM	0.40	0.10	0.90	0.13
CWH	0.81	0.23	1.56	0.23
TL	0.10	0.00	0.38	0.06
TM	0.22	0.04	0.63	0.08
TH	0.46	0.11	1.10	0.14
HDL	0.22	0.01	0.69	0.12
HDM	0.52	0.12	1.16	0.17
HDH	1.05	0.29	2.12	0.29
HWL	0.13	0.01	0.52	0.07
HWM	0.30	0.06	0.87	0.11
HWH	0.62	0.14	1.39	0.19
Overall	0.44	0.00	2.12	0.33

Table 9.7. Summary statistics for predicted total rutting – HMA Over Stiff Foundation.

Scenario	Mean	Minimum	Maximum	Std Dev
CDL	0.44	0.22	1.12	0.12
CDM	0.69	0.40	1.44	0.14
CDH	1.14	0.62	2.14	0.22
CWL	0.41	0.21	1.05	0.11
CWM	0.63	0.37	1.37	0.13
CWH	1.04	0.56	2.04	0.21
TL	0.31	0.16	0.86	0.09
TM	0.43	0.27	1.16	0.11
TH	0.67	0.41	1.72	0.15
HDL	0.42	0.18	1.13	0.14
HDM	0.72	0.37	1.59	0.17
HDH	1.25	0.57	2.34	0.28
HWL	0.36	0.19	1.06	0.11
HWM	0.53	0.34	1.40	0.13
HWH	0.85	0.47	2.07	0.19
Overall	0.66	0.16	2.34	0.33

Table 9.8. Summary statistics for predicted IRI – HMA Over Stiff Foundation.

Scenario	Mean	Minimum	Maximum	Std Dev
CDL	103	94	131	4.9
CDM	113	102	144	5.8
CDH	131	110	183	9.1
CWL	101	94	128	4.6
CWM	110	100	140	5.5
CWH	127	108	174	8.5
TL	90	83	113	4.0
TM	95	88	125	4.6
TH	105	93	147	6.3
HDL	93	83	122	5.6
HDM	105	92	141	7.1
HDH	127	99	173	11.3
HWL	94	87	123	4.6
HWM	101	93	137	5.6
HWH	114	99	167	7.9
Overall	107	83	183	14.1

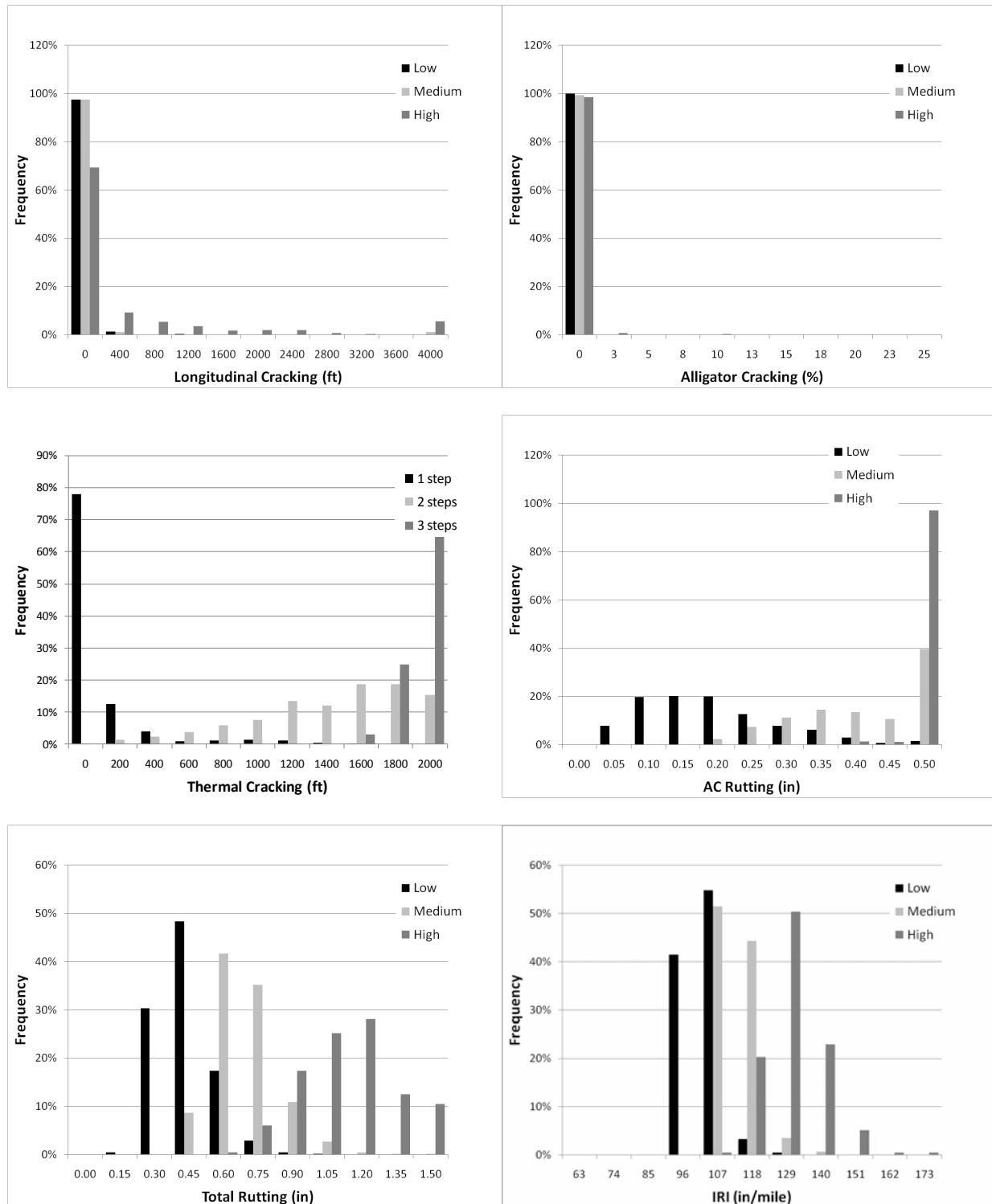


Figure 9.1. Distribution of predicted distresses – HMA Over Stiff Foundation/Cold-Dry climate.

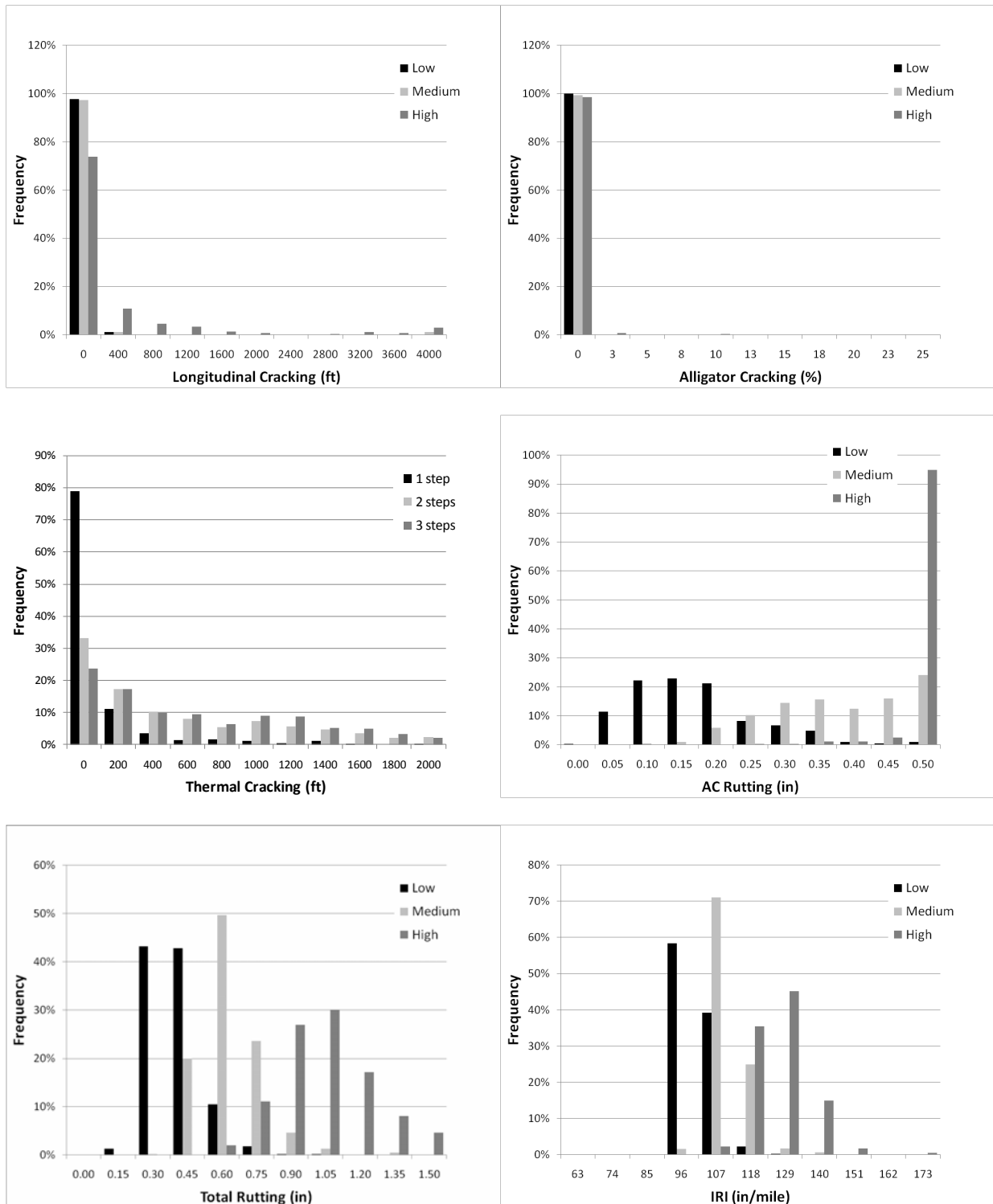


Figure 9.2. Distribution of predicted distresses – HMA Over Stiff Foundation/Cold-Wet climate.

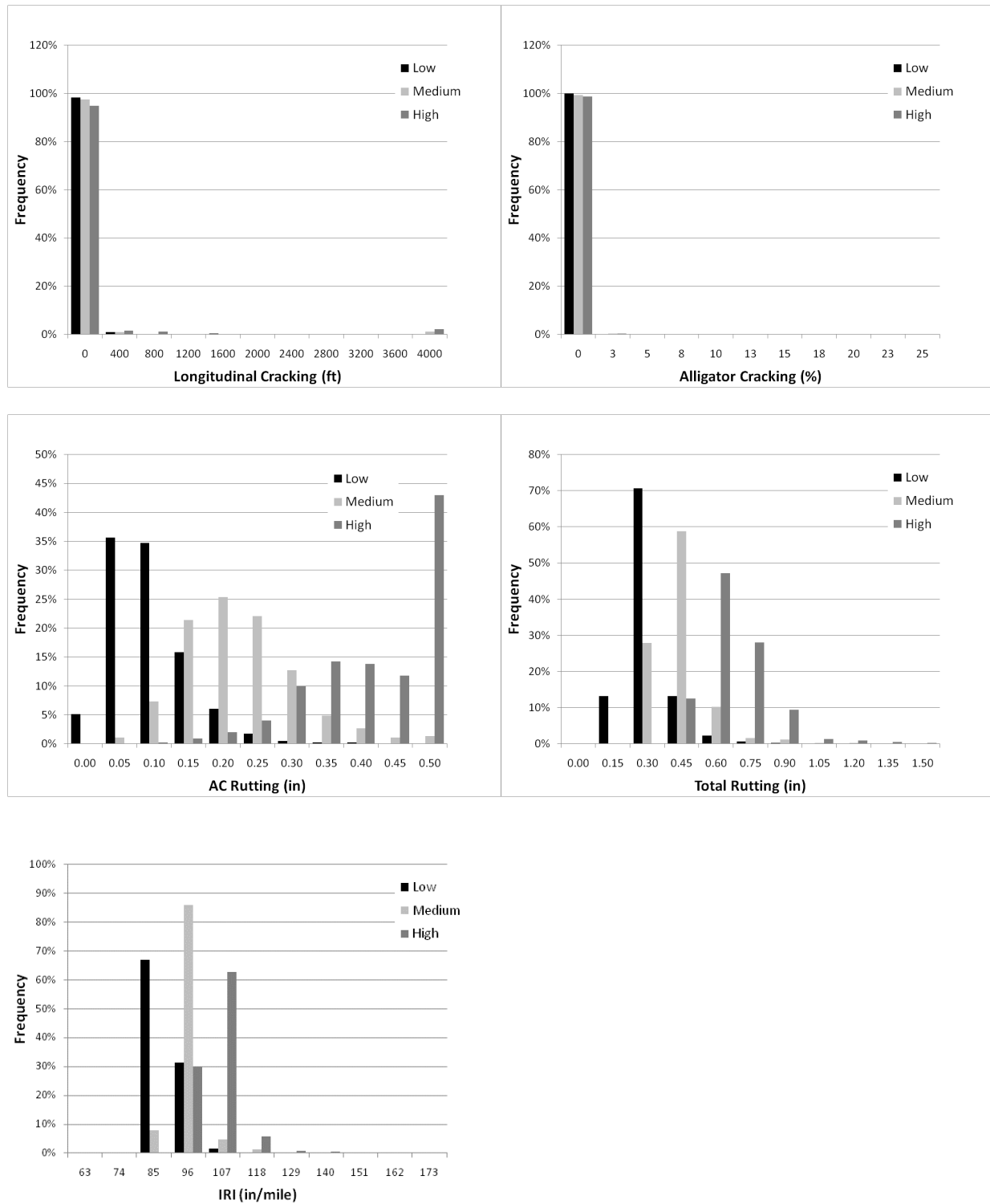


Figure 9.3. Distribution of predicted distresses – HMA Over Stiff Foundation/Temperate climate.

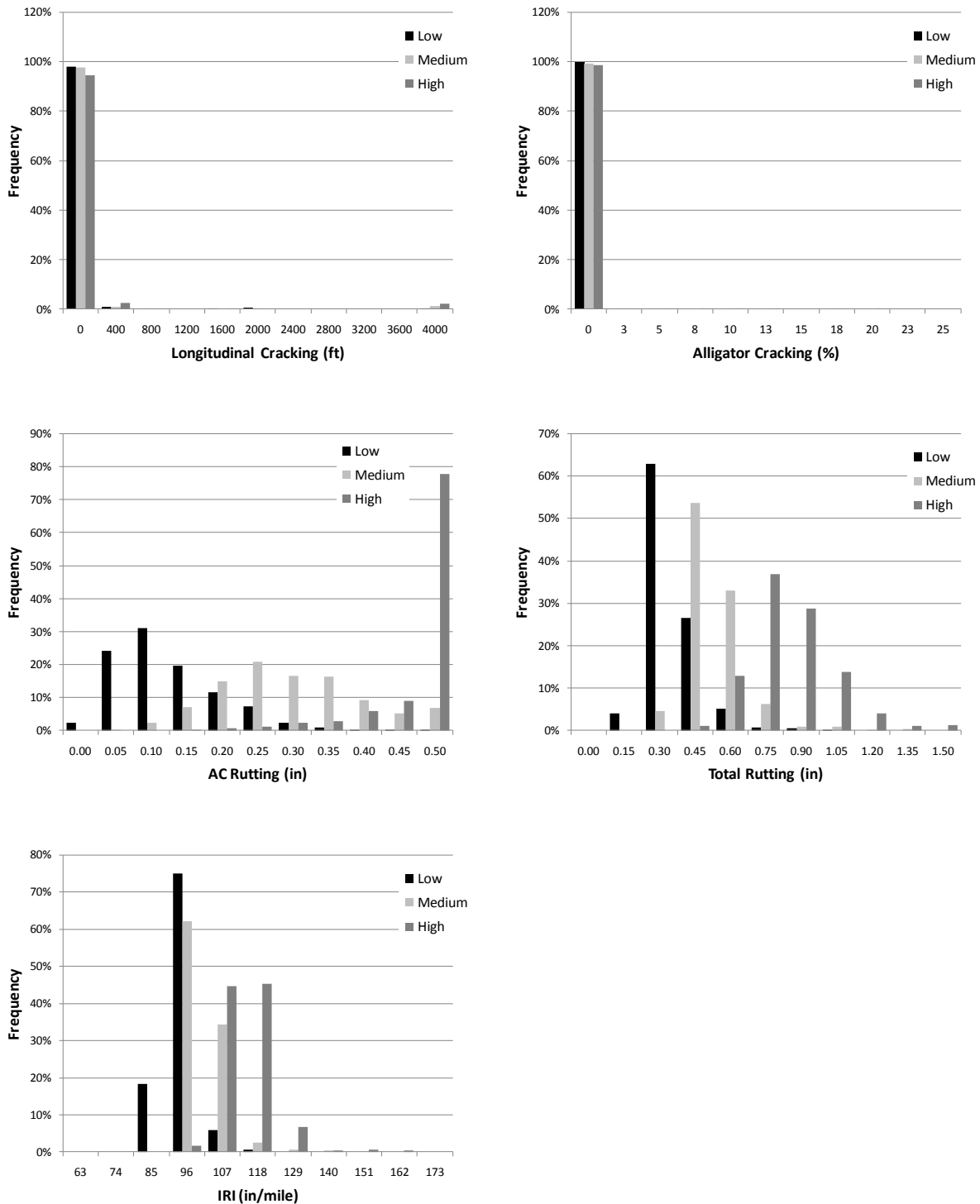


Figure 9.4. Distribution of predicted distresses – HMA Over Stiff Foundation/Hot-Dry climate.

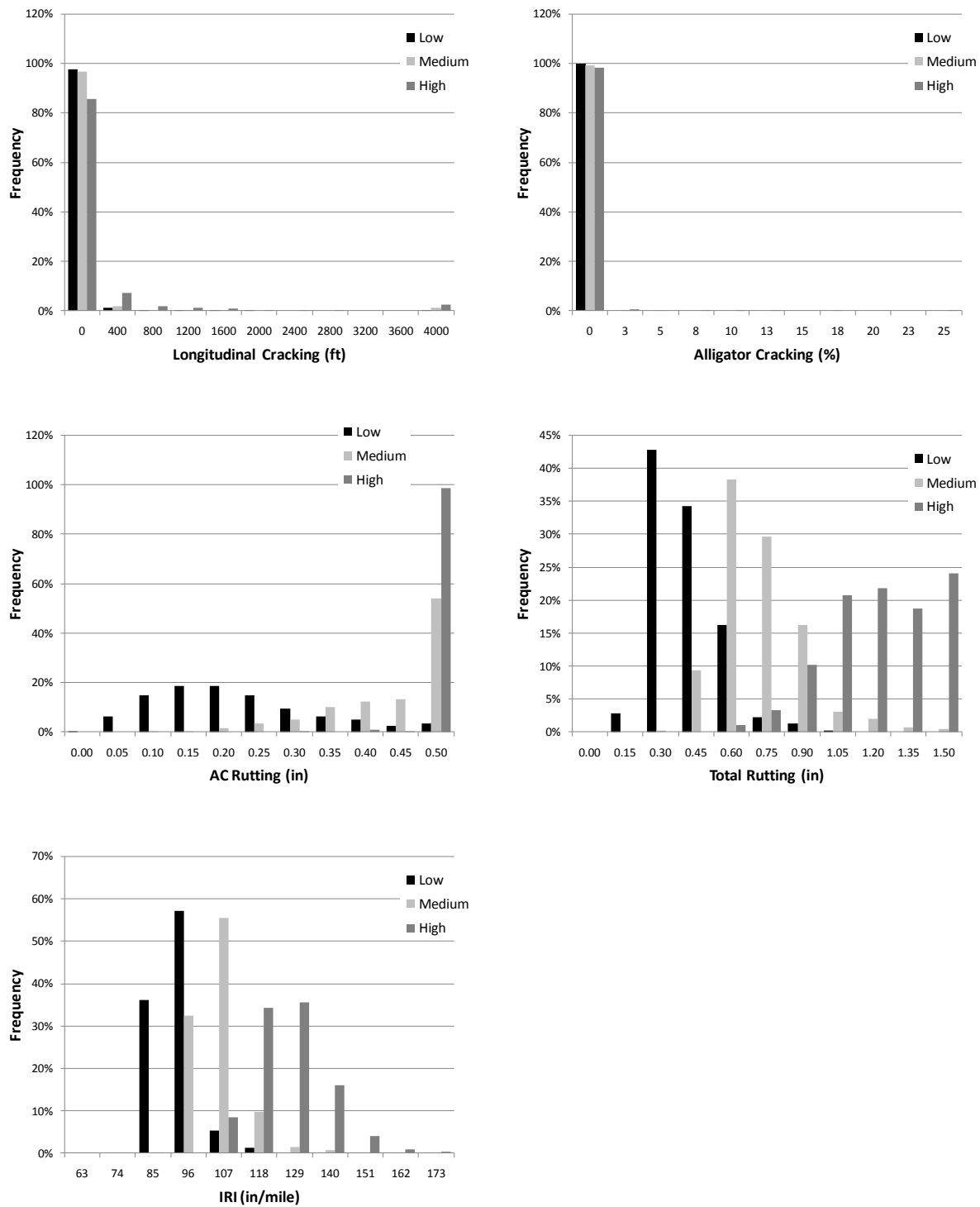


Figure 9.5. Distribution of predicted distresses – HMA Over Stiff Foundation/Hot-Wet climate.

9.3 Response Surface Modeling

Table 9.9 defines the inputs used for the RSMs. The outputs from the RSMs are the predicted distresses: longitudinal cracking, alligator cracking, thermal cracking, AC rutting, total rutting, and IRI. Separate RSMs were developed for each distress.

Table 9.9. Definition of inputs for response surface modeling - HMA Over Stiff Foundation scenarios.

Input No.	Name of Design Input	Description
1	AADTTperLane	Average Annual Daily Truck Traffic in design lane
2	HMAThickness	HMA layer thickness
3	BaseThickness	Base layer thickness
4	OpSpd	Average vehicle travel speed
5	PGHigh	High temperature binder grade. The NSI was calculated by decreasing the high temperature grade by one step from baseline.
6	PGLow	Low temperature binder grade. The NSI was calculated by increasing the low temperature grade by one step from baseline.
7	GWD	Ground Water Depth
8	SSA	Surface Shortwave Absorption
9	UnitW	Unit weight of HMA
10	Pratio	Poisson's ratio of HMA
11	ThmlCn	Thermal conductivity of HMA
12	HtCp	Heat capacity of HMA
13	Delta	The lower limit of the sigmoidal function for $\log(E^*)$
14	Alpha	The upper limit of the sigmoidal function for $\log(E^*)$
15	Vbeff	HMA volume of effective binder
16	Va	HMA air voids
17	BaseUnitW	Unit weight of base layer material
18	BasePR	Poisson's ratio of granular base layer material
19	BaseMr	Resilient modulus of base layer material
20	BaseThmlCn	Thermal conductivity of base layer material
21	BaseHtCp	Heat capacity of base layer material
22	SubMr	Resilient modulus of subgrade material
23	SubN200	Percentage passing #200 sieve of subgrade material
24	SubPI	Plasticity Index of subgrade material
25	SubLL	Liquid Limit of subgrade material
26	TenStr14 ¹	HMA tensile strength at 14°F
27	D ¹	HMA creep compliance constant (averaged over 3 temperatures)
28	m ¹	HMA creep compliance exponent (averaged over 3 temperatures)
29	AggCoefContr ¹	Aggregate coefficient of thermal contraction

¹For thermal cracking RSMs only.

Goodness-of-fit statistics R^2 , root mean squared error (RMSE), and normalized standard error (Se/Sy) for the MVL RSMs are summarized in Table 9.10 by climate zone and distress. Note that RMSE is in the units of the predicted distress while R^2 and Se/Sy are dimensionless. The R^2 values range from very poor values approaching 0.05 to quite acceptable values are around 0.8, with the alligator cracking distresses tending to have smaller R^2 values and the rutting and IRI distresses tending to

have better goodness-of-fit statistics. The low R^2 values for many of the MVLR RSMs are not unexpected. The relationships between design inputs and distress outputs are expected to be complexly nonlinear; the multivariate linear regressions were intended only as a rough “first cut” assessment of sensitivities.

Goodness-of-fit statistics for the ANN RSMs are summarized in Table 9.11 by climate zone and distress. The ‘NN’ column describes the ANN network architecture; most ANN RSMs for the HMA over stiff foundation scenarios employed 25 input neurons, 5 hidden neurons in one layer, and one output neuron. The ANN RSMs for the thermal cracking models have 29 input neurons because of the additional 4 design inputs. The ANN RSM for the thermal cracking in CW had 8 hidden neurons in one layer in order to achieve better accuracy. The ‘n’ column gives the combined number of GSA simulations used for training/validating/testing the model. Overall, the ANN RSM model fits are very good. The R^2 values approach 1.00 for rutting and IRI and are only slightly smaller for the cracking distresses; the lowest R^2 value is a very respectable 0.86 (alligator cracking/cold-dry climate and thermal cracking/cold-wet climate).

Scatter plots for ANN predicted vs. MEPDG predicted distresses are provided in Figure 9.6 for longitudinal cracking, alligator cracking, AC rutting, total rutting, and IRI by climate zone and in Figure 9.7 for thermal cracking for the two cold climate zones. These scatter plots graphically confirm the conclusions from the goodness-of-fit statistics that the ANN RSM models provide excellent fits for rutting and IRI and very good fits for the cracking distresses. The high quality of the fits for these ANN RSMs suggest the possibility that enhanced versions of the RMS might be adequate substitutes in some cases for the more rigorous but laborious computations in the MEPDG.

Table 9.10. Goodness-of-fit statistics for MVLR RSMs –HMA Over Stiff Foundation.

Climate	Distress	R²	RMSE	Se/Sy
CD	Longitudinal Cracking	0.169	0.454	0.920
	Alligator Cracking	0.045	0.040	0.986
	Thermal Cracking	0.885	0.275	0.344
	AC Rutting	0.919	0.383	0.287
	Total Rutting	0.883	0.152	0.345
	IRI	0.874	0.044	0.358
CW	Longitudinal Cracking	0.129	0.420	0.942
	Alligator Cracking	0.047	0.035	0.985
	Thermal Cracking	0.607	0.336	0.634
	AC Rutting	0.913	0.363	0.298
	Total Rutting	0.874	0.144	0.358
	IRI	0.866	0.041	0.370
T	Longitudinal Cracking	0.107	0.370	0.954
	Alligator Cracking	0.050	0.026	0.984
	AC Rutting	0.864	0.267	0.372
	Total Rutting	0.786	0.117	0.467
	IRI	0.779	0.034	0.474
HD	Longitudinal Cracking	0.111	0.395	0.951
	Alligator Cracking	0.047	0.038	0.985
	AC Rutting	0.911	0.477	0.302
	Total Rutting	0.886	0.180	0.341
	IRI	0.879	0.051	0.351
HW	Longitudinal Cracking	0.112	0.387	0.951
	Alligator Cracking	0.049	0.035	0.984
	AC Rutting	0.869	0.355	0.366
	Total Rutting	0.803	0.148	0.448
	IRI	0.792	0.043	0.460

Table 9.11. Goodness-of-fit statistics for ANN RSMs – HMA Over Stiff Foundation.

Climate	Distress	NN	n	R²	RMSE	Se/Sy
CD	Longitudinal Cracking	25-5-1	1397	0.95	218.80	0.22
	Alligator Cracking	25-5-1	1397	0.86	0.38	0.38
	Thermal Cracking	29-5-1	911	0.97	147.43	0.18
	AC Rutting	25-5-1	1397	0.98	0.05	0.14
	Total Rutting	25-5-1	1397	0.99	0.04	0.11
	IRI	25-5-1	1397	0.99	1.38	0.10
CW	Longitudinal Cracking	25-5-1	1400	0.94	223.31	0.25
	Alligator Cracking	25-5-1	1400	0.88	0.31	0.35
	Thermal Cracking	29-8-1	1360	0.86	197.16	0.37
	AC Rutting	25-5-1	1400	0.98	0.04	0.13
	Total Rutting	25-5-1	1400	0.99	0.03	0.11
	IRI	25-5-1	1400	0.99	1.18	0.10
T	Longitudinal Cracking	25-5-1	1402	0.94	197.76	0.25
	Alligator Cracking	25-5-1	1402	0.87	0.25	0.37
	AC Rutting	25-5-1	1402	0.99	0.02	0.12
	Total Rutting	25-5-1	1402	0.99	0.02	0.12
	IRI	25-5-1	1402	0.99	0.81	0.10
HD	Longitudinal Cracking	25-5-1	1400	0.94	197.53	0.24
	Alligator Cracking	25-5-1	1400	0.87	0.35	0.37
	AC Rutting	25-5-1	1400	0.99	0.05	0.12
	Total Rutting	25-5-1	1400	0.99	0.04	0.10
	IRI	25-5-1	1400	0.99	1.50	0.09
HW	Longitudinal Cracking	25-5-1	1363	0.95	182.70	0.22
	Alligator Cracking	25-5-1	1363	0.91	0.27	0.31
	AC Rutting	25-5-1	1363	0.99	0.03	0.12
	Total Rutting	25-5-1	1363	0.99	0.03	0.11
	IRI	25-5-1	1363	0.99	1.10	0.11

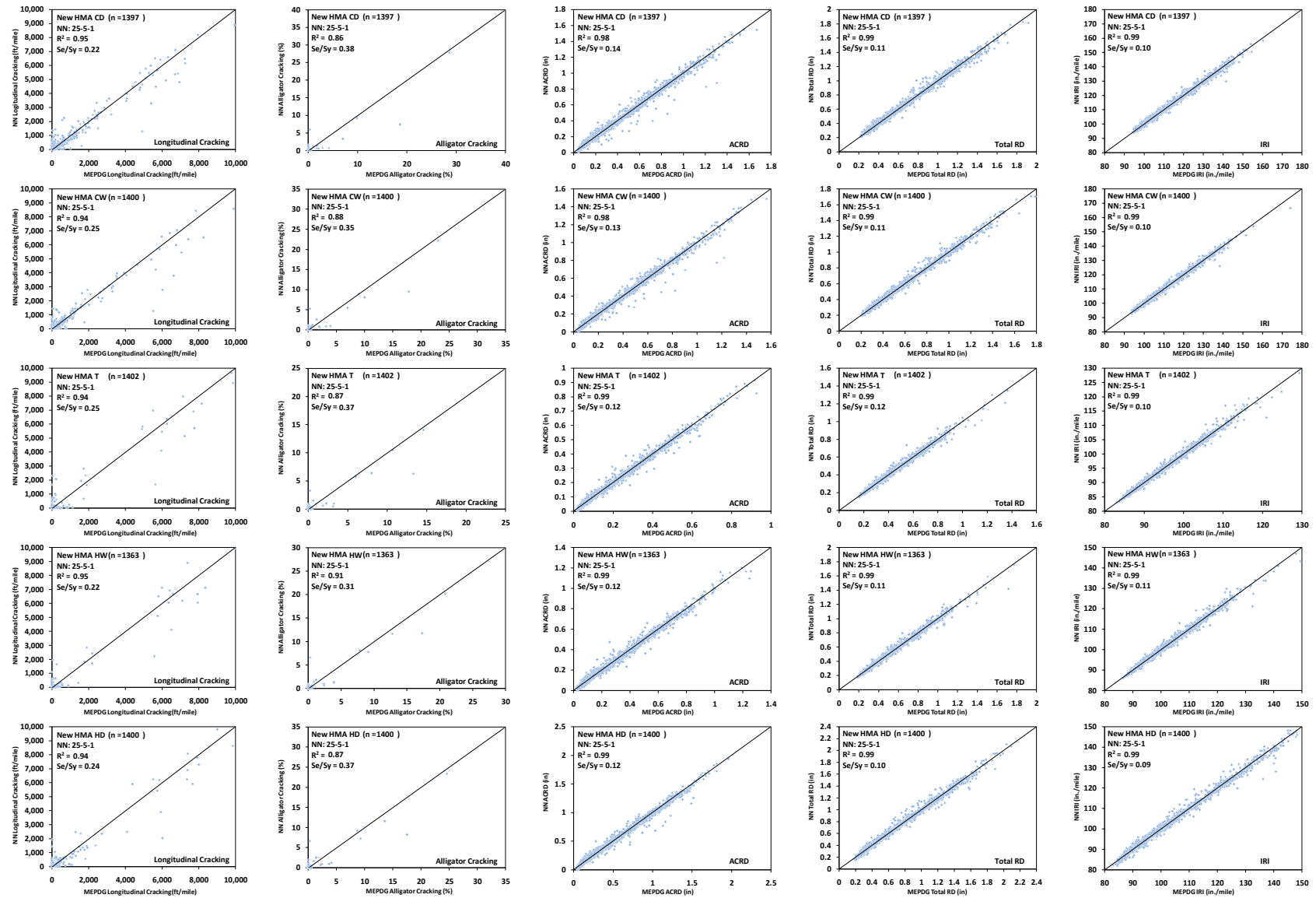


Figure 9.6. ANN predicted vs. MEDPG predicted distresses – HMA Over Stiff Foundation.

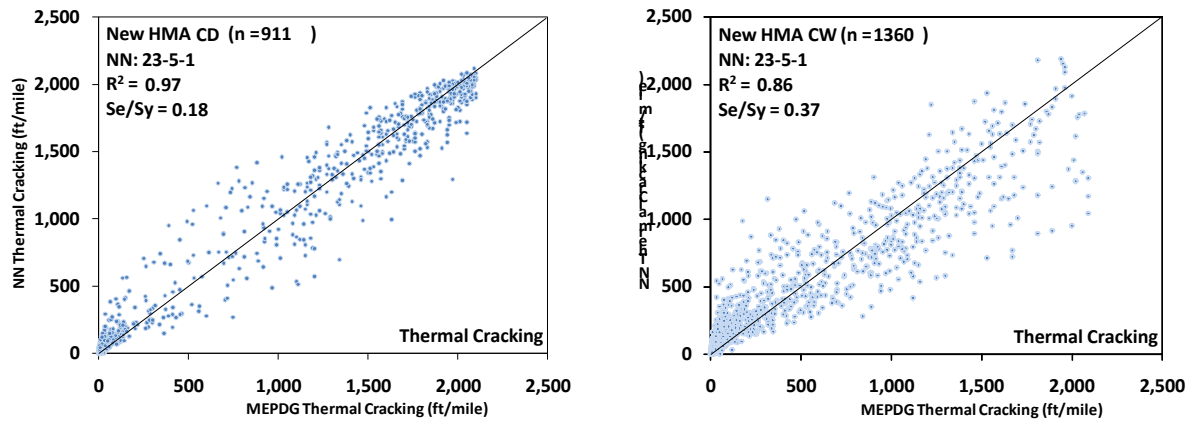


Figure 9.7. ANN predicted vs. MEDPG predicted distresses – HMA Over Stiff Foundation/Thermal Cracking.

9.4 Sensitivity Metrics

The average sensitivity indices from the MVL RSMs are summarized in Table 9.12 through Table 9.17. Recall that these average sensitivity indices quantify the percentage change in predicted distress relative to its design limit caused by a given percentage change in each design input relative to its mean value. The average sensitivities are just the regression coefficients from the normalized MVL RSMs, many of which had relatively poor goodness-of-fit statistics (Table 9.10). The values for the average sensitivity indices are all much smaller than the corresponding sensitivity indices computed in the OAT analyses, but this is because the OAT values represented the maximum across all of the base cases, not average values. The values in Table 9.12 through Table 9.17 are just very rough indicators of average sensitivities and do not account for variations in sensitivities across the problem domain.

Figure 9.8 and Figure 9.9 provide graphical summaries by distress and climate zone of the average sensitivities calculated using the MVL RSMs. The high-low-average plots in Figure 9.9 are additionally sorted by maximum average sensitivity (in an absolute value sense) to indicate more clearly the most important design inputs. The most sensitive inputs according to the MVL RSMs in rank order in terms of maximum absolute sensitivity across climate zones (sensitivity values equal to 0.50 or greater) by distress type are (the definitions of parameter can be found at Table 9.9):

- Longitudinal Cracking: Delta, Alpha, SubMr, SubLL, SSA
- Alligator Cracking: (none)
- Thermal Cracking: m, Alpha, Delta, TenStr14, Va, PGLow, D
- AC Rutting: Delta, Alpha, PRatio, SSA, HMAThickness, AADTTperLane, PGHigh, BaseThickness, OpSpd, PGLow
- Total Rutting: Delta, Alpha, SSA, PRatio
- IRI: Delta, Alpha

Most of these rankings are consistent with engineering judgment. However, there were a few surprises. Liquid limit for the subgrade (SubLL) has a surprising high sensitivity for longitudinal cracking. However, this may be due to the poor quality of fit for the longitudinal cracking MVL RSM ($R^2 < 0.2$, see Table 9.10). Poisson's ratio for HMA is conventionally thought to have only a minor influence on pavement performance but has surprisingly high sensitivity for AC and total rutting; the results here suggest that this conventional wisdom may need to be re-examined.

**Table 9.12. Average sensitivities from MVL RSMs – HMA Over Stiff Foundation
/Longitudinal Cracking.**

Design Input	Climate Zone				
	CD	CW	T	HD	HW
Constant	4.64	3.08	-0.18	1.45	-0.16
AADTTperLane	0.04	0.04	0.03	0.03	0.02
HMAThickness	0.38	0.25	0.06	0.14	0.07
BaseThickness	0.10	0.02	-0.07	-0.03	-0.08
OpSpd	0.01	0.05	0.10	0.09	0.11
PGHigh ¹	N.A.	N.A.	0.00	-0.02	0.01
PGLow ¹	-0.03	-0.02	N.A.	N.A.	N.A.
GWD	-0.02	-0.03	-0.03	-0.02	-0.03
SSA	0.64	0.45	0.07	0.22	0.05
UnitW	0.00	0.03	0.05	0.02	0.04
Pratio	-0.28	-0.23	-0.14	-0.17	-0.16
ThmlCn	-0.11	-0.12	-0.09	-0.08	-0.10
HtCp	-0.21	-0.22	-0.17	-0.19	-0.19
Delta	-3.78	-2.78	-0.73	-1.66	-0.82
Alpha	-2.93	-2.06	-0.24	-0.98	-0.22
Vbeff	-0.34	-0.26	-0.12	-0.21	-0.11
Va	-0.04	-0.12	-0.19	-0.16	-0.23
BaseUnitW	-0.12	-0.14	-0.10	-0.12	-0.13
BasePR	0.07	0.08	0.03	0.05	0.02
BaseMr	0.06	0.02	-0.05	-0.02	-0.05
BaseThCnd	0.08	0.02	-0.07	-0.02	-0.09
BaseHtCp	-0.20	-0.19	-0.15	-0.16	-0.15
SubMr	1.08	1.18	1.12	1.16	1.23
SubN200	0.02	0.05	0.07	0.05	0.08
SubPI	0.05	0.05	0.04	0.05	0.05
SubLL	0.82	0.85	0.79	0.87	0.85

¹Sensitivity per one grade increase in binder stiffness.

Table 9.13. Average sensitivities from MVL RSMs – HMA Over Stiff Foundation /Alligator Cracking.

Design Input	Climate Zone				
	CD	CW	T	HD	HW
Constant	-0.14	-0.13	-0.08	-0.11	-0.12
AADTTperLane	0.00	0.00	0.00	0.00	0.00
HMAThickness	0.00	0.00	0.00	0.00	0.00
BaseThickness	0.00	0.00	0.00	0.00	0.00
OpSpd	0.00	0.00	0.00	0.00	0.00
PGHigh ¹	0.00	0.00	0.00	0.00	0.00
PGLow ¹	0.00	0.00	0.00	0.00	0.00
GWD	0.00	0.00	0.00	0.00	0.00
SSA	-0.01	-0.01	0.00	-0.01	-0.01
UnitW	0.00	0.00	0.01	0.00	0.01
Pratio	0.00	0.00	0.00	0.00	0.00
ThmlCn	0.00	0.00	0.00	0.00	-0.01
HtCp	-0.01	-0.01	-0.01	-0.01	-0.01
Delta	0.05	0.05	0.03	0.05	0.04
Alpha	0.02	0.01	0.00	0.02	0.02
Vbeff	-0.01	0.00	0.00	-0.01	-0.01
Va	-0.02	-0.01	-0.01	-0.01	-0.01
BaseUnitW	-0.01	-0.01	-0.01	-0.01	-0.01
BasePR	0.02	0.01	0.00	0.01	0.01
BaseMr	0.00	0.00	0.00	0.00	0.00
BaseThCnd	-0.01	-0.01	0.00	-0.01	-0.01
BaseHtCp	-0.02	-0.01	-0.01	-0.01	-0.01
SubMr	0.07	0.06	0.05	0.07	0.07
SubN200	0.00	0.00	0.00	0.00	0.00
SubPI	0.00	0.00	0.00	0.00	0.00
SubLL	0.06	0.05	0.04	0.06	0.05

¹Sensitivity per one grade increase in binder stiffness.

Table 9.14. Average sensitivities from MVL RSMs – HMA Over Stiff Foundation /Thermal Cracking.

Design Input	Climate Zone	
	CD	CW
Constant	8.29	6.55
AADTTperLane	0.00	-0.01
HMAThickness	-0.37	-0.36
BaseThickness	0.08	0.10
OpSpd	0.00	-0.07
PGHigh ¹	0.01	0.01
PGLow ¹	0.63	0.08
GWD	0.04	0.00
SSA	-0.09	-0.14
UnitW	-0.28	-0.34
Pratio	-0.14	0.08
ThmlCn	-0.03	-0.37
HtCp	-0.25	-0.43
AggCoefContr	-0.02	-0.04
Delta	1.61	2.17
Alpha	-1.19	-1.69
Vbeff	0.21	0.10
Va	0.69	1.03
BaseUnitW	-0.23	-0.10
BasePR	-0.04	0.38
BaseMr	-0.06	0.01
BaseThCnd	-0.34	-0.48
BaseHtCp	-0.03	-0.15
SubMr	0.17	-0.27
SubN200	-0.07	-0.23
SubPI	-0.01	-0.01
SubLL	0.03	0.05
TenStr14	-0.52	-0.70
D	-0.49	-0.60
m	-3.07	-3.98

¹Sensitivity per one grade increase in binder stiffness.

Table 9.15. Average sensitivities from MVL RSMs – HMA Over Stiff Foundation/AC Rutting.

Design Input	Climate Zone				
	CD	CW	T	HD	HW
Constant	19.93	19.72	18.45	42.04	25.74
AADTTperLane	0.99	0.89	0.51	1.15	0.69
HMAThickness	1.15	1.04	0.56	1.38	0.79
BaseThickness	0.71	0.67	0.45	0.85	0.65
OpSpd	-0.55	-0.49	-0.20	-0.60	-0.29
PGHigh ¹	0.80	0.57	-0.24	-0.51	-0.28
PGLow ¹	-0.18	-0.16	0.38	0.85	0.50
GWD	0.00	-0.01	0.01	0.04	0.00
SSA	3.11	3.05	1.54	2.66	1.59
UnitW	-0.10	-0.14	-0.03	-0.09	0.01
Pratio	-2.53	-2.33	-1.51	-3.11	-2.08
ThmlCn	0.27	0.13	0.02	0.17	0.03
HtCp	-0.41	-0.43	-0.26	-0.48	-0.32
Delta	-14.95	-13.47	-8.17	-17.59	-11.25
Alpha	-13.72	-12.76	-7.98	-17.07	-10.79
Vbeff	-0.04	-0.06	-0.09	-0.07	-0.12
Va	0.05	0.04	0.05	0.09	0.07
BaseUnitW	-0.24	-0.17	-0.12	-0.19	-0.15
BasePR	0.03	0.05	0.00	0.07	0.01
BaseMr	0.31	0.28	0.12	0.32	0.17
BaseThCnd	-0.34	-0.25	-0.02	-0.17	-0.05
BaseHtCp	-0.09	-0.04	-0.06	-0.07	-0.07
SubMr	0.28	0.29	0.37	0.44	0.47
SubN200	0.10	0.08	0.02	0.09	0.01
SubPI	0.01	0.02	0.02	0.03	0.03
SubLL	0.06	0.09	0.29	0.29	0.38

¹Sensitivity per one grade increase in binder stiffness.

Table 9.16. Average sensitivities from MLVR RSMs – HMA Over Stiff Foundation /Total Rutting.

Design Input	Climate Zone				
	CD	CW	T	HD	HW
Constant	6.02	5.94	7.45	15.19	10.02
AADTTperLane	0.38	0.34	0.21	0.42	0.28
HMAThickness	0.32	0.29	0.14	0.42	0.21
BaseThickness	0.01	0.03	-0.01	0.14	0.03
OpSpd	-0.18	-0.16	-0.06	-0.19	-0.10
PGHigh ¹	0.48	0.40	-0.08	-0.17	-0.09
PGLow ¹	-0.06	-0.06	0.30	0.44	0.36
GWD	-0.01	-0.01	-0.02	-0.03	-0.01
SSA	1.09	1.07	0.56	0.92	0.57
UnitW	-0.04	-0.06	-0.02	-0.05	-0.01
Pratio	-0.89	-0.81	-0.52	-1.05	-0.72
ThmlCn	0.08	0.03	-0.01	0.04	-0.01
HtCp	-0.14	-0.15	-0.09	-0.17	-0.11
Delta	-5.36	-4.86	-3.03	-6.16	-4.09
Alpha	-4.80	-4.46	-2.84	-5.88	-3.77
Vbeff	-0.03	-0.04	-0.05	-0.04	-0.05
Va	0.05	0.04	0.04	0.05	0.05
BaseUnitW	-0.09	-0.06	-0.05	-0.07	-0.05
BasePR	-0.02	0.00	-0.02	0.02	-0.02
BaseMr	0.02	0.02	-0.02	0.06	0.00
BaseThCnd	-0.09	-0.05	0.02	-0.03	0.02
BaseHtCp	-0.08	-0.06	-0.05	-0.05	-0.06
SubMr	0.08	0.04	0.05	0.10	0.07
SubN200	-0.04	-0.03	-0.05	-0.02	-0.06
SubPI	0.02	0.02	0.02	0.02	0.02
SubLL	0.17	0.17	0.22	0.23	0.25

¹Sensitivity per one grade increase in binder stiffness.

Table 9.17. Average sensitivities from MVL RSMs – HMA Over Stiff Foundation/IRI.

Design Input	Climate Zone				
	CD	CW	T	HD	HW
Constant	0.03	0.08	2.40	4.50	3.16
AADTTperLane	0.10	0.09	0.06	0.12	0.08
HMAThickness	0.09	0.08	0.04	0.12	0.06
BaseThickness	0.00	0.01	0.00	0.04	0.01
OpSpd	-0.05	-0.04	-0.02	-0.05	-0.03
PGHigh ¹	0.34	0.31	-0.02	-0.05	-0.03
PGLow ¹	-0.02	-0.01	0.21	0.24	0.24
GWD	0.00	0.00	-0.01	-0.01	0.00
SSA	0.30	0.29	0.15	0.25	0.15
UnitW	-0.01	-0.02	0.00	-0.01	0.00
Pratio	-0.25	-0.22	-0.14	-0.29	-0.20
ThmlCn	0.02	0.01	0.00	0.01	0.00
HtCp	-0.04	-0.04	-0.03	-0.05	-0.03
Delta	-1.46	-1.32	-0.83	-1.69	-1.12
Alpha	-1.32	-1.23	-0.78	-1.62	-1.04
Vbeff	-0.01	-0.01	-0.01	-0.01	-0.02
Va	0.01	0.01	0.01	0.01	0.01
BaseUnitW	-0.03	-0.02	-0.01	-0.02	-0.01
BasePR	0.00	0.00	0.00	0.01	0.00
BaseMr	0.01	0.01	-0.01	0.02	0.00
BaseThCnd	-0.03	-0.02	0.00	-0.01	0.00
BaseHtCp	-0.02	-0.02	-0.01	-0.01	-0.02
SubMr	0.01	0.00	0.01	0.02	0.01
SubN200	0.00	0.00	-0.01	0.00	-0.01
SubPI	0.00	0.00	0.00	0.00	0.01
SubLL	0.05	0.05	0.06	0.07	0.08

¹Sensitivity per one grade increase in binder stiffness.

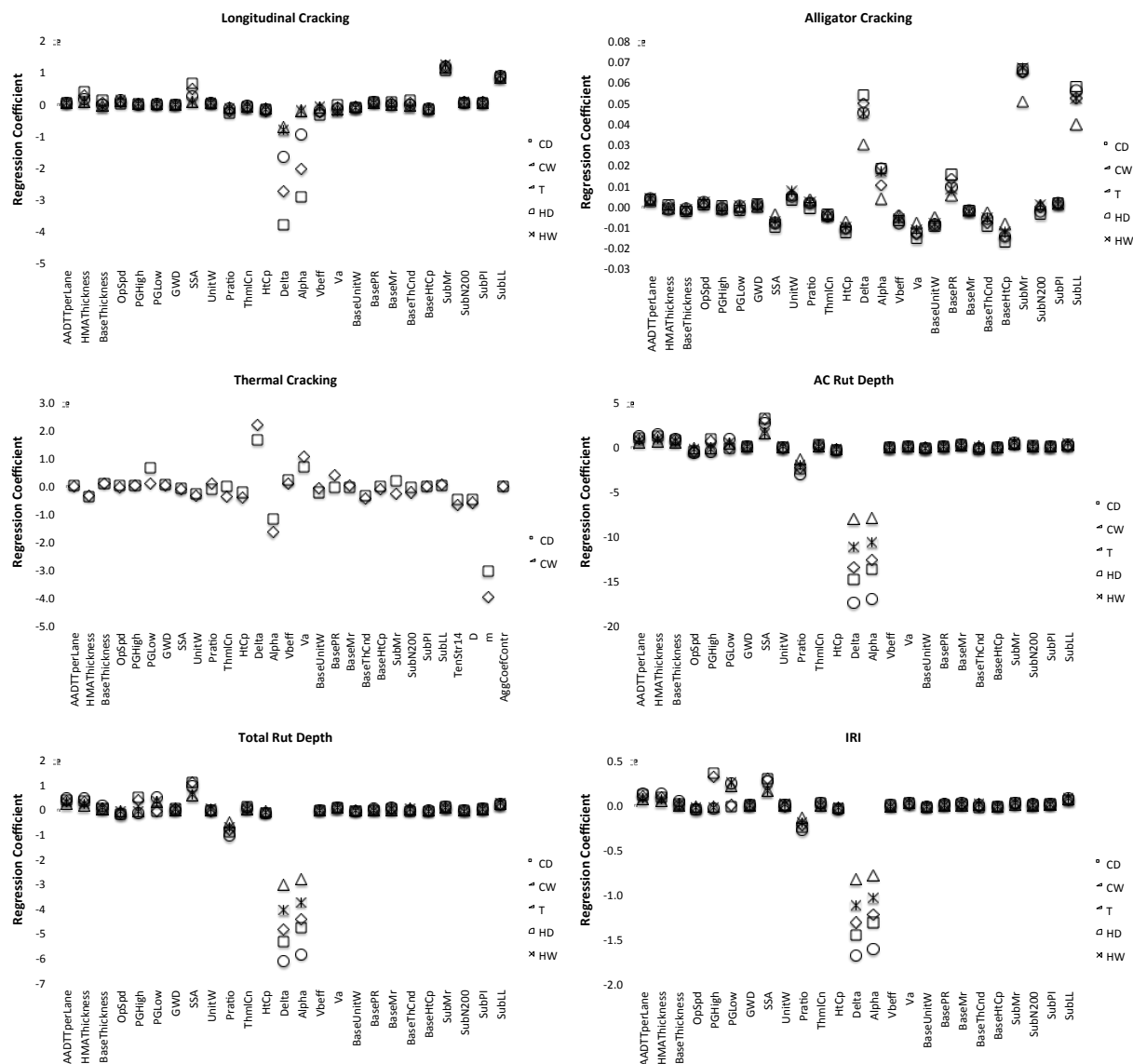


Figure 9.8. Average sensitivities from MVL RSMs – HMA Over Stiff Foundation.

