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Mechanistic-Empirical Pavement Design Guide Implementation Plan

Study SD2005-01

Final Report

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October 2007

DISCLAIMER

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16. Abstract

In recent years, the AASHTO Joint Task Force on Pavements, in conjunction with the National Cooperative Highway Research Program (NCHRP), has been working on the development of a Mechanistic-Empirical Pavement Design Guide (MEPDG). As AASHTO is expected to eventually adopt the MEPDG at its primary pavement design method, it is critical that the SDDOT become familiar with the MEPDG documentation and associated design software. The research conducted under this project was a first step toward achieving this goal.

The research effort began with a sensitivity analysis of selected inputs associated with five typical SDDOT pavement designs. These included three new construction designs (*rural jointed plain concrete pavement [JPCP]*; *rural asphalt concrete [AC]*, and *continuously reinforced concrete pavement [CRCP] interstate*) and two rehabilitation designs (*AC overlay over existing rural AC* and *AC overlay over rubblized rural JPCP*). Over 600 runs of the MEPDG software (version 0.9) were conducted to determine how changing selected MEPDG inputs impacted pavement performance (i.e., distress and International Roughness Index [IRI]). Next, the research team ranked the investigated inputs in order of their significance to the prediction of pavement performance for each design, and identified SDDOT "target" MEPDG input levels. Finally, the research team estimated the resources needed for the SDDOT to collect the data that is needed to support the MEPDG at the target input levels. Also as part of this research, a stand alone MEPDG implementation plan was developed to outline other MEPDG-related activities that are deemed necessary over the next few years in order for the SDDOT to continue gaining valuable experience with the new MEPDG approach.

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LIST OF INPUT VARIABLE ABBREVIATIONS

%STEEL	Percent steel, %
AADTT	Initial two-way average annual daily truck traffic
ACBIND	Asphalt concrete (AC) binder grade
ACCRIP	AC creep compliance
ACGRAD	AC mix gradation information (percent retained on sieves)
ACOLBIND	AC overlay binder grade
ACOLCRIP	AC overlay creep compliance
ACOLGRAD	AC overlay gradation information (percent retained on sieves)
ACRUT	Total AC layer rutting predicted by the model
AGG	Aggregate type
ALLIGCRACK	Total AC alligator cracking (bottom-up) predicted by the model
BARD	Steel bar diameter, in.
BSFRIC	Base/slab friction coefficient
CC	Cementitious material content
CLIMATE	Climatic characteristics (location)
COTE	Coefficient of thermal expansion
CRACK	Total PCC transverse cracking predicted by the model
CRACKLTE	Minimum crack load transfer efficiency, %
CTC	Coefficient of thermal contraction
DWT	Depth of water table
EB	Base resilient modulus
EPCC	Elastic resilient modulus of the fractured slab, psi
ES	Subgrade resilient modulus
FAULT	Average PCC faulting predicted by the model
HAC	Asphalt layer thickness
HACOL	AC overlay thickness, in.
HBASE	Base layer thickness
HMILL	Milled thickness, in. (thickness of milling)
HPCC	PCC slab thickness
LONGCRACK	Total AC longitudinal cracking (top-down) predicted by the model
MR	PCC 28-day modulus of rupture
PIBASE	Base plasticity index

LIST OF INPUT VARIABLE ABBREVIATIONS (continued)

PR	Pavement rating
REFCRACK	Total AC reflective cracking predicted by the model
SG	Subgrade type
SHOULD	Shoulder type
STDEPTH	Steel depth, in.
TGR	Traffic growth rate, %
THD	Truck hourly distribution factors
TOTRUT	Total AC rutting predicted by the model
TOTRUTEXIST	Total rutting in the existing AC layer, in.
TPRESS	Tire pressure, psi
VCD	Vehicle class distribution factors
ZST	PCC zero-stress temperature

1.0 EXECUTIVE SUMMARY

Introduction

The South Dakota Department of Transportation (SDDOT) currently designs its highway pavements in accordance with the 1993 American Association of State Highway and Transportation Officials (AASHTO) *Guide for Design of Pavement Structures*, which along with its predecessors is considered the standard design procedure among virtually all state highway agencies (SHAs), as well as in several other countries. This design approach is based on empirical relationships derived from the *AASHO Road Test* conducted from 1958 to 1960. As such, the relationships are truly representative only of the design conditions present at the Road Test in Ottawa, Illinois. Since that time, changes in cross sectional design, advances in material science, vehicular design changes, and increased volume and weight distribution of traffic have all served to make this empirical data archaic. Because of these limitations, the majority of pavement designs conducted using the 1993 design guide are outside the inference space of the original data.

Since 1996, the AASHTO Joint Task Force on Pavements, in conjunction with the National Cooperative Highway Research Program (NCHRP), has been working on the development of a mechanistic-empirical pavement design guide (MEPDG) to address these limitations. Under this new MEPDG approach, the principles of engineering mechanics are used to compute the internal material behaviors in a pavement structure (i.e., deflections, stresses, and strains) as it is subjected to predicted future traffic loadings and environmental conditions (e.g., moisture and temperature). Those predicted material behaviors are then related to accumulated pavement damage through developed "transfer" functions, and then correlated with actual performance (distress) data. For the initial development of the MEPDG models, the data was calibrated with pavement-performance data from the Federal Highway Administration's (FHWA's) Long-Term Pavement Performance (LTPP) program.

The new MEPDG requires an extensive number of inputs, although there is some flexibility in the level of precision that is used for the required traffic, materials, and environmental variables. Level 1 data offer the highest reliability, but require site-specific data such as laboratory testing on soils or construction materials. Level 2 data provide intermediate accuracy, but require less site-specific testing. At Level 2, inputs may be selected based on previous tests that have been conducted on similar types of materials or other forms of agency experience. At Level 3, agencies select default values that represent typical averages for the geographic region where the design project is located. For a given paving project, all inputs do not have to be at the same input level. That is, an agency may choose input levels depending on the availability of different types of data and the resources available to support the data-collection efforts.

Because AASHTO is expected to adopt the newly developed MEPDG in the near future, it is critical that the SDDOT become familiar with the MEPDG documentation and software to ready those involved for its implementation. This research effort investigated the types of inputs required by the MEPDG for typical SDDOT designs, and identified those inputs that are most significant to the prediction of pavement performance for each design. Based on the findings, the research team developed recommendations for input levels and assessed the resources needed to provide the necessary data. The research also resulted in the development of an implementation plan that can serve as a “road map” to help lay the groundwork for implementing the MEPDG.

Sensitivity Analysis

To determine the sensitivity of the most critical MEPDG inputs for South Dakota conditions, the research team conducted a sensitivity analysis of the inputs associated with five typical SDDOT pavement designs. Over 600 runs of the MEPDG software were conducted to determine what impact changing various MEPDG inputs had on pavement performance (i.e., distress and International Roughness Index [IRI] predictions).

Five design types were defined for the sensitivity study, and reasonable ranges of data inputs (reflecting South Dakota conditions and practices) for each design type were defined to determine the impact of changes in these inputs on predicted pavement performance. With input from the Technical Panel, ten different combinations of pavement design type, expected traffic conditions, and project location (as shown in table 1-1) were identified for investigation within the sensitivity analysis.

Standard pavement designs for each of the five chosen design types were selected to reflect the most typical variable inputs used in South Dakota. The expected performance associated with each “standard” design was then predicted using version 0.9 of the MEPDG software and used as the baseline performance values for the different standard designs.

Table 1-1. Initial combinations of design type, traffic-, and climate-related variables that define individual scenarios for use in the sensitivity analyses.

Scenario	Design Type	Traffic	Climate (Location)
1	New design—Rural jointed plain concrete pavement (JPCP)	Rural	Brookings
2			Winner
3	New design—Rural asphalt concrete (AC)	Rural	Brookings
4			Winner
5	New design—Continuously reinforced concrete pavement (CRCP) interstate	Interstate	Brookings
6			Winner
7	Rehabilitation—AC overlay (ACOL) over rubblized rural JPCP	Rural	Brookings
8			Winner
9	Rehabilitation—ACOL over existing rural AC	Rural	Brookings
10			Winner

Each selected MEPDG input was investigated at two or three input values. Using these two or three input levels, the sensitivity analysis was conducted and performance measures over time (e.g., total rutting, IRI, cracking, and so on) were obtained as outputs from the MEPDG software. After conducting over 600 MEPDG software runs, the predicted performance versus pavement age data were extracted from the MEPDG output and used to determine the relative effect of each variable on performance. An example showing a plot of the extracted performance data for the transverse cracking model for new JPCP design is presented in figure 1-1. For this example, the performance values associated with three different levels of annual average daily truck traffic (AADTT)—50, 250, and 450 trucks daily—at the Brookings location are illustrated. Note that the performance values (in terms of percent of slabs cracked) at the JPCP pavement's design life (40 years) are noted on the chart for each AADTT level (i.e., 77.4 percent for AADTT = 450, 50.5 percent for AADTT = 250, and 3.9 percent for AADTT = 50).

After extracting the performance data from the MEPDG output files, the results associated with each investigated input were plotted together on summary charts for each performance indicator. Building on the example data illustrated in figure 1-1, figure 1-2 contains an example of a summary chart that shows the relative effects of the investigated variables on the JPCP cracking model. Note: For a complete description of the variable abbreviations used in figure 1-2, see the *List of Input Variable Abbreviations* on page *x* in the front matter of this report.

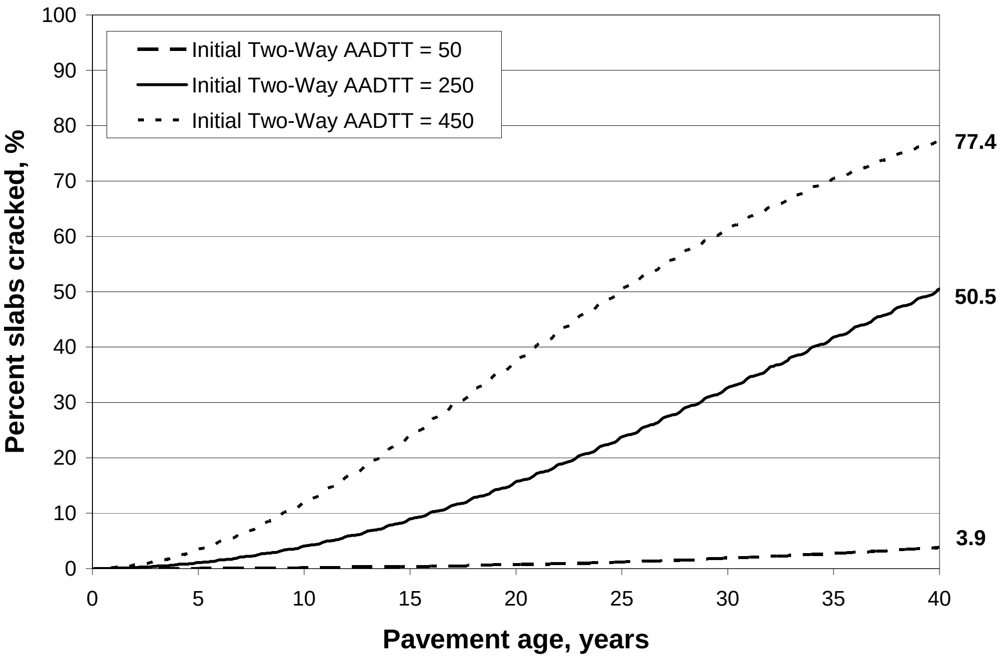

Figure 1-1. Example performance trend plot showing effect of AADTT on predicted JPCP cracking (location = Brookings).

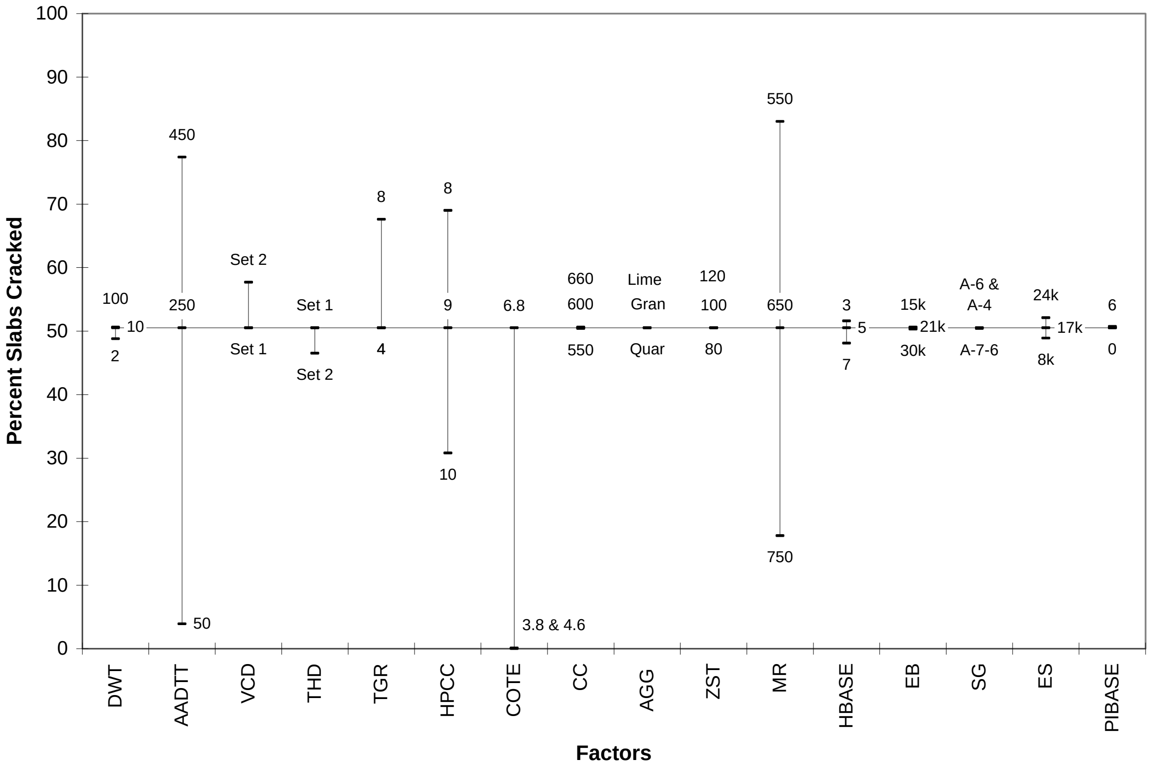

Figure 1-2. Example summary chart of relative effects for the transverse cracking model for new JPCP design (Location = Brookings).

For the summary charts, all of the investigated variables (associated with the particular performance-indicator model) are plotted on the x-axis. The performance-indicator values are plotted along the y-axis. The horizontal line on the chart indicates the expected performance of the "standard" pavement section. That is, the performance value at the pavement's design life when all MEPDG inputs are set to their "standard" values. For the example shown in figure 1-2, the horizontal line at 50.5 percent slabs cracked indicates that the 40-year (design life) cracking associated with the "standard" JPCP pavement section (i.e., an analysis where all of the inputs were set to their "standard" values) was 50.5 percent slabs cracked. This is an important reference point as the performance of the "standard" pavement section is used as the baseline to which all other individual results are compared.

The results of the individual MEPDG software runs are used to build the vertical lines plotted for each investigated input variable. For example, note that the three 40-year (design life) AADTT-related performance values displayed on figure 1-1 (i.e., 77.4 percent for AADTT = 450, 50.5 percent for AADTT = 250, and 3.9 percent for AADTT = 50) are plotted in figure 1-2 for the "AADTT" variable. The length of each vertical line provides a visual indication of the magnitude of the within-sample variation associated with each input variable. Therefore, a simple conclusion from the visual interpretation of these plots is that the inputs with longer vertical lines have a larger impact on the prediction of the distress than those inputs with shorter vertical lines (i.e., longer lines indicate more significance in the prediction of the distress). For example in figure 1-2, based on the relative difference in the length of vertical lines, one would conclude that AADTT has much more of a significant effect on the occurrence of cracking in JPCP than subgrade type (SG). The complete results of the sensitivity analysis are presented separately for each pavement type in Appendix C to this report.

Recommended Input Levels

The statistical results of the sensitivity analysis were used to rank the investigated inputs (within each pavement type) in order of most significant to least significant. Finally, these input rankings were used to develop recommendations that specify the appropriate MEPDG input level (i.e., Level 1, Level 2, or Level 3) for the inputs that were included in the sensitivity analysis. For example, a Level 1 or Level 2 MEPDG input procedure (sampling and testing procedure) was determined to be the most appropriate input level for those variables classified as "highly significant" or "moderately significant," while Level 3 inputs were found to be acceptable for most of the inputs classified as “mildly significant” or “not significant.” These most-appropriate input levels associated with each MEPDG input were classified as “target” MEPDG levels in the task results.

The recommended input levels were then used to 1) determine what MEPDG input levels represent the current SDDOT practice, 2) illustrate where there are differences between the “target” MEPDG input levels and the current SDDOT practices, and 3) document the sampling and testing protocol changes that would need to be made to achieve the target MEPDG input levels. The results of this analysis are presented in tables 1-2 through 1-4, which summarize the recommended data-collection protocols required to implement the MEPDG at the target input levels by input type category. These tables reflect only the instances in which current procedures were not found to match the requirements for the recommended input level. Where these differences exist, it requires either 1) the need to change to a new sampling and testing method for the input, or 2) the need to conduct more sampling or testing using the same current SDDOT sampling and testing method. Specifically, tables 1-2 through 1-4 include the following types of information:

- Data availability for target input levels—Is the data required for the target MEPDG input level currently collected by SDDOT or available in existing SDDOT or other databases?
- Data-collection changes—If the data required for the target input level is not available, what procedural changes need to be made to obtain the needed data at the target input?
- Target level data source—Where does one go to obtain the needed data to meet the target input level needs? For inputs where this data is currently available, this may be the name of a particular SDDOT database. For inputs where this data is not currently available, guidance on how this data would be collected in the future is provided.
- Data-collection frequency—The final type of information in the tables describes how often it is expected that a pavement designer would have to determine new values for the given input. For example, some inputs would be project specific, and therefore, new values for the input would need to be determined for each project. For other inputs, it may be acceptable to revisit the values on an annual basis and determine representative values that can be used for all of the projects designed in the next year.

Table 1-2. Summary of data-collection requirements to meet target input levels for general variables used in all designs.

Input Parameter	Pavement Type	Level			Data Availability for Target Level	Data-Collection Changes	Target Level Details	
		3	2	1			Data Source	Data-Collection Frequency
TRAFFIC-RELATED VARIABLES								
Annual average daily truck traffic	All		⦿		Available	None. Current data-collection procedures are acceptable.	Traffic Data Management System (TDMS)	Continuously for automatic traffic recorders (ATR); Annually for short-term volume counts.
Traffic growth rate	All		⦿		Available	None. Current data-collection procedures are applicable.	Traffic Data Management System (TDMS)	Project specific. Determined from analysis of traffic data.
Vehicle class distribution factors	All		⦿		Available	None. Current data-collection procedures are applicable.	Traffic Data Management System (TDMS)	Continuously for automatic traffic recorders (ATR); Annually for short-term volume counts.
Truck hourly distribution factors	All		⦿		Available	None. Current data-collection procedures are applicable.	Traffic Data Management System (TDMS)	Project specific. Determined from analysis of traffic data.
CLIMATE-RELATED VARIABLES								
Climatic characteristics	All	N/A			Available	None	Weather data within the MEPDG software	No additional data collection required
Depth to water table	All	○			Available	This input is not currently measured, therefore Level 3 is assumed. At Level 3, average annual or seasonal values can be obtained from the State Geological Survey or an alternative data source.	State Geological Survey or alternate data source	Update database as necessary to correspond with latest State Geological Survey data
SUBGRADE-RELATED VARIABLES								
Subgrade resilient modulus (Mr)	All		⦿		Available	None. Determine subgrade Mr values indirectly using correlations to another material-related characteristic (i.e., California bearing ratio [CBR], R-value, layer coefficient, dynamic cone penetrometer [DCP], or plasticity index [PI] and gradation).	Determine from project-specific field testing (e.g., CBR)	Project specific. Determine during preliminary site investigation steps.
Subgrade type	All	N/A			Available	None. Classify material using AASHTO (AASHTO M 145) or unified soil classification (ASTM D2487) definitions.	County soil reports or field testing results	No additional data collection required
BASE-RELATED VARIABLES								
Base layer thickness	All	N/A			Design Input	None.	Design standards or Pavement Design Engineer	No required data collection
Base resilient modulus	All		⦿		Available	None. Determine base Mr values indirectly using correlations to another material-related characteristic (i.e., CBR, R-value, layer coefficient, DCP, or PI and gradation).	Materials Sampling and Testing (MST) or new database from laboratory or field acceptance data	Annual analysis of the available acceptance testing results from past projects.
Base plasticity index	All	N/A			Available	Hierarchical levels are not appropriate for this input. Laboratory testing used to determine PI, liquid limit (LL), and plastic limit (PL) (AASHTO T90 and T89).	Typical values determined from past experience or laboratory testing (if necessary)	As needed. Typical or estimated values can be used.

For the "Level" columns, the symbols are defined as the following: ○ = Target input level; • = Current SDDOT input level; N/A = Not applicable.

Table 1-3. Summary of data-collection requirements to meet target input levels for JPCP- and CRCP-related variables.

Input Parameter	Pavement Type	Level			Data Availability for Target Level	Data Collection Changes	Target Level Details	
		3	2	1			Data Source	Data Collection Frequency
JPCP- AND CRCP-RELATED VARIABLES								
Portland cement concrete (PCC) slab thickness	JPCP and CRCP	N/A			Design Input	None.	Design standards or Pavement Design Engineer	No required data collection
PCC strength	JPCP and CRCP	●	○		Additional Testing Required	The Level 3 approach only requires a 28-day strength. Moving to Level 2 requires that modulus of rupture (MR) values be determined indirectly from compressive strength (f'c) tests at 7, 14, 28, and 90 days (ASTM C 39). While this move will require more testing, no new testing equipment is required.	Laboratory testing	Annual laboratory testing of typical mixes. Additional testing is recommended when the current mix is deemed significantly different from a "typical" mix.
PCC coefficient of thermal expansion	JPCP and CRCP	●		○	New Testing Method	Because SDDOT does not currently measure this variable, analyses must currently be completed using Level 3 (default value) inputs. Moving to the recommended Level 1 procedure requires that this input be measured directly from laboratory testing (AASHTO TP 60).	Laboratory testing	Additional testing is recommended when the current mix is deemed significantly different from a "typical" mix. Tests should be conducted to reflect three main aggregates in South Dakota.
PCC zero-stress temperature	JPCP and CRCP	N/A			Computed Value	None. This variable is computed by the software as a function of cement content and mean monthly ambient temperature during construction.	Value will be computed by software	No required data collection
Cementitious material content	JPCP and CRCP	N/A			Design Input	None. Chosen material-related input.	Design standards or Pavement Design Engineer	No required data collection
PCC aggregate type	JPCP and CRCP	N/A			Design Input	None. Chosen material-related input.	Pavement Design Engineer	No required data collection
Percent Steel, %	CRCP	N/A			Design Input	None. Design input.	Design standards or Pavement Design Engineer	No required data collection
Base/slab friction coefficient	CRCP	N/A			Design Input	None. This value is selected from default base-specific values in software.	Pavement Design Engineer	No required data collection
Bar diameter	CRCP	N/A			Design Input	None. Design input.	Design standards or Pavement Design Engineer	No required data collection
Steel depth	CRCP	N/A			Design Input	None. Design input.	Design standards or Pavement Design Engineer	No required data collection
Shoulder type	CRCP	N/A			Design Input	None. Design input.	Design standards or Pavement Design Engineer	No required data collection

For the "Level" columns, the symbols are defined as the following: ○ = Target input level; ● = Current SDDOT input level; N/A = Not applicable.

Table 1-4. Summary of data-collection requirements to meet target input levels for pavement types with AC surfaces.

Input Parameter	**Pavement Type**	**Level**			**Data Availability for Target Level**	**Data Collection Changes**	**Target Level Details**	
		3	**2**	**1**			**Data Source**	**Data Collection Frequency**
AC SURFACE-RELATED VARIABLES								
New AC layer thickness (new AC) or ACOL thickness (rehabilitation)	New AC, AC/AC, AC/JPCP	N/A			Design Input	None. Design input.	Pavement Design Engineer	No required data collection
New AC or ACOL binder properties	New AC, AC/AC, AC/JPCP	•	○		New Testing Method	The Level 3 method for this variable uses a Superpave binder grading, conventional viscosity grade, or conventional penetration grade to estimate a temperature-viscosity relationship for the binder. For Levels 1 and 2, laboratory testing is required to determine binder properties directly. Because SDDOT is not currently conducting binder property testing, this represents a significant change in current SDDOT practice.	Laboratory testing	Annual laboratory testing of typical mixes. Additional testing is recommended when the current mix is deemed significantly different from a "typical" mix.
Tire pressure	New AC, AC/AC, AC/JPCP	N/A			Assumed Value	None. Assumed value.	Fix to assumed value of 120 psi	No required data collection
New AC or ACOL mix properties	New AC, AC/AC, AC/JPCP	•		○	New Testing Method	For Levels 2 and 3 (same method) aggregate gradation information is used to estimate the dynamic modulus (E*) of the mix. For Level 1, actual E* testing data is required. Because this variable was found to be one of the more significant variables for AC-surfaced pavements, moving toward Level 1 is an appropriate target. Because SDDOT is not currently conducting binder property testing, this represents a significant change in current practice.	Laboratory testing	Annual laboratory testing of typical mixes. Additional testing is recommended when the current mix is deemed significantly different from a "typical" mix.
AC creep compliance	New AC, AC/AC, AC/JPCP	○			Available	At this time, it is recommended that typical creep compliance values in the MEPDG software *Help* be used. These values are specific to a given binder type.	Default values in MEPDG software *Help*	No required data collection
AC coefficient of thermal contraction	New AC, AC/AC, AC/JPCP	N/A			Computed Value	Because there are no AASHTO or ASTM standard tests for this variable, it is recommended that it be computed by the software as a function of HMA volumetric properties and the thermal contraction coefficient for the aggregate.	Value will be computed by software	No required data collection
Elastic resilient modulus of the fractured slab	AC/JPCP	⦿			Available	Because the Level 3 approach requires typical values based on past SDDOT testing data or experience, or representative values from other documented studies, no data-collection changes are required for this variable.	Typical value selected by the Pavement Design Engineer	No required data collection
Existing fractured JPCP thickness	AC/JPCP	N/A			New Testing Required	Cores are recommended during the design process to more accurately determine PCC thickness.	Determine from project-specific field testing	Project specific. Determine during preliminary site investigation steps.

For the "Level" columns, the symbols are defined as the following: ○ = Target input level; • = Current SDDOT input level; N/A = Not applicable.

Table 1-4. Summary of data-collection requirements to meet target input levels for pavement types with AC surfaces (continued).

Input Parameter	Pavement Type	Level			Data Availability for Target Level	Data Collection Changes	Target Level Details	
		3	2	1			Data Source	Data Collection Frequency
AC SURFACE-RELATED VARIABLES (continued)								
Existing Condition (Rehabilitation Level) for AC/JPCP	AC/JPCP	○	●		Design Input	The software interface for this input is confusing in that it is under the heading of “Flexible Rehabilitation.” Also, some of the inputs for Levels 1 and 2 ask for flexible pavement-related condition information such as “total rutting” and “milled thickness.” Because of this confusion, the data-collection effort to support this design input is actually simplified to providing a Level 3 subjective pavement rating.	Determine from a project-specific field assessment	Project specific. Determine during preliminary site investigation steps.
Existing Condition (Rehabilitation Level) for AC/AC	AC/AC		○	●	Design Input	The Level 2 approach for this input requires the user to enter estimated rut data for each layer and percent fatigue cracking data for the existing HMA surface. Currently, the software does not support the entering of Level 1 falling weight deflectometer (FWD) data. Because of this deficiency, the data-collection effort to support this input is simplified by limiting the process to using Level 2 procedures.	Determine from a project-specific field assessment	Project specific. Determine during preliminary site investigation steps.
Existing AC binder properties	AC/AC	○	●		New Testing Method	To adequately determine values for this input, binder-related testing needs to be conducted on materials extracted (cores) from the existing AC pavement. The Level 3 method for assessing the materials requires a Superpave binder grading, conventional viscosity grade, or conventional penetration grade to estimate a temperature-viscosity relationship for the binder. Because SDDOT is not currently conducting binder property testing, this represents a significant change in current SDDOT practice.	Determine from a project-specific field and laboratory assessment	Project specific. Determine during preliminary site investigation steps.
Existing AC mix properties	AC/AC	○	●		New Testing Method	The Level 3 procedure for this input requires gradation information of the mix (i.e., percent retained on 3/4”, 3/8”, and #4 sieves, and the percent passing #200). Ideally, laboratory testing will be conducted on materials extracted (cores) from the existing AC pavement to determine the required characteristics. This represents additional testing for rehabilitation projects. Note that the level for this input will need to be revisited when Level 1 and 2 methods become better established in the software.	Determine from a project-specific field and laboratory assessment	Project specific. Determine during preliminary site investigation steps.
Total rutting in existing AC layer	AC/AC	N/A			Not Applicable	None. This input is not required unless a Level 3 pavement evaluation is utilized. Because a Level 2 is recommended for “Rehabilitation Level,” this input is not required.	Not applicable	Not applicable
Milled thickness	AC/AC	N/A			Design Input	None. Value chosen based on existing condition.	Determine from a project-specific field assessment	Project specific. Determine during preliminary site investigation steps.

For the “Level” columns, the symbols are defined as the following: ○ = Target input level; ● = Current SDDOT input level; N/A = Not applicable.

Resource Requirements To Meet Recommended Input Levels

Where gaps exist between the current SDDOT data and data protocols and the target MEPDG input levels, the research team estimated the resources that are needed by the SDDOT to fully implement the MEPDG approach at the "target" input levels. First, the research team identified personnel requirements, additional testing that must be performed, equipment that must be obtained, databases that must be developed, and training that might be needed. The results are presented in tables 1-5 through 1-8. The combination of the information presented in these tables provides an estimate of the additional staffing, equipment, sampling and testing, and training needs associated with implementing the MEPDG in South Dakota.

Implementation Plan

One of the most important tasks of this project was the development of the MEPDG implementation plan. The MEPDG implementation plan is a stand-alone document that outlines the types of activities the SDDOT will need to complete over the next 3 years to ready itself for adopting and implementing the MEPDG as the primary pavement design tool in South Dakota. The basic implementation plan consists of twelve general steps, many of which will be completed concurrently. These twelve general implementation steps consist of the following:

1. Conduct sensitivity analysis of MEPDG inputs.
2. Recommend MEPDG input levels and required resources to obtain those inputs.
3. Obtain necessary testing equipment to implement the MEPDG at the target MEPDG input levels.
4. Review version 1.0 of the MEPDG software.
5. Form a SDDOT MEPDG Implementation Team and develop and implement a communication plan.
6. Conduct staff training.
7. Develop formal SDDOT-specific MEPDG-related documentation.
8. Develop and populate a central database (or databases) with required MEPDG input values.

Table 1-5. Summary of additional resources needed.

Input Parameter	Pavement Type	Additional Required Testing and Staffing Effort			Equipment and Training Needs		Notes
		Additional Testing	Additional Staff Hours	Information Technology Staff Time	New Equipment	Staff Training	
Depth to water table	All		○	○			Because depth of water table is currently not a design input used by SDDOT, some additional person hours may be required to obtain the necessary information from the State Geological Survey or an alternate data source. If these data are available electronically, some help may be needed by the information technology (IT) department to obtain or organize the data.
Base resilient modulus	All	○	○	○			Representative values for the typical SDDOT bases should be determined from laboratory or field testing results. Once typical values are established, additional testing is only required when the typical modulus values may have changed. If data are not currently available in the SDDOT Materials Sampling and Testing (MST) database, the IT department may need to establish a new database.
Base plasticity index	All	○	○	○			Representative values for the typical SDDOT bases should be determined from laboratory or field testing results. Once typical values are established, additional testing would only be required when the typical modulus values have changed. If data are not currently available in the SDDOT MST database, the IT department may need to establish a new database to store this information.
PCC strength	JPCP and CRCP	◑	◑				It is currently recommended that PCC strength be measured using Level 2 procedures (i.e., compressive strength tests measured at 7, 14, 28, and 90 days). Implementing such a procedure requires laboratory testing of design mixes prior to the construction of the project.
PCC coefficient of thermal expansion	JPCP and CRCP	● New Method	●		✓	✓	The MEPDG predictions are very sensitive to this variable. Because SDDOT is not currently measuring this variable, moving toward measuring COTE will require purchasing new testing equipment and training laboratory staff. Additional laboratory staffing hours will most likely be required to conduct the laboratory testing.
New AC or ACOL binder properties	New AC, AC/AC, AC/JPCP	● New Method	●				One significant testing change is using laboratory testing (Levels 1 and 2) to determine AC binder properties. For conventional binders, properties are determined by tests for viscosity, penetration, specific gravity, and softening point. For Superpave binders, properties are determined by measuring complex shear modulus (G*) and phase angle (δ) using different equipment. Regardless of the method, it is envisioned that the additional testing would require additional laboratory staffing hours.
New AC or ACOL mix properties	New AC, AC/AC, AC/JPCP	● New Method	●		✓	✓	Another significant testing change is using laboratory testing (Level 1) to determine AC mix properties. For Level 1, dynamic modulus (E*) testing is required. Similar to the new testing of AC binders, conducting E* testing most likely requires new equipment and additional testing, and additional staffing hours and training.

Notes:

- The level of additional required effort/testing is indicated in the table by the following symbols: ○ = Minimal, ◑ = Moderate, ● = Significant, ✓ = Required.
- This table includes all variables that have changes from current SDDOT practices.

Table 1-5. Summary of additional resources needed (continued).

Input Parameter	Pavement Type	Additional Required Testing and Staffing Effort			Equipment and Training Needs		Notes
		Additional Testing	**Additional Staff Hours**	**Information Technology Staff Time**	**New Equipment**	**Staff Training**	
AC creep compliance	New AC, AC/AC, AC/JPCP						While SDDOT is not currently measuring AC creep compliance data directly, the recommended Level 3 approach of using default values in the MEPDG software and Guide results in no additional needed resources at this time.
Existing fractured JPCP thickness	AC/JPCP	●		◑			If SDDOT is not currently determining this thickness as part of the design process, it is recommended that cores be taken to more accurately determine JPCP layer thickness as part of the new MEPDG design process.
Existing Condition (Rehabilitation Level) for AC/JPCP	AC/JPCP						For completeness, this variable is included in this table because the current SDDOT input Level is at Level 2 while a Level 3 input is recommended. As stated previously, the software interface for this input is confusing in that it is under the heading of “Flexible Rehabilitation.” Also, some of the inputs for Levels 1 and 2 ask for flexible pavement-related condition information such as “total rutting” and “milled thickness.” Because of this confusion a Level 3 subjective pavement rating is recommended. No additional resources are required to make this simplification.
Existing Condition (Rehabilitation Level) for AC/AC	AC/AC						For completeness, this variable is also included in this table because the current SDDOT input is at Level 1 while a Level 2 input is recommended. As stated previously, the Level 1 approach required FWD data, but the current software interface does accept this testing data. Therefore, the data-collection effort to support this input is simplified by limiting the process to using Level 2 distress observation data. No additional resources are required to make this simplification.
Existing AC binder properties	AC/AC	●		◑			For this input, binder-related testing needs to be conducted on materials extracted (cores) from the existing AC pavement. The Level 3 method requires Superpave binder grading, conventional viscosity grade, or conventional penetration grade to estimate a temperature-viscosity relationship for the binder. This testing represents a significant change in current SDDOT procedures.
Existing AC mix properties	AC/AC	●		◑			The Level 3 procedure for this input requires gradation information of the mix. Laboratory testing will be conducted on materials extracted (cores) from the existing AC pavement. This testing represents a significant change in current SDDOT procedures. Note that the level for this input will need to be revisited when Level 1 and 2 methods become better established in the software.

Notes:

- The level of additional required effort/testing is indicated in the table by the following symbols: ○ = Minimal, ◑ = Moderate, ● = Significant, ✓ = Required.
- This table includes all variables that have changes from current SDDOT practices.

Table 1-6. Summary of information associated with new or additional laboratory testing requirements for base layers.

Input Parameter	Design Type	Target Level	Testing Description	Test Method	SDDOT Equipment Needs	Time Per Test
BASE-RELATED VARIABLES						
Base resilient modulus	JPCP, CRCP, New AC, AC/AC, AC/JPCP	2	The focus of any base resilient modulus testing is to determine representative values for the typical SDDOT bases. For Level 2, resilient modulus values are determined by correlating to another material index or strength property (i.e., CBR, R-value, AASHTO layer coefficient, PI and gradation, or penetration from DCP). Therefore, resilient modulus values can be determined by either 1) correlating to historical data, or 2) conducting new field testing on various projects to determine typical base properties.	Recommended correlations to different field testing results are summarized in table 2.2.50 on p. 2.2.68 of the MEPDG guide. If needed, test standards for the discussed material indices and strength properties are the following: • CBR (AASHTO T193). • R-value (AASHTO T190). • AASHTO layer coefficient (AASHTO Guide for the Design of Pavement Structures). • PI and gradation (AASHTO T27 and T90). • DCP (ASTM D 6951).	Because Level 2 uses correlations to many different well-established field testing methods, no new equipment is required.	Not applicable
Base plasticity index	JPCP, CRCP, New AC, AC/AC, AC/JPCP	N/A	As with base resilient modulus, the focus of any base plasticity index testing is to determine representative values for the typical SDDOT bases. Therefore, plasticity index values can be determined by either 1) reviewing historical testing data, or 2) conducting new laboratory testing on base material samples to determine typical values. Any technician experienced in soils testing can easily conduct needed testing.	If laboratory testing is required, plasticity index testing should be conducted in accordance with AASHTO T90 and T89.	SDDOT currently owns all needed equipment to conduct plasticity index testing.	Test duration: Less than 1 day Technician time per test: 1 hour

Table 1-7. Summary of information associated with new or additional laboratory testing requirements for PCC layers.

Input Parameter	Design Type	Target Level	Testing Description	Test Method	SDDOT Equipment Needs	Time Per Test
JPCP- AND CRCP-RELATED VARIABLES						
PCC strength	JPCP, CRCP	2	For Level 2, PCC flexural strength (used in the actual models) is estimated from compressive strength (f’c) values at 7, 14, 28, and 90 days.	Level 2 compressive strength testing requires laboratory testing of design mixes prior to the construction of the project. All specimen preparation and testing should be conducted in accordance with AASHTO T22.	SDDOT currently owns all needed equipment to prepare and conduct compressive testing of PCC cylinder specimens.	<u>Test duration</u>: 90 days <u>Technician time per test</u>: 8 hours
PCC coefficient of thermal expansion	JPCP, CRCP	1	The MEPDG predictions are very sensitive to this variable. Level 1 requires COTE laboratory testing of design mixes prior to the construction of the project. Technicians should be experienced using sample instrumentation and computers.	COTE testing is conducted on prepared PCC cylinders. All specimen preparation and testing should be conducted in accordance with AASHTO TP60. Specifically, the standard features of a COTE test set-up include the following: • Concrete saw for creating specimens. • Balance with capacity of 44 lbs and accuracy of 0.1%. • Caliper or other device to measure specimen length to nearest 0.004 in. • Water bath with temperature range of 50 to 122 °F, capable of controlling temperature to 0.2 °F. • Support frame that has minimal influence on length change measurements. • Temperature measuring devices with resolution of 0.2 °F and accurate to 0.4 °F. • Submersible LVDT gage with minimum resolution of 0.00001 in and typical measuring range of ± 0.1 in. • Micrometer or other calibration device for LVDT with minimum resolution of 0.00001 in.	SDDOT does not currently own the COTE test equipment. The cost for this testing equipment is approximately $15,000.	<u>Test duration</u>: Approximately 1 week <u>Technician time per test</u>: 10 hours

Table 1-8. Summary of information associated with new or additional laboratory testing requirements for AC layers.