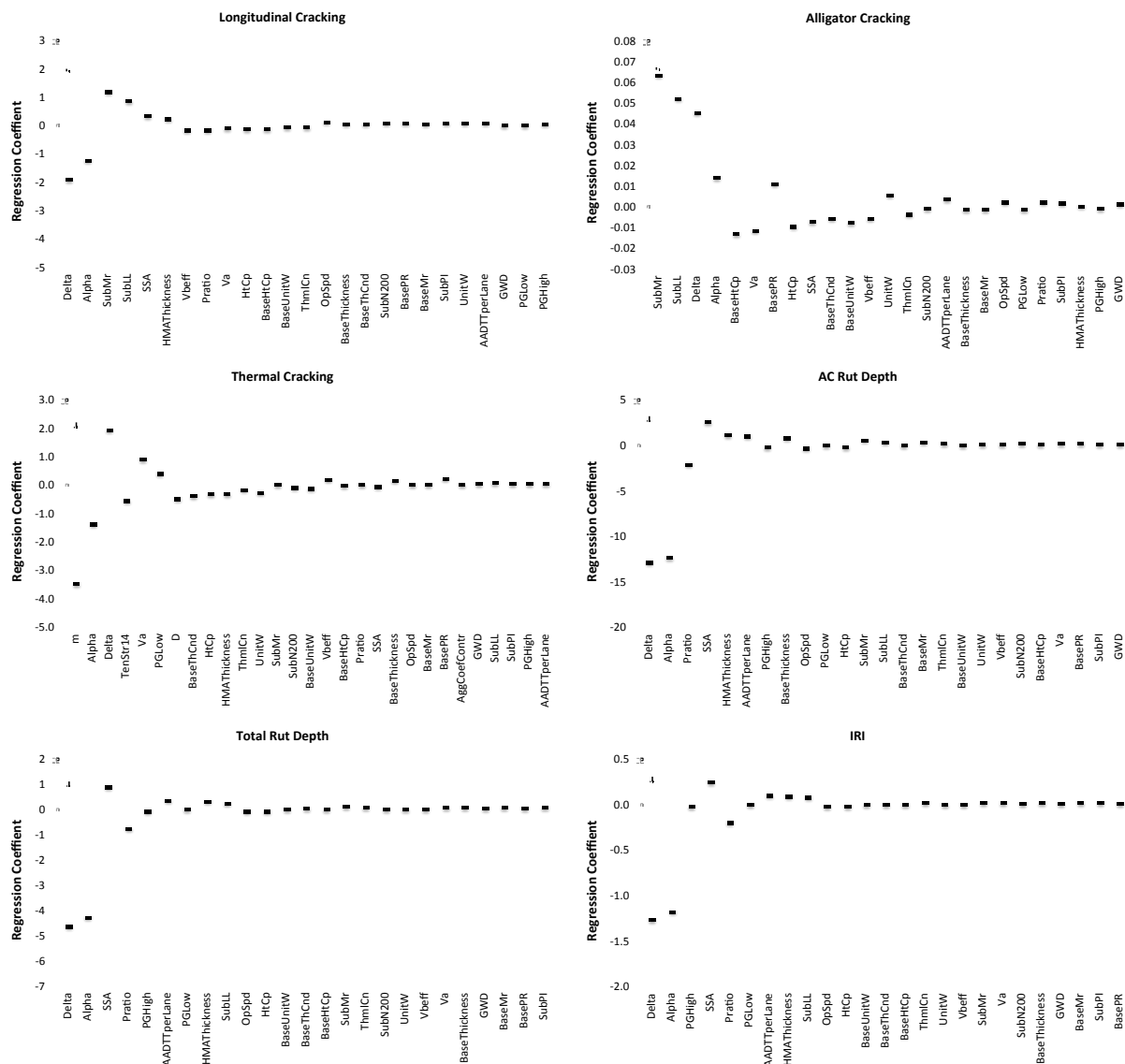


Figure 9.9. Ranking of average sensitivities from MVLR RSMs – HMA Over Stiff Foundation.

The ANN RSMs permit a more in-depth evaluation of sensitivities than does the MVLR approach. Ten thousand ANN RSMs were performed for each climate zone and distress combination using random sampling of all design inputs across the problem domain. The random sampling for these simulations was not by traffic level but rather spanned the full range of AADTT, HMA thickness, and base thickness values. Some of the random samples inevitably gave unrealistic pavement sections that produced excessively large predicted distresses—e.g., very high AADTT values combined with thin HMA and base layers. Consequently, any simulation for which any predicted distress exceeded three times its design limit was censored from the database. In general, fewer than 30% of the simulations for each climate zone-distress combination were censored.

Normalized sensitivity index (NSI) values were calculated for each of the 10,000 simulations for each climate zone-distress combination. The mean and standard deviations of the NSI values are summarized by climate zone in Table 9.18 through Table 9.23 for each respective distress. Full frequency distributions of the computed NSI values by design input and climate zone are depicted in

Figure 9.10 through Figure 9.15 for each respective distress. An important feature to note in the frequency distributions is that most have well-defined peaks: This implies that the NSI values are close to the mode at nearly all locations in the problem domain—i.e., NSI does not vary significantly over the problem domain. There are some exceptions where the NSI distributions are more broad, but in these instances all of the NSI values are either very low and not of interest or all very high and thus always of interest regardless of value. In no cases are there multiple peaks in the distributions. The influence of climate zone on the frequency distributions is also negligible in most cases. Where there are climate zone differences, they are nonsystematic.

Table 9.18. NSI statistics from ANN RSMs – HMA Over Stiff Foundation/Longitudinal Cracking.

Design Input	Climate Zone									
	CD		CW		T		HD		HW	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
AADTTperLane	0.14	0.30	0.16	0.29	0.04	0.13	0.07	0.16	0.04	0.24
HMAThickness	0.40	1.16	0.21	0.76	-0.03	0.28	0.13	0.38	0.14	0.44
BaseThickness	0.61	1.32	0.47	1.04	0.33	1.21	0.40	1.20	0.38	1.19
OpSpd	0.32	1.30	0.30	1.06	0.39	1.35	0.37	1.34	0.38	1.11
PGHigh	0.00	0.00	0.00	0.00	-0.10	0.25	-0.16	0.26	-0.08	0.22
PGLow	-0.02	0.25	0.00	0.13	0.00	0.00	0.00	0.00	0.00	0.00
GWD	-0.17	0.49	-0.13	0.40	-0.15	0.57	-0.11	0.46	-0.15	0.48
SSA	-0.02	2.44	0.51	1.87	-0.06	1.54	0.28	1.67	-0.02	1.24
UnitW	1.64	4.56	1.33	3.67	0.98	4.56	1.18	4.42	0.72	3.08
Pratio	-0.70	2.35	-0.38	1.40	-0.53	2.94	-1.00	2.97	-0.73	2.33
ThmlCn	-0.03	0.20	-0.14	0.30	0.06	0.34	0.07	0.35	0.02	0.41
HtCp	-0.78	1.82	-0.79	1.66	-0.72	2.26	-0.80	2.21	-0.59	1.57
Delta	-2.72	8.44	-0.26	7.39	0.39	5.34	0.38	5.29	0.51	6.47
Alpha	-2.75	9.64	-1.64	6.56	2.54	8.26	-1.49	4.45	1.03	4.13
Vbeff	-0.99	2.31	-0.54	1.39	-0.63	2.09	-0.59	1.39	-0.59	1.47
Va	-0.63	3.00	-0.54	2.55	-0.97	3.40	-0.99	3.57	-0.76	2.49
BaseUnitW	0.09	0.38	-0.16	0.65	-0.04	0.44	-0.11	0.46	-0.17	0.83
BasePR	0.66	2.11	0.65	2.18	0.75	2.40	0.61	2.16	0.19	1.73
BaseMr	-0.02	0.73	-0.08	0.57	-0.19	0.72	-0.11	0.56	-0.15	0.58
BaseThmlCn	-0.67	1.78	-0.56	1.69	-0.67	2.19	-0.61	1.90	-0.46	1.51
BaseHtCp	-0.32	0.90	-0.27	0.70	-0.24	0.88	-0.39	0.89	-0.19	0.87
SubMr	0.71	2.37	0.83	1.98	0.72	2.55	0.45	1.41	0.44	1.58
SubN200	0.24	1.02	0.20	0.61	0.34	1.22	0.16	0.60	0.18	0.70
SubPI	0.21	0.60	0.22	0.59	0.19	0.65	0.24	0.71	0.26	0.68
SubLL	1.11	2.83	1.12	2.60	0.84	2.41	1.05	2.71	0.87	2.07

Table 9.19. NSI statistics from ANN RSMs – HMA Over Stiff Foundation/Alligator Cracking.

Design Input	Climate Zone									
	CD		CW		T		HD		HW	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
AADTTperLane	0.07	0.24	0.03	0.24	-0.01	0.14	0.04	0.15	-0.03	0.24
HMAThickness	0.02	0.12	0.18	0.52	0.17	0.48	0.02	0.10	0.30	0.76
BaseThickness	0.03	0.09	0.08	0.17	0.02	0.07	0.01	0.07	0.15	0.76
OpSpd	0.04	0.13	0.02	0.16	0.01	0.09	0.03	0.09	0.03	0.27
PGHigh	0.00	0.00	0.00	0.00	-0.01	0.03	-0.01	0.02	-0.03	0.10
PGLow	-0.01	0.03	-0.02	0.04	0.00	0.00	0.00	0.00	0.00	0.00
GWD	0.00	0.02	0.00	0.02	0.00	0.02	0.00	0.03	-0.01	0.11
SSA	0.03	0.21	0.03	0.17	-0.01	0.10	0.04	0.13	-0.10	0.88
UnitW	0.06	0.16	0.16	0.42	0.12	0.24	0.03	0.16	0.39	1.65
Pratio	-0.05	0.17	-0.09	0.20	-0.02	0.07	-0.04	0.17	-0.19	0.96
ThmlCn	-0.02	0.10	-0.06	0.19	-0.04	0.11	-0.02	0.06	-0.09	0.26
HtCp	-0.08	0.18	-0.13	0.23	-0.09	0.16	-0.06	0.13	-0.21	0.84
Delta	0.92	2.00	1.18	2.13	0.88	1.62	0.55	1.05	1.75	3.63
Alpha	0.44	1.40	-0.04	0.69	-0.15	0.54	0.12	0.59	-0.09	1.91
Vbeff	-0.03	0.28	0.03	0.32	0.02	0.18	-0.03	0.25	0.09	0.41
Va	-0.08	0.20	-0.10	0.33	-0.08	0.20	-0.02	0.13	-0.30	1.11
BaseUnitW	-0.06	0.17	-0.01	0.11	-0.02	0.08	-0.02	0.09	0.00	0.29
BasePR	0.12	0.27	0.11	0.27	0.07	0.18	0.05	0.17	0.19	1.03
BaseMr	-0.01	0.04	0.00	0.03	0.00	0.02	-0.01	0.04	-0.01	0.12
BaseThmlCn	-0.12	0.24	-0.12	0.22	-0.06	0.12	-0.10	0.19	-0.17	0.62
BaseHtCp	-0.10	0.20	-0.09	0.15	-0.05	0.09	-0.05	0.09	-0.09	0.19
SubMr	0.16	0.32	0.16	0.27	0.10	0.17	0.06	0.14	0.17	0.39
SubN200	0.00	0.07	0.03	0.15	0.03	0.10	-0.01	0.07	0.06	0.23
SubPI	0.03	0.10	0.03	0.08	0.02	0.04	0.02	0.06	0.04	0.22
SubLL	0.26	0.62	0.29	0.61	0.16	0.32	0.19	0.46	0.35	1.06

Table 9.20. NSI statistics from ANN RSMs – HMA Over Stiff Foundation/Thermal Cracking.

Design Input	Climate Zone			
	CD		CW	
	Mean	Std Dev	Mean	Std Dev
AADTTperLane	0.00	0.02	0.00	0.03
HMAThickness	-0.23	0.24	-0.13	0.24
BaseThickness	0.07	0.07	0.06	0.08
OpSpd	0.01	0.03	-0.03	0.06
PGHigh	0.00	0.00	0.00	0.00
PGLow	-0.36	0.28	-0.04	0.04
GWD	0.02	0.03	0.00	0.03
SSA	-0.11	0.14	-0.03	0.12
UnitW	-0.35	0.33	-0.20	0.28
Pratio	0.06	0.10	-0.02	0.14
ThmlCn	-0.07	0.14	-0.16	0.20
HtCp	-0.16	0.18	-0.17	0.25
AggCoefContr	0.00	0.06	0.00	0.08
Delta	0.99	1.26	-0.07	0.45
Alpha	-0.16	0.66	-0.40	1.21
Vbeff	0.02	0.06	-0.19	0.26
Va	0.52	0.56	0.45	0.69
BaseUnitW	-0.11	0.18	-0.06	0.12
BasePR	-0.12	0.17	0.10	0.16
BaseMr	-0.02	0.04	0.00	0.03
BaseThmlCn	-0.28	0.28	-0.14	0.23
BaseHtCp	0.02	0.05	-0.07	0.17
SubMr	-0.06	0.14	0.01	0.18
SubN200	-0.10	0.13	-0.04	0.11
SubPI	-0.01	0.03	0.00	0.02
SubLL	-0.01	0.06	0.03	0.07
TenStr14	-0.51	0.57	-0.41	0.55
D	-0.34	0.37	-0.26	0.42
m	-2.22	2.21	-1.60	2.25

Table 9.21. NSI statistics from ANN RSMs – HMA Over Stiff Foundation/AC Rutting.

Design Input	Climate Zone									
	CD		CW		T		HD		HW	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
AADTTperLane	1.21	0.62	1.12	0.58	0.63	0.36	1.37	0.79	0.87	0.50
HMAThickness	0.80	0.89	0.68	0.87	0.41	0.49	1.21	0.95	0.58	0.63
BaseThickness	0.67	0.32	0.63	0.33	0.49	0.35	0.92	0.54	0.68	0.38
OpSpd	-0.72	0.34	-0.63	0.33	-0.28	0.25	-0.79	0.41	-0.43	0.31
PGHigh	0.00	0.00	0.00	0.00	-0.28	0.13	-0.66	0.25	-0.34	0.16
PGLow	0.22	0.08	0.20	0.08	0.00	0.00	0.00	0.00	0.00	0.00
GWD	0.02	0.06	0.00	0.06	0.02	0.04	0.09	0.13	0.00	0.04
SSA	4.14	1.65	3.88	1.73	1.87	0.84	3.40	1.53	1.91	0.85
UnitW	-0.25	0.21	-0.27	0.22	-0.03	0.83	-0.20	0.63	-0.07	0.75
Pratio	-2.80	0.80	-2.52	0.83	-1.62	0.64	-3.47	1.05	-2.20	0.84
ThmlCn	0.30	0.16	0.11	0.10	0.06	0.10	0.23	0.18	0.09	0.09
HtCp	-0.51	0.26	-0.54	0.26	-0.31	0.23	-0.58	0.39	-0.32	0.20
Delta	-18.73	6.53	-16.22	6.80	-10.02	5.07	-22.74	10.26	-12.90	5.25
Alpha	-17.34	7.05	-15.86	7.01	-10.41	4.42	-21.29	9.02	-13.62	5.77
Vbeff	-0.10	0.23	-0.09	0.31	-0.08	0.30	-0.23	0.88	-0.10	0.44
Va	-0.06	0.13	-0.04	0.14	-0.07	0.21	0.03	0.29	0.04	0.20
BaseUnitW	-0.54	0.39	-0.37	0.41	-0.16	0.31	-0.52	0.85	-0.10	0.23
BasePR	-0.19	0.36	-0.05	0.39	-0.01	0.28	-0.26	1.26	0.12	0.25
BaseMr	0.32	0.23	0.28	0.22	0.11	0.23	0.31	0.32	0.20	0.28
BaseThmlCn	-0.54	0.25	-0.41	0.24	-0.17	0.16	-0.46	0.33	-0.20	0.20
BaseHtCp	-0.17	0.13	-0.13	0.11	-0.07	0.27	-0.08	0.17	-0.13	0.36
SubMr	0.09	0.42	0.10	0.43	0.05	0.66	0.13	0.42	0.26	0.80
SubN200	0.08	0.20	0.08	0.25	0.00	0.23	0.08	0.19	0.06	0.21
SubPI	0.02	0.05	0.04	0.11	0.01	0.07	0.09	0.30	0.01	0.05
SubLL	-0.02	0.28	-0.05	0.26	0.00	0.29	0.06	0.46	0.04	0.24

Table 9.22. NSI statistics from ANN RSMs – HMA Over Stiff Foundation/Total Rutting.

Design Input	Climate Zone									
	CD		CW		T		HD		HW	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
AADTTperLane	0.41	0.17	0.40	0.17	0.23	0.11	0.49	0.21	0.32	0.15
HMAThickness	0.29	0.19	0.18	0.26	0.11	0.14	0.32	0.27	0.12	0.23
BaseThickness	0.01	0.07	0.03	0.08	-0.01	0.07	0.13	0.09	0.01	0.08
OpSpd	-0.24	0.16	-0.22	0.13	-0.09	0.11	-0.27	0.16	-0.14	0.11
PGHigh	0.00	0.00	0.00	0.00	-0.10	0.05	-0.20	0.09	-0.10	0.06
PGLow	0.07	0.04	0.06	0.03	0.00	0.00	0.00	0.00	0.00	0.00
GWD	-0.01	0.02	0.00	0.03	-0.01	0.01	-0.02	0.02	-0.01	0.01
SSA	1.32	0.59	1.29	0.58	0.64	0.31	1.08	0.47	0.65	0.30
UnitW	-0.08	0.24	-0.11	0.27	-0.07	0.04	-0.10	0.14	-0.06	0.11
Pratio	-1.06	0.39	-0.91	0.38	-0.56	0.34	-1.09	0.44	-0.71	0.41
ThmlCn	0.11	0.07	0.05	0.05	0.02	0.03	0.09	0.05	0.03	0.02
HtCp	-0.18	0.10	-0.16	0.10	-0.09	0.06	-0.18	0.09	-0.11	0.06
Delta	-6.30	2.46	-5.56	2.31	-3.41	1.53	-7.07	2.84	-4.38	1.95
Alpha	-5.95	2.32	-5.39	2.31	-3.52	1.77	-7.10	3.01	-4.51	2.10
Vbeff	0.01	0.11	-0.02	0.07	-0.03	0.19	-0.01	0.12	-0.02	0.10
Va	-0.01	0.10	-0.04	0.11	-0.01	0.05	0.01	0.05	0.00	0.02
BaseUnitW	-0.09	0.12	-0.07	0.09	0.01	0.13	-0.03	0.05	-0.02	0.05
BasePR	-0.05	0.25	-0.04	0.18	0.00	0.11	0.07	0.08	0.02	0.06
BaseMr	0.03	0.08	0.03	0.08	0.00	0.08	0.07	0.12	0.01	0.10
BaseThmlCn	-0.17	0.12	-0.13	0.09	-0.05	0.08	-0.13	0.10	-0.07	0.10
BaseHtCp	-0.06	0.08	-0.03	0.06	-0.04	0.20	-0.03	0.13	-0.03	0.11
SubMr	-0.12	0.80	-0.13	0.46	-0.06	0.08	-0.03	0.15	-0.06	0.12
SubN200	-0.01	0.11	-0.03	0.09	-0.01	0.06	-0.01	0.07	-0.02	0.05
SubPI	0.01	0.02	0.01	0.01	0.01	0.04	0.00	0.01	0.01	0.01
SubLL	0.04	0.07	0.00	0.05	0.01	0.07	0.03	0.08	0.02	0.04

Table 9.23. NSI statistics from ANN RSMs – HMA Over Stiff Foundation/IRI.

Design Input	Climate Zone									
	CD		CW		T		HD		HW	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
AADTTperLane	0.12	0.05	0.11	0.05	0.07	0.03	0.14	0.06	0.09	0.04
HMAThickness	0.04	0.11	0.03	0.11	0.01	0.06	0.07	0.11	0.03	0.08
BaseThickness	0.00	0.02	0.01	0.04	0.00	0.02	0.04	0.03	0.01	0.04
OpSpd	-0.07	0.04	-0.06	0.05	-0.03	0.02	-0.07	0.05	-0.03	0.04
PGHigh	0.00	0.00	0.00	0.00	-0.03	0.01	-0.05	0.03	-0.03	0.03
PGLow	0.02	0.01	0.01	0.03	0.00	0.00	0.00	0.00	0.00	0.00
GWD	0.00	0.00	0.00	0.01	0.00	0.01	-0.01	0.01	0.00	0.01
SSA	0.35	0.17	0.33	0.26	0.18	0.09	0.29	0.14	0.18	0.10
UnitW	-0.03	0.06	-0.01	0.18	-0.01	0.06	-0.02	0.08	-0.01	0.07
Pratio	-0.26	0.10	-0.25	0.14	-0.14	0.08	-0.29	0.14	-0.22	0.20
ThmlCn	0.03	0.03	0.00	0.07	0.00	0.01	0.02	0.01	0.00	0.03
HtCp	-0.04	0.03	-0.05	0.04	-0.03	0.02	-0.05	0.04	-0.04	0.10
Delta	-1.69	0.67	-1.52	0.63	-0.93	0.40	-1.89	0.80	-1.18	0.63
Alpha	-1.62	0.74	-1.49	0.70	-0.97	0.44	-1.95	0.86	-1.36	0.86
Vbeff	-0.01	0.05	-0.01	0.08	-0.01	0.02	0.00	0.02	0.00	0.05
Va	0.00	0.02	-0.01	0.04	0.00	0.03	0.00	0.02	0.00	0.04
BaseUnitW	-0.02	0.03	0.00	0.06	-0.01	0.02	-0.01	0.01	0.01	0.10
BasePR	0.00	0.06	0.00	0.08	0.01	0.01	0.01	0.02	0.00	0.05
BaseMr	0.01	0.03	0.00	0.04	0.00	0.02	0.01	0.03	0.00	0.06
BaseThmlCn	-0.05	0.04	-0.04	0.07	-0.01	0.02	-0.03	0.03	-0.02	0.05
BaseHtCp	-0.02	0.04	-0.02	0.07	-0.01	0.03	-0.01	0.05	-0.03	0.10
SubMr	-0.04	0.10	-0.04	0.12	-0.05	0.08	-0.03	0.11	-0.04	0.09
SubN200	0.00	0.03	0.00	0.03	0.00	0.01	0.01	0.03	0.00	0.05
SubPI	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
SubLL	0.00	0.03	0.00	0.03	0.00	0.01	0.01	0.04	-0.01	0.08

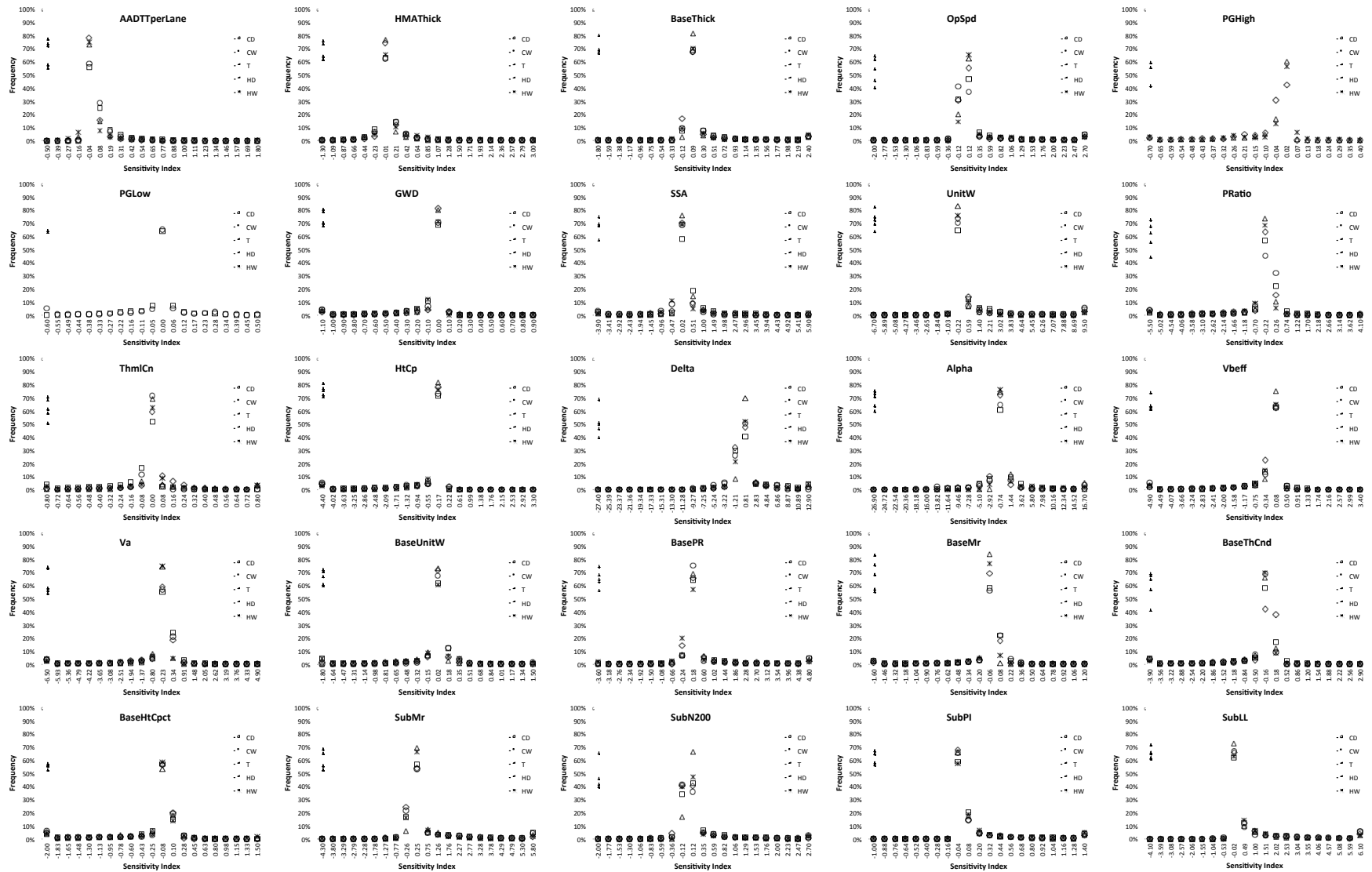


Figure 9.10. Distributions of NSI values – HMA Over Stiff Foundation/Longitudinal Cracking.

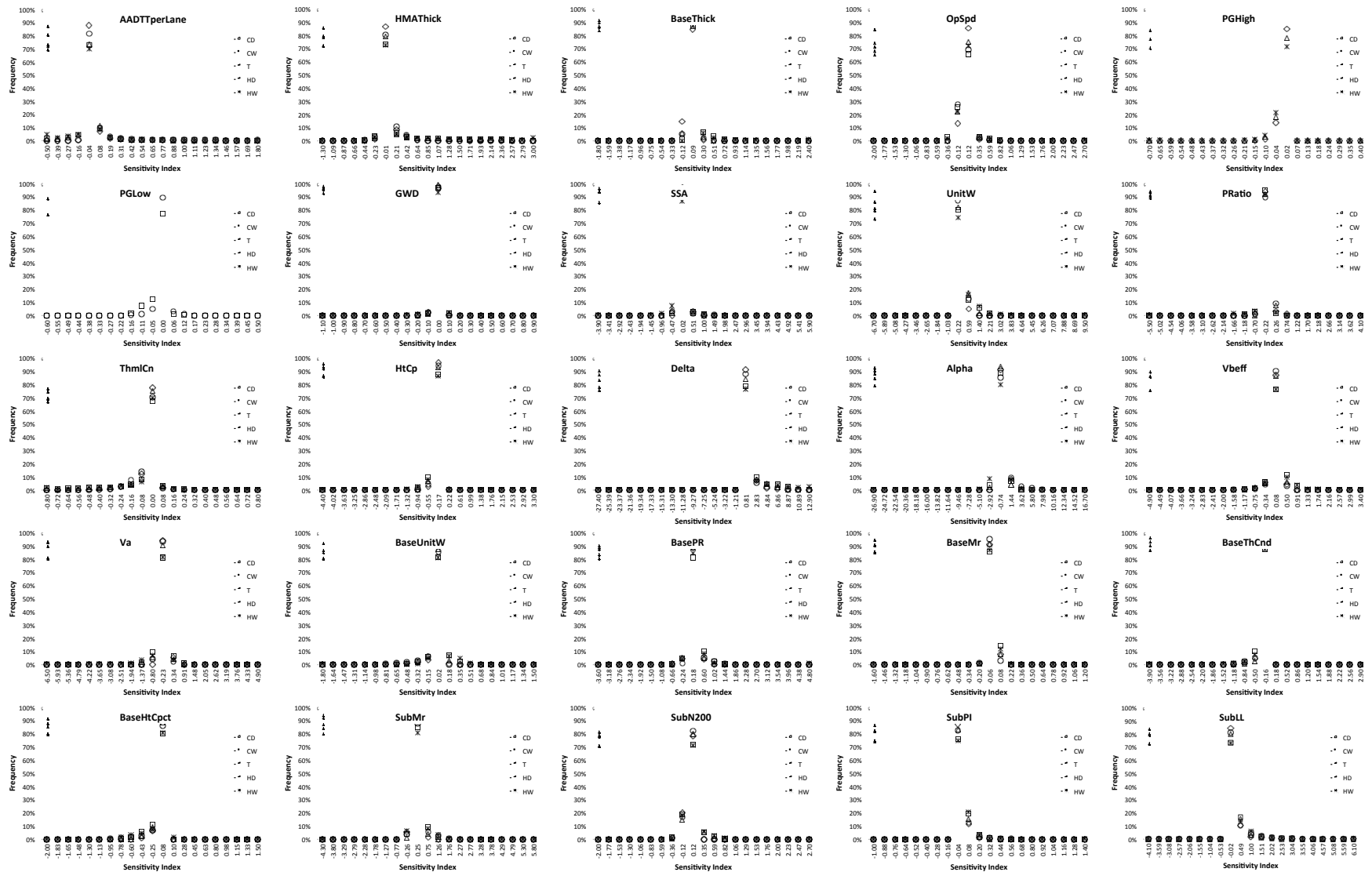


Figure 9.11. Distributions of NSI values – HMA Over Stiff Foundation/Alligator Cracking.

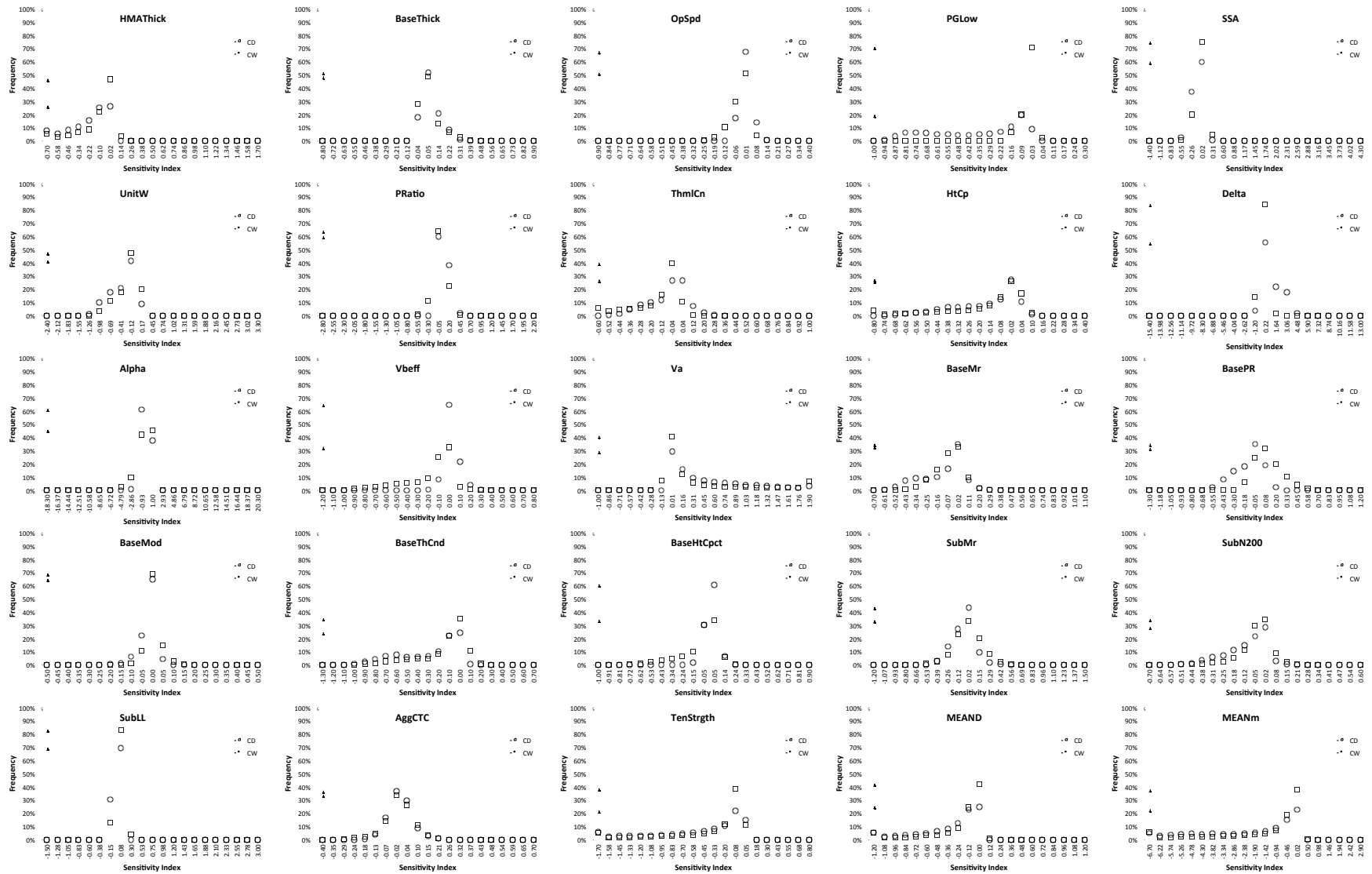


Figure 9.12. Distributions of NSI values – HMA Over Stiff Foundation/Thermal Cracking.

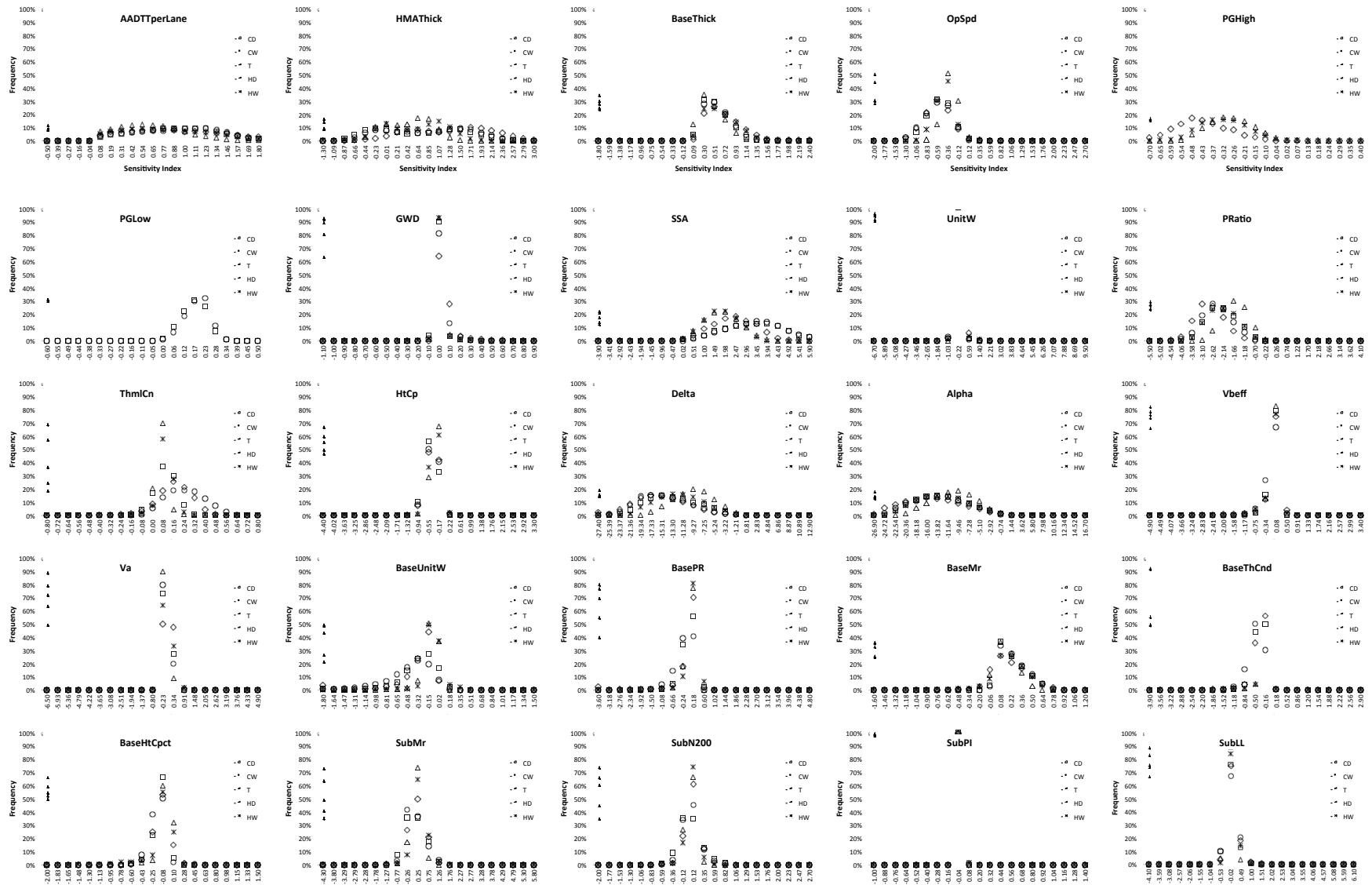


Figure 9.13. Distributions of NSI values – HMA Over Stiff Foundation/AC Rutting

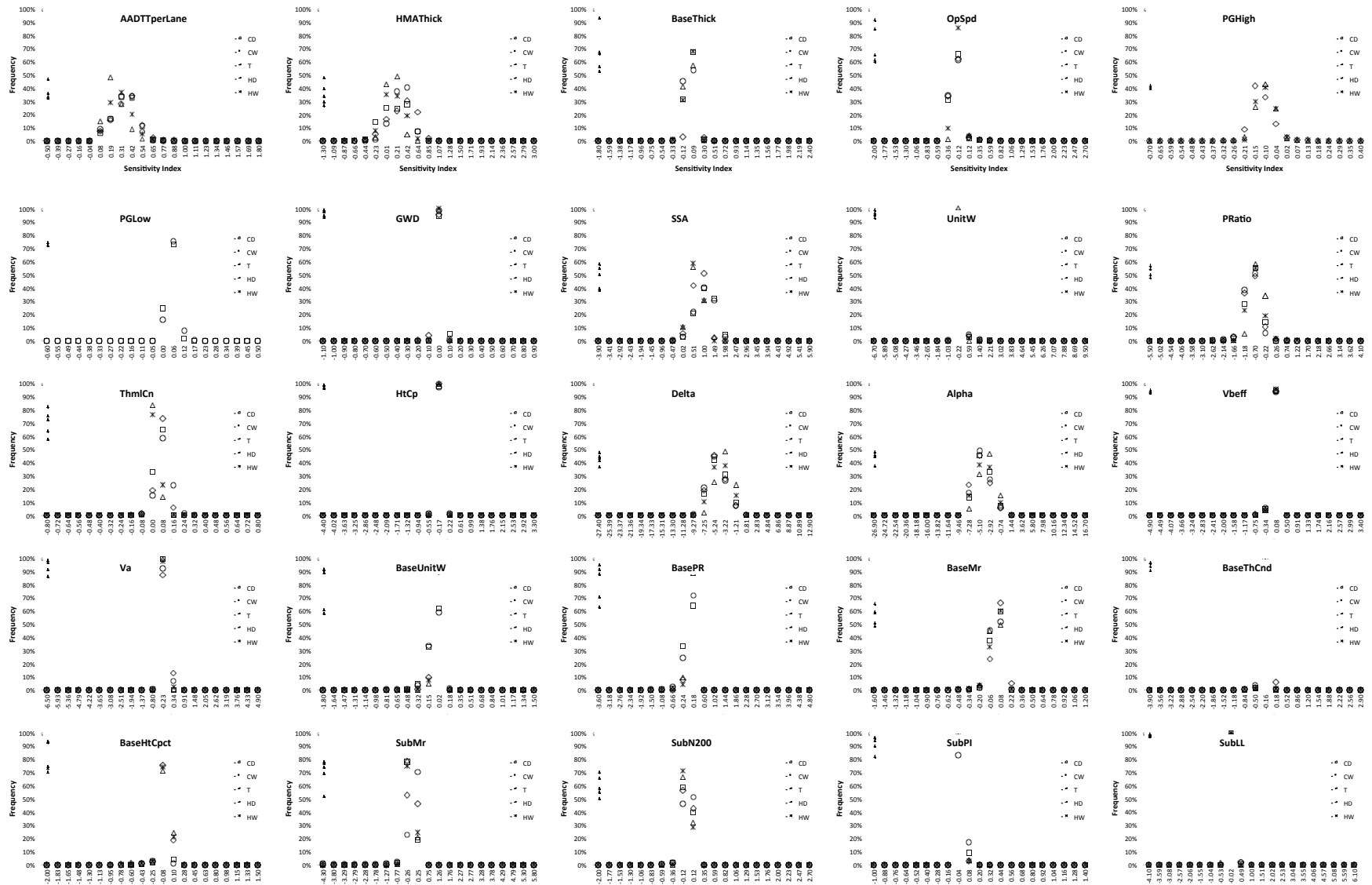


Figure 9.14. Distributions of NSI values – HMA Over Stiff Foundation./Total Rutting

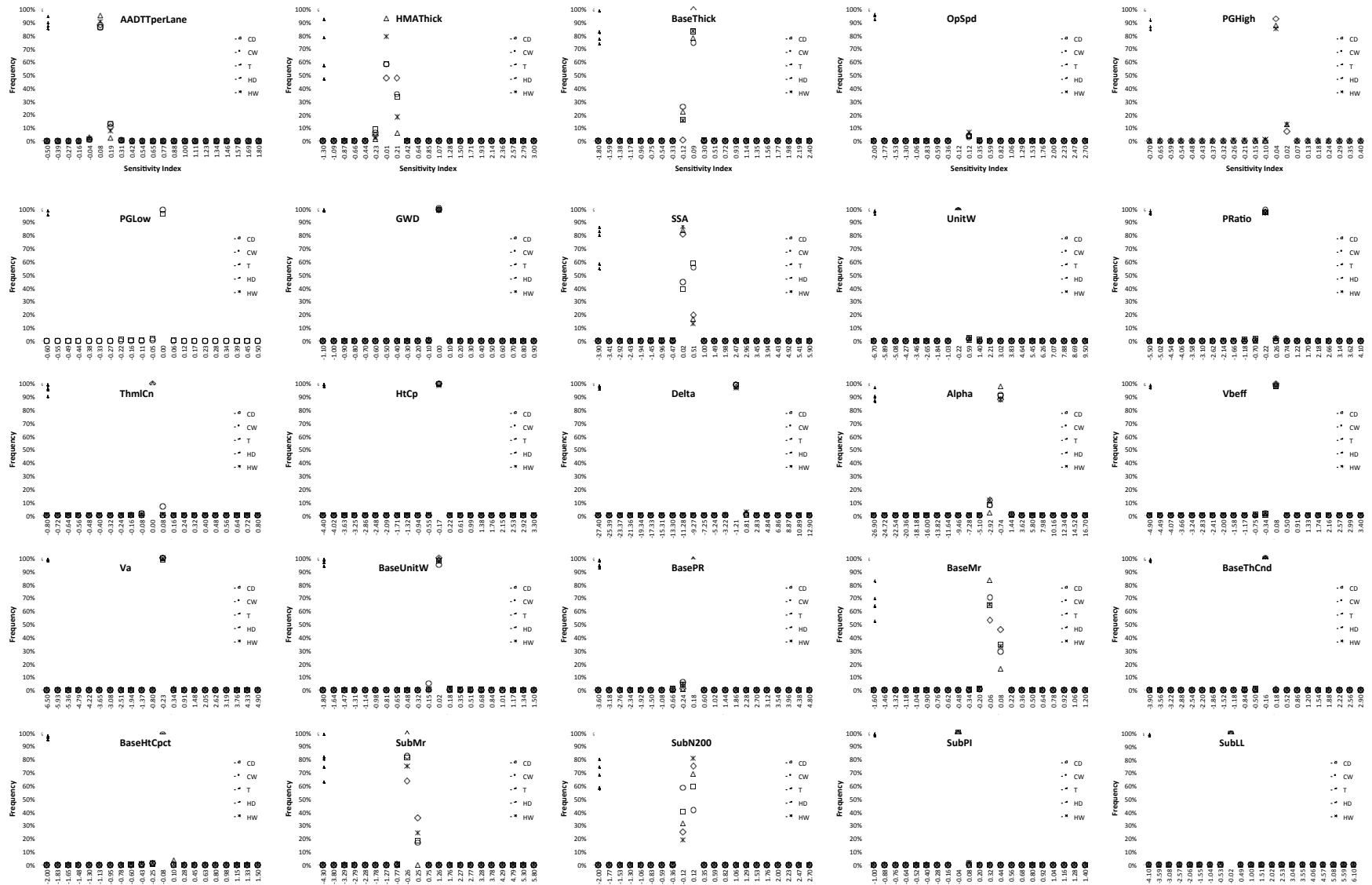


Figure 9.15. Distributions of NSI values – HMA Over Stiff Foundation./IRI

9.5 Conclusions – HMA Over Stiff Foundation

The maximum average sensitivity coefficients from the MVL RSMs across climate zones for all distress and design input combinations are ranked by maximum absolute sensitivity across distresses in Table 9.24. Even though the ranking is by maximum absolute sensitivity, the plus and minus signs are retained for each individual sensitivity coefficient to indicate whether distress increases (+) or decreases (-) with increasing input value. Usually—and especially for the highest sensitivity inputs—the plus/minus signs for each design input are consistent across all distresses.

The OAT local sensitivity category (Appendix B) for each design input is also indicated in Table 9.24. There is a lack of full congruence between the ranking of inputs from the MVL RSMs and the categorization from the OAT analyses. The four design inputs categorized as HS in the OAT analyses are also the highest-ranked design inputs in Table 9.24, and most of the inputs categorized as VS in the OAT analyses also appear high in the list. However, there is some mixing of the VS and S inputs in the middle and lower portion of the rankings. Recall, however, that the goodness-of-fit statistics for many of the MVL RSMs were quite low and that the computed sensitivity coefficients are averages across the problem domain.

Table 9.24. Ranking of HMA Over Stiff Foundation design inputs by overall maximum |Average Sensitivity Coefficient| (MVL RSMs).

Design Input	Maximum Average Sensitivity Coefficient (MVL RSM)							OAT Category ¹
	Long Crk	AllCrk	ThermCrk	ACRD	TotRD	IRI	Maximum	
Delta	-3.78	0.05	1.61	-17.59	-6.16	-1.69	-17.59	HS
Alpha	-2.93	0.02	-1.69	-17.07	-5.88	-1.62	-17.07	HS
m	N.A.	N.A.	-3.98	N.A.	N.A.	N.A.	-3.98	VS
Pratio	-0.28	0.00	-0.14	-3.11	-1.05	-0.29	-3.11	HS
SSA	0.64	-0.01	-0.14	3.11	1.09	0.30	3.11	HS
SubMr	1.23	0.07	-0.27	0.47	0.08	0.01	1.23	S
HMAThickness	0.38	0.00	-0.37	1.15	0.32	0.09	1.15	VS
AADTTperLane	0.04	0.00	-0.01	0.99	0.38	0.10	0.99	VS
SubLL	0.85	0.06	0.03	0.38	0.25	0.08	0.85	S
PGHigh	-0.02	0.00	0.01	0.80	0.48	0.34	0.80	VS
BaseThickness	0.10	0.00	0.08	0.71	0.03	0.01	0.71	VS
TenStr14	N.A.	N.A.	-0.70	N.A.	N.A.	N.A.	-0.70	VS
Va	-0.23	-0.02	0.69	0.07	0.05	0.01	0.69	VS
PGLow	-0.03	0.00	0.63	0.50	0.36	0.24	0.63	S
D	N.A.	N.A.	-0.60	N.A.	N.A.	N.A.	-0.60	VS
OpSpd	0.11	0.00	-0.07	-0.60	-0.19	-0.05	-0.60	VS
BaseThCnd	-0.09	-0.01	-0.48	-0.34	-0.09	-0.03	-0.48	S
HtCp	-0.22	-0.01	-0.43	-0.48	-0.17	-0.05	-0.48	S
ThmlCn	-0.12	-0.01	-0.37	0.27	0.08	0.02	-0.37	S
Vbeff	-0.34	-0.01	0.21	-0.12	-0.05	-0.02	-0.34	VS
UnitW	0.04	0.01	-0.34	-0.14	-0.06	-0.02	-0.34	VS
BaseMr	0.06	0.00	-0.06	0.31	0.02	0.01	0.31	S
BaseUnitW	-0.14	-0.01	-0.23	-0.24	-0.09	-0.03	-0.24	S
SubN200	0.08	0.00	-0.23	0.10	-0.06	-0.01	-0.23	S
BaseHtCp	-0.20	-0.02	-0.15	-0.09	-0.08	-0.02	-0.20	S
BasePR	0.07	0.02	-0.04	0.03	-0.02	0.00	0.07	S
SubPI	0.05	0.00	-0.01	0.03	0.02	0.01	0.05	S
AggCoefContr	N.A.	N.A.	-0.04	N.A.	N.A.	N.A.	-0.04	NS
GWD	-0.03	0.00	0.04	-0.01	-0.03	-0.01	0.04	S

¹HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Non-Sensitive

The maximum Mean NSI values across climate zones for all distress and design input combinations are ranked by maximum absolute sensitivity across distresses in Table 9.25. The Mean NSI values were computed from the 10,000 ANN RSM evaluations for each climate zone and distress combination (Table 9.12 through Table 9.17). The plus and minus signs are again retained for each individual sensitivity index to indicate whether distress increases (+) or decreases (-) with increasing input value.

The OAT local sensitivity category (Appendix B) for each design input is also indicated in Table 9.25. There is a lack of full congruence between the ranking of inputs from the ANN RSMs and the categorization from the OAT analyses. Four of the five design inputs categorized as HS in the OAT analyses are the highest-ranked design inputs in Table 9.25. Thermal conductivity of base layer (BaseThCnd), which was categorized as HS in the OAT analyses, dropped into middle range in Table 9.25. Recall that the ANN RSMs evaluates global sensitivity to thermal properties over 3 different binder grades while the OAT analyses calculate local sensitivities only around a single reference case. There is some additional mixing of the VS and S inputs in the middle portion of the rankings,

suggesting that the OAT analyses may over- or underestimate the sensitivity of some of the design inputs.

Table 9.25. Ranking of HMA Over Stiff Foundation design inputs by maximum |Mean| NSI values (ANN RSMs).

Design Input	Maximum Mean NSI Values (ANN RSMs)							OAT Category
	Long Crk	AllCrk	ThermCrk	ACRD	TotRD	IRI	Maximum	
Delta	-2.72	1.75	0.99	-22.74	-7.07	-1.89	-22.74	HS
Alpha	-2.75	0.44	-0.40	-21.29	-7.10	-1.95	-21.29	HS
SSA	0.51	-0.10	-0.11	4.14	1.32	0.35	4.14	HS
Pratio	-1.00	-0.19	0.06	-3.47	-1.09	-0.29	-3.47	HS
m	N.A.	N.A.	-2.22	N.A.	N.A.	N.A.	-2.22	VS
UnitW	1.64	0.39	-0.35	-0.27	-0.11	-0.03	1.64	VS
AADTTperLane	0.16	0.07	0.00	1.37	0.49	0.14	1.37	VS
HMAThick	0.40	0.30	-0.23	1.21	0.32	0.07	1.21	VS
SubLL	1.12	0.35	0.03	0.06	0.04	0.01	1.12	S
Vbeff	-0.99	0.09	-0.19	-0.23	-0.03	-0.01	-0.99	VS
Va	-0.99	-0.30	0.52	-0.07	-0.04	-0.01	-0.99	VS
BaseThick	0.61	0.15	0.07	0.92	0.13	0.04	0.92	VS
SubMr	0.83	0.17	-0.06	0.26	-0.13	-0.05	0.83	S
HtCp	-0.80	-0.21	-0.17	-0.58	-0.18	-0.05	-0.80	S
OpSpd	0.39	0.04	-0.03	-0.79	-0.27	-0.07	-0.79	VS
BasePR	0.75	0.19	-0.12	-0.26	0.07	0.01	0.75	S
BaseThCnd	-0.67	-0.17	-0.28	-0.54	-0.17	-0.05	-0.67	HS
PGHigh	-0.16	-0.03	0.00	-0.66	-0.20	-0.05	-0.66	VS
BaseUnitW	-0.17	-0.06	-0.11	-0.54	-0.09	-0.02	-0.54	S
TenStrgth	N.A.	N.A.	-0.51	N.A.	N.A.	N.A.	-0.51	VS
BaseHtCp	-0.39	-0.10	-0.07	-0.17	-0.06	-0.03	-0.39	S
PGLow	-0.02	-0.02	-0.36	0.22	0.07	0.02	-0.36	S
D	N.A.	N.A.	-0.34	N.A.	N.A.	N.A.	-0.34	VS
SubN200	0.34	0.06	-0.10	0.08	-0.03	0.01	0.34	S
BaseMr	-0.19	-0.01	-0.02	0.32	0.07	0.01	0.32	S
ThmlCn	-0.14	-0.09	-0.16	0.30	0.11	0.03	0.30	S
SubPI	0.26	0.04	-0.01	0.09	0.01	0.00	0.26	S
GWD	-0.17	-0.01	0.02	0.09	-0.02	-0.01	-0.17	S
AggCoefContr	N.A.	N.A.	0.00	N.A.	N.A.	N.A.	0.00	NS

¹HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Non-Sensitive

As a more severe measure of sensitivity, the mean plus/minus two standard deviation ($\mu \pm 2\sigma$) NSI values were computed using the statistics in Table 9.18 through Table 9.23 based on the 10,000 ANN RSM evaluations for each climate zone and distress combination. These sensitivity limits are ranked by maximum absolute value across distresses in Table 9.26. The plus and minus signs are again retained for each individual sensitivity index to indicate whether distress increases (+) or decreases (-) with increasing input value. There is moderate to good agreement between the input rankings in Table 9.26 and those in based on the mean NSI values in Table 9.25.

The OAT local sensitivity category (Appendix B) for each design input is also indicated in Table 9.26. There is a lack of full congruence between the ranking of inputs from the ANN RSMs and the categorization from the OAT analyses. This is likely because the OAT sensitivities are local measures that do not necessarily fully represent the global sensitivity.

The $\mu \pm 2\sigma$ sensitivity indices in Table 9.26 are categorized in the same manner as done earlier for Table 8.28. The sensitivity categories are highlighted by font: **Bold** = Hypersensitive (HS), $\mu \pm 2\sigma > 5$; **Bold Italic** = Very Sensitive (VS), $1 < \mu \pm 2\sigma < 5$; *Italic* = Sensitive (S), $0.1 < \mu \pm 2\sigma < 1$; and Regular = Non-Sensitive (NS), $\mu \pm 2\sigma < 0.1$. Overall, the sensitivities of all of the design inputs evaluated in the HMA Over Stiff Foundation scenarios were quite high, and because of this there is a possibility that some of the MEPDG design inputs not evaluated here might also have higher-than-expected sensitivities. Nonetheless, the rankings and $\mu \pm 2\sigma$ values in Table 9.26 are judged to be the best overall measures of the design input sensitivities in the MEPDG.

Table 9.26. Ranking of HMA Over Stiff Foundation design inputs by maximum $|\mu \pm 2\sigma|$ NSI values (ANN RSMs).

Design Input	Maximum $\mu \pm 2\sigma$ NSI Values (ANN RSMs)							OAT Category
	Long Crk	AllCrk	ThermCrk	ACRD	TotRD	IRI	Maximum	
Delta	-19.60	9.00	3.52	-43.25	-12.76	-3.49	-43.25	HS
Alpha	-22.02	-3.91	-2.82	-39.33	-13.12	-3.67	-39.33	HS
UnitW	10.77	3.69	-1.02	-1.70	-0.65	-0.38	10.77	VS
Va	-8.12	-2.53	1.84	0.62	-0.26	-0.08	-8.12	VS
SSA	-4.90	-1.86	-0.38	7.43	2.50	0.86	7.43	HS
Pratio	-6.93	-2.11	-0.30	-5.57	-1.96	-0.61	-6.93	HS
SubLL	6.76	2.47	0.18	0.97	0.19	-0.16	6.76	S
m	N.A.	N.A.	-6.65	N.A.	N.A.	N.A.	-6.65	VS
SubMr	5.82	0.94	0.37	1.85	-1.72	-0.29	5.82	S
Vbeff	-5.61	0.90	-0.70	-1.98	-0.40	-0.16	-5.61	VS
BasePR	5.55	2.26	-0.46	-2.78	-0.56	-0.16	5.55	S
HtCp	-5.24	-1.88	-0.68	-1.36	-0.38	-0.24	-5.24	S
BaseThCnd	-5.05	-1.42	-0.84	-1.13	-0.42	-0.18	-5.05	HS
BaseThick	3.25	1.67	0.22	2.00	0.32	0.10	3.25	VS
HMAThick	2.73	1.82	-0.70	3.11	0.87	0.30	3.11	VS
OpSpd	3.09	0.56	-0.14	-1.62	-0.58	-0.16	3.09	VS
AADTTperLane	0.74	0.56	-0.06	2.94	0.91	0.26	2.94	VS
SubN200	2.78	0.53	-0.35	0.57	-0.23	0.10	2.78	S
BaseMr	-1.84	0.58	-0.47	-2.23	-0.33	0.22	-2.23	S
BaseHtCp	-2.18	-0.50	-0.40	-0.86	-0.45	-0.23	-2.18	S
SubPI	1.66	0.49	-0.07	0.70	0.09	0.02	1.66	S
TenStrgth	N.A.	N.A.	-1.65	N.A.	N.A.	N.A.	-1.65	VS
BaseMr	-1.63	-0.25	-0.09	0.94	0.30	-0.13	-1.63	S
GWD	-1.30	-0.24	0.09	0.34	-0.06	-0.02	-1.30	S
PGHigh	-0.68	-0.23	0.00	-1.15	-0.38	-0.11	-1.15	VS
D	N.A.	N.A.	-1.10	N.A.	N.A.	N.A.	-1.10	VS
PGLow	-0.51	-0.09	-0.92	0.38	0.15	0.07	-0.92	S
ThmlCn	0.83	-0.60	-0.56	0.62	0.24	0.15	0.83	S
AggCoefContr	N.A.	N.A.	-0.16	N.A.	N.A.	N.A.	-0.16	NS

¹HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Non-Sensitive

Figure 9.16 through Figure 9.20 provide graphical summaries of the input sensitivities by distress. These figures highlight the difference in sensitivities between Hypersensitive and Very Sensitive and between Very Sensitive and Sensitive. All of the figures have the same horizontal axis range so that the differences in sensitivities across distresses can be more clearly evaluated. The solid bars in the figures indicate the mean NSI values, and the error bars correspond to one standard deviation. The sensitivities are also broken down by climate zone for each design input. No systematic or substantial effect of climate zone on the design input sensitivity statistics is observed.

Figure 9.16. Ranking of HMA Over Stiff Foundation design inputs by $|\mu \pm 2\sigma|$ NSI values: longitudinal cracking.

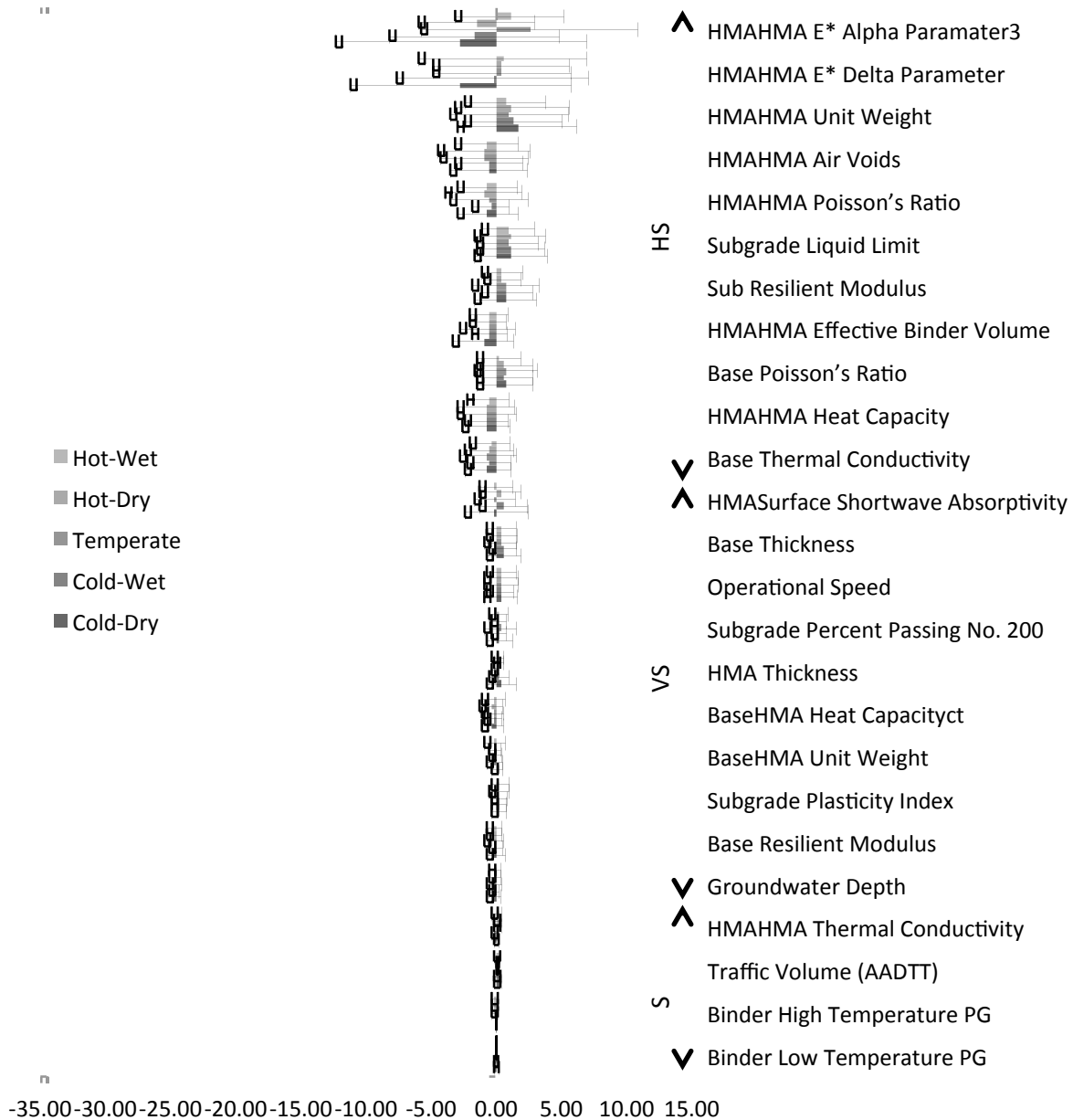


Figure 9.17. Ranking of HMA Over Stiff Foundation design inputs by $|\mu \pm 2\sigma|$ NSI values: alligator cracking.

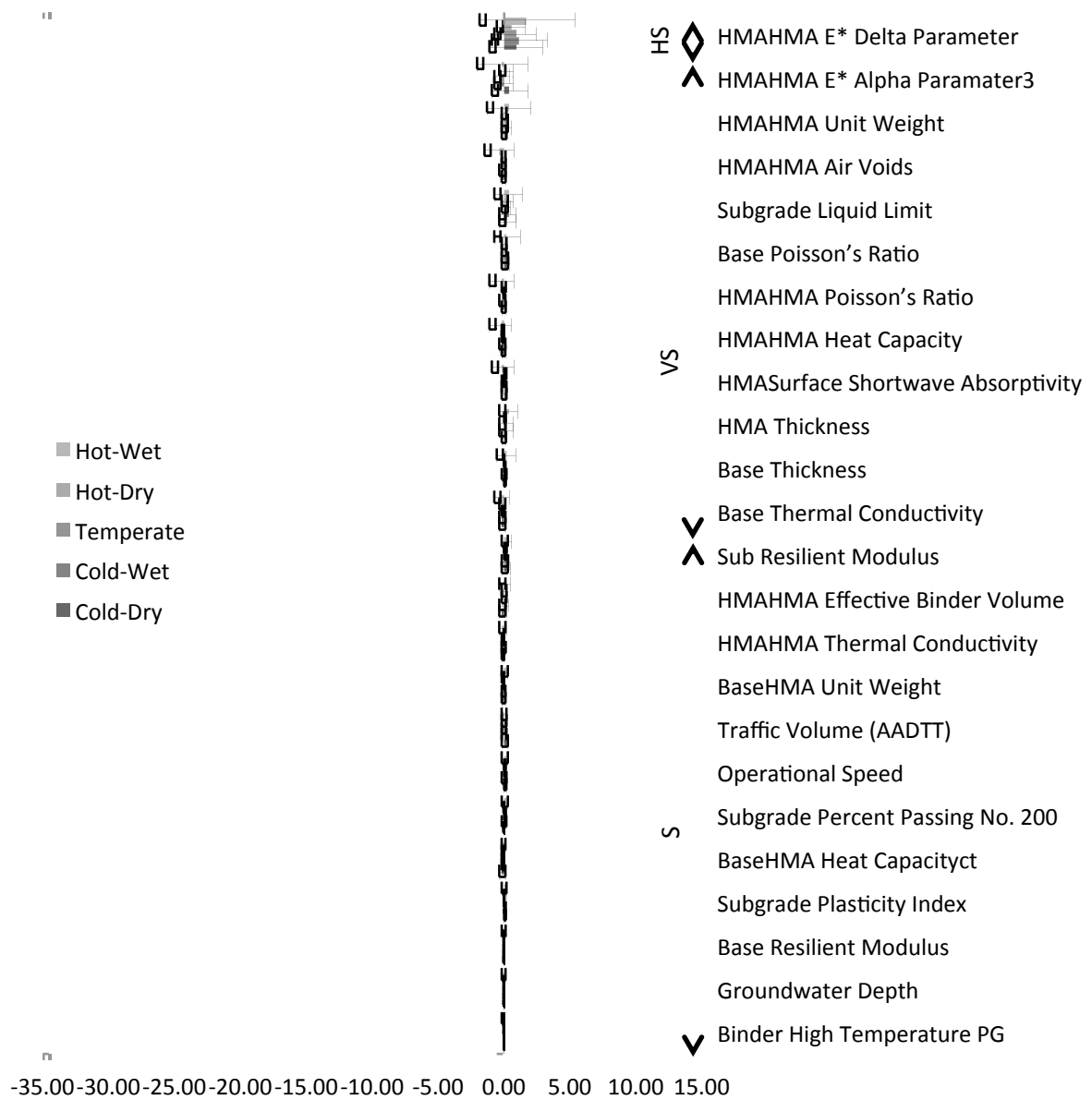


Figure 9.18. Ranking of HMA Over Stiff Foundation design inputs by $|\mu \pm 2\sigma|$ NSI values: AC rutting.



Figure 9.19. Ranking of HMA Over Stiff Foundation design inputs by $|\mu \pm 2\sigma|$ NSI values: Total rutting.

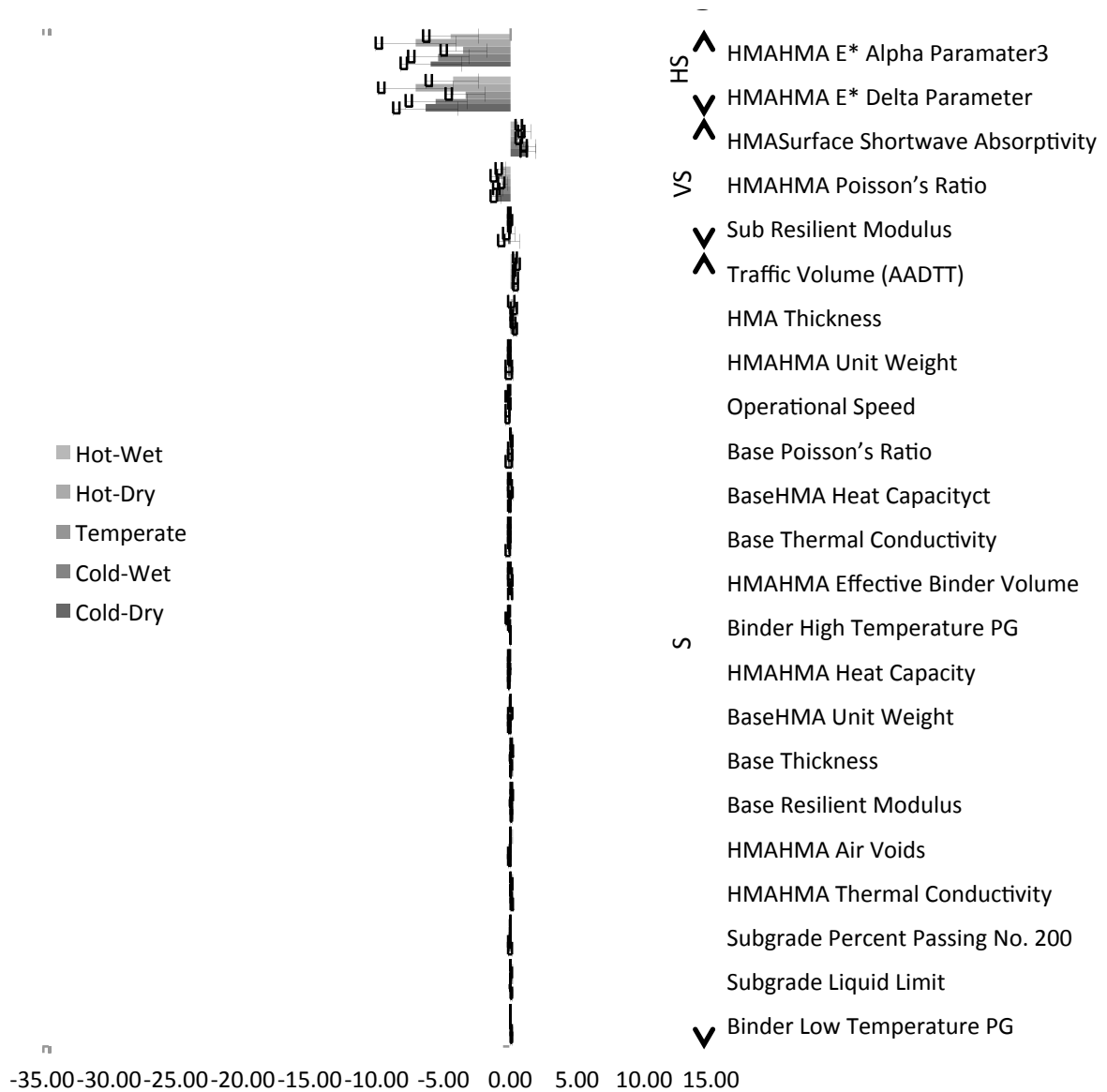
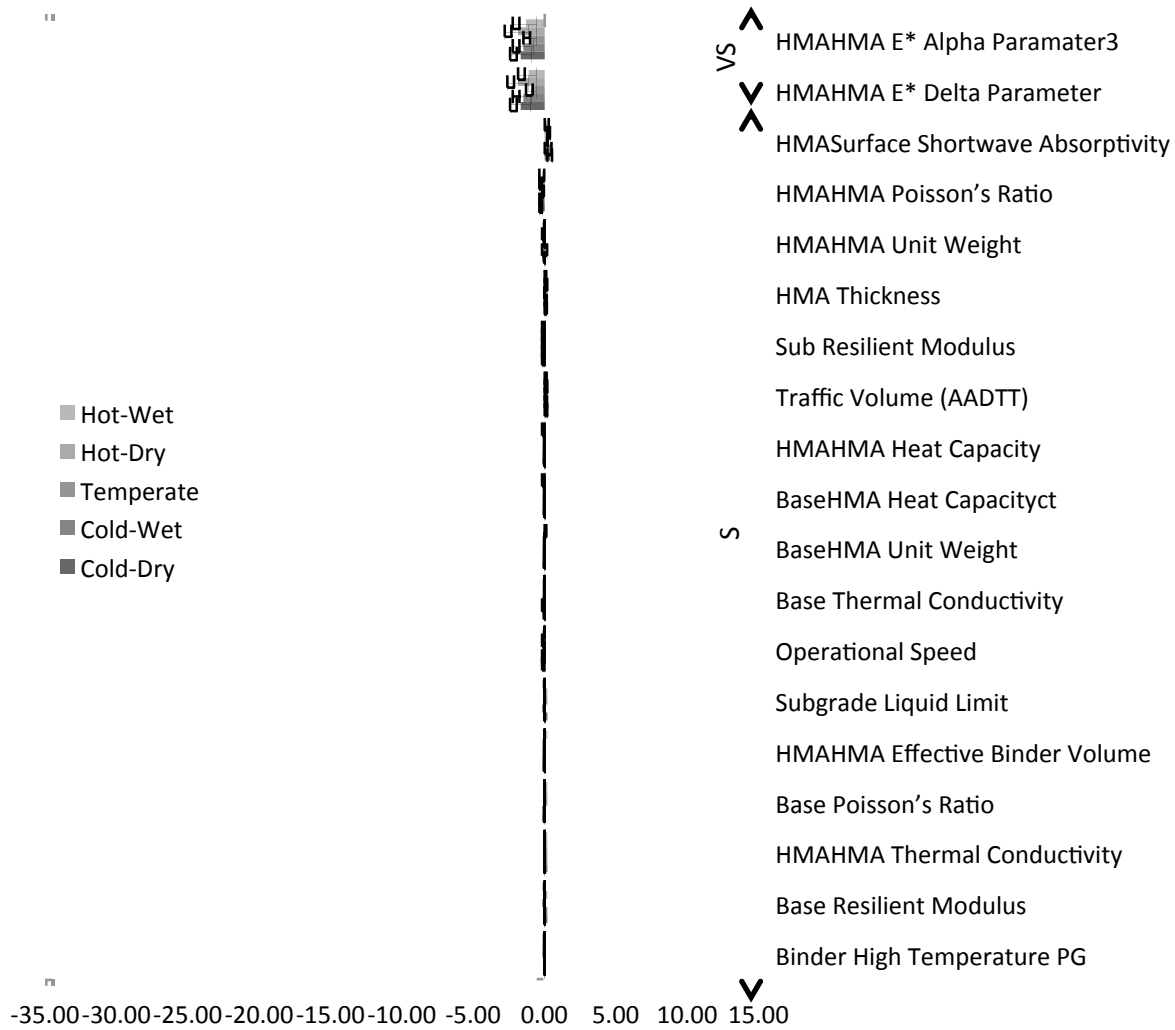


Figure 9.20. Ranking of HMA Over Stiff Foundation design inputs by $|\mu \pm 2\sigma|$ NSI values: IRI.



As a more practical aid to the pavement designer, Table 9.27 summarizes in rank order the Hypersensitive, Very Sensitive, and Sensitive design inputs by material category (HMA, base, subgrade, other) for each distress. The design inputs that fall in the Hypersensitive or Very Sensitive categories for most (4 out of 5) distresses are indicated by bold font in the table. Overall, the findings for HMA Over Stiff Foundation scenarios were similar to those for the New HMA cases. For the HMA Over Stiff Foundation scenarios, the consistently highest sensitivity design inputs are all HMA properties: the E* master curve δ and α parameters (i.e., the lower and upper shelves of the master curve), surface shortwave absorptivity, and Poisson's ratio. None of the base, subgrade, or other properties (e.g., traffic volume) was as consistently in the two highest sensitivity categories.

There are some additional observations that merit special note and discussion:

- The relatively high sensitivities for HMA air voids and effective binder volume are in addition to any influence they may have on HMA dynamic modulus and/or low temperature strength and creep compliance. Recall that the GSA simulations used synthetic Level 1 inputs

for the HMA dynamic modulus and low temperature properties. Formulating these properties in terms of the Level 3 empirical relations would increase the sensitivities attributable to air voids and effective binder volume.

- The thermal conductivity and heat capacity of the stabilized base are highly sensitive design inputs for longitudinal cracking and, to a lesser extent, for alligator cracking and asphalt rutting. These may also be sensitive inputs for conventional granular bases, but the MEPDG does not permit input of these values for this layer type.
- The moderately high sensitivity of longitudinal cracking and AC rutting on traffic speed is noteworthy. This is likely due to its influence on the dynamic modulus value used in the pavement structural response calculations.

Table 9.27. Hypersensitive, Very Sensitive, and Sensitive design inputs by distress and input category for HMA Over Stiff Foundation pavements. $NSI_{\mu+2\sigma}$ values are given in parentheses. Inputs in bold font are Hypersensitive or Very Sensitive for most (4 out of 5) distresses.

<i>Distress</i>	<i>Input Category</i>	<i>Hypersensitive (>5)</i>	<i>Very Sensitive (1-5)</i>	<i>Sensitive (0.1-1)</i>
Longitudinal Cracking	HMA Properties	E* Alpha (-22.0) E* Delta (-19.6) Unit Weight (+10.8) Air Voids (-8.12) Poisson's Ratio (-6.9) Effective Binder Volume (-5.6) Heat Capacity (-5.2)	Surface Shortwave Absorptivity (-4.9) Thickness (2.7)	High Temperature PG (-0.7) Thermal Conductivity (+0.8) Low Temperature PG (-0.5)
	Base Properties	Thermal Conductivity (-5.1)	Poisson's Ratio (+4.9) Thickness (+3.25) Heat Capacity (-2.2) Unit Weight (-1.8) Resilient Modulus (-1.6)	
	Subgrade Properties	Liquid Limit (+6.8) Resilient Modulus (-5.5)	Percent Passing No. 200 (+2.3) Plasticity Index (+1.6) Groundwater Depth (-1.3)	
	Other Properties		Operating Speed (+2.9)	Traffic Volume (+0.7)
Alligator Cracking	HMA Properties	E* Delta (+9.0)	E* Alpha (-3.9) Unit Weight (+3.7) Air Voids (-2.5) Poisson's Ratio (-2.1) Surface Shortwave Absorptivity (-1.9) Heat Capacity (-1.9) Thickness (+1.8) High Temperature PG (-1.2)	Effective Binder Volume (+0.9) Thermal Conductivity (+0.6) Low Temperature PG (+0.4)
	Base Properties		Poisson's Ratio (+2.3) Thickness (+1.7) Thermal Conductivity (-1.4)	Unit Weight (+0.6) Heat Capacity (-0.5) Resilient Modulus (-0.3)
	Subgrade Properties		Liquid Limit (+2.5)	Resilient Modulus (+0.9) Plasticity Index (+0.5) Percent Passing No. 200 (+0.5) Groundwater Depth (-0.2)

<i>Distress</i>	<i>Input Category</i>	<i>Hypersensitive (>5)</i>	<i>Very Sensitive (1-5)</i>	<i>Sensitive (0.1-1)</i>
Alligator Cracking	Other Properties			Operating Speed (+0.6) Traffic Volume (+0.6)
AC Rutting	HMA Properties	E* Delta (-43.3) E* Alpha (-39.3) Surface Shortwave Absorptivity (+7.4) Poisson's Ratio (-5.6)	Thickness (+2.6) Effective Binder Volume (-2.0) Unit Weight (-1.7) Heat Capacity (-1.4) High Temperature PG (-1.2)	Thermal Conductivity (+0.6) Air Voids (+0.4) Low Temperature PG (+0.4)
	Base Properties		Poisson's Ratio (-2.8) Unit Weight (-2.2) Thickness (+1.4) Thermal Conductivity (-1.1)	Heat Capacity (-0.9) Resilient Modulus (+0.8)
	Subgrade Properties		Resilient Modulus (+1.9)	Percent Passing No. 200 (+0.5) Liquid Limit (+0.1) Plastic Limit (+0.1) Groundwater Depth (+0.1)
	Other Properties		Traffic Volume (+2.5) Operating speed (-1.6)	
Total Rutting	HMA Properties	E* Alpha (-13.1) E* Delta (-12.8)	Surface Shortwave Absorptivity (+2.5) Poisson's Ratio (-2.0)	Thickness (+0.7) Unit Weight (-0.7) High Temperature PG (-0.4) Effective Binder Volume (-0.4) Heat Capacity (-0.4) Air Voids (-0.3) Thermal Conductivity (+0.2) Low Temperature PG (+0.2)
	Base Properties			Poisson's Ratio (-0.6) Heat Capacity (-0.5) Thermal Conductivity (-0.4) Unit Weight (-0.3) Thickness (+0.2) Resilient Modulus (+0.2)
	Subgrade Properties		Resilient Modulus (-1.7)	Percent Passing No. 200 (-0.2) Liquid Limit (+0.2) Groundwater Depth (-0.1)

<i>Distress</i>	<i>Input Category</i>	<i>Hypersensitive (>5)</i>	<i>Very Sensitive (1-5)</i>	<i>Sensitive (0.1-1)</i>
Total Rutting	Other Properties			Traffic Volume (+0.8) Operating Speed (-0.6)
IRI	HMA Properties		E* Alpha (-3.7) E* Delta (-3.5)	Surface Shortwave Absorptivity (+0.7) Poisson's Ratio (-0.6) Unit Weight (-0.4) Thickness (+0.3) Effective Binder Volume (-0.2) Heat Capacity (-0.2) High Temperature PG (-0.1) Thermal Conductivity (+0.1) Air Voids (-0.1)
	Base Properties			Thermal Conductivity (-0.2) Heat Capacity (-0.2) Poisson's Ratio (-0.2) Unit Weight (+0.2) Thickness (+0.1) Resilient Modulus (-0.1)
	Subgrade Properties			Resilient Modulus (-0.3) Liquid Limit (-0.2) Percent Passing No.200 (+0.1)
	Other Properties			Traffic Volume (+0.2) Operating Speed (-0.2)

10 NEW JPCP

10.1 Analysis Inputs

The GSA analyses of New JPCP rigid pavements encompassed a total of 15 base cases spanning five climate zones with three traffic levels each. Table 10.1 summarizes the project-specific parameters that were fixed for all New JPCP analyses.

Table 10.1. Fixed design inputs for New JPCP cases.

Input Parameter	Value
Design Life	25 years
Reliability	90% for all distresses
AADTT Category	Principal Arterials – Interstate and Defense Rout
TTC	4
Number of Lanes in Design Direction	2 for low traffic/3 for medium and high traffic
Truck Direction Factor	50
Truck Lane Factor	75 for low traffic/55 for medium traffic/50 for high traffic
Default Growth Rate	No growth
First Layer Material Type	Portland Cement Concrete
Second Layer Material Type	Granular Base
Subgrade Material Type	Soil

Table 10.2 summarizes the design inputs that are strongly correlated to traffic level. Higher traffic levels require correspondingly thicker PCC and base layers. AADTT, PCC thickness, and base thickness were determined in the OAT local sensitivity analyses to be very sensitive, hypersensitive, and sensitive inputs, respectively (see Appendix B). The GSA simulations use random input values for the AADTT and the PCC and base thicknesses ranging between the minimum and maximum limits for each traffic level as determined by the Latin Hypercube algorithm.

Table 10.2. Design inputs related to traffic levels in New JPCP cases.

Traffic Level Input Parameter	Low Traffic			Medium Traffic			High Traffic		
	Baseline	Min	Max	Baseline	Min	Max	Baseline	Min	Max
AADTT-Nominal	1000	500	5000	7500	5000	10000	25000	20000	30000
Design Lane	375	188	1875	2063	1375	2750	6250	5000	7500
PCC Thickness	8	6	10	10	8	12	12	10	14
Base Thickness	4	2	6	6	3	9	8	5	12

The remaining design inputs varied in the GSA simulations are summarized in Table 10.3. These inputs correspond to the “Hypersensitive,” “Highly Sensitive,” and “Sensitive” design inputs as identified in the initial triage and confirmed by the OAT local sensitivity analysis findings. The baseline, minimum, and maximum values are listed for each design input. Unlike in the OAT local sensitivity analyses, the baseline values have no special significance in the GSA simulations and are provided in Table 10.2 and Table 10.3 only to provide context. The Latin Hypercube algorithm used

for generating the GSA simulations randomly samples each design input uniformly over each sampling interval between the minimum and maximum limits.

The values of PCC MOR and E_c at various ages are determined using the procedures described in in Section 3.4. As stated in Sections 3.5 and 3.6, the values of w/c were determined from the correlation with PCC strength and the values of dowel diameter were determined from the correlation with PCC thickness. As stated in Section 3.7, LTE and/or slab width were utilized to represent edge support inputs in MEPDG JPCP analyses.

Table 10.3. Input parameter ranges for New JPCP.

Input Parameter	OAT Sensitivity ¹	Baseline Value ²	Minimum ²	Maximum ²
Construction Month	S	July 2006	March 2006	October 2006
Design Lane Width	S	12	11	12
Joint Spacing	HS	15	10	20
Dowel Diameter	HS	Various	1.00	1.75
Edge Support – LTE	VS	5 (no support)	5	80
Edge Support – Widened Slab	HS	12 (no support)	12	14
Erodibility Index	S	3	1	5
Surface Shortwave Absorption	HS	0.85	0.8	0.98
PCC Unit Weight	HS	150	140	160
PCC Poisson Ratio	VS	0.15	0.10	0.20
PCC Coef. of Thermal Expansion	VS	5.56	2	10
PCC Thermal Conductivity	HS	1.25	0.50	2.00
PCC Cement Content	VS	500	400	700
PCC W/C	VS	Various	0.30	0.70
PCC 7-Day MOR	-- ³	572	414	812
PCC 7-Day E	-- ³	3,650,255	2,144,002	5,700,014
PCC 14-Day MOR	-- ³	597	433	847
PCC 14-Day E	-- ³	3,809,795	2,242,398	5,945,704
PCC 28-Day MOR	HS	620	450	880
PCC 28-Day E	HS	3,956,571	2,330,437	6,177,355
PCC 90-Day MOR	-- ³	655	475	931
PCC 90-Day E	-- ³	4,179,925	2,459,906	6,535,361
PCC 20-year MOR to 28-day MOR	-- ³	1.2	1	1.5
Base Resilient Modulus	S	25,000	15,000	40,000
Subgrade Resilient Modulus	VS	15,000	10,000	20,000
GWD	NS	10	2	18

¹HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Not Sensitive

²Same units as for MEDPG input.

³7-, 14- and 90-day and 20-year strength and stiffness values not considered explicitly in OAT analyses.

10.2 Predicted Distresses

Over 5900 MEPDG runs were performed for the New JPCP GSA. Table 10.4 through Table 10.6 provide summary statistics for predicted faulting, cracking, and IRI, respectively, for the GSA simulations for each base case combination of climate zone and traffic level. Overall, the Latin hypercube sampling scheme generated input data sets that produced a wide range for each of the

predicted distresses. The range of predicted distresses in most cases is from zero or near zero to values several times the default design limit. For instance, the JPCP design limit is 15% for predicted transverse cracking. The correlation between traffic level and JPCP cracking is clearly seen (i.e., higher the traffic, lower the cracking). The average values for faulting and IRI were relatively insensitive to traffic level and climate zone.

Figure 10.1 through Figure 10.5 provide frequency distributions of predicted distresses by climate zone and traffic level. These results confirm that the GSA simulations for the New JPCP cases span a wide range of the model output (distress) space as well as the model inputs domain.

Table 10.4. Summary statistics for predicted faulting – New JPCP.

Scenario	Mean	Minimum	Maximum	Std Dev
CDL	0.04	0.00	0.56	0.07
CDM	0.05	0.00	0.40	0.07
CDH	0.07	0.00	0.48	0.08
CWL	0.05	0.00	0.54	0.07
CWM	0.06	0.00	0.43	0.07
CWH	0.07	0.00	0.37	0.08
TL	0.02	0.00	0.30	0.03
TM	0.02	0.00	0.23	0.03
TH	0.03	0.00	0.21	0.03
HDL	0.03	0.00	0.30	0.04
HDM	0.03	0.00	0.27	0.04
HDH	0.04	0.00	0.26	0.04
HWL	0.03	0.00	0.30	0.04
HWM	0.03	0.00	0.31	0.04
HWH	0.04	0.00	0.29	0.05
Overall	0.04	0.00	0.56	0.06

Table 10.5. Summary statistics for predicted cracking – New JPCP.

Scenario	Mean	Minimum	Maximum	Std Dev
CDL	43	0	100	45
CDM	35	0	100	43
CDH	28	0	100	40
CWL	40	0	100	43
CWM	31	0	100	41
CWH	29	0	100	42
TL	39	0	100	43
TM	29	0	100	40
TH	22	0	100	37
HDL	42	0	100	44
HDM	33	0	100	42
HDH	31	0	100	42
HWL	46	0	100	44
HWM	32	0	100	42
HWH	24	0	100	39
Overall	34	0	100	42

Table 10.6. Summary statistics for predicted IRI – New JPCP.

Scenario	Mean	Minimum	Maximum	Std Dev
CDL	183	90	430	65
CDM	176	93	415	62
CDH	178	90	418	69
CWL	147	72	408	63
CWM	141	72	370	63
CWH	145	72	336	64
TL	106	63	277	44
TM	99	63	250	43
TH	97	63	238	43
HDL	112	63	274	47
HDM	107	63	266	49
HDH	111	63	250	50
HWL	116	63	277	51
HWM	106	63	271	50
HWH	105	63	262	49
Overall	129	63	430	62

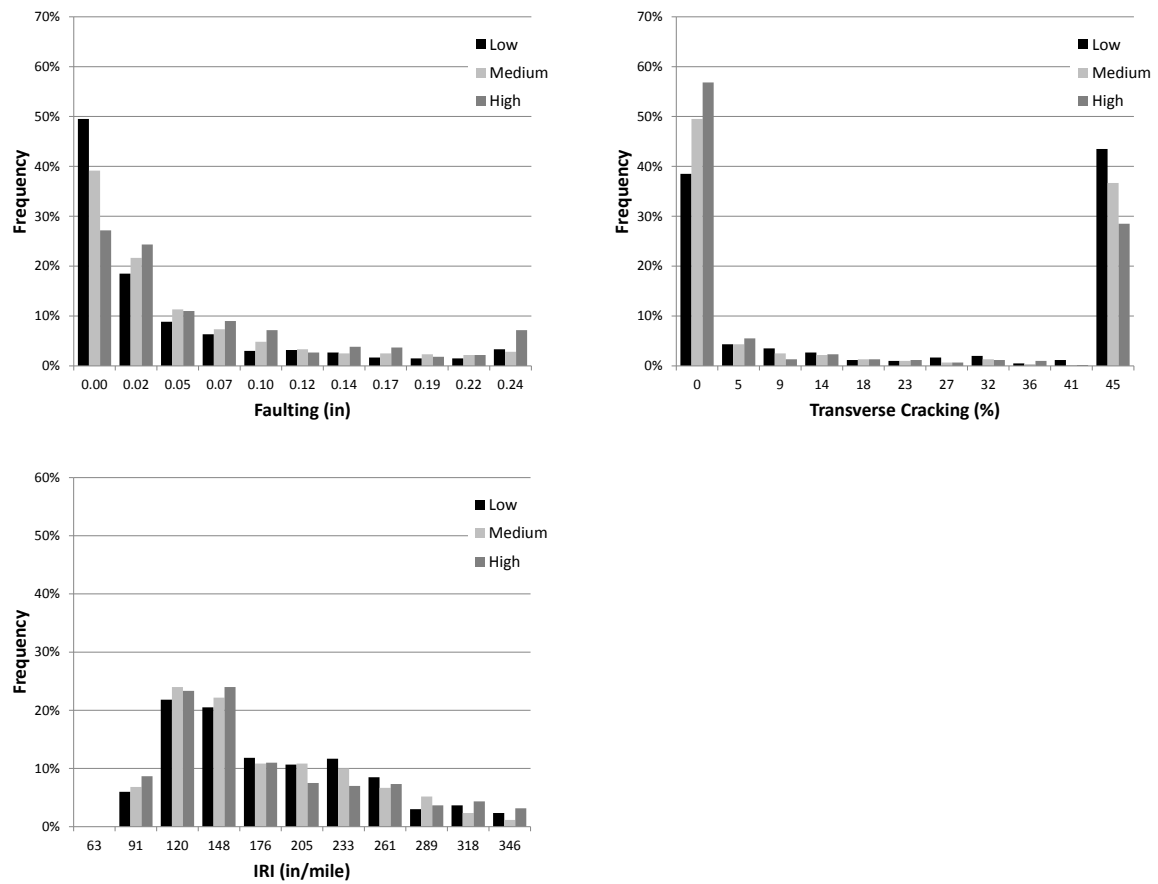


Figure 10.1. Distribution of predicted distresses – New JPCP/Cold-Dry climate.

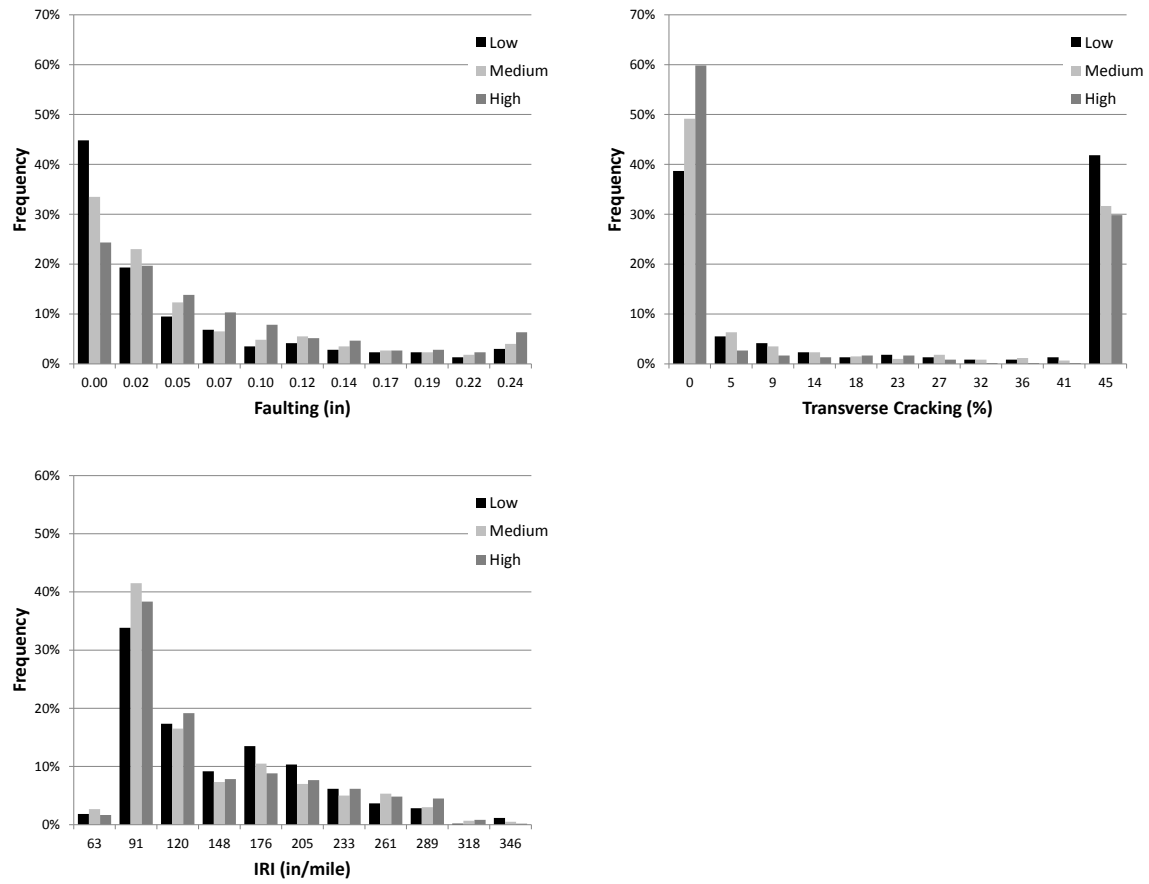


Figure 10.2. Distribution of predicted distresses – New JPCP/Cold-Wet climate.

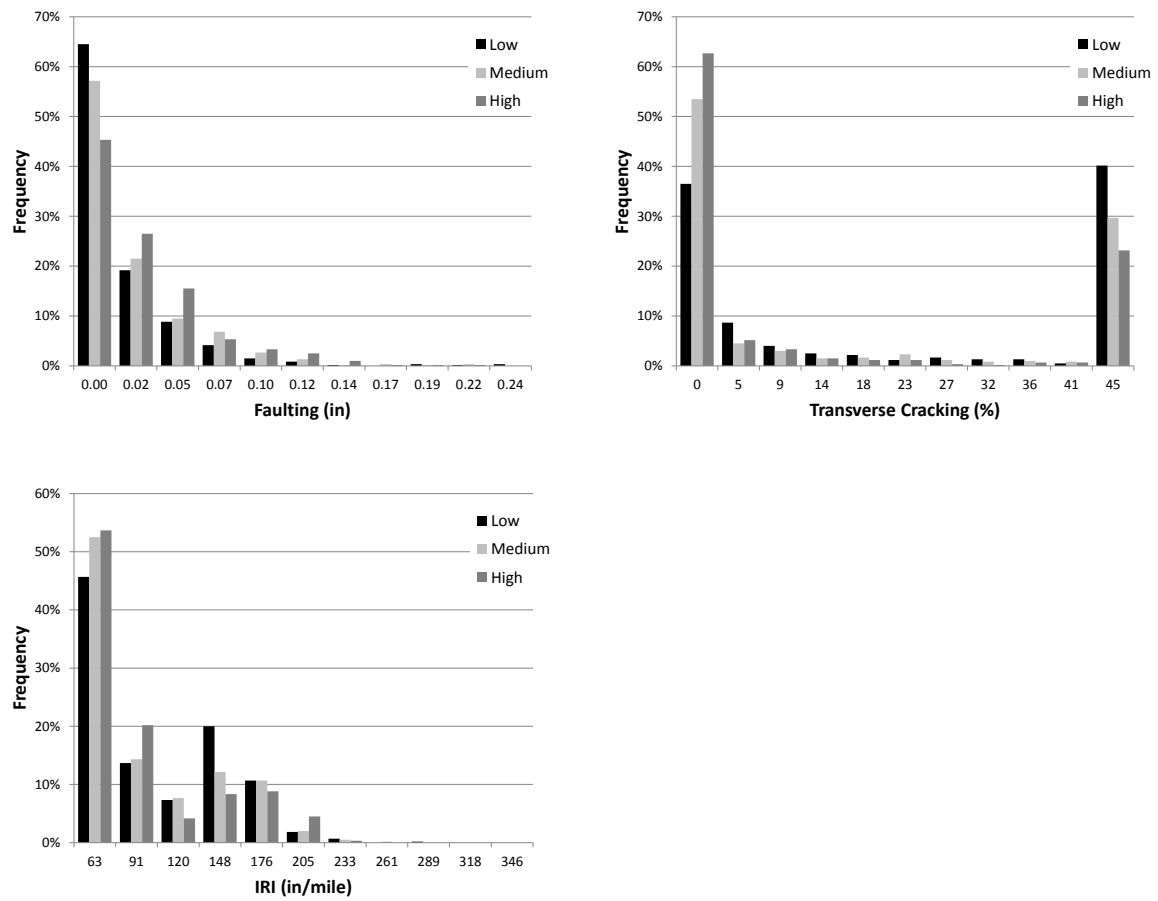


Figure 10.3. Distribution of predicted distresses – New JPCP/Temperate climate.

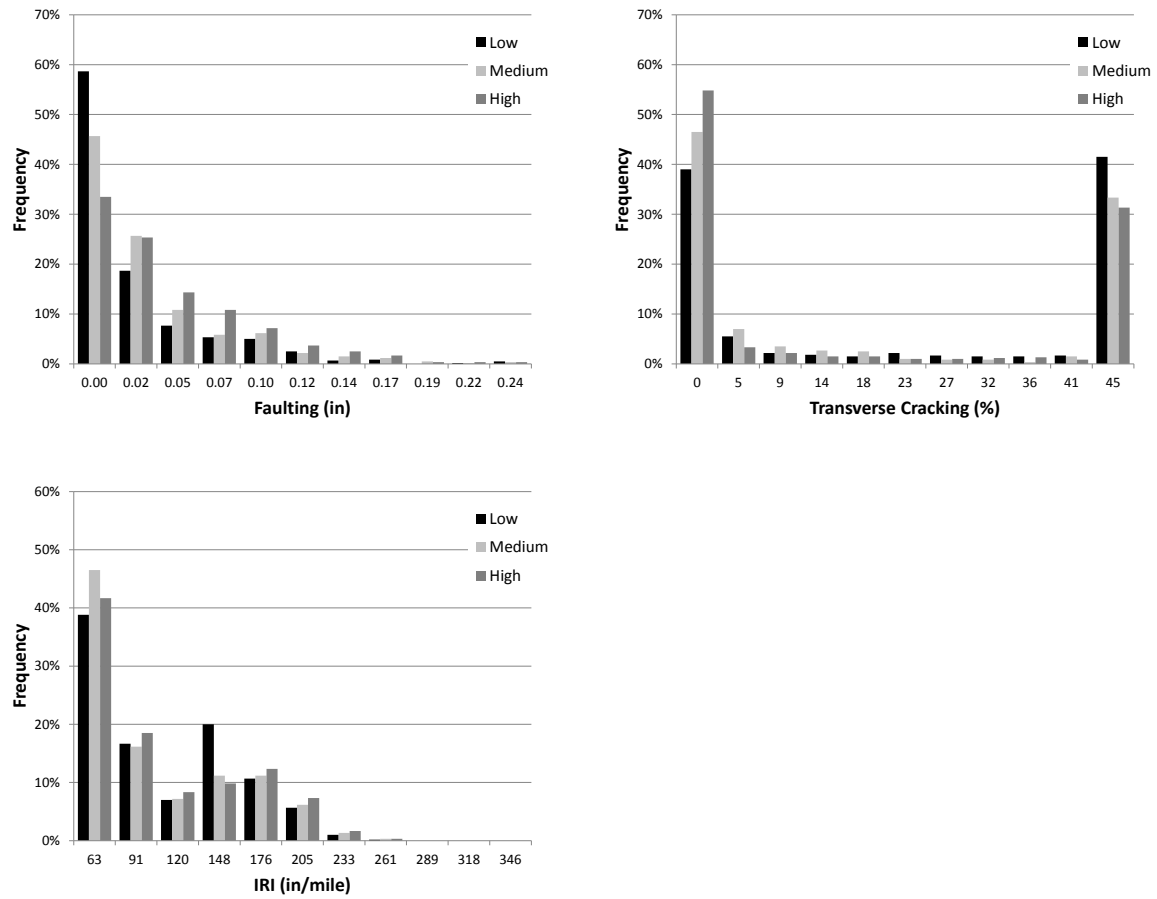


Figure 10.4. Distribution of predicted distresses – New JPCP/Hot-Dry climate.