Input Parameter	Design Type	Target Level	Testing Description	Test Method	SDDOT Equipment Needs	Time Per Test
AC SURFACE-RELATED VARIABLES						
New AC or ACOL binder properties	New AC, AC/AC, AC/JPCP	1 and 2 (same method)	Asphalt binder testing is needed to develop a viscosity temperature relationship for Levels 1 and 2 and to assist in developing the shift factors for Level 1 designs. The MEPDG recommends the dynamic shear rheometer (DSR) for this testing.	AASHTO T315 is the test method for the DSR. This test is run as part of the Superpave performance grading system; therefore, developing a database of test results should be relatively easy. The complex modulus (G*) and phase angle (δ) will have to be determined at additional temperatures.	SDDOT currently owns all needed equipment to conduct binder testing at Level 1 and 2. The equipment was provided to the SDDOT as part of a pooled fund purchase in the 1990s.	Test duration: Less than 1 day Technician time per test: 4 hours
New AC or ACOL mix properties	New AC, AC/AC, AC/JPCP	1	Dynamic Modulus Testing—For Level 1 designs, E* testing is required. Mixture should be short-term aged (AASHTO R30) prior to compacting the sample.	Available test methods include AASHTO TP62 and NCHRP 1-28A. AASHTO TP62 requires the use of the Simple Performance Tester (SPT) recommended during NCHRP 9-29. NCHRP 1-28A can be conducted with most servo-hydraulic systems that include an environmental chamber. A Superpave Gyratory Compactor, capable of compacting samples that are 6.7 in (170 mm) in height, is needed for the SPT testing.	SDDOT does not currently own the SPT equipment or the Gyratory Compactor equipment required to prepare SPT samples. The cost of the SPT is approximately $40,000 to $50,000. The cost of the Gyratory Compactor is approximately $25,000.	Test duration: Approximately 5 days; however, test times can be longer if target air void contents are not met. Technician time per test: 24 hours
Existing AC binder properties	AC/AC	3	For Level 3, asphalt binder is recovered from cores and tested using one of three methods to determine the binder's performance grade (PG), viscosity grade, or penetration grade.	One of the following methods applies: • Performance grade is determined using AASHTO M320. Regression intercept (A) and regression slope of viscosity temperature susceptibility (VTS) parameters are estimated from table 2.2.10 in the MEPDG documentation. • Viscosity grade is determined using AASHTO M226. *A* and *VTS* are estimated from table 2.2.11 in the MEPDG documentation. • Penetration grade is determined using AASHTO M20. *A* and *VTS* are estimated from table 2.2.12 in the MEPDG documentation.	SDDOT currently owns all needed equipment to conduct binder testing using any of these three methods.	Test duration: Less than 1 day Technician time per test: 5 hours (not including coring time)
Existing AC mix properties	AC/AC	3	For Level 3, the gradation of the existing AC mix is determined from conducting a sieve analysis on material collected from the existing pavement (i.e., cores).	Aggregates obtained after extracting bitumen from cores can be used for the sieve analysis. Bitumen extraction is conducted in accordance with ASTM D2172, while sieve analyses of aggregate are conducted in accordance with AASHTO T27.	SDDOT currently owns all needed equipment to conduct sieve analyses.	Test duration: Less than 1 day Technician time per test: 3 hours (not including coring time)

9. Resolve differences between the MEPDG predicted distresses and those currently collected for the SDDOT pavement management system (PMS).
10. Calibrate and validate MEPDG performance prediction models to local conditions.
11. Define the long-term plan for adopting the MEPDG design procedure as the official SDDOT pavement design method.
12. Develop a design catalog.

While steps 1 and 2 of the recommended implementation plan steps have been completed under this project, the remaining steps outline the work that will prepare the SDDOT for making a decision about when or if to adopt the new MEPDG as its primary design method. One of the most important recommendations under the implementation plan is the formation of a SDDOT MEPDG Implementation Team. While the presented implementation plan provides some general guidance on the tasks that are foreseen as part of the MEPDG implementation, the detailed decisions and guidance on these tasks will need to come directly from the SDDOT MEPDG Implementation Team. The final stand-alone implementation plan is presented as Appendix E to this report (i.e., *South Dakota MEPDG Implementation Plan*).

Recommendations

After a collective review of the findings and conclusions generated under this project, the following five recommendations are presented for consideration by the Technical Panel.

1. Adopt the prepared SDDOT implementation plan.
2. Continue to focus on gaining experience with the MEPDG design method while moving toward the planned adoption of the MEPDG approach as the primary pavement design method in South Dakota.
3. Review the distress definitions and measurement protocols associated with both the MEPDG models and the current SDDOT pavement management system, and develop a plan for resolving any differences between the two.
4. Review the Local Calibration Guidance for the Recommended Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures final report (developed

under project NCHRP 1-40B) and conduct any additional preliminary activities necessary for implementing the recommended model calibration procedure.

5. Implement identified data testing protocols at the MEPDG input target levels.

The adoption of the recommendations from this project are expected to enable the SDDOT to produce more effective and reliable pavement designs, therefore, resulting in extended pavement service life and more cost effective investment decisions. More detailed explanations of each of these recommendations are presented in Chapter 6 of the research report.

2.0 PROBLEM DESCRIPTION

The SDDOT currently designs its highway pavements in accordance with the 1993 *AASHTO Guide for Design of Pavement Structures*. The current version of the AASHTO guide, as well as its predecessors released in 1961 (original), 1972 (interim), and 1986 (same as the 1993 version except for the overlay design section) has been a widely accepted standard design procedure among virtually all SHAs, as well as in several other countries. However, the current version is not without limitations, the foremost being that it is based on empirical relationships derived from the AASHO Road Test conducted from 1958 to 1960. As such, the relationships are truly representative only of the design conditions present at the Road Test, including the single type of subgrade, the limited range of materials used, the limited pavement cross sections, the limited number of traffic loading applications, the now outdated tires and suspension systems on the test trucks, and the single environmental location (Ottawa, Illinois) and limited environmental effects (2 years) to which the pavements were exposed. Since 1960, changes in cross-sectional design, advances in material science, vehicular design changes, and increased volume and weight distribution of traffic have all served to make this empirical data archaic. Because of these limitations, the majority of pavement designs conducted using the 1993 design guide are outside the inference space of the original data.

To address these limitations, the AASHTO Joint Task Force on Pavements, in conjunction with the NCHRP, has been working since 1996 on the development of the MEPDG. Under this new MEPDG approach, the principles of engineering mechanics are used to compute the internal material behaviors in a pavement structure (i.e., deflections, stresses, and strains) as it is subjected to predicted future traffic loadings and environmental conditions (e.g., moisture and temperature). Those predicted material behaviors are then related to accumulated pavement damage through developed “transfer” functions, and then correlated with actual performance (distress) data. For the initial development of the MEPDG models, the data was calibrated with pavement-performance data from the LTPP program. This research effort was conducted under NCHRP Project 1-37A, and a draft version of the guide was completed in 2004 and made available to SHAs for review and evaluation. Since then, several versions of the design software have been released after certain changes were made. A final version of the MEPDG guide and design software is expected to be released in 2007.

Because AASHTO is expected to adopt the newly developed MEPDG in the near future, it is critical that the SDDOT become familiar with the MEPDG documentation and software to ready those involved for its implementation. In preparation for this impending design procedure change, SDDOT has sponsored this preliminary research to answer the following questions:

- What inputs are required by the MEPDG for typical SDDOT designs?
- Which of the required inputs are the most critical (or most significant) to the prediction of pavement performance for each of the typical SDDOT designs?
- What inputs required within the MEPDG process are not currently being measured by SDDOT?
- For those inputs that don't have data currently available, what methods are recommended for collecting that needed data?
- What equipment and personnel resources are necessary to adequately implement the MEPDG?
- What is the suggested timeline for implementing the MEPDG?

With the answers to these questions, and the development of a stand-alone implementation plan document under this project, SDDOT will have conducted the necessary groundwork to implement the MEPDG in the future. By moving toward the implementation of the MEPDG, it is envisioned that the SDDOT will be able to produce more effective and reliable pavement designs, therefore, resulting in extended pavement service life and more cost-effective investment decisions.

3.0 OBJECTIVES

Two specific objectives were identified to be achieved through the research effort. Each of the research objectives is discussed in this section, along with how the objective was accomplished.

Objective 1: Identify the requirements and resources that will be needed for SDDOT to implement the M-E Pavement Design Guide

To provide a smooth transition from the SDDOT's empirical-based design methods to the new MEPDG procedures developed under NCHRP Project 1-37A, it is important that the implementation be tailored specifically to the conditions that exist, and the data that are available, in South Dakota. Differences in maintenance practices, construction techniques and specifications, aggregate and binder types, and mix design procedures can all contribute to variations in pavement performance. One of the primary goals of this study is to determine which input variables have the largest impact on pavement performance in South Dakota. By identifying the most significant inputs associated with each pavement type, the current SDDOT sampling and testing methods can be assessed to determine where more accurate measurement methods may be required, and at what cost to the SDDOT.

To determine the most critical MEPDG inputs for South Dakota conditions, under Task 3 of the project, the project team conducted a sensitivity analysis of the inputs associated with five typical SDDOT pavement designs. During this task, the project team conducted over 600 runs of the MEPDG software to determine what impact changing various MEPDG inputs had on pavement performance (i.e., distress and IRI predictions). During Task 4, the statistical results of the sensitivity analysis were used to rank the investigated inputs (within each pavement type) in order of most significant to least significant. Finally, these input rankings were used to develop recommendations that specify the appropriate MEPDG input level (i.e., Level 1, Level 2, or Level 3) for the inputs that were included in the sensitivity analysis.

During Task 5 of the project, the project team assessed the materials-, traffic-, and condition-related data currently available in SDDOT databases to identify any gaps between the currently available data and the MEPDG input requirements. In addition, the project team reviewed the SDDOT current sampling and testing methods and determined the MEPDG input level associated with the current SDDOT methods. By comparing the current SDDOT information and practices to the recommended input levels determined as a result of the Task 4 work, the project team prepared an estimate of the resources needed to collect required input data at the respective recommended input levels. In addition, this report also includes information regarding the skills that will be needed to use the new pavement design tools effectively and the types of training that will be required. Specifically, the summary of resource requirements primarily focuses on identifying the additional staffing needs associated with obtaining required inputs, and the cost of any new required testing equipment.

Objective 2: Develop M-E Pavement Design implementation plan for SDDOT

To address the second SDDOT research objective, the project team developed a stand-alone implementation plan that outlines the tasks that will need to be implemented by the SDDOT over the next 3 years to ready itself for the successful implementation of the MEPDG. The prepared implementation plan consists of twelve general steps, many of which will be completed concurrently. These twelve general implementation steps consist of the following:

1. Conduct sensitivity analysis of MEPDG inputs.
2. Recommend MEPDG input levels and required resources to obtain those inputs.
3. Obtain necessary testing equipment to implement the MEPDG at the target MEPDG input levels.
4. Review version 1.0 of the MEPDG software.
5. Form a SDDOT MEPDG Implementation Team and develop and implement a communication plan.
6. Conduct staff training.
7. Develop formal SDDOT-specific MEPDG-related documentation.
8. Develop and populate a central database (or databases) with required MEPDG input values.
9. Resolve differences between the MEPDG predicted distresses and those currently collected for the SDDOT pavement management system.
10. Calibrate and validate MEPDG performance prediction models to local conditions.

11. Define the long-term plan for adopting the MEPDG design procedure as the official SDDOT pavement design method.
12. Develop a design catalog.

While steps 1 and 2 of the recommended implementation plan have been completed under this project, the remaining steps outline the work that will prepare the SDDOT for making a decision on when or if to adopt the new MEPDG as its primary design method.

4.0 TASK DESCRIPTION

This study consists of twelve tasks. This chapter describes each task as it originally was proposed, and how and to what extent each task was completed under this study. Each of the individual tasks is discussed separately.

Task 1: Meet with the project's Technical Panel to review project scope and work plan.

The first project task was to travel to the SDDOT offices to hold a project kick-off meeting with the Technical Panel, and to meet with different SDDOT individuals with first-hand knowledge of the current SDDOT design-related procedures. The specific goals of the project kick-off meeting were the following:

- To provide an opportunity for the project team to discuss its proposed approach for the project with the Technical Panel.
- To make any revisions necessary to achieve the goals and objectives identified by the Technical Panel.
- To provide an opportunity for the project team to discuss the new design procedures with the Technical Panel and to obtain the Panel members' initial thoughts for the input levels that might be appropriate for each of the inputs required.
- To seek input from the Technical Panel on the baseline values that will be used as inputs in the sensitivity analysis conducted during Task 3.
- To identify the available data sources and contact information that will be used during Task 5, and to discuss the general approach that was to be used to evaluate data sources and the logistics of obtaining that information.

The project kick-off meeting was held on June 14, 2005, in Pierre, South Dakota. During the meeting, the research team reviewed the project objectives and presented the approach for completing each project task. In addition, the research team reviewed some of the features associated with the new design procedures and presented a short summary of the results of the literature search, including a summary of the implementation activities that have been conducted in other state highway agencies since the release of the new MEPDG procedures. Specifically, the ongoing activities in Mississippi, Arizona, Florida, Indiana, Kansas, Kentucky, Texas, Utah, Virginia, Washington, Wisconsin, and Minnesota were introduced to the Technical Panel. Additionally, a report documenting the conduct of a sensitivity analysis on selected portland cement concrete inputs to the design models by the University of Arkansas was discussed with the Panel. A summary of the results of the literature search was distributed to the members of the Panel.

During the remainder of the trip, the research team met with representatives from the Materials, Traffic Information Management, Pavement Management, and Road Design departments to discuss the availability of data to support the efforts of the research team. Many useful pieces of information were collected during this initial trip.

Task 2: Review current literature, including other states' experiences regarding implementation of the M-E Pavement Design Guide.

During this project, the project team conducted a comprehensive literature search to locate documents associated with the development and implementation of the MEPDG, with the specific focus on the experiences of other SHAs with the MEPDG. The starting source of the literature review was the Transportation Research Information Service (TRIS) database. In addition, the project team expanded the search to include the Internet and conference websites and/or CD-ROMs where significant attention has been focused on the implementation of the new MEPDG. For instance, at the 2004 Southeastern States Pavement Management and Design Conference (held in Baton Rouge, Louisiana) the presentations focused almost exclusively on the new MEPDG.

As a part of this review, over 100 different MEPDG-related documents were obtained and reviewed. To help summarize the information, the reviewed information was categorized into the following four general categories:

- General experiences with mechanistic-empirical design procedures.
- General information on model development and calibration for the new mechanistic-empirical design procedures.
- Activities to define the inputs required for the new mechanistic-empirical design procedures.

- Calibration studies and sensitivity analyses in anticipation of the implementation of the new design procedures.

Throughout the conduct of the project, additional references became available as other agencies investigated the MEPDG procedures. The project team continually monitored these additional references as they became available and attended several technical presentations by the MEPDG development team during the conduct of this project. A complete summary of the literature search results is contained in Appendix A to this report. An updated list of useful MEPDG-related resources is presented in Appendix F to this report.

Task 3: Perform sensitivity analysis on all design inputs to the M-E pavement design software for typical South Dakota site conditions. The analysis must cover the full range of inputs, including mix properties, design features, traffic loading, environmental zones of the state, subgrade types, design reliability, performance criteria, and other variables required in the design procedure.

The release of the MEPDG represents the culmination of many years of research into the development of models that analyze inputs for traffic, climate, materials, and design features to estimate pavement performance for new, reconstructed, or rehabilitated flexible, rigid, and semi-rigid (composite) pavements. Default input values that were developed using data from FHWA's LTPP program are available, but more precise data inputs for traffic, materials, and environmental variables may be used to improve the reliability and accuracy of the pavement performance predictions. Level 1 data offer the highest reliability, but require site-specific data such as laboratory testing on soils or construction materials. Level 2 data provide intermediate accuracy, but require less site-specific testing. At Level 2, inputs may be selected based on previous tests that have been conducted on similar types of materials or other forms of agency experience. At Level 3, agencies select default values that represent typical averages for the geographic region where the design project is located. For a given paving project, all inputs do not have to be at the same input level. That is, an agency may choose input levels depending on the availability of different types of data and the resources available to support the data-collection efforts.

One disadvantage to the new MEPDG procedure is that it does require a large number of inputs. However, it is known that not all inputs into the performance models have an equal impact on the predicted distresses. Therefore, it is important to try to determine which variables have the largest impact (i.e., are most significant) on the predicted distresses for the typical pavement designs used in South Dakota. Under the direction of the Technical Panel, the project team conducted a sensitivity analysis for the following five design types commonly used by the SDDOT:

- New design – Rural jointed plain concrete pavement (JPCP).
- New design – Rural asphalt concrete (AC).
- New design – Continuously reinforced concrete pavement (CRCP) interstate.
- Rehabilitation – AC overlay over existing rural AC.
- Rehabilitation – AC overlay over rubblized rural JPCP.

Reasonable ranges of data inputs (reflecting South Dakota conditions and practices) for each of the five design types were defined, and a sensitivity analysis was conducted under Task 3 to determine the impact of changes in these inputs on predicted pavement performance. With input from the Technical Panel, ten different combinations of pavement design type, expected traffic conditions, and selected project locations (as shown in table 4-1) were identified for investigation within the sensitivity analysis.

Table 4-1. Initial combinations of design type, traffic-, and climate-related variables that define individual scenarios for use in the sensitivity analyses.

Scenario	Design Type	Traffic	Climate (Location)
1	New design—Rural JPCP	Rural	Brookings
2			Winner
3	New design—Rural AC	Rural	Brookings
4			Winner
5	New design—CRCP interstate	Interstate	Brookings
6			Winner
7	Rehabilitation—AC overlay (ACOL) over rubblized rural JPCP	Rural	Brookings
8			Winner
9	Rehabilitation—ACOL over existing rural AC	Rural	Brookings
10			Winner

The first step of the sensitivity analysis was to define "standard" pavement designs for each of the five chosen design types that reflect the most typical variable inputs used in South Dakota. The expected performance associated with each "standard" design was then predicted using version 0.9 of the MEPDG software and used as the baseline performance values for the different standard designs. The specific performance indicators used to define pavement performance in the sensitivity analysis are summarized by design type in table 4-2.

Table 4-2. Distress indicator models associated with the included design types.

Design Type/ Pavement Type	Included Performance Indicator Models
New design—Rural JPCP	• Transverse cracking • Joint faulting • International Roughness Index (IRI)
New design—Rural AC	• Longitudinal cracking (top-down fatigue) • Alligator cracking (bottom-up fatigue) • Thermal cracking • AC layer rutting • Total rutting • IRI
New design—CRCP interstate	• Punchouts • IRI
Rehabilitation—AC overlay over rubblized rural JPCP	• Longitudinal cracking (top-down fatigue) • Alligator cracking (bottom-up fatigue) • Thermal cracking • AC layer rutting • Total rutting • IRI
Rehabilitation—AC overlay over existing rural AC	• Longitudinal cracking (top-down fatigue) • Alligator cracking (bottom-up fatigue) • Reflective cracking • Thermal cracking • AC layer rutting • Total rutting • IRI

For the Task 3 sensitivity analysis, each selected MEPDG input was investigated at two or three input values. Using these two or three input levels, the sensitivity analysis was conducted and performance measures over time (e.g., total rutting, IRI, cracking, and so on) were obtained as outputs from the MEPDG software. After conducting over 600 MEPDG software runs, the predicted performance versus pavement age data were extracted from the MEPDG output and used to determine the relative effect of each variable on performance. An example showing a plot of the extracted performance data for the transverse cracking model for new JPCP design is presented in figure 4-1. For this example, the performance values associated with three different

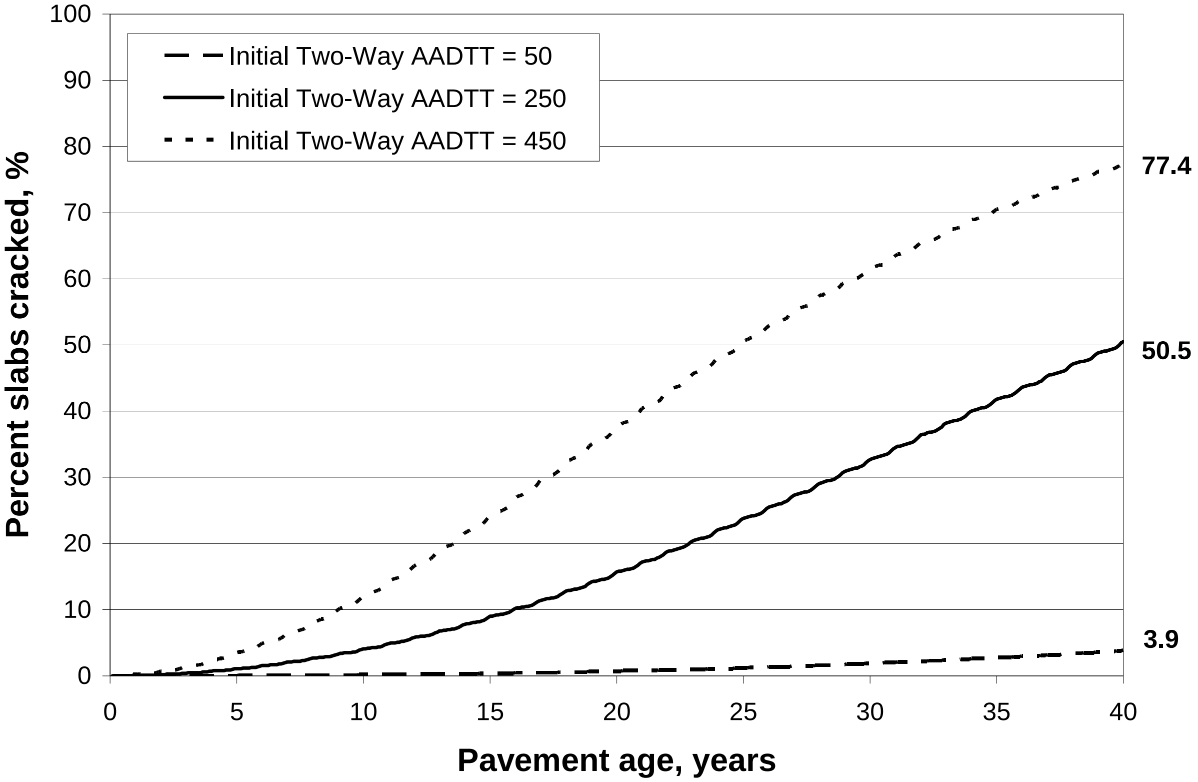

Figure 4-1. Example performance trend plot showing effect of AADTT on predicted JPCP cracking (location = Brookings).

levels of annual average daily truck traffic (AADTT)—50, 250, and 450 trucks daily—at the Brookings location are illustrated. Note that the performance values (in terms of percent of slabs cracked) at the JPCP pavement's design life (40 years) are noted on the chart for each AADTT level (i.e., 77.4 percent for AADTT = 450, 50.5 percent for AADTT = 250, and 3.9 percent for AADTT = 50). A complete listing of the input values used in the sensitivity analysis is provided in Appendix B.

After extracting the performance data from the MEPDG output files, the results associated with each investigated input were plotted together on summary charts for each performance indicator. Building on the example data illustrated in figure 4-1, figure 4-2 contains an example of a summary chart that shows the relative effects of the investigated variables on the JPCP cracking model. Note: For a complete description of the variable abbreviations used in figure 4-2, see the *List of Input Variable Abbreviations* on page *x* in the front matter of this report.

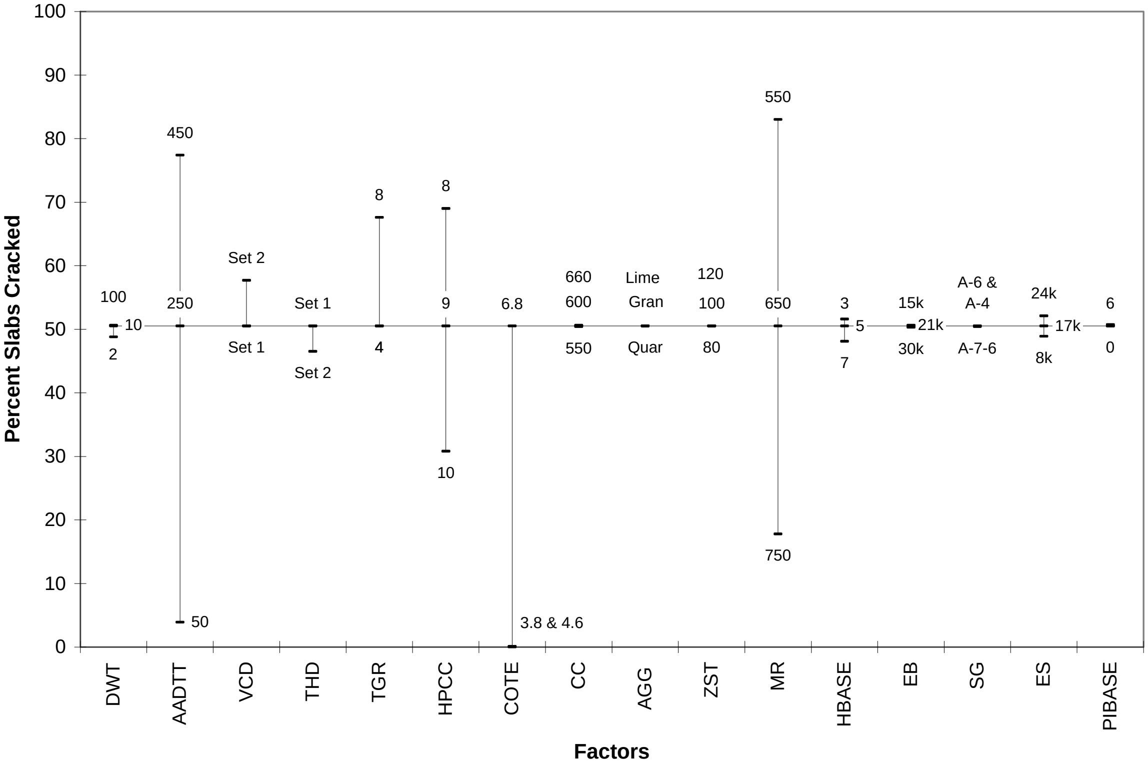

Figure 4-2. Example summary chart of relative effects for the transverse cracking model for new JPCP design (Location = Brookings).

For the summary charts, all of the investigated variables (associated with the particular performance-indicator model) are plotted on the x-axis. The performance-indicator values are plotted along the y-axis. The horizontal line on the chart indicates the expected performance of the "standard" pavement section. That is, the performance value at the pavement's design life when all MEPDG inputs are set to their "standard" values. For the example shown in figure 4-2, the horizontal line at 50.5 percent slabs cracked indicates that the 40-year (design life) cracking associated with the "standard" JPCP pavement section (i.e., an analysis where all of the inputs were set to their "standard" values) was 50.5 percent slabs cracked. This is an important reference point as the performance of the "standard" pavement section is used as the baseline to which all other individual results are compared.

The results of the individual MEPDG software runs are used to build the vertical lines plotted for each investigated input variable. For example, note that the three 40-year (design life) AADTT-related performance values displayed on figure 4-1 (i.e., 77.4 percent for AADTT = 450, 50.5 percent for AADTT = 250, and 3.9 percent for AADTT = 50) are plotted in figure 4-2 for the

"AADTT" variable. The length of each vertical line provides a visual indication of the magnitude of the within-sample variation associated with each input variable. Therefore, a simple conclusion from the visual interpretation of these plots is that the inputs with longer vertical lines have a larger impact on the prediction of the distress than those inputs with shorter vertical lines (i.e., longer lines indicate more significance in the prediction of the distress). For example in figure 4-2, based on the relative difference in the length of vertical lines, one would conclude that AADTT has much more of a significant effect on the occurrence of cracking in JPCP than subgrade type (SG). The complete results of the sensitivity analysis are presented separately for each pavement type in Appendix C.

Task 4: Rank the design inputs in order of their effect on predicted pavement performance and determine the level of detail actually required for the numerous inputs to the program. Specify testing protocols needed to acquire the data at the specified levels of detail.

While a visual examination of the summary charts of relative effects gives a quick indication of which inputs are the most significant for the prediction of a particular distress, a more formal statistical analysis of variance (ANOVA) was needed to verify the findings. Task 4 of the project focused on evaluating the ANOVA results from the senility analysis, ranking the investigated inputs (within each pavement type) in order of most significant to least significant, and determining the most appropriate input levels for each included MEPDG input. The remainder of this section provides more details on the procedures used to complete this task.

By applying an ANOVA, the statistical significance of individual MEPDG inputs can be determined for a selected distress prediction model. In an ANOVA procedure, the significance of an individual MEPDG input is indicated by the magnitude of a computed *F-ratio* associated with the input (note: a more detailed explanation of the calculation of F-ratios is included in Appendix C). The p-value associated with each F-ratio explains the level of significance for the F-ratio, and thus the level of importance of the MEPDG input for the model. Based upon standard statistical practices, the MEPDG inputs with p-values less than 0.05 are considered significant with 95 percent confidence (i.e., $\alpha = 0.05$). Expanding on the previous example, table 4-3 shows a summary of the ANOVA results for the JPCP transverse cracking model.

Table 4-3. ANOVA results for the JPCP transverse cracking model.

Order No.	Factor Abbreviation	Factor Name	F	p-value	Model Significance (α=0.05)	Assessed Level of Significance
1	AADTT	Initial two-way average annual daily truck traffic	160.80	0.000	Yes	Highly Significant
2	COTE	Coefficient of thermal expansion	134.59	0.000	Yes	
3	MR	PCC 28-day modulus of rupture	104.89	0.000	Yes	
4	HPCC	PCC slab thickness	36.87	0.000	Yes	Moderately Significant
5	CLIMATE	Climatic characteristics (location)	17.70	0.000	Yes	
6	TGR	Traffic growth rate (%)	9.99	0.004	Yes	
7	VCD	Vehicle class distribution factors	2.85	0.103	No	Not Significant
8	THD	Truck hourly distribution factors	0.50	0.484	No	
9	ES	Subgrade resilient modulus	0.16	0.853	No	
10	HBASE	Base layer thickness	0.08	0.923	No	
11	CC	Cementitious material content	0.01	0.994	No	
12	EB	Base resilient modulus	0.01	0.995	No	
13	SG	Subgrade type	0.01	0.994	No	
14	AGG	Aggregate type	0.00	0.996	No	
15	DWT	Depth of water table	0.00	0.997	No	
16	PIBASE	Base plasticity index	0.00	0.959	No	
17	ZST	PCC zero-stress temperature	0.00	0.996	No	

Note: Shaded cells indicate those variables that were found to be insignificant.

Under Task 4, the first step in interpreting the ANOVA results was to rank the individual MEPDG inputs in order of decreasing F-ratio. Next, the associated p-values were evaluated to determine which inputs were significant and which were not. As stated above, all inputs with an associated p-value greater than 0.05 were classified as “not significant.” For those variables that had p-values less than 0.05, a subjective assessment of the resulting F-ratios was used to classify each input as “highly significant,” “moderately significant,” or “mildly significant.” For the JPCP cracking model example, there was a large drop-off in F-ratio values between the MR (F-ratio = 104.89) and HPCC (F-ratio = 36.87) variables. Therefore, MR and all inputs with higher F-ratios were subjectively classified as “highly significant” while HPCC and the other significant variables (i.e., p-values < 0.05) were subjectively classified as “moderately significant.”

The magnitude of the relative F-ratios and these subjective categories of significance were used by the research team to select the most appropriate input levels for each included MEPDG input. For example, a Level 1 or Level 2 MEPDG input procedure (sampling and testing procedure) was determined to be the most appropriate input level for those variables classified as “highly significant” or “moderately significant” while Level 3 inputs were found to be acceptable for most of the inputs classified as “mildly significant” or “not significant.” These most appropriate input levels associated with each MEPDG input were classified as “target” MEPDG levels in the task results.

The final part of the Task 4 work required the research team to 1) determine what MEPDG input levels represent the current SDDOT practice, 2) illustrate where there are differences between the “target” MEPDG input levels and the current SDDOT practices, and 3) document the sampling and testing protocol changes that would need to be made to achieve the target MEPDG input levels. The results of this exercise are summarized in a series of tables associated with the five different investigated design types. These tables are contained in section 5.2 (*Input Significance and Recommended MEPDG Input Levels in South Dakota*) of the *Findings and Conclusions* section of this report.

Task 5: Describe existing SDDOT data that can be used for design inputs to the M-E pavement design software at the required levels of detail.

Once the target testing protocols associated with each input variable were defined, the project team reviewed the existing SDDOT data sources to assess how well the currently available data would support the sampling and testing protocols defined for the “target” MEPDG input levels. Specifically, the assessment of the SDDOT data looked at what data are currently available in the exact form required by the target MEPDG input testing protocol, what data are available but may need to be collected in a slightly different manner to conform to the testing protocol, and what data that are not currently available (i.e., prompting the need for a new sampling or testing method). The results of this data assessment are summarized in a series of tables that provide the following information for each MEPDG input included in the sensitivity analysis:

- Information on whether data associated with each input is currently available.
- The location of that data in SDDOT if it is available (i.e., a particular database or a particular department from which the data could be obtained).
- An explanation of how the data-collection process would need to change from the current SDDOT process to implement the “target” input levels.

The complete results of this data-assessment task are summarized in a series of tables presented in section 5.3 (*Summary of Additional Resources Needed for MEPDG Target Input Levels*) of the *Findings and Conclusions* section of this report.

Task 6: Identify resources (staff, testing capabilities, equipment, information systems, knowledge, training, etc.) needed to obtain necessary design inputs.

Because the Task 5 results identify where gaps exist between the current SDDOT data and data protocols and the target MEPDG input levels, the next logical question is "What resources are needed by SDDOT to fully implement the MEPDG approach at the "target" input levels?" The first part of the answer to this question is to identify any additional required resources in terms of personnel, additional testing that must be performed, equipment that must be obtained, databases that must be developed, training that might be needed, and so on. The second part of the answer is then to associate a real monetary cost with each newly needed resource. The results of this task are presented in three tables in section 5.4 (*Summary of Additional Resources Needed for MEPDG Target Input Levels*) of the *Findings and Conclusions* section of this report. The combination of the information in these tables provides an estimate of the overall cost of additional staffing, equipment, sampling and testing, and training needs associated with implementing the MEPDG in South Dakota.

Task 7: Evaluate the applicability of performance models in the M-E pavement design guide to South Dakota conditions and identify needed development of local calibrations.

The MEPDG considers both structural and functional pavement performance characteristics in the analysis of estimated damage to a pavement over time. The roughness models are based on the initial as-constructed pavement smoothness and changes in smoothness due to the propagation of distress, site factors, and maintenance activities. For flexible pavements, smoothness is based on the amount of load-related fatigue cracking, thermal cracking, and pavement deformation (rutting). The distress types considered in rigid pavements include faulting, transverse cracking, and punchouts for CRCP. The default models incorporated into the design software have been calibrated at the national level using data from the LTPP program. However, they are not representative of all conditions and regions of the country. For that reason, it is important that the models be calibrated and validated to conditions in South Dakota.

The original goal of this task was to assess how well the MEPDG models predicted actual performance and to identify which models would benefit from calibration to local conditions. This goal was to be achieved by completing the following procedure:

1. Work with SDDOT personnel to find data for a small set of projects (for each pavement type) that had good time-series performance data, and where the construction, climatic, and material properties and design inputs were well documented.
2. Enter the collected construction, climatic, and material information into the MDPDG software and simulate the predicted performance for each chosen actual project.
3. For each prediction model, compare the predicted distresses from the MEPDG software to the actual measured distresses stored in the pavement management system and use statistical procedures to determine if there was any significant difference between the two data sets.
4. Assess the correlation between the predicted and actual data and make a recommendation for each individual model on whether a local calibration is expected to be needed.

While completing these preliminary work steps toward model calibration was the initial plan under Task 7 of the project, a number of model inconsistencies observed during the Task 3 sensitivity analysis (e.g., the problem with the thermal cracking model), and the model deficiencies documented in both NCHRP 307 and 308 indicated that true model calibration exercises were premature (NCHRP 2006a; NCHRP 2006b). Therefore, discussions with SDDOT personnel resulted in an agreement to limit the scope of this task to documenting the calibration approach that would be used after a more stable version of the software was available. This final model calibration documentation is presented in section 5.5 (*MEPDG Model Calibration Issues*) of the *Findings and Conclusions* section of this report.

Task 8: Prepare a detailed implementation plan that outlines elements of work necessary to utilize the pavement design methodology at SDDOT. The plan must include but not be limited to estimated costs and recommended schedule for input acquisition, evaluating and recalibrating performance models, operation, and maintenance.

The full implementation of the MEPDG requires a well thought-out plan that identifies each activity to be conducted, reveals any interdependence between tasks, provides a realistic schedule for accomplishing each activity, and includes an estimate of the costs associated with conducting each activity. A number of states have developed, or are in the process of developing, implementation plans to guide their implementation activities. The detailed implementation plan developed during this task incorporates the results of the previous activities into a document that can serve as a road map for the SDDOT to evaluate the MEPDG and determine if or when to adopt the MEPDG as the primary pavement design method in South Dakota. The basic implementation plan consists of twelve general steps, many of which will be completed concurrently. One of the most important recommendations under the implementation plan is the formation of a SDDOT MEPDG Implementation Team. While the presented implementation plan provides some general guidance on the tasks that are foreseen as part of the MEPDG implementation, the detailed decisions and guidance on these tasks will need to come directly from the SDDOT MEPDG Implementation Team. The final stand-alone implementation plan is presented as Appendix E to this report.

Task 9: Submit the implementation plan for review and meet with the Technical Panel.

Under Task 9 of the project, the stand-alone implementation plan developed under Task 8 was submitted to the Technical Panel for review and comment. The original draft implementation plan document was first presented to the Technical Panel at a project meeting in the SDDOT offices on June 21, 2007.

Task 10: Modify the implementation plan based on Panel comments.

The Technical Panel indicated that it agreed with the direction and structure outlined in the initial implementation plan. Several minor suggestions were offered to the research team, and these changes have been incorporated into the implementation plan included in Appendix E.

Task 11: Prepare a final report and executive summary of the research methodology, findings, conclusions, and recommendations.

This submittal represents the culmination of the research activities. The final report includes an Executive Summary and documentation of the project objectives, significant findings, and final conclusions and recommendations.

Task 12: Make an executive presentation to the SDDOT Research Review Board at the conclusion of the project.

The project team presented a summary of the project at a Research Review Board meeting on August 30, 2007. The presentation included a summary of the project objectives, the technical approach that was followed, significant findings from the research, and the final conclusions and recommendations.

5.0 FINDINGS AND CONCLUSIONS

Significant findings and conclusions from the study are presented in this section of the report. Findings from each of the major areas of the study are documented separately, as shown in table 5-1. The implementation recommendations that were developed as a result of these findings are presented in Chapter 6.

Table 5-1. Organization of Chapter 5.

Report Section	Topic Discussed
5.1	Documentation of Unusual Trends
5.2	Input Significance and Recommended MEPDG Input Levels in South Dakota
5.3	Data-Collection Requirements to Meet Target MEPDG Input Levels
5.4	Summary of Additional Resources Needed for MEPDG Target Input Levels
5.5	MEPDG Model Calibration Issues
5.6	Implementation Plan

5.1 Documentation of Unusual Trends

When reviewing the results of the sensitivity analysis, a number of software problems and counterintuitive model trends were encountered and documented. This section summarizes all of these observations, and provides explanations for each observation when available. Because the MEPDG runs for the sensitivity analysis were conducted using version 0.9 of the MEPDG software, it is expected that many of these observations may be addressed within version 1.0. Note that this section not only points out many real counterintuitive trends, but it explains many of the trends that could be perceived to be counterintuitive by a user if not viewed in the context used for the sensitivity analysis.