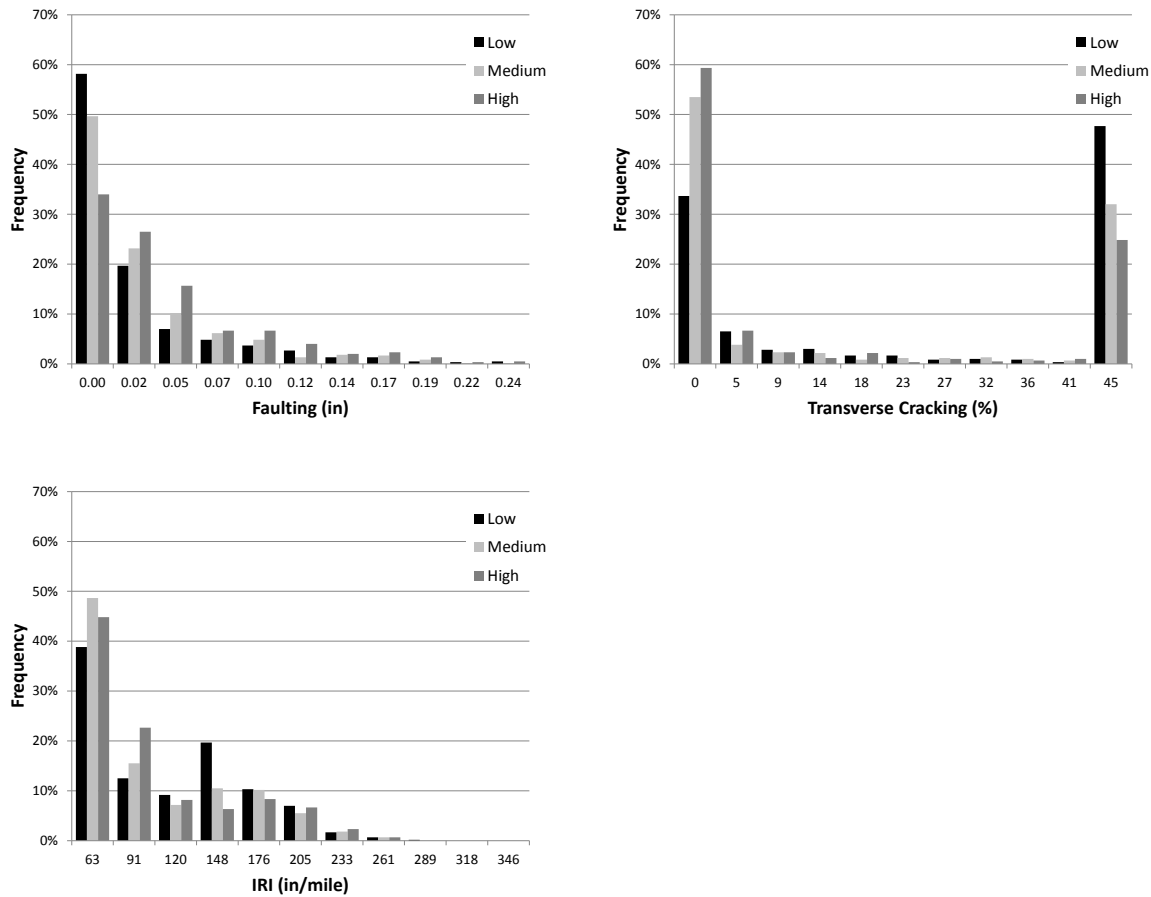


Figure 10.5. Distribution of predicted distresses – New JPCP/Hot-Wet climate.

10.3 Response Surface Modeling

Table 10.7 defines the inputs used for the RSMs. These design inputs are similar to those given previously in Table 10.1, Table 10.2, and Table 10.3. There is one difference: the 7-day, 14-day and 90-day MOR and E values were not included for the RSMs since the inclusion of 28-day MOR and E alone was found to be sufficient in uniquely capturing the input sensitivities associated with PCC MOR and E. Note that the 7-day, 14-day, and 90-day MOR and E values are derived from 28-day MOR and E values based on PCC strength-age correlations. The preliminary RSMs, which were conducted by including all the MOR and E values, produced less accurate prediction models, possibly due to the presence of multicollinearity among the input variables. Therefore, only the 28-day MOR and E were included in all of the RSMs (including JPCP over Stiff Foundation and New CRCP) although it is still considered a Level 1 sensitivity analysis.

The outputs for the RSMs are the predicted distresses: faulting, cracking, and IRI. Separate RSMs were developed for each distress. As described previously in Section 6, each input for the MVL RSMs is normalized by its mean value from the GSA simulations and each output distress is normalized by its default design limit. As described previously in Section 7, IRI is treated as a special case because it has a nonzero lower bound.

The regression coefficients in the normalized MVL RSMs can be interpreted as average sensitivity indices quantifying the percentage change in distress relative to design limit caused by a given percentage change in the design input relative to its mean value. These average sensitivity indices are constant across the problem domain—i.e., the MVL RSMs do not capture any variations of sensitivity with location in the problem domain.

Table 10.7. Definition of inputs for response surface modeling - New JPCP.

Input No.	Name of Design Input	Description
1	AADTT per Lane	Average Annual Daily Truck Traffic in design lane
2	JPCP Thick	PCC slab thickness
3	Base Thick	Base layer thickness
4	SSA	Surface Shortwave Absorption
5	Joint Spacing	Transverse joint spacing of JPCP
6	Dowel Diameter	Diameter of dowel bar
7	Edge Support - LTE	Load Transfer Efficiency of tied shoulder for edge support
8	Edge Support - Widen Slab	Widened slab widths for edge support
9	Erodibility Index	Erodibility condition of base material layer
10	PCC Unit Weight	Unit weight of Portland Cement Concrete
11	PCC Poisson Ratio	Poisson's ratio of Portland Cement Concrete
12	PCC CTE	Coefficient of Thermal Contraction of Portland Cement Concrete
13	PCC Thermal Conductivity	Thermal conductivity of Portland Cement Concrete
14	PCC Cement Content	Cement content of Portland Cement Concrete
15	PCC W/C	Ratio of water to cement of Portland Cement Concrete
16	PCC 28-Day MOR	28-day Modulus of Rupture of Portland Cement Concrete
17	PCC 28-Day E	28-day elastic modulus of Portland Cement Concrete
18	PCC 20-year MOR to 28-day MOR	Ratio of 20-year Modulus of Rupture of Portland Cement Concrete to 28-day Modulus of Rupture of Portland Cement Concrete
19	Base Mr	Resilient modulus of base material
20	Subgrade Mr	Resilient modulus of subgrade material
21	GWD	Ground Water Depth
22	Construction Month	Base/Subgrade construction time, usually one month ahead of pavement construction month
23	Design Lane Width	Distance between the lane markings on either side of the design lane (not the "slab width")

Goodness-of-fit statistics R^2 , root mean squared error (RMSE), and normalized standard error (Se/Sy) for the MVL RSMs are summarized in Table 10.8 by climate zone and distress. Note that the dimensions of RMSE are same as those of the predicted distress while R^2 and Se/Sy are dimensionless. The R^2 values range from about 0.2 to 0.7, with the cracking distresses tending to have smaller R^2 values and the faulting and IRI distresses tending to have relatively better goodness-of-fit statistics. The low R^2 values for many of the MVL RSMs are not unexpected. The relationships

between design inputs and distress outputs is expected to be complexly nonlinear; the multivariate linear regressions are intended only as a rough “first cut” assessment of sensitivities.

Goodness-of-fit statistics for the ANN RSMs are summarized in Table 10.9 by climate zone and distress. The ‘NN’ column describes the ANN network architecture; all ANN RSMs for the New JPCP scenarios employed 23 input neurons, 5 hidden neurons in one layer, and one output neuron. The ‘n’ column gives the total number of GSA simulations used for training/validating/testing the model. Overall, the ANN RSM model fits are reasonable with the faulting prediction models being the best and the cracking models being the worst.

The lower prediction accuracies for the ANN RSM cracking models could be attributed to one or more of the following reasons. Unlike the other distress predictions, the scale for MEPDG predicted cracking is fixed, ranging from 0 to 100%. In practical experience, lower PCC MOR (e.g., 500 psi) is acceptable when using lower joint spacing (e.g., 15 ft) while higher PCC MOR (e.g., 650 psi) is required when using higher joint spacing (e.g., 20 ft). Such implicit correlations were not considered in LHS sampling in generating the input data sets for the RSMs. Because of this, some unusual scenarios were generated – for instance, it is possible to have 0% cracking in the RSM input datasets for both higher MOR plus lower joint spacing as well as higher PCC MOR plus higher joint spacing.

Scatter plots for ANN predicted vs. MEPDG predicted distresses are provided in Figure 10.6 for faulting, cracking, and IRI by climate zone. These scatter plots graphically confirm the conclusions from the goodness-of-fit statistics that the ANN RSM models provide very good fits for faulting and IRI and not such good fits for the cracking distresses for the reasons discussed in the previous paragraph. It is expected that the prediction accuracies of the ANN RSM cracking models would improve significantly using a reduced input feature space. However, this is outside the scope and objective of the current study. The high quality of the fits for at least some of these ANN RSMs suggest the possibility that enhanced versions of the RMS might be adequate substitutes in some cases for the more rigorous but laborious geomechanics computations in the MEPDG.

Table 10.8. Goodness-of-fit statistics for multivariate linear regression response surface models – New JPCP.

Climate	Distress	R ²	RMSE	Se/Sy
CD	Faulting	0.58	0.21	0.66
	Cracking	0.24	0.55	0.88
	IRI	0.73	0.15	0.53
CW	Faulting	0.61	0.21	0.63
	Cracking	0.19	0.54	0.91
	IRI	0.61	0.15	0.63
T	Faulting	0.60	0.09	0.64
	Cracking	0.27	0.50	0.86
	IRI	0.53	0.09	0.69
HD	Faulting	0.65	0.12	0.60
	Cracking	0.18	0.61	0.92
	IRI	0.55	0.11	0.68
HW	Faulting	0.66	0.11	0.59
	Cracking	0.29	0.50	0.85
	IRI	0.62	0.09	0.62

Table 10.9. Goodness-of-fit statistics for neural network response surface models – New JPCP.

Climate	Distress	NN	n	R ²	RMSE	Se/Sy
CD	Faulting	23-5-1	1160	0.89	0.013	0.33
	Cracking	23-5-1	1160	0.46	6.922	0.73
	IRI	23-5-1	1160	0.89	10.611	0.34
CW	Faulting	23-5-1	1188	0.88	0.014	0.35
	Cracking	23-5-1	1188	0.47	6.565	0.72
	IRI	23-5-1	1188	0.82	11.499	0.43
T	Faulting	23-5-1	1247	0.84	0.007	0.40
	Cracking	23-5-1	1247	0.50	6.284	0.71
	IRI	23-5-1	1247	0.78	6.402	0.47
HD	Faulting	23-5-1	1169	0.93	0.006	0.26
	Cracking	23-5-1	1169	0.49	7.195	0.71
	IRI	23-5-1	1169	0.78	8.330	0.46
HW	Faulting	23-5-1	1180	0.93	0.006	0.27
	Cracking	23-5-1	1180	0.54	6.049	0.67
	IRI	23-5-1	1180	0.79	7.218	0.45

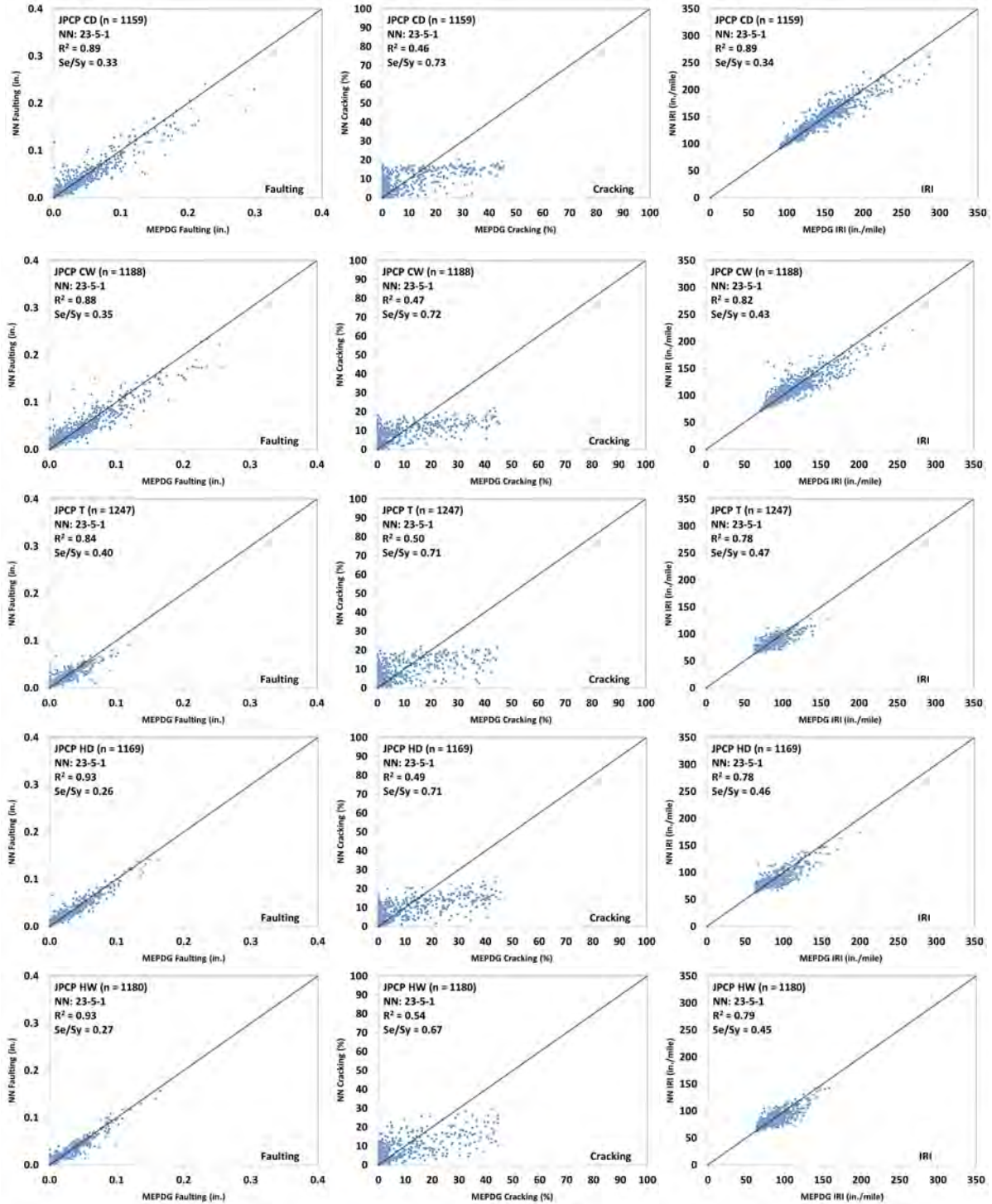


Figure 10.6. ANN predicted vs. MEDPG predicted distresses – New JPCP.

10.4 Sensitivity Metrics

The average sensitivity indices from the MVL RSMs are summarized in Table 10.10 through Table 10.12. Recall that these average sensitivity indices quantify the percentage change in predicted distress relative to its design limit caused by a given percentage change in each design input relative

to its mean value. The average sensitivities are just the regression coefficients from the normalized MVLR RSMs, many of which had relatively poor goodness-of-fit statistics (Table 10.8). Similar to the MVLR RSMs of flexible pavements, the values for the average sensitivity indices of MVLR RSMs of new JPCP are all much smaller than the corresponding sensitivity indices computed in the OAT analyses, but this is because the OAT values represented the maximum across all of the base cases, not average values. The values in Table 10.10 through Table 10.12 are just very rough indicators of average sensitivities and do not account for variations in sensitivities across the problem domain.

Figure 10.7 and Figure 10.8 provide graphical summaries by distress and climate zone of the average sensitivities calculated using the MVLR RSMs. The high-low-average plots in Figure 10.8 are additionally sorted by maximum average sensitivity (in an absolute value sense) to indicate more clearly the most important design inputs. The most sensitive inputs according to the MVLR RSMs in rank order in terms of maximum absolute sensitivity across climate zones (sensitivity values equal to 0.50 or greater) by distress type are:

- Faulting: Slab Width, PCC Unit Weight, Dowel Diameter
- Transverse Cracking: JPCP Thick, PCC 28-Day MOR, Slab Width, Joint Spacing, PCC 20-year MOR to 28-day MOR, PCC CTE, PCC Unit Weight
- IRI: Slab Width

Most of these rankings are consistent with engineering judgment and OAT analyses.

Table 10.10. Average sensitivities from MVLR RSMs – New JPCP/Faulting.

Design Input	Climate Zone				
	CD	CW	T	HD	HW
Constant (intercept)	1.00	1.73	1.26	1.77	1.24
AADTT Per Lane	0.15	0.15	0.07	0.11	0.11
JPCP Thick	-0.12	0.18	0.01	0.08	0.01
Base Thick	-0.06	-0.02	0.00	-0.01	0.01
SSA	0.04	0.34	0.01	0.02	0.10
Joint Spacing	0.32	0.31	0.13	0.18	0.22
Dowel Diameter	-0.20	-0.95	-0.38	-0.59	-0.51
LTE	-0.01	0.00	0.00	0.00	0.00
Slab Width	-2.03	-2.22	-0.89	-1.29	-1.13
Erodibility Index	0.08	0.09	0.03	0.04	0.04
PCC Unit Weight	-0.78	-0.86	-0.52	-0.60	-0.57
PCC Poisson Ratio	0.12	0.05	0.03	0.06	0.03
PCC CTE	0.53	0.55	0.22	0.34	0.30
PCC Thermal Conductivity	-0.04	-0.09	-0.02	-0.05	-0.02
PCC Cement Content	0.11	0.12	0.05	0.03	0.10
PCC W/C	0.35	0.11	0.00	0.05	0.07
PCC 28-Day MOR	0.40	0.29	-0.07	0.14	0.13
PCC 28-Day E	0.08	-0.08	0.06	-0.04	-0.02
PCC 20-year MOR to 28-day MOR	0.10	0.14	0.06	0.02	0.04
Base Mr	0.13	0.03	-0.02	0.02	-0.02
Subgrade Mr	-0.07	-0.09	-0.04	-0.08	-0.06
GWD	-0.02	-0.01	0.01	0.00	-0.02
Construction Month	0.02	0.04	0.01	0.01	0.00
Design Lane Width	0.12	0.45	0.09	-0.04	0.09

Table 10.11. Average sensitivities from MVLR RSMs – New JPCP/ Transverse Cracking.

Design Input	Climate Zone				
	CD	CW	T	HD	HW
Constant (intercept)	0.91	1.67	1.08	0.98	1.07
AADTT Per Lane	0.09	0.02	0.12	0.06	0.09
JPCP Thick	-0.72	-0.26	-1.54	-1.14	-1.57
Base Thick	-0.04	-0.07	-0.02	0.07	0.12
SSA	0.50	0.16	0.44	0.19	0.81
Joint Spacing	0.91	0.74	0.70	0.58	0.79
Dowel Diameter	-0.24	-0.78	0.69	0.75	0.51
LTE	-0.02	-0.01	-0.04	-0.04	-0.02
Slab Width	-0.60	-0.53	-0.76	-0.57	-1.31
Erodibility Index	0.03	-0.01	-0.05	0.00	-0.06
PCC Unit Weight	0.89	1.07	0.53	0.46	-0.06
PCC Poisson Ratio	0.10	-0.25	0.19	0.13	0.08
PCC CTE	0.66	0.51	0.61	0.58	0.67
PCC Thermal Conductivity	-0.35	-0.27	-0.27	-0.18	-0.27
PCC Cement Content	-0.10	-0.06	0.16	-0.04	-0.10
PCC W/C	0.14	-0.10	0.05	0.01	0.69
PCC 28-Day MOR	-0.73	-0.99	-1.10	-1.52	-0.77
PCC 28-Day E	0.15	0.02	0.35	0.53	0.80
PCC 20-year MOR to 28-day MOR	-0.66	-0.43	-0.56	-0.50	-0.94
Base Mr	0.12	0.01	0.05	-0.10	0.01
Subgrade Mr	-0.03	-0.11	-0.12	-0.05	-0.05
GWD	0.04	-0.03	0.00	-0.01	-0.11
Construction Month	-0.04	0.06	-0.07	0.02	-0.05
Design Lane Width	-0.73	-0.09	-0.18	0.10	-0.07

Table 10.12. Average sensitivities from MVL RSMs – New JPCP/ IRI.

Design Input	Climate Zone				
	CD	CW	T	HD	HW
Constant (intercept)	1.92	1.66	0.97	1.32	0.96
AADTT Per Lane	0.11	0.10	0.06	0.08	0.08
JPCP Thick	-0.31	-0.05	-0.20	-0.12	-0.20
Base Thick	-0.05	-0.02	0.00	0.00	0.02
SSA	0.10	0.25	0.06	0.05	0.16
Joint Spacing	0.18	0.13	0.11	0.10	0.15
Dowel Diameter	-0.08	-0.66	-0.14	-0.28	-0.26
LTE	-0.01	0.00	-0.01	-0.01	0.00
Slab Width	-1.37	-1.47	-0.66	-0.91	-0.89
Erodibility Index	0.06	0.06	0.01	0.03	0.02
PCC Unit Weight	-0.33	-0.36	-0.26	-0.34	-0.35
PCC Poisson Ratio	0.09	0.02	0.04	0.05	0.03
PCC CTE	0.41	0.41	0.21	0.28	0.27
PCC Thermal Conductivity	-0.07	-0.10	-0.05	-0.05	-0.05
PCC Cement Content	0.06	0.06	0.05	0.01	0.05
PCC W/C	0.45	0.29	0.05	0.09	0.18
PCC 28-Day MOR	0.15	0.07	-0.18	-0.09	-0.02
PCC 28-Day E	0.06	-0.08	0.08	0.03	0.10
PCC 20-year MOR to 28-day MOR	-0.02	0.04	-0.02	-0.04	-0.10
Base Mr	0.09	0.01	0.00	0.00	0.00
Subgrade Mr	-0.82	-0.30	-0.04	-0.05	-0.04
GWD	-0.01	-0.01	0.00	0.00	-0.02
Construction Month	0.01	0.04	-0.01	0.01	-0.01
Design Lane Width	0.06	0.32	0.03	-0.02	0.07

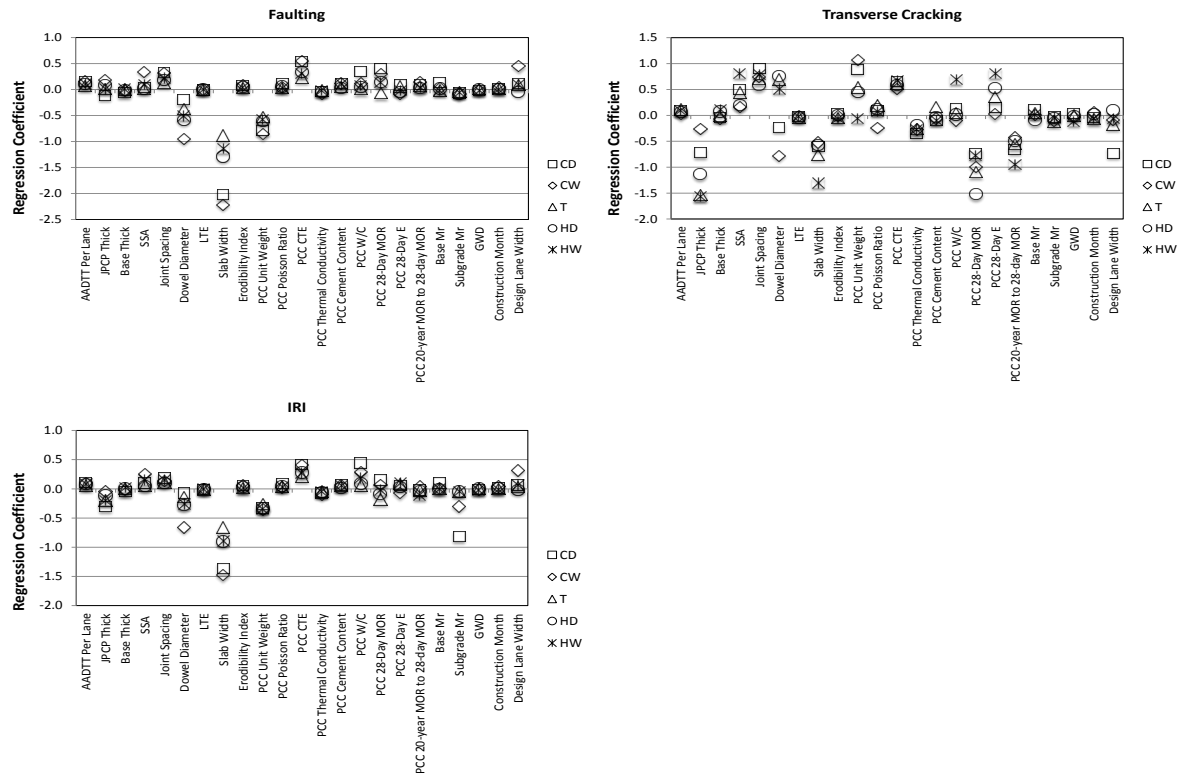


Figure 10.7. Average sensitivities from MVL RSMs – New JPCP.

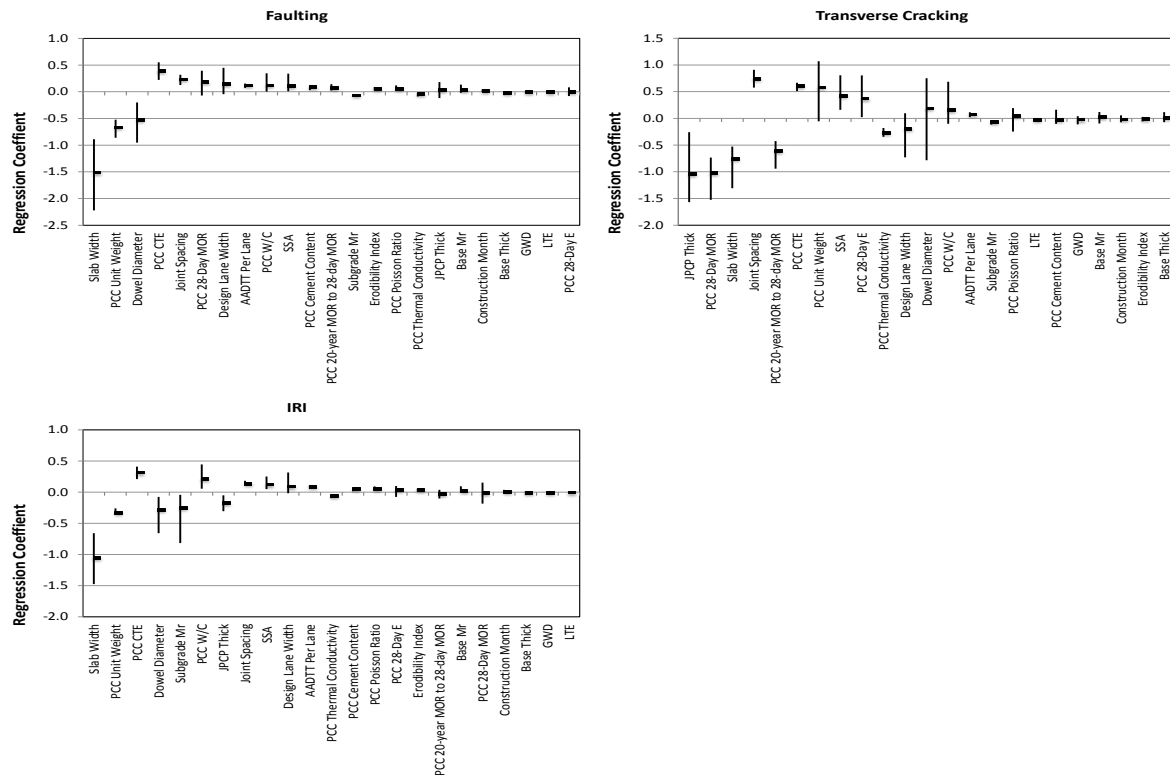


Figure 10.8. Ranking of average sensitivities from MVL RSMs – New JPCP.

The ANN RSMs permit a more in-depth evaluation of sensitivities than does the MVLR approach. Ten thousand ANN RSMs were performed for each climate zone and distress combination using random sampling of all design inputs across the problem domain. The random sampling for these simulations was not by traffic level but rather spanned the full range of AADTT, JPCP thickness, and base thickness values. Some of the random samples inevitably gave unrealistic pavement sections that produced excessively large predicted distresses—e.g., very high AADTT values combined with thin PCC and base layers. Consequently, any simulation for which any predicted distress exceeded three times its design limit was censored from the database. In general, fewer than 30% of the simulations for each climate zone-distress combination were censored.

Normalized sensitivity index (NSI) values were calculated using Eq. 3.19 or Eq. 3.20 for each of the 10,000 simulations for each climate zone-distress combination. The mean and standard deviations of the NSI values are summarized by climate zone in Table 10.13 through Table 10.15 for each respective distress. Full frequency distributions of the computed NSI values by design input and climate zone are depicted in Figure 10.9 through Figure 10.11 for each respective distress. Similar to the finding of flexible pavements, an important feature to note in the frequency distributions is that most have well-defined peaks: this implies that the NSI values are close to the mode at nearly all locations in the problem domain—i.e., NSI does not vary significantly over the problem domain. There are some exceptions where the NSI distributions are more spread out, but in these instances all of the NSI values are either very low and not of interest or all very high and thus always of interest regardless of value. The broad distribution for the sensitivity of JPCP transverse cracking to Joint Spacing for JPCP transverse cracking is a case in point; the high-frequency NSI values range from around 0.1 to 1. It is hypothesized that the spread in the NSI distribution results from joint spacing combining with other critical JPCP inputs (e.g., slab width, slab thickness, etc.). Nevertheless, all of the high-frequency NSI values for this distress-input combination lie within the Sensitive category (see Section 10.5).

Table 10.13. NSI statistics from ANN RSMs – New JPCP/Faulting.

Design Input	Climate Zone									
	CD		CW		T		HD		HW	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
AADTT Per Lane	0.18	0.22	0.21	0.19	0.09	0.11	0.09	0.13	0.11	0.12
JPCP Thick	-0.09	0.14	0.11	0.20	0.01	0.05	0.08	0.08	0.02	0.05
Base Thick	-0.03	0.05	0.00	0.04	0.00	0.01	0.00	0.01	0.00	0.01
SSA	0.02	0.08	0.18	0.25	0.10	0.12	0.02	0.08	0.19	0.17
Joint Spacing	0.20	0.23	0.15	0.18	0.08	0.10	0.10	0.11	0.15	0.16
Dowel Diameter	-0.13	0.14	-0.27	0.17	-0.21	0.16	-0.26	0.21	-0.26	0.20
LTE	-0.03	0.05	-0.01	0.02	-0.01	0.02	-0.01	0.03	-0.03	0.03
Slab Width	-3.80	7.09	-3.42	6.99	-1.13	1.32	-1.77	3.74	-1.46	2.51
Erodibility Index	0.06	0.09	0.05	0.07	0.02	0.03	0.03	0.05	0.05	0.05
PCC Unit Weight	-0.71	0.81	-0.61	0.78	-0.34	0.41	-0.43	0.60	-0.40	0.47
PCC Poisson Ratio	0.09	0.09	0.05	0.05	0.04	0.05	0.04	0.04	0.05	0.04
PCC CTE	0.65	0.76	0.45	0.52	0.24	0.29	0.28	0.36	0.38	0.40
PCC Thermal Conductivity	-0.04	0.07	-0.07	0.07	-0.03	0.04	-0.03	0.04	-0.02	0.03
PCC Cement Content	0.09	0.11	0.03	0.07	0.05	0.05	0.03	0.03	0.09	0.09
PCC W/C	0.18	0.22	0.01	0.07	0.12	0.14	-0.01	0.13	0.05	0.07
PCC 28-Day MOR	0.25	0.34	0.07	0.12	0.08	0.12	0.01	0.18	0.09	0.12
PCC 28-Day E	0.04	0.05	0.01	0.10	0.04	0.04	0.01	0.05	0.00	0.03
PCC 20-year MOR to 28-day MOR	0.17	0.17	0.07	0.05	0.05	0.06	0.02	0.05	0.03	0.04
Base Mr	0.09	0.12	-0.01	0.02	-0.01	0.01	0.01	0.02	-0.01	0.01
Subgrade Mr	-0.08	0.06	-0.05	0.05	-0.04	0.03	-0.06	0.06	-0.04	0.04
GWD	0.02	0.03	0.00	0.02	0.00	0.01	0.00	0.01	-0.01	0.01
Construction Month	0.02	0.03	0.04	0.04	0.01	0.01	0.01	0.02	0.02	0.02
Design Lane Width	0.00	0.36	0.48	0.55	0.05	0.15	0.12	0.21	0.07	0.06

Table 10.14. NSI statistics from ANN RSMs – New JPCP/Transverse Cracking.

Design Input	Climate Zone									
	CD		CW		T		HD		HW	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
AADTT Per Lane	0.08	0.13	0.02	0.14	0.17	0.20	-0.01	0.21	0.13	0.14
JPCP Thick	-0.67	1.04	-0.36	0.80	-1.20	1.34	-0.66	1.27	-1.53	1.17
Base Thick	-0.01	0.04	-0.03	0.08	-0.05	0.10	0.07	0.07	0.12	0.12
SSA	0.36	0.41	0.20	0.38	0.56	0.56	0.22	0.39	0.91	0.68
Joint Spacing	0.63	0.38	0.58	0.36	0.56	0.44	0.43	0.47	0.79	0.50
Dowel Diameter	0.10	0.08	-0.22	0.28	0.10	0.12	0.47	0.26	0.01	0.11
LTE	-0.05	0.07	-0.02	0.06	-0.05	0.09	-0.08	0.09	-0.06	0.07
Slab Width	-0.56	0.99	-0.66	0.76	-0.74	0.90	0.12	1.49	-1.90	1.57
Erodibility Index	0.03	0.06	-0.02	0.04	-0.04	0.05	-0.03	0.05	-0.06	0.06
PCC Unit Weight	0.54	0.62	0.98	0.73	0.39	1.37	0.55	0.63	0.49	0.66
PCC Poisson Ratio	0.08	0.15	-0.26	0.24	0.20	0.24	0.06	0.27	0.14	0.12
PCC CTE	0.57	0.68	0.61	0.64	0.77	0.85	0.52	0.79	1.03	0.89
PCC Thermal Conductivity	-0.30	0.37	-0.30	0.33	-0.35	0.38	-0.18	0.41	-0.42	0.35
PCC Cement Content	-0.04	0.08	0.07	0.24	0.11	0.12	0.06	0.20	-0.01	0.06
PCC W/C	0.00	0.24	-0.08	0.42	0.23	0.46	-0.22	0.70	0.48	0.41
PCC 28-Day MOR	-0.92	1.16	-0.95	1.10	-1.11	1.53	-1.45	1.35	-1.60	1.30
PCC 28-Day E	0.26	0.27	0.06	0.49	0.54	0.51	0.31	0.89	1.01	0.78
PCC 20-year MOR to 28-day MOR	-0.57	0.55	-0.56	0.55	-0.61	0.64	-0.45	0.45	-1.09	0.80
Base Mr	0.09	0.08	-0.08	0.16	0.06	0.07	-0.06	0.16	0.00	0.05
Subgrade Mr	-0.02	0.08	-0.05	0.12	-0.07	0.13	-0.03	0.13	-0.08	0.09
GWD	0.04	0.04	-0.01	0.06	0.04	0.07	0.01	0.04	-0.13	0.12
Construction Month	-0.03	0.06	0.04	0.09	-0.03	0.04	0.00	0.06	-0.02	0.05
Design Lane Width	-0.80	0.60	-0.05	0.84	-0.88	1.45	0.29	1.39	-0.33	0.59

Table 10.15. NSI statistics from ANN RSMs – New JPCP/IRI.

Design Input	Climate Zone									
	CD		CW		T		HD		HW	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
AADTT Per Lane	0.12	0.13	0.08	0.07	0.07	0.07	0.04	0.07	0.10	0.10
JPCP Thick	-0.24	0.13	-0.02	0.07	-0.15	0.14	-0.07	0.12	-0.20	0.15
Base Thick	-0.03	0.03	0.00	0.02	0.00	0.01	0.01	0.02	0.02	0.02
SSA	0.06	0.06	0.13	0.17	0.11	0.07	0.04	0.06	0.20	0.17
Joint Spacing	0.13	0.07	0.07	0.06	0.09	0.07	0.06	0.05	0.13	0.12
Dowel Diameter	-0.05	0.03	-0.20	0.08	-0.07	0.05	-0.09	0.14	-0.16	0.10
LTE	-0.02	0.02	-0.01	0.01	-0.01	0.02	-0.01	0.02	-0.02	0.02
Slab Width	-2.20	2.80	-1.87	3.47	-0.99	1.03	-0.98	2.29	-1.51	1.25
Erodibility Index	0.05	0.06	0.02	0.03	0.01	0.02	0.01	0.03	0.02	0.02
PCC Unit Weight	-0.33	0.43	-0.19	0.36	-0.23	0.17	-0.20	0.39	-0.35	0.31
PCC Poisson Ratio	0.07	0.06	0.00	0.03	0.03	0.03	0.03	0.02	0.05	0.04
PCC CTE	0.46	0.39	0.29	0.27	0.23	0.20	0.18	0.22	0.39	0.36
PCC Thermal Conductivity	-0.07	0.05	-0.04	0.05	-0.05	0.05	-0.04	0.04	-0.07	0.07
PCC Cement Content	0.05	0.05	0.03	0.03	0.05	0.03	0.02	0.02	0.07	0.05
PCC W/C	0.39	0.21	0.17	0.11	0.14	0.13	0.01	0.18	0.20	0.18
PCC 28-Day MOR	0.12	0.20	-0.06	0.12	-0.08	0.10	-0.16	0.23	-0.06	0.05
PCC 28-Day E	0.07	0.06	-0.02	0.06	0.11	0.07	0.08	0.07	0.13	0.12
PCC 20-year MOR to 28-day MOR	-0.01	0.04	-0.02	0.04	-0.05	0.05	-0.03	0.06	-0.11	0.08
Base Mr	0.08	0.07	-0.01	0.02	-0.01	0.01	0.00	0.01	0.00	0.01
Subgrade Mr	-0.69	0.15	-0.21	0.07	-0.03	0.02	-0.03	0.03	-0.06	0.05
GWD	-0.01	0.02	0.00	0.01	0.00	0.01	0.00	0.01	-0.02	0.02
Construction Month	0.01	0.02	0.03	0.02	0.00	0.01	0.01	0.01	0.00	0.01
Design Lane Width	-0.02	0.17	0.11	0.27	-0.06	0.12	0.08	0.27	0.07	0.08

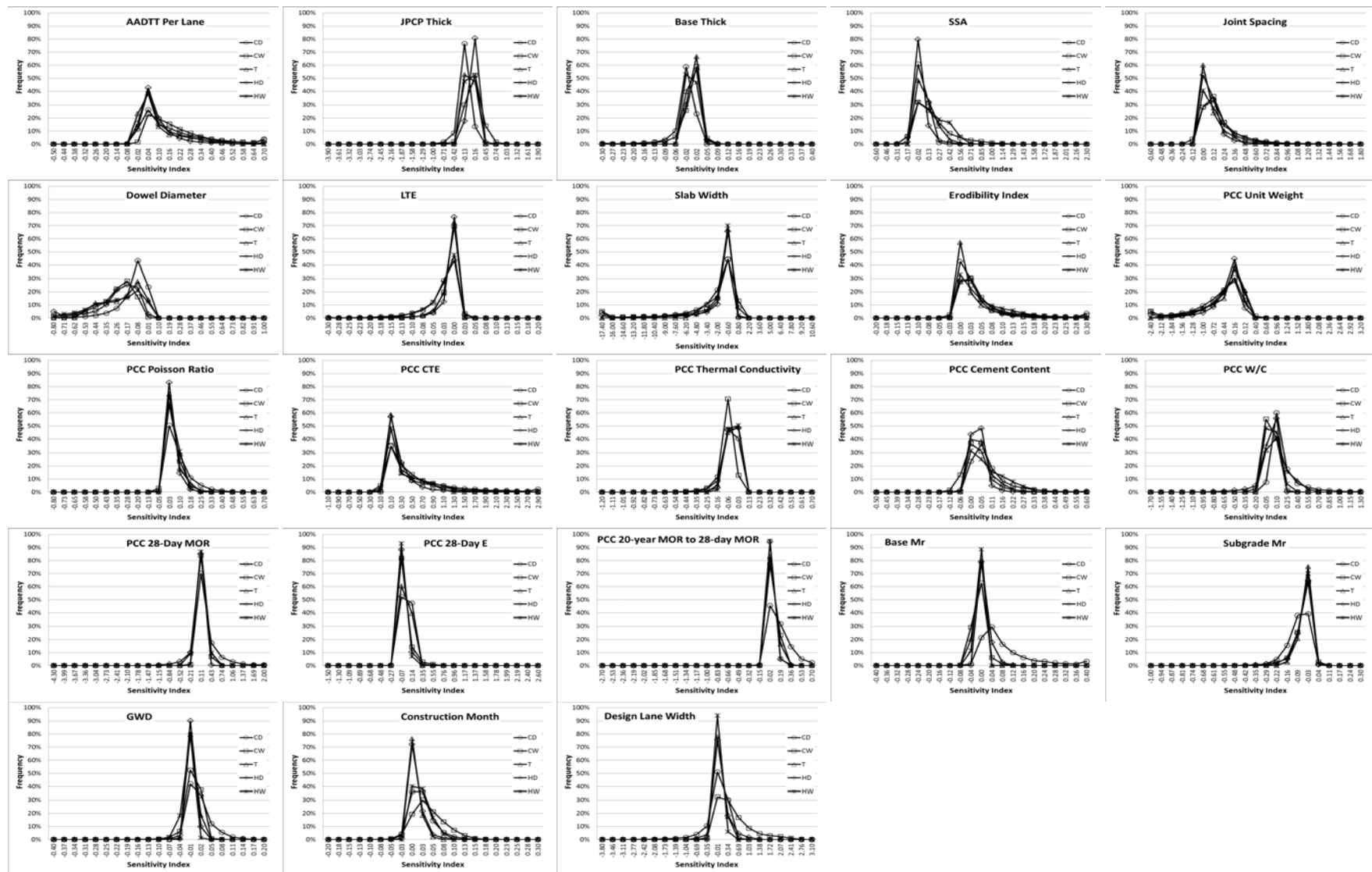


Figure 10.9. Distributions of NSI values – New JPCP/Faulting.

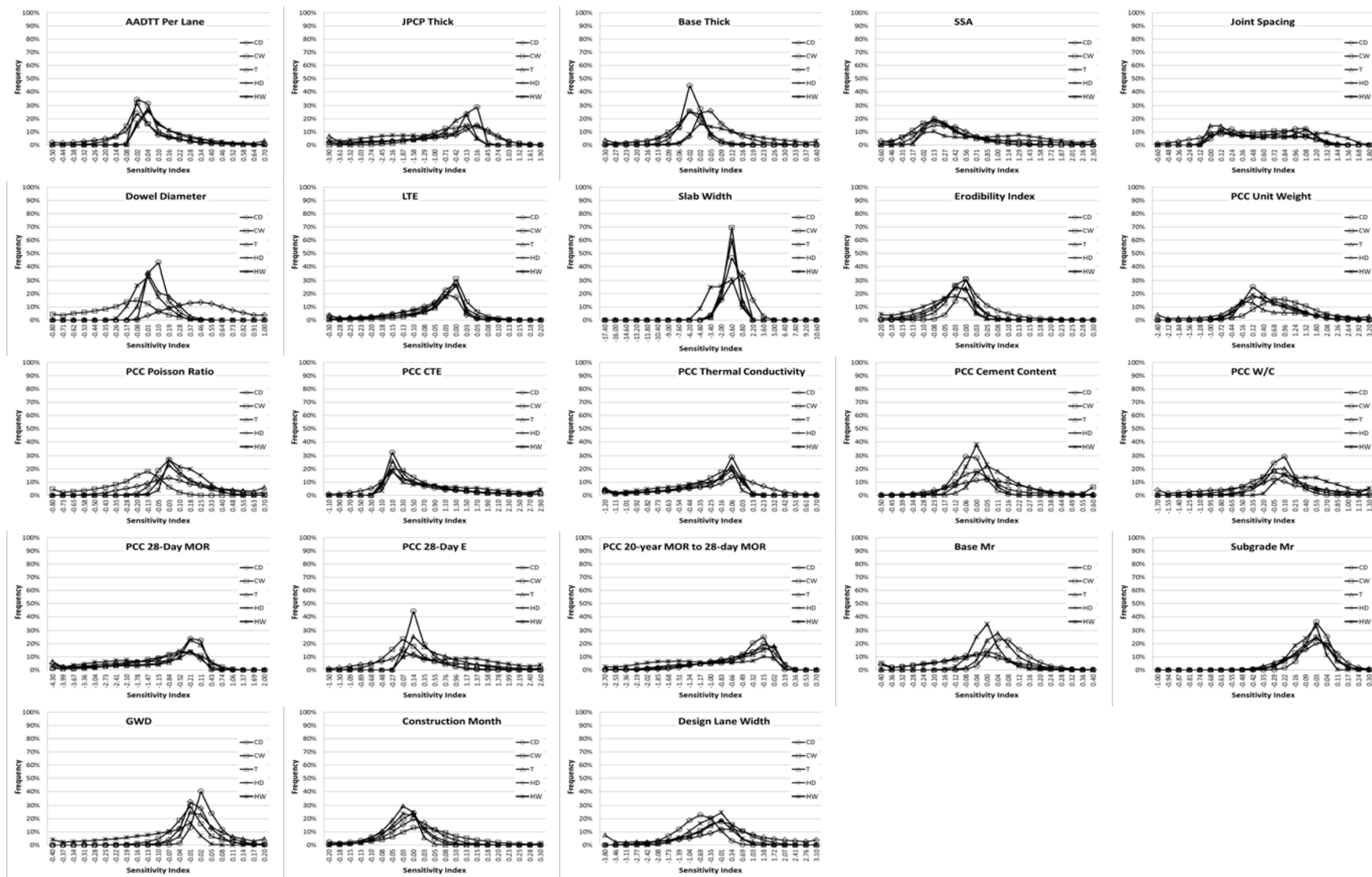


Figure 10.10. Distributions of NSI values – New JPCP/Transverse Cracking.

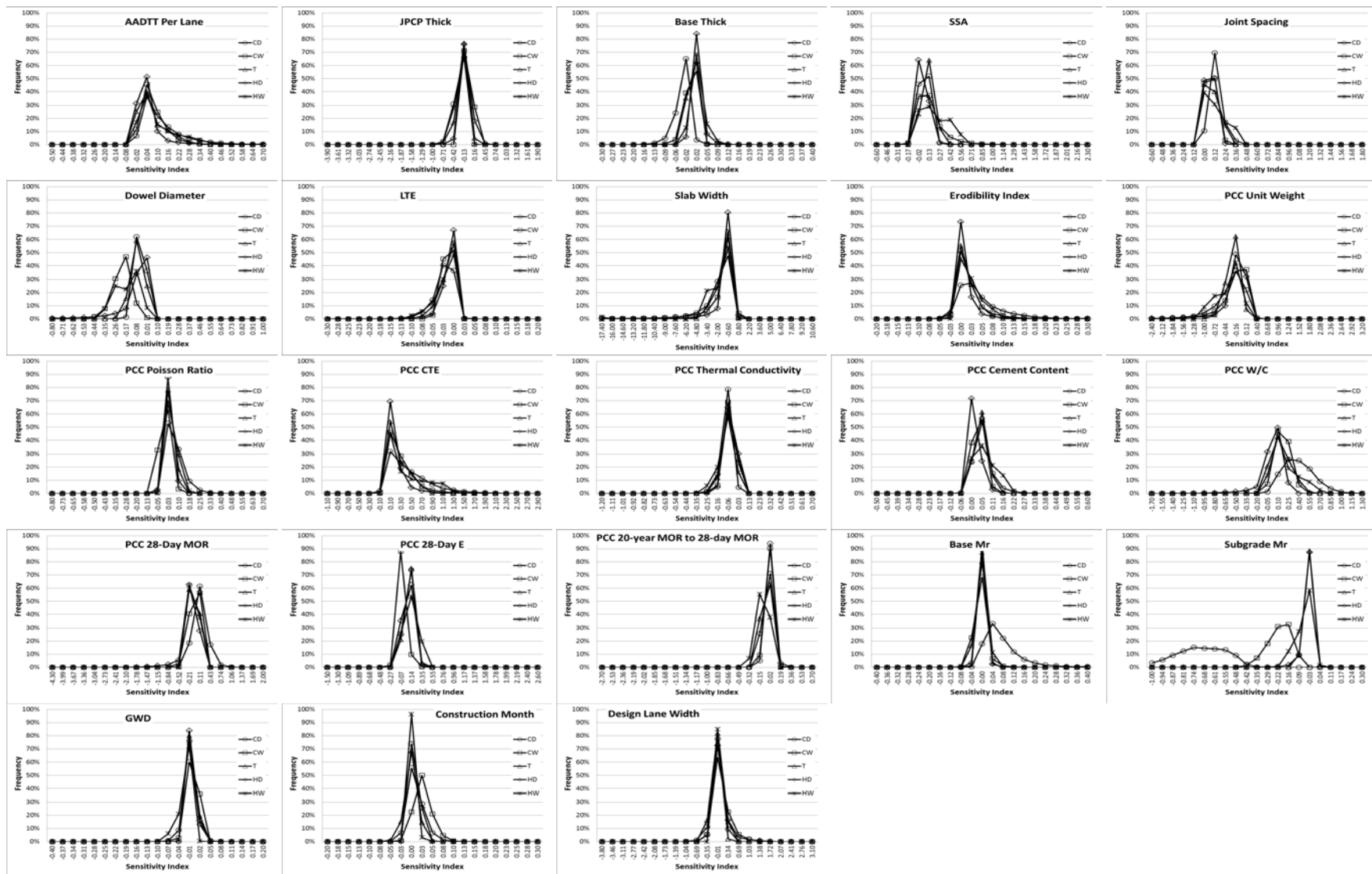


Figure 10.11. Distributions of NSI values – New JPCP/IRI.

10.5 Conclusions – New JPCP

The maximum average sensitivity coefficients from the MVLR RSMs across climate zones for all distress and design input combinations are ranked by maximum absolute value across distresses in Table 10.16. Even though the ranking is by maximum absolute value, the plus and minus signs are retained for each individual sensitivity coefficient to indicate whether distress increases (+) or decreases (-) with increasing input value. Usually—and especially for the highest sensitivity inputs—the plus/minus signs for each design input are consistent across all distresses.

The OAT local sensitivity category (Appendix B) for each design input is also indicated in Table 10.16. There is a lack of full congruence between the ranking of inputs from the MVLR RSMs and the categorization from the OAT analyses. The four design inputs categorized as HS in the OAT analyses are also the highest-ranked design inputs in Table 10.16, and most of the inputs categorized as VS in the OAT analyses also appear high in the list. However, there is some mixing of the VS and S inputs in the middle and lower portion of the rankings. Recall, however, that the goodness-of-fit statistics for many of the MVLR RSMs were quite low and that the computed sensitivity coefficients are averages across the problem domain.

Table 10.16. Ranking of New JPCP design inputs by overall maximum |Average Sensitivity Coefficient| (MVL RSMs).

Design Input	Maximum Average Sensitivity Coefficient (MVL RSM)				OAT Category ¹
	Faulting	Transverse Cracking	IRI	Maximum	
Slab Width	-1.51	-0.75	-1.06	-1.51	HS
JPCP Thick	0.03	-1.05	-0.17	-1.05	HS
PCC 28-Day MOR	0.18	-1.02	-0.01	-1.02	HS
Joint Spacing	0.23	0.74	0.13	0.74	HS
PCC Unit Weight	-0.67	0.58	-0.33	-0.67	VS
PCC 20-year MOR to 28-day MOR	0.07	-0.62	-0.03	-0.62	- ²
PCC CTE	0.39	0.61	0.31	0.61	VS
Dowel Diameter	-0.52	0.19	-0.28	-0.52	VS
SSA	0.10	0.42	0.12	0.42	HS
PCC 28-Day E	0.00	0.37	0.04	0.37	HS
PCC Thermal Conductivity	-0.04	-0.27	-0.06	-0.27	HS
Subgrade Mr	-0.07	-0.07	-0.25	-0.25	S
PCC W/C	0.12	0.16	0.21	0.21	S
Design Lane Width	0.14	-0.19	0.09	-0.19	HS/NS ³
AADTT Per Lane	0.12	0.08	0.09	0.12	VS
PCC Cement Content	0.08	-0.03	0.05	0.08	S
Erodibility Index	0.06	-0.02	0.03	0.06	S
PCC Poisson Ratio	0.06	0.05	0.05	0.06	VS
Base Mr	0.03	0.02	0.02	0.03	VS
LTE	0.00	-0.03	-0.01	-0.03	NS
GWD	-0.01	-0.02	-0.01	-0.02	S
Construction Month	0.02	-0.02	0.01	-0.02	S
Base Thick	-0.02	0.01	-0.01	-0.02	S

¹HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Non-Sensitive

²20-year strength ratio values not considered explicitly in OAT analyses

³Design lane width under widen slab condition was Hyper Sensitive/ Design lane width under tied shoulder or no edge support condition was Non Sensitive in OAT analyses

The maximum Mean NSI values from the ANN RSMs across climate zones for all distress and design input combinations are ranked by the maximum absolute value across distresses in Table 10.17. The Mean NSI values were computed from the 10,000 ANN RSM evaluations for each climate zone and distress combination (Table 10.13 through Table 10.15). The plus and minus signs are again retained for each individual sensitivity index to indicate whether distress increases (+) or decreases (-) with increasing input value. Usually—and especially for the highest sensitivity inputs—the plus/minus signs for each design input are consistent across all distresses.