1. <u>Inconsistent prediction of thermal cracking on computers with different operating systems</u>—When conducting the sensitivity-analysis runs for design types New AC, ACOL on existing AC, and ACOL on rubblized JPCP, it was discovered that the results for the transverse (thermal) cracking model were different between computers with different operating systems. Those runs completed on computers with the *Windows XP* operating system showed values of "0" at the 20-year design life for <u>all</u> investigated runs. Those runs completed on computers with the *Windows 2000* operating system showed

nonzero values for almost all completed runs. It is worth noting that the thermal cracking model was the only model that showed different results between the different operating systems. After the project team made this operating system-dependent discovery, it was discovered that the University of Minnesota had discovered the same dependency during its ongoing sensitivity work. University of Minnesota personnel reported the operating system dependency to the MEPDG software developers.

2. Limit on CRCP punchout data. Four investigated CRCP runs (two within each climate) failed to predict 40 years of distress data. These runs correspond to the case where slab thickness was set to 9 inches (std = 10 inches), and the case where PCC modulus of rupture was set to 550 psi (std = 650 psi). The data prediction stopped between years 35 and 37 for these runs. It appears they reached an arbitrary model limit near 101 punchouts per mile.

3. Batch program feature failed during some batches of runs. During verification, errors were encountered that crashed the program while running JPCP and CRCP batch files. All runs were able to be completed either by running smaller batches or by performing the runs individually.

4. Documented problem with models for HMA overlay of JPCP design type. A review of the recent NCHRP document that summarizes MEPDG software changes made through version 0.9 found some documented known problems in the models for the HMA overlay of JPCP and CRCP designs. The following are two excerpts from NCHRP Research Results Digest 308 (pages 15 and 17, respectively) that document these known model problems (NCHRP 2006b):

> ***(#428) HMA overlay of JPCP and CRCP includes several major deficiencies that require updating.*** *The modeling of HMA over JPCP and CRCP in the existing version has serious deficiencies in how the overlay and concrete slab and base course are transformed into an equivalent section for stress calculation purposes. Major modifications are required for both HMA over JPCP and HMA over CRCP to make this a more effective overlay design procedure. [Note: These modifications have not been completed in Version 0.900 yet. It is recommended that this overlay design procedure not be used until this is completed in late July 2006.]*
>
> *The AC/JPCP or AC/CRCP overlay design procedure was found to contain various technical deficiencies. One problem was that the 2004 version did not fully consider the width of transverse cracking (after many years of aging), the load transfer efficiency (which may have deteriorated), and the extent of erosion along the slab edge that exists in the field at the time of placement of a new overlay. In addition, procedures to calculate the equivalent slab thickness (where the overlay is combined with the CRCP slab) with proper*

> *full friction included errors. These deficiencies are being fixed in the software and this type of overlay is being tested to ensure reasonableness. This fix is not in Version 0.900 but will be in the next version.*

The documentation of these known model deficiencies gives little confidence in the sensitivity-analysis results associated with the HMA overlay of JPCP design type.

5. Known deficiency in permanent curl/warp prediction for JPCP and CRCP pavements. The following is an excerpt from NCHRP Research Results Digest 308 (p.17) that documents a known deficiency in the modeling of permanent curl/warp for PCC pavements (NCHRP 2006b):

   > ***(#240) Permanent curl/warp input needs further examination to determine improved estimation procedures.*** *Currently, a –10 °F is recommended for design. This is inadequate as the permanent curl/warp is known to depend on several key factors. Develop procedures to estimate the permanent curl/warp input for JPCP and CRCP separately. Through the calibration process, attempt to identify values or relationships that will minimize error of prediction for all JPCP and CRCP distress models. Time and resources were insufficient to solve this problem at this time. It is recommended that it be addressed in the next program version.*

6. The overall predicted alligator cracking values for both ACOL designs seem very low—A review of the sensitivity analysis results found that the predicted alligator-cracking values were much less than originally expected. While this does not necessarily constitute a problem, it is worth noting that the predicted 20-year values from this model are typically less than 1 percent of the area for ACOL on rubblized JPCP, and less than 0.05 percent of the area for ACOL on existing AC. Predicted values for this distress are smaller than the expected range of 5 percent to 25 percent (note 25 percent was the identified limit at 90 percent reliability). It is believed that this model would benefit from calibration to local SDDOT conditions.

7. The impact of AC layer thickness (HAC) on bottom-up alligator cracking appears counterintuitive for the new AC design. While there is no known problem with the output of the alligator cracking model, a discussion of the model trends is included here as the trends may initially be counterintuitive to some software users. Figure 5-1 illustrates the typical trends of the bottom-up longitudinal fatigue cracking (i.e., alligator cracking) model. The natural reaction to this model is to ask, "Why is the peak distress value associated with an AC thickness in the 2- and 5-in range?" Also, when looking at

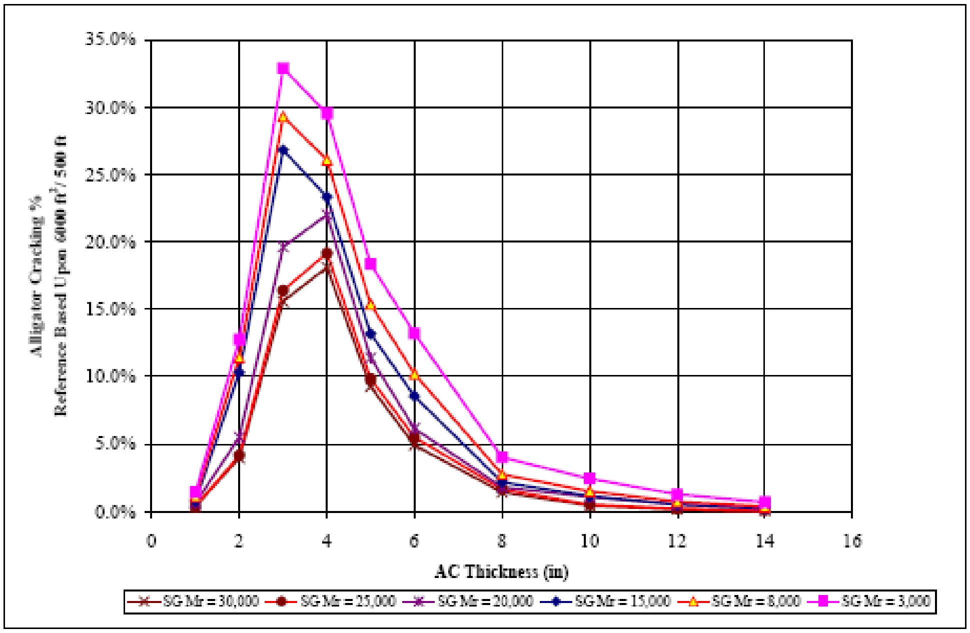

Figure 5-1. Effect of HMA layer thickness on bottom-up “alligator” fatigue cracking (NCHRP 2004).

this figure, someone may incorrectly conclude that overall pavement distress is less for very thin sections (i.e., sections with AC layers less than 3 in thick). However, what the trend on this chart really indicates is that when the AC thickness is less than 3 inches, the typical failure method is not bottom-up fatigue cracking, but something else.

8. <u>The impact of AC layer thickness (HAC) on longitudinal top-down fatigue cracking appears counterintuitive</u>. In the sensitivity analysis, a section with an AC thickness of 4 inches was found to be performing better than the case where AC thickness was 5 inches. A review of the MEPDG documentation found that this is a well-documented trend in the top-down longitudinal cracking model (Appendix II-3, p.18 of the MEPDG documentation) (NCHRP 2004). A review of the model documentation finds an example that shows as AC thickness **increases** from approximately 2 inches to an optimum value near 6 inches, cracking **increases**. As AC thickness **increases** after this optimum thickness value, cracking **decreases**. While the specific values in this example are not important, the shape of the trend is important. No detailed explanation for this trend was offered in Appendix II-3 of the MEPDG documentation. An example of this trend (shown on p. 19 of Appendix II-3 of the MDPDG documentation) is illustrated in figure 5-2 below.

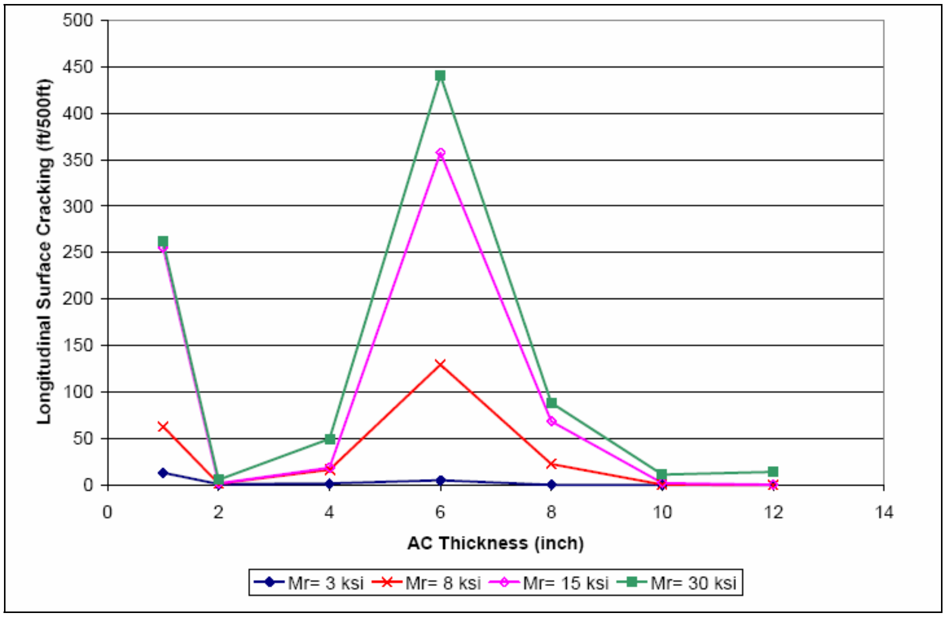

Figure 5-2. Example trend associated with the effect of AC thickness on longitudinal surface cracking (NCHRP 2004).

Figure 5-2 also shows another initially counterintuitive trend as it shows that as the subgrade layer stiffness increases, so does the amount of top-down longitudinal cracking. This trend is clearly defined in the MEPDG documentation as it is explained that the top-down "surface longitudinal cracking increases as the foundation support layer also increases. That is, any variable that tends to increase the foundation support (stiffer subgrade, stabilized base/subbase, very low ground water table location, and presence of bedrock near surface) will tend to cause a larger tensile strain at the surface layer and tend to increase longitudinal surface cracking" (NCHRP 2004).

9. Counterintuitive trends associated with the depth of water table (DWT) variable. For many cases in the sensitivity analysis, distress values were observed to *decrease* as the depth of water table *decreased* (i.e., the more saturated the subgrade below the pavement, the less distress that was predicted). While the source of these non-intuitive trends could not be easily traced in the JPCP and CRCP-related distresses, there was documentation associated with the AC-related distress models to confirm that some of these counterintuitive trends are inherent in the models. The following are examples documented in the MEPDG documentation (NCHRP 2004):

   - AC layer rutting—Although the displayed trend shows that rutting increases as DWT increases, the documentation says that DWT is not one of the influencing factors on

AC layer rutting. The documentation indicates that only the thickness of the AC layer (HAC), the AC mixture quality, and the amount of traffic influence AC layer rutting (Appendix GG-2, p. 92 of the MEPDG documentation) (NCHRP 2004).

- Total rutting in AC—The rutting model shows the following: 1) As depth to water table **increases**, AC rutting **increases** (very small slope); 2) As depth to water table **increases**, base rutting **increases** (very small slope); 3) For subgrades with elastic moduli (ES) greater than 10,000 psi, subgrade rutting **decreases** as DWT **increases** from 2 to 7 feet. After a minimum value near 7 feet, subgrade rutting **increases** as DWT **increases**.

10. The impact of base plasticity index (PI) on distress prediction is opposite of what would be expected for most cases. In the sensitivity analysis, two levels of PI (0 and 6) were investigated, and for most cases, more distress was associated with the PI = 0 than for PI = 6. Although this counterintuitive trend was consistent over different pavement types and distress models, it should be noted that in all cases, the change in distress for this variable is very small. Because the subgrade characteristics are influenced greatly by the modeled climatic characteristics, it is very likely this interaction is influencing this observed trend.

11. The impact of PCC slab thickness (HPCC) on faulting is counterintuitive. For JPCP pavements, faulting increased as slab thickness increased. While this trend appears to be counterintuitive by itself, this trend is a documented trend in the model for doweled pavements. On page 66 of Appendix JJ in the MEPDG, the documentation states "an increase in PCC thickness from 10 to 12 in leads to higher faulting because an increase in PCC thickness leads to a decrease in the ratio of dowel cross section to PCC cross section which, in turn, reduces dowel shear effectiveness. Thus, an increase in PCC thickness may require an increase in dowel diameter" (NCHRP 2004). This trend is illustrated below in figure 5-3 (p. 66 of Appendix JJ of the MEPDG documentation) (NCHRP 2004).

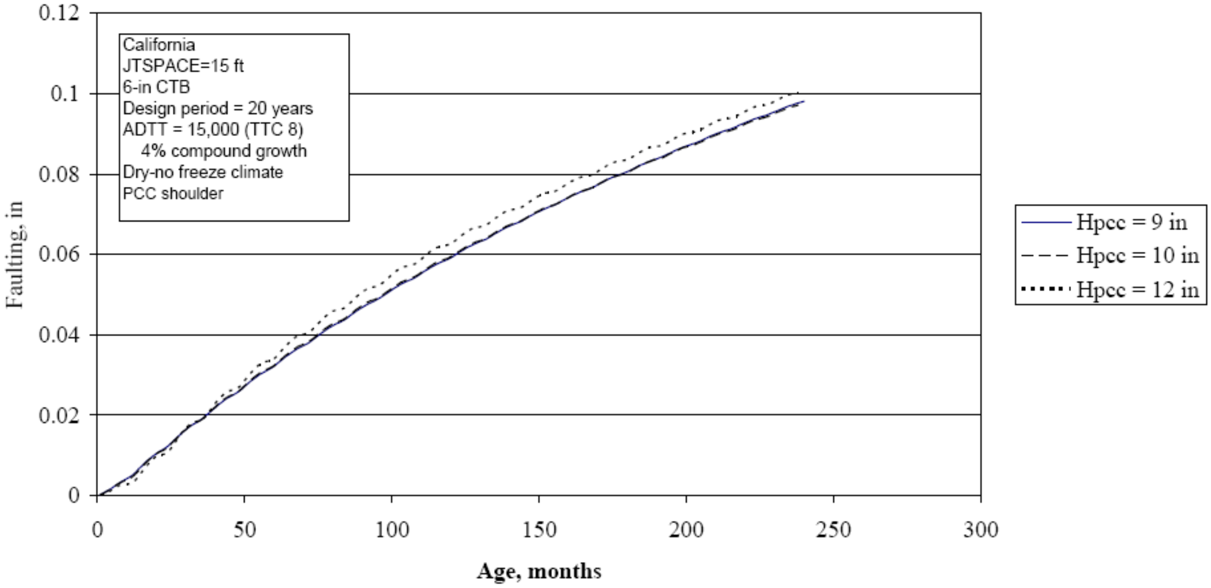

Figure 5-3. Effect of slab thickness on JPCP faulting (NCHRP 2004).

Although this PCC thickness-related trend by itself is counterintuitive, it is important to remember the context in which it was investigated under the sensitivity analysis. Because only one variable was changed at a time, an increase in slab thickness was not accompanied with an increase in dowel diameter as it would most likely be in the real world. Therefore, using the standard design practice of increasing dowel diameter with slab thickness would most likely eliminate this counterintuitive trend.

12. <u>The impact of tire pressure (TPRESS) on longitudinal cracking is counterintuitive</u>. The sensitivity analysis results show that for all three design types with AC surfaces (i.e., *New AC*, *ACOL on existing AC*, and *ACOL on rubblized JPCP*) top-down longitudinal cracking decreases as tire pressure increases. The research team was unable to find any model documentation that explained this trend.

13. <u>The "Pavement Rating" input is not well documented in the MEPDG documentation</u>. The results of the sensitivity analysis found that the most significant variable to pavement distress predicted for the *ACOL of existing AC* design type was the "pavement rating" variable. This discovery is worrisome in that "pavement rating" is a subjective rating (excellent, good, fair, poor, and very poor) that is not well defined in the documentation. Because of the lack of definition associated with the pavement rating variable, it is recommended that a Level 2 or Level 1 pavement assessment be used when conducting ACOL designs. For the *ACOL of existing AC* design type, a Level 2 existing pavement

assessment requires the input of individual layer rutting value (for each layer) and the measured alligator cracking as a percent area. At Level 1, non-destructive testing (NDT) is used to better assess the properties of the existing AC layer instead of entering the measured alligator cracking (note: this information is summarized on p. 3.6.29 of the MEPDG documentation) (NCHRP 2004).

14. <u>The impact of the amount of total existing rutting (TOTRUTEXIST) on future rutting is counterintuitive</u>. In the MEPDG approach, the "total rutting" variable for the existing pavement is defined as "the rutting observed in the pavement after the pavement has been milled." In the sensitivity analysis results, it is observed that as TOTRUTEXIST increases, the future AC rutting and total rutting increases. This trend is counterintuitive as one would typically expect more future rutting if all of the existing rutting was not removed during the milling process. This is because the presence of rutting indicates either a problem with the existing AC layer material or a more serious problem of rutting in the base or subgrade layers due to some underlying instability. No further explanation of the non-intuitive trends was able to be located in the MEPDG documentation. Similar to the concerns over the "Pavement Rating" variable, it will be recommended that Level 2 or Level 1 inputs be used when assessing the existing pavement condition. For rutting, this requires that the layer-by-layer rutting values be input.

5.2 Input Significance and Recommended MEPDG Input Levels in South Dakota

Because the MEPDG requires the entry of a large number of inputs, it is important to understand which variables have the largest impact (i.e., are most significant) on the predicted distresses. In the Task 3 sensitivity analysis conducted for this study, the sensitivity of selected inputs was investigated for the following five design types commonly used by the SDDOT:

- New design—Rural JPCP.
- New design—Rural AC.
- New design—CRCP interstate.
- Rehabilitation—AC overlay over existing rural AC.
- Rehabilitation—AC overlay over rubblized rural JPCP.

For each pavement design type, the sensitivity of predicted distresses to changes in selected traffic-, construction-, climatic-, and material-related inputs was evaluated. The sensitivity analysis consisted of completing over 600 runs of the MEPDG software, preparing summary charts showing the relative effect of each variable on each related distress, and conducting a more detailed statistical analysis of variance (ANOVA) of the MEPDG results. While the summary charts visually showed the expected range of predicted distress associated with a range of typical values for each input, the statistical results of the ANOVA analysis provided a more objective assessment of the significance of each input on each predicted distress. The primary result of the sensitivity analysis was the development of a ranked list of inputs (in order of greatest to least significance) for each of the five different pavement design types. A complete summary of the detailed sensitivity-analysis results that went into the preparation of these ranked lists of inputs is presented in Appendix C of this report.

With these ranked lists of inputs completed, the next step was to determine the recommended MEPDG input levels associated with each input within each design. Within the MEPDG approach, the three different levels of inputs are described as the following (NCHRP 2004):

- **Level 1** inputs provide the highest level of accuracy and, thus, the lowest level of uncertainty or error. Level 1 design generally requires project-specific inputs such as material inputs measured by laboratory or field testing, site-specific axle load spectra data, or nondestructive deflection testing.
- **Level 2** inputs provide an intermediate level of accuracy that is closest to the typical procedures used with earlier editions of the AASHTO guide. Level 2 inputs would most likely be user-selected from an agency database, derived from a limited testing program, or be estimated through correlations. Examples include estimating asphalt concrete dynamic modulus from binder, aggregate, and mix properties; estimating portland cement concrete elastic moduli from compressive strength tests; or using site-specific traffic volume and traffic classification data in conjunction with agency-specific axle load spectra.
- **Level 3** inputs provide the lowest level of accuracy, and are expected to be used with “routine” projects. This level of input is most applicable where there are minimal consequences for early failure (e.g., on low-volume roads). A source for Level 3 inputs could be average values for a particular region or perhaps even “default” values within the software program.

It is important to note that 1) the three input level approach does not apply to all inputs, and 2) all inputs do not have to be at the same input level to complete an analysis.

For each input included in the analysis, the research team used the compiled ranking of inputs to determine the most appropriate MEPDG input level for those variables where input levels were applicable. The basis of these decisions comes from the logic that the more significant an input is to the prediction of a distress (i.e., the higher the input ranking in the list), the more accurate the method should be for determining values for that input. Therefore, in most cases, a Level 1 or Level 2 MEPDG input method was typically recommended for inputs classified as “highly significant” to “moderately significant,” whereas Level 3 input methods were typically determined to be good enough for those variables in the “mildly significant” or “not significant” categories. A complete summary of the ranked lists of inputs, and the corresponding target MEPDG input levels, are presented by pavement design type in tables 5-2 through 5-6. Note that the “Explanation of Current SDDOT and Target Input Levels” column in these tables only presents information on what type of information SDDOT currently measures, and how it differs from what is required in the target input level. For more information on the data-collection or sampling and testing protocols associated with all of the MEPDG input levels, see Appendix D, *Summary of MEPDG Hierarchical Input Levels*.

5.3 Data-Collection Requirements to Meet Target MEPDG Input Levels

In tables 5-2 through 5-6, both the current SDDOT input levels and target input levels for those inputs investigated in the sensitivity analysis are identified. Where the current procedures were found to match those associated with the target MEPDG input level, no change in current SDDOT procedures needs to be considered. However, a difference between the current and target input levels indicates some change is needed in how SDDOT is currently sampling and testing (or collecting) the data associated with that input. For most of the inputs investigated in the sensitivity analysis, this difference indicates 1) the need to change to a new sampling and testing method for the input, or 2) the need to conduct more sampling or testing using the same current SDDOT sampling and testing method.

Table 5-2. Input level summary (investigated inputs only) for new JPCP (rural design).

Input Parameter	**Significance**		**Input Type**	**Level**			**Explanation of Current SDDOT and Target Input Levels**
	Rank	**Category**		**3**	**2**	**1**	
Annual average daily truck traffic	1	More Critical Inputs	Traffic		⦿		Level 2—Estimate from 1) regional/statewide WIM, AVC, 2) vehicle count data, 3) or regional traffic forecasting and trip generation models.
PCC coefficient of thermal expansion	2		Material	•		○	Level 3—Historical averages. Level 1—Direct measurement from laboratory testing (AASHTO TP 60). This is the procedure used for the LTPP program and all of the sections used for calibration of the Guide. It is highly recommended that an agency test its typical PCC mixes containing a range of aggregate types and cement contents to obtain typical values.
PCC strength	3		Material	•	○		Level 3—28-day strength (for the specific mix or an agency default) specified as either a modulus of rupture (MR) or compressive strength (f'c) value. E may be computed or entered directly. These values may be determined using standard tests (i.e., ASTM C 469, ASTM C 78, and the ASTM C 39 for E, MR, and f'c, respectively) of agency-specific or mix-specific defaults can be used. Level 2—MR values determined from f'c tests at 7, 14, 28, and 90 days (ASTM C 39). User is required to enter an estimate of the long-term strength as a 20-year to 28-day strength ratio (a ratio of 1.44 is recommended).
PCC slab thickness	4		Design	N/A			Design input.
Climatic characteristics	5		Climate	N/A			Select climatic data for a specific weather station or interpolate climatic data between weather stations.
Traffic growth rate	6		Traffic		⦿		Level 2—Regional/statewide information or site-specific values if available.
Vehicle class distribution factors	7	Less Critical Inputs	Traffic		⦿		Level 2—Data from regional/statewide WIM, AVC, or vehicle counts. It is recommended that current data be used to develop representative tables for different logical project classifications.
Truck hourly distribution factors	8		Traffic		⦿		Level 2—Regional/statewide distribution factors determined from WIM, AVC, and vehicle count data. Current data should be used to develop representative tables for different logical project classifications.
Subgrade resilient modulus	9		Material		⦿	▨	Level 2—Resilient modulus (Mr) values are determined indirectly using correlations to other material-related characteristics (i.e., CBR, R-value, AASHTO layer coefficient, DCP results, or plasticity and gradation information). Note: The software does not currently support Level 1 inputs.
Base layer thickness	10		Design	N/A			Design input.
Cementitious material content	11		Material	N/A			Chosen material-related input.
Base resilient modulus	12		Material		⦿	▨	Level 2—Mr values are determined indirectly using correlations to other material-related characteristics (i.e., CBR, R-value, AASHTO layer coefficient, DCP results, or plasticity and gradation information). Note: The software does not currently support Level 1 inputs.
Subgrade type	13		Material	N/A			Classify material using standard AASHTO (AASHTO M 145) or unified soil classification (ASTM D2487) definitions.
PCC aggregate type	14		Material	N/A			Chosen material-related input.
Depth to water table	15		Climate	○			Level 3—Average annual or seasonal values from county soil reports. SDDOT does not currently measure this variable.
Base plasticity index	16		Material	N/A			Hierarchical levels are not appropriate for this input as the Guide recommends laboratory testing be used to determine PI, LL, and PL (AASHTO T90 and AASHTO T89).
PCC zero-stress temperature	17		Material	N/A			It is recommended that this variable be computed by the software. Note: This value is a function of cement content and mean monthly ambient temperature during construction.

Notes: ○ = Target input level; • = Current SDDOT input level; N/A = not applicable.

Table 5-3. Input level summary (investigated inputs only) for new AC (rural design).

Input Parameter	Significance		Input Type	Level			Explanation of Current SDDOT and Target Input Levels
	Rank	Category		3	2	1	
Average annual daily truck traffic	1	More Critical Inputs	Traffic		⦿		Level 2—Estimate from regional/statewide WIM, AVC, or vehicle count data or from regional traffic forecasting and trip generation models.
AC layer thickness	2		Design	N/A			Design input.
AC binder properties	3		Material	●	○		Level 3—This level uses a Superpave binder grading, conventional viscosity grade, or conventional penetration grade to estimate a temperature-viscosity relationship for the binder. Levels 1 and 2 (same method)—Laboratory testing is required to determine binder properties directly. The specific testing procedures depend on whether a Superpave or conventional binder is being used.
Base resilient modulus	4		Material		⦿	▨	Level 2—Mr values are determined indirectly using correlations to other material-related characteristics (i.e., CBR, R-value, AASHTO layer coefficient, DCP results, or plasticity and gradation information). Note: The software does not currently support Level 1 inputs.
Subgrade resilient modulus	5		Material		⦿	▨	
Traffic growth rate	6		Traffic		⦿		Level 2—Regional/statewide information or site-specific values if available.
Base layer thickness	7		Design	N/A			Design input.
Climatic characteristics	8		Climate	N/A			Select climatic data for a specific weather station or interpolate climatic data between weather stations.
Tire pressure	9		Traffic	N/A			It is recommended that this input be fixed to the software default of 120 psi.
Depth to water table	10	Less Critical Inputs	Climate	○			Level 3—Average annual or seasonal values from county soil reports. SDDOT does not currently measure this variable.
Vehicle class distribution factors	11		Traffic		⦿		Level 2—Data from regional/statewide WIM, AVC, or vehicle counts. It is recommended that current data be used to develop representative tables for different logical project classifications.
AC mix properties	12		Material	●		○	Levels 2 and 3 (same method)—Aggregate gradation information (i.e., percent retained on 3/4”, 3/8”, and #4 sieves, and the percent passing #200). Level 1—Laboratory dynamic modulus (E*) frequency sweep testing (NCHRP 1-28A). If Level 1 binder testing is adopted, it is recommended that Level 1 testing also be adopted for this variable.
AC creep compliance	13		Material	○			Level 3—Typical creep compliance values from the Agency or MEPDG Guide (i.e., software *Help*). SDDOT does not currently measure this variable. Values are specific to a given binder type.
Base plasticity index	14		Material	N/A			Hierarchical levels are not appropriate for this input as the Guide recommends laboratory testing be used to determine PI, LL, and PL (AASHTO T90 and AASHTO T89).
Coefficient of thermal contraction	15		Material	N/A			Because there are no AASHTO or ASTM standard tests for this variable, this value should be computed by the software as a function of HMA volumetric properties and the thermal contraction coefficient for the aggregate.
Subgrade type	16		Material	N/A			Classify material using standard AASHTO (AASHTO M 145) or unified soil classification (ASTM D2487) definitions.
Truck hourly distribution factors	17		Traffic		⦿		Level 2—Regional/statewide distribution factors determined from WIM, AVC, and vehicle count data. It is recommended that current data be used to develop representative tables for different logical project classifications.

Notes: ○ = Target input level; ● = Current SDDOT input level; N/A = not applicable.

Table 5-4. Input level summary (investigated inputs only) for new CRCP (interstate design).

Input Parameter	**Significance**		**Input Type**	**Level**			**Explanation of Current SDDOT and Target Input Levels**
	Rank	**Category**		**3**	**2**	**1**	
Percent Steel, %	1	More Critical Inputs	Design	N/A			Design input.
PCC strength	2		Material	●	○		Level 3—28-day strength (for the specific mix or an agency default) specified as either a Mr or f'c value. E may be computed or entered directly. These values may be determined using standard tests (i.e., ASTM C 469, ASTM C 78, and the ASTM C 39 for E, Mr, and f'c, respectively) of agency-specific or mix-specific defaults can be used. Level 2—Modulus of rupture (MR) values determined from compressive strength (f'c) tests at 7, 14, 28, and 90 days (ASTM C 39). User is required to enter an estimate of the long term strength as a 20-year to 28-day strength ratio (a value of 1.44 is recommended for this ratio).
PCC slab thickness	3		Design	N/A			Design input.
Base/slab friction coefficient	4		Design	N/A			Select from the default base-specific values in the software.
Average annual daily truck traffic	5		Traffic		⦿		Level 2—Estimate from 1) regional/statewide WIM, AVC, 2) vehicle count data, 3) or regional traffic forecasting and trip generation models.
PCC zero-stress temperature	6		Material	N/A			Computed by software. This value is a function of cement content and mean monthly ambient temperature during construction.
PCC coefficient of thermal expansion	7		Material	●		○	Level 3—Historical averages. Level 1—Laboratory testing (AASHTO TP 60). It is highly recommended that an agency test its typical PCC mixes containing a range of aggregate types and cement contents to obtain typical values.
Bar diameter	8		Design	N/A			Design input.
Steel depth	9		Design	N/A			Design input.
Traffic growth factor	10		Traffic		⦿		Level 2—Regional/statewide information or site-specific values if available.
Subgrade resilient modulus	11		Material		⦿	▨	Level 2—Indirect Mr values from correlations to other material-related characteristics (i.e., CBR, R-value, AASHTO layer coefficient, DCP results, or plasticity and gradation information). Note: The software does not currently support Level 1 inputs.
Shoulder type	12		Design	N/A			Design input.
Climatic characteristics	13		Climate	N/A			Select climatic data for a specific weather station or interpolate climatic data between weather stations.
Cementitious material content	14		Material	N/A			Chosen material-related input.
Vehicle class distribution factors	15	Less Critical Inputs	Traffic		⦿		Level 2—Data from regional/statewide WIM, AVC, or vehicle counts. It is recommended that current data be used to develop representative tables for different logical project classifications.
Subgrade type	16		Material	N/A			Classify using AASHTO (AASHTO M 145) or unified soil classification (ASTM D2487).
PCC aggregate type	17		Material	N/A			Chosen material-related input.
Base layer thickness	18		Design	N/A			Design input.
Base plasticity index	19		Material	N/A			Hierarchical levels are not really appropriate for this input as the Guide recommends laboratory testing be used to determine PI, LL, and PL (AASHTO T90 and AASHTO T89).
Depth to water table	20		Climate	○			Level 3—Average annual or seasonal values from county soil reports. SDDOT does not currently measure this variable.
Base resilient modulus	21		Material		⦿	▨	Level 2—Mr values are determined indirectly using correlations to other material-related characteristics (i.e., CBR, R-value, AASHTO layer coefficient, DCP results, or plasticity and gradation information). Note: The software does not currently support Level 1 inputs.
Truck hourly distribution factor	22		Traffic		⦿		Level 2—Regional/statewide distribution factors determined from WIM, AVC, and vehicle count data. It is recommended that current data be used to develop representative tables for different logical project classifications.

Notes: ○ = Target input level; ● = Current SDDOT input level; N/A = not applicable.

Table 5-5. Input level summary (investigated inputs only) for ACOL on rubblized JPCP pavement (rural design).

Input Parameter	Significance		Input Type	Level			Explanation of Current SDDOT and Target Input Levels
	Rank	Category		3	2	1	
Annual average daily truck traffic	1	More Critical Inputs	Traffic		⦿		Level 2—Estimate from regional/statewide WIM, AVC, or vehicle count data or from regional traffic forecasting and trip generation models.
Subgrade resilient modulus	2		Material		⦿	▨	Level 2—Mr values are determined indirectly using correlations to other material-related characteristics (i.e., CBR, R-value, AASHTO layer coefficient, DCP results, or plasticity and gradation information). Note: The software does not currently support Level 1 inputs. If a backcalculated Mr is available from FWD data, that value can be entered as a Level 3 input.
Depth to water table	3		Climate	○			Level 3—Average annual or seasonal values from county soil reports. SDDOT does not currently measure this variable.
AC overlay binder properties	4		Material	•	○		Level 3—Superpave binder grading, conventional viscosity grade, or conventional penetration grade is used to estimate a temperature-viscosity relationship for the binder. Levels 1 and 2 (same method)—Laboratory testing is required to determine binder properties directly. The specific testing procedures depend on whether a Superpave or conventional binder is being used.
Climatic characteristics	5		Climate	N/A			Select climatic data for a specific weather station or interpolate climatic data between weather stations.
Traffic growth rate	6		Traffic		⦿		Level 2—Regional/statewide information or site-specific values if available.
Elastic resilient modulus of the fractured slab	7		Material	⦿			Level 3—Typical values based on past SDDOT testing data or experience, or use representative values from other documented studies.
Existing fractured JPCP thickness	8		Material	N/A			Cores recommended for determining PCC thickness.
AC overlay thickness	9		Design	N/A			Design input.
Tire pressure	10		Traffic	N/A			It is recommended that this input be fixed to the software default of 120 psi.
Base resilient modulus	11		Material		⦿	▨	Level 2—Mr values are determined indirectly using correlations to other material-related characteristics (i.e., CBR, R-value, AASHTO layer coefficient, DCP results, or plasticity and gradation information). Note: The software does not currently support Level 1 inputs.
AC overlay mix properties	12	Less-Critical Inputs	Material	•		○	Levels 2 and 3 (same method)—Aggregate gradation information (i.e., percent retained on 3/4", 3/8", and #4 sieves, and the percent passing #200). Level 1—Laboratory dynamic modulus (E*) frequency sweep testing (NCHRP 1-28A). If Level 1 binder testing is adopted, it is recommended that Level 1 testing also be adopted for this variable.
Base layer thickness	13		Design	N/A			Determine from construction records or cores taken prior to rubblization.
Base plasticity index	14		Material	N/A			Hierarchical levels are not appropriate for this input as the Guide recommends laboratory testing be used to determine PI, LL, and PL (AASHTO T90 and AASHTO T89).
Vehicle class distribution factors	15		Traffic		⦿		Level 2—Data from regional/statewide WIM, AVC, or vehicle counts. It is recommended that current data be used to develop representative tables for different logical project classifications.
ACOL creep compliance	16		Material	○			Level 3—Typical creep compliance values from the Agency or MEPDG Guide (i.e., software Help). SDDOT does not currently measure this variable. Values are specific to a given binder type.
Coefficient of thermal contraction	17		Material	N/A			Because there are no AASHTO or ASTM standard tests for this variable, this value should be computed by the software as a function of HMA volumetric properties and the thermal contraction coefficient for the aggregate.
Existing condition of JPCP pavement (rehabilitation level)	18		Survey	○			The interface for this input is currently confusing in that it is under the heading of "Flexible Rehabilitation." Also, some of the inputs for Levels 1 and 2 ask for flexible pavement-related condition information. It is recommended that a Level 3 "Pavement Rating" be selected.
Subgrade type	19		Material	N/A			Classify material using standard AASHTO (AASHTO M 145) or unified soil classification (ASTM D2487) definitions.
Truck hourly distribution	20		Traffic		⦿		Level 2—Regional/statewide distribution factors determined from WIM, AVC, and vehicle count data. It is recommended that current data be used to develop representative tables for different logical project classifications.

Notes: ○ = Target input level; • = Current SDDOT input level; N/A = not applicable.

Table 5-6. Input level summary (investigated inputs only) for ACOL on existing AC pavement (rural design).

Input Parameter	Significance		Input Type	Level			Explanation of Current SDDOT and Target Input Levels
	Rank	Category		3	2	1	
Existing condition of AC pavement (rehabilitation level)	1	More Critical Inputs	Survey		⦿		The Level 2 approach requires rut and fatigue cracking data for the existing HMA surface. While SDDOT currently conducts FWD testing on existing pavements, version 0.9 of the software does not support the use of that data.
Annual average daily truck traffic	2		Traffic		⦿		Level 2—Estimate from regional/statewide WIM, AVC, or vehicle count data or from regional traffic forecasting and trip generation models.
Existing AC layer thickness	3		Material	N/A			Cores recommended for determining existing AC thickness.
AC overlay thickness	4		Design	N/A			Design input.
Existing AC binder properties	5		Material	●	○		Level 3—Select a Superpave binder grading, conventional viscosity grade, or conventional penetration grade that represents the in-place HMA material. Levels 1 and 2 (same method)—Laboratory testing is required to determine binder properties directly.
AC overlay binder properties	6		Material	●	○		Level 3—A Superpave binder grading, conventional viscosity grade, or conventional penetration grade is used to estimate a temperature-viscosity relationship for the binder. Levels 1 and 2 (same method)—Laboratory testing is required to determine binder properties directly.
Subgrade resilient modulus	7		Material		⦿	▨	Level 2—Mr values are determined indirectly using correlations to other material-related characteristics. Note: The software does not currently support Level 1 inputs.
Climatic characteristics	8		Climate	N/A			Select climatic data for a specific weather station or interpolate climatic data between weather stations.
Base resilient modulus	9		Material		⦿	▨	Level 2—Mr values are determined from correlations to other material-related characteristics. Note: Level 1 inputs are not currently supported.
Tire pressure	10		Traffic	N/A			It is recommended that this input be fixed to the software default of 120 psi.
Traffic growth rate	11		Traffic		⦿		Level 2—Regional/statewide information or site-specific values if available.
Depth to water table	12	Less Critical Inputs	Climate	○			Level 3—Average annual or seasonal values from county soil reports. SDDOT does not currently measure this variable.
Base layer thickness	13		Design	N/A			Determine from construction records or cores.
Existing AC mix properties	14		Material	●	○		Level 3—"Typical" mix volumetric parameters (i.e., air voids, asphalt volume, gradation, and asphalt viscosity parameters) are used to estimate a dynamic modulus for the existing HMA layer. Levels 1 and 2—These levels use the same user interface as Level 3, however, laboratory testing is required to determine mix properties directly.
AC overlay mix properties	15		Material	⦿			Levels 2 and 3—Aggregate gradation information (i.e., percent retained on 3/4", 3/8", and #4 sieves, and the percent passing #200).
Vehicle class distribution factors	16		Traffic		⦿		Level 2—Data from regional/statewide WIM, AVC, or vehicle counts. It is recommended that current data be used to develop representative tables for different logical project classifications.
Total rutting in existing AC layer	17		Survey	N/A			This input is only required if a Level 3 "Rehabilitation Level" is selected. A Level 2 "Rehabilitation Level" is currently recommended.
Base plasticity index	18		Material	N/A			The Guide recommends laboratory testing be used to determine PI, LL, and PL (AASHTO T90 and AASHTO T89).
ACOL creep compliance	19		Material	○			Level 3—Typical values from the Agency or MEPDG Guide (i.e., software Help). SDDOT does not currently measure this variable.
Milled thickness	20		Design	N/A			Value chosen based on existing condition.
Coefficient of thermal contraction	21		Material	N/A			Because there are no AASHTO or ASTM standard tests for this variable, this value should be computed by the software as a function of HMA volumetric properties and the thermal contraction coefficient for the aggregate.
Subgrade type	22		Material	N/A			Classify using AASHTO or unified soil classification.
Truck hourly distribution	23		Traffic		⦿		Level 2—Regional/statewide distribution factors determined from WIM, AVC, and vehicle count data.

Notes: ○ = Target input level; ● = Current SDDOT input level; N/A = not applicable.