The OAT local sensitivity category (Appendix B) for each design input is also indicated in Table 10.17. There is a lack of full congruence between the ranking of inputs from the ANN RSMs and the categorization from the OAT analyses. The three design inputs categorized as HS in the OAT analyses are also the highest-ranked design inputs in Table 10.17, and most of the inputs categorized as VS in the OAT analyses also appear high in the list. However, there is some mixing of the HS, VS and S inputs in the middle and lower portion of the rankings. Recall, however, that the goodness-of-fit statistics for most of the ANN RSMs for transverse cracking were quite low.

Table 10.17. Ranking of New JPCP design inputs by maximum |Mean| NSI values (ANN RSMs).

Design Input	Maximum Mean NSI Values (ANN RSMs)				OAT Category ¹
	Faulting	Transverse Cracking	IRI	Maximum	
Slab Width	-3.80	-1.90	-2.20	-3.80	HS
PCC 28-Day MOR	0.25	-1.60	-0.16	-1.60	HS
JPCP Thick	0.11	-1.53	-0.24	-1.53	HS
PCC 20-year MOR to 28-day MOR	0.17	-1.09	-0.11	-1.09	- ²
PCC CTE	0.65	1.03	0.46	1.03	VS
PCC 28-Day E	0.04	1.01	0.13	1.01	HS
PCC Unit Weight	-0.71	0.98	-0.35	0.98	VS
SSA	0.19	0.91	0.20	0.91	HS
Design Lane Width	0.48	-0.88	0.11	-0.88	HS/NS ³
Joint Spacing	0.20	0.79	0.13	0.79	HS
Subgrade Mr	-0.08	-0.08	-0.69	-0.69	S
PCC W/C	0.18	0.48	0.39	0.48	S
Dowel Diameter	-0.27	0.47	-0.20	0.47	VS
PCC Thermal Conductivity	-0.07	-0.42	-0.07	-0.42	HS
PCC Poisson Ratio	0.09	-0.26	0.07	-0.26	VS
AADTT Per Lane	0.21	0.17	0.12	0.21	VS
GWD	0.02	-0.13	-0.02	-0.13	S
Base Thick	-0.03	0.12	-0.03	0.12	S
PCC Cement Content	0.09	0.11	0.07	0.11	S
Base Mr	0.09	0.09	0.08	0.09	VS
LTE	-0.03	-0.08	-0.02	-0.08	NS
Erodibility Index	0.06	-0.06	0.05	-0.06	S
Construction Month	0.04	0.04	0.03	0.04	S

¹HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Non-Sensitive

²20-year strength ratio values not considered explicitly in OAT analyses

³Design lane width under widen slab condition was Hyper Sensitive/ Design lane width under tied shoulder or no edge support condition was Non Sensitive in OAT analyses

As a more severe measure of sensitivity, the mean plus/minus two standard deviation ($\mu \pm 2\sigma$) NSI values were computed using the statistics in Table 10.13 through Table 10.15 based on the 10,000 ANN RSM evaluations for each climate zone and distress combination. These sensitivity limits are ranked by maximum absolute value across distresses in Table 10.18. The plus and minus signs are again retained for each individual sensitivity index to indicate whether distress increases (+) or decreases (-) with increasing input value. Usually—and especially for the highest sensitivity inputs—the plus/minus signs for each design input are consistent across all distresses. There is very good agreement between the input rankings in Table 10.18 and those based on the mean NSI values in Table 10.17.

The OAT local sensitivity category (Appendix B) for each design input is also indicated in Table 10.18. Not only is there a better congruence between the ranking of inputs from the ANN RSMs and the categorization from the OAT analyses, but the ranges of $\mu \pm 2\sigma$ in Table 10.18 also line up closely with the ranges of normalized sensitivity index values used to define the OAT categories. These

sensitivity categories are highlighted by the fonts in Table 10.18: **Bold** = Hypersensitive (HS), $\mu+2\sigma > 5$; ***Bold Italic*** = Very Sensitive (VS), $1 < \mu+2\sigma < 5$; *Italic* = Sensitive (S), $0.1 < \mu+2\sigma < 1$; and Regular = Non-Sensitive (NS), $\mu+2\sigma < 0.1$. The rankings and $\mu+2\sigma$ values in Table 10.18 are judged to be the best measures of the design input sensitivities in the MEPDG.

Table 10.18. Ranking of New JPCP design inputs by maximum $|\mu+2\sigma|$ NSI values (ANN RSMs).

Design Input	Maximum $\mu+2\sigma$ NSI Values (ANN RSMs)				OAT Category ¹
	Faulting	Transverse Cracking	IRI	Maximum	
Slab Width	-17.97	-5.04	-8.81	-17.97	HS
PCC 28-Day MOR	0.92	-4.21	-0.63	-4.21	HS
JPCP Thick	0.51	-3.88	-0.50	-3.88	HS
Design Lane Width	1.58	-3.78	0.65	-3.78	HS/NS ³
PCC Unit Weight	-2.33	3.13	-1.19	3.13	VS
PCC CTE	2.16	2.81	1.25	2.81	VS
PCC 20-year MOR to 28-day MOR	0.50	-2.69	-0.26	-2.69	- ²
PCC 28-Day E	0.21	2.57	0.37	2.57	HS
SSA	0.68	2.27	0.55	2.27	HS
Joint Spacing	0.66	1.79	0.36	1.79	HS
PCC W/C	0.62	1.62	0.82	1.62	S
PCC Thermal Conductivity	-0.21	-1.12	-0.21	-1.12	HS
Subgrade Mr	-0.20	-0.34	-0.99	-0.99	S
Dowel Diameter	-0.69	0.98	-0.37	0.98	VS
PCC Poisson Ratio	0.26	-0.75	0.19	-0.75	VS
AADTT Per Lane	0.63	0.56	0.37	0.63	VS
PCC Cement Content	0.30	0.55	0.18	0.55	S
Base Mr	0.33	0.40	0.22	0.40	VS
GWD	0.08	-0.37	-0.06	-0.37	S
Base Thick	-0.12	0.35	-0.08	0.35	S
LTE	-0.13	-0.26	-0.07	-0.26	NS
Erodibility Index	0.25	-0.19	0.16	0.25	S
Construction Month	0.11	0.22	0.07	0.22	S

¹HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Non-Sensitive

²20-year strength ratio values not considered explicitly in OAT analyses

³Design lane width under widen slab condition was Hyper Sensitive/ Design lane width under tied shoulder or no edge support condition was Non Sensitive in OAT analyses

Figure 10.12 through Figure 10.14 provide graphical summaries of the input sensitivities by distress. These figures highlight the difference in sensitivities between Hypersensitive and Very Sensitive and between Very Sensitive and Sensitive. All of the figures have the same horizontal axis range so that the differences in sensitivities across distresses can be more clearly evaluated. The solid bars in the figures indicate the mean NSI values, and the error bars correspond to one standard deviation. The sensitivities are also broken down by climate zone for each design input. No systematic or substantial effect of climate zone on the design input sensitivity statistics is observed.

Figure 10.12. Ranking of New JPCP design inputs by $|\mu \pm 2\sigma|$ NSI values: faulting.

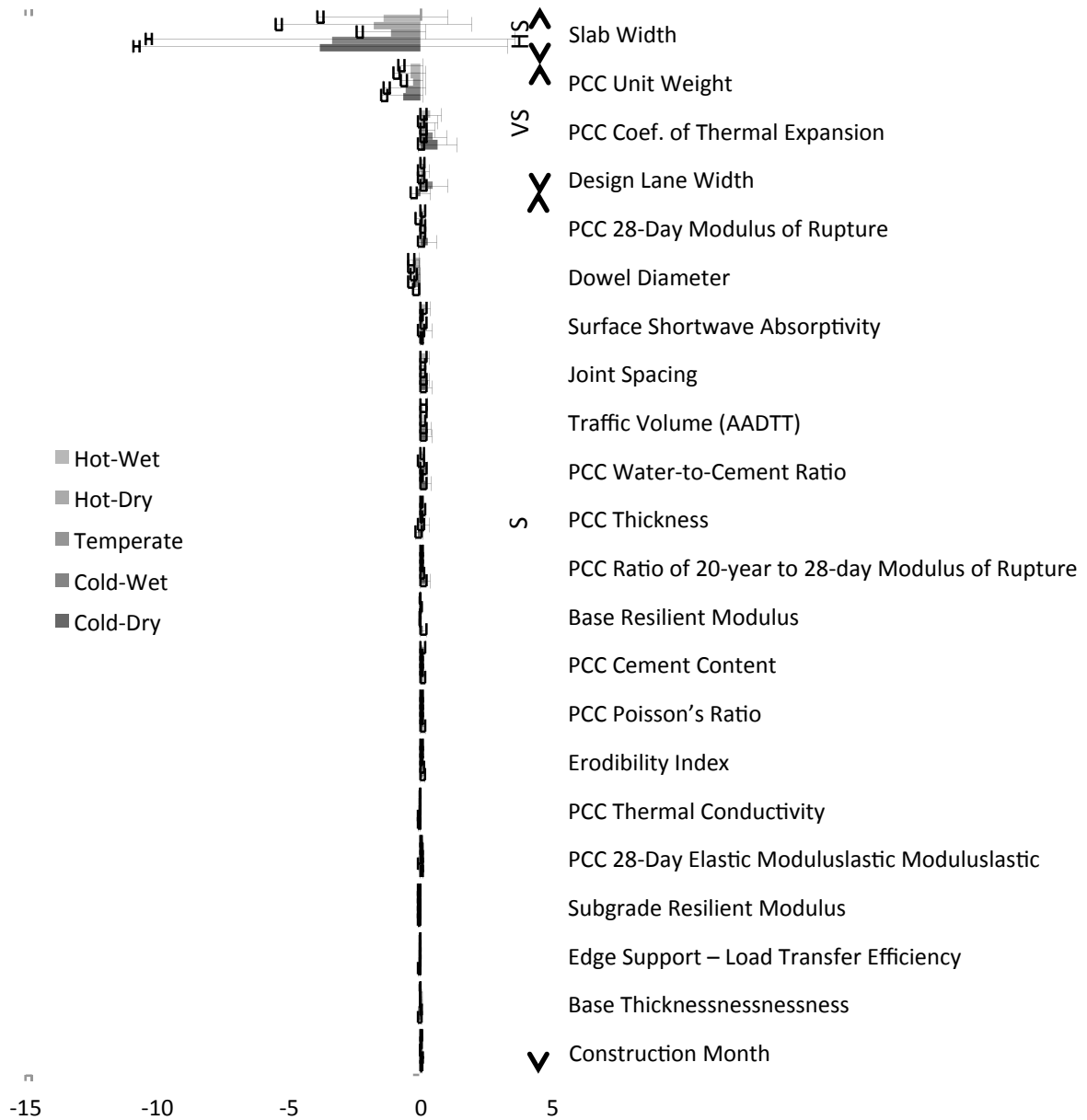


Figure 10.13. Ranking of New JPCP design inputs by $|\mu \pm 2\sigma|$ NSI values: transverse cracking.



Figure 10.14. Ranking of New JPCP design inputs by $|\mu \pm 2\sigma|$ NSI values: IRI.



As a more practical aid to the pavement designer, Table 10.19 summarizes in rank order the Hypersensitive, Very Sensitive, and Sensitive design inputs by material category (PCC, base, subgrade, other) for each distress. The design inputs that fall in the Hypersensitive or Very Sensitive categories for most (2 out of 3) distresses are indicated by bold font in the table. For the New JPCP scenarios, these include the PCC properties of unit weight and coefficient of thermal expansion and the geometric properties of slab width and design lane width. The PCC 28-day modulus of rupture, surface shortwave absorptivity, and thickness were also in the Very Sensitive or at the high end of the Sensitive category for all three distresses, followed closely by the ratio of 20-year to 28-day modulus of rupture and the 28-day elastic modulus. None of the base or subgrade properties was as consistently in the two highest sensitivity categories.

There are few observations that merit special discussion:

- When interpreting the sensitivity of design lane width, it is important to remember that it was evaluated under three different edge support conditions (no edge support, tied shoulder edge support, and widened slab edge support condition). Design lane width under widened slab edge support showed high sensitivity for transverse cracking but design lane width under either no edge support or tied shoulder edge support was not sensitive.
- PCC Unit Weight was a surprisingly sensitive input. The PCC unit weight is an important factor in the calculation of critical responses in the rigid pavement structural response models employed in MEPDG through its influence on curling deflections (faulting) and curling stresses (transverse cracking). It is also an input parameter to the Level 3 empirical regression equation for estimating E, but this is not reflected in the GSA which employed synthetic Level 1 PCC strength and stiffness inputs.

As described previously, the evaluation of the sensitivity of transverse cracking to the design inputs is less certain than for faulting and IRI. The JPCP cracking predictions could not be accurately characterized with either the classical MVLRL or the more advanced ANN response surface modeling methodologies.

Table 10.19. Hypersensitive, Very Sensitive, and Sensitive design inputs by distress and input category for New JPCP pavements. $NSI_{\mu \pm 2\sigma}$ values are given in parentheses. Inputs in bold font are Hypersensitive or Very Sensitive for most (2 out of 3) distresses.

<i>Distress</i>	<i>Input Category</i>	<i>Hypersensitive (>5)</i>	<i>Very Sensitive (1-5)</i>	<i>Sensitive (0.1-1)</i>
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)

<i>Distress</i>	<i>Input Category</i>	<i>Hypersensitive (>5)</i>	<i>Very Sensitive (1-5)</i>	<i>Sensitive (0.1-1)</i>
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)

11 JPCP OVER STIFF FOUNDATION

11.1 Analysis Inputs

This pavement type is intended to encompass JPCP on stiff stabilized base/subgrade layers. The project-specific parameters for all GSA analyses of JPCP over Stiff Foundation cases were the same as the ones for the New JPCP cases (see Table 10.1) except for the second layer material type. The JPCP Over Stiff Foundation cases utilized stabilized unbound materials as the second layer material type instead of the granular materials used in the New JPCP scenarios. Stabilized unbound materials were characterized in terms of their resilient modulus values.

Table 11.1 summarizes the design inputs that are related to traffic level. The 5-in. baseline JPCP slab thickness with variations ranging from 3 in. to 7 in. was initially suggested for the low traffic level. However, the MEPDG requires a minimum PCC slab thickness of 6 inches. Therefore, an 8-in. baseline PCC slab thickness (with values ranging from 7 to 9 in.) was selected to evaluate the sensitivity of MEPDG distress predictions to PCC thickness under low traffic condition.

Table 11.1. Design inputs related to traffic levels in JPCP Over Stiff Foundation cases.

Traffic Level Input Parameter	Low Traffic			Medium Traffic			High Traffic		
	Baseline	Min	Max	Baseline	Min	Max	Baseline	Min	Max
AADTT-Nominal	1000	500	5000	7500	5000	10000	25000	20000	30000
Design Lane	375	188	1875	2063	1375	2750	6250	5000	7500
PCC Thickness	8	7	9	9	8	10	11	9	13
Base Thickness	4	3	6	6	4	8	8	6	10

Most of the remaining design inputs in the stiff foundation simulations were varied over the same ranges as shown in Table 10.3 for the New JPCP scenarios. Changed or added design inputs for the JPCP Over Stiff Foundation cases are summarized in Table 11.2.

Table 11.2. Input parameters and variations in JPCP Over Stiff Foundation.

Input Parameter	OAT Sensitivity ¹	Baseline Value ²	Minimum ²	Maximum ²
Stabilized Base Resilient Modulus	NS	100,000	40,000	3,000,000
Loss of Full Friction	S	136	0	150

¹HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Not Sensitive

²Same units as for MEDPG input.

11.2 Predicted Distresses

Over 6400 MEPDG runs were performed for the JPCP Over Stiff Foundation GSA. Table 11.3 through Table 11.5 provide summary statistics for predicted faulting, cracking, and IRI, respectively, for the GSA simulations for each base case combination of climate zone and traffic level. Overall, the Latin hypercube sampling scheme generated input data sets that produced a wide range for each of the predicted distresses. The range of predicted distresses in most cases is from zero or near zero to values several times the default design limit. A correlation between traffic level and JPCP cracking

was observed (i.e., higher the traffic, lower the cracking), although it is not as strong as that for New JPCP. The average values for faulting and IRI were relatively insensitive to traffic level and climate zone.

Figure 11.1 through Figure 11.5 provide frequency distributions of predicted distresses by climate zone and traffic level. These results confirm that the GSA simulations for the JPCP Over Stiff Foundation cases span a wide range of the model output (distress) space as well as the model inputs domain.

Table 11.3. Summary statistics for predicted faulting – JPCP Over Stiff Foundation.

Scenario	Mean	Minimum	Maximum	Std Dev
CDL	0.04	0.00	0.44	0.06
CDM	0.05	0.00	0.45	0.07
CDH	0.07	0.00	0.47	0.08
CWL	0.04	0.00	0.33	0.06
CWM	0.05	0.00	0.36	0.07
CWH	0.06	0.00	0.37	0.07
TL	0.01	0.00	0.23	0.02
TM	0.02	0.00	0.16	0.02
TH	0.02	0.00	0.17	0.03
HDL	0.02	0.00	0.33	0.04
HDM	0.03	0.00	0.28	0.04
HDH	0.04	0.00	0.26	0.05
HWL	0.02	0.00	0.20	0.03
HWM	0.02	0.00	0.19	0.03
HWH	0.03	0.00	0.29	0.04
Overall	0.03	0.00	0.47	0.05

Table 11.4. Summary statistics for predicted cracking – JPCP Over Stiff Foundation.

Scenario	Mean	Minimum	Maximum	Std Dev
CDL	38	0	100	43
CDM	34	0	100	43
CDH	29	0	100	41
CWL	38	0	100	43
CWM	34	0	100	43
CWH	27	0	100	40
TL	26	0	100	38
TM	22	0	100	37
TH	20	0	100	36
HDL	41	0	100	44
HDM	35	0	100	43
HDH	32	0	100	42
HWL	31	0	100	41
HWM	30	0	100	41
HWH	26	0	100	40
Overall	31	0	100	42

Table 11.5. Summary statistics for predicted IRI – JPCP Over Stiff Foundation.

Scenario	Mean	Minimum	Maximum	Std Dev
CDL	174	91	407	59
CDM	176	93	401	63
CDH	178	95	412	67
CWL	139	73	322	57
CWM	142	73	326	62
CWH	140	72	331	63
TL	92	63	243	38
TM	91	63	214	39
TH	92	63	221	40
HDL	109	63	281	48
HDM	109	63	269	49
HDH	110	63	259	51
HWL	100	63	245	44
HWM	102	63	235	45
HWH	102	63	261	47
Overall	124	63	412	61

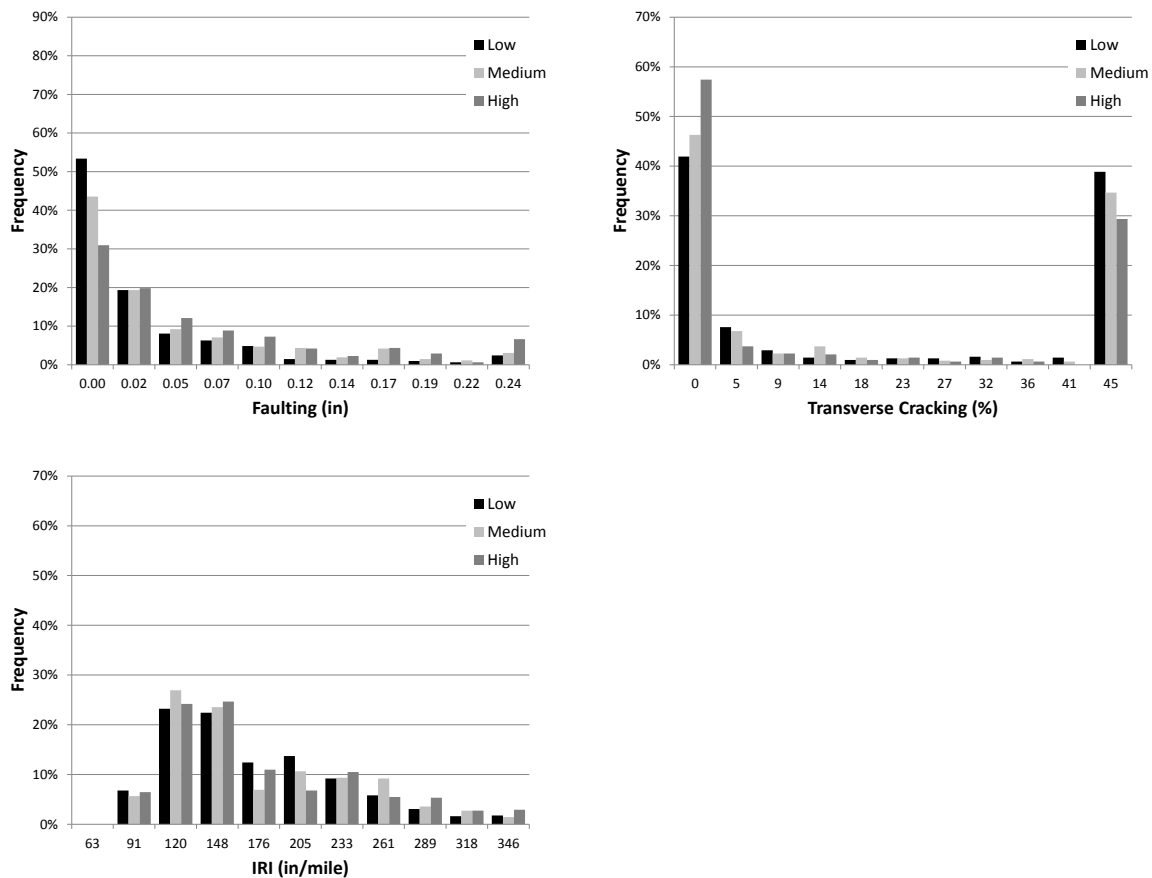


Figure 11.1. Distribution of predicted distresses – JPCP Over Stiff Foundation/Cold-Dry.

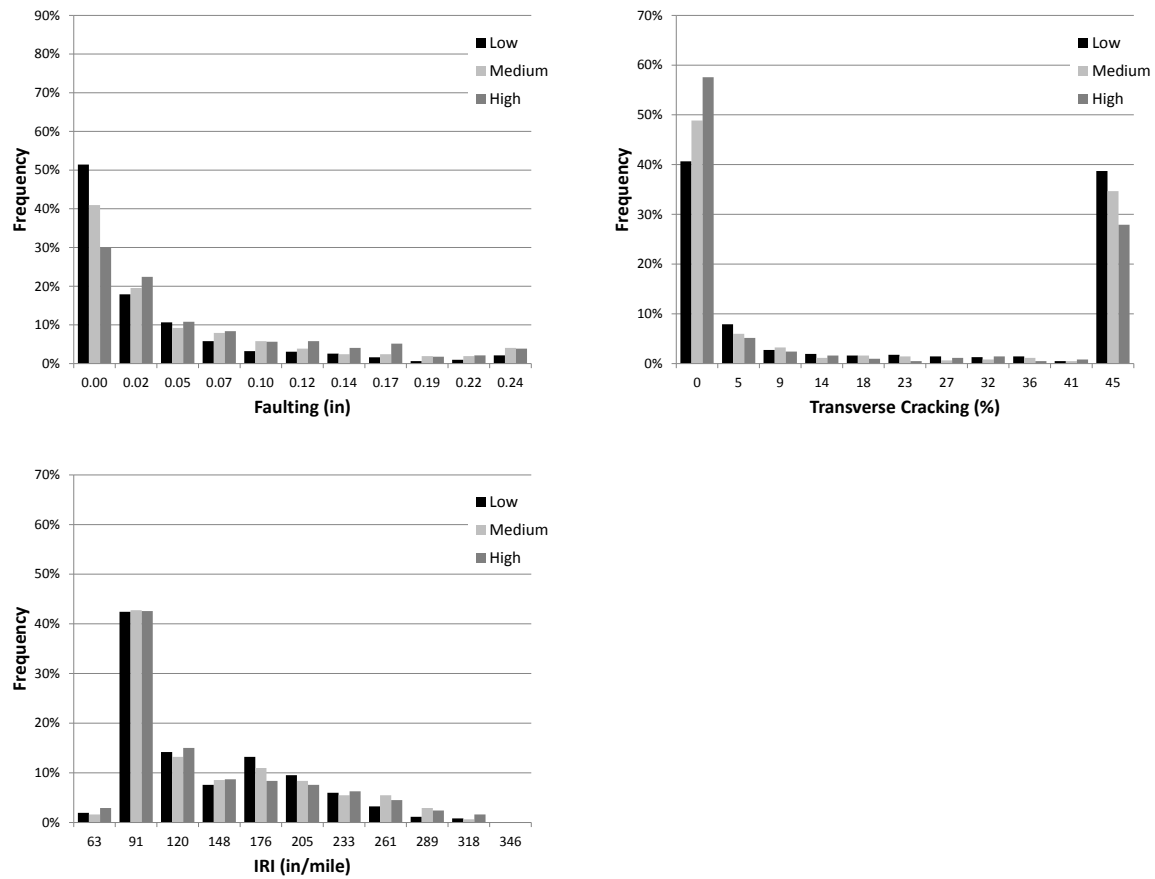


Figure 11.2. Distribution of predicted distresses – JPCP Over Stiff Foundation/Cold-Wet.

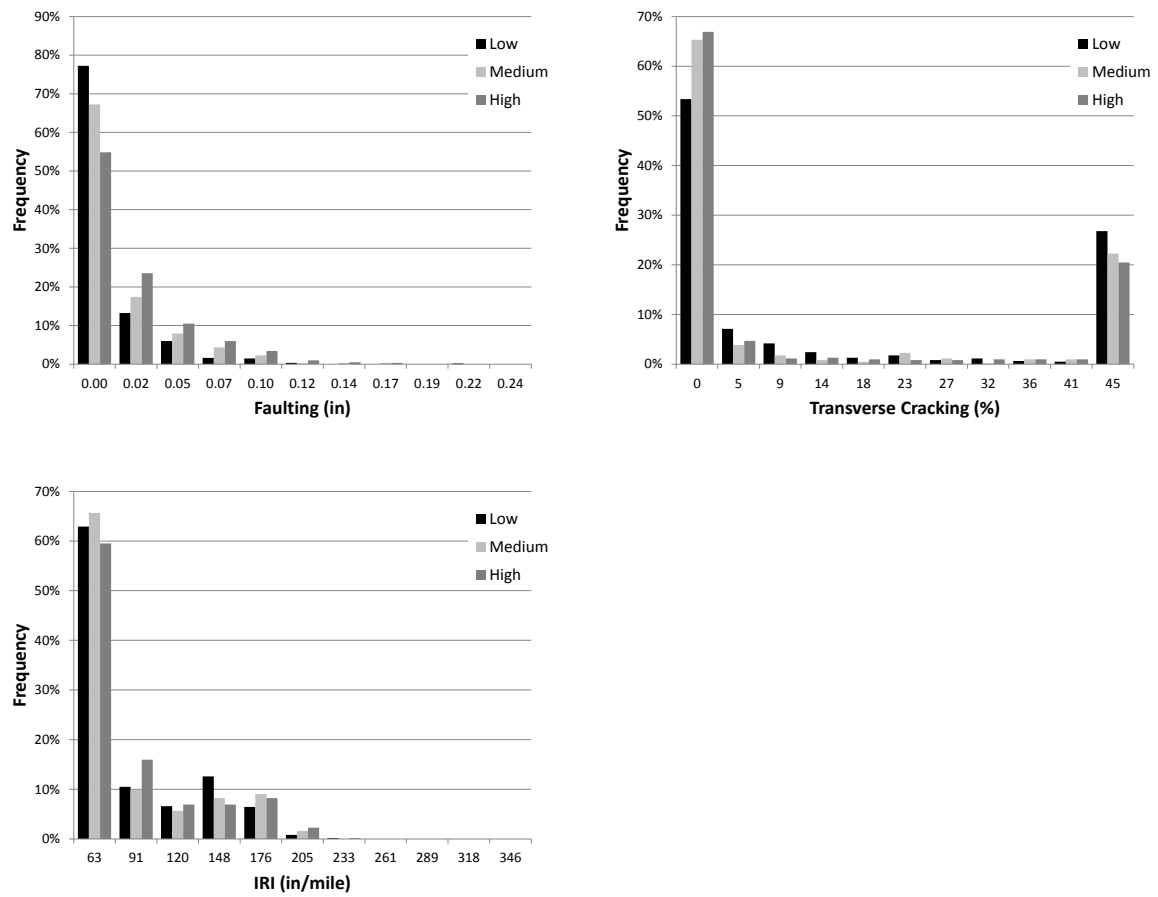


Figure 11.3. Distribution of predicted distresses – JPCP Over Stiff Foundation/Temperate.

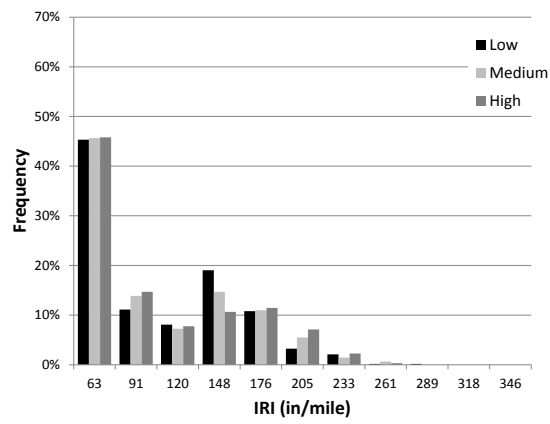
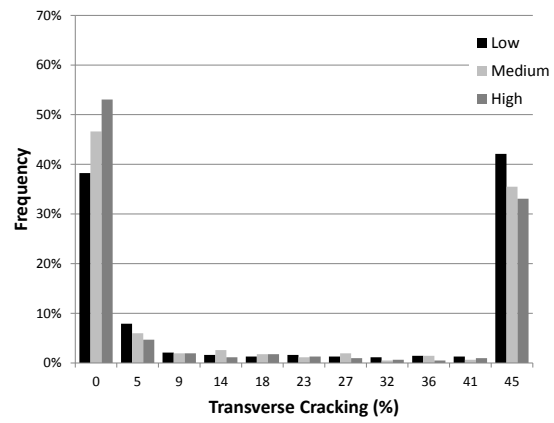
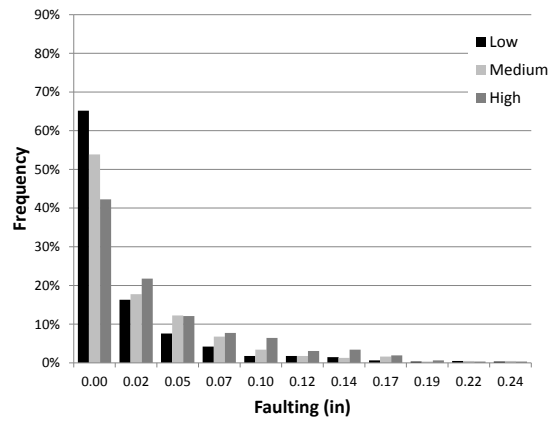


Figure 11.4. Distribution of predicted distresses – JPCP Over Stiff Foundation/Hot-Dry

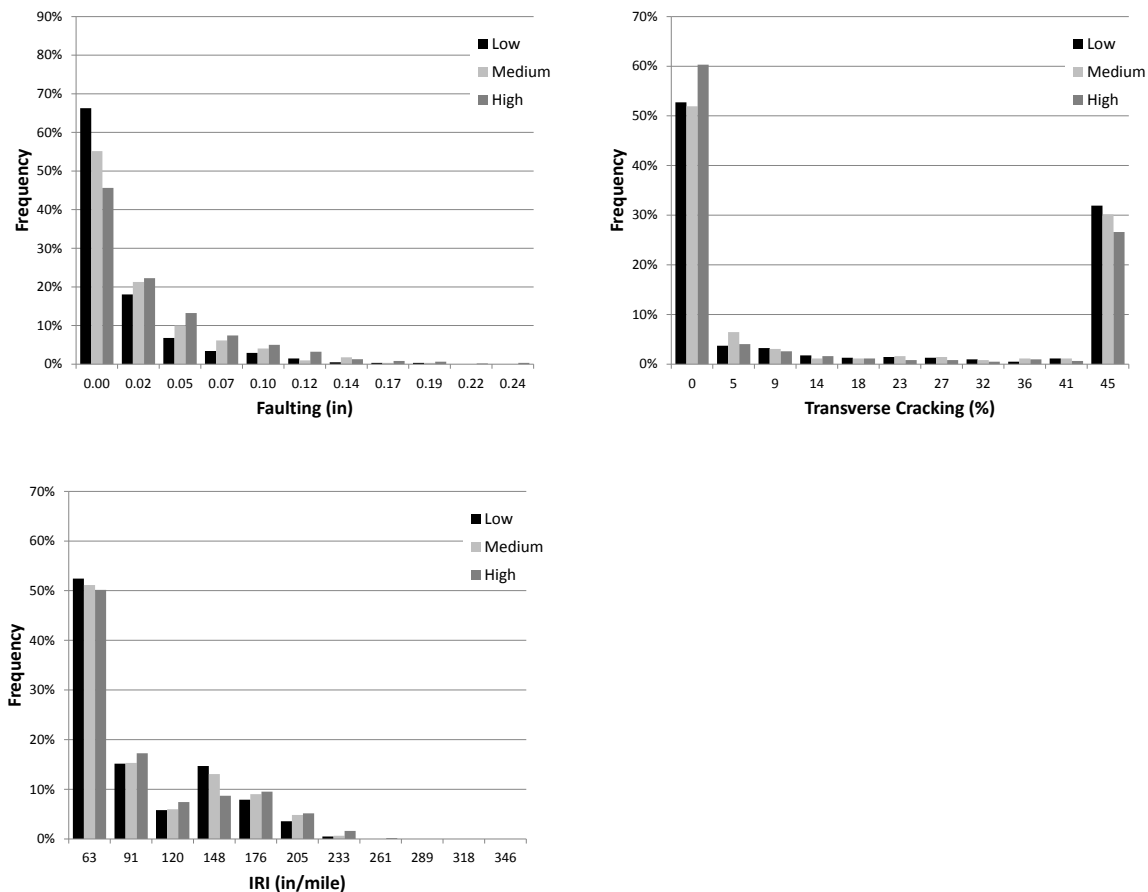


Figure 11.5. Distribution of predicted distresses – JPCP Over Stiff/Hot-Wet.

11.3 Response Surface Modeling

Table 11.6 defines the inputs used for the RSMs. These design inputs are the same as those given previously in Table 11.1 and Table 11.2. As discussed previously under New JPCP, there is one difference: the 7-day, 14-day and 90-day MOR and E values were not included for the RSMs since the inclusion of 28-day MOR and E alone was found to be sufficient in uniquely capturing the input sensitivities associated with PCC MOR and E.

The outputs for the RSMs are the predicted distresses: faulting, cracking, and IRI. Separate RSMs were developed for each distress. As described previously in Section 6, each input for the MVLR RSMs is normalized by its mean value from the GSA simulations and each output distress is normalized by its default design limit. As described previously in Section 7, IRI is treated as a special case because it has a nonzero lower bound

The regression coefficients in the normalized MVLR RSMs can be interpreted as average sensitivity indices quantifying the percentage change in distress relative to design limit caused by a given percentage change in the design input relative to its mean value. These average sensitivity indices are

constant across the problem domain—i.e., the MVL RSMs do not capture any variations of sensitivity with location in the problem domain.

Table 11.6. Definition of ANN input labels for JPCP Over Stiff Foundation cases.

ANN Input No.	Name of Design Input	Description
1	AADTT per Lane	Average Annual Daily Truck Traffic in design lane
2	JPCP Thick	PCC slab thickness
3	Base Thick	Base layer thickness
4	SSA	Surface Shortwave Absorption
5	Joint Spacing	Transverse joint spacing of JPCP
6	Dowel Diameter	Diameter of dowel bar
7	Edge Support - LTE	Load Transfer Efficiency of tied shoulder for edge support
8	Edge Support - Widen Slab	Widened slab widths for edge support
9	Erodibility Index	Erodibility condition of base material layer
10	PCC Unit Weight	Unit weight of Portland Cement Concrete
11	PCC Poisson Ratio	Poisson's ratio of Portland Cement Concrete
12	PCC CTE	Coefficient of Thermal Contraction of Portland Cement Concrete
13	PCC Thermal Conductivity	Thermal conductivity of Portland Cement Concrete
14	PCC Cement Content	Cement content of Portland Cement Concrete
15	PCC W/C	Ratio of water to cement of Portland Cement Concrete
16	PCC 28-Day MOR	28-day Modulus of Rupture of Portland Cement Concrete
17	PCC 28-Day E	28-day elastic modulus of Portland Cement Concrete
18	PCC 20-year MOR to 28-day MOR	Ratio of 20-year Modulus of Rupture of Portland Cement Concrete to 28-day Modulus of Rupture of Portland Cement Concrete
19	Stabilized Base Mr	Resilient modulus of stiff base material
20	Subgrade Mr	Resilient modulus of subgrade material
21	GWD	Ground Water Depth
22	Construction Month	Base/Subgrade construction time, usually one month ahead of pavement construction month
23	Loss of Full Friction	Pavement age at which the debonding occurs
24	Design Lane Width	Distance between the lane markings on either side of the design lane (not the "slab width")

Goodness-of-fit statistics R^2 , root mean squared error (RMSE), and normalized standard error (Se/Sy) for the MVL RSMs are summarized in Table 11.7 by climate zone and distress. Note that the dimensions of RMSE are same as those of the predicted distress while R^2 and Se/Sy are dimensionless. The R^2 values range from about 0.2 to 0.7, with the cracking distresses tending to have smaller R^2 values and the faulting and IRI distresses tending to have relatively better goodness-of-fit statistics. The low R^2 values for many of the MVL RSMs are not unexpected. The relationships between design inputs and distress outputs are expected to be complexly nonlinear; the multivariate linear regressions are intended only as a rough “first cut” assessment of sensitivities.

Goodness-of-fit statistics for the ANN RSMs are summarized in Table 11.8 by climate zone and distress. The ‘NN’ column describes the ANN network architecture; all ANN RSMs for the JPCP Over Stiff Foundation scenarios employed 24 input neurons, 5 hidden neurons in one layer, and one output neuron. The ‘n’ column gives the total number of GSA simulations used for training/validating/testing the model. Overall, the ANN RSM model fits are reasonable with the faulting prediction models being the best and the cracking models being the worst, similar to New JPCP results.

Scatter plots for ANN predicted vs. MEPDG predicted distresses are provided in Figure 11.6 for faulting, cracking, and IRI by climate zone. These scatter plots graphically confirm the conclusions from the goodness-of-fit statistics that the ANN RSM models provide very good fits for faulting and IRI and less good fits for the cracking distresses due to reasons discussed in the previous paragraph. It is expected that the prediction accuracies of the ANN RSM cracking models would improve significantly using a reduced input feature space. However, this is outside the scope and objective of the current study. The high quality of the fits for these ANN RSMs suggest the possibility that enhanced versions of the RMS might be adequate substitutes in some cases for the more rigorous but laborious geomechanics computations in the MEPDG.

Table 11.7. Goodness-of-fit statistics for multivariate linear regression response surface models – JPCP Over Stiff Foundation.

Climate	Distress	R^2	RMSE	Se/Sy
CD	Faulting	0.62	0.21	0.62
	Cracking	0.26	0.53	0.87
	IRI	0.72	0.16	0.54
CW	Faulting	0.62	0.19	0.62
	Cracking	0.31	0.52	0.84
	IRI	0.65	0.14	0.59
T	Faulting	0.56	0.08	0.67
	Cracking	0.24	0.48	0.88
	IRI	0.50	0.08	0.72
HD	Faulting	0.60	0.12	0.64
	Cracking	0.29	0.54	0.85
	IRI	0.57	0.10	0.66
HW	Faulting	0.61	0.11	0.63
	Cracking	0.24	0.53	0.88
	IRI	0.54	0.10	0.68

Table 11.8. Goodness-of-fit statistics for neural network response surface models – JPCP Over Stiff Foundation.

Climate	Distress	NN	n	R²	RMSE	Se/Sy
CD	Faulting	24-5-1	1230	0.94	0.010	0.25
	Cracking	24-5-1	1230	0.42	6.965	0.76
	IRI	24-5-1	1230	0.91	9.708	0.30
CW	Faulting	24-5-1	1242	0.93	0.010	0.27
	Cracking	24-5-1	1242	0.59	6.002	0.64
	IRI	24-5-1	1242	0.90	8.175	0.32
T	Faulting	24-5-1	1433	0.93	0.004	0.26
	Cracking	24-5-1	1433	0.46	5.989	0.73
	IRI	24-5-1	1433	0.77	5.613	0.48
HD	Faulting	24-5-1	1179	0.94	0.006	0.25
	Cracking	24-5-1	1179	0.51	6.670	0.70
	IRI	24-5-1	1179	0.82	7.168	0.43
HW	Faulting	24-5-1	1320	0.93	0.005	0.25
	Cracking	24-5-1	1320	0.46	6.728	0.73
	IRI	24-5-1	1320	0.78	7.128	0.46

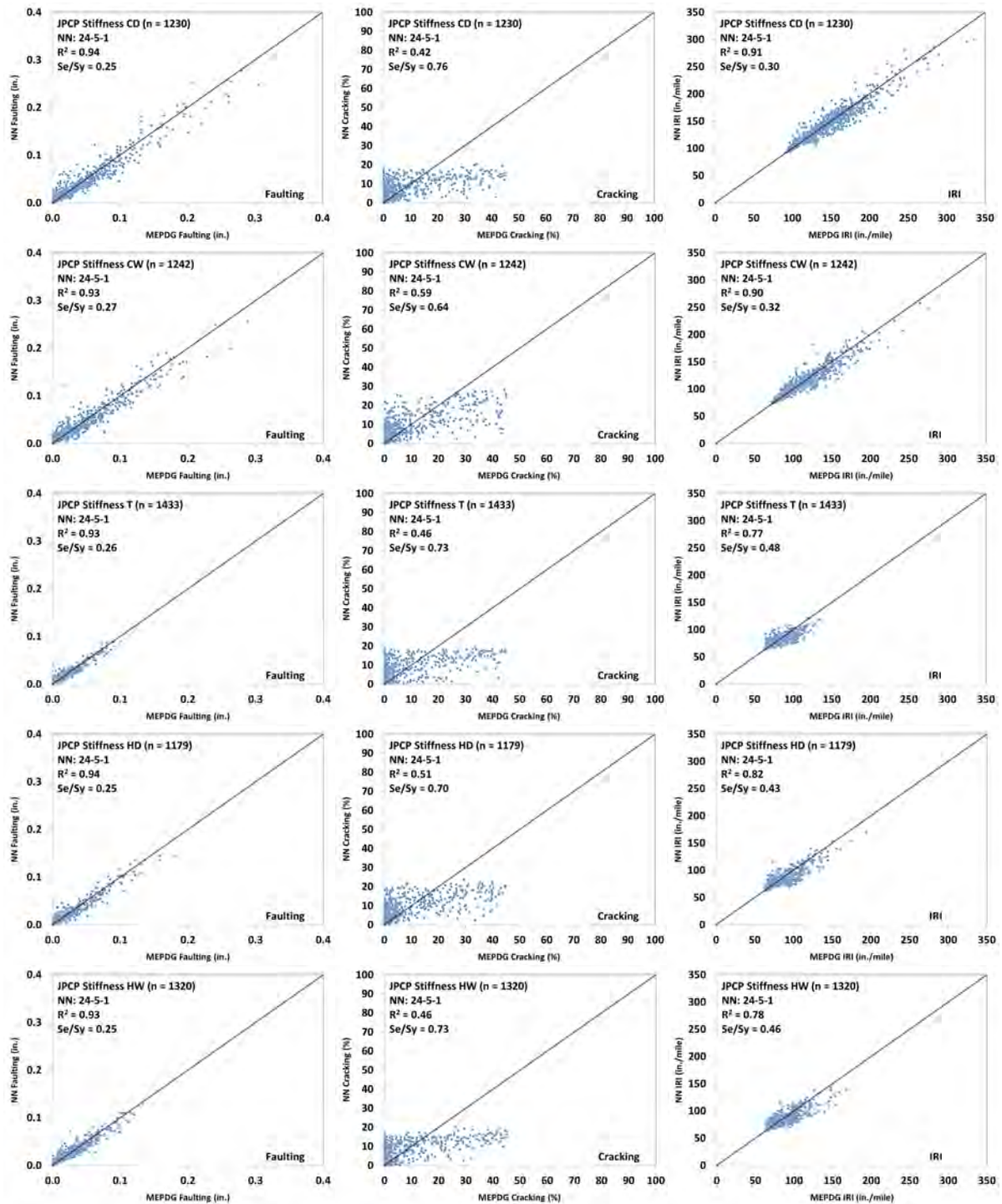


Figure 11.6. ANN predicted vs. MEDPG predicted distresses – JPCP Over Stiff Foundation.

11.4 Sensitivity Metrics

The average sensitivity indices from the MVL RSMs are summarized in Table 11.9 through Table 11.11. Similar to the preceding MVL RSMs of HMA pavements and JPCP, the values for the average sensitivity indices of MVL RSMs of JPCP Over Stiff Foundation are all much smaller than the corresponding sensitivity indices computed in the OAT analyses.

Figure 11.7 and Figure 11.8 provide graphical summaries by distress and climate zone of the average sensitivities calculated using the MVL RSMs. The high-low-average plots in Figure 11.8 are additionally sorted by maximum average sensitivity (in an absolute value sense) to indicate more clearly the most important design inputs. The most sensitive inputs according to the MVL RSMs in rank order in terms of maximum absolute sensitivity across climate zones (sensitivity values equal to 0.50 or greater) by distress type are:

- Faulting: Slab Width, PCC Unit Weight,
- Transverse Cracking: JPCP Thick, Slab Width, PCC 20-year MOR to 28-day MOR, Joint Spacing, PCC 28-Day MOR, PCC CTE, Design Lane Width
- IRI: Slab Width

Most of these rankings are consistent with engineering judgment and OAT analyses. There is one exception. In OAT analyses, design lane width was evaluated under three conditions: no edge support, tied shoulder edge support, and widen slab edge support condition. Among these conditions, design lane width under ‘widen slab edge support’ had high sensitivity for transverse cracking, but design lane width under either ‘no edge support’ or ‘tied shoulder edge support’ was not sensitive. In GSA, design lane width was not explicitly evaluated under edge support conditions. Among random inputs, the design lane width combined with ‘widened slab edge support’ can provide high sensitivity to transverse cracking and then the level of overall design lane width become sensitive.

Table 11.9. Average sensitivities from MVL RSMs – JPCP Over Stiff Foundation/Faulting.

Design Input	Climate Zone				
	CD	CW	T	HD	HW
Constant	0.84	2.11	1.05	1.00	1.42
AADTT Per Lane	0.12	0.14	0.07	0.08	0.09
JPCP Thick	-0.03	-0.01	0.04	0.13	0.00
Base Thick	-0.04	-0.01	-0.02	-0.01	-0.01
SSA	0.09	0.09	0.03	0.10	0.02
Joint Spacing	0.28	0.27	0.12	0.15	0.15
Dowel Diameter	-0.12	-0.51	-0.40	-0.59	-0.50
LTE	-0.01	0.00	-0.01	0.00	0.00
Slab Width	-2.10	-2.37	-0.79	-1.19	-1.16
Erodibility Index	0.06	0.08	0.01	0.04	0.02
PCC Unit Weight	-1.02	-0.98	-0.32	-0.55	-0.71
PCC Poisson Ratio	0.06	0.11	0.02	0.06	0.03
PCC CTE	0.56	0.51	0.18	0.29	0.27
PCC Thermal Conductivity	-0.18	-0.09	-0.02	-0.07	-0.03
PCC Cement Content	0.07	0.08	0.06	0.07	0.06
PCC W/C	0.42	0.13	-0.02	0.28	0.14
PCC 28-Day MOR	0.75	0.21	-0.01	0.57	0.22
PCC 28-Day E	0.03	-0.04	0.01	-0.07	0.03
PCC 20-year MOR to 28-day MOR	0.12	0.17	0.06	0.07	0.07
Stabilized Base Mr	0.03	-0.02	-0.02	-0.01	-0.02
Subgrade Mr	-0.13	-0.07	-0.04	-0.08	-0.02
GWD	-0.03	0.01	0.00	0.01	0.01
Construction Month	0.03	0.05	0.02	0.01	0.01
Loss of Full Friction	0.01	-0.01	0.01	0.00	0.01
Design Lane Width	0.42	0.37	0.04	-0.16	0.01

Table 11.10. Average sensitivities from MVL RSMs – JPCP Over Stiff Foundation/Transverse Cracking.

Design Input	Climate Zone				
	CD	CW	T	HD	HW
Constant	-1.26	2.34	0.93	3.13	2.88
AADTT Per Lane	0.17	0.17	0.15	0.12	0.10
JPCP Thick	-1.09	-0.79	-0.58	-1.96	-0.67
Base Thick	-0.03	-0.17	-0.09	-0.06	0.02
SSA	0.46	0.56	0.48	0.35	0.03
Joint Spacing	0.81	1.03	0.64	0.85	0.87
Dowel Diameter	-0.58	-0.97	-0.54	2.00	-0.53
LTE	-0.05	-0.06	-0.05	-0.02	-0.06
Slab Width	-1.11	-1.17	-1.07	-0.66	-0.35
Erodibility Index	-0.01	0.00	0.02	0.06	-0.05
PCC Unit Weight	1.26	0.36	0.93	0.15	-0.33
PCC Poisson Ratio	0.34	0.20	0.17	0.23	0.14
PCC CTE	0.63	0.72	0.56	0.73	0.58
PCC Thermal Conductivity	-0.25	-0.37	-0.30	-0.39	-0.26
PCC Cement Content	-0.09	-0.03	0.03	-0.06	0.10
PCC W/C	1.55	0.64	0.18	-0.22	-0.19
PCC 28-Day MOR	1.38	-0.98	-0.80	-1.76	-2.00
PCC 28-Day E	-0.17	0.55	0.34	0.46	0.75
PCC 20-year MOR to 28-day MOR	-1.08	-0.78	-0.55	-1.13	-0.79
Stabilized Base Mr	-0.02	-0.03	-0.05	-0.06	-0.06
Subgrade Mr	0.05	-0.14	-0.06	0.05	0.08
GWD	-0.06	-0.05	-0.06	-0.04	-0.05
Construction Month	-0.02	0.03	0.03	-0.01	0.03
Loss of Full Friction	0.00	-0.06	-0.01	-0.04	0.03
Design Lane Width	-0.54	-0.70	-0.11	-1.40	-0.02

Table 11.11. Average sensitivities from MVLR RSMs – JPCP Over Stiff Foundation/IRI.