Tables 5-7 through 5-9 summarize the recommended data-collection protocols that are required to implement the MEPDG at the target input levels. Specifically, the tables include the following types of information:

- Data availability for target input levels—Is the data required for the target MEPDG input level currently collected by SDDOT or available in existing SDDOT or other databases?
- Data collection changes—If the data required for the target input level is not available, what procedural changes need to be made to obtain the needed data at the target input?
- Target level data source—Where does one go to obtain the needed data to meet the target input level needs? For inputs where this data is currently available, this may be the name of a particular SDDOT database. For inputs where this data is not currently available, guidance on how this data would be collected is provided.
- Data-collection frequency—The final type of information in the tables describes how often it is expected that a pavement designer would have to determine new values for the given input. For example, some inputs would be project specific, and therefore, new values for the input would need to be determined for each individual project. For other inputs, it may be acceptable to revisit the values on an annual basis and determine representative values that can be used for all of the projects designed in the next year.

Because the five different pavement design types have many common inputs, to avoid redundancy in tables 5-7 through 5-9, the inputs are organized by input type category rather than by pavement design type.

Table 5-7. Summary of data collection requirements to meet target input levels for general variables used in all designs.

Input Parameter	Pavement Type	Level			Data Availability for Target Level	Data-Collection Changes	Target Level Details	
		3	2	1			Data Source	Data-Collection Frequency
TRAFFIC-RELATED VARIABLES								
Annual average daily truck traffic	All		⦿		Available	None. Current data-collection procedures are acceptable.	Traffic Data Management System (TDMS)	Continuously for automatic traffic recorders (ATR); Annually for short-term volume counts.
Traffic growth rate	All		⦿		Available	None. Current data-collection procedures are applicable.	Traffic Data Management System (TDMS)	Project specific. Determined from analysis of traffic data.
Vehicle class distribution factors	All		⦿		Available	None. Current data-collection procedures are applicable.	Traffic Data Management System (TDMS)	Continuously for automatic traffic recorders (ATR); Annually for short-term volume counts.
Truck hourly distribution factors	All		⦿		Available	None. Current data-collection procedures are applicable.	Traffic Data Management System (TDMS)	Project specific. Determined from analysis of traffic data.
CLIMATE-RELATED VARIABLES								
Climatic characteristics	All	N/A			Available	None	Weather data within the MEPDG software	No additional data collection required
Depth to water table	All	○			Available	This input is not currently measured, therefore Level 3 is assumed. At Level 3, average annual or seasonal values can be obtained from the State Geological Survey or an alternative data source.	State Geological Survey or alternate data source	Update database as necessary to correspond with latest State Geological Survey data
SUBGRADE-RELATED VARIABLES								
Subgrade resilient modulus (Mr)	All		⦿		Available	None. Determine subgrade Mr values indirectly using correlations to another material-related characteristic (i.e., California bearing ratio [CBR], R-value, layer coefficient, dynamic cone penetrometer [DCP], or plasticity index [PI] and gradation).	Determine from project-specific field testing (e.g., CBR)	Project specific. Determine during preliminary site investigation steps.
Subgrade type	All	N/A			Available	None. Classify material using AASHTO (AASHTO M 145) or unified soil classification (ASTM D2487) definitions.	County soil reports or field testing results	No additional data collection required
BASE-RELATED VARIABLES								
Base layer thickness	All	N/A			Design Input	None.	Design standards or Pavement Design Engineer	No required data collection
Base resilient modulus	All		⦿		Available	None. Determine base Mr values indirectly using correlations to another material-related characteristic (i.e., CBR, R-value, layer coefficient, DCP, or PI and gradation).	Materials Sampling and Testing (MST) or new database from laboratory or field acceptance data	Annual analysis of the available acceptance testing results from past projects.
Base plasticity index	All	N/A			Available	Hierarchical levels are not appropriate for this input. Laboratory testing used to determine PI, liquid limit (LL), and plastic limit (PL) (AASHTO T90 and T89).	Typical values determined from past experience or laboratory testing (if necessary)	As needed. Typical or estimated values can be used.

For the "Level" columns, the symbols are defined as the following: ○ = Target input level; • = Current SDDOT input level; N/A = Not applicable.

Table 5-8. Summary of data-collection requirements to meet target input levels for JPCP- and CRCP-related variables.

Input Parameter	Pavement Type	Level			Data Availability for Target Level	Data Collection Changes	Target Level Details	
		3	2	1			Data Source	Data Collection Frequency
JPCP- AND CRCP-RELATED VARIABLES								
Portland cement concrete (PCC) slab thickness	JPCP and CRCP	N/A			Design Input	None.	Design standards or Pavement Design Engineer	No required data collection
PCC strength	JPCP and CRCP	●	○		Additional Testing Required	The Level 3 approach only requires a 28-day strength. Moving to Level 2 requires that modulus of rupture (MR) values be determined indirectly from compressive strength (f'c) tests at 7, 14, 28, and 90 days (ASTM C 39). While this move will require more testing, no new testing equipment is required.	Laboratory testing	Annual laboratory testing of typical mixes. Additional testing is recommended when the current mix is deemed significantly different from a "typical" mix.
PCC coefficient of thermal expansion	JPCP and CRCP	●		○	New Testing Method	Because SDDOT does not currently measure this variable, analyses must currently be completed using Level 3 (default value) inputs. Moving to the recommended Level 1 procedure requires that this input be measured directly from laboratory testing (AASHTO TP 60).	Laboratory testing	Additional testing is recommended when the current mix is deemed significantly different from a "typical" mix. Tests should be conducted to reflect three main aggregates in South Dakota.
PCC zero-stress temperature	JPCP and CRCP	N/A			Computed Value	None. This variable is computed by the software as a function of cement content and mean monthly ambient temperature during construction.	Value will be computed by software	No required data collection
Cementitious material content	JPCP and CRCP	N/A			Design Input	None. Chosen material-related input.	Design standards or Pavement Design Engineer	No required data collection
PCC aggregate type	JPCP and CRCP	N/A			Design Input	None. Chosen material-related input.	Pavement Design Engineer	No required data collection
Percent Steel, %	CRCP	N/A			Design Input	None. Design input.	Design standards or Pavement Design Engineer	No required data collection
Base/slab friction coefficient	CRCP	N/A			Design Input	None. This value is selected from default base-specific values in software.	Pavement Design Engineer	No required data collection
Bar diameter	CRCP	N/A			Design Input	None. Design input.	Design standards or Pavement Design Engineer	No required data collection
Steel depth	CRCP	N/A			Design Input	None. Design input.	Design standards or Pavement Design Engineer	No required data collection
Shoulder type	CRCP	N/A			Design Input	None. Design input.	Design standards or Pavement Design Engineer	No required data collection

For the "Level" columns, the symbols are defined as the following: ○ = Target input level; • = Current SDDOT input level; N/A = Not applicable.

Table 5-9. Summary of data-collection requirements to meet target input levels for pavement types with AC surfaces.

Input Parameter	Pavement Type	Level			Data Availability for Target Level	Data Collection Changes	Target Level Details	
		3	2	1			Data Source	Data Collection Frequency
AC SURFACE-RELATED VARIABLES								
New AC layer thickness (new AC) or ACOL thickness (rehabilitation)	New AC, AC/AC, AC/JPCP	N/A			Design Input	None. Design input.	Pavement Design Engineer	No required data collection
New AC or ACOL binder properties	New AC, AC/AC, AC/JPCP	●	○		New Testing Method	The Level 3 method for this variable uses a Superpave binder grading, conventional viscosity grade, or conventional penetration grade to estimate a temperature-viscosity relationship for the binder. For Levels 1 and 2, laboratory testing is required to determine binder properties directly. Because SDDOT is not currently conducting binder property testing, this represents a significant change in current SDDOT practice.	Laboratory testing	Annual laboratory testing of typical mixes. Additional testing is recommended when the current mix is deemed significantly different from a "typical" mix.
Tire pressure	New AC, AC/AC, AC/JPCP	N/A			Assumed Value	None. Assumed value.	Fix to assumed value of 120 psi	No required data collection
New AC or ACOL mix properties	New AC, AC/AC, AC/JPCP	●		○	New Testing Method	For Levels 2 and 3 (same method) aggregate gradation information is used to estimate the dynamic modulus (E*) of the mix. For Level 1, actual E* testing data is required. Because this variable was found to be one of the more significant variables for AC-surfaced pavements, moving toward Level 1 is an appropriate target. Because SDDOT is not currently conducting binder property testing, this represents a significant change in current practice.	Laboratory testing	Annual laboratory testing of typical mixes. Additional testing is recommended when the current mix is deemed significantly different from a "typical" mix.
AC creep compliance	New AC, AC/AC, AC/JPCP	○			Available	At this time, it is recommended that typical creep compliance values in the MEPDG software *Help* be used. These values are specific to a given binder type.	Default values in MEPDG software *Help*	No required data collection
AC coefficient of thermal contraction	New AC, AC/AC, AC/JPCP	N/A			Computed Value	Because there are no AASHTO or ASTM standard tests for this variable, it is recommended that it be computed by the software as a function of HMA volumetric properties and the thermal contraction coefficient for the aggregate.	Value will be computed by software	No required data collection
Elastic resilient modulus of the fractured slab	AC/JPCP	◉			Available	Because the Level 3 approach requires typical values based on past SDDOT testing data or experience, or representative values from other documented studies, no data-collection changes are required for this variable.	Typical value selected by the Pavement Design Engineer	No required data collection
Existing fractured JPCP thickness	AC/JPCP	N/A			New Testing Required	Cores are recommended during the design process to more accurately determine PCC thickness.	Determine from project-specific field testing	Project specific. Determine during preliminary site investigation steps.

For the "Level" columns, the symbols are defined as the following: ○ = Target input level; ● = Current SDDOT input level; N/A = Not applicable.

Table 5-9. Summary of data-collection requirements to meet target input levels for pavement types with AC surfaces (continued).

Input Parameter	Pavement Type	Level			Data Availability for Target Level	Data Collection Changes	Target Level Details	
		3	2	1			Data Source	Data Collection Frequency
AC SURFACE-RELATED VARIABLES (continued)								
Existing Condition (Rehabilitation Level) for AC/JPCP	AC/JPCP	○	•		Design Input	The software interface for this input is confusing in that it is under the heading of "Flexible Rehabilitation." Also, some of the inputs for Levels 1 and 2 ask for flexible pavement-related condition information such as "total rutting" and "milled thickness." Because of this confusion, the data-collection effort to support this design input is actually simplified to providing a Level 3 subjective pavement rating.	Determine from a project-specific field assessment	Project specific. Determine during preliminary site investigation steps.
Existing Condition (Rehabilitation Level) for AC/AC	AC/AC		○	•	Design Input	The Level 2 approach for this input requires the user to enter estimated rut data for each layer and percent fatigue cracking data for the existing HMA surface. Currently, the software does not support the entering of Level 1 falling weight deflectometer (FWD) data. Because of this deficiency, the data-collection effort to support this input is simplified by limiting the process to using Level 2 procedures.	Determine from a project-specific field assessment	Project specific. Determine during preliminary site investigation steps.
Existing AC binder properties	AC/AC	○	•		New Testing Method	To adequately determine values for this input, binder-related testing needs to be conducted on materials extracted (cores) from the existing AC pavement. The Level 3 method for assessing the materials requires a Superpave binder grading, conventional viscosity grade, or conventional penetration grade to estimate a temperature-viscosity relationship for the binder. Because SDDOT is not currently conducting binder property testing, this represents a significant change in current SDDOT practice.	Determine from a project-specific field and laboratory assessment	Project specific. Determine during preliminary site investigation steps.
Existing AC mix properties	AC/AC	○	•		New Testing Method	The Level 3 procedure for this input requires gradation information of the mix (i.e., percent retained on 3/4", 3/8", and #4 sieves, and the percent passing #200). Ideally, laboratory testing will be conducted on materials extracted (cores) from the existing AC pavement to determine the required characteristics. This represents additional testing for rehabilitation projects. Note that the level for this input will need to be revisited when Level 1 and 2 methods become better established in the software.	Determine from a project-specific field and laboratory assessment	Project specific. Determine during preliminary site investigation steps.
Total rutting in existing AC layer	AC/AC	N/A			Not Applicable	None. This input is not required unless a Level 3 pavement evaluation is utilized. Because a Level 2 is recommended for "Rehabilitation Level," this input is not required.	Not applicable	Not applicable
Milled thickness	AC/AC	N/A			Design Input	None. Value chosen based on existing condition.	Determine from a project-specific field assessment	Project specific. Determine during preliminary site investigation steps.

For the "Level" columns, the symbols are defined as the following: ○ = Target input level; • = Current SDDOT input level; N/A = Not applicable.

5.4 Summary of Additional Resources Needed for MEPDG Target Input Levels

After identifying where there are gaps between the current SDDOT data and newly recommended testing protocols to support the MEPDG, more information was compiled for all variables where a gap was identified. Table 5-10 identifies those variables where gaps exist between the current SDDOT testing methods and the identified target MEPDG methods. Table 5-10 also identifies the type of resources and anticipated effort to close each of the identified gaps. Tables 5-11 through 5-13 then provide more detailed testing-related information for those variables that required new or additional testing requirements. Note, although these tables focus on the effort and resources SDDOT would need to conduct all required testing in house, one option would still be to outsource some of the required testing (especially for those variables where the effort focuses on obtaining typical values for different material properties).

5.5 MEPDG Model Calibration Issues

An advantage of the MEPDG approach is that it allows a designer to pick combinations of various design features and numerous construction-, traffic-, climatic-, and material-related properties, and simulate the predicted pavement performance prior to actual construction. However, it is important to remember that these default MEPDG performance prediction models were originally calibrated with nationwide data sets such as the LTPP General Pavement Studies (GPS)-3, LTPP Specific Pavement Studies (SPS)-2, and FHWA Performance of Concrete Pavements (RPPR) data sets. Although the performance data from many states were actively used in the original model-calibration activities, these default models will most likely need to be calibrated with real South Dakota data to more accurately predict the performance typically observed under South Dakota conditions.

The need to calibrate the current MEPDG models to South Dakota conditions becomes apparent when the detailed data used in the national model calibrations are reviewed. An investigation of that data finds that only three South Dakota LTPP sections were used for the national calibration of JPCP and CRCP models, and no South Dakota sections were involved in the national calibration of the MEPDG models for flexible pavements (ARA 2003a; ARA 2003b). Therefore, it is very likely the prediction of truly accurate MEPDG performance results in South Dakota depend greatly on the successful recalibration of the MEPDG distress-prediction models with South Dakota-specific data.

Table 5-10. Summary of additional resources needed.

Input Parameter	**Pavement Type**	**Additional Required Testing and Staffing Effort**			**Equipment and Training Needs**		**Notes**
		Additional Testing	**Additional Staff Hours**	**Information Technology Staff Time**	**New Equipment**	**Staff Training**	
Depth to water table	All		○	○			Because depth of water table is currently not a design input used by SDDOT, some additional person hours may be required to obtain the necessary information from the State Geological Survey or an alternate data source. If these data are available electronically, some help may be needed by the information technology (IT) department to obtain or organize the data.
Base resilient modulus	All	○	○	○			Representative values for the typical SDDOT bases should be determined from laboratory or field testing results. Once typical values are established, additional testing is only required when the typical modulus values may have changed. If data are not currently available in the SDDOT Materials Sampling and Testing (MST) database, the IT department may need to establish a new database.
Base plasticity index	All	○	○	○			Representative values for the typical SDDOT bases should be determined from laboratory or field testing results. Once typical values are established, additional testing would only be required when the typical modulus values have changed. If data are not currently available in the SDDOT MST database, the IT department may need to establish a new database to store this information.
PCC strength	JPCP and CRCP	◑	◑				It is currently recommended that PCC strength be measured using Level 2 procedures (i.e., compressive strength tests measured at 7, 14, 28, and 90 days). Implementing such a procedure requires laboratory testing of design mixes prior to the construction of the project.
PCC coefficient of thermal expansion	JPCP and CRCP	● New Method	●		✓	✓	The MEPDG predictions are very sensitive to this variable. Because SDDOT is not currently measuring this variable, moving toward measuring COTE will require purchasing new testing equipment and training laboratory staff. Additional laboratory staffing hours will most likely be required to conduct the laboratory testing.
New AC or ACOL binder properties	New AC, AC/AC, AC/JPCP	● New Method	●				One significant testing change is using laboratory testing (Levels 1 and 2) to determine AC binder properties. For conventional binders, properties are determined by tests for viscosity, penetration, specific gravity, and softening point. For Superpave binders, properties are determined by measuring complex shear modulus (G*) and phase angle (δ) using different equipment. Regardless of the method, it is envisioned that the additional testing would require additional laboratory staffing hours.
New AC or ACOL mix properties	New AC, AC/AC, AC/JPCP	● New Method	●		✓	✓	Another significant testing change is using laboratory testing (Level 1) to determine AC mix properties. For Level 1, dynamic modulus (E*) testing is required. Similar to the new testing of AC binders, conducting E* testing most likely requires new equipment and additional testing, and additional staffing hours and training.

Notes:

- The level of additional required effort/testing is indicated in the table by the following symbols: ○ = Minimal, ◑ = Moderate, ● = Significant, ✓ = Required.
- This table includes all variables that have changes from current SDDOT practices.

Table 5-10. Summary of additional resources needed (continued).

Input Parameter	Pavement Type	Additional Required Testing and Staffing Effort			Equipment and Training Needs		Notes
		Additional Testing	**Additional Staff Hours**	**Information Technology Staff Time**	**New Equipment**	**Staff Training**	
AC creep compliance	New AC, AC/AC, AC/JPCP						While SDDOT is not currently measuring AC creep compliance data directly, the recommended Level 3 approach of using default values in the MEPDG software and Guide results in no additional needed resources at this time.
Existing fractured JPCP thickness	AC/JPCP	●		◑			If SDDOT is not currently determining this thickness as part of the design process, it is recommended that cores be taken to more accurately determine JPCP layer thickness as part of the new MEPDG design process.
Existing Condition (Rehabilitation Level) for AC/JPCP	AC/JPCP						For completeness, this variable is included in this table because the current SDDOT input Level is at Level 2 while a Level 3 input is recommended. As stated previously, the software interface for this input is confusing in that it is under the heading of “Flexible Rehabilitation.” Also, some of the inputs for Levels 1 and 2 ask for flexible pavement-related condition information such as “total rutting” and “milled thickness.” Because of this confusion a Level 3 subjective pavement rating is recommended. No additional resources are required to make this simplification.
Existing Condition (Rehabilitation Level) for AC/AC	AC/AC						For completeness, this variable is also included in this table because the current SDDOT input is at Level 1 while a Level 2 input is recommended. As stated previously, the Level 1 approach required FWD data, but the current software interface does accept this testing data. Therefore, the data-collection effort to support this input is simplified by limiting the process to using Level 2 distress observation data. No additional resources are required to make this simplification.
Existing AC binder properties	AC/AC	●		◑			For this input, binder-related testing needs to be conducted on materials extracted (cores) from the existing AC pavement. The Level 3 method requires Superpave binder grading, conventional viscosity grade, or conventional penetration grade to estimate a temperature-viscosity relationship for the binder. This testing represents a significant change in current SDDOT procedures.
Existing AC mix properties	AC/AC	●		◑			The Level 3 procedure for this input requires gradation information of the mix. Laboratory testing will be conducted on materials extracted (cores) from the existing AC pavement. This testing represents a significant change in current SDDOT procedures. Note that the level for this input will need to be revisited when Level 1 and 2 methods become better established in the software.

Notes:

- The level of additional required effort/testing is indicated in the table by the following symbols: ○ = Minimal, ◑ = Moderate, ● = Significant, ✓ = Required.
- This table includes all variables that have changes from current SDDOT practices.

Table 5-11. Summary of information associated with new or additional laboratory testing requirements for base layers.

Input Parameter	Design Type	Target Level	Testing Description	Test Method	SDDOT Equipment Needs	Time Per Test
BASE-RELATED VARIABLES						
Base resilient modulus	JPCP, CRCP, New AC, AC/AC, AC/JPCP	2	The focus of any base resilient modulus testing is to determine representative values for the typical SDDOT bases. For Level 2, resilient modulus values are determined by correlating to another material index or strength property (i.e., CBR, R-value, AASHTO layer coefficient, PI and gradation, or penetration from DCP). Therefore, resilient modulus values can be determined by either 1) correlating to historical data, or 2) conducting new field testing on various projects to determine typical base properties.	Recommended correlations to different field testing results are summarized in table 2.2.50 on p. 2.2.68 of the MEPDG guide. If needed, test standards for the discussed material indices and strength properties are the following: • CBR (AASHTO T193). • R-value (AASHTO T190). • AASHTO layer coefficient (AASHTO Guide for the Design of Pavement Structures). • PI and gradation (AASHTO T27 and T90). • DCP (ASTM D 6951).	Because Level 2 uses correlations to many different well-established field testing methods, no new equipment is required.	Not applicable
Base plasticity index	JPCP, CRCP, New AC, AC/AC, AC/JPCP	N/A	As with base resilient modulus, the focus of any base plasticity index testing is to determine representative values for the typical SDDOT bases. Therefore, plasticity index values can be determined by either 1) reviewing historical testing data, or 2) conducting new laboratory testing on base material samples to determine typical values. Any technician experienced in soils testing can easily conduct needed testing.	If laboratory testing is required, plasticity index testing should be conducted in accordance with AASHTO T90 and T89.	SDDOT currently owns all needed equipment to conduct plasticity index testing.	Test duration: Less than 1 day Technician time per test: 1 hour

Table 5-12. Summary of information associated with new or additional laboratory testing requirements for PCC layers.

Input Parameter	Design Type	Target Level	Testing Description	Test Method	SDDOT Equipment Needs	Time Per Test
JPCP- AND CRCP-RELATED VARIABLES						
PCC strength	JPCP, CRCP	2	For Level 2, PCC flexural strength (used in the actual models) is estimated from compressive strength (f'c) values at 7, 14, 28, and 90 days.	Level 2 compressive strength testing requires laboratory testing of design mixes prior to the construction of the project. All specimen preparation and testing should be conducted in accordance with AASHTO T22.	SDDOT currently owns all needed equipment to prepare and conduct compressive testing of PCC cylinder specimens.	Test duration: 90 days Technician time per test: 8 hours
PCC coefficient of thermal expansion	JPCP, CRCP	1	The MEPDG predictions are very sensitive to this variable. Level 1 requires COTE laboratory testing of design mixes prior to the construction of the project. Technicians should be experienced using sample instrumentation and computers.	COTE testing is conducted on prepared PCC cylinders. All specimen preparation and testing should be conducted in accordance with AASHTO TP60. Specifically, the standard features of a COTE test set-up include the following: • Concrete saw for creating specimens. • Balance with capacity of 44 lbs and accuracy of 0.1%. • Caliper or other device to measure specimen length to nearest 0.004 in. • Water bath with temperature range of 50 to 122 °F, capable of controlling temperature to 0.2 °F. • Support frame that has minimal influence on length change measurements. • Temperature measuring devices with resolution of 0.2 °F and accurate to 0.4 °F. • Submersible LVDT gage with minimum resolution of 0.00001 in and typical measuring range of ± 0.1 in. • Micrometer or other calibration device for LVDT with minimum resolution of 0.00001 in.	SDDOT does not currently own the COTE test equipment. The cost for this testing equipment is approximately $15,000.	Test duration: Approximately 1 week Technician time per test: 10 hours

Table 5-13. Summary of information associated with new or additional laboratory testing requirements for AC layers.

Input Parameter	Design Type	Target Level	Testing Description	Test Method	SDDOT Equipment Needs	Time Per Test
AC SURFACE-RELATED VARIABLES						
New AC or ACOL binder properties	New AC, AC/AC, AC/JPCP	1 and 2 (same method)	Asphalt binder testing is needed to develop a viscosity temperature relationship for Levels 1 and 2 and to assist in developing the shift factors for Level 1 designs. The MEPDG recommends the dynamic shear rheometer (DSR) for this testing.	AASHTO T315 is the test method for the DSR. This test is run as part of the Superpave performance grading system; therefore, developing a database of test results should be relatively easy. The complex modulus (G*) and phase angle (δ) will have to be determined at additional temperatures.	SDDOT currently owns all needed equipment to conduct binder testing at Level 1 and 2. The equipment was provided to the SDDOT as part of a pooled fund purchase in the 1990s.	Test duration: Less than 1 day Technician time per test: 4 hours
New AC or ACOL mix properties	New AC, AC/AC, AC/JPCP	1	Dynamic Modulus Testing—For Level 1 designs, E* testing is required. Mixture should be short-term aged (AASHTO R30) prior to compacting the sample.	Available test methods include AASHTO TP62 and NCHRP 1-28A. AASHTO TP62 requires the use of the Simple Performance Tester (SPT) recommended during NCHRP 9-29. NCHRP 1-28A can be conducted with most servo-hydraulic systems that include an environmental chamber. A Superpave Gyratory Compactor, capable of compacting samples that are 6.7 in (170 mm) in height, is needed for the SPT testing.	SDDOT does not currently own the SPT equipment or the Gyratory Compactor equipment required to prepare SPT samples. The cost of the SPT is approximately $40,000 to $50,000. The cost of the Gyratory Compactor is approximately $25,000.	Test duration: Approximately 5 days; however, test times can be longer if target air void contents are not met. Technician time per test: 24 hours
Existing AC binder properties	AC/AC	3	For Level 3, asphalt binder is recovered from cores and tested using one of three methods to determine the binder's performance grade (PG), viscosity grade, or penetration grade.	One of the following methods applies: • Performance grade is determined using AASHTO M320. Regression intercept (A) and regression slope of viscosity temperature susceptibility (VTS) parameters are estimated from table 2.2.10 in the MEPDG documentation. • Viscosity grade is determined using AASHTO M226. *A* and *VTS* are estimated from table 2.2.11 in the MEPDG documentation. • Penetration grade is determined using AASHTO M20. *A* and *VTS* are estimated from table 2.2.12 in the MEPDG documentation.	SDDOT currently owns all needed equipment to conduct binder testing using any of these three methods.	Test duration: Less than 1 day Technician time per test: 5 hours (not including coring time)
Existing AC mix properties	AC/AC	3	For Level 3, the gradation of the existing AC mix is determined from conducting a sieve analysis on material collected from the existing pavement (i.e., cores).	Aggregates obtained after extracting bitumen from cores can be used for the sieve analysis. Bitumen extraction is conducted in accordance with ASTM D2172, while sieve analyses of aggregate are conducted in accordance with AASHTO T27.	SDDOT currently owns all needed equipment to conduct sieve analyses.	Test duration: Less than 1 day Technician time per test: 3 hours (not including coring time)

While it is recommended that model-recalibration activities not be considered until SDDOT personnel have had a chance to review and gain considerable experience using version 1.0 of the MEPDG software, the following two preliminary steps can be initiated now:

1. Review the distress definitions and measurement protocols associated with both the MEPDG models and the current SDDOT PMS, and develop a plan for resolving any differences between the two.
2. When available, review the *Local Calibration Guidance for the Recommended Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures* (developed under project NCHRP 1-40B) and conduct any additional preliminary activities necessary for implementing the recommended model-calibration procedure.

The remainder of this section contains separate discussions of both of these recommended preliminary activities.

Preparation of the Pavement Management Data for Use in Model Calibration

The calibration of the performance models included in the MEPDG software requires the use of comparable pavement performance data for each distress type. Because the SDDOT PMS is the most logical source for data to calibrate the MEPDG models, any discrepancies between the current PMS data and the required distress data for the MEPDG must be resolved before going forward. Therefore, one of the steps of the implementation process is to concurrently review the distress definitions and measurement protocols associated with both the MEPDG models and the current SDDOT PMS, and develop a plan for resolving any differences.

The MEPDG considers both structural and functional pavement performance characteristics in its estimates of predicted pavement damage. The International Roughness Index (IRI), a functional performance indicator, is used to forecast pavement smoothness using the initial as-constructed IRI and changes in smoothness due to the propagation of distress, site factors (such as subgrade), and maintenance activities.

For flexible pavements, smoothness is based on the amount of load-related fatigue cracking (including both bottom-up and top-down fatigue cracking), thermal cracking, and permanent deformation (rutting) (NCHRP 2004). The distress considered in rigid pavements includes faulting and transverse cracking, and punchouts on CRCP (NCHRP 2004).

The recalibration of the models incorporated into the MEPDG software requires the use of comparable pavement performance data for each distress type. To determine how comparable the pavement distress data collected as part of SDDOT's pavement management surveys are to the MEPDG models involves a two-step process. First, the types of distress being collected by the SDDOT are matched to the distress models used in the MEPDG software and then the manner in which distress severity and extent are determined is compared. The first step in this process involves matching the MEPDG distress types with the distress currently collected as part of SDDOT's pavement management activities. The general differences between the included distress types for both flexible and rigid pavement types are presented in table 5-14.

Table 5-14. Distress type comparison (FHWA 2003; SDDOT 2005).

MEPDG Distress Type	SDDOT Pavement Management Distress Type	Comments
Flexible Pavement Distress		
Fatigue Cracking (top-down and bottom-up)	Fatigue Cracking (assumed to be bottom-up)	No differentiation for top-down fatigue cracking in the current SDDOT measurement protocols; however, the identification of top-down cracking requires coring which is not practical on a network level.
Thermal Cracking	Transverse Cracking	Comparable, but SDDOT-measured transverse cracking may not be limited to thermal cracking
Permanent Deformation (rutting in AC layer and total rutting)	Rutting (total rutting)	SDDOT measurements are comparable to the MEPDG total rutting model. SDDOT does not currently measure AC layer rutting; however, this measurement is not practical on a network level.
IRI	IRI	Comparable
Rigid Pavement Distress		
Faulting	Faulting	Comparable
Transverse Cracking	No equivalent distress measurement	Not currently collected by SDDOT
Punchouts (CRCP only)	Punchouts	Comparable
IRI	IRI	Comparable

A comparison of the distress data in table 5-14 shows the SDDOT pavement condition survey procedures include the majority of distress types incorporated into the MEPDG models. Notable exceptions where the distress measurement protocols differ include the measurement of fatigue cracking and rutting on flexible pavements, and the lack of measurement of transverse cracking on rigid pavements. Each of these discrepancies is discussed in more detail below.

For fatigue cracking on flexible pavements, the MEPDG has separate models for top-down and bottom-up cracking that are not differentiated in the SDDOT pavement condition surveys. In the SDDOT procedure, fatigue cracking is representative of any longitudinal cracking in the wheel path. Because there is no easy way to determine if a longitudinal crack is a top-down crack (i.e., without coring), it is currently recommended that the SDDOT-measured fatigue cracking data be used to calibrate the MEPDG bottom-up fatigue cracking model only. It is then recommended that the MEPDG default top-down fatigue cracking model be used without calibration; however, the results of the top-down fatigue cracking model should be carefully monitored to judge the model’s reasonableness. By taking this approach, no changes to the SDDOT flexible pavement fatigue cracking measurement protocols are deemed necessary.

For rutting on flexible pavements, the MEPDG has separate models for AC layer rutting and total rutting. Because there is no easy way to determine AC layer rutting (i.e., without coring), it is currently recommended that the SDDOT-measured rutting data be used to calibrate the MEPDG total rutting model only. It is then recommended that the MEPDG default AC layer rutting model be used without calibration; however, the results of this model should be carefully monitored to judge the model’s reasonableness. By taking this approach, no changes to the SDDOT rutting measurement protocols are deemed necessary at this time.

For rigid pavements, while the MEPDG includes a transverse cracking model, the SDDOT does not currently measure this distress. However, because the transverse cracking model in the MEPDG approach is an important indicator of the pavement’s structural condition, it is recommended that this model be calibrated with actual SDDOT data. If the SDDOT wants to use the pavement management data as the primary source for calibrating all included MEPDG models, it is recommended that the SDDOT consider changing the current PMS data collection protocols to include the measurement of transverse cracking on rigid pavements.

The second step in evaluating the appropriateness of the distress data for use in calibrating the MEPDG models is comparing the definitions used to define distress severity and extent. The MEDPG calibration was based on distress definitions found in the *Distress Identification Manual for the Long-Term Pavement Performance Program* (FHWA 2003). Therefore, for the pavement management distress information to be comparable, it is important that similar procedures are used in South Dakota. Fortunately, at the time the SDDOT developed its pavement condition survey procedures, the distress severities and extents were developed based on the 1993 edition of the *Distress Identification Manual*. However, some changes were made to better reflect conditions that existed in South Dakota. A comparison of the definitions used in calibrating the MEPDG models and those used by the SDDOT is presented in tables 5-15 and 5-16 for flexible and rigid pavements, respectively. Only those distress types that are used in both procedures are included in these tables.

As shown in tables 5-15 and 5-16, there are significant differences in the definitions used to describe distress severity and extent between the two approaches. The magnitude of these differences will need to be explored further during the calibration process. While differences in the definitions of medium- and high-severity levels are not expected to be significant (because the MEPDG models combine all severity levels), the calibration process could be affected if there is a difference in how a low-severity distress is defined. That is, if there is a significant difference in the protocols, one protocol might identify an occurrence of a distress as being low severity, while another protocol may not yet classify that occurrence as a distress. Such a difference in protocols could have a significant impact on the amount of identified distress at any given time, and therefore, may cause difficulty during the calibration steps. None of these types of differences is currently evident in the SDDOT distress definitions.

Based on the results of the side-by-side comparison of MEPDG and SDDOT distress types and definitions, the only current recommended change to the SDDOT distress identification procedures is the measurement of transverse cracking on rigid pavements. Although the current SDDOT PMS data collection procedures do not include the measurement of top-down longitudinal cracking and AC layer rutting on flexible pavements, it is recommended that the default models for those distresses be used at this time.

Table 5-15. Comparison of distress severity and extent definitions for flexible pavements (FHWA 2003; SDDOT 2005).

Topic	Primary LTPP Definitions	SDDOT Definitions
Fatigue Cracking		
Definition of *Low* severity	An area of cracks with no or only a few connecting cracks	Fine parallel cracks in the wheel path
Definition of *Medium* severity	An area of interconnected cracks forming a complete pattern	Alligator pattern clearly developed
Definition of *High* severity	An area of moderately or severely spalled interconnected cracks forming a complete pattern	Alligator pattern clearly developed with spalling and distortion
Measurement Notes	Square meters of affected area at each severity level	Low: 1 to 9% of wheel path Moderate: 10 to 24% of wheel path High: 25 to 49% of wheel path Extreme: >40% of wheel path
Thermal Cracking (Transverse Cracking)		
Definition of *Low* severity	An unsealed crack ≤ 0.25 in or a sealed crack with sealant material in good condition	Crack width is ≤ 0.25 in or routed and sealed crack width < 0.5 in
Definition of *Medium* severity	Any crack with a mean width > 0.25 in and ≤ 0.75 in	Crack width is > 0.25 in and < 1 in or depression caused by crack is < 0.25 in
Definition of *High* severity	Any crack with a mean width > 0.75 in	Crack width is > 1 in or crack width is > 0.25 mm and depression caused by crack is > 0.25 in
Measurement Notes	Number and length at each severity level	Low: > 50-ft avg. spacing Moderate: < 50-ft and > 25-ft avg. spacing High: < 25-ft avg. spacing
Permanent Deformation (Rutting)		
Definition of *Low* severity	Not Applicable	< 0.125 in
Definition of *Medium* severity	Not Applicable	0.125 to 0.25 in
Definition of *High* severity	Not Applicable	0.25 to 0.5 in
Definition of *Extreme* severity	Not Applicable	> 0.5 in
Measurement Notes	Measured with a Dipstick profiler at 50-ft intervals	Measured using automated equipment

Determination of the Specific Procedures to be Used for Calibrating and Validating the MEPDG Performance Prediction Models to Local Conditions

The term *calibration* refers to the mathematical process through which the total error or difference between observed and predicted values of distress is minimized (NCHRP 2003b). The term *validation* refers to the process to confirm that the calibrated model can produce robust and accurate predictions for cases other than those used for model calibration (NCHRP 2003b).

Table 5-16. Comparison of distress severity and extent definitions for rigid pavements (FHWA 2003; SDDOT 2005).

Topic	Primary LTPP Definitions	SDDOT Definitions
Faulting		
Definition of *Low* severity	Not Applicable	0.1 to 0.2 in
Definition of *Medium* severity	Not Applicable	0.2 to 0.3 in
Definition of *High* severity	Not Applicable	> 0.3 in
Measurement Notes	Record in millimeters, to the nearest millimeter: 1 ft and 2.5 ft from the outside slab edge	Low: 1 to 9% of slabs Moderate: 10 to 24% of slabs High: 25 to 49% of slabs Extreme: > 49% of slabs Measured using automated equipment
Punchouts		
Definition of *Low* severity	Longitudinal and transverse cracks are tight and may have spalling < 3 in or faulting < 0.25 in with no loss of material and no patching	Not applicable
Definition of *Medium* severity	Spalling ≥ 3 in and < 6 in or faulting ≥ 0.25 in and < 0.5 in exists	Not applicable
Definition of *High* severity	Spalling ≥ 6 in	Not applicable
Measurement Notes	Record number of punchouts at each severity level	Low: < 10 per mile Moderate: 10 to 25 per mile High: > 25 per mile

As mentioned previously, in order for the MEPDG performance models to more accurately predict pavement performance typical of local South Dakota conditions, the default national performance models in the MEPDG must be recalibrated using South Dakota-specific data sets. The developers of the MEPDG are currently preparing specific guidelines that outline recommended model calibration and validation procedures. These guidelines are being developed under NCHRP research project 1-40B and will be published in a document titled *Local Calibration Guidance for the Recommended Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures*. At the time of the writing of this final report, this document is not yet available (this final document is expected to be published in the latter half of 2007), therefore, it is premature to discuss the specific steps SDDOT will need to perform to recalibrate a model. It is, however, expected that this process will include the detailed guidelines for 1) identifying whether a particular model needs to be calibrated, and 2) calibrating and validating those models where recalibration is deemed necessary.

While the project team is not currently privy to the detailed calibration and validation procedures being recommended under the NCHRP 1-40B project, past research efforts indicate the recommended method will be based on the *split-sample jackknifing* approach (as outlined in NCHRP Project 9-30 "Experimental Plan for Calibration and Validation of HMA Performance Models for Mix and Structural Design"). The split-sample jackknifing approach (a combination of the separate jackknifing and split-sample validation methods) is a statistical method that uses a single database to both calibrate and validate a given model. This is an important concept in the calibration and validation of pavement performance prediction models because actual distress data are expensive and time consuming to collect (NCHRP 2003b). More detailed information on the use of the split-sample jackknifing approach is currently available in two NCHRP Research Results Digests 283 and 284 (NCHRP 2003a; NCHRP 2003b).

Within the MEPDG design program, calibration factors will be used to adjust the distress predictions to reflect the performance characteristics expected in South Dakota. This will involve an iterative process in which the calibration factors are adjusted until they fall within a tolerance range. This process is illustrated in figure 5-4.

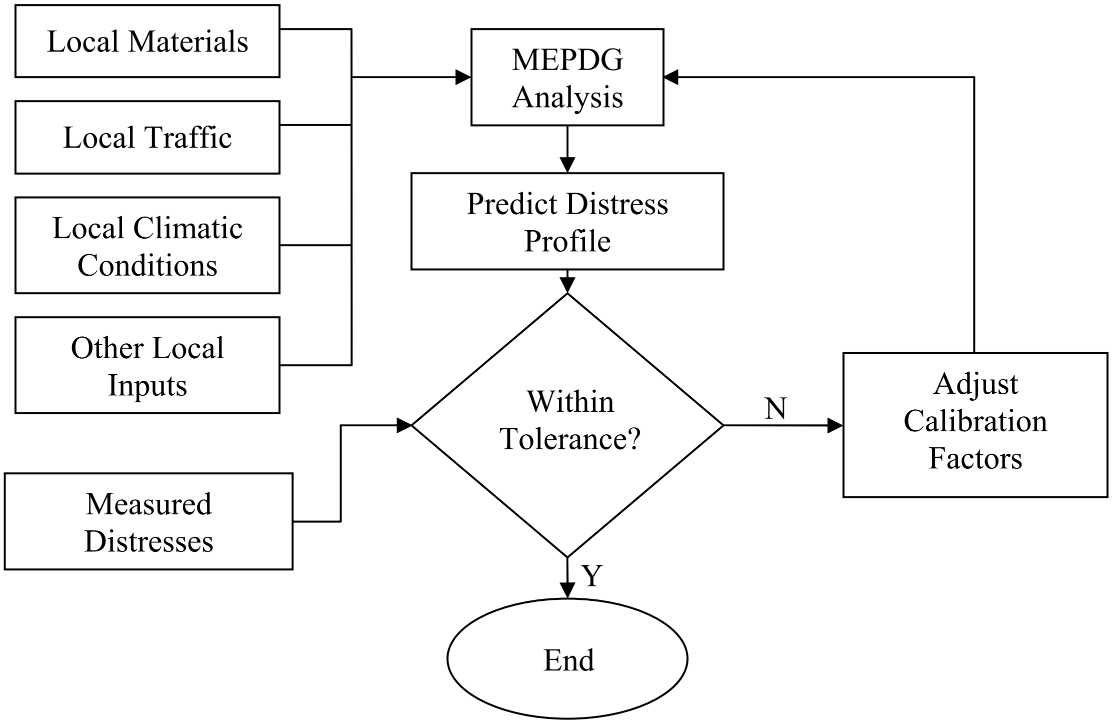

Figure 5-4. Calibration process.

5.6 Implementation Plan

One of the most important tasks of this project was the development of the MEPDG implementation plan. The MEPDG implementation plan is a stand-alone document that outlines the types of activities the SDDOT will need to complete over the next 3 years to ready itself for adopting and implementing the MEPDG as the primary pavement design tool in South Dakota. The basic implementation plan consists of twelve general steps, many of which will be completed concurrently. These twelve general implementation steps consist of the following:

1. Conduct sensitivity analysis of MEPDG inputs.
2. Recommend MEPDG input levels and required resources to obtain those inputs.
3. Obtain necessary testing equipment to implement the MEPDG at the target MEPDG input levels.
4. Review version 1.0 of the MEPDG software.
5. Form a SDDOT MEPDG Implementation Team and develop and implement a communication plan.
6. Conduct staff training.
7. Develop formal SDDOT-specific MEPDG-related documentation.
8. Develop and populate a central database (or databases) with required MEPDG input values.
9. Resolve differences between the MEPDG predicted distresses and those currently collected for the SDDOT pavement management system (PMS).
10. Calibrate and validate MEPDG performance prediction models to local conditions.
11. Define the long-term plan for adopting the MEPDG design procedure as the official SDDOT pavement design method.
12. Develop a design catalog.

While steps 1 and 2 of the recommended implementation plan steps have been completed under this project, the remaining steps outline the work that will prepare the SDDOT for making a decision on when or if to adopt the new MEPDG as its primary design method. One of the most important recommendations under the implementation plan is the formation of a SDDOT

MEPDG Implementation Team. While the presented implementation plan provides some general guidance on the tasks that are foreseen as part of the MEPDG implementation, the detailed decisions and guidance on these tasks will need to come directly from the SDDOT MEPDG Implementation Team. The final stand-alone implementation plan is presented as Appendix E to this report (i.e., *South Dakota MEPDG Implementation Plan*).

6.0 IMPLEMENTATION RECOMMENDATIONS

Chapter 5 presents the findings and conclusions that were generated from the research work on this project. In this chapter, the research team presents the resulting recommendations that will guide the SDDOT through the implementation of the research results. The following five recommendations are presented for consideration by the Technical Panel.

1. <u>Adopt the prepared SDDOT implementation plan</u>. One product from this research project is the stand-alone SDDOT MEPDG implementation plan (included as Appendix E to this report). This implementation plan is a stand-alone document that outlines twelve different MEPDG-related activities that are recommended to be completed over the next 3 years. One of the most important recommended activities in the implementation plan is the formation of a SDDOT MEPDG Implementation Team that will be responsible for directing the Department's MEPDG-related activities and achieved milestones. Other included implementation steps focus on needed activities such as conducting necessary training, developing necessary SDDOT-specific MEPDG-related documentation, building databases used to store necessary MEPDG inputs, and preparing for the validation and calibration of MEPDG models to SDDOT local conditions. It is recommended that this current implementation plan be adopted to provide a working road map toward the expected full implementation of the MEPDG design guide in the future.
2. <u>Continue to focus on gaining experience with the MEPDG design method while moving toward the planned adoption of the MEPDG approach as the primary pavement design method in South Dakota</u>. It is recognized that the current MEPDG utilizes a very sound pavement design approach that when finalized, is expected to be a very valuable tool that can be used to optimize both new and rehabilitation pavement designs. However, it is also recognized that the current versions of the guide documentation and accompanying software (version 0.9) reviewed under this project are still in draft states. Because version 0.9 of the software is considered a "beta" version of the software (i.e., it is functionally complete, but still contains recognized inconsistencies or "bugs"), it is recommended that SDDOT continue to review later versions of the software and stay abreast of documented improvements to both the MEPDG software and documentation. As indicated in step 10 of the implementation plan, over the next 3 years, it is

recommended that a "shadow" MEPDG analysis be conducted alongside every pavement design conducted using the currently accepted pavement design procedure (i.e., the 1993 AASHTO guide). The primary purpose of this exercise is to produce and review expected performance data for given pavement designs, with the ultimate goal of gaining confidence in the MEPDG predicted performance. All selected MEPDG inputs and collected performance data should be recorded and stored so it can be used in future calibration and validation efforts. The final decision to officially adopt the MEPDG design procedure as SDDOT's official pavement design procedure rests with the SDDOT MEPDG Implementation Team. Such a decision should not be made until the SDDOT MEPDG Implementation Team members have great confidence that the calibrated and validated MEPDG performance models are predicting distress values that are reasonable and considered to be acceptably accurate for South Dakota conditions.

3. Review the distress definitions and measurement protocols associated with both the MEPDG models and the current SDDOT pavement management system (PMS), and develop a plan for resolving any differences between the two. Because the SDDOT PMS is the most logical source for data to calibrate the MEPDG models, any discrepancies between the current PMS data and the required distress data for the MEPDG must be resolved before going forward with any calibration activities. During the current research activities, a cursory comparison of these measurement protocols was conducted, and some of the general differences were documented. One such noted difference is that the MEPDG differentiates longitudinal cracking between "top-down fatigue" and "bottom-up fatigue," whereas the SDDOT protocols do not. Therefore, it is recommended that the differences between the MEPDG and SDDOT distress definitions and measurement protocols be investigated in more detail with the focus on finalizing a plan that outlines the use of PMS data in the calibration of the MEPDG distress models.
4. Review the *Local Calibration Guidance for the Recommended Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures* final report (developed under project NCHRP 1-40B) and conduct any additional preliminary activities necessary for implementing the recommended model-calibration procedure. In order for the MEPDG performance models to more accurately predict pavement performance typical of local South Dakota conditions, the default national performance models in the

MEPDG must be recalibrated using South Dakota-specific data sets. The developers of the MEPDG are currently preparing specific guidelines that outline recommended model calibration and validation procedures. These guidelines are being developed under NCHRP research project 1-40B and will be published in a document titled Local Calibration Guidance for the Recommended Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures. At the time of the writing of this final report this document is not yet available (this final document is expected to be published in the latter half of 2007), therefore, no specific guidance on calibrating SDDOT models has been provided under the current research. When available, it is recommended that SDDOT review the NCHRP 1-40B report and use its information to develop a calibration plan that can be used to 1) identify whether or not a particular model needs to be calibrated, and 2) identify the specific procedures required to calibrate and validate those models where recalibration is deemed necessary.

5. <u>Implement identified data-testing protocols at the MEPDG input target levels</u>. The majority of the work conducted under the current research project focused on determining the most appropriate MEPDG input level for each MEPDG input, and outlining the data testing protocol associated with that target input. Therefore, in preparation for the continued investigation of the MEPDG method, it is recommended that the SDDOT move toward implementing sampling and testing all MEPDG-related inputs at the identified target levels. In many cases, this requires the use of new sampling or testing methods, or the conduction of more sampling and testing than is required under current SDDOT practices. All of these recommended sampling and testing protocols are outlined in Chapter 5 of this report.

7.0 ANALYSIS OF RESEARCH BENEFITS

In its report documenting the development of the new design procedures, *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures*, the authors estimate that collectively, highway agencies could save approximately $1.3 billion per year if the savings that result from better pavement designs improve performance by only 10 percent (approximately half of what is expected) (NCHRP 2004). The authors further estimate that savings to the users of the facility could approximate $350 million per year on the interstate network alone from increased smoothness, fewer lane closures, and less congestion (NCHRP 2004).

The portion of these benefits that will be realized by the SDDOT and its highway facility users is difficult to estimate at this time without a clearer understanding of the differences in pavement performance that will be realized by the Department's implementation of the new MEPDG. However, improvements in pavement performance, if realized, have a direct benefit to the Department in terms of longer pavement design life and its corresponding reduction in pavement rehabilitation needs, better overall network conditions, and smoother roads for the traveling public.

It is expected that additional cost savings can be realized by SDDOT if the MEPDG approach is eventually used to optimize the typical pavement designs. The optimization of pavement design involves investigating tradeoffs between different design features (e.g., slab thickness, base type, and dowel diameter for PCC pavements) and monitoring their impact on both performance and costs. The goal of this step would be to find the optimal combination of design features that maximizes performance while minimizing costs. After the SDDOT is able to gain some confidence in the performance values predicted from the MEPDG software, it is expected that this design optimization is the next logical step in the implementation process. If current pavement designs are able to be optimized, this improvement should result in better performing pavements, less required maintenance, and delayed future rehabilitation activities. Reduced maintenance and delayed rehabilitation activities directly translate into cost savings that would be expected to be realized by SDDOT.

Several direct benefits to the SDDOT will be realized as a result of the activities conducted during this research effort. These benefits are expected to include the following:

1. A better understanding of the inputs required to tailor the new MEPDG to conditions in South Dakota and the availability of those inputs within existing data sources.
2. Knowledge of the impact that each input has on predicted pavement performance so the Department can make the most cost-effective use of its data-collection resources.
3. An understanding of the resources required to implement the MEPDG at the most desirable input level.
4. A detailed implementation plan that included recommended activities to be conducted over the next three years.
5. A strategy for altering the current SDDOT PMS data-collection activities (as needed) in preparation for the future calibration of the pavement performance models to conditions in South Dakota.

As a result, the SDDOT will be better prepared to evaluate the options available for the implementation of the new design procedure so that informed, knowledgeable decisions are made regarding the commitment of additional resources to implementation.

8.0 REFERENCES

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APPENDIX A: LITERATURE REVIEW RESULTS

Introduction

During this project, the research team conducted a comprehensive literature search to locate documents associated with the development and implementation of the mechanistic-empirical pavement design guide (MEPDG), with the specific focus on the experiences of other state highway agencies (SHAs). The results of the focused literature search are summarized in this appendix.

This appendix begins by providing a brief history of the American Association of State Highway and Transportation Officials (AASHTO) pavement design procedure and describing the need for moving toward a more substantial mechanistic-empirical-based approach. Next, this introductory material is followed by an explanation of many of the general concepts and required inputs of the MEPDG approach that make it different from older design methods. Finally, some basic recommendations for implementing the MEPDG are discussed, followed by a summary of other SHA past and ongoing implementation and MEPDG-research efforts.

History

In the late 1950s, the *AASHO road test* was constructed in Ottawa, Illinois, for the primary purpose of developing a fair tax scheme for different vehicle types based on fuel consumption (Galal and Chehab 2005; Smith, Zimmerman, and Finn 2004). From 1958 to 1960, just over one million loads were applied to the test sections and their performance histories were recorded. Eventually, the design data of the carefully controlled test sections and the measured traffic and performance histories formed the basis for the 1972 AASHO design guide. The 1972 design guide was innovative in many ways, including the fact that it introduced many design concepts that have withstood the test of time, such as present serviceability index (PSI), traffic damage factors and equivalent single-axle loads (ESALs), and the structural number (SN). The 1972 Guide was revised in 1986 and again in 1993, the latter revision only focusing on pavement overlay design procedures (AASHTO 1993).

The majority of State department of transportations have adopted a version of the AASHTO design guide as their method for designing new and rehabilitated designs for their pavement structures. In a 2004 survey of state agency pavement design practices, 24 of the 49 responding agencies (51 percent) indicated that they use the 1993 AASHTO guide, 3 agencies (6 percent) stated that they still use the 1972 AASHTO guide, 14 agencies (29 percent) use a combination of AASHTO and State practices, while the rest use another design procedure (FHWA 2004). As the SDDOT currently uses the 1993 AASHTO design guide, this section introduces the new MEPDG concepts, reviews the significant differences in methodology and inputs between the 1993 guide and the MEPDG, and summarizes some of the implementation activities under way in other SHAs.

Need for the Development of the New M-E Pavement Design Guide

While the original versions of the *AASHTO Guide for Design of Pavement Structures* (i.e., 1972, 1986, and 1993) have served the pavement design community well, the fact that all of these previous versions are based on the empirical results of one road test in the late 1950s led to an obvious need for an improved pavement design procedure. The most notable limitations of the previous AASHTO design guide versions are the following (NCHRP 2004):

- **Traffic loading deficiencies**—The pavements at the original AASHTO road test received just over one million axle load replications. Because modern-day projects are typically subjected to much greater traffic levels, these designs extrapolate the design methodology far beyond the inference space of the original model. In addition, truck characteristics have also changed significantly from the late 1950s, with the most significant changes being made to vehicle suspensions, axle configurations, and tire types and pressures.
- **Climatic effects deficiencies—**Because the AASHTO Road Test was conducted at one specific geographic location (i.e., Ottawa, Illinois), its results are only directly applicable to the climate representative of that one location. The short duration of the original AASHTO road test (conducted over 2 years) was also not adequate to observe the long-term effects of climate and material aging on pavement performance.
- **Surfacing materials deficiencies—**Only one hot mix asphalt (HMA) mixture and one portland cement concrete (PCC) mixture were used at the AASHTO Road Test. Today, there are many newer types of HMA and PCC mixtures (e.g., Superpave, stone-matrix asphalt, high-strength PCC, and so on) that are not correctly represented in the previous versions of the AASHTO design guide.
- **Base course deficiencies—**Only two unbound, dense granular base/subbase materials were included in the main flexible and rigid pavement sections at the AASHO Road Test (limited testing of stabilized bases was included for flexible pavements). The higher-

quality base materials routinely used in today's pavement designs are not fully represented in the previous versions of the design guide.

- **Performance deficiencies—**While the previous versions of the AASHTO guide are based on an underlying correlation between surface layer thicknesses and serviceability, research over the years has shown that pavements often require rehabilitation for reasons that might not be related to the thickness of the pavement layers (e.g., rutting, thermal cracking, joint faulting).

The inherent limitations of the early versions of the AASHTO design guide created a need for the development of a new pavement design guide based on more fundamental engineering principles and relationships. In the mid-1990s, the AASHTO Joint Task Force on Pavements (JTFP) proposed research to develop a pavement design guide based on M-E principles with numerical models calibrated with pavement-performance data from the Long Term Pavement Performance (LTPP) program (AASHTO 2004). This research has been conducted as National Cooperative Highway Research Program (NCHRP) Project 1-37A under the oversight of an NCHRP technical panel with membership drawn from State DOTs representing the JTFP, the HMA and PCC paving industries, academia, and FHWA (AASHTO 2004). A draft version of the new MEPDG and its accompanying software were recently completed and distributed for review in 2004.

While previous versions of the design guide are strictly based on empirical relationships of performance data (i.e., statistical regression models of performance measurements or observations at the AASHTO road test), the new M-E procedure analyzes input data for traffic, climate, materials, and proposed structure to estimate damage accumulation over the service life of the pavement (AASHTO 2004). The fundamental differences between the new approach to pavement design and the approach used in the older versions of the AASHTO design guide are best explained in this excerpt from the new guide document (NCHRP 2004):

> *The Design Guide represents a major change in the way pavement design is performed. The designer first considers site conditions (traffic, climate, subgrade, existing pavement condition for rehabilitation) and construction conditions in proposing a trial design for a new pavement or rehabilitation. The trial design is then evaluated for adequacy through the prediction of key distresses and smoothness. If the design does not meet desired performance criteria, it is revised and the evaluation process repeated as necessary. Thus, the designer is fully involved in the design process and has the flexibility to consider different design*

> *features and materials for the prevailing site conditions. This approach makes it possible to optimize the design and to more fully ensure that specific distress types will not develop.*

In a recent memo from AASHTO addressing the implementation of the new MEPDG, the benefits of moving to the new guide are documented as the following (AASHTO 2004):

> *The M-E pavement design guide provides significant potential benefits over the 1993 AASHTO design guide in achieving cost-effective pavement designs and rehabilitation strategies. Most importantly, its user-oriented computational software implements an integrated analysis approach for predicting pavement condition over time that accounts for the interaction of traffic, climate, and pavement structure; allows consideration of special loadings with multiple tires or axles; and provides a means for evaluating design variability and reliability. The M-E pavement design guide will allow pavement designers to make better-informed decisions and take cost-effective advantage of new materials and features. The software can also serve as a forensic tool for analyzing the condition of existing pavements and pinpointing deficiencies in past designs.*

Summary of the M-E Pavement Design Guide Approach

Before addressing the detailed inputs required by the new MEPDG, it is important to understand its underlying methodology. First, the new design procedure considers the following types of information in its approach (NCHRP 2004):

- Foundation/subgrade.
- Existing pavement condition (rehabilitation only).
- Paving materials.
- Construction factors.
- Environmental factors (temperature and moisture).
- Traffic loadings.
- Subdrainage.
- Shoulder design.
- Rehabilitation treatments and strategies.
- New pavement and rehabilitation options.
- Pavement performance (key distresses and smoothness).
- Design reliability.
- Life-cycle costs.

The underlying concept of the approach is that the performance of the designed pavement is simulated to determine the expected accumulated damage on a monthly basis over the selected design period. Incremental damage calculations are based on monthly changes of traffic, climate, and material properties that are computed within the design software. Finally, the incremental damage accumulated on a monthly basis is converted into physical pavement distresses and expected smoothness using calibrated models that relate the damage to observable distresses (NCHRP 2004). For flexible pavements, performance is expressed in terms of longitudinal cracking, transverse cracking, fatigue (alligator) cracking, rutting, and smoothness (International Roughness Index [IRI]). For rigid pavements, performance is expressed in terms of faulting, cracking, IRI, and punchouts (for continuously reinforced concrete pavements [CRCP] only).

Required Inputs for the M-E Pavement Design Guide

While the new MEPDG software is used to calculate all of the pavement responses and predict the resulting pavement distresses, each state agency is responsible for gathering the relatively large number of design inputs required by the pavement design approach, many of which are much more sophisticated than those inputs currently being collected by SHAs. This section provides some examples of the more-significant changes between the inputs required by the 1993 design guide and the new MEPDG. It is important to note that this section is not intended to discuss all of the inputs required by the MEPDG, but rather to illustrate some of the significant differences in the inputs required by the 1993 approach and the new MEPDG.

Hierarchical Approach to Inputs

One unique characteristic of the new design guide is that it uses a hierarchical approach to traffic, materials, and environmental design inputs. This hierarchical approach provides the designer with flexibility in obtaining the design inputs for a design project based on the criticality of the project and available resources (NCHRP 2004). The three different levels of inputs are described as the following (NCHRP 2004):

- **Level 1** inputs provide the highest level of accuracy and, thus, the lowest level of uncertainty or error. Level 1 design generally requires project-specific inputs such as material inputs measured by laboratory or field testing, site-specific axle load spectra data, or nondestructive deflection testing. Because such inputs require more time and resources to obtain, Level 1 inputs are generally used for research, forensic studies, or projects where a low probability of failure is important.

- **Level 2** inputs provide an intermediate level of accuracy that is closest to the typical procedures used with earlier editions of the AASHTO guide. Level 2 inputs would most likely be user-selected from an agency database, derived from a limited testing program, or be estimated through correlations. Examples include estimating asphalt concrete dynamic modulus from binder, aggregate, and mix properties; estimating portland cement concrete elastic moduli from compressive strength tests; or using site-specific traffic volume and traffic classification data in conjunction with agency-specific axle load spectra. Level 2 inputs are most applicable for routine projects with no special degree of significance.
- **Level 3** inputs provide the lowest level of accuracy, and are expected to be used with "routine" projects. This level of input is most applicable where there are minimal consequences for early failure (e.g., on low-volume roads). A source for Level 3 inputs could be average values for a particular region or perhaps even "default" values within the software program.

For a given project, inputs may be a mixture of different levels. However, the computation process employed by the software is still the same regardless of the quality of the input data.

Climatic Inputs

In the previous versions of the AASHTO guide, the climatic variables were primarily handled with seasonal adjustment values and the application of drainage coefficients. In the new MEPDG procedure, changing temperature and moisture profiles in the pavement structure and subgrade over the design life of a pavement are fully considered in the design guide by using a sophisticated climatic modeling tool called the Enhanced Integrated Climatic Model (EICM) (NCHRP 2004). The EICM model simulates changes in behavior and characteristics of pavement and subgrade materials in conjunction with climatic conditions over the design life of the pavement (NCHRP 2004). To use this model, a relatively large number of input parameters are needed, including the following (NCHRP 2004):

- **General Information.**
  - Base/subgrade construction completion month and year (for new flexible pavement design only).

  - Existing pavement construction month and year (required for both HMA and PCC overlays only).
  - Pavement construction month and year (required for both new and rehabilitation design.
  - Month and year when the pavement will be opened to traffic after construction.
  - Type of design (new or rehabilitation and HMA or PCC).

- **Weather-Related Information—**To accomplish the climatic analysis required for incremental damage accumulation, the MEPDG approach requires hourly values for air temperature, precipitation, wind speed, percentage sunshine, and relative humidity over the entire design life of the project being designed. This required information is available from nearly 800 weather stations throughout the United States.
- **Groundwater Table Depth—**The depth to the water table at the project site may be determined from the best available information. At input Level 1, the depth to groundwater could be determined from profile characterization borings prior to design. At the Level 3 input level, the water table depth might be determined from county soil reports produced by the National Resources Conservation Service.
- **Drainage and Surface Properties—**These inputs consist of surface short wave absorptivity, water infiltration potential of the pavement over its design life (i.e., none, minor [10 percent of precipitation enters the pavement], moderate [50 percent infiltration], and extreme [100 percent infiltration]), drainage path length, and the pavement cross slope. All of these inputs reflect how well water is kept out of the pavement structure.
- **Pavement Structure Materials—**Material-related inputs that are required for the EICM model include layer thicknesses and assorted material properties for the HMA or PCC layers, such as surface shortwave absorptivity, thermal conductivity (K), and heat or thermal capacity (Q). For unbound materials, the EICM model requires a number of more obscure inputs, including specific gravity, saturated hydraulic conductivity, maximum dry unit weight, dry thermal conductivity, heat capacity, plasticity index, percent passing the number 200, 4, and 60 sieves, optimum gravimetric water, and equilibrium gravimetric water content.

Traffic Inputs

For the traffic analysis, the inputs for the new MEPDG are much more sophisticated than those required by previous versions of the AASHTO design guide. In the 1993 design guide, the primary traffic-related input was the total design 18-kip equivalent single axle loads (ESALs) expected over the design life of the pavement. In contrast, the more sophisticated traffic analysis in the MEPDG uses axle load spectra data, which includes collecting the following traffic-related inputs (NCHRP 2004):

- Base year truck-traffic volume (the year used as the basis for design computations).
- Vehicle (truck) operational speed.
- Truck-traffic directional and lane distribution factors.
- Vehicle (truck) class distribution.
- Axle load distribution factors.
- Axle and wheel base configurations.
- Tire characteristics and inflation pressure.
- Truck lateral distribution factor.
- Truck growth factors.

Keeping with the hierarchical approach to inputs in the guide, the following three levels of traffic data are described in the design guide (NCHRP 2004):

- Level 1 requires project-specific axle load spectra data (including axle loadings by vehicle classification) along or near the roadway segment to be designed.
- Level 2 data is used if modest knowledge of past and future traffic characteristics is available. This typically requires the availability of regional or statewide truck volume and weights.
- Level 3 data represents the case where the designer has poor knowledge of past and future traffic characteristics. For these cases, it is assumed that the designer will use default data from a national database.

Foundation Inputs

In the 1993 AASHTO design guide, the roadbed soil support was characterized through the roadbed soil resilient modulus (M_R). The MEPDG determines the foundation support by using a universal nonlinear resilient modulus model. The MEPDG outlines the following means for subgrade or foundation characterization (NCHRP 2004):

- Laboratory testing of undisturbed or reconstituted field samples recovered from the subsurface exploration process.
- Nondestructive testing of existing pavements found to have similar subgrade materials.
- Intrusive testing, such as the Dynamic Cone Penetrometer (DCP).
- Reliance on an agency's experience with the subgrade type.
- The current guide recommends laboratory testing or nondestructive testing be used to determine the characteristics of the foundation support.

Material-Related Inputs

Because the new guide covers a large number of design alternatives (e.g., new flexible pavement design, new rigid pavement design, and rehabilitation design), there are a large number of different types of materials that must be accounted for in the design process. A brief summary of the different types of required material inputs, for different materials categories, is included in table A-1.

Implementation of the M-E Pavement Design Guide

With the completion of the draft version of the MEPDG in 2004, the JTFP focus has now turned toward helping states to ready themselves for the implementation of the guide. With AASHTO expecting to adopt the design guide within a few years, many state highway agencies are already preparing for that transition. Most of the initial implementation-related work being conducted by other agencies focuses on understanding the relatively large number of new inputs required by the new design guide, determining what type of effort (and cost) is necessary to collect all of the required inputs, and what types of new or additional testing equipment are needed to accomplish the data-collection effort.

Table A-1. Materials-related inputs required by the MEPDG (NCHRP 2004).

Materials Category	**Required Materials Inputs**		
	Materials Inputs Required for Critical Response Computations	**Additional Materials Inputs Required for Distress/Transfer Functions**	**Additional Materials Inputs Required for Climatic Modeling**
HMA Materials (surface, binder, base and subbase courses)	• Time-temperature dependent dynamic modulus of HMA mixture • Poisson's ratio	• Tensile strength • Creep compliance • Coefficient of thermal expansion	• Surface shortwave absorptivity (only required for surface course), thermal conductivity, and heat capacity of HMA • Asphalt binder viscosity characterization to account aging
PCC Materials (this covers surface layer only)	• Time-adjusted static modulus of elasticity • Poisson's ratio • Unit weight • Coefficient of thermal expansion	• Modulus of rupture • Split tensile strength • Compressive strength • Cement type, content • Water-to-cement ratio • Ultimate shrinkage, reversible shrinkage	• Surface shortwave absorptivity • Thermal conductivity • Heat capacity
Chemically/Cementitously Stabilized Materials (lean concrete, cement treated, soil cement, lime-cement-flyash, lime-flyash, and lime modified/stabilized layers)	• Elastic modulus • Poisson's ratio • Unit weight	• Minimum resilient modulus (used in flexible design) • Modulus of rupture (used in flexible design) • Base erodibility (for rigid design)	Thermal conductivity and heat capacity of PCC
Unbound Base/Subbase and Subgrade Materials	• Seasonally adjusted resilient modulus • Poisson's ratio • Unit weight • Coefficient of lateral pressure	• Gradation parameters • Base erodibility (for rigid design)	Plasticity index, gradation parameters, effective grain sizes, specific gravity, hydraulic conductivity, optimum moisture contents, parameters to define the soil water characteristic curve
Recycled Concrete Materials – fractured PCC slabs	• Resilient modulus • Poisson's ratio	Base erodibility (for rigid design)	Thermal conductivity and heat capacity
Recycled HMA (central plant processed)	Treated same as HMA surface course		
Recycled cold asphalt mix (central plant or on-grade)	Treated same as HMA base course		
Cold recycled asphalt pavement (used as aggregate)	Treated same as granular materials with no moisture sensitivity		
Bedrock	• Elastic modulus • Poisson's ratio • Unit weight	None	None

More specifically, the initial steps agencies have used to begin the implementation process include:

1. Reviewing of all design inputs required by the MEPDG and determining which required inputs are not currently being collected by the agency.
2. Performing a sensitivity analysis on all of the design inputs to the MEPDG to see which have the greatest impact on the design procedure, given the local agency conditions.
3. Ranking the design inputs in order of their effect on predicted pavement performance and determining the level of detail actually required for the numerous inputs to the program.
4. Identifying resources (staff, testing capabilities, equipment, information systems, knowledge, training, and so on) required to obtain necessary design inputs.
5. Evaluating the applicability of performance models in the new MEPDG and identifying which models need to be calibrated to local conditions.
6. Preparing a detailed implementation plan that outlines elements of work necessary to utilize the pavement design methodology at the agency. The plan must include, but not be limited to estimated costs and recommended schedule for input acquisition, evaluating and recalibrating performance models, operation, and maintenance.

Eventually, the more advanced stages of the implementation procedure will involve establishing local default inputs where applicable, calibrating and validating the distress prediction models to local agency conditions, customizing the design guide software to include agency-calibrated performance models and default inputs, and preparing detailed design and training manuals for training and future reference (Saeed and Hall 2003).

A 2004 JTFP survey of state highway agencies found many agencies have already begun the preliminary tasks of the implementation process. Three questions in particular focused on the work that had been initiated by the agencies toward the implementation of the guide. These questions and a summary of the survey responses to those questions are summarized below (FHWA 2004):

- Does your State currently have an implementation plan in place for the new M-E design guide?

  - Yes: 20 agencies (42 percent).
  - No: 28 agencies (58 percent).

- Does your State currently have a local calibration plan in place for the new M-E design guide?
  - Yes: 15 agencies (31 percent).
  - No: 33 agencies (69 percent).

- Is your State currently performing data collection to support local calibration of the new M-E design guide?
  - Yes: 22 agencies (46 percent).
  - No: 26 agencies (54 percent).

Based on the results of the 2004 survey, almost half of the states are in the midst of research to develop an implementation plan for the MEPDG. To supplement the individual SHA details included in the survey results, a literature search was conducted as part of this proposal process to locate more details regarding current implementation efforts by other SHAs. This consisted of conducting internet searches (including the Transportation Research Information System [TRIS]), reviewing the Transportation Research Board (TRB) Research In Progress database, and reviewing the contents of the recent CD-ROMs compiled for the TRB annual meetings. Brief summaries of the individual SHA research and implementation efforts are included below:

- **Arizona**—In its response to the 2004 FHWA survey, the Arizona Department of Transportation (ADOT) indicated it is currently involved in a research project with Arizona State University (ASU) to develop information for the eventual implementation of the guide. Current work has focused on characterizing several HMA mixes, aggregate materials, and subgrade materials using the new guide tests (FHWA 2004). In addition, ADOT has been working with ASU and the concrete industry to develop coefficients of thermal expansion for various concrete mixes (FHWA 2004). Work is also under way to characterize asphalt rubber mixes commonly used in Arizona (FHWA 2004).

- **Arkansas**—The University of Arkansas has conducted research for the Arkansas State Highway and Transportation Department (AHTD) to develop an implementation plan that includes a sensitivity of analysis inputs (AHTD 2007). As part of this study, the research team completed a sensitivity analysis of the models used in the MEPDG for jointed plain concrete pavements (JPCP) pavements. In this task, the sensitivity of the models was assessed by evaluating the distress model results associated with varying

Another recent AHTD-sponsored study focused on developing statewide truck traffic volume adjustment factors (including class, monthly and hourly distribution factors) and evaluating the significance of using the statewide factors in the MEPDG software. The study concluded that while the software defaults for monthly and hourly distribution factors were adequate, it is recommended that state-specific class distribution factors be used in the MEPDG software (Tran and Hall 2007).

- **California—**In a recent research effort, University of California-Davis researchers conducted a sensitivity analysis of the JPCP prediction models used in the MEPDG software to understand the reasonableness of the model predictions for California conditions. The results of this study found that although on average both the cracking and faulting models showed trends that agree with prevailing knowledge in pavement engineering and California experience, there were some cases where results were counterintuitive (Kannekanti and Harvey 2006). Examples of these counterintuitive trends included results showing thinner sections performing better than thicker sections and pavements with asphalt shoulders performing better than those with tied shoulders or widened lanes. It was also found that the models fail to capture the effect of soil type and erodibility index and that the cracking model is sensitive to surface absorption (Kannekanti and Harvey 2006).
- **Florida—**In 2003, the Florida Department of Transportation (FDOT) entered into a research project with the Texas Transportation Institute (TTI) in which TTI was tasked with developing a framework for implementing the MEPDG in Florida. Under this study, TTI was to develop short-term (3-year) and long-term (4- to 10-year) implementation plans. In a separate study begun in 2006, Florida State University was contracted to evaluate the thermal engineering properties of typical Florida PCC mixes. These mix properties are being investigated to develop Florida-specific concrete material-related inputs that can be used in the MEPDG software (FDOT 2007).

- **Indiana**—The Indiana Department of Transportation (INDOT) has evaluated its current program and has identified many specific needs with regards to the required inputs for the MEPDG. As part of the ongoing INDOT research related to evaluating the effectiveness and practicality of implementing the new guide, a number of flexible test sections were used to verify and validate the new design procedure (Galal and Chehab 2005). The results of this study included the following four asphalt-related implementation initiatives for INDOT as research continues toward implementing the MEPDG (Galal and Chehab 2005):
    - Build a comprehensive asphalt-material database that incorporates necessary materials inputs as well as binder-related properties.
    - Continue the research directed toward the design and analysis of existing roads and compare the M-E predicted distresses to those collected on roadways to provide a framework for statewide calibration processes.
    - Using proposed "mini-LTPP" sites, calibrate all distress models to produce results equivalent to observed distress data and recommend to NCHRP and AASHTO the importance of incorporating reflective cracking distress model on the current MEPDG software.
    - Validate calibrated models using INDOT Accelerated Pavement Tester and the proposed Indiana mini-LTPP sites.
- **Iowa**—In 2003, the Iowa Department of Transportation entered into a research project with Iowa State University's *Center for Transportation Research and Education* (CTRE) in which CTRE was tasked with conducting a study of the MEPDG software and reports to determine the availability of design inputs, and to conduct a sensitivity analysis for both PCC and HMA pavement types to determine which variables will require better data and which can be set to Iowa defaults. The results of this study were compiled and published in separate *Technical Report and Implementation Plan* documents (Coree, Ceylan, and Harrington 2005a; Coree, Ceylan, and Harrington 2005b). Since the publishing of this work, additional work has been conducted by Iowa State University on the topic of calibrating some of the distress models associated with HMA pavements (Ceylan et al. 2006).

- **Kansas**—Kansas State University (KSU) is currently assisting the Kansas Department of Transportation (KDOT) with its MEPDG implementation effort. An ongoing research project with KSU is focusing on developing the model calibration procedure for the MEPDG for both flexible and rigid pavement structures. The results of some of this research were recently published in a paper that discusses some rigid pavement-related results (Khanum et al. 2005). This 2005 paper discusses research in which five rigid roadway sections designed by KDOT using the 1986 and 1993 AASHTO pavement design procedures and three long-term pavement performance (LTPP) rigid sections in Kansas were analyzed using the MEPDG software. Some rigid-pavement conclusions from this study are the following (Khanum et al. 2005):
    - Predicted IRI values are similar to the measured values.
    - The MEPDG analysis showed minimal or no faulting, although both predicted and measured faulting values were insignificant for all practical purposes. Faulting was found to be the least sensitive parameter.
    - The sensitivity analysis results show that IRI is the most sensitive output with respect to the traffic inputs.
    - Percentage of slabs cracked increases significantly with increasing truck traffic and decreases with increasing slab thickness.

  Another study conducted by KSU investigated the influence of traffic inputs on rigid pavement designs evaluated using the MEPDG. The results of this study indicated a lower level of cracking associated with using the local Kansas traffic inputs instead of MEPDG default values (Khanum, Hossain and Schieber 2006).

- **Kentucky—**The University of Kentucky is working on a project for the Kentucky Transportation Cabinet that identifies all of the necessary input and analysis parameters required by the new guide, and develops a detailed implementation plan for the Cabinet. A second project, also being conducted by the University of Kentucky, is focusing on developing load spectra traffic data for use in the MEPDG. The results of part of this initial research effort were recently published in a 2006 paper by Graves and Mahboub (2006) that describes the sensitivity analysis approach used for HMA pavements in Kentucky. The sensitivity analysis approach is different from the approach used in other states as it uses random sampling techniques over the entire input parameter space. This described study was limited to the flexible pavement type and considered the following input variables: HMA base nominal aggregate size, climate location, HMA thickness, annual average daily truck traffic (AADTT), subgrade strength, truck traffic category, construction season, and binder grade. A total of 100 design sections were randomly sampled from these input parameters, and the predicted performance (i.e., longitudinal and alligator cracking, HMA and total rutting, and IRI) were analyzed by using the Pearson's and Spearman's correlation coefficients (Graves and Mahboub 2006). Some specific results of the analysis found that 1) AADTT, HMA thickness, and subgrade strength have a significant impact on performance, whereas the remaining parameters have lesser impacts; and 2) in general, the results demonstrated that this type of sensitivity analysis may be used to identify important input parameters across the entire parameter space (Graves and Mahboub 2006).

- **Minnesota—**The University of Minnesota is assisting the Minnesota Department of Transportation in its implementation efforts for the MEPDG. The main objectives of the study are (1) to calibrate the MEPDG for Minnesota local conditions, (2) to develop default inputs and a catalog of trail designs, and (3) to develop training materials (MnDOT 2004a). A comprehensive sensitivity analysis has been conducted for both rigid (200,000 runs) and flexible pavements (2,000 runs) to determine the most significant factors on pavement performance. Another study is focusing on adapting the MEPDG for use with Minnesota's low-volume PCC pavements (MnDOT 2004b). Under this study, the MEPDG distress prediction models (transverse cracking and joint faulting) have been validated and calibrated to the traffic and environmental conditions (location and subgrade type), and a catalog of trail designs has been developed. The catalog includes recommended inputs for PCC pavement structure (i.e., PCC and base thickness and material properties) and design features (i.e., slab width, joint spacing, shoulder type, and dowel diameter) based on the performance criteria (i.e., maximum allowed percentage of slab cracked).

- **Mississippi—**One of the most well-documented references located in the literature search was a 2003 report titled "Mississippi DOT's Plan to Implement the 2002 Design Guide" (Saeed and Hall 2003). This report describes the research activities that have been sponsored by the Mississippi DOT in preparation for the adoption of the new MEPDG procedure. Specifically, the two-phase implementation initiated by the Mississippi DOT consisted of developing an implementation plan in Phase I and actually implementing the design guide in Phase II. In Phase I, the implementation plan included familiarizing DOT staff with the MEPDG, establishing the scope of pavement types and rehabilitation activities of interest to the DOT, developing a factorial experiment design, recommending test sections for use in calibrating and validating performance models, preparing a detailed plan for the Phase II implementation, and estimating a budget for implementing the MEPDG (Saeed and Hall 2003). The specific Phase II work plan in Mississippi includes the following research tasks (Saeed and Hall 2003):

  - Review all design inputs.
  - Conduct an initial sensitivity analysis and compare with current DOT procedures.
  - Provide guidance to carry out the required field and laboratory testing.
  - Outline work related to obtaining all design inputs, including detailed traffic inputs, selection of performance criteria, and material testing.
  - Establish default inputs where applicable.
  - Calibrate and validate the distress prediction models with Mississippi pavement performance data.
  - Conduct additional sensitivity analysis and comparison of the design guide procedure with current Mississippi DOT design procedure results.
  - Prepare detailed design and training manuals for training and future reference.
  - Customize the design guide software to include Mississippi-calibrated performance models and default inputs.
  - Provide training to Mississippi DOT staff.

- **Missouri**—The Missouri Department of Transportation is conducting internal research that is focusing on investigating the use of the MEPDG for use in Missouri (MoDOT 2007).