Design Input	Climate Zone				
	CD	CW	T	HD	HW
Constant	1.87	2.11	0.68	1.09	1.22
AADTT Per Lane	0.10	0.10	0.06	0.06	0.07
JPCP Thick	-0.28	-0.20	-0.07	-0.17	-0.12
Base Thick	-0.03	-0.02	-0.02	-0.01	-0.01
SSA	0.11	0.16	0.08	0.11	0.01
Joint Spacing	0.15	0.18	0.11	0.14	0.13
Dowel Diameter	-0.11	-0.44	-0.29	-0.19	-0.35
LTE	-0.01	-0.01	-0.01	-0.01	-0.01
Slab Width	-1.48	-1.63	-0.62	-0.85	-0.78
Erodibility Index	0.04	0.05	0.01	0.03	0.01
PCC Unit Weight	-0.54	-0.56	-0.08	-0.34	-0.49
PCC Poisson Ratio	0.08	0.10	0.04	0.06	0.04
PCC CTE	0.43	0.40	0.17	0.27	0.23
PCC Thermal Conductivity	-0.15	-0.10	-0.05	-0.09	-0.05
PCC Cement Content	0.03	0.04	0.04	0.04	0.06
PCC W/C	0.66	0.36	0.09	0.22	0.14
PCC 28-Day MOR	0.54	-0.09	-0.08	0.15	-0.10
PCC 28-Day E	0.03	0.07	0.05	0.02	0.12
PCC 20-year MOR to 28-day MOR	-0.07	-0.01	-0.03	-0.09	-0.04
Stabilized Base Mr	0.02	-0.01	-0.02	-0.02	-0.02
Subgrade Mr	-0.86	-0.30	-0.03	-0.05	-0.01
GWD	-0.02	0.00	0.00	0.00	0.00
Construction Month	0.01	0.04	0.01	0.00	0.01
Loss of Full Friction	0.00	-0.01	0.00	0.00	0.01
Design Lane Width	0.21	0.15	0.03	-0.26	0.02

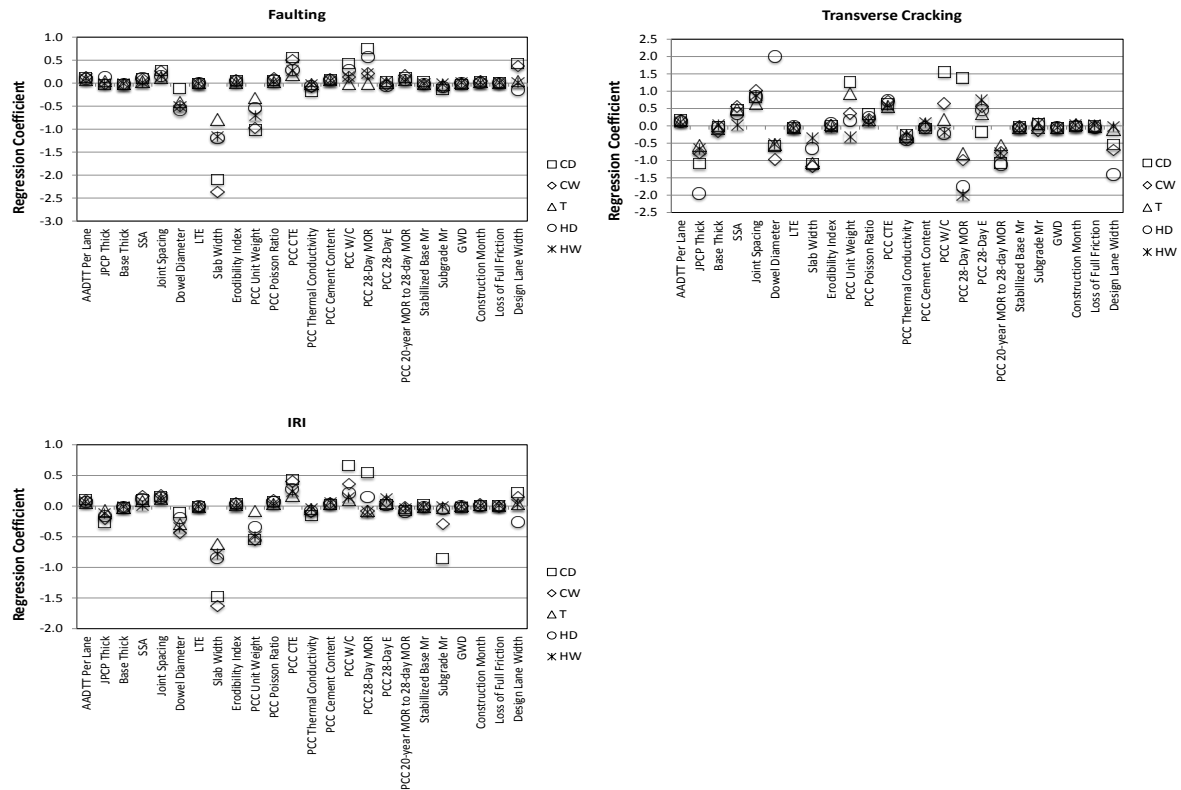


Figure 11.7. Average sensitivities from MVL RSMs – JPCP Over Stiff Foundation.

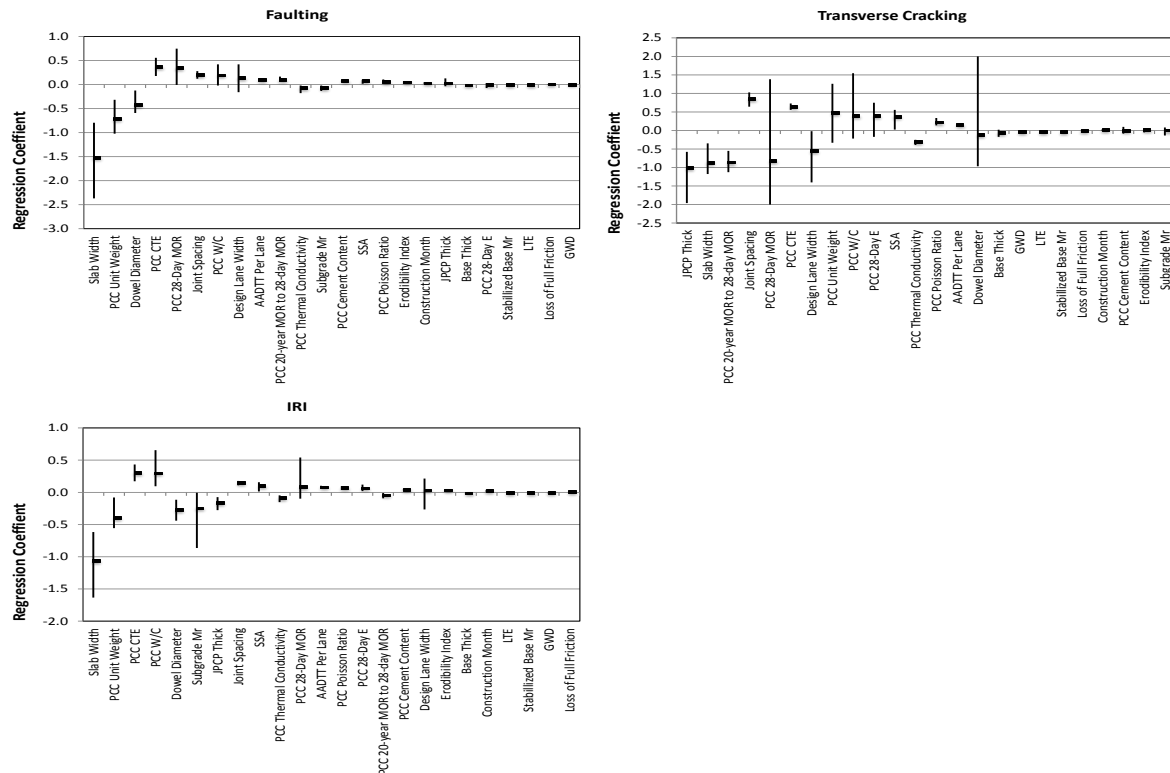


Figure 11.8. Ranking of average sensitivities from MVL RSMs – JPCP Over Stiff Foundation.

As described in previous sections, the ANN RSMs permit a more in-depth evaluation of sensitivities than does the MVLRL approach. The mean and standard deviations of the NSI values are summarized by climate zone in Table 11.12 through Table 11.14 for each respective distress. Full frequency distributions of the computed NSI values by design input and climate zone are depicted in Figure 11.9 through Figure 11.11 for each respective distress. Similar to the findings for flexible pavements and New JPCP, most frequency distributions have well-defined peaks which indicate NSI does not vary significantly over the problem domain. The influence of climate zone on the frequency distributions is also negligible in most cases.

Table 11.12. NSI statistics from ANN RSMs – JPCP Over Stiff Foundation/Faulting.

Design Input	Climate Zone									
	CD		CW		T		HD		HW	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
AADTT Per Lane	0.14	0.17	0.10	0.17	0.05	0.08	0.07	0.11	0.06	0.08
JPCP Thick	0.13	0.13	-0.02	0.10	0.03	0.05	0.05	0.05	0.08	0.08
Base Thick	-0.08	0.12	-0.03	0.07	-0.02	0.03	-0.01	0.02	-0.02	0.02
SSA	-0.09	0.14	0.14	0.27	0.05	0.07	0.10	0.09	0.06	0.04
Joint Spacing	0.22	0.24	0.11	0.17	0.07	0.09	0.08	0.12	0.06	0.08
Dowel Diameter	-0.12	0.11	-0.13	0.15	-0.11	0.12	-0.15	0.15	-0.11	0.09
LTE	-0.02	0.05	-0.02	0.04	-0.01	0.01	-0.01	0.02	-0.01	0.01
Slab Width	-3.27	5.36	-3.35	6.49	-1.05	2.24	-1.68	2.98	-1.59	3.94
Erodibility Index	0.08	0.10	0.03	0.06	0.02	0.03	0.03	0.05	0.01	0.03
PCC Unit Weight	-1.20	1.48	-0.37	0.98	-0.33	0.38	-0.33	0.54	-0.29	0.44
PCC Poisson Ratio	0.08	0.09	0.04	0.08	0.02	0.03	0.03	0.06	0.03	0.03
PCC CTE	0.73	0.91	0.38	0.60	0.19	0.25	0.29	0.42	0.19	0.25
PCC Thermal Conductivity	-0.17	0.19	-0.05	0.08	-0.02	0.02	-0.04	0.07	-0.02	0.03
PCC Cement Content	0.07	0.07	0.06	0.07	0.04	0.05	0.02	0.04	0.05	0.06
PCC W/C	-0.05	0.10	0.07	0.10	-0.05	0.08	0.06	0.08	0.01	0.04
PCC 28-Day MOR	0.02	0.06	0.06	0.08	-0.10	0.12	0.14	0.17	0.01	0.06
PCC 28-Day E	0.07	0.20	0.05	0.09	0.06	0.07	-0.02	0.03	0.03	0.04
PCC 20-year MOR to 28-day MOR	0.11	0.10	0.04	0.08	0.05	0.05	0.03	0.05	0.04	0.04
Stabilized Base Mr	0.01	0.01	-0.01	0.03	-0.01	0.02	-0.01	0.02	-0.01	0.02
Subgrade Mr	-0.11	0.13	-0.04	0.04	-0.04	0.03	-0.04	0.06	-0.02	0.01
GWD	-0.02	0.02	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.01
Construction Month	0.02	0.02	0.02	0.04	0.01	0.01	0.01	0.02	0.01	0.01
Loss of Full Friction	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00
Design Lane Width	0.61	0.53	0.20	0.26	0.10	0.16	0.12	0.15	0.08	0.10

Table 11.13. NSI statistics from ANN RSMs – JPCP Over Stiff Foundation/Transverse Cracking.

Design Input	Climate Zone									
	CD		CW		T		HD		HW	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
AADTT Per Lane	0.14	0.15	0.20	0.26	0.11	0.16	0.11	0.17	0.14	0.17
JPCP Thick	-0.87	0.78	-1.08	1.12	-0.49	0.59	-1.46	1.80	-0.84	0.96
Base Thick	-0.03	0.05	-0.16	0.18	-0.06	0.06	-0.07	0.10	0.00	0.15
SSA	0.35	0.35	0.61	0.68	0.36	0.42	0.42	0.53	0.20	0.44
Joint Spacing	0.46	0.31	0.75	0.62	0.45	0.41	0.59	0.49	0.52	0.40
Dowel Diameter	-0.13	0.08	-0.31	0.25	-0.16	0.21	0.39	0.37	-0.07	0.14
LTE	-0.08	0.08	-0.12	0.18	-0.07	0.11	-0.05	0.11	-0.07	0.09
Slab Width	-0.86	0.68	-1.39	1.67	-0.98	1.13	-0.68	0.94	-0.29	0.52
Erodibility Index	0.00	0.03	0.02	0.03	0.02	0.03	0.03	0.05	-0.03	0.05
PCC Unit Weight	0.48	0.51	0.75	0.61	0.81	0.94	-0.03	0.44	-0.13	0.29
PCC Poisson Ratio	0.20	0.17	0.24	0.24	0.15	0.16	0.12	0.22	0.11	0.11
PCC CTE	0.54	0.53	0.97	1.07	0.70	0.91	0.58	0.82	0.51	0.67
PCC Thermal Conductivity	-0.20	0.21	-0.40	0.44	-0.29	0.36	-0.28	0.38	-0.24	0.32
PCC Cement Content	-0.02	0.06	-0.03	0.10	-0.03	0.07	0.01	0.07	0.05	0.08
PCC W/C	0.75	0.74	0.21	0.24	0.22	0.38	-0.15	0.21	0.00	0.32
PCC 28-Day MOR	0.24	0.43	-1.81	1.85	-0.88	1.00	-1.56	1.65	-1.36	1.52
PCC 28-Day E	0.13	0.22	0.79	0.80	0.60	0.75	0.55	0.72	0.73	0.79
PCC 20-year MOR to 28-day MOR	-0.69	0.56	-1.09	0.97	-0.58	0.66	-0.75	0.89	-0.67	0.79
Stabilized Base Mr	-0.02	0.03	-0.04	0.06	-0.05	0.07	-0.03	0.07	-0.05	0.07
Subgrade Mr	0.04	0.06	-0.06	0.09	-0.04	0.05	0.07	0.08	0.06	0.09
GWD	-0.02	0.03	-0.04	0.06	-0.05	0.08	-0.02	0.04	-0.02	0.05
Construction Month	-0.03	0.04	0.03	0.05	-0.01	0.02	-0.01	0.04	0.04	0.05
Loss of Full Friction	-0.01	0.02	-0.07	0.10	-0.02	0.03	-0.03	0.05	0.00	0.04
Design Lane Width	-0.48	0.61	-0.80	1.14	-0.28	0.27	-1.04	1.10	-0.11	0.93

Table 11.14. NSI statistics from ANN RSMs – JPCP Over Stiff Foundation/IRI.

Design Input	Climate Zone									
	CD		CW		T		HD		HW	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
AADTT Per Lane	0.10	0.13	0.09	0.12	0.05	0.06	0.06	0.08	0.05	0.06
JPCP Thick	-0.13	0.11	-0.25	0.13	-0.04	0.05	-0.21	0.14	-0.08	0.07
Base Thick	-0.04	0.06	-0.03	0.06	-0.02	0.02	-0.01	0.01	-0.02	0.02
SSA	0.05	0.08	0.17	0.21	0.05	0.06	0.13	0.07	0.05	0.08
Joint Spacing	0.09	0.07	0.12	0.10	0.06	0.06	0.11	0.09	0.07	0.05
Dowel Diameter	-0.09	0.04	-0.11	0.13	-0.09	0.07	-0.03	0.07	-0.07	0.03
LTE	-0.02	0.04	-0.02	0.03	-0.01	0.02	-0.02	0.02	-0.01	0.01
Slab Width	-1.90	3.23	-1.96	3.84	-0.74	0.99	-1.43	2.31	-0.93	1.94
Erodibility Index	0.03	0.06	0.02	0.04	0.01	0.01	0.03	0.03	0.01	0.01
PCC Unit Weight	-0.41	1.11	-0.21	0.46	-0.08	0.09	-0.27	0.30	-0.15	0.21
PCC Poisson Ratio	0.06	0.09	0.06	0.06	0.02	0.03	0.05	0.04	0.02	0.02
PCC CTE	0.41	0.51	0.37	0.42	0.16	0.16	0.30	0.33	0.16	0.15
PCC Thermal Conductivity	-0.10	0.11	-0.08	0.07	-0.04	0.04	-0.07	0.07	-0.04	0.03
PCC Cement Content	0.03	0.03	0.04	0.04	0.03	0.03	0.03	0.04	0.04	0.04
PCC W/C	0.43	0.18	0.22	0.15	0.02	0.06	0.08	0.05	0.06	0.13
PCC 28-Day MOR	0.17	0.17	-0.34	0.14	-0.15	0.14	-0.12	0.11	-0.13	0.13
PCC 28-Day E	0.10	0.18	0.16	0.11	0.08	0.08	0.09	0.07	0.09	0.07
PCC 20-year MOR to 28-day MOR	-0.09	0.04	-0.12	0.09	-0.05	0.04	-0.10	0.06	-0.06	0.06
Stabilized Base Mr	0.00	0.01	-0.01	0.02	-0.01	0.01	-0.02	0.02	-0.01	0.01
Subgrade Mr	-0.71	0.17	-0.23	0.08	-0.01	0.01	-0.02	0.04	-0.01	0.02
GWD	-0.01	0.02	0.00	0.01	-0.01	0.01	0.00	0.01	0.00	0.01
Construction Month	0.00	0.01	0.02	0.02	0.00	0.01	0.00	0.01	0.00	0.01
Loss of Full Friction	0.00	0.01	-0.01	0.01	0.00	0.01	-0.01	0.01	0.00	0.01
Design Lane Width	0.14	0.30	0.02	0.15	0.00	0.13	-0.15	0.09	0.01	0.09

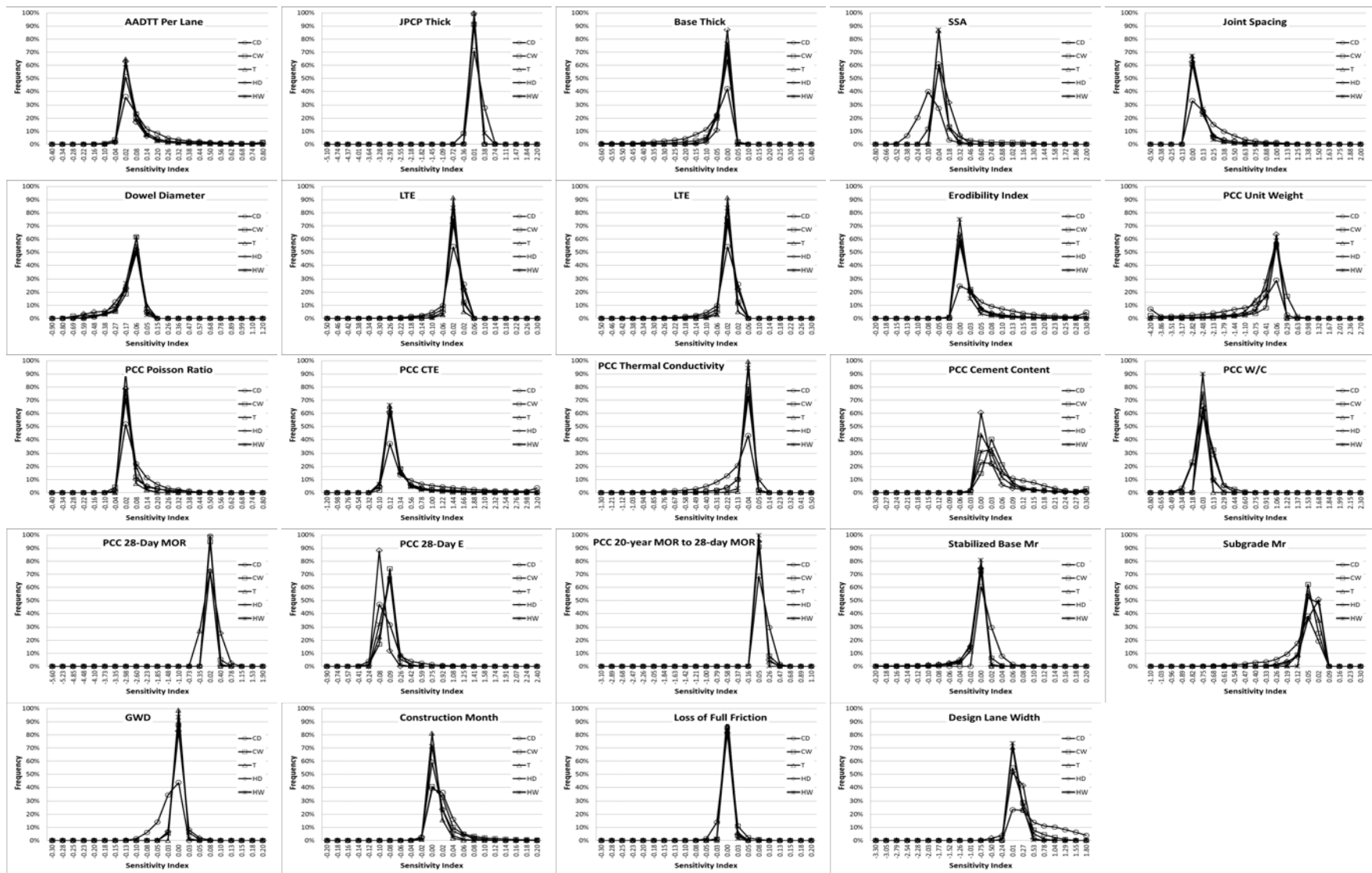


Figure 11.9. Distributions of NSI values – JPCP Over Stiff Foundation/Faulting.

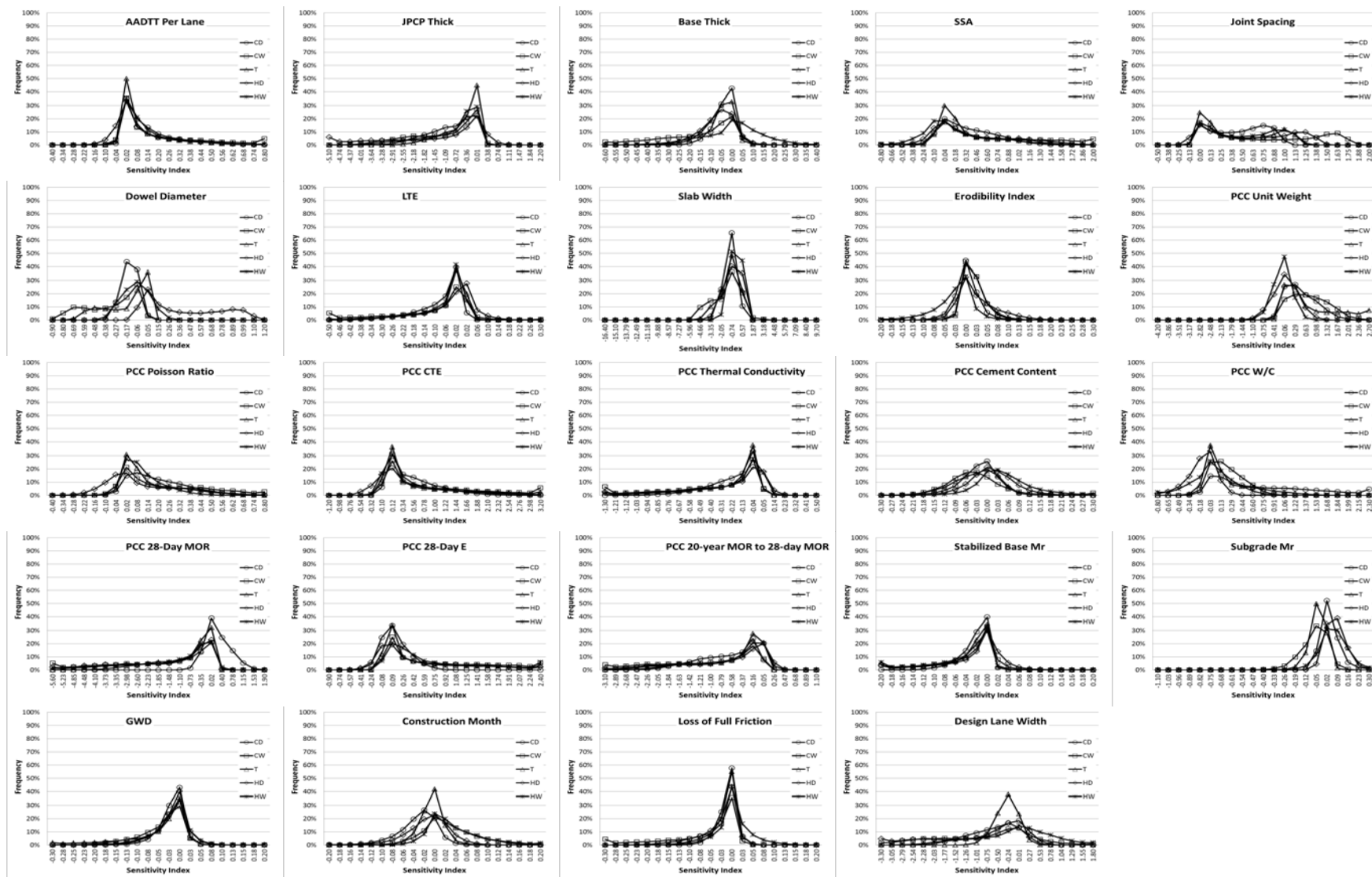


Figure 11.10. Distributions of NSI values – JPCP Over Stiff Foundation/Transverse Cracking.

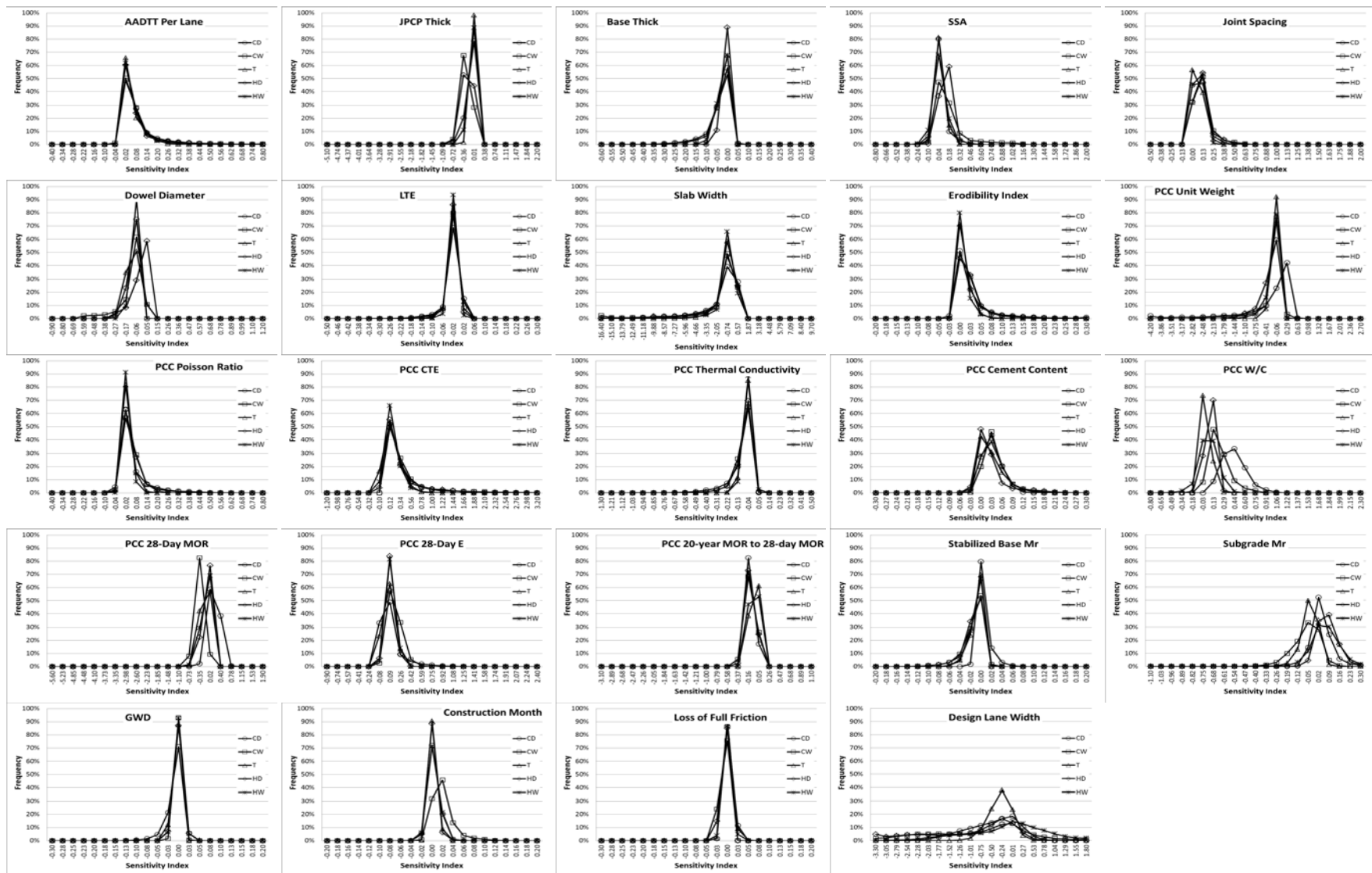


Figure 11.11. Distributions of NSI values – JPCP Over Stiff Foundation/IRI.

11.5 Conclusions – JPCP Over Stiff Foundation

The maximum average sensitivity coefficients from the MVLR RSMs across climate zones for all distress and design input combinations are ranked by maximum absolute sensitivity across distresses in Table 11.15. Even though the ranking is by maximum absolute sensitivity, the plus and minus signs are retained for each individual sensitivity coefficient to indicate whether distress increases (+) or decreases (-) with increasing input value. Usually—and especially for the highest sensitivity inputs—the plus/minus signs for each design input are consistent across all distresses.

The OAT local sensitivity category (Appendix B) for each design input is also indicated in Table 11.15. There is a lack of full congruence between the ranking of inputs from the MVLR RSMs and the categorization from the OAT analyses. The five design inputs categorized as HS in the OAT analyses are also the highest-ranked design inputs in Table 11.15, and most of the inputs categorized as VS in the OAT analyses also appear high in the list. However, there is some mixing of the VS and S inputs in the middle and lower portion of the rankings. Recall, however, that the goodness-of-fit statistics for many of the MVLR RSMs were quite low and that the computed sensitivity coefficients are averages across the problem domain.

The maximum Mean NSI values across climate zones for all distress and design input combinations are ranked by maximum absolute sensitivity across distresses in Table 11.16. The Mean NSI values were computed from the 10,000 ANN RSM evaluations for each climate zone and distress combination (Table 11.12 through Table 11.14). The plus and minus signs are again retained for each individual sensitivity index to indicate whether distress increases (+) or decreases (-) with increasing input value. Usually—and especially for the highest sensitivity inputs—the plus/minus signs for each design input are consistent across all distresses.

The OAT local sensitivity category (Appendix B) for each design input is also indicated in Table 11.16. There is a better congruence between the ranking of inputs from the ANN RSMs and the categorization from the OAT analyses. Most of design inputs categorized as HS in the OAT analyses are the highest-ranked design inputs, most of the inputs categorized as VS in the OAT analyses appear high in the list, and most of the inputs categorized as S in the OAT analyses also appear lower portion of the rankings in in Table 11.15.

Table 11.15. Ranking of JPCP Over Stiff Foundation design inputs by overall maximum |Average Sensitivity Coefficient| (MVLR RSMs).

Design Input	Maximum Average Sensitivity Coefficient (MVLR RSM)				OAT Category ¹
	Faulting	Transverse Cracking	IRI	Maximum	
Slab Width	-1.52	-0.87	-1.07	-1.52	HS
JPCP Thick	0.02	-1.02	-0.17	-1.02	HS
PCC 20-year MOR to 28-day MOR	0.10	-0.87	-0.05	-0.87	- ²
Joint Spacing	0.20	0.84	0.14	0.84	HS
PCC 28-Day MOR	0.35	-0.83	0.09	-0.83	HS
PCC Unit Weight	-0.72	0.47	-0.40	-0.72	HS
PCC CTE	0.36	0.64	0.30	0.64	VS
Design Lane Width	0.14	-0.55	0.03	-0.55	HS/NS ³
Dowel Diameter	-0.43	-0.12	-0.28	-0.43	VS
PCC W/C	0.19	0.39	0.29	0.39	S
PCC 28-Day E	-0.01	0.39	0.06	0.39	HS
SSA	0.07	0.37	0.09	0.37	HS
PCC Thermal Conductivity	-0.08	-0.32	-0.09	-0.32	HS
Subgrade Mr	-0.07	0.00	-0.25	-0.25	VS
PCC Poisson Ratio	0.06	0.21	0.06	0.21	VS
AADTT Per Lane	0.10	0.14	0.08	0.14	VS
PCC Cement Content	0.07	-0.01	0.04	0.07	S
Base Thick	-0.02	-0.07	-0.02	-0.07	VS
GWD	0.00	-0.05	0.00	-0.05	S
LTE	-0.01	-0.05	-0.01	-0.05	S
Stabilized Base Mr	-0.01	-0.04	-0.01	-0.04	NS
Erodibility Index	0.04	0.01	0.03	0.04	S
Construction Month	0.02	0.01	0.02	0.02	VS
Loss of Full Friction	0.00	-0.02	0.00	-0.02	S

¹HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Non-Sensitive

²20-year strength ratio values not considered explicitly in OAT analyses

³Design lane width under widen slab condition was Hyper Sensitive/ Design lane width under tied shoulder or no edge support condition was Non Sensitive in OAT analyses

Table 11.16. Ranking of JPCP Over Stiff Foundation design inputs by maximum |Mean| NSI values (ANN RSMs).

Design Input	Maximum Mean NSI Values (ANN RSMs)				OAT Category ¹
	Faulting	Transverse Cracking	IRI	Maximum	
Slab Width	-3.35	-1.39	-1.96	-3.35	HS
PCC 28-Day MOR	0.14	-1.81	-0.34	-1.81	HS
JPCP Thick	0.13	-1.46	-0.25	-1.46	HS
PCC Unit Weight	-1.20	0.81	-0.41	-1.20	HS
PCC 20-year MOR to 28-day MOR	0.11	-1.09	-0.12	-1.09	- ²
Design Lane Width	0.61	-1.04	-0.15	-1.04	HS/NS ³
PCC CTE	0.73	0.97	0.41	0.97	VS
PCC 28-Day E	0.07	0.79	0.16	0.79	HS
PCC W/C	0.07	0.75	0.43	0.75	S
Joint Spacing	0.22	0.75	0.12	0.75	HS
Subgrade Mr	-0.11	0.07	-0.71	-0.71	VS
SSA	0.14	0.61	0.17	0.61	HS
PCC Thermal Conductivity	-0.17	-0.40	-0.10	-0.40	HS
Dowel Diameter	-0.15	0.39	-0.11	0.39	VS
PCC Poisson Ratio	0.08	0.24	0.06	0.24	VS
AADTT Per Lane	0.14	0.20	0.10	0.20	VS
Base Thick	-0.08	-0.16	-0.04	-0.16	VS
LTE	-0.02	-0.12	-0.02	-0.12	S
Erodibility Index	0.08	-0.03	0.03	0.08	S
Loss of Full Friction	0.00	-0.07	-0.01	-0.07	S
PCC Cement Content	0.07	0.05	0.04	0.07	S
GWD	-0.02	-0.05	-0.01	-0.05	S
Stabilized Base Mr	0.01	-0.05	-0.02	-0.05	NS
Construction Month	0.02	0.04	0.02	0.04	VS

¹HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Non-Sensitive

²20-year strength ratio values not considered explicitly in OAT analyses

³Design lane width under widen slab condition was Hyper Sensitive/ Design lane width under tied shoulder or no edge support condition was Non Sensitive in OAT analyses

As a more severe measure of sensitivity, the mean plus/minus two standard deviation ($\mu \pm 2\sigma$) NSI values were computed using the statistics in Table 11.12 through Table 11.14 based on the 10,000 ANN RSM evaluations for each climate zone and distress combination. These sensitivity limits are ranked by maximum absolute value across distresses in Table 11.17. The plus and minus signs are again retained for each individual sensitivity index to indicate whether distress increases (+) or decreases (-) with increasing input value. Usually—and especially for the highest sensitivity inputs—the plus/minus signs for each design input are consistent across all distresses.

There is very good agreement between the input rankings in Table 11.17 and those based on the mean NSI values in Table 11.16. The OAT local sensitivity category (Appendix B) for each design input is also indicated in Table 11.17. Not only is there is better congruence between the ranking of inputs from the ANN RSMs and the categorization from the OAT analyses, but the ranges of $\mu \pm 2\sigma$ in Table

11.17 also line up closely with the ranges of normalized sensitivity index values used to define the OAT categories. These sensitivity categories are highlighted by the fonts in Table 11.17: **Bold** = Hypersensitive (HS), $\mu+2\sigma > 5$; **Bold Italic** = Very Sensitive (VS), $1 < \mu+2\sigma < 5$; *Italic* = Sensitive (S), $0.1 < \mu+2\sigma < 1$; and Regular = Non-Sensitive (NS), $\mu+2\sigma < 0.1$. The rankings and $\mu+2\sigma$ values in Table 11.17 are judged to be the best measures of the design input sensitivities in the MEPDG.

Table 11.17. Ranking of JPCP Over Stiff Foundation design inputs by maximum $|\mu+2\sigma|$ NSI values (ANN RSMs).

Design Input	Maximum $\mu+2\sigma$ NSI Values (ANN RSMs)				OAT Category ¹
	Faulting	Transverse Cracking	IRI	Maximum	
Slab Width	-16.34	-4.74	-9.63	-16.34	HS
PCC 28-Day MOR	0.49	-5.52	-0.62	-5.52	HS
JPCP Thick	0.40	-5.05	-0.51	-5.05	HS
PCC Unit Weight	-4.16	2.68	-2.63	-4.16	<i>HS</i>
Design Lane Width	1.67	-3.23	-0.74	-3.23	<i>HS/NS</i> ³
PCC CTE	2.54	3.10	1.42	3.10	VS
PCC 20-year MOR to 28-day MOR	0.31	-3.02	-0.29	-3.02	- ²
PCC 28-Day E	0.47	2.40	0.45	2.40	<i>HS</i>
PCC W/C	0.28	2.23	0.78	2.23	<i>S</i>
Joint Spacing	0.70	1.98	0.33	1.98	<i>HS</i>
SSA	0.67	1.97	0.58	1.97	<i>HS</i>
PCC Thermal Conductivity	-0.54	-1.29	-0.33	-1.29	<i>HS</i>
Dowel Diameter	-0.44	1.13	-0.36	1.13	VS
Subgrade Mr	-0.38	0.24	-1.06	-1.06	VS
PCC Poisson Ratio	0.26	0.72	0.24	0.72	<i>VS</i>
AADTT Per Lane	0.47	0.72	0.35	0.72	<i>VS</i>
Base Thick	-0.32	-0.51	-0.17	-0.51	<i>VS</i>
LTE	-0.12	-0.47	-0.10	-0.47	<i>S</i>
Erodibility Index	0.27	-0.12	0.15	0.27	<i>S</i>
Loss of Full Friction	0.03	-0.26	-0.02	-0.26	<i>S</i>
PCC Cement Content	0.21	0.22	0.12	0.22	<i>S</i>
GWD	-0.07	-0.21	-0.05	-0.21	<i>S</i>
Stabilized Base Mr	0.06	-0.19	-0.06	-0.19	<i>NS</i>
Construction Month	0.10	0.14	0.06	0.14	<i>VS</i>

¹HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Non-Sensitive

²20-year strength ratio values not considered explicitly in OAT analyses

³Design lane width under widen slab condition was Hyper Sensitive/ Design lane width under tied shoulder or no edge support condition was Non Sensitive in OAT analyses

Figure 11.12 through Figure 11.14 provide graphical summaries of the input sensitivities by distress. These figures highlight the difference in sensitivities between Hypersensitive and Very Sensitive and between Very Sensitive and Sensitive. All of the figures have the same horizontal axis range so that the differences in sensitivities across distresses can be more clearly evaluated. The solid bars in the figures indicate the mean NSI values, and the error bars correspond to one standard deviation. The sensitivities are also broken down by climate zone for each design input. No systematic or substantial effect of climate zone on the design input sensitivity statistics is observed.

Figure 11.12. Ranking of JPCP Over Stiff Foundation design inputs by $|\mu \pm 2\sigma|$ NSI values: faulting.

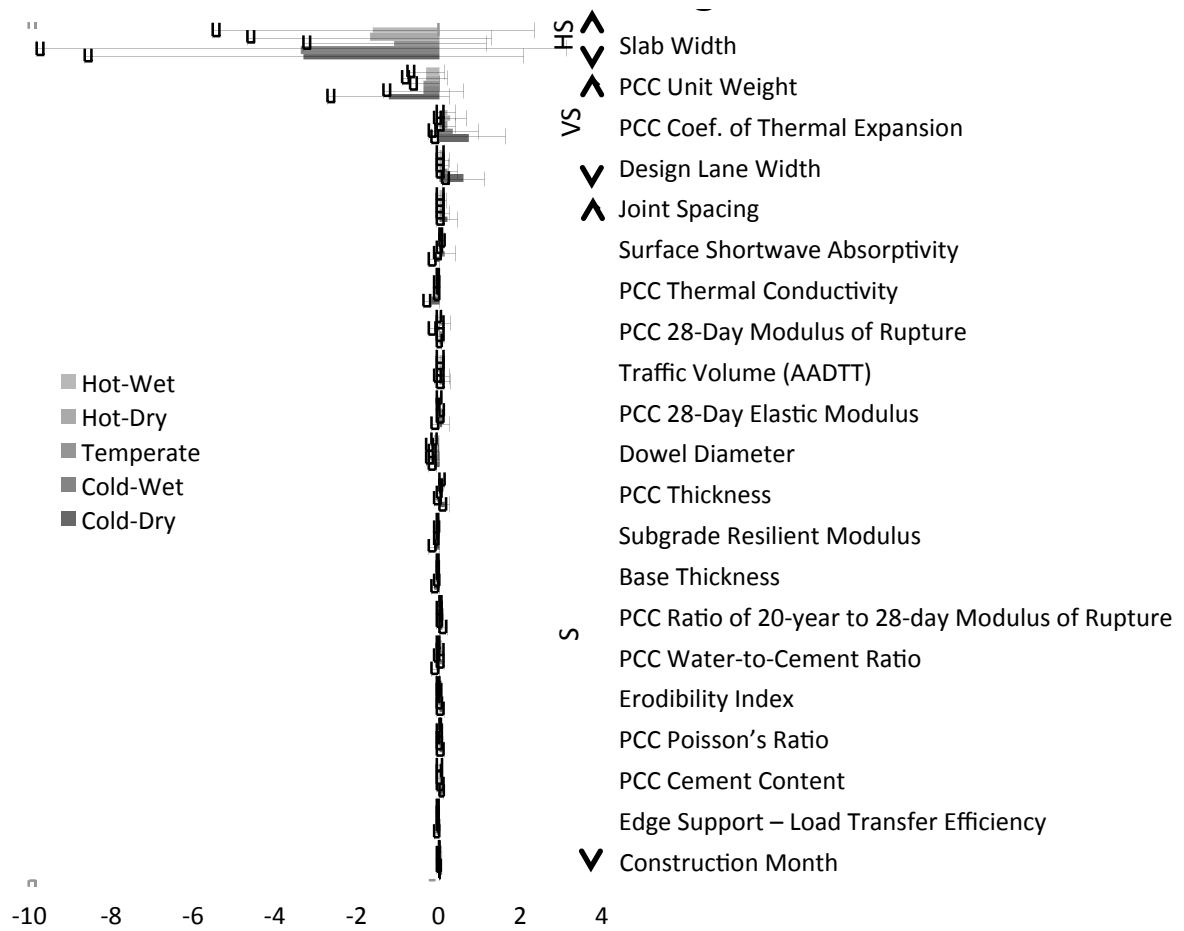


Figure 11.13. Ranking of JPCP Over Stiff Foundation design inputs by $|\mu \pm 2\sigma|$ NSI values: transverse cracking.

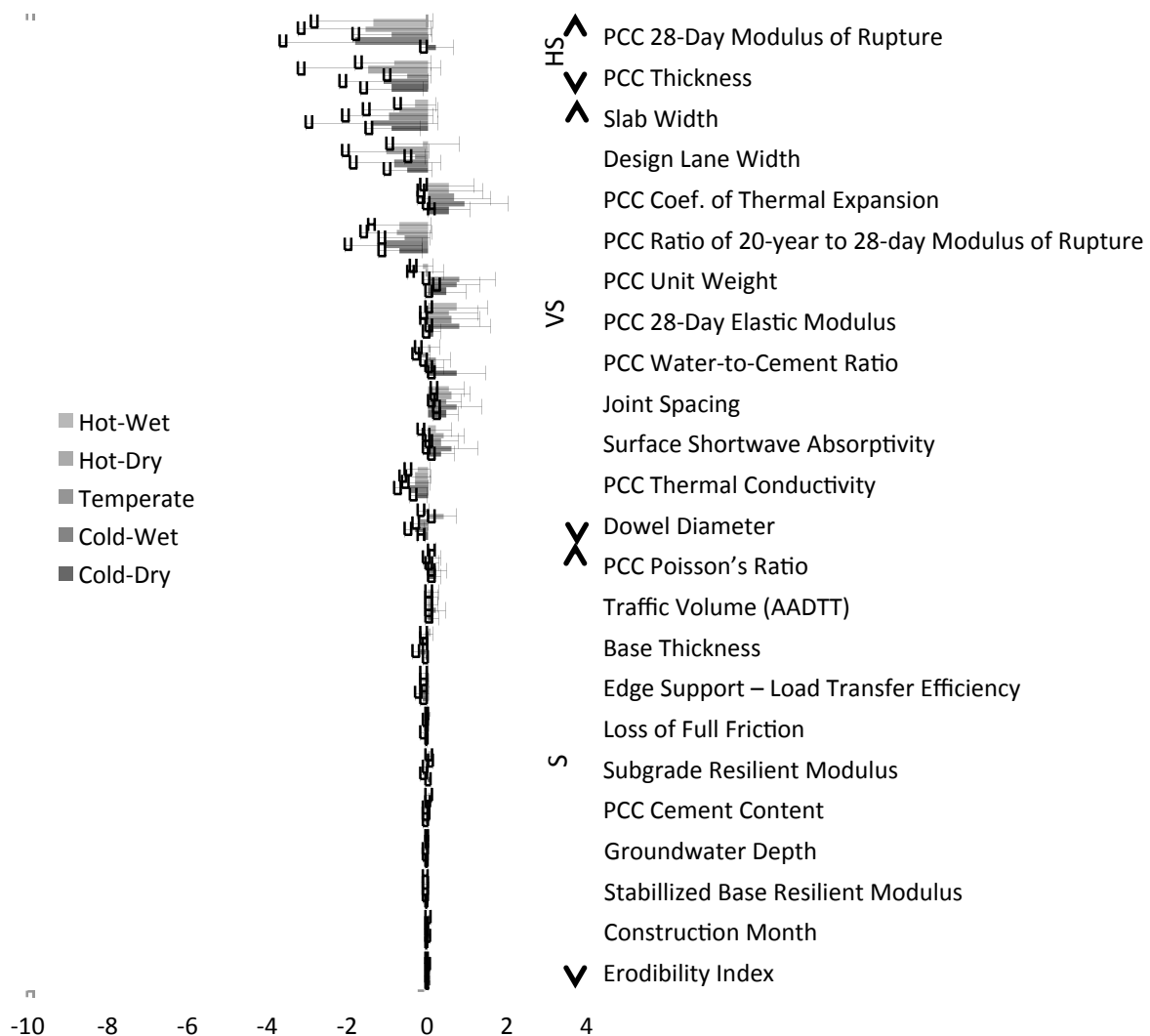
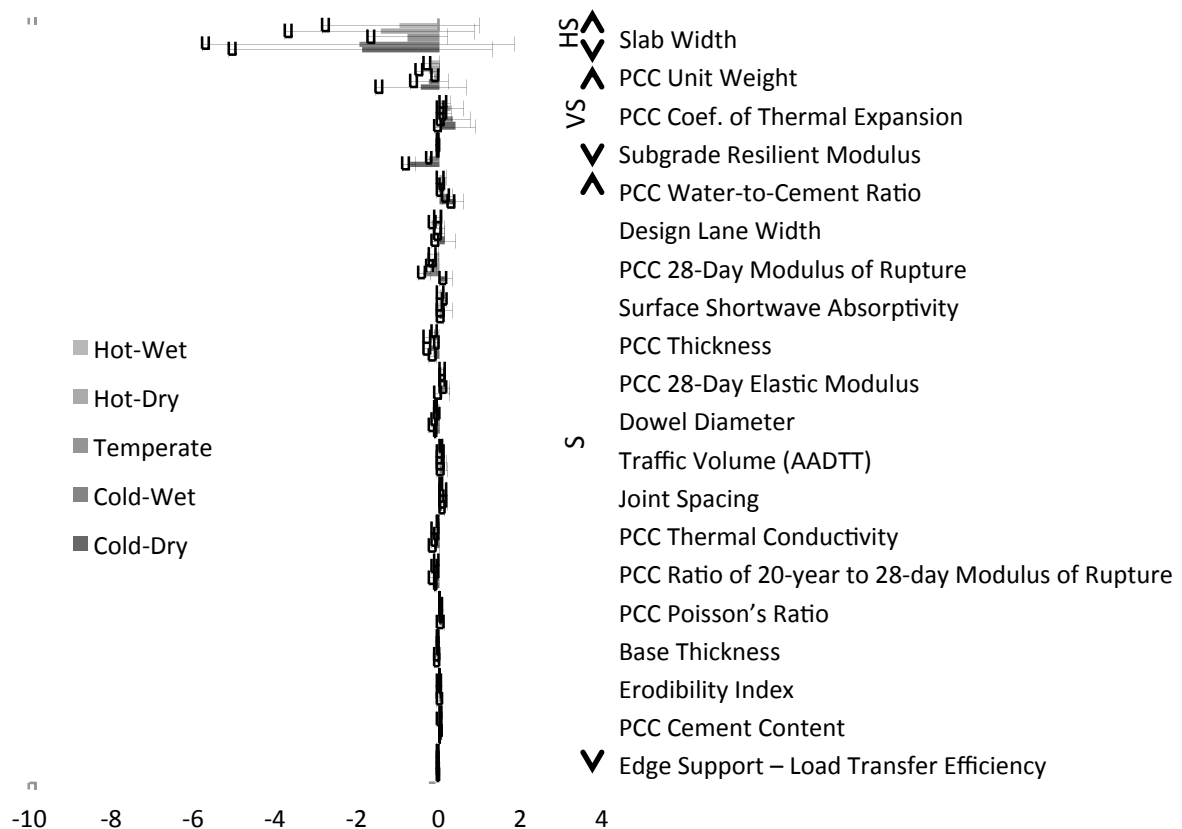


Figure 11.14. Ranking of JPCP Over Stiff Foundation design inputs by $|\mu \pm 2\sigma|$ NSI values: IRI.



As a more practical aid to the pavement designer, Table 11.18 summarizes in rank order the Hypersensitive, Very Sensitive, and Sensitive design inputs by material category (PCC, base, subgrade, other) for each distress. The design inputs that fall in the Hypersensitive or Very Sensitive categories for most (2 out of 3) distresses are indicated by bold font in the table. Overall, the sensitivity results for the JPCP Over Stiff Foundation scenarios were very similar to those from the New JPCP cases. For the JPCP Over Stiff Foundation scenarios, these are the PCC properties unit weight and coefficient of thermal expansion and the geometric properties slab width and design lane width. The PCC 28-day modulus of rupture, 28-day elastic modulus, thickness, and surface shortwave absorptivity also ranked in the upper portion of the Sensitive category or above for all three distresses. None of the base, subgrade, or other properties (e.g., traffic volume) ranked in the two highest sensitivity categories.

Table 11.18. Hypersensitive, Very Sensitive, and Sensitive design inputs by distress and input category for JPCP Over Stiff Foundation pavements. NSIm+2s values are given in parentheses. Inputs in bold font are Hypersensitive or Very Sensitive for most (2 out of 3) distresses.