- **Ohio**—The Ohio Department of Transportation (ODOT) has initiated multiple research projects focusing on preparing for the implementation of MEPDG. The primary objectives of one general study are to validate the applicability of the MEPDG approach for Ohio, identify gaps in ODOT's current data, calibrate the MEPDG models for Ohio conditions, and develop guidelines for implementation of the MEPDG (ODOT 2007a). A second ongoing study is a more detailed study being conducted that is focusing on investigating the influence of the mechanical properties of individual material layers on pavement response and performance. Specifically, this second research study has the following objectives (ODOT 2007b): 1) monitor the new perpetual AC and long-lasting PCC pavements in Ohio, the rehabilitated PCC pavements in New York State, and other existing instrumented pavements in both states, 2) verify ME design procedures for all pavements in the study, 3) calibrate ME procedures presented in the NCHRP 1-37A AASHTO Pavement Guide for Ohio and New York State, and develop calibration factors for the distress models in the MEPDG software, and 4) conduct controlled testing of perpetual pavement systems (ODOT 2007b).

- **Nebraska—**The Nebraska Department of Roads (NDOR) has used its pavement management data to calibrate two MEPDG smoothness models at the local project level. The focused dataset was categorized by annual daily truck traffic (ADTT) and surface layer thickness. The results showed that project-level calibrations reduced default model prediction error by nearly twice that of network-level calibration (Shram and Abdelrahman 2006).
- **Pennsylvania—**The Pennsylvania Department of Transportation (PennDOT) is involved with two research projects expected to provide the local calibration of the MEPDG models (PennDOT 2007).
- **Texas—**In Texas, research has recently been completed to develop a strategic plan for the implementation of the MEPDG in the Texas Department of Transportation. One of the objectives of this research was to develop an implementation strategy. The resulting implementation plan included the following steps (Uzan, Freeman, and Cleveland 2005):
    - Training—The first step in the plan is to train the TxDOT engineering staff in the general concepts of the guide so they can comprehend the M-E models included in the guide.
    - Laboratory—As TxDOT does not currently have all of the equipment needed for characterizing the pavement materials as required by the guide (i.e., testing for

resilient or dynamic modulus), it was recommended to equip the Central and select District laboratories with the needed testing equipment.

  - Field and Forensic Studies—As part of the calibration and validation stages, a series of field studies were recommended to collect needed data. Examples of these studies include conducting FWD and GPR measurements, cutting trenches to verify layer thicknesses, measuring rutting depths to calibrate the permanent deformation models, and measuring the moisture distribution needed to validate the EICM predictions; and finally, to obtain undisturbed and disturbed samples for laboratory testing.
  - Calibration and Validation of the Guide—The researchers in the TxDOT study recommended that "calibration and validation of the guide should follow the jackknifing statistical procedures recommended from NCHRP 9-30 *Experimental Plan for Calibration and Validation of HMA Performance Models for Mix and Structural Design* (NCHRP 2003). Approximately 40 test sections are expected to be needed to complete the calibration and validation process.
  - Additional Studies—Finally, the research team recommended that TxDOT conduct three additional studies as part of the implementation process. These consist of 1) studying the projection of truck traffic distribution, 2) enhancing and continually updating the database that contains the default values for traffic and material properties, and 3) developing an expert system that will guide the engineer in choosing initial structures and materials.

Other research initiated in 2005 is focused on developing an enhanced database for use with the MEPDG. The integrated database is being designed with the goal of developing, validating, and calibrating M-E flexible pavement design models at the project level. As such, it will interact with and complement the existing Pavement Management Information System (PMIS), which is a network-level application (TxDOT 2007).

- **Utah**—The Utah Department of Transportation (UDOT) is sponsoring research that identifies the needed modifications to many pavement design protocols (e.g., testing equipment, testing procedures, traffic input formats, environmental data applications, software issues, design output interpretation, and so on) as a result of implementing the

MEPDG (UDOT 2007). The objective of the current research is to prioritize the most important issues the agency will face during the local validation and calibration activities.

- **Virginia—**According to the 2004 FHWA survey, the Virginia Department of Transportation (VDOT) is one of the agencies that has implementation and local calibration plans in place. Evidence of their implementation work is reported in a paper by Cotrell, Schinkel, and Clark (2003) that describes VDOT's effort to collect traffic and truck axle weight data to support the Level 2 pavement designs in the new MEPDG.
- **Washington—**In the state of Washington, preliminary work focuses on many aspects of implementing the MEPDG. Examples of preliminary work include conducting an initial sensitivity analysis of design inputs, investigating the traffic and climatic data needs, reviewing the current field evaluation methods to determine if additional field studies are necessary (e.g., GPR and DCP), investigating the use of pavement management data to calibrate the models to local conditions, and reviewing the additional laboratory testing needs (Willoughby and Pierce, Date Unknown). Some preliminary research results are presented in 2006 paper by Li, et al. (2006). This paper discusses a research effort in Washington in which a calibration procedure was developed and used to calibrate the rigid pavement designs models in the MEPDG software to data obtained from the Washington State Pavement Management System (WSPMS). The results of this research indicate that for Washington State rigid pavements, the calibrated software can be used to predict future deterioration due to faulting, but cannot be used to predict cracking due to the transverse/longitudinal crack issues (Li et al. 2006).
- **Wisconsin—**In the 2004 FHWA survey, the Wisconsin Department of Transportation (WisDOT) indicated it had developed an implementation plan for the MEPDG (FHWA 2004). WisDOT is reviewing the procedure, performing an initial sensitivity analysis of design inputs, and determining the effort required to adopt and implement the procedure. One ongoing research study sponsored by WisDOT is titled "Testing Wisconsin Asphalt Mixtures for the AASHTO 2002 Mechanistic Design Procedure" (WisDOT 2007). Another recent research problem statement is for a project titled "Investigation of Concrete Properties to Support Implementation of the New AASHTO Pavement Design Guide."

As many of these other agencies are also moving from the 1993 design guide, much can be learned from these other ongoing research activities that will directly benefit the MEPDG implementation effort in South Dakota.

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APPENDIX B: SUMMARY OF SENSITIVITY ANALYSIS INPUTS

Introduction

The new mechanistic-empirical pavement design guide (MEPDG) procedure requires that a large number of material-, traffic, climate-, and design-related inputs be defined by the pavement designer before conducting an analysis. Therefore, before conducting any runs under the task 3 sensitivity analysis, the research team first had to work with the Technical Panel to determine 1) what variables were to remain fixed in the sensitivity analysis and at what values, 2) what inputs needed to be investigated (varied) within the sensitivity analysis, and 3) what input value ranges were to be used within the sensitivity analysis to represent typical South Dakota conditions. As discussed in the body of this report, the following five pavement design types were investigated in the task 3 sensitivity analysis:

- New design – Rural jointed plain concrete pavement (JPCP).
- New design – Rural asphalt concrete (AC).
- New design – Continuously reinforced concrete pavement (CRCP) interstate.
- Rehabilitation – AC overlay over existing rural AC.
- Rehabilitation – AC overlay over rubblized rural JPCP.

The remainder of this appendix includes a series of tables that summarize all of the MEPDG software inputs used in conducting the task 3 sensitivity analysis for the five aforementioned pavement designs. These tables are organized into logical categories and contain the following types of information:

- Input name—The name of the variable as described in the MEPDG software.
- Input type—Whether the variable is “Fixed,” “Variable,” or “Computed” within the sensitivity analysis.
- Input value(s)—The actual values used to conduct the sensitivity analysis runs (i.e., a single value if “Fixed,” or multiple values if “Variable”).
- Input notes—Notes in these tables describe associated information of interest.

Note that all inputs for a specific pavement type are not all grouped together. For example, the traffic-related inputs are included in two separate tables for the *Rural* and *Urban* traffic scenarios, respectively, and are presented within their own section titled “*Traffic” Inputs*.

Because all five pavement designs use one of two bases (i.e., *Gravel Cushion* layer or *Granular Base* layer) a similar approach was used for presenting the base-related information, as this information is presented in two tables within the section titled *Base Layer-Related Inputs*. All of the other inputs are organized into logical groups and are presented in this appendix.

Summary of "General Information" Inputs

Table B-1. Summary of "General Information" inputs.

Input Variable	Variable Type	Value(s)	Notes
Base/subgrade construction month	**FIXED**	June (not applicable for JPCP)	Values were chosen to reflect the typical SDDOT construction season
Pavement construction month	**FIXED**	August	
Traffic open month	**FIXED**	October	
Design life	**FIXED**	20 for AC designs; 40 for PCC designs	Values provided by SDDOT
Type of design	**FIXED**	New Flexible Pavement; New Jointed Plain Concrete Pavement (JPCP); New Continuously Reinforced Concrete Pavement (CRCP); Asphalt Concrete Overlay over AC; Asphalt Concrete Overlay over JPCP (fractured)	Five different design types (see left) were chosen by SDDOT

Table B-2. Summary of "Site/Project Information" inputs.

Input Variable	Variable Type	Value(s)	Notes
Location	**INFO ONLY**	None needed	All of these information only inputs are for documentation purposes only
Project ID	**INFO ONLY**	None needed	
Section ID	**INFO ONLY**	None needed	
Date (of Analysis Setup)	**INFO ONLY**	None needed	
Station/milepost format	**INFO ONLY**	None needed	
Station/milepost begin	**INFO ONLY**	None needed	
Station/milepost end	**INFO ONLY**	None needed	
Traffic direction	**INFO ONLY**	None needed	

"Analysis Parameter" Inputs

Table B-3. Summary of "Analysis Parameter" inputs.

Input Variable	Variable Type	Value(s)	Notes
DESIGN TYPES = New AC (Rural); AC Overlay Over Existing AC (Rural); AC Overlay Over Rubblized JPCP (Rural)			
Initial IRI (in/mile)	**FIXED**	62 in/mi	62 is the average IRI value of new construction projects in South Dakota
Terminal IRI (in/mile)	**FIXED**	Limit: 178 in/mi, Reliability 90%	178 in/mi is the IRI value equal to a SDDOT Roughness Index of 3.0
AC surface down cracking, long cracking (ft/mi)	**FIXED**	Limit: 1,000 ft/mi, Reliability 90%	MEPDG default values
AC bottom up cracking, alligator cracking (%)	**FIXED**	Limit: 25%, Reliability 90%	25% is equivalent to SDDOT's Fatigue Cracking Index = 3.0 for medium-severity fatigue cracking
AC thermal fatigue (ft/mi)	**FIXED**	Limit: 1,000 ft/mi, Reliability 90%	MEPDG default values
Chemically stabilized layer fatigue fracture (%)	**FIXED**	Not applicable	Stabilized layers are not used
Permanent deformation – total pavement (in)	**FIXED**	Limit: 0.43 in, Reliability 90%	0.43 in rut depth equals SDDOT's Rut Index of 3.0. Cannot differentiate between rutting in surface and total rutting.
Permanent deformation – AC only (in)	**FIXED**	Limit: 0.43 in, Reliability 90%	
DESIGN TYPE = New Design—Rural JPCP			
Initial IRI (in/mile)	**FIXED**	62 in/mi	62 is the average IRI value of new construction projects in South Dakota
Terminal IRI (in/mile)	**FIXED**	Limit: 178 in/mi, Reliability 90%	178 in/mi is the IRI value equal to a SDDOT Roughness Index of 3.0
Transverse cracking (% cracked slabs)	**FIXED**	Limit: 15%, Reliability 90%	Default values. SDDOT does not measure percent of cracked slabs.
Mean joint faulting (in)	**FIXED**	Limit: 0.15 in, Reliability 90%	0.15 in is an estimate based on how SDDOT determines its Faulting Index
DESIGN TYPE = New Design—CRCP Interstate			
Initial IRI (in/mile)	**FIXED**	62 in/mi	62 is the average IRI value of new construction projects in South Dakota
Terminal IRI (in/mile)	**FIXED**	Limit: 178 in/mi, Reliability 90%	178 in/mi is the IRI value equal to a SDDOT Roughness Index of 3.0
CRCP punchouts (per mile)	**FIXED**	Limit: 25, Reliability 90%	25 to 50 punchouts per mile equals a SDDOT punchout index of 3.0
Max. CRCP Crack Width (in)	**FIXED**	0.02	MEPDG default value
Min. Crack Load Transfer Efficiency (LTE%)	**VARIABLE**	L: 50 M: 80 (standard) H: 90	Software shows an acceptable range of 50 to 90; therefore, this variable was varied to see if any effect was observed.
Minimum Crack Spacing (ft)	**FIXED**	3 ft	MEPDG default value
Maximum Crack Spacing (ft)	**FIXED**	6 ft	MEPDG default value

“Traffic” Inputs

Rural Design Traffic

Table B-4. Traffic inputs associated with “Rural” pavement designs.

<table>
<tr><th>Variable</th><th>Variable Type</th><th>Value(s)</th><th>Notes/Assumptions</th></tr>
<tr><td colspan="4">MAIN TRAFFIC INPUTS</td></tr>
<tr><td>Initial two-way AADTT</td><td>VARIABLE</td><td>L: 50
M: 250 (standard)
H: 450</td><td>SDDOT provided values</td></tr>
<tr><td>Number of lanes in design direction</td><td>FIXED</td><td>1</td><td>“Rural” pavements are assumed to be two-lane undivided highways</td></tr>
<tr><td>Percent of trucks in design direction</td><td>FIXED</td><td>55%</td><td>55% is typical for SDDOT</td></tr>
<tr><td>Percent of trucks in design lane</td><td>FIXED</td><td>100%</td><td>“Rural” pavements are assumed to be two-lane undivided highways</td></tr>
<tr><td>Operational speed (mph)</td><td>FIXED</td><td>65 mph</td><td>65 mph is typical for “Rural” pavements in SDDOT</td></tr>
<tr><td colspan="4">TRAFFIC VOLUME ADJUSTMENT FACTOR INPUTS</td></tr>
<tr><td>Monthly adjustment factors (MAF)</td><td>FIXED</td><td>Fixed to SDDOT provided values (see right)</td><td>
<table>
<tr><th>Month</th><th>Adjustment Factor</th></tr>
<tr><td>January</td><td>0.79</td></tr>
<tr><td>February</td><td>0.89</td></tr>
<tr><td>March</td><td>0.89</td></tr>
<tr><td>April</td><td>0.96</td></tr>
<tr><td>May</td><td>1.05</td></tr>
<tr><td>June</td><td>1.17</td></tr>
<tr><td>July</td><td>1.25</td></tr>
<tr><td>August</td><td>1.29</td></tr>
<tr><td>September</td><td>1.13</td></tr>
<tr><td>October</td><td>1.07</td></tr>
<tr><td>November</td><td>0.94</td></tr>
<tr><td>December</td><td>0.94</td></tr>
</table>
</td></tr>
<tr><td>Vehicle class distribution</td><td>VARIABLE</td><td>SDDOT provided values (see right):

L: Set 1 (standard)
H: Set 2</td><td>
<table>
<tr><th>Vehicle Class</th><th>Set 1 (standard)</th><th>Set 2</th></tr>
<tr><td>1</td><td>0.0</td><td>0.0</td></tr>
<tr><td>2</td><td>0.0</td><td>0.0</td></tr>
<tr><td>3</td><td>0.0</td><td>0.0</td></tr>
<tr><td>4</td><td>0.5</td><td>0.6</td></tr>
<tr><td>5</td><td>41.6</td><td>33.3</td></tr>
<tr><td>6</td><td>5.0</td><td>4.3</td></tr>
<tr><td>7</td><td>1.1</td><td>0.1</td></tr>
<tr><td>8</td><td>4.6</td><td>4.9</td></tr>
<tr><td>9</td><td>32.3</td><td>39.9</td></tr>
<tr><td>10</td><td>7.8</td><td>12.8</td></tr>
<tr><td>11</td><td>0.0</td><td>0.0</td></tr>
<tr><td>12</td><td>0.0</td><td>0.0</td></tr>
<tr><td>13</td><td>7.1</td><td>4.1</td></tr>
</table>
</td></tr>
</table>

Table B-4. Traffic inputs associated with "Rural" pavement designs (continued).

<table>
<tr><th>Variable</th><th>Variable Type</th><th>Value(s)</th><th>Notes/Assumptions</th></tr>
<tr><td>Truck hourly distribution factors</td><td>VARIABLE</td><td>SDDOT provided values (see right):
L: Set 1 (standard)
H: Set 2</td><td>
<table>
<tr><th>Hour</th><th>Set 1 (STD)</th><th>Set 2</th></tr>
<tr><td>0 (Midnight to 1 a.m.)</td><td>1.7</td><td>1.4</td></tr>
<tr><td>1 (1 a.m. to 2 a.m.)</td><td>1.5</td><td>1.0</td></tr>
<tr><td>2 (2 a.m. to 3 a.m.)</td><td>1.3</td><td>0.8</td></tr>
<tr><td>3 (3 a.m. to 4 a.m.)</td><td>0.9</td><td>0.4</td></tr>
<tr><td>4 (4 a.m. to 5 a.m.)</td><td>0.5</td><td>0.2</td></tr>
<tr><td>5 (5 a.m. to 6 a.m.)</td><td>1.3</td><td>1.5</td></tr>
<tr><td>6 (6 a.m. to 7 a.m.)</td><td>3.0</td><td>1.8</td></tr>
<tr><td>7 (7 a.m. to 8 a.m.)</td><td>4.8</td><td>3.5</td></tr>
<tr><td>8 (8 a.m. to 9 a.m.)</td><td>6.6</td><td>6.0</td></tr>
<tr><td>9 (9 a.m. to 10 a.m.)</td><td>8.0</td><td>6.5</td></tr>
<tr><td>10 (10 a.m. to 11 a.m.)</td><td>7.5</td><td>7.2</td></tr>
<tr><td>11 (11 a.m. to Noon)</td><td>6.7</td><td>7.6</td></tr>
<tr><td>12 (Noon to 1 p.m.)</td><td>6.7</td><td>6.6</td></tr>
<tr><td>13 (1 p.m. to 2 p.m.)</td><td>7.4</td><td>6.3</td></tr>
<tr><td>14 (2 p.m. to 3 p.m.)</td><td>7.5</td><td>6.9</td></tr>
<tr><td>15 (3 p.m. to 4 p.m.)</td><td>6.7</td><td>8.1</td></tr>
<tr><td>16 (4 p.m. to 5 p.m.)</td><td>4.8</td><td>8.2</td></tr>
<tr><td>17 (5 p.m. to 6 p.m.)</td><td>4.3</td><td>6.3</td></tr>
<tr><td>18 (6 p.m. to 7 p.m.)</td><td>3.8</td><td>4.5</td></tr>
<tr><td>19 (7 p.m. to 8 p.m.)</td><td>4.0</td><td>3.9</td></tr>
<tr><td>20 (8 p.m. to 9 p.m.)</td><td>3.2</td><td>3.3</td></tr>
<tr><td>21 (9 p.m. to 10 p.m.)</td><td>2.8</td><td>3.2</td></tr>
<tr><td>22 (10 p.m. to 11 p.m.)</td><td>2.6</td><td>2.8</td></tr>
<tr><td>23 (11 p.m. to 12 p.m.)</td><td>2.4</td><td>2.0</td></tr>
</table>
</td></tr>
<tr><td>Traffic growth factors</td><td>VARIABLE</td><td>L: 4.0% (standard)
H: 8.0%</td><td>Growth type was fixed to "Linear" based on discussions with SDDOT</td></tr>
<tr><th colspan="4">AXLE LOAD DISTRIBUTION FACTORS</th></tr>
<tr><td>Axle factors by axle type</td><td>FIXED</td><td>Level 3 default values</td><td>Table of MEPDG default Level 3 values used in all analysis runs</td></tr>
<tr><th colspan="4">GENERAL TRAFFIC INPUTS (LATERAL TRAFFIC WANDER)</th></tr>
<tr><td>Mean wheel location</td><td>FIXED</td><td>18 in</td><td>MEPDG default value</td></tr>
<tr><td>Traffic wander standard deviation</td><td>FIXED</td><td>10 in</td><td>MEPDG default value</td></tr>
<tr><td>Design lane width (note: this is not slab width)</td><td>FIXED</td><td>12 ft</td><td>MEPDG default value</td></tr>
<tr><th colspan="4">GENERAL TRAFFIC INPUTS (NUMBER OF AXLES PER TRUCK)</th></tr>
<tr><td>Number of axle types per truck class</td><td>FIXED</td><td>Fixed to SDDOT provided values (see right)</td><td>
<table>
<tr><th rowspan="2">Class</th><th colspan="3">Average # Axles per Truck</th></tr>
<tr><th>Single</th><th>Tandem</th><th>Tridem</th></tr>
<tr><td>4</td><td>0.51</td><td>0.00</td><td>0.00</td></tr>
<tr><td>5</td><td>1.74</td><td>0.00</td><td>0.00</td></tr>
<tr><td>6</td><td>0.90</td><td>0.91</td><td>0.00</td></tr>
<tr><td>7</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
<tr><td>8</td><td>2.36</td><td>0.40</td><td>0.00</td></tr>
<tr><td>9</td><td>1.24</td><td>1.71</td><td>0.00</td></tr>
<tr><td>10</td><td>0.97</td><td>1.25</td><td>0.62</td></tr>
<tr><td>11</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
<tr><td>12</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
<tr><td>13</td><td>1.38</td><td>1.41</td><td>0.94</td></tr>
</table>
</td></tr>
</table>

Table B-4. Traffic inputs associated with "Rural" pavement designs (continued).

Variable	Variable Type	Value(s)	Notes/Assumptions
GENERAL TRAFFIC INPUTS (AXLE CONFIGURATION)			
Average axle width (edge-to-edge) outside dimensions	**FIXED**	8.5 ft	MEPDG default value
Dual tire spacing	**FIXED**	12 in	MEPDG default value
Tire pressure (for both single and dual tires)	**VARIABLE for AC; FIXED for PCC**	For AC: L: 120 psi (standard) H: 140 psi For PCC: 120 psi	Version 0.9 of the MEPDG software shows 120 psi as only valid value
Axle spacing (tandem axle)	**FIXED**	52.0 in	SDDOT provided value
Axle spacing (tridem axle)	**FIXED**	54.0 in	SDDOT provided value
Axle spacing (quad axle)	**FIXED**	54.0 in	SDDOT provided value
GENERAL TRAFFIC INPUTS (WHEELBASE DISTRIBUTION INFORMATION)			
Average axle spacing (short)	**FIXED (Used for JPCP ONLY)**	12 ft	MEPDG default value
Average axle spacing (med)		15 ft	SDDOT provided value
Average axle spacing (long)		18 ft	MEPDG default value
Percent of trucks (short, medium, and long)		33% for short; 33% for med; 34% for long	MEPDG default value

Interstate Design Traffic

Table B-5. Traffic inputs associated with “Interstate” pavement designs.

<table>
<tr><th>Variable</th><th>Variable Type</th><th>Value(s)</th><th>Notes/Assumptions</th></tr>
<tr><th colspan="4">MAIN TRAFFIC INPUTS</th></tr>
<tr><td>Initial two-way AADTT</td><td>VARIABLE</td><td>L: 800
M: 1600 (standard)
H: 2400</td><td>SDDOT provided values</td></tr>
<tr><td>Number of lanes in design direction</td><td>FIXED</td><td>2</td><td>“Interstate” pavements are assumed to be four-lane divided highways</td></tr>
<tr><td>Percent of trucks in design direction</td><td>FIXED</td><td>55%</td><td>55% is typical for SDDOT</td></tr>
<tr><td>Percent of trucks in design lane</td><td>FIXED</td><td>90%</td><td>“Interstate” pavements are assumed to be four-lane divided highways</td></tr>
<tr><td>Operational speed (mph)</td><td>FIXED</td><td>75 mph</td><td>SDDOT provided value</td></tr>
<tr><th colspan="4">TRAFFIC VOLUME ADJUSTMENT FACTOR INPUTS</th></tr>
<tr><td>Monthly adjustment factors (MAF)</td><td>FIXED</td><td>Fixed to SDDOT provided values (see right)</td><td>
<table>
<tr><th>Month</th><th>Adjustment Factor</th></tr>
<tr><td>January</td><td>0.51</td></tr>
<tr><td>February</td><td>0.58</td></tr>
<tr><td>March</td><td>0.69</td></tr>
<tr><td>April</td><td>0.80</td></tr>
<tr><td>May</td><td>1.01</td></tr>
<tr><td>June</td><td>1.20</td></tr>
<tr><td>July</td><td>1.29</td></tr>
<tr><td>August</td><td>1.34</td></tr>
<tr><td>September</td><td>1.09</td></tr>
<tr><td>October</td><td>1.03</td></tr>
<tr><td>November</td><td>0.85</td></tr>
<tr><td>December</td><td>0.73</td></tr>
</table>
</td></tr>
<tr><td>Vehicle class distribution</td><td>VARIABLE</td><td>SDDOT provided values (see right):

L: Set 1 (standard)
H: Set 2</td><td>
<table>
<tr><th>Vehicle Class</th><th>Set 1 (standard)</th><th>Set 2</th></tr>
<tr><td>1</td><td>0.0</td><td>0.0</td></tr>
<tr><td>2</td><td>0.0</td><td>0.0</td></tr>
<tr><td>3</td><td>0.0</td><td>0.0</td></tr>
<tr><td>4</td><td>1.1</td><td>0.7</td></tr>
<tr><td>5</td><td>22.0</td><td>29.4</td></tr>
<tr><td>6</td><td>6.3</td><td>1.4</td></tr>
<tr><td>7</td><td>1.2</td><td>0.1</td></tr>
<tr><td>8</td><td>4.8</td><td>7.3</td></tr>
<tr><td>9</td><td>55.1</td><td>54.3</td></tr>
<tr><td>10</td><td>4.8</td><td>2.7</td></tr>
<tr><td>11</td><td>0.9</td><td>0.4</td></tr>
<tr><td>12</td><td>0.2</td><td>0.1</td></tr>
<tr><td>13</td><td>3.6</td><td>3.6</td></tr>
</table>
</td></tr>
</table>

Table B-5. Traffic inputs associated with "Interstate" pavement designs (continued).

<table>
<tr><th>Variable</th><th>Variable Type</th><th>Value(s)</th><th>Notes/Assumptions</th></tr>
<tr><td>Truck hourly distribution factors</td><td>VARIABLE</td><td>SDDOT provided values (see right):
L: Set 1 (standard)
H: Set 2</td><td>
<table>
<tr><th>Hour</th><th>Set 1 (STD)</th><th>Set 2</th></tr>
<tr><td>0 (Midnight to 1 a.m.)</td><td>2.1</td><td>2.5</td></tr>
<tr><td>1 (1 a.m. to 2 a.m.)</td><td>1.5</td><td>1.7</td></tr>
<tr><td>2 (2 a.m. to 3 a.m.)</td><td>1.3</td><td>1.4</td></tr>
<tr><td>3 (3 a.m. to 4 a.m.)</td><td>2.3</td><td>1.5</td></tr>
<tr><td>4 (4 a.m. to 5 a.m.)</td><td>2.4</td><td>1.1</td></tr>
<tr><td>5 (5 a.m. to 6 a.m.)</td><td>2.9</td><td>1.2</td></tr>
<tr><td>6 (6 a.m. to 7 a.m.)</td><td>4.2</td><td>1.6</td></tr>
<tr><td>7 (7 a.m. to 8 a.m.)</td><td>5.4</td><td>2.7</td></tr>
<tr><td>8 (8 a.m. to 9 a.m.)</td><td>5.8</td><td>3.7</td></tr>
<tr><td>9 (9 a.m. to 10 a.m.)</td><td>6.6</td><td>4.5</td></tr>
<tr><td>10 (10 a.m. to 11 a.m.)</td><td>7.0</td><td>5.5</td></tr>
<tr><td>11 (11 a.m. to Noon)</td><td>6.0</td><td>5.8</td></tr>
<tr><td>12 (Noon to 1 p.m.)</td><td>5.9</td><td>7.2</td></tr>
<tr><td>13 (1 p.m. to 2 p.m.)</td><td>5.5</td><td>6.1</td></tr>
<tr><td>14 (2 p.m. to 3 p.m.)</td><td>5.7</td><td>6.4</td></tr>
<tr><td>15 (3 p.m. to 4 p.m.)</td><td>5.3</td><td>6.1</td></tr>
<tr><td>16 (4 p.m. to 5 p.m.)</td><td>4.9</td><td>5.9</td></tr>
<tr><td>17 (5 p.m. to 6 p.m.)</td><td>4.4</td><td>6.5</td></tr>
<tr><td>18 (6 p.m. to 7 p.m.)</td><td>4.3</td><td>6.2</td></tr>
<tr><td>19 (7 p.m. to 8 p.m.)</td><td>4.4</td><td>5.7</td></tr>
<tr><td>20 (8 p.m. to 9 p.m.)</td><td>3.6</td><td>4.8</td></tr>
<tr><td>21 (9 p.m. to 10 p.m.)</td><td>3.2</td><td>4.6</td></tr>
<tr><td>22 (10 p.m. to 11 p.m.)</td><td>3.0</td><td>3.7</td></tr>
<tr><td>23 (11 p.m. to 12 p.m.)</td><td>2.3</td><td>3.6</td></tr>
</table>
</td></tr>
<tr><td>Traffic growth factors</td><td>VARIABLE</td><td>L: 4.0% (standard)
H: 8.0%</td><td>Growth type was fixed to "Linear" based on discussions with SDDOT</td></tr>
<tr><td colspan="4">AXLE LOAD DISTRIBUTION FACTORS</td></tr>
<tr><td>Axle factors by axle type</td><td>FIXED</td><td>Level 3 default values</td><td>Table of MEPDG default Level 3 values used in all analysis runs</td></tr>
<tr><td colspan="4">GENERAL TRAFFIC INPUTS (LATERAL TRAFFIC WANDER)</td></tr>
<tr><td>Mean wheel location</td><td>FIXED</td><td>18 in</td><td>MEPDG default value</td></tr>
<tr><td>Traffic wander standard deviation</td><td>FIXED</td><td>10 in</td><td>MEPDG default value</td></tr>
<tr><td>Design lane width (note: this is not slab width)</td><td>FIXED</td><td>12 ft</td><td>MEPDG default value</td></tr>
<tr><td colspan="4">GENERAL TRAFFIC INPUTS (NUMBER OF AXLES PER TRUCK)</td></tr>
<tr><td>Number of axle types per truck class</td><td>FIXED</td><td>Fixed to SDDOT provided values (see right)</td><td>
<table>
<tr><th rowspan="2">Class</th><th colspan="3">Average # Axles per Truck</th></tr>
<tr><th>Single</th><th>Tandem</th><th>Tridem</th></tr>
<tr><td>4</td><td>0.79</td><td>0.54</td><td>0.00</td></tr>
<tr><td>5</td><td>1.77</td><td>0.00</td><td>0.00</td></tr>
<tr><td>6</td><td>0.93</td><td>0.95</td><td>0.00</td></tr>
<tr><td>7</td><td>0.18</td><td>0.00</td><td>0.00</td></tr>
<tr><td>8</td><td>2.51</td><td>0.36</td><td>0.00</td></tr>
<tr><td>9</td><td>1.22</td><td>1.75</td><td>0.00</td></tr>
<tr><td>10</td><td>0.92</td><td>1.20</td><td>0.61</td></tr>
<tr><td>11</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
<tr><td>12</td><td>0.00</td><td>0.00</td><td>0.00</td></tr>
<tr><td>13</td><td>1.94</td><td>1.87</td><td>0.63</td></tr>
</table>
</td></tr>
</table>

Table B-5. Traffic inputs associated with “Interstate” pavement designs (continued).

Variable	Variable Type	Value(s)	Notes/Assumptions
GENERAL TRAFFIC INPUTS (AXLE CONFIGURATION)			
Average axle width (edge-to-edge) outside dimensions	**FIXED**	8.5 ft	MEPDG default value
Dual tire spacing	**FIXED**	12 in	MEPDG default value
Tire pressure (for both single and dual tires)	**VARIABLE for AC; FIXED for PCC**	For AC: L: 120 psi (standard) H: 140 psi For PCC: 120 psi	Version 0.9 of the MEPDG software shows 120 psi as only valid value
Axle spacing (tandem axle)	**FIXED**	52.0 in	SDDOT provided value
Axle spacing (tridem axle)	**FIXED**	54.0 in	SDDOT provided value
Axle spacing (quad axle)	**FIXED**	54.0 in	SDDOT provided value
GENERAL TRAFFIC INPUTS (WHEELBASE DISTRIBUTION INFORMATION)			
Average axle spacing (short)	**FIXED (Used for JPCP ONLY)**	12 ft	MEPDG default value
Average axle spacing (medium)		15 ft	SDDOT provided value
Average axle spacing (long)		18 ft	MEPDG default value
Percent of trucks (short, medium, and long)		33% for short; 33% for med; 34% for long	MEPDG default value

"Climate" Inputs

Table B-6. Climatic data inputs.

Variable	Variable Type	Value(s)	Notes/Assumptions
Depth of water table	**VARIABLE**	L: 10 ft (standard for Brookings) M: 25 ft H: 100 ft (standard for Winner)	Depth of water table was investigated independently for the two different climate locations of Brookings and Winner
Project location (climatic data)	**VARIABLE**	L: Brookings H: Winner	Brookings, SD • Fairly cold with large amount of rainfall • Latitude = 44.30° N, Longitude = -96.80° N • Elevation = 1,647 ft • Climate file interpolated from data associated with Watertown, Huron, Sioux Falls, and Redwood Falls, MN Winner, SD • Represents typical climate for large part of state. Higher temperatures than Brookings • Latitude = 43.23° N, Longitude = -99.50° N • Elevation = 2,042 ft • Climate file for Winner was available in data included with MEPDG software

Base Layer-Related Inputs

Gravel Cushion Base Layer (Used Under JPCP and CRCP)

Table B-7. Traffic inputs associated with the *Gravel Cushion Base* layer (used under JPCP and CRCP pavement designs only).

Variable	Variable Type	Value(s)	Notes/Assumptions
GENERAL INPUTS			
Granular base layer thickness	**VARIABLE**	L: 3.0 in M: 5.0 in (standard) H: 7.0 in	The standard SDDOT JPCP design is a 9-in PCC layer on a 5-in *Gravel Cushion* layer
Unbound material type	**FIXED**	Crushed Gravel	The "Crushed Gravel" value is the most appropriate of those choices in the MEPDG software
STRENGTH-RELATED INPUTS			
Strength Properties; Analysis Type	**FIXED**	Input Level = "Level 3"; Analysis Type = "Representative Value (design value)"	This choice was made so we could investigate the direct influence of changing the base resilient modulus value
Resilient modulus, M_r	**VARIABLE**	L: 15,000 psi M: 21,000 psi (standard) H: 30,000 psi	The standard value was provided by SDDOT. The L and H values of 15ksi and 30 ksi, respectively, were estimated to be a reasonable range for the analysis.
Poisson's ratio, µ	**FIXED**	0.3	Assumed value. Typical range of 0.15 to 0.45.
Coefficient of lateral pressure, k_o	**FIXED**	0.5	Assumed value. Typical range of 0.4 to 0.6.
INTEGRATED CLIMATIC MODEL-RELATED (ICM) INPUTS			
Plasticity index, PI	**VARIABLE**	L: 0 (standard) H: 6	SDDOT specification is 0 to 6
Liquid Limit, LL	**FIXED**	25	SDDOT specification is 25 max
Compacted vs. uncompacted layer	**FIXED**	Compacted	This input is fixed to "Compacted"
Maximum dry unit weight of solids	**COMPUTED**	These values are computed internally using entered plasticity index and gradation information.	Computed values
Specific gravity of solids, Gs	**COMPUTED**		
Saturated hydraulic conductivity	**COMPUTED**		
Optimum gravimetric water content, w_{opt}	**COMPUTED**		
Parameters to define the soil water characteristic curve (a_f, b_f, c_f, and h_r)	**COMPUTED**		
Detailed gradation information (minimum of 5 sieves)	**FIXED**	<u>Sieve "Upper" and "Lower" Bound Values:</u> #200: LB = 3, UB = 12 #40: LB = 15, UB = 35 #8: LB = 38, UB = 64 #4: LB = 50, UB = 75 3/4": LB = 100, UB = 100	SDDOT provided values

Granular Base Layer (Used Under HMA Pavements)

Table B-8. Traffic inputs associated with the *Granular Base* layer
(used under original HMA pavement designs only).

Variable	Variable Type	Value(s)	Notes/Assumptions
GENERAL INPUTS			
Granular base layer thickness	**VARIABLE**	L: 10.0 in M: 12.0 in (standard) H: 14.0 in	The standard SDDOT new HMA design is a 4-in HMA layer on a 12-in *Granular Base* layer
Unbound material type	**FIXED**	Crushed Gravel	The "Crushed Gravel" value is the most appropriate of those choices in the MEPDG software
STRENGTH-RELATED INPUTS			
Strength Properties; Analysis Type	**FIXED**	Input Level = "Level 3"; Analysis Type = "Representative Value (design value)"	This choice was made so we could investigate the direct influence of changing the base resilient modulus value
Resilient modulus, M_r	**VARIABLE**	L: 15,000 psi M: 21,000 psi (standard) H: 30,000 psi	The standard value was provided by SDDOT. The L and H values of 15ksi and 30 ksi, respectively, were estimated to be a reasonable range for the analysis.
Poisson's ratio, μ	**FIXED**	0.3	Assumed value. Typical range of 0.15 to 0.45.
Coefficient of lateral pressure, k_o	**FIXED**	0.5	Assumed value. Typical range of 0.4 to 0.6.
INTEGRATED CLIMATIC MODEL-RELATED (ICM) INPUTS			
Plasticity index, PI	**VARIABLE**	L: 0 (standard) H: 6	SDDOT specification is 0 to 6
Liquid Limit, LL	**FIXED**	25	SDDOT specification is 25 max
Compacted vs. uncompacted layer	**FIXED**	Compacted	This input is fixed to "Compacted"
Maximum dry unit weight of solids	**COMPUTED**	These values are computed internally using entered plasticity index and gradation information.	Computed values
Specific gravity of solids, Gs	**COMPUTED**		
Saturated hydraulic conductivity	**COMPUTED**		
Optimum gravimetric water content, w_{opt}	**COMPUTED**		
Parameters to define the soil water characteristic curve (a_f, b_f, c_f, and h_r)	**COMPUTED**		
Detailed gradation information (minimum of 5 sieves)	**FIXED**	Sieve "Upper" and "Lower" Bound Values: #200: LB = 3, UB = 12 #40: LB = 13, UB = 35 #8: LB = 34, UB = 58 #4: LB = 46, UB = 70 1/2": LB = 68, UB = 91 3/4": LB = 80, UB = 100 1": LB = 100, UB = 100	SDDOT provided values

Subgrade Layer-Related Inputs

Table B-9. Inputs associated with the *Subgrade* layer (used for all pavement designs).

Variable	Variable Type	Value(s)	Notes/Assumptions
GENERAL INPUTS			
Subgrade layer thickness	**FIXED**	“Semi-infinite”	If depth to bedrock is "shallow" then a layer thickness for subgrade is required. Otherwise, it is selected as the last layer with a thickness of "semi-infinite"
Unbound material type	**VARIABLE**	L: A-7-6 M: A-6 (standard) H: A-4	These three soil types were provided by SDDOT for use in the analysis
STRENGTH-RELATED INPUTS			
Strength Properties; Analysis Type	**FIXED**	Input Level = “Level 3”; Analysis Type = “Representative Value (design value)”	This choice was made so we could investigate the direct influence of changing the base resilient modulus value
Resilient modulus, M_r	**VARIABLE**	L: 8,000 psi M: 17,000 psi (STD) H: 24,000 psi	Default values in the Guide for A-7-6, A-6, and A-4 are 8,000 psi, 17,000 psi, and 24,000 psi, respectively
Poisson’s ratio, μ	**FIXED**	0.45	Assumed value
Coefficient of lateral pressure, k_o	**FIXED**	0.5	Assumed value
INTEGRATED CLIMATIC MODEL-RELATED (ICM) INPUTS			
Compacted vs. uncompacted layer	**FIXED**	Compacted	This input is fixed to “Compacted”
Maximum dry unit weight of solids	**COMPUTED**	These values are computed internally using entered plasticity index and gradation information.	Computed values
Specific gravity of solids, Gs	**COMPUTED**		
Saturated hydraulic conductivity	**COMPUTED**		
Optimum gravimetric water content, w_{opt}	**COMPUTED**		
Soil water characteristic curve (a_f, b_f, c_f, and h_r)	**COMPUTED**		
Plasticity index, PI	**VARIABLE**	A-7-6: 33; A-6: 17; A-4: 8	These variables are varied as a group for the three provided material classifications (i.e., A-7-6, A-6, and A-4)
Liquid Limit, LL	**VARIABLE**	A-7-6: 58; A-6: 34; A-4: 25	
Detailed gradation information (minimum of 5 sieves)	**VARIABLE**	A-7-6 Values: #200: LB = 38.4, UB = 99.2 #40: LB = 69.7, UB = 99.8 #10: LB = 80.2, UB = 100 #4: LB = 84.2, UB = 100 3/8": LB = 92.9, UB = 100 A-6 Values: #200: LB = 36.1, UB = 98.2 #40: LB = 54, UB = 99.7 #10: LB = 70.4, UB = 100 #4: LB = 76.7, UB = 100 3/8": LB = 86.6, UB = 100 A-4 Values: #200: LB = 37.3, UB = 69.2 #40: LB = 44.2, UB = 98.9 #10: LB = 45.2, UB = 99.9 #4: LB = 51.6, UB = 100 3/8": LB = 70.8, UB = 100	

Inputs Specific to JPCP and CRCP Designs

JPCP Design Feature-Related Inputs

Table B-10. JPCP design feature-related inputs.

Variable	Variable Type	Value(s)	Notes/Assumptions
GENERAL INPUTS			
Slab thickness	**VARIABLE**	L: 8.0 in M: 9.0 in (standard) H: 10.0 in	The standard JPCP design is a 9-in PCC slab on a 5-in *Gravel Cushion*
Permanent curl/warp effective temperature difference	**FIXED**	-10 °F	Value recommended in the Guide
Surface short-wave absorptivity	**FIXED**	0.85	Recommended value for PCC pavements
JOINT DESIGN INPUTS			
Joint spacing (ft)	**FIXED**	20 ft	20 ft is the SDDOT standard joint spacing
Sealant type	**FIXED**	Silicone	Silicone is the SDDOT standard joint sealant
Doweled vs. undoweled joints	**FIXED**	Doweled	SDDOT's standard design contains dowels
Dowel bar diameter (in)	**FIXED**	1.25 in	SDDOT provided input
Dowel bar spacing (in)	**FIXED**	12 in	Assumed value
EDGE SUPPORT INPUTS			
Edge support type	**FIXED**	Widened Slab	SDDOT provided input
Tied PCC shoulder - Long term LTE	**NOT NEEDED**	Not applicable	This value is not needed since the edge support type is fixed to "Widened Slab"
Widened slab - slab width	**FIXED**	14 ft	SDDOT provided input
BASE-RELATED PROPERTIES			
Base type	**FIXED**	Crushed Gravel	*Gravel Cushion* is standard base under JPCP; therefore, the "Crushed Gravel" value is the most appropriate of those choices in the MEPDG software.
Erodibility index	**FIXED**	Erodibility Class = 4	Guide recommend value for "Unbound crushed granular material having dense gradation and high quality aggregates"
PCC-base interface	**FIXED**	Zero-friction contact	For a granular layer, this interface is fixed to "zero-friction contact"
Loss of full friction (age in months)	**NOT APPLICABLE**	Not applicable	Not applicable for chosen "PCC-base interface" is set to "Zero-friction contact"

CRCP Design Feature-Related Inputs

Table B-11. CRCP design feature-related inputs.

Variable	Variable Type	Value(s)	Notes/Assumptions
GENERAL INPUTS			
Slab thickness	**VARIABLE**	L: 9 in M: 10 in (standard) H: 11 in	The standard CRCP design is a 10-in PCC slab on a 5-in *Gravel Cushion* layer
Permanent curl/warp effective temperature difference	**FIXED**	-10 °F	Value recommended in the Guide
Shoulder type	**VARIABLE**	L: Tied - Separate H: Tied – Monolithic (standard)	The typical SDDOT design is a widened lane. Since "Widened lane" is not a choice in the software, a "Tied - Monolithic" shoulder was assumed to be the standard value.
Surface short-wave absorptivity	**FIXED**	0.85	Recommended value for PCC pavements
STEEL REINFORCEMENT INPUTS			
Percent steel (%)	**VARIABLE**	L: 0.5 % M: 0.6 % (standard) H: 0.7 %	SDDOT provided values
Bar diameter (in)	**VARIABLE**	L: 0.625 in (standard) H: 0.75 in	Standard bar size in SDDOT is a #5 bar
Steel depth (in)	**VARIABLE**	L: 3.0 in M: 3.5 in (standard) H: 4 in	SDDOT provided values
BASE-RELATED PROPERTIES			
Base type	**FIXED**	Crushed Gravel	*Gravel Cushion* is standard base under JPCP; therefore, the "Crushed Gravel" value is the most appropriate of those choices in the MEPDG software.
Erodibility index	**COMPUTED**	Computed value	In previous versions of the software this was a user input; however, in version 0.9 it is computed.
Base/slab friction coefficient	**VARIABLE**	L: 0.5 M: 2.5 (standard) H: 4.0	Will be varied over the typical range provided in the Guide for a granular base
CRACK SPACING-RELATED INPUTS			
Mean crack spacing cracking model	**FIXED**	"Generate using model"	The mean crack spacing cracking model choice is selected to be "Generate using model"
Mean crack spacing	**COMPUTED**	Computed value	This value is computed internally

PCC Material-Related Inputs

The PCC material-related information presented in table B-12 below is used in both the new JPCP and new CRCP pavement designs investigated in the sensitivity analysis.

Table B-12. PCC material-related inputs (for JPCP and CRCP designs).

Variable	Variable Type	Value(s)	Notes/Assumptions
GENERAL PROPERTIES			
Unit weight	**FIXED**	145 lb/ft^3	SDDOT provided input
Poisson's ratio, μ	**FIXED**	0.15	Assumed value is widely accepted for PCC
PCC THERMAL PROPERTIES			
Coefficient of thermal expansion	**VARIABLE**	L: 3.8 x 10^{-6} / °F (Limestone) M: 4.6 x 10^{-6} / °F (Granite) H: 6.8 x 10^{-6} / °F (Quartzite) (standard)	Recommended values from Guide based on aggregate type. Typical ranges are 3.4 to 5.1 for limestones, 6.6 to 7.1 for Quartzite, and 3.8 to 5.3 for Granite.
Thermal conductivity, K	**FIXED**	1.25 BTU/(hr)(ft)(°F)	Recommended value in the Guide
Heat capacity, Q	**FIXED**	0.28 Btu/(lb)(°F)	Recommended value in the Guide
PCC MIX PROPERTIES			
Cement type	**FIXED**	Type II	SDDOT provided input
Cementitious material content	**VARIABLE**	L: 550 M: 600 (standard) H: 660	SDDOT provided input
Water-to-cement ratio, w/c	**FIXED**	0.40	SDDOT provided input
Aggregate type	**VARIABLE**	L: Limestone M: Quartzite (standard) H: Granite	These three aggregate types were provided by SDDOT
PCC zero-stress temperature	**VARIABLE**	L: 80 °F M: 100 °F (standard) H: 120 °F	Assumed range of values from a table of default values in the Guide
Ultimate shrinkage at 40% relative humidity (microstrain)	**COMPUTED**	Computed internally	Computed value
Reversible shrinkage (% of ultimate shrinkage)	**FIXED**	50 percent	Recommended value in the Guide
Time to develop 50% of ultimate shrinkage	**FIXED**	35 days	Recommended value in the Guide
Curing method	**FIXED**	Curing compound	Curing compound is standard in South Dakota
PCC STRENGTH PROPERTIES			
Strength input level	**FIXED**	Level 3	For the sensitivity analysis, Level 3 was chosen so strength values could be input directly
28-day modulus of rupture	**VARIABLE**	L: 550 M: 650 (standard) H: 750	Range of values suggested by SDDOT
28-day Elastic modulus, E	**COMPUTED**	Computed value	Computed from the user-defined modulus of rupture (M_r)

Inputs Specific to the New AC Design

Table B-13. Summary of inputs associated with the new AC design.

Variable	Variable Type	Value(s)	Notes/Assumptions
STRUCTURE-RELATED INPUTS			
Interface	**FIXED**	"1" for all layers	Default values in the software
Surface short-wave absorptivity	**FIXED**	0.9	Recommended value for AC surfaces
GENERAL ASPHALT MATERIAL PROPERTIES INPUTS			
Asphalt material properties "Level"	**FIXED**	Level 3	Level 3 was used to simplify the sensitivity analysis
Asphalt material type	**FIXED**	Asphalt concrete	Best suited material type from provided list
Asphalt layer thickness	**VARIABLE**	L: 3 in M: 4 in (standard) H: 5 in	Based on discussions with SDDOT, the standard design is a 4-in AC pavement on a 12-in "Granular Base" layer.
ASPHALT MIX-RELATED INPUTS (AGGREGATE GRADATION)			
Percent retained on 3/4-in sieve (%)	**VARIABLE**	SDDOT spec is 0.	Level 3 inputs were chosen to test Asphalt dynamic modulus in the sensitivity analysis. Note that the L, M, and H values for the given gradations are grouped together into three different gradations (i.e., the L gradation is 0, 23, 42, and 5.3 for the respective inputs).
Percent retained on 3/8-in sieve (%)		L: 23 M: 18 (standard) H: 24	
Percent retained on #4 sieve (%)		L: 42 M: 34 (standard) H: 35	
Percent passing the #200 sieve (%)		L: 5.3 M: 4.3 (standard) H: 3.0	
ASPHALT BINDER-RELATED INPUTS			
Asphalt binder grade type	**FIXED**	"Superpave binder grading"	SDDOT personnel provided three typical Superpave binder gradings for use within the sensitivity analysis, therefore, the "Superpave binder grading" option was selected for this input.
Superpave binder grade	**VARIABLE**	L: 58-28 M: 64-28 (standard) H: 70-34	These three binder grades were provided by SDDOT personnel
ASPHALT GENERAL-RELATED INPUTS			
Reference Temperature (°F)	**FIXED**	70 °F	Default value in Guide
Effective binder content (%)	**VARIABLE (linked to gradations defined above)**	L: 5.5% M: 5.0% (standard) H: 4.8%	These variables will be varied together as a group based on the three gradations provided by SDDOT
Air voids (%)		L: 9.0% M: 7.0% (standard) H: 6.0%	
Total unit weight (pcf)		L: 145 M: 148 (standard) H: 150	
Poisson's ratio of asphalt, μ	**FIXED**	0.35	Fixed to the recommendation in the Guide
Thermal conductivity, K	**FIXED**	0.67 BTU/(hr)(ft)(°F)	Fixed to the recommendation in the Guide
Heat capacity, Q	**FIXED**	0.23 Btu/(lb)(°F)	Fixed to the recommendation in the Guide
THERMAL CRACKING-RELATED INPUTS			
Thermal cracking inputs for the new AC layer are described in detail in tables B-16 and B-17			

Inputs Specific to the ACOL on Existing AC Design

Table B-14. Summary of inputs associated with the ACOL on existing AC design.

Variable	Variable Type	Value(s)	Notes/Assumptions
GENERAL STRUCTURE-RELATED INPUTS			
Interface	**FIXED**	"1" for all layers	Default values in the software
Surface short-wave absorptivity	**FIXED**	0.9	Recommended value for AC surfaces
FLEXIBLE REHABILITATION-RELATED INPUTS			
Rehabilitation Level	**FIXED**	Level 3	Set to Level 3 based on lack of documentation in the Guide
Milled thickness (in)	**VARIABLE**	L: 0.5 M: 1.0 (standard) H: 2.0	Assumed values
Geotextile present on existing surface	**FIXED**	FALSE	Assumed that no geotextile is used on typical designs
Pavement rating	**VARIABLE**	L: Good M: Fair (standard) H: Poor	Assumed values representing a range of pavement condition
Total rutting (in)	**VARIABLE**	L: 0 in (standard) M: 0.125 in H: 0.25 in	Three typical values provided by SDDOT
LAYER THICKNESSES			
Asphalt overlay layer thickness	**VARIABLE**	L: 2 in M: 3 in (standard)	Based on discussions with SDDOT, the typical overlay thickness is 2.0 to 3.0 inches for AC over existing AC pavements
Asphalt concrete (existing) layer thickness	**VARIABLE**	L: 3 in M: 4 in (standard) H: 5 in	Based on discussions with SDDOT, the standard design is a 4-in AC pavement on a 12-in "Granular Base" layer
GENERAL ASPHALT MATERIAL PROPERTIES			
Asphalt material properties "Level" (for both the ACOL and existing AC layers)	**FIXED**	Level 3	Level 3 was used to simplify the sensitivity analysis
Asphalt overlay material type	**FIXED**	Asphalt concrete	Best suited material type from provided list
Asphalt material type for the existing AC layer	**FIXED**	Asphalt concrete (existing)	Best suited material type from provided list
ASPHALT MIX-RELATED INPUTS (AGGREGATE GRADATION) (BOTH NEW AND EXISTING AC LAYERS)			
Percent retained on 3/4-in sieve (%)	**VARIABLE**	SDDOT spec is 0.	Level 3 inputs were chosen to test Asphalt dynamic modulus in the sensitivity analysis. Note that the L, M, and H values for the given gradations are grouped together into three different gradations (i.e., the L gradation is 0, 23, 42, and 5.3 for the respective inputs).
Percent retained on 3/8-in sieve (%)		L: 23 M: 18 (standard) H: 24	
Percent retained on #4 sieve (%)		L: 42 M: 34 (standard) H: 35	
Percent passing the #200 sieve (%)		L: 5.3 M: 4.3 (standard) H: 3.0	

Table B-14. Summary of inputs associated with the ACOL on existing AC design (continued).

Variable	Variable Type	Value(s)	Notes/Assumptions
ASPHALT BINDER-RELATED INPUTS (BOTH NEW AND EXISTING AC LAYERS)			
Asphalt binder grade type	**FIXED**	“Superpave binder grading”	SDDOT personnel provided three typical Superpave binder gradings for use within the sensitivity analysis, therefore, the “Superpave binder grading” option was selected for this input.
Superpave binder grade	**VARIABLE**	L: 58-28 M: 64-28 (standard) H: 70-34	These three binder grades were provided by SDDOT personnel
ASPHALT GENERAL-RELATED INPUTS (BOTH NEW AND EXISTING AC LAYERS)			
Reference Temperature (°F)	**FIXED**	70 °F	Default value in Guide
Effective binder content (%)	**VARIABLE (linked to gradations defined above)**	L: 5.5% M: 5.0% (standard) H: 4.8%	These variables will be varied together as a group based on the three gradations provided by SDDOT
Air voids (%)		L: 9.0% M: 7.0% (standard) H: 6.0%	
Total unit weight (pcf)		L: 145 M: 148 (standard) H: 150	
Poisson’s ratio of asphalt, μ	**FIXED**	0.35	Fixed to the recommendation in the Guide
Thermal conductivity, K	**FIXED**	0.67 BTU/(hr)(ft)(°F)	Fixed to the recommendation in the Guide
Heat capacity, Q	**FIXED**	0.23 Btu/(lb)(°F)	Fixed to the recommendation in the Guide
THERMAL CRACKING-RELATED INPUTS			
Thermal cracking inputs for the new AC layer are described in detail in tables B-16 and B-17			

Inputs Specific to the ACOL on Rubblized JPCP Design

Table B-15. Summary of inputs associated with the ACOL on rubblized JPCP design.

Variable	Variable Type	Value(s)	Notes/Assumptions
GENERAL STRUCTURE-RELATED INPUTS			
Interface	**FIXED**	"1" for all layers	Default values in the software
Surface short-wave absorptivity	**FIXED**	0.9	Recommended value for AC surfaces
FLEXIBLE REHABILITATION-RELATED INPUTS			
Rehabilitation Level	**FIXED**	Level 3	Set to Level 3 based on lack of documentation in the Guide
Milled thickness (in)	**FIXED**	0	Value will be fixed to zero for this rehabilitation design
Geotextile present on existing surface	**FIXED**	FALSE	Assumed that no geotextile is used on typical designs
Pavement rating	**VARIABLE**	L: Fair M: Poor (standard) H: Very Poor	Assumed values representing a range of pavement condition
Total rutting (in)	**FIXED**	0	This input does not apply for this rehabilitation design
LAYER THICKNESSES			
Asphalt overlay layer thickness	**VARIABLE**	L: 4.0 in M: 4.5 in (standard) H: 5.0 in	Based on discussions with SDDOT personnel, the standard design is a 4.5 in AC overlay on rubblized JPCP for Rural conditions
JPCP (existing) layer thickness	**VARIABLE**	L: 8.0 in M: 9.0 in (standard) H: 10.0 in	Based on discussions with SDDOT personnel, the standard design is a 9 in JPCP pavement on a 5 in Gravel Cushion
GENERAL ACOL ASPHALT MATERIAL PROPERTIES			
Asphalt material properties "Level" (for both the ACOL and existing AC layers)	**FIXED**	Level 3	Level 3 was used to simplify the sensitivity analysis
Asphalt overlay material type	**FIXED**	Asphalt concrete	Best suited material type from provided list
ACOL ASPHALT MIX-RELATED INPUTS (AGGREGATE GRADATION)			
Percent retained on 3/4-in sieve (%)	**VARIABLE**	SDDOT spec is 0.	Level 3 inputs were chosen to test Asphalt dynamic modulus in the sensitivity analysis. Note that the L, M, and H values for the given gradations are grouped together into three different gradations (i.e., the L gradation is 0, 23, 42, and 5.3 for the respective inputs).
Percent retained on 3/8-in sieve (%)		L: 23 M: 18 (standard) H: 24	
Percent retained on #4 sieve (%)		L: 42 M: 34 (standard) H: 35	
Percent passing the #200 sieve (%)		L: 5.3 M: 4.3 (standard) H: 3.0	
ACOL ASPHALT BINDER-RELATED INPUTS			
Asphalt binder grade type	**FIXED**	"Superpave binder grading"	SDDOT personnel provided three typical Superpave binder gradings for use within the sensitivity analysis, therefore, the "Superpave binder grading" option was selected for this input.
Superpave binder grade	**VARIABLE**	L: 58-28 M: 64-28 (standard) H: 70-34	These three binder grades were provided by SDDOT personnel

Table B-15. Summary of inputs associated with the ACOL on rubblized JPCP design (continued).

Variable	Variable Type	Value(s)	Notes/Assumptions
ACOL ASPHALT GENERAL-RELATED INPUTS			
Reference Temperature (°F)	**FIXED**	70 °F	Default value in Guide
Effective binder content (%)	**VARIABLE (linked to gradations defined above)**	L: 5.5% M: 5.0% (standard) H: 4.8%	These variables were varied together as a group based on the three gradations provided by SDDOT
Air voids (%)		L: 9.0% M: 7.0% (standard) H: 6.0%	
Total unit weight (pcf)		L: 145 M: 148 (standard) H: 150	
Poisson's ratio of asphalt, μ	**FIXED**	0.35	Fixed to the recommendation in the Guide
Thermal conductivity, K	**FIXED**	0.67 BTU/(hr)(ft)(°F)	Fixed to the recommendation in the Guide
Heat capacity, Q	**FIXED**	0.23 Btu/(lb)(°F)	Fixed to the recommendation in the Guide
ACOL THERMAL CRACKING-RELATED INPUTS			
Thermal cracking inputs for the new AC layer are described in detail in tables B-16 and B-17.			
PCC SLAB LAYER MATERIAL-RELATED INPUTS			
Unit weight (pcf)	**FIXED**	150 lb/ft^3	Fixed to a typical unit weight of 150 lb/ft^3
Poisson's ratio of PCC, μ	**FIXED**	0.15	Fixed to a widely accepted value of 0.15 for PCC
Elastic resilient modulus of the fractured slab (psi)	**VARIABLE**	L: 100 ksi M: 150 ksi H: 200 ksi	This value was varied around the recommended value of 150 ksi for rubblization
Type of Fracture	**FIXED**	Rubblization	This value is fixed to rubblization
Thermal conductivity, K	**FIXED**	1.25 BTU/(hr)(ft)(°F)	Fixed to the recommendation in the Guide
Heat capacity, Q	**FIXED**	0.28 Btu/(lb)(°F)	Fixed to the recommendation in the Guide

AC Thermal Cracking-Related Inputs

Table B-16. General thermal cracking-related inputs for AC layers.

Variable	Variable Type	Value(s)	Notes/Assumptions
Thermal cracking input "Level"	**FIXED**	Level 3	Level 3 was used to simplify the sensitivity analysis
Creep compliance and testing duration	**VARIABLE**	L: Binder = 58-28, S = 444 psi. M: Binder = 64-28, S = 511 psi. H: Binder = 70-34, S = 590 psi.	Binder-specific tables of creep compliance values and corresponding average tensile strength (S) were selected from the recommendations in the Guide (i.e., from the MEPDG software help). The three combinations of binder type and average tensile strength are shown in the "Value(s)" column. Specific creep compliance values are summarized in table B-15 below.
Average tensile strength at 14°F (psi)			
Coefficient of thermal contraction (in/in/°F)	**VARIABLE**	L: 0.0000001 M: 0.00001 (standard) H: 0.0001	Three values provided by SDDOT

Table B-17. Specific creep compliance values associated with the three typical SDDOT binder types (values taken from tables MEPDG software help).

Binder Grade	**Time (sec)**	**Creep Compliance (1/psi)**			**Tensile Strength at 14 °F, psi**
		-4 °F	**14 °F**	**32 °F**	
PG 58-28	1	2.82685E-07	4.13685E-07	5.30896E-07	444
	2	2.96475E-07	4.2058E-07	6.20528E-07	
	5	3.30948E-07	5.24002E-07	7.79108E-07	
	10	3.37843E-07	5.86054E-07	8.75634E-07	
	20	3.65422E-07	6.48107E-07	1.048E-06	
	50	3.79212E-07	7.99792E-07	1.35827E-06	
	100	3.99896E-07	9.10108E-07	1.69611E-06	
PG 64-28	1	3.86106E-07	5.17107E-07	6.20528E-07	511
	2	4.41264E-07	5.51581E-07	7.2395E-07	
	5	4.75738E-07	6.20528E-07	9.37687E-07	
	10	5.17107E-07	7.1016E-07	1.15832E-06	
	20	5.6537E-07	8.06687E-07	1.46169E-06	
	50	6.68791E-07	9.58371E-07	1.98569E-06	
	100	7.17055E-07	1.11695E-06	2.58553E-06	
PG 70-34	1	4.3437E-07	8.27371E-07	1.3169E-06	590
	2	7.30844E-07	1.02042E-06	1.7099E-06	
	5	8.5495E-07	1.37206E-06	2.3649E-06	
	10	9.92845E-07	1.78574E-06	3.16469E-06	
	20	1.15832E-06	2.28906E-06	4.19891E-06	
	50	1.47548E-06	3.25433E-06	6.37076E-06	
	100	1.79953E-06	4.21959E-06	8.79771E-06	

APPENDIX C: SENSITIVITY ANALYSIS RESULTS

Introduction

The new mechanistic-empirical pavement design guide (MEPDG) requires the pavement design engineer to define a large number of inputs. However, it is known that not all inputs in the performance models have an equal impact on the predicted distresses. Therefore, it is important to try to determine which variables have the largest impact (i.e., are most significant) on the predicted distresses for the typical pavement designs used in South Dakota. Under the direction of the Technical Panel, the project team conducted a sensitivity analysis for the following five design types commonly used by the South Dakota Department of Transportation (SDDOT):

- New design—Rural jointed plain concrete pavement (JPCP).
- New design—Rural asphalt concrete (AC).
- New design—Continuously reinforced concrete pavement (CRCP) interstate.
- Rehabilitation—AC overlay (ACOL) over rubblized rural JPCP.
- Rehabilitation—ACOL over existing rural AC.

With the help of the Technical Panel, reasonable ranges of data inputs (reflecting South Dakota conditions and practices) were defined for each of the five identified design types. Next, a sensitivity analysis was designed to determine the impact on pavement performance caused by individual changes in the selected design inputs. With input from the Technical Panel, a total of ten scenarios were defined for these unique combinations of design type, traffic, and climate, as shown in table C-1.

Table C-1. Initial combinations of design type, traffic-, and climate-related variables that define individual scenarios for use in the sensitivity analyses.

Scenario	Design Type	Traffic	Climate (Location)
1	New design—Rural JPCP	Rural	Brookings
2			Winner
3	New design—Rural AC	Rural	Brookings
4			Winner
5	New design—CRCP interstate	Interstate	Brookings
6			Winner
7	Rehabilitation—AC overlay over rubblized rural JPCP	Rural	Brookings
8			Winner
9	Rehabilitation—AC overlay over existing rural AC	Rural	Brookings
10			Winner

The first step of the sensitivity analysis was to define "standard" pavement designs for each of the five chosen design types that reflect the most typical variable inputs used in South Dakota. The expected performance associated with each "standard" design was then predicted using version 0.9 of the MEPDG software and used to define the baseline performance for each design type. The specific performance indicators used to define pavement performance in the sensitivity analysis are summarized by design type in table C-2.

During the process of defining the specific sensitivity analysis runs, the project team worked with the Technical Panel to not only define which variables would be fixed and which would be varied in the analyses, but also to determine the typical ranges of values for the varying inputs that reflect South Dakota conditions. Once these were established, the sensitivity of each nonfixed input variable was estimated by changing the value of the variable, calculating the resulting pavement performance using the MEPDG software, and then comparing the predicted pavement performance to the established baseline performance for the given design. It is important to note that in order to keep the sensitivity analysis to a reasonable number of runs, each "run" of the software was defined by changing only <u>one</u> variable at a time. That is, the sensitivity did not attempt to identify or explore all possible combinations or all input variable interactions. The remainder of this document describes the results of the sensitivity analysis conducted for each of the five chosen pavement design types.

Analysis Approach

Under Task 3 of this project, selected design factors and site conditions were analyzed to determine the significance of their effect on predicted pavement performance. The analysis procedures used for this project consisted of the preparation of summary charts showing the relative effect of each variable, and a more detailed statistical analysis of variance (ANOVA), as described in the following sections.

Summary Charts Showing Relative Effects of Inputs

For the sensitivity analysis under Task 3, each selected MEPDG input was investigated at two or three input values. Using these two or three input levels, the sensitivity analysis was conducted and performance measures over time (e.g., total rutting, International Roughness Index [IRI], cracking, and so on) were obtained as outputs from the MEPDG software. After conducting over 600 MEPDG software runs, the predicted performance versus pavement age data were extracted

Table C-2. Performance indicator models associated with the included design types.

Design Type/ Pavement Type	**Included Performance Indicator Models**
New design—Rural JPCP	• Transverse cracking • Joint faulting • IRI
New design—Rural AC	• Longitudinal cracking (top-down fatigue) • Alligator cracking (bottom-up fatigue) • Thermal cracking • AC layer rutting • Total rutting • IRI
New design—CRCP interstate	• Punchouts • IRI
Rehabilitation—AC overlay over rubblized rural JPCP	• Longitudinal cracking (top-down fatigue) • Alligator cracking (bottom-up fatigue) • Thermal cracking • AC layer rutting • Total rutting • IRI
Rehabilitation—AC overlay over existing rural AC	• Longitudinal cracking (top-down fatigue) • Alligator cracking (bottom-up fatigue) • Reflective cracking • Thermal cracking • AC layer rutting • Total rutting • IRI

from the MEPDG output and used to determine the relative effect of each variable on performance. An example showing a plot of the extracted performance data for the transverse cracking model for new JPCP design is presented in figure C-1. For this example, the performance values associated with three different levels of annual average daily truck traffic (AADTT)—50, 250, and 450 trucks daily—at the Brookings location are illustrated. Note that the performance values at the JPCP pavement's design life (40 years) are noted on the chart for each AADTT level (i.e., 77.4 percent for AADTT = 450, 50.5 percent for AADTT = 250, and 3.9 percent for AADTT = 50). Note that the critical level of cracking for a JPCP pavement is 10 percent slabs cracked.

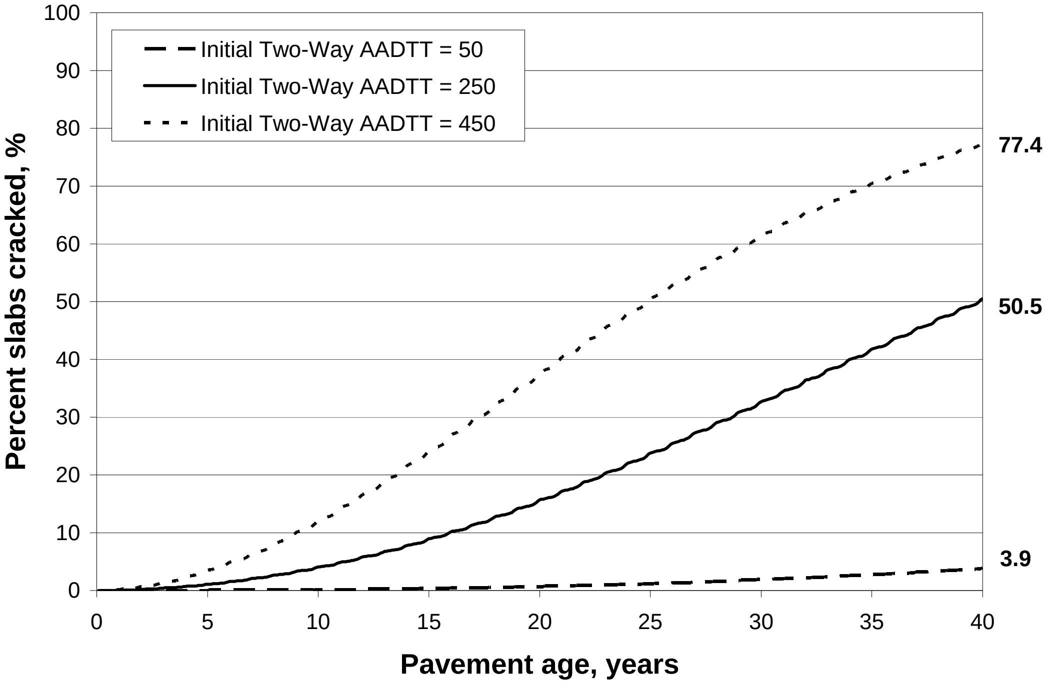

Figure C-1. Example performance trend plot showing effect of AADTT on predicted JPCP cracking (location = Brookings).

After extracting the performance data from the MEPDG output files, the results associated with each investigated input were plotted together on summary charts for each performance indicator. Building on the example data illustrated in figure C-1, figure C-2 contains an example of a summary chart that shows the relative effects of all of the investigated variables on the JPCP cracking model (Note: The variable abbreviations shown along the x-axis of figure C-2 are defined later in this section in table C-3).

For the summary charts, all of the investigated variables (associated with the particular performance indicator model) are plotted on the x-axis. The performance indicator values are plotted along the y-axis. The horizontal line on the chart indicates the expected performance of the "standard" pavement section. That is, the performance value at the pavement's design life when all MEPDG inputs are set to their "standard" values. For the example shown in figure C-2, the horizontal line at 50.5 percent slabs cracked indicates that the 40-year (design life) cracking associated with the "standard" JPCP pavement section (i.e., an analysis where all of the inputs were set to their "standard" values) was 50.5 percent slabs cracked. This is an important reference point as the performance of the "standard" pavement section is used as the baseline to which all other individual results are compared.

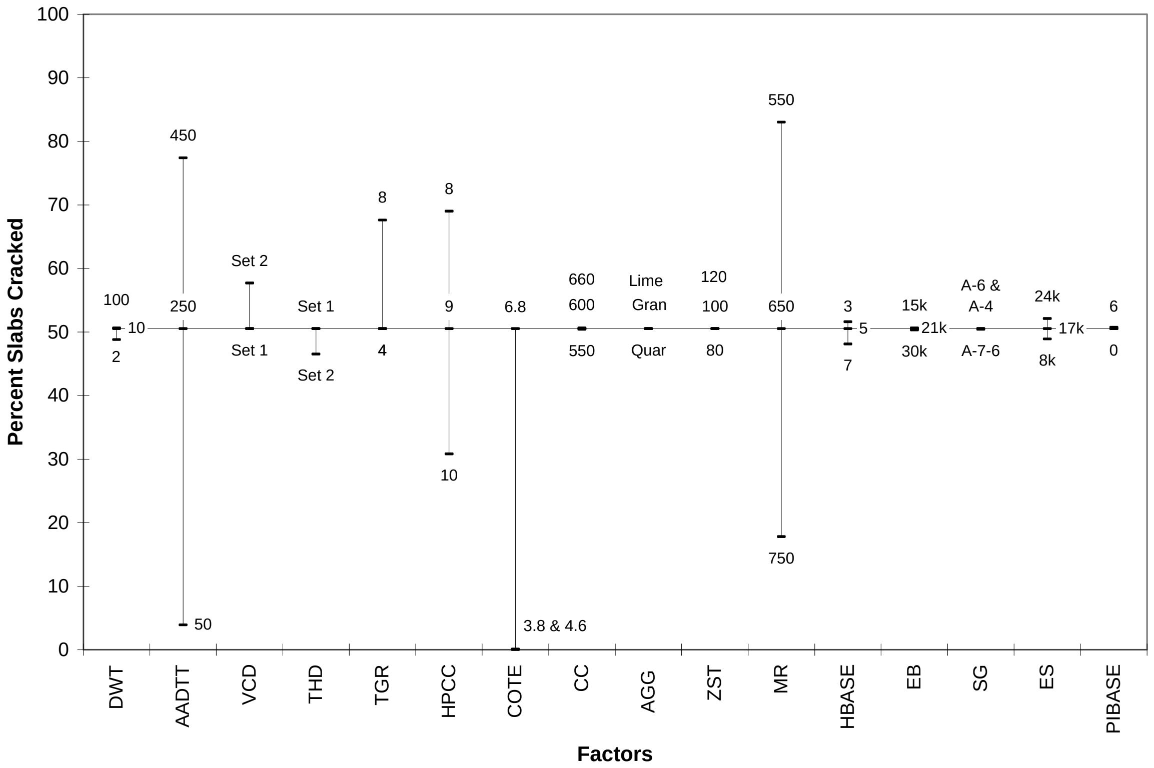

Figure C-2. Example summary chart of relative effects for the transverse cracking model for new JPCP design (Location = Brookings).

The results of the individual MEPDG software runs are used to build the vertical lines plotted for each investigated input variable. For example, note that the three 40-year (design life) AADTT-related performance values displayed on figure C-1 (i.e., 77.4 percent for AADTT = 450, 50.5 percent for AADTT = 250, and 3.9 percent for AADTT = 50) are plotted in figure C-2 for the "AADTT" variable. The length of each vertical line provides a visual indication of the magnitude of the within-sample variation associated with each input variable. Therefore, a simple conclusion from the visual interpretation of these plots is that the inputs with longer vertical lines have a larger impact on the prediction of the distress than those inputs with shorter vertical lines (i.e., longer lines indicate more significance in the prediction of the distress). For example, in figure C-2, based on the relative difference in the length of vertical lines, one would conclude that AADTT has much more of a significant effect on the occurrence of cracking in JPCP than, say, subgrade type (SG).

Analysis of Variance (ANOVA)

While a visual examination of the summary charts of relative effects gives a quick indication of which inputs are the most significant on the prediction of a particular distress, a more formal statistical analysis of variance (ANOVA) is used to verify the findings. By applying an ANOVA, the statistical significance of individual MEPDG inputs can be determined for a selected distress prediction model.

Under the sensitivity analysis conducted for this study, two or three different input values (representing the typical range of input values in South Dakota) were investigated for each individual MEPDG input. As described previously, only one input variable was investigated at a time. For example, if three input levels were investigated for a given MEPDG input, three separate MEPDG software runs were used to get the predicted performance values associated with those selected input values. Figure C-2 presents an example of a complete set of predicted distress results for the JPCP cracking model. In the ANOVA procedure, the variance of the predicted distress values associated with a given MEPDG input is ultimately used to determine the significance of that input on the distress prediction model.

In an ANOVA, the significance of an individual MEPDG input is indicated by the magnitude of the calculated *F-ratio* associated with the input. Specifically, the F-ratio associated with a given MEPDG input is computed using the following equation:

$$F = \frac{MSE_{MEPDG\ Input}}{MSE_{Total}} \qquad \text{Eq. C-1}$$

where:

F = F-ratio.

$MSE_{MEPDG\ Input}$ = Mean square error of the predicted distress data associated with the individual MEPDG input being investigated.

MSE_{Total} = Mean square error of the predicted distress data associated with all investigated MEPDG inputs.

Therefore, while the $MSE_{MEPDG\ Input}$ provides an indication of the variability associated with the distress values predicted for a specific MEPDG input, the MSE_{Total} is an estimate of the variability of the predicted distress values associated with all included MEPDG inputs.

The larger the F-ratio related to a particular MEPDG input, the higher its contribution to the overall variability in response and, consequently, the more important the term is for the model. The p-value for the F-ratio explains the level of significance for the F-ratio, and thus the level of importance of the MEPDG input for the model. A significance level (p-value) of 0.05 was selected for this study.

Expanding on the previous example, table C-3 shows a summary of the ANOVA results for the JPCP transverse cracking model. Note that in this table, the inputs are sorted from top to bottom in order of decreasing F-ratio. The first interpretation of this data was to use the p-value to determine which inputs were determined to be significant. As stated above, all inputs with an associated p-value greater than 0.05 (i.e., $\alpha = 0.05$) were classified as "not significant." For those variables that had p-values less than 0.05, a subjective assessment of the resulting F-ratios were used to classify each input as "highly significant," "moderately significant," or "mildly significant." For the JPCP cracking model results shown in table C-3, there was a large drop-off in F-ratio value between the MR (F-ratio = 104.89) and HPCC (F-ratio = 36.87) variables. Therefore, MR and all inputs with higher F-ratios were subjectively classified as "highly significant" while HPCC and the other significant variables were subjectively classified as "moderately significant."

To complete the sensitivity analysis, the statistical approach described above was used to assess the significance of MEPDG inputs on each individual performance model associated with the chosen five typical SDDOT pavement designs. The results are presented separately for each pavement type in the next sections.

Table C-3. ANOVA results for the JPCP transverse cracking model.

Order No.	Factor Abbreviation	Factor Name	F	p-value	Model Significance (α=0.05)	Assessed Level of Significance
1	AADTT	Initial two-way average annual daily truck traffic	160.80	0.000	Yes	Highly Significant
2	COTE	Coefficient of thermal expansion	134.59	0.000	Yes	
3	MR	PCC 28-day modulus of rupture	104.89	0.000	Yes	
4	HPCC	PCC slab thickness	36.87	0.000	Yes	Moderately Significant
5	CLIMATE	Climatic characteristics (location)	17.70	0.000	Yes	
6	TGR	Traffic growth rate (%)	9.99	0.004	Yes	
7	VCD	Vehicle class distribution factors	2.85	0.103	No	Not Significant
8	THD	Truck hourly distribution factors	0.50	0.484	No	
9	ES	Subgrade resilient modulus	0.16	0.853	No	
10	HBASE	Base layer thickness	0.08	0.923	No	
11	CC	Cementitious material content	0.01	0.994	No	
12	EB	Base resilient modulus	0.01	0.995	No	
13	SG	Subgrade type	0.01	0.994	No	
14	AGG	Aggregate type	0.00	0.996	No	
15	DWT	Depth of water table	0.00	0.997	No	
16	PIBASE	Base plasticity index	0.00	0.959	No	
17	ZST	PCC zero-stress temperature	0.00	0.996	No	

Note: Shaded cells indicate those variables that were found to be insignificant.

Analysis Results: New JPCP—Rural Design

For the sensitivity analysis of the new JPCP rural design, the pavement performance is expressed in terms of the following performance indicators:

- Transverse cracking.
- Transverse joint faulting.
- IRI.

This section provides the details of the analysis of sensitivity performed for the new JPCP pavement design. Specifically it includes a summary of the investigated inputs, detailed descriptions of the model-by-model analyses of significance, and a ranking of variables in terms of their significance for the typical JPCP pavement design subjected to common South Dakota conditions.