<i>Distress</i>	<i>Input Category</i>	<i>Hypersensitive (>5)</i>	<i>Very Sensitive (1-5)</i>	<i>Sensitive (0.1-1)</i>
Faulting	PCC Properties		Unit Weight (-4.2) Coefficient of Thermal Expansion (+2.6)	Surface Shortwave Absorptivity (+0.7) 28-Day Modulus of Rupture (+0.5) 28-Day Elastic Modulus (+0.5) Thermal Conductivity (-0.5) Thickness (+0.4) 20-year to 28-day Modulus of Rupture (+0.3) Water-to-Cement Ratio (+0.3) Poisson's Ratio (+0.3) Cement Content (+0.2)
	Base Properties			Thickness (-0.3) Erodibility Index (+0.3)
	Subgrade Properties			Resilient Modulus (-0.4)
	Other Properties	Slab Width (-16.3)	Design Lane Width (+1.7)	Joint Spacing (+0.7) Traffic Volume (+0.5) Dowel Diameter (-0.4) Edge Support LTE (-0.1) Construction Month (+0.1)
Transverse Cracking	PCC Properties	28-Day Modulus of Rupture (-5.5) Thickness (-5.1) 28-Day Elastic Modulus (+2.4)	Coefficient of Thermal Expansion (+3.1) 20-year to 28-day Modulus of Rupture (-3.0) Unit Weight (+2.7) Water-to-Cement Ratio (+2.2) Surface Shortwave Absorptivity (+2.0) Thermal Conductivity (-1.3)	Poisson's Ratio (+0.7) Cement Content (+0.2)
	Base Properties			Thickness (-0.5) Loss of Friction (-0.3) Resilient Modulus (-0.2)
	Subgrade Properties			Resilient Modulus (+0.2) Groundwater Depth (-0.2)
	Other Properties		Slab Width (-4.7) Design Lane Width (-3.2) Joint Spacing (+2.0) Dowel Diameter (+1.1)	Traffic Volume (+0.7) Edge Support LTE (-0.5) Erodibility Index (-0.1) Construction Month (+0.1)

<i>Distress</i>	<i>Input Category</i>	<i>Hypersensitive (>5)</i>	<i>Very Sensitive (1-5)</i>	<i>Sensitive (0.1-1)</i>
IRI	PCC Properties		Unit Weight (-2.6) Coefficient of Thermal Expansion (+1.4)	Water-to-Cement Ratio (+0.8) Surface Shortwave Absorptivity (+0.6) 28-Day Modulus of Rupture (-0.6) 28-Day Elastic Modulus (+0.5) Thickness (-0.5) 20-year to 28-day Modulus of Rupture (-0.3) Thermal Conductivity (-0.3) Poisson's Ratio (+0.2) Cement Content (+0.1)
	Base Properties			Thickness (-0.2) Erodibility Index (+0.2)
	Subgrade Properties		Resilient Modulus (-1.1)	
	Other Properties		Slab Width (-9.6)	Design Lane Width (-0.7) Traffic Volume (+0.4) Dowel Diameter (-0.4) Joint Spacing (+0.3) Edge Support LTE (-0.1)

12 NEW CRCP

12.1 Analysis Inputs

Similar to the preceding GSA scenarios, the GSA analyses of the New CRCP cases encompassed a total of 15 base cases associated with five climatic conditions at three traffic levels. The project-specific parameters for all GSA analyses of New CRCP cases are the same as the ones for the New JPCP cases shown previously in Table 10.1.

Table 12.1 summarizes the design inputs that are related to traffic level. A 6-in. reduced PCC thickness for the low traffic level was initially proposed. However, the MEPDG requires a minimum CRCP slab thickness of 7 inches. Therefore, an 8-in. baseline PCC slab thickness (with values ranging from 7 to 9 in.) was selected to evaluate the sensitivity of MEPDG distress predictions to PCC thickness under low traffic condition.

The design inputs varied in the GSA sensitivity analyses for New CRCP are summarized in Table 12.2. The values of PCC MOR, E and ST at various ages were determined from the procedures described in in Section 3.4. As stated in Sections 3.4 and 3.5, the values of w/c were varied from the correlation of PCC strength under given ranges and the steel depth values were only varied under half of PCC thickness value inputted.

Table 12.1. Design inputs related to traffic levels in New CRCP.

Traffic Level Input Parameter	Low Traffic			Medium Traffic			High Traffic		
	Baseline	Min	Max	Baseline	Min	Max	Baseline	Min	Max
AADTT-Nominal	1000	500	5000	7500	5000	10000	25000	20000	30000
Design Lane	375	188	1875	2063	1375	2750	6250	5000	7500
PCC Thickness	8	7	9	10	8	12	12	10	14
Base Thickness	4	2	6	6	4	8	8	6	10

Table 12.2. Input parameters and variations in New CRCP.

Input Parameter	OAT Sensitivity ¹	Baseline Value ²	Minimum ²	Maximum ²
Construction Month	S	July/2006	March/2006	October/2006
Bar Diameter	HS	0.60	0.50	1.00
Percent Steel	HS	0.75	0.50	1.00
Steel Depth	HS	Various	2.50	7.00
Edge Support – LTE for Shoulder Type	S	5 for Asphalt or Gravel	N/A	70 for Tied PCC
Base Slab Friction Coef.	HS	2.5	0.5	4
Surface Shortwave Absorption	HS	0.85	0.80	0.98
PCC Unit Weight	HS	150	140	160
PCC Poisson Ratio	S	0.15	0.10	0.20
PCC Coef. of Thermal Expansion	VS	5.56	2	10
PCC Cement Content	HS	500	400	700
PCC W/C	HS	Various	0.3	0.7
PCC 7-Day MOR	-- ³	572	414	812

PCC 7-Day E	-- ³	3,650,255	2,144,002	5,700,014
PCC 7-Day ST	-- ³	383	250	598
PCC 14-Day MOR	-- ³	597	433	847
PCC 14-Day E	-- ³	3,809,795	2,242,398	5,945,704
PCC 14-Day ST	-- ³	400	261	624
PCC 28-Day MOR	HS	620	450	880
PCC 28-Day E	HS	3,956,571	2,330,437	6,177,355
PCC 28-Day ST	-- ³	415	271	649
PCC 90-Day MOR	-- ³	655	475	931
PCC 90-Day E	-- ³	4,179,925	2,459,906	6,535,361
PCC 90-Day ST	-- ³	439	286	686
PCC 20-year MOR to 28-day MOR	-- ³	1.2	1.0	1.5
PCC 20-year ST to 28-day ST	-- ³	1.2	1.0	1.5
Base Resilient Modulus	VS	25,000	15,000	40,000
Subgrade Resilient Modulus	VS	15,000	10,000	20,000
GWD	S	10	2	18

¹HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Not Sensitive

²Same units as for MEDPG input.

³7-, 14- and 90-day and 20-year strength and stiffness values not considered explicitly in OAT analyses.

12.2 Predicted Distresses

Approximately 9900 MEDPG runs were performed for the New CRCP GSA. Table 12.3 through Table 12.6 provide summary statistics for predicted punchout, crack width, crack LTE and IRI, respectively, for the GSA simulations for each base case combination of climate zone and traffic level. Overall, the Latin hypercube sampling scheme generated input data sets that produced a wide range for each of the predicted distresses. The range of predicted distresses in most cases is from zero or near zero to values several times the default design limit. An inverse relation between traffic level and CRCP punchout is observed (i.e., higher the traffic, lower the punchout, probably because of the thinner PCC layers, on average). The average values for crack width, crack LTE and IRI were relatively insensitive to traffic level and climate zone.

Figure 12.1 through Figure 12.5 provide frequency distributions of predicted distresses by climate zone and traffic level. These results confirm that the GSA simulations for the New CRCP cases span a wide range of the model output (distress) space as well as the model inputs domain.

Table 12.3. Summary statistics for predicted punchout – New CRCP.

Scenario	Mean	Minimum	Maximum	Std Dev
CDL	70.41	0.00	203.12	65.32
CDM	40.26	0.00	196.99	51.73
CDH	34.44	0.00	188.54	43.62
CWL	70.41	0.00	203.12	65.32
CWM	42.80	0.00	203.14	54.34
CWH	34.98	0.00	176.56	43.90
TL	67.68	0.00	201.28	64.92
TM	30.10	0.00	179.01	37.60
TH	27.18	0.00	186.96	36.71
HDL	69.51	0.00	196.48	59.86
HDM	40.57	0.00	189.60	50.54
HDH	30.10	0.00	179.01	37.60
HWL	66.62	0.01	200.37	67.60
HWM	38.01	0.00	192.96	49.13
HWH	31.71	0.00	193.23	40.75
Overall	46.81	0.00	204.71	55.78

Table 12.4. Summary statistics for predicted crack width – New CRCP.

Scenario	Mean	Minimum	Maximum	Std Dev
CDL	0.0477	0.0063	0.5223	0.0548
CDM	0.0530	0.0061	0.4655	0.0526
CDH	0.0588	0.0037	0.5298	0.0669
CWL	0.0477	0.0063	0.5223	0.0548
CWM	0.0577	0.0061	0.5712	0.0566
CWH	0.0629	0.0057	0.8237	0.0707
TL	0.0527	0.0049	0.4505	0.0477
TM	0.0814	0.0050	0.7823	0.0897
TH	0.0596	0.0044	0.5699	0.0557
HDL	0.0667	0.0062	0.6462	0.0749
HDM	0.0737	0.0070	0.5950	0.0768
HDH	0.0814	0.0050	0.7823	0.0897
HWL	0.0440	0.0041	0.3950	0.0420
HWM	0.0508	0.0050	0.5799	0.0533
HWH	0.0524	0.0025	0.3630	0.0484
Overall	0.0584	0.0025	0.8237	0.0627

Table 12.5. Summary statistics for predicted crack LTE – New CRCP.

Scenario	Mean	Minimum	Maximum	Std Dev
CDL	64	29.1	100	25
CDM	65	29.1	100	26
CDH	61	29.0	100	25
CWL	64	29.1	100	25
CWM	63	29.0	100	25
CWH	58	29.0	100	23
TL	61	29.1	100	24
TM	54	29.0	100	20
TH	59	29.2	100	23
HDL	58	29.3	100	22
HDM	59	29.0	100	23
HDH	54	29.0	100	20
HWL	64	29.2	100	25
HWM	65	29.0	100	25
HWH	61	29.0	100	25
Overall	61	29.0	100	24

Table 12.6. Summary statistics for predicted IRI – New CRCP.

Scenario	Mean	Minimum	Maximum	Std Dev
CDL	261	92	549	130
CDM	201	92	528	104
CDH	189	92	482	88
CWL	261	92	549	130
CWM	165	72	490	107
CWH	149	72	426	86
TL	196	63	468	128
TM	122	63	414	74
TH	116	63	430	72
HDL	201	63	456	120
HDM	143	63	455	100
HDH	122	63	414	74
HWL	195	63	470	134
HWM	138	63	444	96
HWH	125	63	442	80
Overall	171	63	549	113

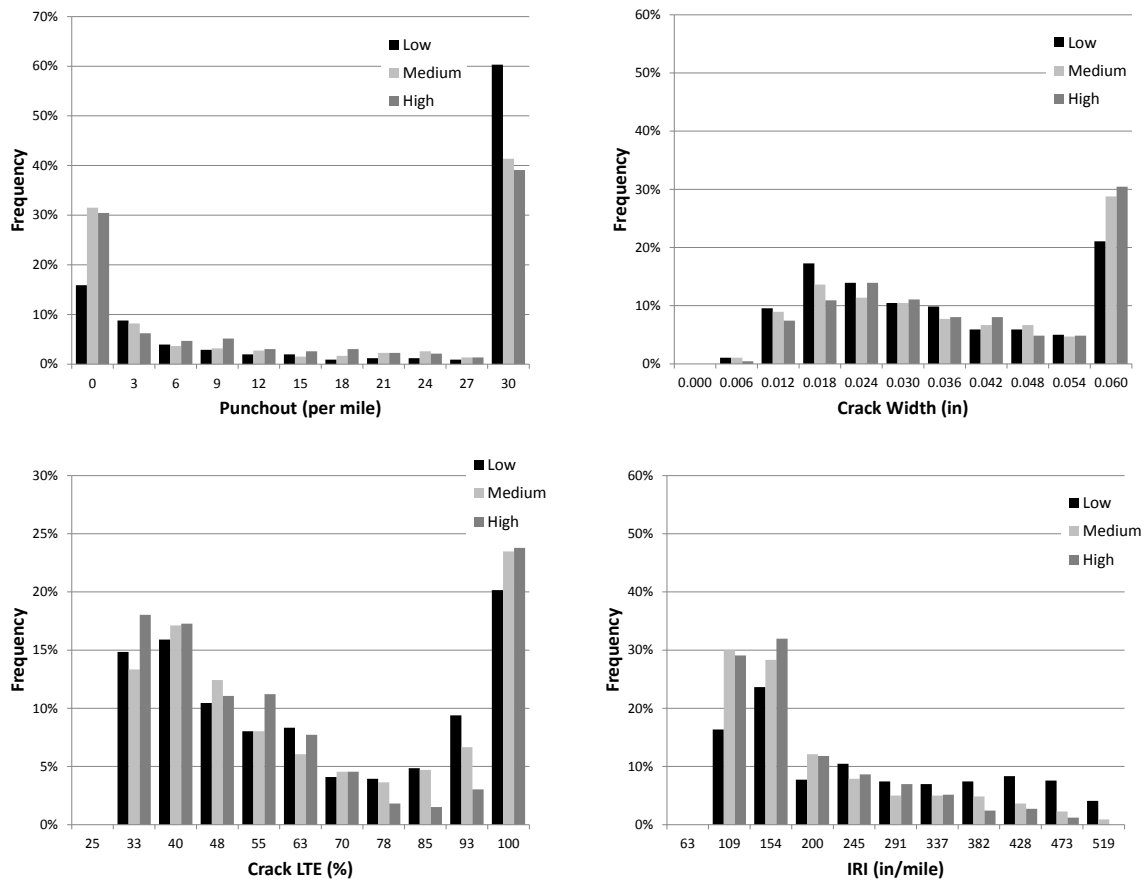


Figure 12.1. Distribution of predicted distresses – New CRCP/Cold-Dry climate

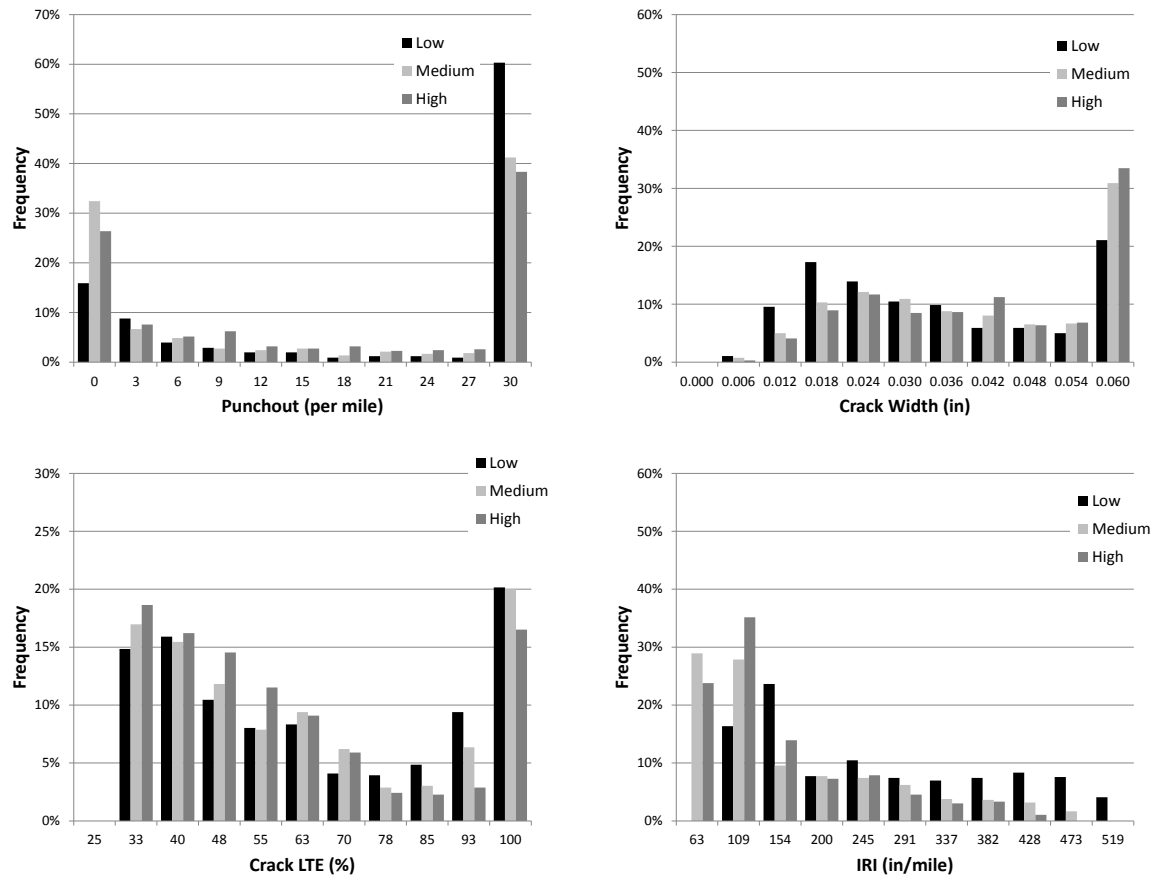


Figure 12.2. Distribution of predicted distresses – New CRCP/Cold-Wet climate.

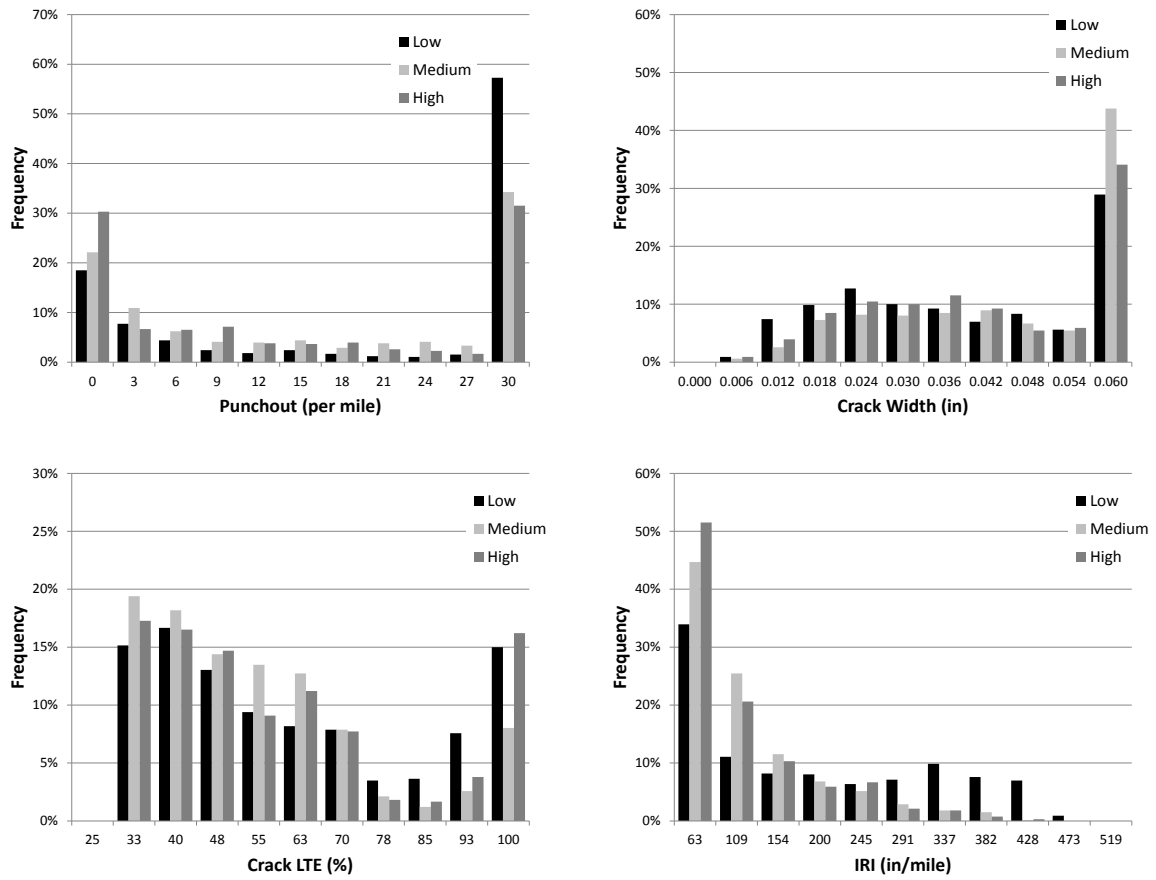


Figure 12.3. Distribution of predicted distresses – New CRCP/Temperature climate.

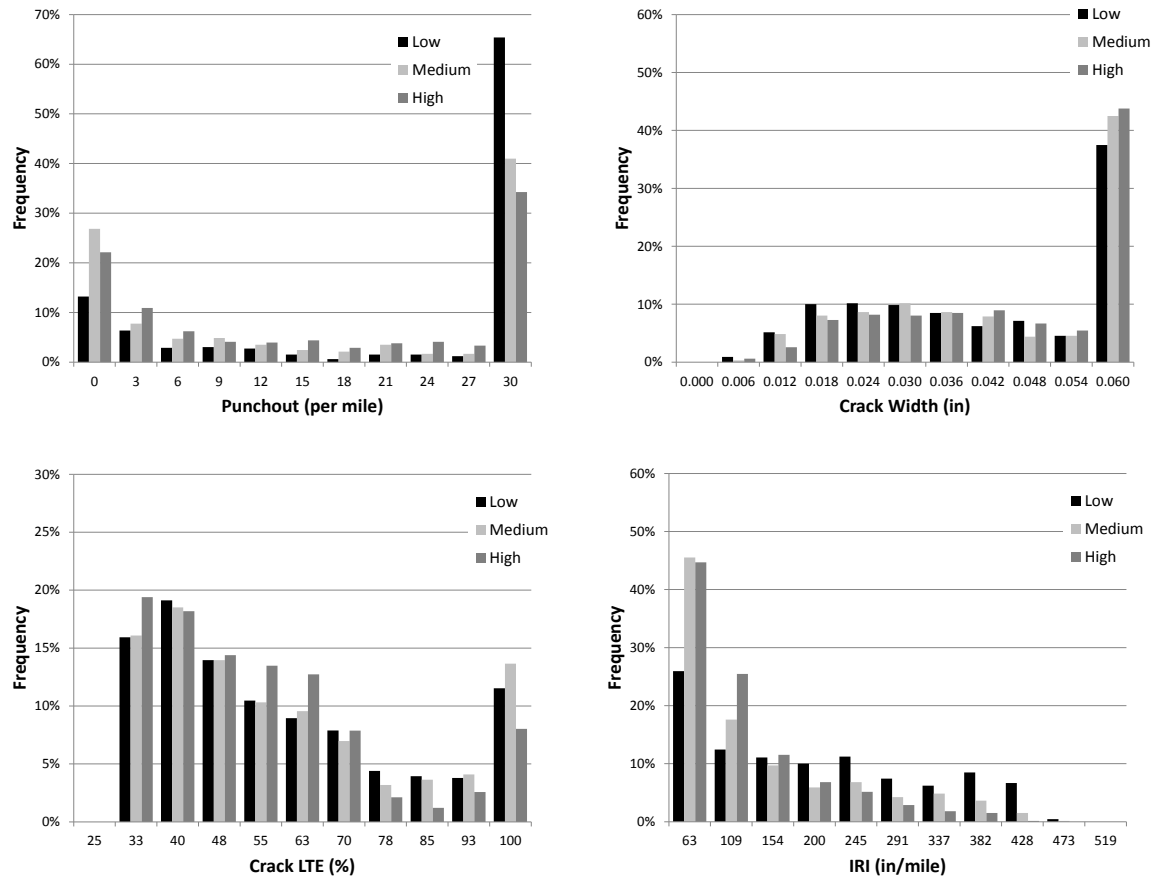


Figure 12.4. Distribution of predicted distresses – New CRCP/Hot-Dry climate.

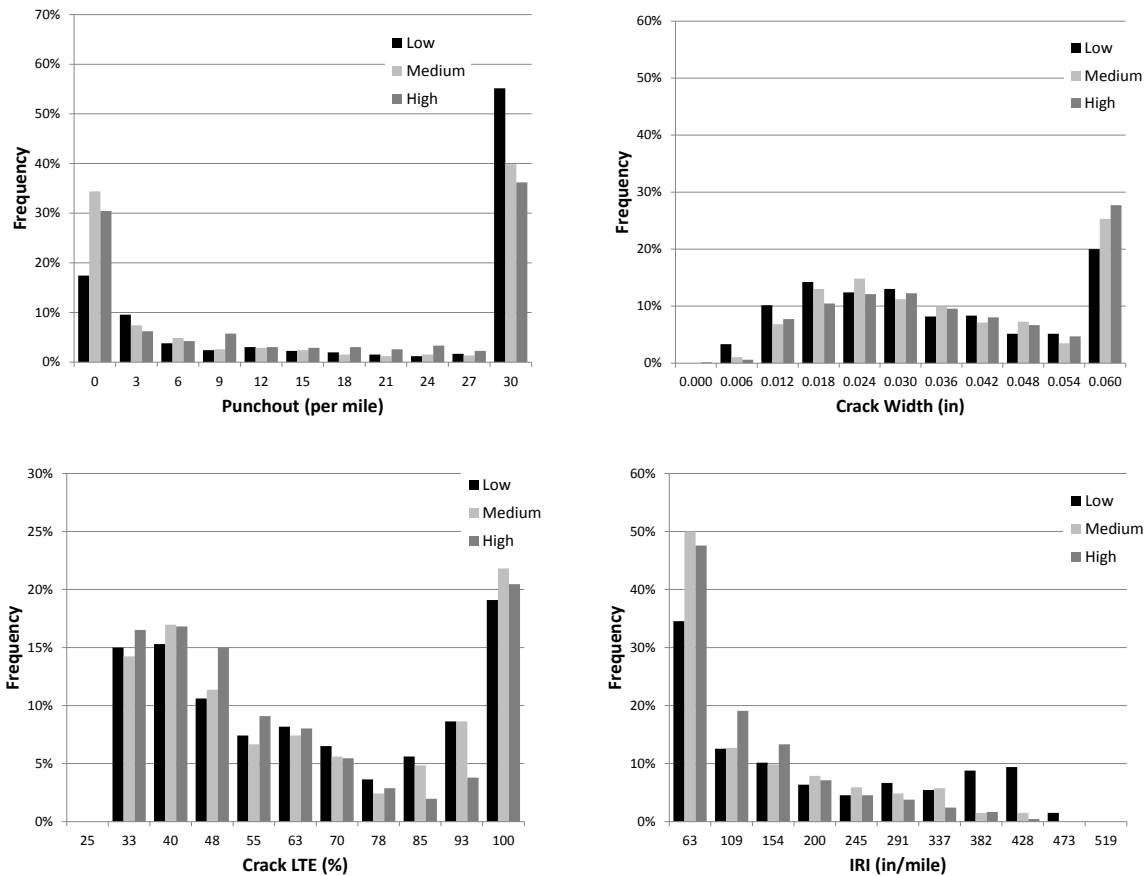


Figure 12.5. Distribution of predicted distresses – New CRCP/Hot-Wet climate

12.3 Response Surface Modeling

Table 12.7 defines the inputs used for the RSMs. These design inputs are the same as those given previously in Table 12.1 and Table 12.2. As discussed previously under New JPCP and JPCP Over Stiff Foundation, there is one difference: the 7-day, 14-day and 90-day MOR, E, and ST values were not included for the RSMs since the inclusion of 28-day MOR, E, and ST alone was found to be sufficient in uniquely capturing the input sensitivities associated with PCC MOR, E and ST.

The outputs for the RSMs are the predicted distresses: punchout, crack width, crack LTE, and IRI. Separate RSMs were developed for each distress. As described previously in Section 6, each input for the MVL RSMs is normalized by its mean value from the GSA simulations and each output distress is normalized by its default design limit. As previously described in Section 7, IRI is treated as a special case because it has a nonzero lower bound.

The regression coefficients in the normalized MVL RSMs can be interpreted as average sensitivity indices quantifying the percentage change in distress relative to design limit caused by a given percentage change in the design input relative to its mean value. These average sensitivity indices are constant across the problem domain—i.e., the MVL RSMs do not capture any variations of sensitivity with location in the problem domain.

Table 12.7. Definition of ANN input labels for CRCP cases.

ANN Input No.	Name of Design Input	Description
1	AADTT per Lane	Average Annual Daily Truck Traffic in design lane
2	CRCP Thick	PCC slab thickness
3	Base Thick	Base layer thickness
4	SSA	Surface Shortwave Absorption
5	Edge Support – LTE for Shoulder Type	Load Transfer Efficiency of shoulder types for edge support of CRCP
6	Percent Steel	Steel content expressed as a percentage of steel cross sectional area of the PCC cross section
7	Bar Diameter	Diameter of the reinforcing bar
8	Steel Depth	Depth from pavement surface to the center of reinforcing steel
9	Base Slab Friction Coef.	Coefficient of friction of base material
10	PCC Unit Weight	Unit weight of Portland Cement Concrete
11	PCC Poisson Ratio	Poisson's ratio of Portland Cement Concrete
12	PCC CTE	Coefficient of Thermal Contraction of Portland Cement Concrete
13	PCC Cement Content	Cement content of Portland Cement Concrete
14	PCC W/C	Ratio of water to cement of Portland Cement Concrete
15	PCC 28-Day MOR	28-day Modulus of Rupture of Portland Cement Concrete
16	PCC 28-Day E	28-day Elastic modulus of Portland Cement Concrete
17	PCC 28-Day ST	28-day Split Tensile strength of Portland Cement Concrete
18	PCC 20-year MOR to 28-day MOR	Ratio of 20-year Modulus of Rupture of Portland Cement Concrete to 28-day Modulus of Rupture of Portland Cement Concrete
19	PCC 20-year ST to 28-day ST	Ratio of 20-year Split Tensile strength of Portland Cement Concrete to 28-day Split Tensile strength of Portland Cement Concrete
20	Base Mr	Resilient modulus of stiff base material
21	Subgrade Mr	Resilient modulus of subgrade material
22	GWD	Ground Water Depth
23	Construction Month	Base/Subgrade construction time, usually one month ahead of pavement construction month

Goodness-of-fit statistics R^2 , root mean squared error (RMSE), and normalized standard error (Se/Sy) for the MVL RSMs are summarized in Table 12.8 by climate zone and distress. Note that the

dimensions of RMSE are same as those of the predicted distress while R^2 and Se/Sy are dimensionless. The R^2 values range from about 0.5 to 0.8, with the crack width distresses tending to have smaller R^2 values and the punchout, crack LTE, and IRI distresses tending to have relatively better goodness-of-fit statistics. The relatively low R^2 values for many of the MVLR RSMs are not unexpected. The relationships between design inputs and distress outputs are expected to be complexly nonlinear; the multivariate linear regressions are intended only as a rough “first cut” assessment of sensitivities.

Goodness-of-fit statistics for the ANN RSMs are summarized in Table 12.9 by climate zone and distress. The ‘NN’ column describes the ANN network architecture; all ANN RSMs for the New CRCP scenarios employed 23 input neurons, 5 hidden neurons in one layer, and one output neuron. The ‘n’ column gives the total number of GSA simulations used for training/validating/testing the model. Overall, the ANN RSM model fits are excellent with the lowest one being 0.88 for crack LTE. Scatter plots for ANN predicted vs. MEPDG predicted distresses are provided in Figure 12.6 for punchout, crack width, crack LTE, and IRI. These scatter plots graphically confirm the conclusions from the goodness-of-fit statistics that the ANN RSM models provide excellent fits. The high quality of the fits for these ANN RSMs suggest the possibility that enhanced versions of the RMS might be adequate substitutes in some cases for the more rigorous but laborious geomechanics computations in the MEPDG.

Table 12.8. Goodness-of-fit statistics for multivariate linear regression response surface models – New CRCP.

Climate	Distress	R^2	RMSE	Se/Sy
CD	Punchout	0.73	2.95	0.52
	Crack Width	0.54	1.98	0.68
	Crack LTE	0.77	0.16	0.48
	IRI	0.74	0.53	0.52
CW	Punchout	0.72	3.01	0.53
	Crack Width	0.54	2.08	0.68
	Crack LTE	0.77	0.16	0.48
	IRI	0.75	0.55	0.51
T	Punchout	0.70	2.81	0.55
	Crack Width	0.55	2.28	0.68
	Crack LTE	0.75	0.15	0.51
	IRI	0.70	0.51	0.55
HD	Punchout	0.73	2.75	0.52
	Crack Width	0.58	2.61	0.65
	Crack LTE	0.78	0.13	0.47
	IRI	0.73	0.50	0.52
HW	Punchout	0.71	3.01	0.54
	Crack Width	0.58	1.56	0.65
	Crack LTE	0.77	0.16	0.49
	IRI	0.71	0.55	0.54

Table 12.9. Goodness-of-fit statistics for neural network response surface models – New CRCP.

Climat	Distress	NN	n	R²	RMSE	Se/Sy
CD	Punchout	23-5-1	1980	0.93	15.467	0.27
	Crack Width	23-5-1	1980	0.94	0.014	0.24
	Crack LTE	23-5-1	1980	0.89	8.332	0.33
	IRI	23-5-1	1980	0.90	35.472	0.31
CW	Punchout	23-5-1	1980	0.92	15.769	0.28
	Crack Width	23-5-1	1980	0.95	0.014	0.23
	Crack LTE	23-5-1	1980	0.90	7.612	0.31
	IRI	23-5-1	1980	0.91	36.427	0.30
T	Punchout	23-5-1	1980	0.94	13.022	0.25
	Crack Width	23-5-1	1980	0.93	0.017	0.26
	Crack LTE	23-5-1	1980	0.88	7.613	0.34
	IRI	23-5-1	1980	0.92	28.203	0.28
HD	Punchout	23-5-1	1980	0.94	12.472	0.24
	Crack Width	23-5-1	1980	0.96	0.016	0.20
	Crack LTE	23-5-1	1980	0.93	5.504	0.26
	IRI	23-5-1	1980	0.95	24.467	0.23
HW	Punchout	23-5-1	1980	0.93	14.332	0.26
	Crack Width	23-5-1	1980	0.97	0.008	0.16
	Crack LTE	23-5-1	1980	0.88	8.483	0.34
	IRI	23-5-1	1980	0.91	33.684	0.31

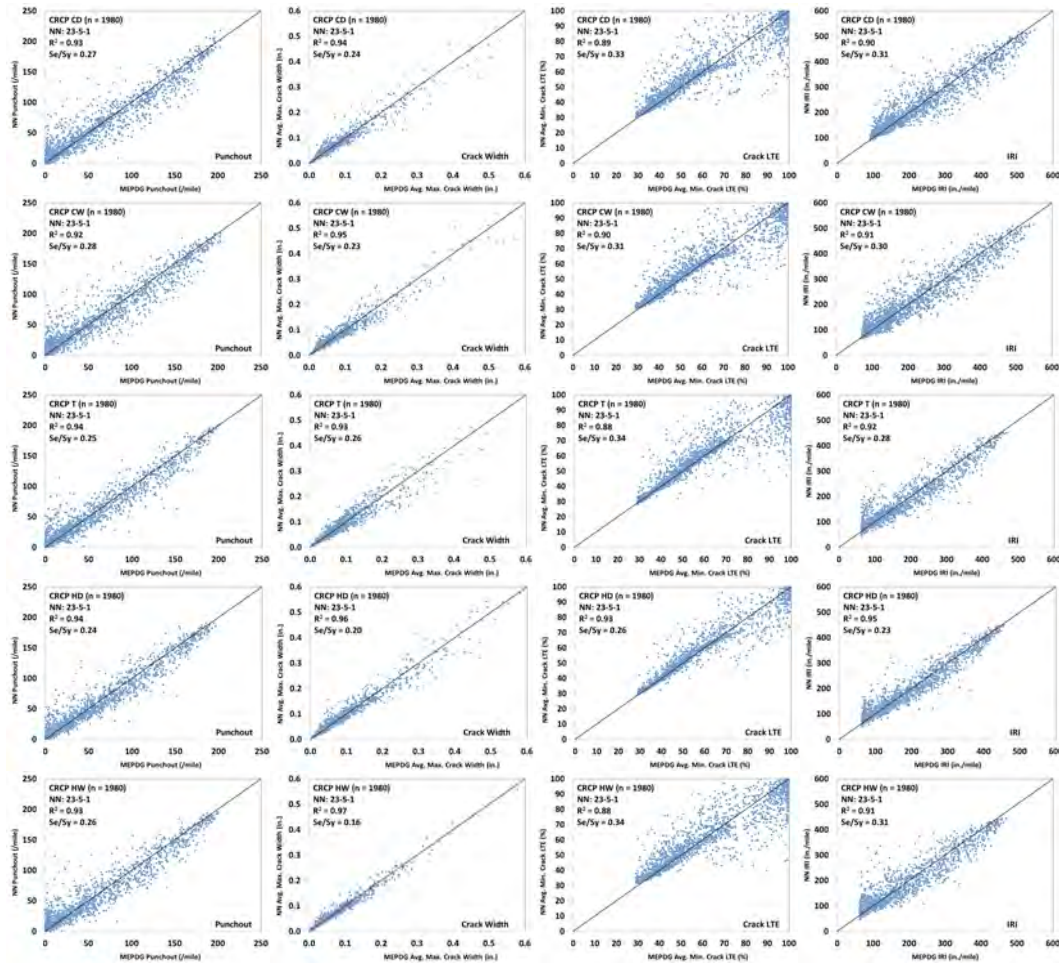


Figure 12.6. ANN predicted vs. MEDPG predicted distresses – New CRCP.

11.4 Sensitivity Metrics

The average sensitivity indices from the MVL RSMs are summarized in Table 12.10 through Table 12.13. Similar to the preceding MVL RSMs, the values for the average sensitivity indices of MVL RSMs of new CRCP are all smaller than the corresponding sensitivity indices computed in the OAT analyses. Figure 12.7 and Figure 12.8 provide graphical summaries by distress and climate zone of the average sensitivities calculated using the MVL RSMs. The high-low-average plot in Figure 12.8 are additionally sorted by maximum average sensitivity (in an absolute value sense) to indicate more clearly the most important design inputs. The most sensitive inputs according to the MVL RSMs in rank order in terms of maximum absolute sensitivity across climate zones (sensitivity values equal to 0.50 or greater) by distress type are:

- Punchout: CRCP Thick, PCC 28-Day MOR, Percent Steel, PCC 20-year MOR to 28-day MOR, PCC Unit Weight, PCC W/C, PCC 28-Day ST, Bar Diameter, PCC 28-Day E, PCC Cement Content, PCC CTE, AADTT Per Lane, Steel Depth, Base Mr, Base Slab Friction, Shoulder LTE, Subgrade Mr, Base Thick

- Crack Width: PCC 28-Day ST, PCC 28-Day MOR, Percent Steel, Bar Diameter, PCC W/C, Base Slab Friction, PCC Cement Content, Steel Depth, PCC 20-year MOR to 28-day MOR, PCC CTE, PCC 28-Day E, SSA, CRCP Thick
- Crack LTE: Percent Steel, PCC 28-Day MOR, CRCP Thick, Bar Diameter
- IRI: CRCP Thick, PCC 28-Day MOR, Percent Steel, PCC 20-year MOR to 28-day MOR, PCC Unit Weight, PCC W/C, PCC 28-Day ST, Bar Diameter, PCC 28-Day E, PCC Cement Content

Most of these rankings are consistent with engineering judgment and the findings from the OAT analyses.

Table 12.10. Average sensitivities from MVL RSMs – New CRCP/Punchout.

Design Input	Climate Zone				
	CD	CW	T	HD	HW
Constant	45.02	52.50	46.24	44.02	26.17
AADTT Per Lane	2.62	2.47	1.81	2.01	2.41
CRCP Thick	-21.99	-21.00	-16.34	-16.70	-20.02
Base Thick	-0.97	-0.73	-0.48	-0.93	0.03
SSA	-1.74	-0.65	0.24	-0.12	1.73
Shoulder LTE	-0.99	-0.99	-0.84	-0.73	-0.92
Percent Steel	-13.13	-13.22	-11.80	-11.55	-14.00
Bar Diameter	6.09	6.04	4.18	3.49	5.36
Steel Depth	3.99	3.16	1.50	0.28	1.44
Base Slab Friction	-2.05	-1.91	-1.26	-0.38	-2.13
PCC Unit Weight	-12.95	-13.70	-7.97	-1.38	-3.26
PCC Poisson Ratio	0.44	0.35	-0.07	0.66	0.74
PCC CTE	2.65	2.37	2.12	2.84	2.47
PCC Cement Content	3.07	3.50	2.50	1.96	3.88
PCC W/C	8.85	5.94	5.19	4.72	10.57
PCC 28-Day MOR	-14.83	-21.05	-14.92	-15.11	-12.53
PCC 28-Day E	4.57	6.71	3.20	0.44	3.43
PCC 28-Day ST	5.13	5.35	3.22	5.04	7.44
PCC 20-year MOR to 28-day MOR	-8.27	-8.57	-8.30	-9.62	-6.97
PCC 20-year ST to 28-day ST	0.04	-0.60	-0.21	0.03	0.50
Base Mr	-0.80	-0.98	-2.88	-3.26	-1.12
Subgrade Mr	-0.33	-0.36	-1.34	-1.16	-0.95
GWD	0.02	-0.03	0.19	-0.14	0.00
Construction Month	0.40	0.33	0.17	0.27	0.27

Table 12.11. Average sensitivities from MVLR RSMs – New CRCP/Crack Width.

Design Input	Climate Zone				
	CD	CW	T	HD	HW
Constant	-2.04	-1.20	-3.54	-14.44	-2.58
AADTT Per Lane	0.08	0.01	0.40	0.04	-0.06
CRCP Thick	-0.20	0.03	-0.93	-1.03	-0.41
Base Thick	-0.35	-0.09	0.28	0.29	-0.01
SSA	0.60	-0.54	-0.76	-1.31	-0.57
Shoulder LTE	-0.03	-0.12	-0.04	0.13	-0.06
Percent Steel	-5.67	-6.03	-6.01	-7.95	-4.65
Bar Diameter	5.41	5.87	5.84	7.65	4.27
Steel Depth	1.88	1.79	1.60	2.26	1.64
Base Slab Friction	-2.79	-2.99	-3.40	-3.89	-2.55
PCC Unit Weight	-0.63	0.64	0.86	-0.36	1.56
PCC Poisson Ratio	0.09	-0.41	0.15	-0.03	-0.08
PCC CTE	0.73	0.63	0.72	0.96	0.45
PCC Cement Content	2.09	2.78	3.32	3.68	2.69
PCC W/C	2.44	2.50	4.32	10.33	2.43
PCC 28-Day MOR	-9.22	-8.91	-8.02	-4.53	-6.38
PCC 28-Day E	1.34	0.65	0.34	0.76	0.07
PCC 28-Day ST	7.47	7.33	7.54	9.35	6.15
PCC 20-year MOR to 28-day MOR	1.35	1.55	1.23	1.34	1.02
PCC 20-year ST to 28-day ST	0.09	-0.29	-0.02	1.02	-0.13
Base Mr	-0.02	-0.03	-0.33	-0.28	0.08
Subgrade Mr	-0.37	-0.50	-0.47	-0.66	-0.48
GWD	-0.06	-0.24	-0.01	-0.04	-0.13
Construction Month	0.48	0.35	0.15	0.41	0.16

Table 12.12. Average sensitivities from MVLR RSMs – New CRCP/ Crack LTE.

Design Input	Climate Zone				
	CD	CW	T	HD	HW
Constant	-0.27	-0.27	-0.59	-1.16	0.07
AADTT Per Lane	-0.11	-0.11	-0.14	-0.08	-0.11
CRCP Thick	0.61	0.44	0.47	0.47	0.55
Base Thick	0.00	-0.01	-0.02	-0.02	-0.03
SSA	0.07	0.14	0.06	-0.04	-0.07
Shoulder LTE	0.10	0.11	0.09	0.08	0.10
Percent Steel	1.23	1.19	1.12	1.13	1.21
Bar Diameter	-0.58	-0.54	-0.44	-0.40	-0.57
Steel Depth	-0.23	-0.16	-0.16	-0.20	-0.16
Base Slab Friction	0.14	0.12	0.10	0.06	0.16
PCC Unit Weight	0.32	0.22	0.17	0.00	0.04
PCC Poisson Ratio	0.02	0.00	0.01	0.00	-0.01
PCC CTE	-0.03	-0.01	-0.02	-0.02	-0.03
PCC Cement Content	-0.27	-0.24	-0.24	-0.17	-0.28
PCC W/C	-0.16	-0.12	0.07	0.32	-0.12
PCC 28-Day MOR	0.95	1.04	0.99	1.21	0.98
PCC 28-Day E	-0.25	-0.24	-0.19	-0.02	-0.24
PCC 28-Day ST	-0.44	-0.46	-0.31	-0.35	-0.47
PCC 20-year MOR to 28-day MOR	-0.18	-0.22	-0.19	-0.08	-0.20
PCC 20-year ST to 28-day ST	0.02	-0.03	0.03	0.01	0.01
Base Mr	-0.03	0.01	-0.01	0.01	0.03
Subgrade Mr	-0.03	-0.01	0.00	0.01	-0.01
GWD	0.01	0.00	-0.01	0.01	-0.01
Construction Month	-0.03	-0.02	-0.01	-0.02	-0.03

Table 12.13. Average sensitivities from MVL RSMs – New CRCP/IRI.

Design Input	Climate Zone				
	CD	CW	T	HD	HW
Constant	9.51	10.59	8.38	7.87	4.66
AADTT Per Lane	0.48	0.46	0.33	0.37	0.44
CRCP Thick	-4.00	-4.34	-2.95	-3.05	-3.64
Base Thick	-0.18	-0.36	-0.09	-0.18	0.00
SSA	-0.32	-0.10	0.04	-0.04	0.32
Shoulder LTE	-0.18	-0.18	-0.15	-0.13	-0.16
Percent Steel	-2.36	-2.35	-2.12	-2.08	-2.52
Bar Diameter	1.10	1.08	0.75	0.63	0.96
Steel Depth	0.72	0.63	0.27	0.05	0.26
Base Slab Friction	-0.37	-0.34	-0.23	-0.07	-0.38
PCC Unit Weight	-2.32	-2.40	-1.43	-0.24	-0.56
PCC Poisson Ratio	0.08	0.07	-0.01	0.12	0.14
PCC CTE	0.49	0.44	0.39	0.53	0.46
PCC Cement Content	0.56	0.63	0.45	0.36	0.69
PCC W/C	1.61	1.16	0.91	0.90	1.93
PCC 28-Day MOR	-2.68	-3.65	-2.73	-2.71	-2.25
PCC 28-Day E	0.83	1.15	0.58	0.09	0.62
PCC 28-Day ST	0.92	1.00	0.58	0.91	1.35
PCC 20-year MOR to 28-day MOR	-1.49	-1.54	-1.49	-1.72	-1.25
PCC 20-year ST to 28-day ST	0.01	-0.11	-0.04	-0.01	0.09
Base Mr	-0.14	-0.17	-0.52	-0.59	-0.20
Subgrade Mr	-0.94	-0.53	-0.24	-0.19	-0.17
GWD	0.00	-0.01	0.03	-0.02	0.00
Construction Month	0.07	0.06	0.03	0.05	0.05

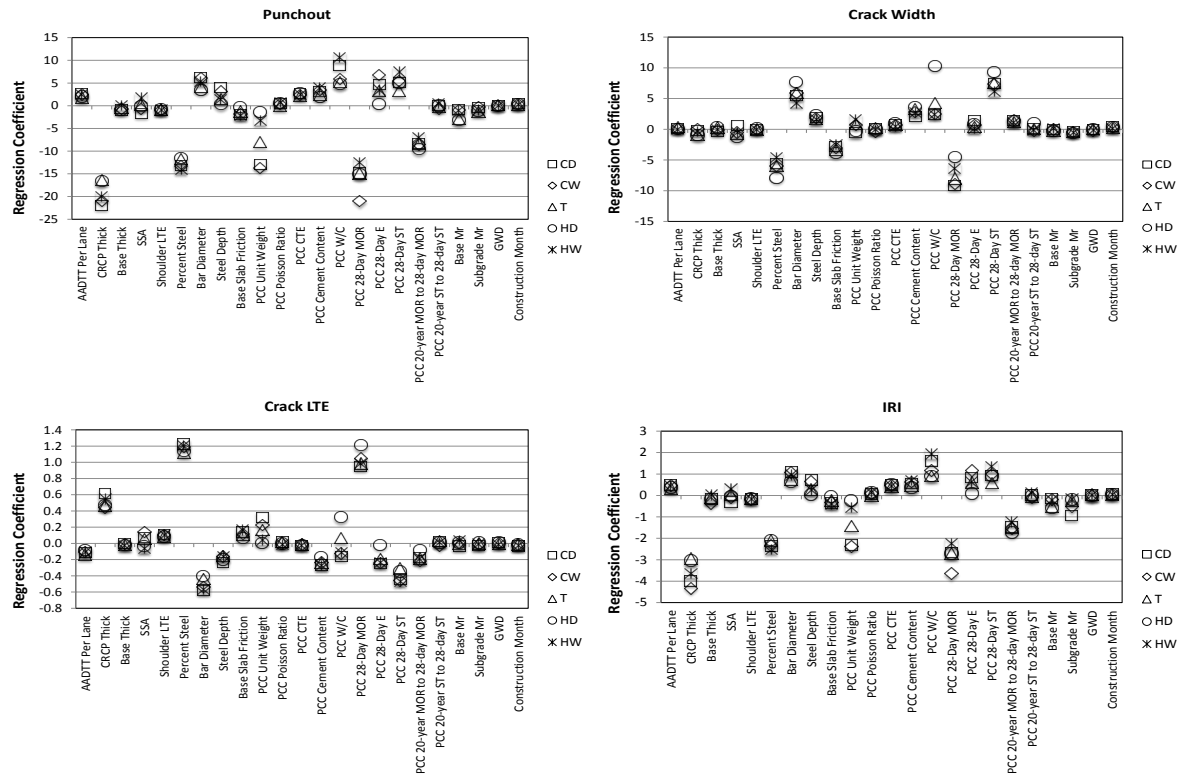


Figure 12.7. Average sensitivities from MVL RSMs – New CRCP.

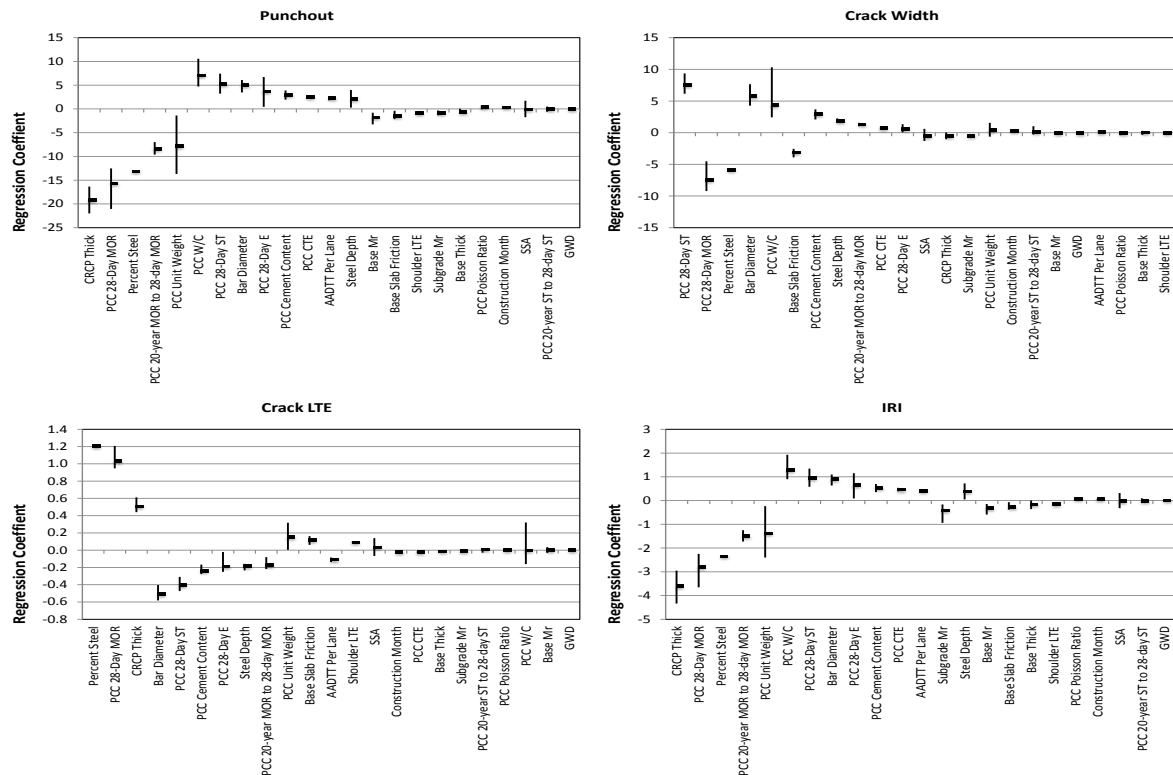


Figure 12.8. Ranking of average sensitivities from MVL RSMs – New CRCP.

The ANN RSMs permit a more in-depth evaluation of sensitivities than does the MVLR approach. The mean and standard deviations of the NSI distributions are summarized by climate zone in Table 12.14 through Table 12.17 for each respective distress. Full frequency distributions of the computed NSI values by design input and climate zone are depicted in Figure 12.9 through Figure 12.12 for each respective distress. Similar to the finding of preceding analyses, most frequency distributions have well-defined peaks that indicate NSI does not vary significantly over the problem domain. The influence of climate zone on the frequency distributions is also negligible in most cases.

Table 12.14. NSI statistics from ANN RSMs – New CRCP/Punchout.

Design Input	Climate Zone									
	CD		CW		T		HD		HW	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
AADTT Per Lane	2.29	3.09	2.16	3.06	1.71	2.02	1.82	2.50	1.88	2.69
CRCP Thick	-14.39	15.02	-13.74	15.01	-12.36	12.58	-12.11	14.10	-12.68	14.12
Base Thick	-0.38	0.70	-0.18	0.35	-0.35	0.45	-0.14	0.32	-0.19	0.23
SSA	-0.78	1.27	0.24	1.01	0.27	0.86	0.41	0.67	0.90	1.06
Shoulder LTE	-1.04	1.11	-1.04	1.06	-0.86	0.72	-0.84	0.80	-0.89	1.02
Percent Steel	-6.46	4.38	-6.06	4.30	-5.80	4.02	-5.72	4.03	-6.35	4.53
Bar Diameter	2.89	4.26	2.91	3.63	2.19	2.38	2.01	2.01	2.55	2.89
Steel Depth	1.73	2.35	1.68	2.30	0.95	1.84	0.43	0.92	0.66	1.58
Base Slab Friction	-0.95	1.57	-0.90	1.38	-0.85	0.95	-0.36	0.37	-1.03	1.57
PCC Unit Weight	-5.69	5.22	-6.46	5.38	-4.35	6.44	-3.43	2.70	-3.67	4.15
PCC Poisson Ratio	0.19	0.45	0.15	0.37	0.29	0.32	0.42	0.69	0.41	0.44
PCC CTE	1.65	1.99	1.39	1.97	1.33	1.66	1.73	2.23	1.33	1.86
PCC Cement Content	1.51	2.77	1.34	2.26	1.68	1.79	1.07	1.03	1.90	2.83
PCC W/C	2.40	3.01	2.07	1.78	1.04	1.53	0.62	0.95	2.84	2.70
PCC 28-Day MOR	-12.28	11.80	-12.65	13.82	-11.10	12.09	-12.42	13.10	-10.93	13.34
PCC 28-Day E	2.94	2.91	3.36	3.18	2.96	3.72	2.00	2.39	2.81	4.05
PCC 28-Day ST	3.35	3.89	3.19	3.22	1.28	2.40	2.25	2.27	3.22	3.76
PCC 20-year MOR to 28-day MOR	-5.69	5.66	-5.98	5.73	-5.50	5.86	-6.06	6.37	-5.42	5.91
PCC 20-year ST to 28-day ST	0.21	0.69	-0.08	0.28	-0.15	0.74	0.07	0.29	0.20	0.56
Base Mr	-0.61	0.57	-1.05	0.99	-1.70	1.94	-2.02	2.18	-0.97	1.03
Subgrade Mr	-0.32	0.60	-0.57	0.62	-0.99	1.12	-0.95	1.09	-0.66	0.64
GWD	0.04	0.16	0.04	0.11	-0.02	0.15	-0.01	0.11	0.04	0.20
Construction Month	0.21	0.70	0.04	0.50	0.16	0.27	0.10	0.20	0.18	0.34

Table 12.15. NSI statistics from ANN RSMs – New CRCP/Crack Width.

Design Input	Climate Zone									
	CD		CW		T		HD		HW	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
AADTT Per Lane	0.0	0.2	0.0	0.2	0.1	0.5	0.0	0.1	0.0	0.1
CRCP Thick	0.4	3.2	0.1	2.4	-1.6	4.4	-0.7	0.8	-0.6	0.8
Base Thick	-0.1	0.5	0.1	0.3	0.7	2.0	0.2	0.6	0.1	0.2
SSA	0.1	1.1	-0.6	2.4	0.4	2.0	-0.1	1.1	-0.1	1.0
Shoulder LTE	0.0	0.1	-0.1	0.4	0.3	0.9	0.0	0.1	0.0	0.1
Percent Steel	-4.6	4.9	-4.8	5.9	-4.6	5.3	-5.8	6.1	-4.1	5.3
Bar Diameter	4.8	5.6	5.7	8.8	5.0	6.9	6.0	7.9	4.3	6.3
Steel Depth	1.3	1.5	1.7	1.5	2.4	5.5	2.1	2.4	1.7	2.4
Base Slab Friction	-2.2	3.9	-2.8	5.3	-4.4	8.6	-3.1	5.7	-2.2	4.5
PCC Unit Weight	0.4	1.4	-1.9	8.0	-4.8	15.2	-1.5	4.9	0.2	1.2
PCC Poisson Ratio	0.0	0.2	0.1	0.4	-0.4	1.0	-0.3	1.0	-0.1	0.5
PCC CTE	0.7	1.4	0.7	1.8	0.9	2.3	0.8	1.4	0.6	1.5
PCC Cement Content	2.0	3.1	2.5	4.7	4.6	8.5	3.7	6.4	2.4	4.8
PCC W/C	1.2	1.6	3.0	7.2	6.8	14.6	5.4	10.4	1.7	2.7
PCC 28-Day MOR	-7.7	8.6	-6.9	9.6	-11.1	18.4	-8.9	10.5	-6.7	9.2
PCC 28-Day E	0.9	1.3	1.1	1.8	3.0	6.5	1.4	3.0	1.0	1.0
PCC 28-Day ST	6.7	9.2	7.9	14.4	12.2	24.6	9.4	14.0	6.5	12.4
PCC 20-year MOR to 28-day MOR	0.9	0.9	1.6	3.1	0.9	1.3	1.0	1.5	1.4	2.5
PCC 20-year ST to 28-day ST	0.6	1.9	-0.2	0.5	-1.0	2.4	0.4	1.4	0.0	0.2
Base Mr	0.0	0.4	0.2	0.6	-0.7	2.0	0.0	0.2	0.0	0.0
Subgrade Mr	-0.2	0.3	-0.4	0.9	-0.8	1.9	0.0	0.4	-0.3	0.6
GWD	0.1	0.3	0.0	0.3	-0.2	0.5	-0.1	0.2	-0.1	0.3
Construction Month	0.3	1.0	0.3	0.7	0.2	0.5	0.4	0.6	0.1	0.1

Table 12.16. NSI statistics from ANN RSMs – New CRCP/Crack LTE.

Design Input	Climate Zone									
	CD		CW		T		HD		HW	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
AADTT Per Lane	-0.1	0.2	-0.1	0.2	-0.1	0.1	-0.1	0.2	-0.1	0.1
CRCP Thick	0.4	0.6	0.3	0.5	0.4	0.4	0.4	0.5	0.4	0.5
Base Thick	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SSA	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0
Shoulder LTE	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Percent Steel	0.6	0.2	0.6	0.2	0.6	0.2	0.6	0.2	0.6	0.2
Bar Diameter	-0.3	0.6	-0.4	0.6	-0.3	0.5	-0.3	0.5	-0.3	0.5
Steel Depth	-0.2	0.2	-0.1	0.2	-0.1	0.1	-0.1	0.2	-0.1	0.2
Base Slab Friction	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
PCC Unit Weight	0.2	0.2	0.1	0.2	0.0	0.1	0.0	0.1	0.0	0.1
PCC Poisson Ratio	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PCC CTE	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PCC Cement Content	-0.1	0.2	-0.2	0.2	-0.2	0.2	-0.2	0.2	-0.2	0.2
PCC W/C	-0.2	0.3	-0.1	0.2	0.0	0.1	-0.1	0.2	0.0	0.1
PCC 28-Day MOR	0.5	0.8	0.6	0.8	0.6	0.8	0.6	0.8	0.6	0.9
PCC 28-Day E	-0.1	0.2	-0.1	0.2	-0.1	0.1	0.0	0.0	-0.1	0.1
PCC 28-Day ST	-0.3	0.5	-0.3	0.5	-0.2	0.3	-0.3	0.5	-0.3	0.4
PCC 20-year MOR to 28-day MOR	-0.1	0.2	-0.1	0.1	-0.1	0.2	-0.1	0.1	-0.1	0.2
PCC 20-year ST to 28-day ST	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Base Mr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Subgrade Mr	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
GWD	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Construction Month	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 12.17. NSI statistics from ANN RSMs – New CRCP/IRI.

Design Input	Climate Zone									
	CD		CW		T		HD		HW	
	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
AADTT Per Lane	0.4	0.5	0.4	0.6	0.3	0.4	0.3	0.5	0.4	0.5
CRCP Thick	-2.5	2.7	-2.9	3.0	-2.3	2.4	-2.3	2.7	-2.3	2.8
Base Thick	-0.1	0.1	-0.1	0.1	-0.1	0.1	0.0	0.1	0.0	0.0
SSA	-0.1	0.3	0.0	0.2	0.0	0.2	0.1	0.2	0.1	0.2
Shoulder LTE	-0.2	0.2	-0.2	0.2	-0.2	0.1	-0.2	0.2	-0.2	0.2
Percent Steel	-1.2	0.8	-1.1	0.8	-1.1	0.8	-1.0	0.7	-1.2	0.9
Bar Diameter	0.6	0.7	0.6	0.6	0.4	0.5	0.4	0.4	0.6	0.6
Steel Depth	0.3	0.4	0.5	0.5	0.3	0.3	0.1	0.2	0.3	0.3
Base Slab Friction	-0.2	0.3	-0.2	0.2	-0.1	0.2	-0.1	0.1	-0.2	0.3
PCC Unit Weight	-1.0	1.1	-0.9	0.8	-1.0	1.1	-0.6	0.6	-0.6	0.5
PCC Poisson Ratio	0.1	0.1	0.0	0.1	0.0	0.1	0.1	0.1	0.1	0.1
PCC CTE	0.3	0.4	0.3	0.4	0.2	0.3	0.3	0.4	0.3	0.4
PCC Cement Content	0.3	0.4	0.3	0.4	0.3	0.3	0.2	0.2	0.4	0.5
PCC W/C	0.4	0.4	0.3	0.3	0.2	0.2	0.1	0.2	0.6	0.7
PCC 28-Day MOR	-2.2	2.3	-2.4	2.5	-2.2	2.4	-2.2	2.5	-2.1	2.4
PCC 28-Day E	0.6	0.6	0.6	0.6	0.6	0.7	0.4	0.5	0.6	0.8
PCC 28-Day ST	0.6	0.6	0.6	0.6	0.4	0.4	0.4	0.4	0.7	0.8
PCC 20-year MOR to 28-day MOR	-1.0	1.0	-1.0	0.9	-1.0	1.1	-1.1	1.2	-0.9	1.0
PCC 20-year ST to 28-day ST	0.0	0.1	0.0	0.1	-0.1	0.1	0.0	0.1	0.0	0.1
Base Mr	-0.1	0.1	-0.2	0.2	-0.3	0.4	-0.4	0.4	-0.1	0.2
Subgrade Mr	-0.6	0.3	-0.3	0.3	-0.2	0.2	-0.2	0.2	-0.1	0.1
GWD	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Construction Month	0.1	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1

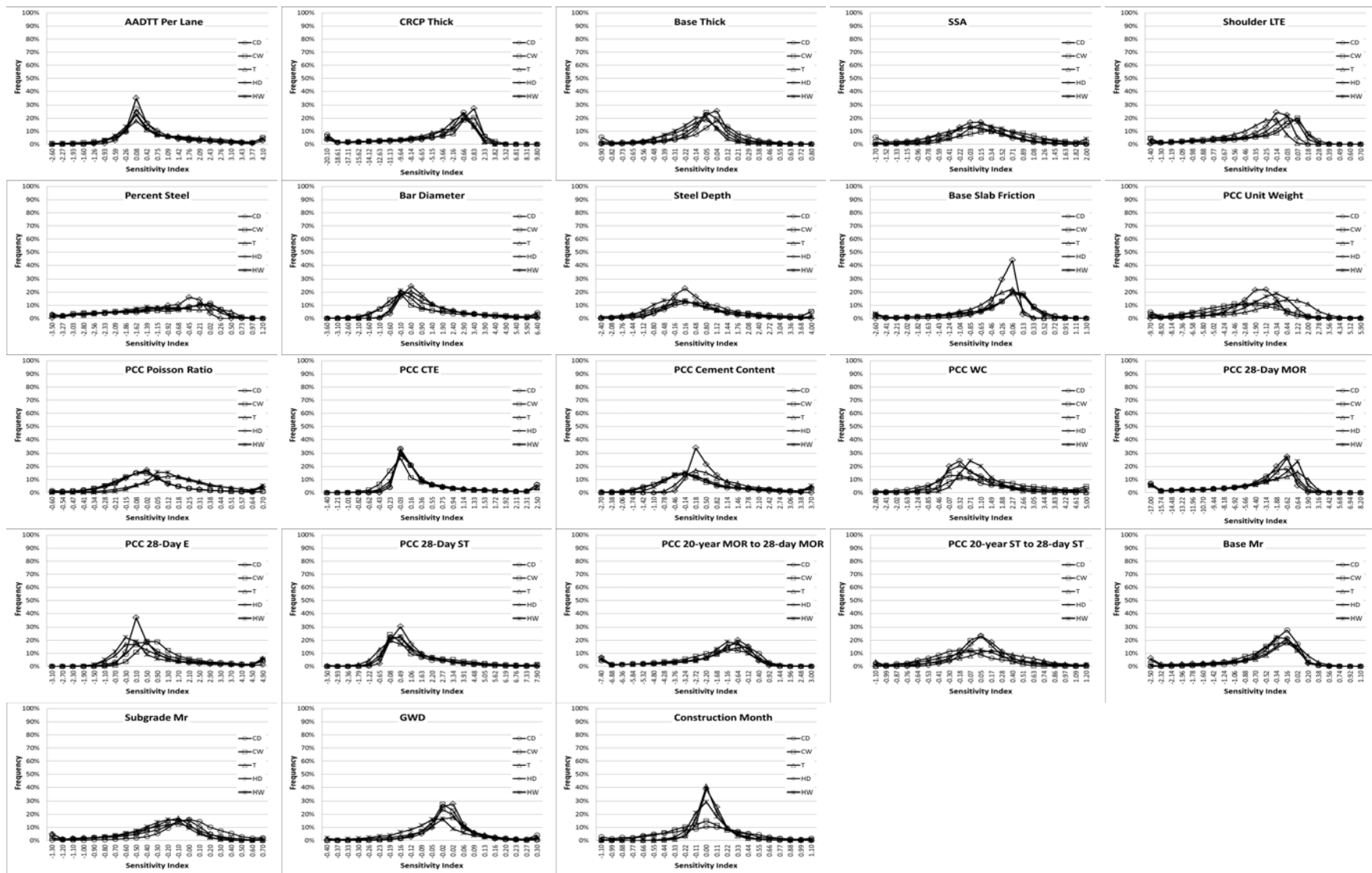


Figure 12.9. Distributions of NSI values – New CRCP/Punchout.

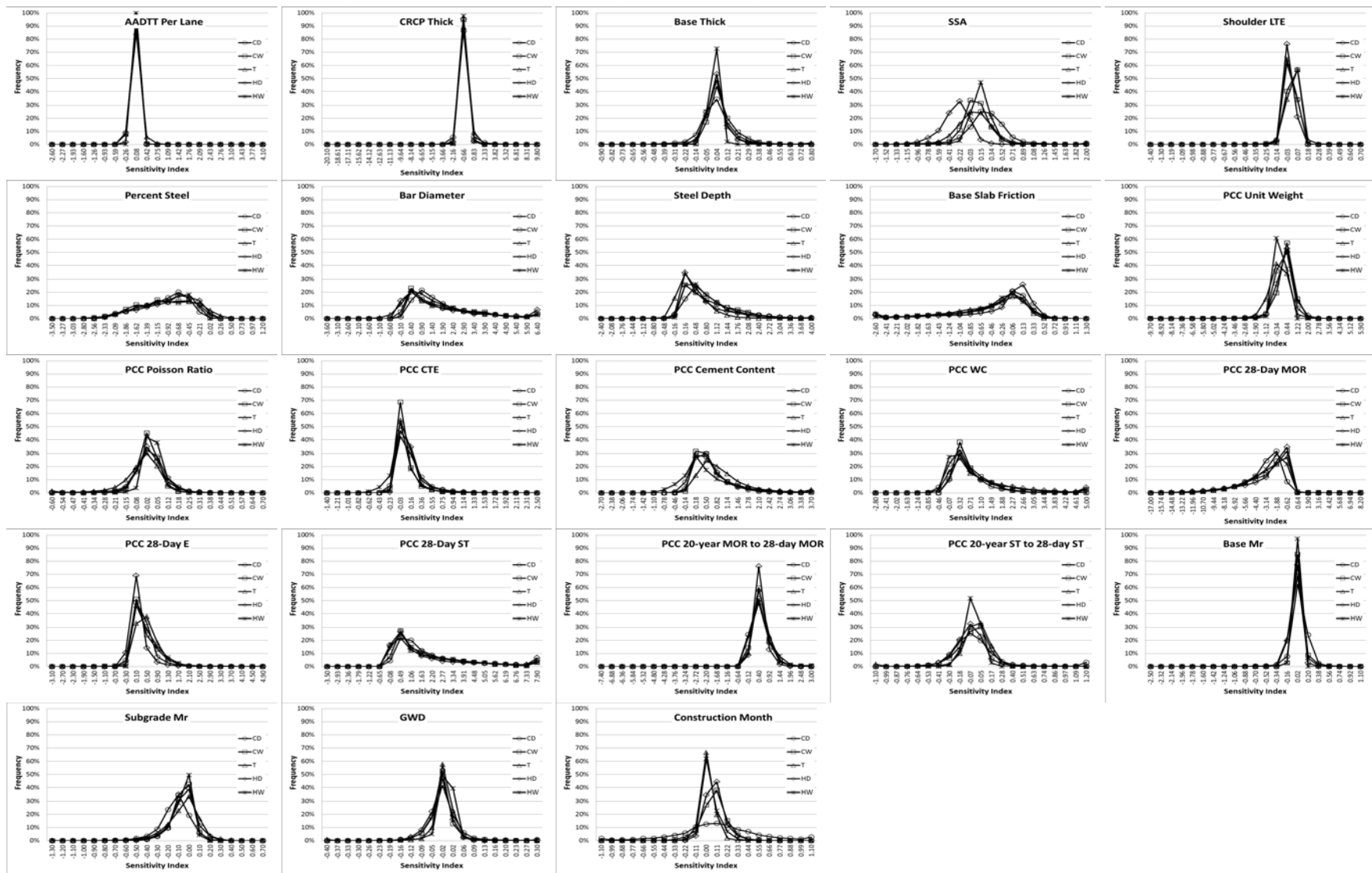


Figure 12.10. Distributions of NSI values – New CRCP/Crack Width.

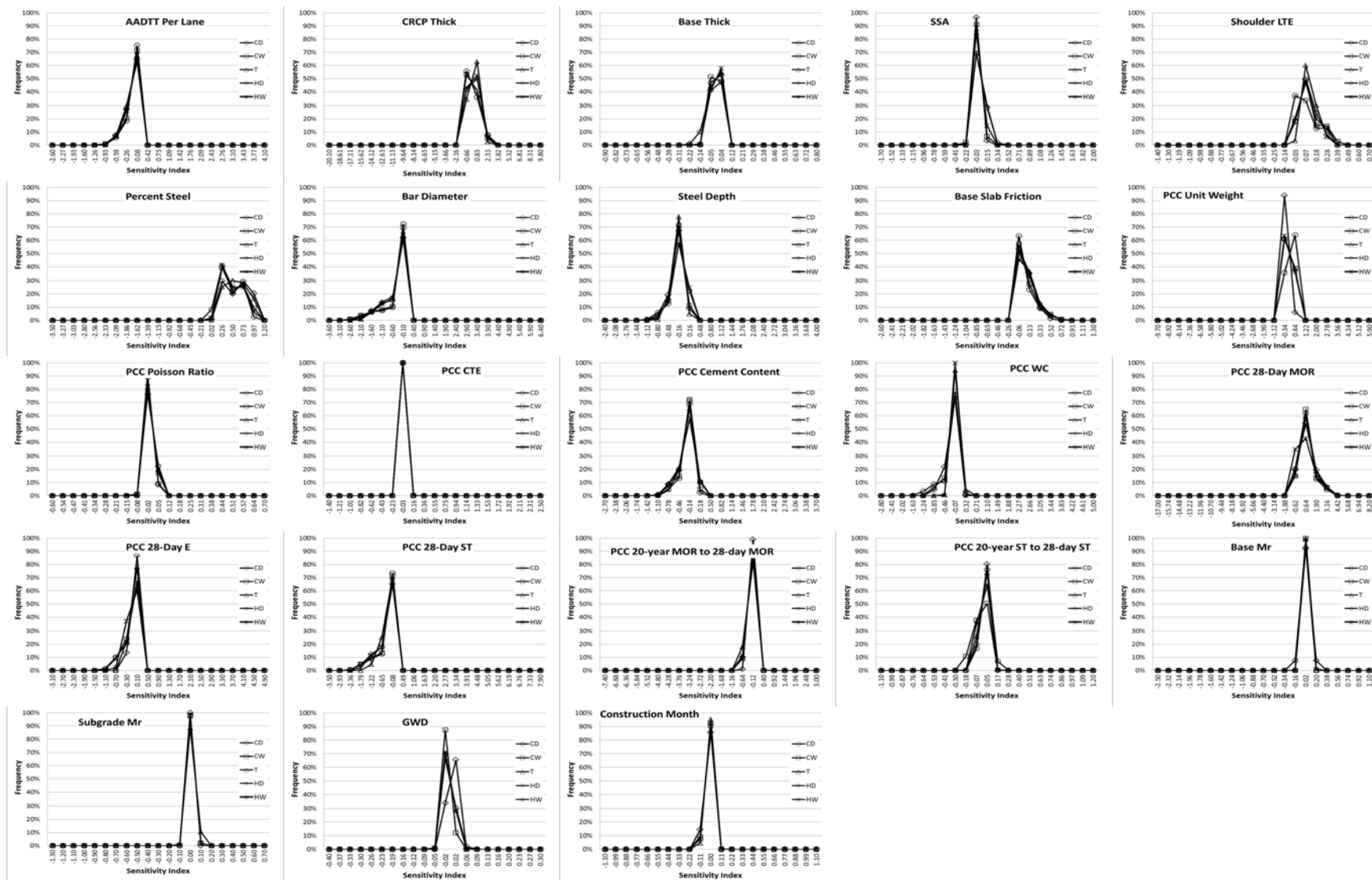


Figure 12.11. Distributions of NSI values – New CRCP/Crack LTE.

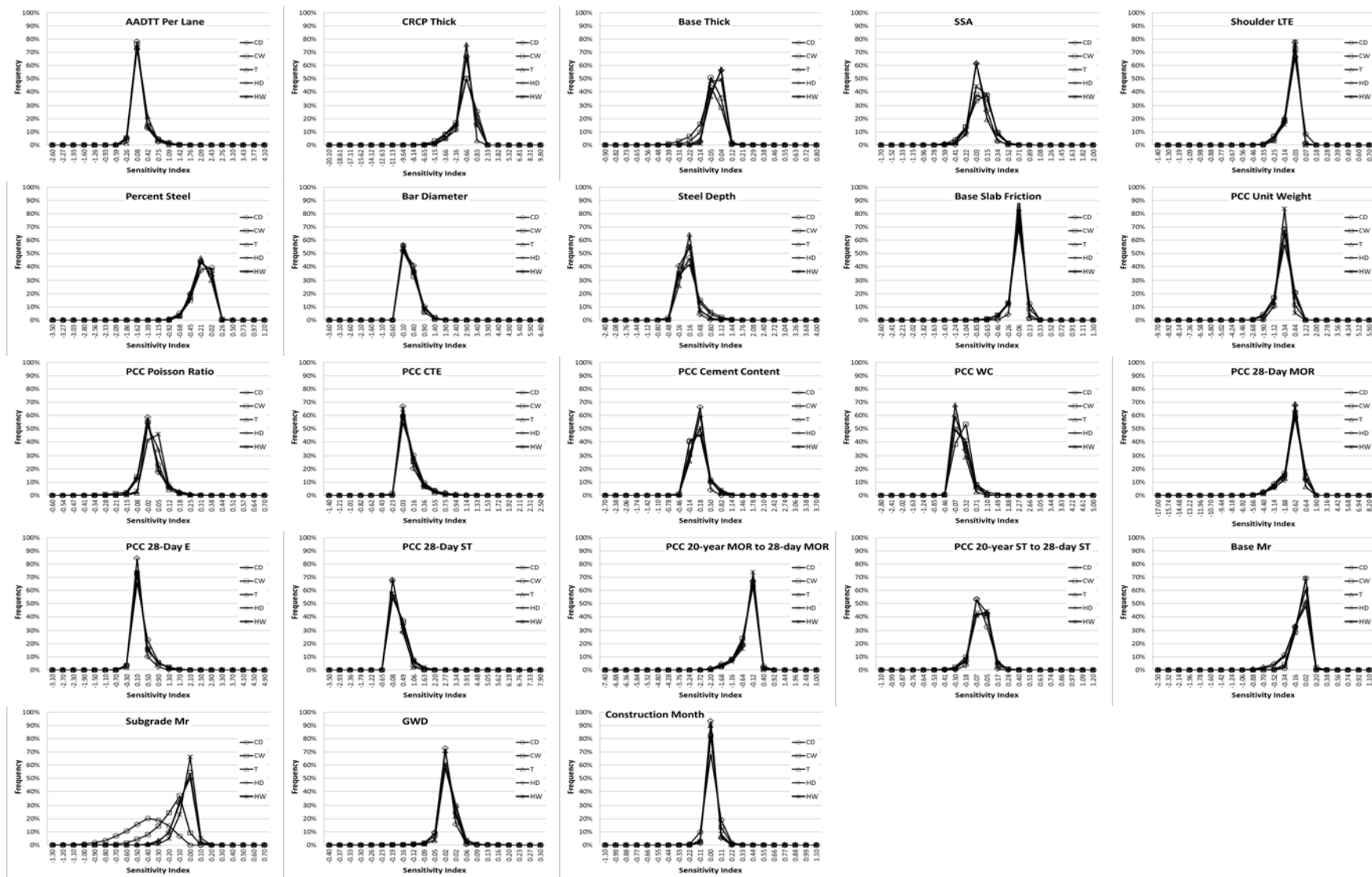


Figure 12.12. Distributions of NSI values – New CRCP/IRI.

11.5 Conclusions – New CRCP

The maximum average sensitivity coefficients from the MVLR RSMs across climate zones for all distress and design input combinations are ranked by maximum absolute sensitivity across distresses in Table 12.18. Even though the ranking is by maximum absolute sensitivity, the plus and minus signs are retained for each individual sensitivity coefficient to indicate whether distress increases (+) or decreases (-) with increasing input value. Usually—and especially for the highest sensitivity inputs—the plus/minus signs for each design input are consistent across all distresses.

The OAT local sensitivity category (Appendix B) for each design input is also indicated in Table 12.18. There is good congruence between the ranking of inputs from the MVLR RSMs and the categorization from the OAT analyses. Most of design inputs categorized as HS in the OAT analyses are the highest-ranked design inputs, most of the inputs categorized as VS in the OAT analyses appear high in the list, and most of the inputs categorized as S in the OAT analyses also appear lower portion of the rankings in Table 12.18.

Table 12.18. Ranking of New CRCP design inputs by overall maximum |Average Sensitivity Coefficient| (MVLR RSMs).

Design Input	Maximum Average Sensitivity Coefficient (MVLR RSM)					OAT Category ¹
	Punchout	Crack Width	Crack LTE	IRI	Maximum	
CRCP Thick	-19.21	-0.51	0.51	-3.60	-19.21	HS
PCC 28-Day MOR	-15.69	-7.41	1.03	-2.80	-15.69	HS
Percent Steel	-13.18	-5.85	1.21	-2.35	-13.18	HS
PCC 20-year MOR to 28-day MOR	-8.35	1.30	-0.17	-1.50	-8.35	- ²
PCC Unit Weight	-7.85	0.42	0.15	-1.39	-7.85	HS
PCC 28-Day ST	5.24	7.57	-0.41	0.95	7.57	- ²
PCC W/C	7.06	4.40	0.00	1.30	7.06	HS
Bar Diameter	5.03	5.81	-0.51	0.90	5.81	HS
PCC 28-Day E	3.67	0.63	-0.19	0.65	3.67	HS
Base Slab Friction	-1.55	-3.12	0.12	-0.28	-3.12	HS
PCC Cement Content	2.98	2.91	-0.24	0.54	2.98	HS
PCC CTE	2.49	0.70	-0.02	0.46	2.49	VS
AADTT Per Lane	2.26	0.09	-0.11	0.41	2.26	HS
Steel Depth	2.07	1.84	-0.18	0.39	2.07	HS
Base Mr	-1.81	-0.11	0.00	-0.33	-1.81	VS
Shoulder LTE	-0.83	0.01	0.09	-0.15	-0.83	S
Subgrade Mr	-0.83	-0.49	-0.01	-0.41	-0.83	VS
Base Thick	-0.62	0.02	-0.02	-0.16	-0.62	S
SSA	-0.11	-0.52	0.03	-0.02	-0.52	HS
PCC Poisson Ratio	0.42	-0.06	0.00	0.08	0.42	S
Construction Month	0.29	0.31	-0.02	0.05	0.31	S
PCC 20-year ST to 28-day ST	-0.05	0.13	0.01	-0.01	0.13	- ²
GWD	0.01	-0.09	0.00	0.00	-0.09	S

¹HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Non-Sensitive

²28-day split tensile strength and 20-year strength ratio values not considered explicitly in OAT analyses

The maximum Mean NSI values across climate zones for all distress and design input combinations are ranked by maximum absolute sensitivity across distresses in Table 12.19. The Mean NSI values were computed from the 10,000 ANN RSM evaluations for each climate zone and distress combination (Table 12.14 and Table 12.17). The plus and minus signs are again retained for each individual sensitivity index to indicate whether distress increases (+) or decreases (-) with increasing input value. Usually—and especially for the highest sensitivity inputs—the plus/minus signs for each design input are consistent across all distresses.

The OAT local sensitivity category (Appendix B) for each design input is also indicated in Table 12.19. There is a good congruence between the ranking of inputs from the MVL RSMs and the categorization from the OAT analyses. Most of design inputs categorized as HS in the OAT analyses are the highest-ranked design inputs, most of the inputs categorized as VS in the OAT analyses appear high in the list, and most of the inputs categorized as S in the OAT analyses also appear lower portion of the rankings in Table 12.19.

Table 12.19. Ranking of New CRCP design inputs by maximum |Mean| NSI values (ANN RSMs).

Design Input	Maximum Mean NSI Values (ANN RSMs)					OAT Category ¹
	Punchout	Crack Width	Crack LTE	IRI	Maximum	
CRCP Thick	-14.39	-1.65	0.39	-2.94	-14.39	HS
PCC 28-Day MOR	-12.65	-11.05	0.64	-2.38	-12.65	HS
PCC 28-Day ST	3.35	12.19	-0.33	0.73	12.19	- ²
PCC W/C	2.84	6.80	-0.16	0.58	6.80	HS
Percent Steel	-6.46	-5.81	0.61	-1.21	-6.46	HS
PCC Unit Weight	-6.46	-4.84	0.16	-1.05	-6.46	HS
PCC 20-year MOR to 28-day MOR	-6.06	1.61	-0.14	-1.09	-6.06	- ²
Bar Diameter	2.91	6.04	-0.35	0.61	6.04	HS
PCC Cement Content	1.90	4.62	-0.18	0.41	4.62	HS
Base Slab Friction	-1.03	-4.38	0.09	-0.21	-4.38	HS
PCC 28-Day E	3.36	2.97	-0.15	0.61	3.36	HS
Steel Depth	1.73	2.42	-0.16	0.47	2.42	HS
AADTT Per Lane	2.29	0.09	-0.10	0.44	2.29	HS
Base Mr	-2.02	-0.69	0.02	-0.37	-2.02	VS
PCC CTE	1.73	0.94	-0.01	0.32	1.73	VS
Shoulder LTE	-1.04	0.30	0.11	-0.20	-1.04	S
Subgrade Mr	-0.99	-0.81	0.01	-0.57	-0.99	VS
PCC 20-year ST to 28-day ST	0.21	-0.96	0.02	-0.05	-0.96	- ²
SSA	0.90	-0.65	0.04	0.14	0.90	HS
Base Thick	-0.38	0.67	-0.02	-0.12	0.67	S
PCC Poisson Ratio	0.42	-0.40	0.00	0.08	0.42	S
Construction Month	0.21	0.36	-0.02	0.06	0.36	S
GWD	0.04	-0.16	0.01	-0.01	-0.16	S

¹HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Non-Sensitive

² 28-day split tensile strength and 20-year strength ratio values not considered explicitly in OAT analyses

As a more severe measure of sensitivity, the mean plus/minus two standard deviation ($\mu \pm 2\sigma$) NSI values were computed using the statistics in Table 12.14 through Table 12.17 based on the 10,000 ANN RSM evaluations for each climate zone and distress combination. These sensitivity limits are

ranked by maximum absolute value across distresses in Table 12.20. The plus and minus signs are again retained for each individual sensitivity index to indicate whether distress increases (+) or decreases (-) with increasing input value. Usually—and especially for the highest sensitivity inputs—the plus/minus signs for each design input are consistent across all distresses.

There is very good agreement between the input rankings in Table 12.20 and those in based on the mean NSI values in Table 12.19. The OAT local sensitivity category (Appendix B) for each design input is also indicated in Table 12.20. Not only is there is a full congruence between the ranking of inputs from the ANN RSMs and the categorization from the OAT analyses, but the ranges of $\mu \pm 2\sigma$ in Table 12.20 also line up closely with the ranges of normalized sensitivity index values used to define the OAT categories. These sensitivity categories are highlighted by the fonts in Table 8.28: **Bold** = Hypersensitive (HS), $\mu \pm 2\sigma > 5$; **Bold Italic** = Very Sensitive (VS), $1 < \mu \pm 2\sigma < 5$; *Italic* = Sensitive (S), $0.1 < \mu \pm 2\sigma < 1$; and Regular = Non-Sensitive (NS), $\mu \pm 2\sigma < 0.1$. The rankings and $\mu \pm 2\sigma$ values in Table 12.20 are judged to be the best measures of the design input sensitivities in the MEPDG.

Table 12.20. Ranking of New CRCP design inputs by maximum $|\mu \pm 2\sigma|$ NSI values (ANN RSMs).

Design Input	Maximum Mean NSI Values (ANN RSMs)					OAT Category ¹
	Punchout	Crack Width	Crack LTE	IRI	Overall	
PCC 28-Day ST	11.13	61.48	-1.33	2.37	61.48	- ²
PCC 28-Day MOR	-40.29	-47.80	2.35	-7.37	-47.80	HS
CRCP Thick	-44.43	-10.47	1.57	-8.94	-44.43	HS
PCC W/C	8.42	36.09	-0.82	1.88	36.09	HS
PCC Unit Weight	-17.22	-35.27	0.53	-3.22	-35.27	HS
Bar Diameter	11.41	23.29	-1.49	1.93	23.29	HS
Base Slab Friction	-4.17	-21.62	0.35	-0.78	-21.62	HS
PCC Cement Content	7.56	21.55	-0.65	1.38	21.55	HS
PCC 20-year MOR to 28-day MOR	-18.81	7.88	-0.50	-3.48	-18.81	- ²
Percent Steel	-15.41	-18.00	1.04	-2.99	-18.00	HS
PCC 28-Day E	10.90	15.97	-0.61	2.13	15.97	HS
Steel Depth	6.43	13.39	-0.61	1.51	13.39	HS
AADTT Per Lane	8.47	1.03	-0.42	1.61	8.47	HS
Base Mr	-6.39	-4.71	0.10	-1.16	-6.39	VS
PCC CTE	6.19	5.54	-0.06	1.19	6.19	VS
PCC 20-year ST to 28-day ST	1.62	-5.81	0.14	-0.29	-5.81	- ²
SSA	3.32	-5.44	0.20	0.74	-5.44	HS
Base Thick	-1.79	4.71	-0.10	-0.42	4.71	S
Subgrade Mr	-3.23	-4.64	0.06	-1.17	-4.64	VS
Shoulder LTE	-3.26	2.16	0.30	-0.59	-3.26	S
PCC Poisson Ratio	1.79	-2.44	0.04	0.34	-2.44	S
Construction Month	1.62	2.33	-0.08	0.25	2.33	S
GWD	0.43	-1.19	0.03	-0.09	-1.19	S

¹HS=Hypersensitive; VS=Very Sensitive; S=Sensitive; NS=Non-Sensitive

² 28-day split tensile strength and 20-year strength ratio values not considered explicitly in OAT analyses

Figure 12.13 through Figure 12.16 provide graphical summaries of the input sensitivities by distress. These figures highlight the difference in sensitivities between Hypersensitive and Very Sensitive and between Very Sensitive and Sensitive. All of the figures have the same horizontal axis range so that the differences in sensitivities across distresses can be more clearly evaluated. The solid bars in the figures indicate the mean NSI values, and the error bars correspond to one standard deviation. The sensitivities are also broken down by climate zone for each design input. No systematic or substantial effect of climate zone on the design input sensitivity statistics is observed. However, the sensitivity indices are systematically and substantially higher for the punchout (Figure 12.13) and crack width (Figure 12.14) distresses than for crack LTE (Figure 12.15) and IRI (Figure 12.16).

Figure 12.13. Ranking of New CRCP design inputs by $|\mu \pm 2\sigma|$ NSI values: punchouts.

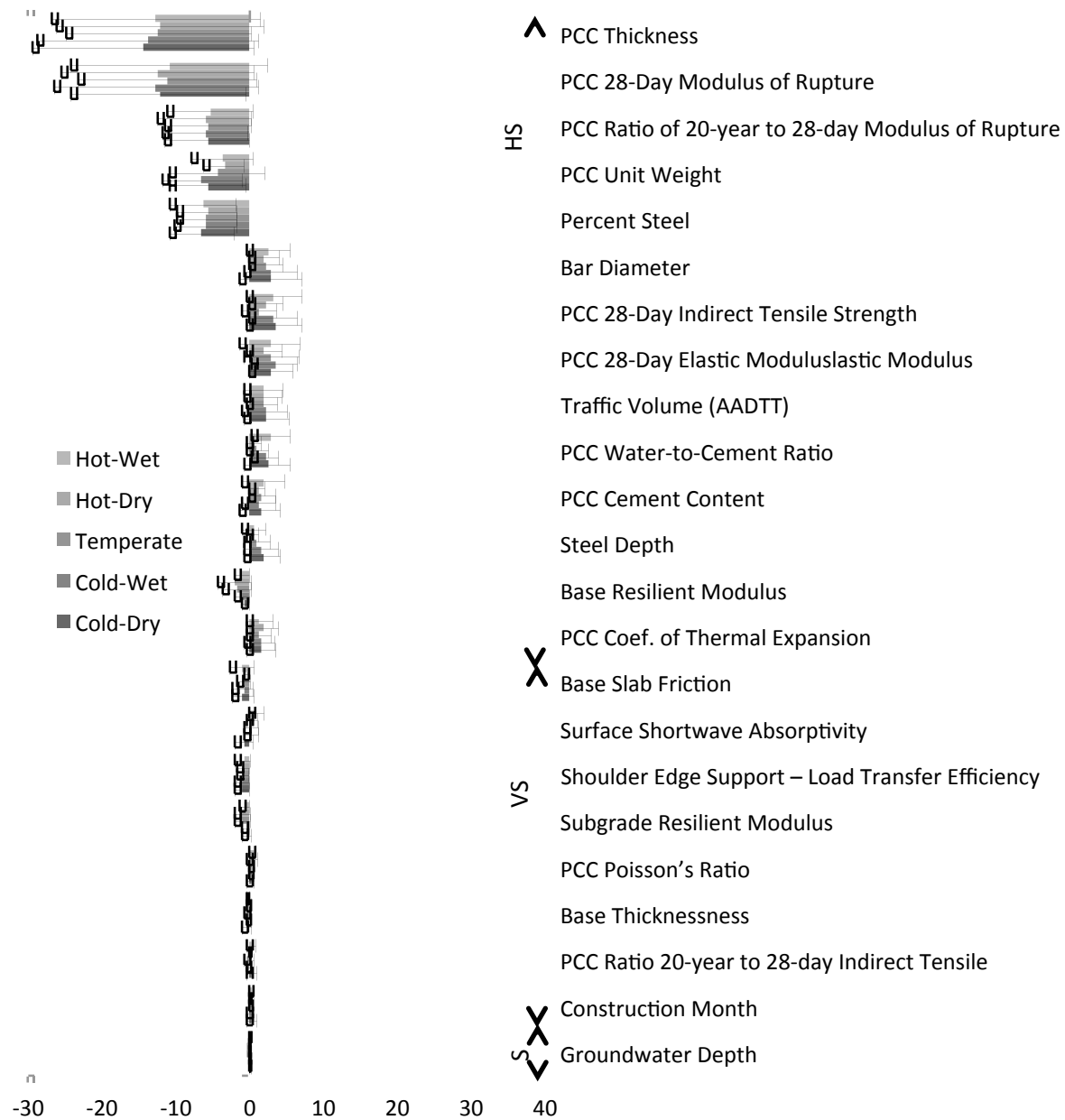


Figure 12.14. Ranking of New CRCP design inputs by $|\mu \pm 2\sigma|$ NSI values: crack width.



Figure 12.15. Ranking of New CRCP design inputs by $|\mu \pm 2\sigma|$ NSI values: crack LTE.

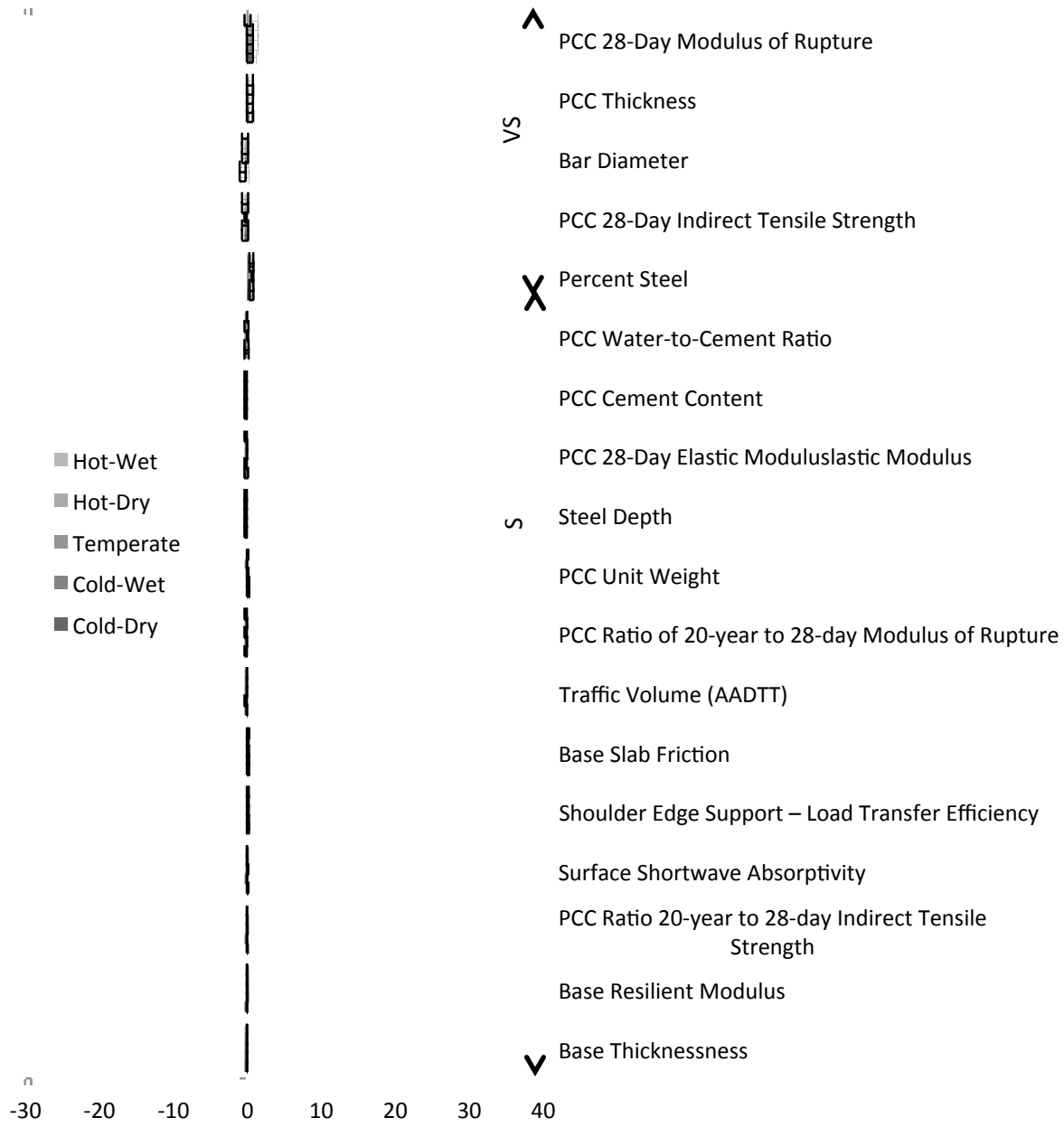
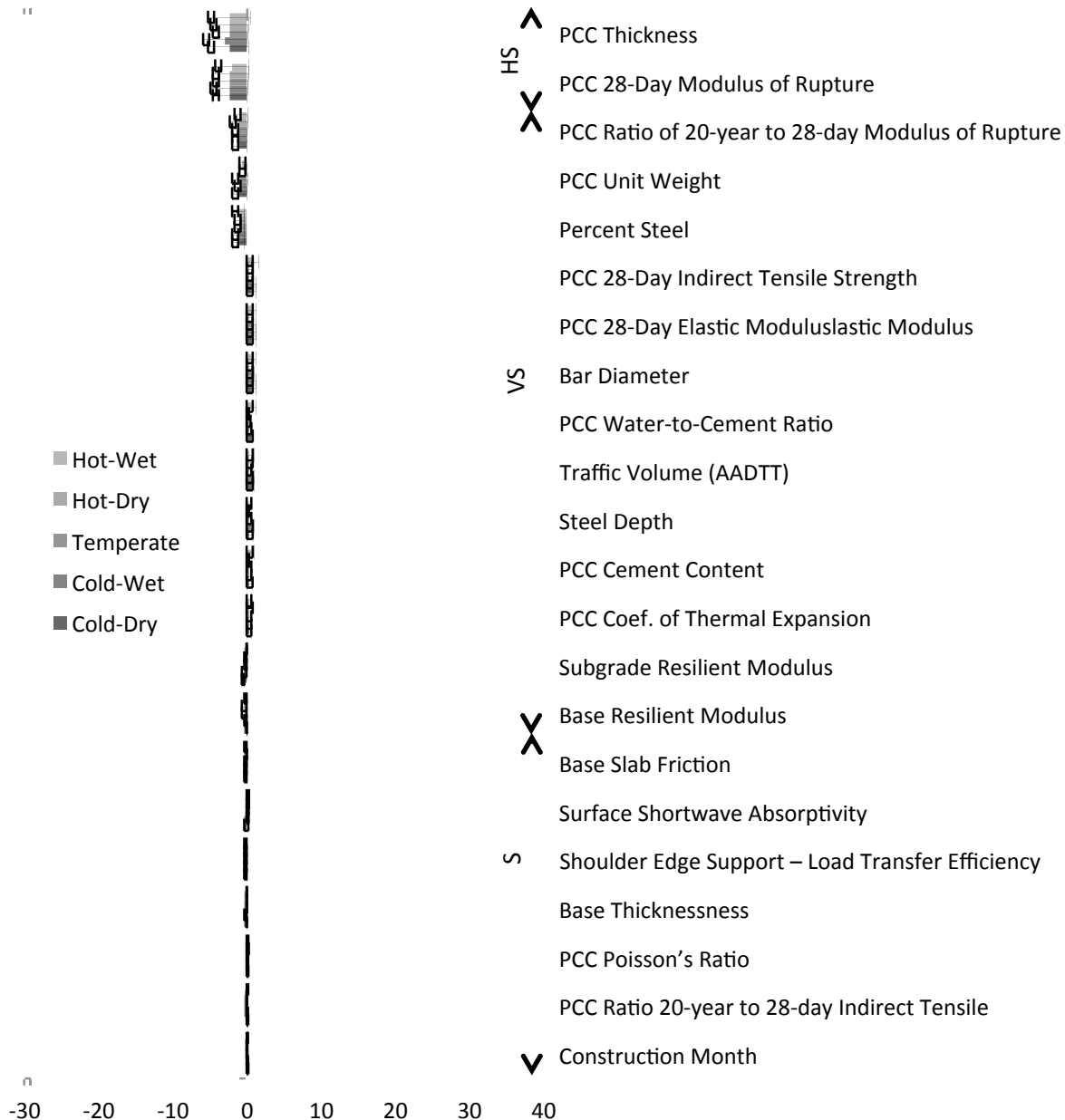


Figure 12.16. Ranking of New CRCP design inputs by $|\mu \pm 2\sigma|$ NSI values: IRI.



As a more practical aid to the pavement designer, Table 12.21 summarizes in rank order the Hypersensitive, Very Sensitive, and Sensitive design inputs by material category (PCC/steel, base, subgrade, other) for each distress. The design inputs that fall in the Hypersensitive or Very Sensitive categories for most (3 out of 4) distresses are indicated by bold font in the table. On average, the sensitivity indices for the New CRCP pavements were substantially higher than for any of the other pavement type scenarios, with most of this attributable to the sensitivities of the punchout and crack width distresses for New CRCP. As a consequence, nearly all of the PCC/steel properties are

consistently in the Hypersensitive or Very Sensitive categories, as are the base resilient modulus, subgrade resilient modulus, the bar diameter and steel depth, and traffic volume.

Table 12.21. Hypersensitive, Very Sensitive, and Sensitive design inputs by distress and input category for New CRCP pavements. $NSI_{\mu \pm 2\sigma}$ values are given in parentheses. Inputs in bold font are Hypersensitive or Very Sensitive for most (3 out of 4) distresses.

<i>Distress</i>	<i>Input Category</i>	<i>Hypersensitive (>5)</i>	<i>Very Sensitive (1-5)</i>	<i>Sensitive (0.1-1)</i>
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)	
Crack LTE	PCC/Steel Properties		28-Day Modulus of Rupture (+2.4) Thickness (+1.6) 28-Day Indirect Tensile Strength (-1.3) Percent Steel (+1.0)	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)

<i>Distress</i>	<i>Input Category</i>	<i>Hypersensitive (>5)</i>	<i>Very Sensitive (1-5)</i>	<i>Sensitive (0.1-1)</i>
Crack LTE	Base Properties			Base Slab Friction (+0.4) Resilient Modulus (+0.1) Thickness (-0.1)
	Subgrade Properties			
	Other Properties		Bar Diameter (-1.5)	Steel Depth (-0.6) Traffic Volume (-0.4) Edge Support LTE (+0.3)
IRI	PCC/Steel Properties	Thickness (-9.0) 28-Day Modulus of Rupture (-7.4)	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)	Surface Shortwave Absorptivity (+0.7) Poisson's Ratio (+0.3) 20-year to 28-day Indirect Tensile Strength (-0.3)
	Base Properties		Resilient Modulus (-1.2)	Base Slab Friction (-0.8) Thickness (-0.4)
	Subgrade Properties		Resilient Modulus (-1.2)	
	Other Properties		Bar Diameter (+1.9) Traffic Volume (+1.6) Steel Depth (+1.5)	Edge Support LTE (-0.6) Construction Month (+0.3)

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