Summary of Investigated Inputs

In the first stage of the analysis, the project team worked with the Technical Panel to determine which JPCP-related inputs would be varied in the sensitivity analysis. For those inputs chosen, two or three values were investigated for each input. Typically the three values consisted of a *low* value, a medium value that represented the “standard" design, and a *high* value. Each run included in the sensitivity analysis represented a scenario when one varying input value was changed to a value other than the standard value (i.e., a high or low value). It is very important to note that only one input was changed at a time. A summary of all of the inputs varied in the JPCP sensitivity analysis is provided in table C-4. Note that the sensitivity analysis inputs outlined in table C-4 were also investigated in two different climatic locations: Brookings and Winner.

To assess the significance of different inputs on the JPCP performance models, the predicted transverse cracking, transverse joint faulting, and IRI values at the chosen design life of 40 years were collected for each of the 58 sensitivity analysis runs. Each of the three models is analyzed separately, and the summary results of the analyses are presented in the following sections.

Analysis of the JPCP Transverse Cracking Model

The results of the analysis of the JPCP transverse cracking model are presented in this section. For this analysis, 58 analysis runs were completed using the inputs defined in table C-4 above. The summary charts of relative effects summarizing the MEPDG run results are presented in figures C-3 and C-4 for Brookings and Winner, respectively. Some notable observations from the summary charts include:

- **Effect of climate-related inputs—**For the "standard" design, a higher level of cracking was predicted in the Winner climate than in the Brookings climate (66.0 percent versus 50.5 percent). Also, although the overall effect on predicted transverse cracking was small for the depth of water table (DWT) variable, the observed trends for this variable on the summary charts were counterintuitive. The observed trends showed the amount of cracking increased as DWT increased. This observed trend is opposite of what is expected in practice.
- **Effect of traffic-related inputs—**The initial two-way AADTT is observed to have the greatest effect of all variables on the level of cracking for both locations. The noticeable effect of traffic growth rate (TGR) and vehicle class distribution (VCD) on cracking also seem to be reasonable, as these are load-related factors, although less important than initial AADTT. The truck hourly distribution factors (THD) variable had the least impact of all of the investigated traffic inputs.

Table C-4. List of inputs for new JPCP design.

Name	**Abbreviation in Analysis**	**Input Values**			***Standard* Value**
		Low	**Med**	**High**	
CLIMATIC INPUTS					
Climatic characteristics (location)	CLIMATE	—	Brookings	Winner	—
Depth of water table (ft)	DWT	2	10	100	10
TRAFFIC INPUTS (RURAL TRAFFIC)					
Initial two-way average annual daily truck traffic	AADTT	50	250	450	250
Vehicle class distribution factors[1]	VCD	Set 1	—	Set 2	Set 1
Truck hourly distribution factors[2]	THD	Set 1	—	Set 2	Set 1
Traffic growth rate (%)	TGR	4	—	8	4
JPCP DESIGN FEATURES AND PCC MATERIAL INPUTS					
PCC slab thickness, in	HPCC	8	9	10	9
Coefficient of thermal expansion (per °F x 10^{-6})	COTE	3.8	4.6	6.8	6.8
Cementitious material content, lb/yd^3	CC	550	600	660	600
Aggregate type	AGG	Limestone	Quartzite	Granite	Quartzite
PCC zero-stress temp.[3], °F	ZST	80	100	120	100
PCC 28-day modulus of rupture, psi	MR	550	650	750	650
BASE INPUTS (GRAVEL CUSHION)					
Base layer thickness, in	HBASE	3	5	7	5
Base resilient modulus, psi	EB	15,000	21,000	30,000	21,000
Base plasticity index, PI	PIBASE	0	—	6	0
SUBGRADE INPUTS					
Subgrade type	SG	A-7-6	A-6	A-4	A-6
Subgrade resilient modulus, psi	ES	8,000	17,000	24,000	17,000
Subgrade plasticity index, PI	Not included directly. Varies with subgrade type.	For A-7-6: 33	For A-6: 17	For A-4: 8	For A-6: 17
Subgrade liquid limit, LL		For A-7-6: 58	For A-6: 34	For A-4: 25	For A-6: 34
Subgrade gradation information (lower and upper bounds)		For A-7-6: #200: 38.4, 99.2 #40: 69.7, 99.8 #10: 80.2, 100 #4: 84.2, 100 3/8": 92.9, 100	For A-6: #200: 36.1, 98.2 #40: 54, 99.7 #10: 70.4, 100 #4: 76.7, 100 3/8": 86.6, 100	For A-4: #200: 37.3, 69.2 #40: 44.2, 98.9 #10: 45.2, 99.9 #4: 51.6, 100 3/8": 70.8, 100	For A-6: #200: 36.1, 98.2 #40: 54, 99.7 #10: 70.4, 100 #4: 76.7, 100 3/8": 86.6, 100

Notes:

1. Vehicle class distribution is the percent distribution of truck traffic based on truck classes (class 4 through 13 according to FHWA classification). Two different SDDOT-provided distributions (shown as “Set 1” and “Set 2” in this table) were investigated in the analysis.
2. The hourly distribution factors are the percentages of truck traffic traveling in each hour of the 24-hour period. Two different SDDOT-provided distributions (shown as “Set 1” and “Set 2” in this table) were investigated in the analysis.
3. PCC zero-stress temperature is the temperature (after placement and during the curing process) at which the PCC becomes sufficiently stiff that it develops stress if restrained.

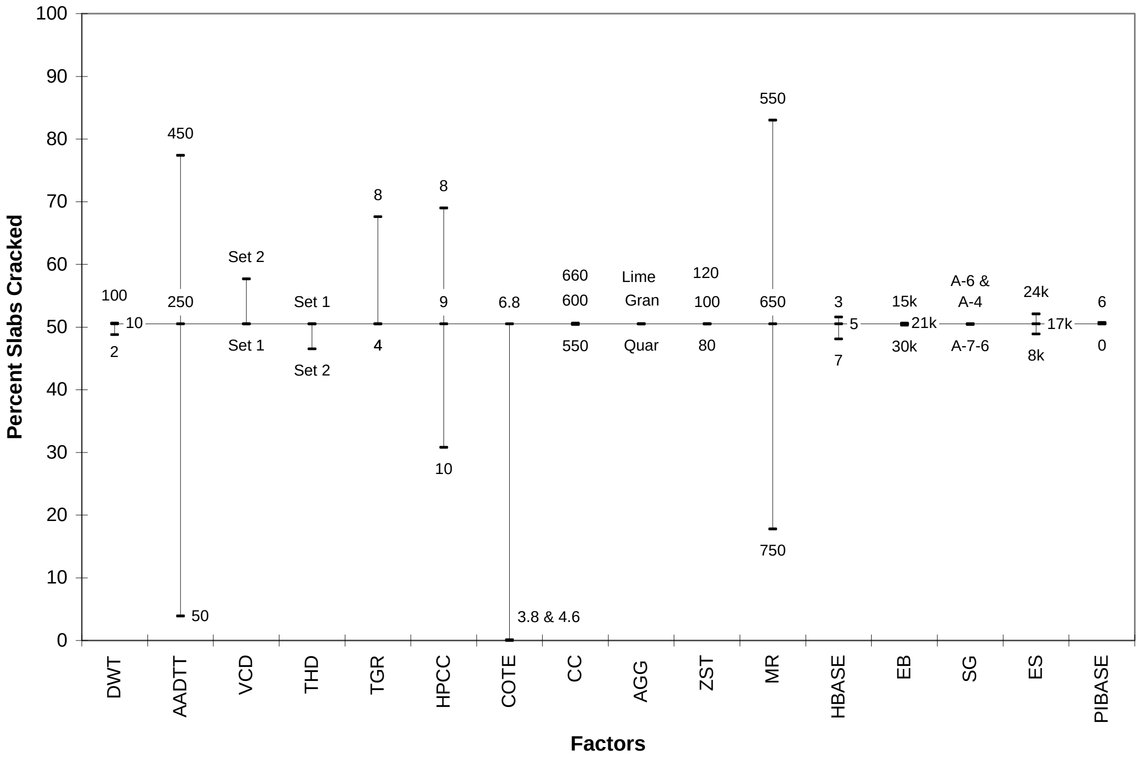

Figure C-3. Relative effect of variables on transverse cracking for new JPCP design (Location = Brookings).

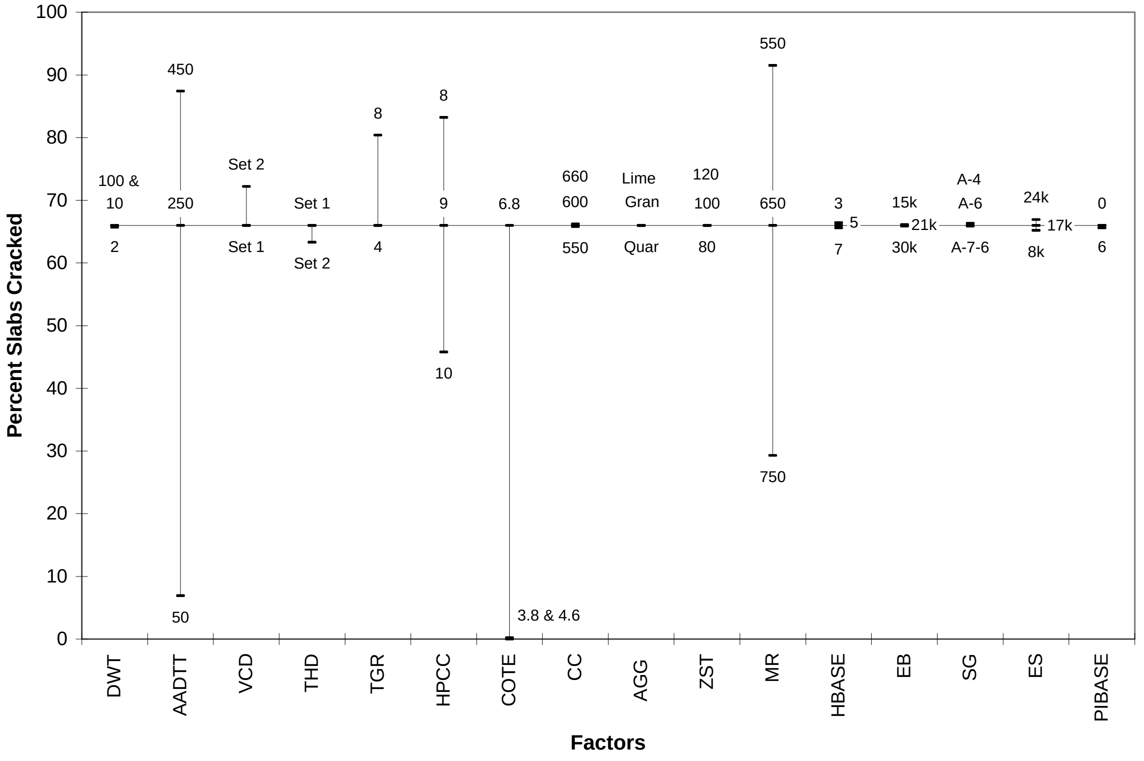

Figure C-4. Relative effect of variables on transverse cracking for new JPCP design (Location = Winner).

- **Effect of PCC layer-related inputs—**The summary charts for this model indicate that after AADTT, the next two most significant variables for cracking are PCC modulus of rupture (MR) and PCC coefficient of thermal expansion (COTE). The trends also indicate that an increase in slab thickness (HPCC) significantly reduces the level of cracking, although to a lesser degree than the PCC 28-day modulus of rupture (MR) and COTE. Finally, the charts indicate there is very little effect of the other investigated PCC mix properties (i.e., cementitious material content [CC], aggregate type [AGG], and zero-stress temperature [ZST]) on the output, which may appear to be illogical. However, this may be explained by the fact that, although the MEPDG software includes PCC mix inputs in calculation of thermal properties (drying shrinkage), their direct effect on cracking in JPCP design is diminished by the effect of COTE and MR. (Recall that MR and COTE were fixed while changing the other mix-related variables).
- **Effect of base and subgrade layer-related inputs—**For both Brookings and Winner, the charts indicate that the supporting layer thicknesses and strengths have little or no effect on transverse cracking. An increase in base thickness does reduce cracking, as does a stronger subgrade, but the effect is not very large. The base layer plasticity and base strength both appear to have little or no effect. One final observation is that the change in cracking related to change in base thickness (HBASE) and subgrade resilient modulus (ES) is slightly greater in the Brookings climate.

A subjective review of the ANOVA analysis results classifies AADTT, COTE, and MR as *Highly Significant*, and HPCC, CLIMATE, and TGR as *Moderately Significant*. The complete ANOVA results are presented in table C-5.

Analysis of the JPCP Transverse Joint Faulting Model

The results of the analysis of the JPCP transverse joint faulting model are presented in this section. For this analysis, 58 analysis runs were completed using the inputs defined in table C-4 above. The summary charts of relative effects summarizing the MEPDG run results are presented in figures C-5 and C-6 for Brookings and Winner, respectively.

One general observation from a review of the summary charts is that the ranges of faulting values shown on both charts are extremely low (i.e., 0.000 to 0.007 in for Brookings and 0.000 to 0.004 for Winner). An explanation for these low faulting values is that the standard JPCP design

Table C-5. ANOVA results for the JPCP transverse cracking model.

Order No.	Factor Abbreviation	Factor Name	F	p-value	Model Significance (α=0.05)	Assessed Level of Significance
1	AADTT	Initial two-way average annual daily truck traffic	160.80	0.000	Yes	Highly Significant
2	COTE	Coefficient of thermal expansion	134.59	0.000	Yes	
3	MR	PCC 28-day modulus of rupture	104.89	0.000	Yes	
4	HPCC	PCC slab thickness	36.87	0.000	Yes	Moderately Significant
5	CLIMATE	Climatic characteristics (location)	17.70	0.000	Yes	
6	TGR	Traffic growth rate (%)	9.99	0.004	Yes	
7	VCD	Vehicle class distribution factors	2.85	0.103	No	Not Significant
8	THD	Truck hourly distribution factors	0.50	0.484	No	
9	ES	Subgrade resilient modulus	0.16	0.853	No	
10	HBASE	Base layer thickness	0.08	0.923	No	
11	CC	Cementitious material content	0.01	0.994	No	
12	EB	Base resilient modulus	0.01	0.995	No	
13	SG	Subgrade type	0.01	0.994	No	
14	AGG	Aggregate type	0.00	0.996	No	
15	DWT	Depth of water table	0.00	0.997	No	
16	PIBASE	Base plasticity index	0.00	0.959	No	
17	ZST	PCC zero-stress temperature	0.00	0.996	No	

Note: Shaded cells indicate those variables that were found to be insignificant.

used for this investigation contains 1.25-in diameter dowels. As previous studies in other states have indicated, the presence of dowels is the main factor affecting transverse joint faulting (Khazanovich et al 2006). To illustrate the impact of dowels on the performance of the SDDOT standard section, some additional runs were conducted to illustrate the performance associated with no dowels, 1.25-in dowels, and 1.5-in dowels. Note: These runs were conducted for the Brookings location only. The results of the additional influence of dowel diameter investigation are presented in figure C-7.

In spite of the dominant effect of dowel bars, a review of the charts still provides useful information regarding the relative impact of the other investigated variables on transverse joint faulting. Other notable observations from the summary charts include:

- **Effect of climate-related inputs—**Overall, a slightly higher level of faulting was predicted in the Brookings climate for most variables. For example, the investigation of the “standard” design resulted in a 0.003-in value for Brookings compared to a 0.002-in value for Winner. However, note that for practical purposes this difference is insignificant. Also, although the overall effect on predicted transverse joint faulting was

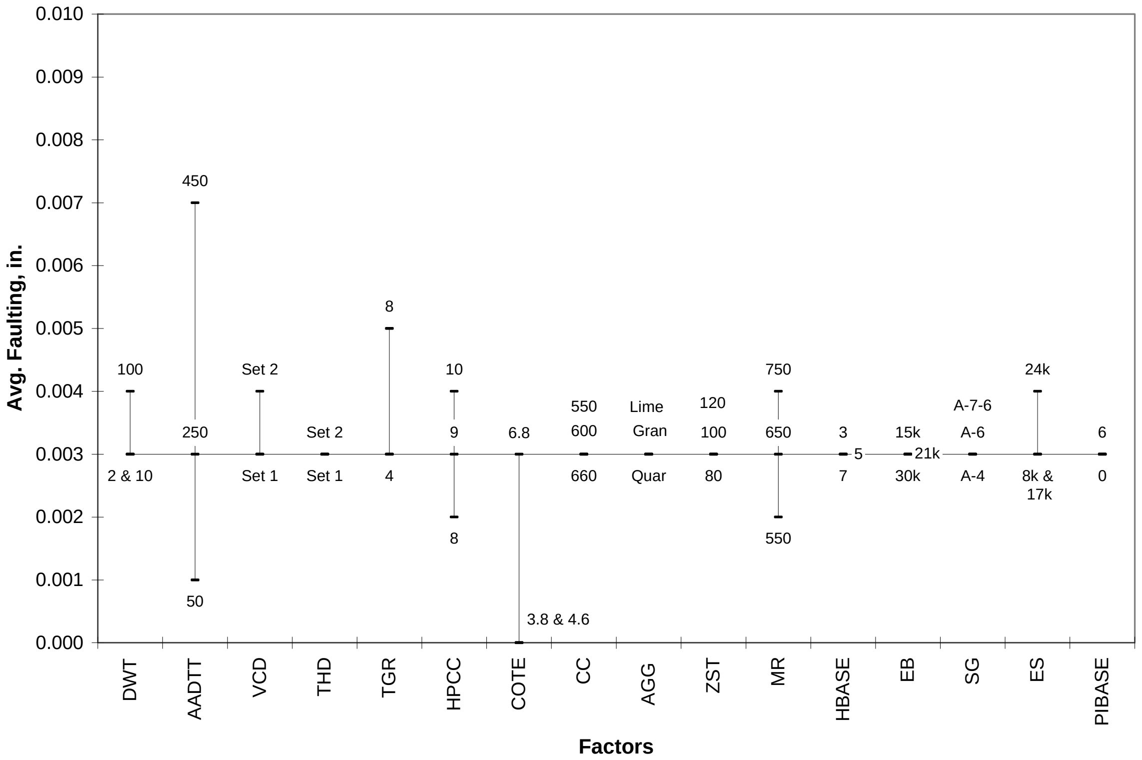

Figure C-5. Relative effect of variables on transverse joint faulting for new JPCP design (Location = Brookings).

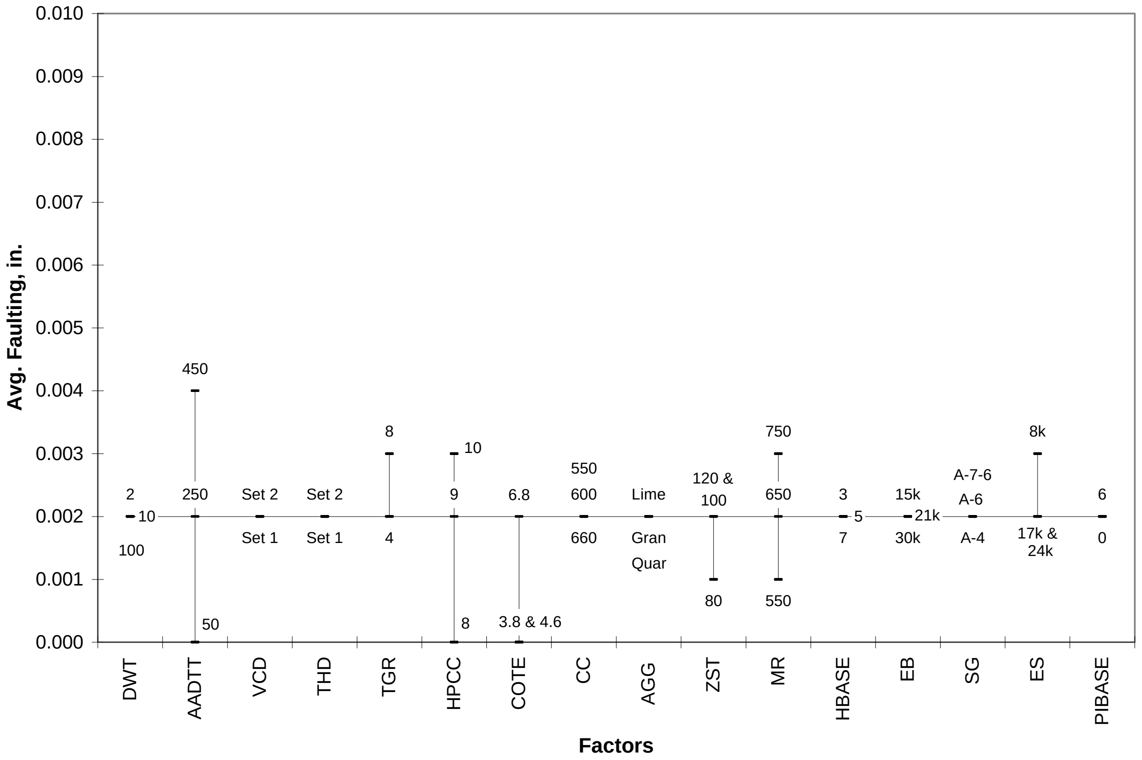

Figure C-6. Relative effect of variables on transverse joint faulting for new JPCP design (Location = Winner).

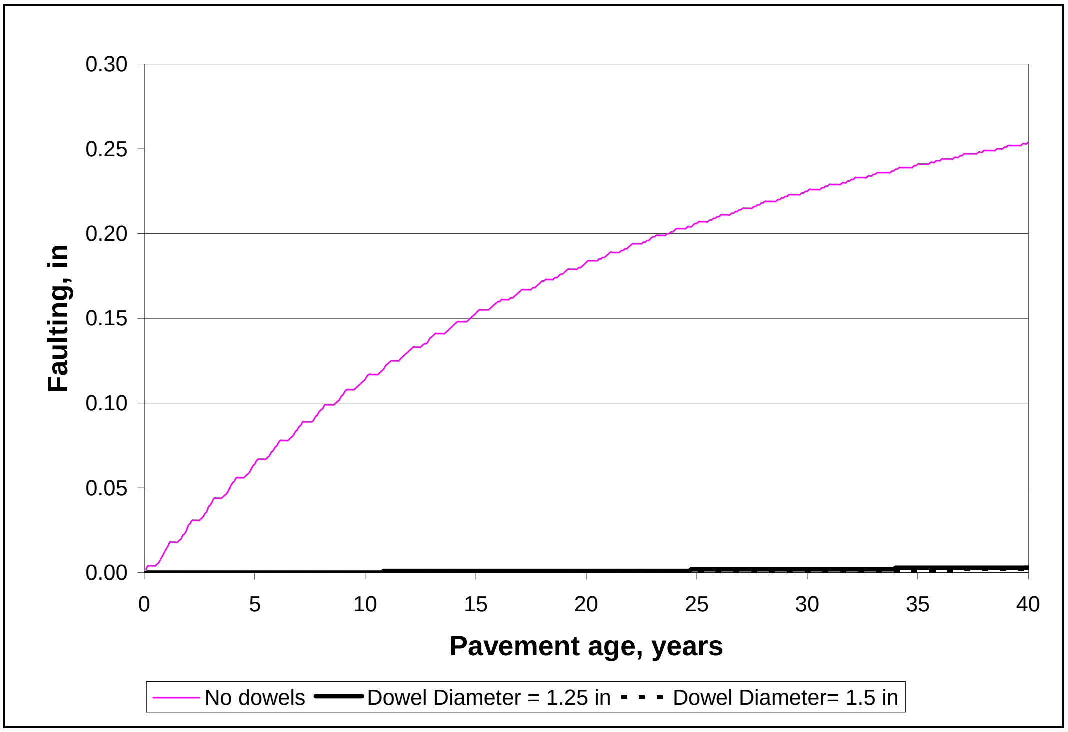

Figure C-7. Effect of dowel diameter on faulting (Location = Brookings).

small for the DWT variable on the Brookings chart, the observed trend was again observed to be counterintuitive. The results showed that the amount of faulting increased as DWT increased. This observed trend is opposite of what is expected in practice.

- **Effect of traffic-related inputs**—AADTT is by far the most influential of the investigated variables on the development of joint faulting. Also, AADTT, TGR, and VCD all have more of an effect at the Brookings location than for the Winner location. Finally, the THD variable was observed to have no affect on JPCP faulting in either climatic location.

- **Effect of PCC layer-related inputs**—Of the different investigated PCC layer-related inputs, only HPCC, COTE, and MR showed any influence on JPCP joint faulting. Overall, the influence of these three variables did not greatly differ between the Brookings and Winner locations. It is, however, important to note that the trends associated with the HPCC variable initially appear to be counterintuitive (i.e., the charts indicate that an increase in slab thickness results in an increase in joint faulting). Although this appears counterintuitive, this is a documented trend in the model for doweled pavements when the dowel diameter is held constant while increasing slab thickness. If the general practice of increasing dowel diameter when slab thickness increased was followed, it is believed that this trend would no longer appear counterintuitive.

- **Effect of base and subgrade layer-related inputs—**All of the base and subgrade layer-related variables were observed to have virtually no impact on transverse joint faulting with the exception of the ES. For ES, the trend shown for the Winner location was found to be intuitive, while the trend displayed for Brookings was not. For Brookings, the trend showed that a very slight increase in faulting was predicted when the ES increased to 24 ksi. While this counterintuitive trend was verified as an actual MEPDG result, it is again important to remember that the faulting difference between all three trials is only 0.001 in.

A subjective review of the ANOVA analysis results classifies AADTT, COTE, CLIMATE, and HPCC as *Highly Significant*, and TGR and MR as *Moderately Significant*. The complete ANOVA results are presented in table C-6.

Table C-6. ANOVA results for the JPCP transverse joint faulting model.

Order No.	Factor Abbreviation	Factor Name	F	p-value	Model Significance (α=0.05)	Assessed Level of Significance
1	AADTT	Initial two-way average annual daily truck traffic	57.81	0.000	Yes	Highly Significant
2	COTE	Coefficient of thermal expansion	34.80	0.000	Yes	
3	CLIMATE	Climatic characteristics (location)	23.69	0.000	Yes	
4	HPCC	PCC slab thickness	15.53	0.000	Yes	
5	TGR	Traffic growth rate (%)	9.59	0.004	Yes	Moderately Significant
6	MR	PCC 28-day modulus of rupture	9.49	0.001	Yes	
7	ZST	PCC zero-stress temperature	1.73	0.197	No	Not Significant
8	DWT	Depth of water table	0.73	0.490	No	
9	PIBASE	Base plasticity index	0.38	0.541	No	
10	THD	Truck hourly distribution factors	0.38	0.541	No	
11	VCD	Vehicle class distribution factors	0.38	0.541	No	
12	AGG	Aggregate type	0.29	0.752	No	
13	CC	Cementitious material content	0.29	0.752	No	
14	EB	Base resilient modulus	0.29	0.752	No	
15	ES	Subgrade resilient modulus	0.29	0.752	No	
16	HBASE	Base layer thickness	0.29	0.752	No	
17	SG	Subgrade type	0.00	1.000	No	

Note: Shaded cells indicate those variables that were found to be insignificant.

Analysis of the JPCP IRI Model

In the MEPDG approach, IRI (an indicator of smoothness) for JPCP is predicted as a function of the initial as-constructed IRI and the predicted transverse slab cracking, joint faulting and joint spalling. The model also includes a site factor for adjusting to the local subgrade and climate. Therefore, the IRI model in this study was evaluated in terms of its correlation with the main performance indicators (cracking and faulting) rather than with the software inputs. Although the visual IRI trends were assessed subjectively based on the same set of inputs as the cracking and faulting trends, the statistical analysis included only performance indicators (cracking and faulting) as variables to evaluate their contribution to the IRI prediction model.

Figures C-8 and C-9 show the relative effects of the detailed variable inputs on predicted IRI (Note that the IRI values plotted in these figures are the predicted values at the end of the 40-year analysis period). A comparison of these figures finds that although the predicted IRI for the "standard" design was different between the two climates (197 in/mile for Brookings and 182 in/mile for Winner), the overall difference between these two values is relatively small on the IRI scale. Also, as expected, the variables found to be significant in the cracking and faulting models appear to significantly affect IRI. One noticeable exception to this trend is the subgrade type (SG) which shows a much higher level of effect on IRI as compared with its zero effect on cracking and faulting. The more significant subgrade contribution to the IRI prediction model can be explained by the fact that it is included in the "site factor" equation.

A subjective review of the ANOVA analysis results shows that both transverse cracking and transverse joint faulting are significant when predicting IRI. Also, it is observed that transverse cracking was found to be more significant than transverse joint faulting in the analysis. The complete ANOVA results are presented in table C-7.

Overall Assessment of Significant Variables for New JPCP (Rural Design)

Fifty-eight MEPDG software simulations were run to obtain the results for predicted transverse slab cracking, transverse joint faulting, and IRI in newly designed rural JPCP. The sensitivity of the prediction models for those performance indicators to the change in design inputs was assessed by reviewing visual trends and conducting a statistical analysis of significance. The outcomes of the statistical analysis were used to *rank* the investigated model inputs from most significant to least significant in terms of how they influence the predicted performance of each

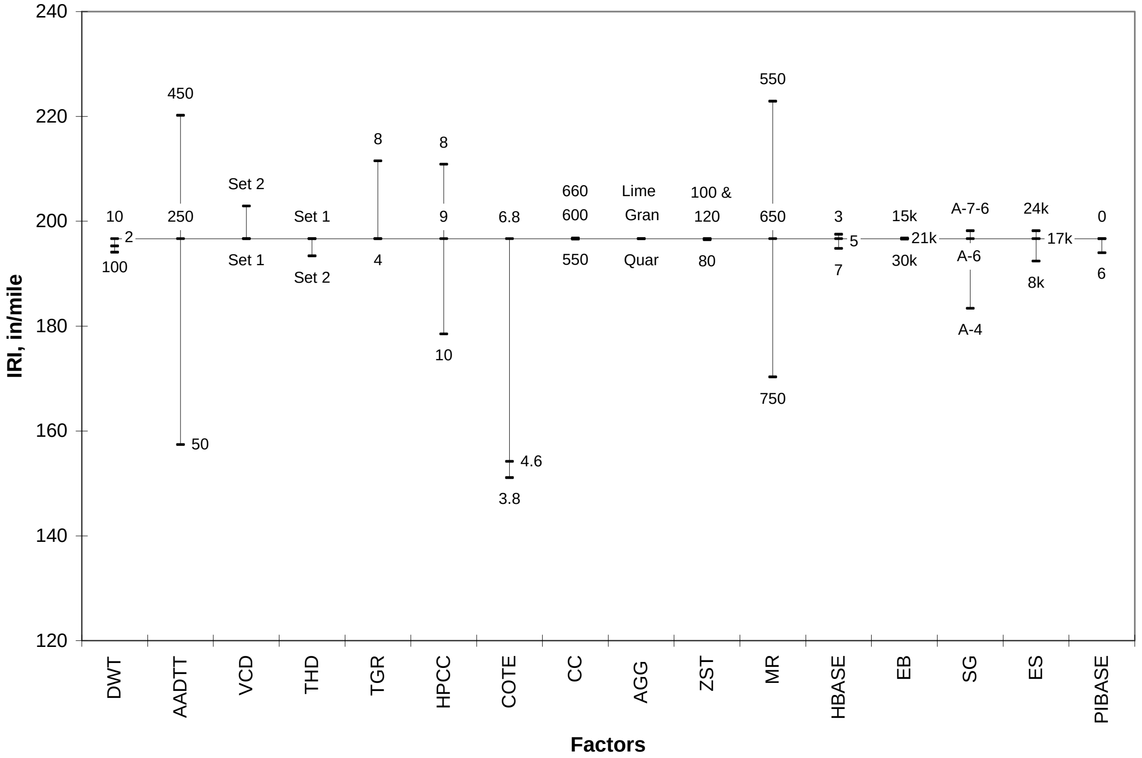

Figure C-8. Relative effect of variables on IRI for new JPCP design (Location = Brookings).

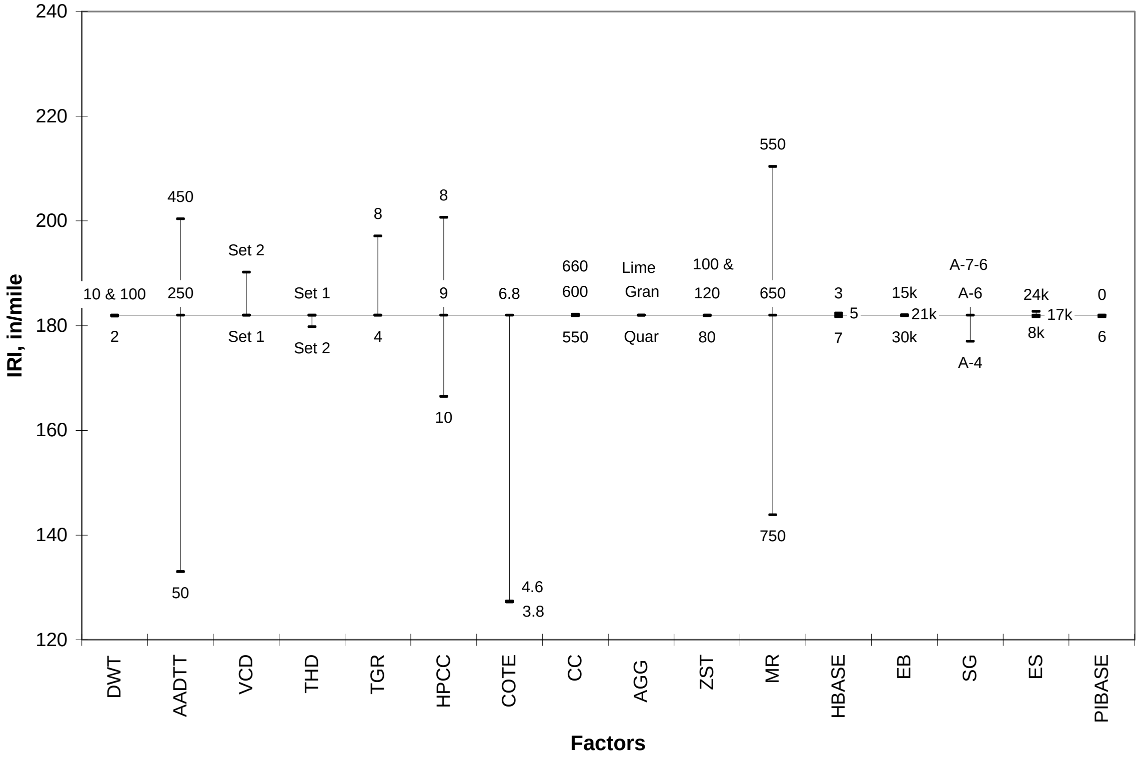

Figure C-9. Relative effect of variables on IRI for new JPCP design (Location = Winner).

Table C-7. ANOVA results for the JPCP IRI model.

Order No.	Factor Abbreviation	Factor Name	F	p-value	Model Significance (α=0.05)
1	CRACK	Transverse cracking	66.85	0.000	Significant
2	FAULT	Transverse joint faulting	27.15	0.000	Significant

individual performance model. Because IRI was found to be very much dependent on the predicted cracking and faulting values, the final results below only display the rankings of the individual inputs for these two models.

Table C-8 presents the input parameters that were found to be most significant for each performance indicator model. The parameters are placed in decreasing order of their significance for each investigated performance indicator. A ranking summary of each input parameter for a new rural JPCP design is also provided in table C-9. The ranking is based upon the results of the analysis of variance for each performance indicator. Shaded values in table C-9 indicate those variables that were found to be “not significant” in the statistical analyses.

Table C-8. Summary of statistically significant variables for new JPCP (rural design).

Performance Indicator	Input Parameter/Predictor
Transverse cracking	• Initial two-way average annual daily truck traffic • PCC coefficient of thermal expansion • PCC modulus of rupture • PCC slab thickness • Climatic characteristics (location) • Traffic growth rate
Transverse joint faulting	• Initial two-way average annual daily truck traffic • PCC coefficient of thermal expansion • Climatic characteristics (location) • PCC slab thickness • Traffic growth rate • PCC modulus of rupture
Smoothness (IRI)	• Transverse slab cracking • Transverse joint faulting

Table C-9. Ranking summary of significance of each input parameter on the performance indicator for new JPCP (rural design).

Input Parameter/Predictor	Rankings for Individual Performance Indicators		Overall Order of Significance
	Transverse Cracking	Transverse Joint Faulting	
Annual average daily truck traffic	1	1	1
PCC coefficient of thermal expansion	2	2	2
PCC modulus of rupture	3	6	3
PCC slab thickness	4	4	4
Climatic characteristics (location)	5	3	5
Traffic Growth Rate	6	5	6
Vehicle class distribution factors	7	11	7
Truck hourly distribution factors	8	10	8
Subgrade resilient modulus	9	15	9
Base layer thickness	10	16	10
Cementitious material content	11	13	11
Base resilient modulus	12	14	12
Subgrade type	13	17	13
PCC Aggregate type	14	12	14
Depth of water table	15	8	15
Base plasticity index	16	9	16
PCC zero-stress temperature	17	7	17

Note: Shaded cells indicate those variables that were found to be insignificant.

Note that because the predicted values of transverse joint faulting were found to be relatively insignificant to overall performance (i.e., the observed range of predicted faulting values only ranged from 0.000 to 0.007 in), it is the transverse cracking ranking that controls the overall ranking of variable significance for this design.

All conclusions about the importance and the order of significance of the inputs are valid for the given range of inputs provided by the SDDOT, and are based on the local South Dakota conditions.

Analysis Results: New AC—Rural Design

For the sensitivity analysis of the new AC rural design, the pavement performance is expressed in terms of the following performance indicators:

- Longitudinal cracking (top-down fatigue).
- Alligator cracking (bottom-up fatigue).
- AC layer rutting.

- Total rutting.
- IRI.

While it is recognized that transverse cracking is also an important performance indicator for AC-surfaced pavements, a problem with the transverse cracking model was encountered when conducting the sensitivity analysis with version 0.9 of the MEPDG software. When reviewing the results from the sensitivity analysis runs, it was discovered that the transverse cracking model consistently predicted 20-year (AC design life) transverse cracking values equal to “0” when the runs were completed using a computer running the Windows XP operating system. Conversely, the same runs completed on computers running Windows NT2000 yielded nonzero results that were typically near the allowable model maximum of 2,110 ft/mi at 20 years. Due to the inability of this model to predict consistent nonzero values for the investigated runs, it was decided to ignore this model in the current sensitivity analysis. However, it is recommended that this model be revisited when a newer version of the MEPDG software is released.

This section provides the details of the analysis of sensitivity performed for the new AC pavement design. Specifically it includes a summary of the investigated inputs, detailed descriptions of the model-by-model analyses of significance, and a ranking of variables in terms of their significance for a “standard” AC pavement design in typical South Dakota conditions.

Summary of Investigated Inputs

In the first stage of the analysis, the input variables and the specific input values for analysis were determined. Based on these inputs, a total of 56 MEPDG software simulations were run to predict the development of longitudinal cracking, alligator cracking, AC layer rutting, total rutting, and IRI in the two climatic locations (Brookings and Winner). The analysis period used for this design was chosen to be 20 years (i.e., all predicted performance values presented in the charts are the values predicted at the end of 20 years). Each run included in the sensitivity analysis represented a scenario in which one input value was changed to a value other than the standard value (i.e., a high or low value). A summary of all of the inputs varied in the AC sensitivity analysis is provided in table C-10.

The sensitivity of the performance models for the different distresses was analyzed separately. The results of these individual analyses are presented in the following sections.

Table C-10. List of inputs for new AC design.

Name	Abbreviation in Analysis	Input Values			*Standard* Value
		Low	Med	High	
CLIMATIC INPUTS					
Climatic characteristics (location)	CLIMATE	—	Brookings	Winner	—
Depth of water table (ft)	DWT	2	10	100	—
TRAFFIC INPUTS (RURAL TRAFFIC)					
Initial two-way average annual daily truck traffic	AADTT	50	250	450	250
Vehicle class distribution factors[1]	VCD	Set 1	—	Set 2	Set 1
Truck hourly distribution factors[2]	THD	Set 1	—	Set 2	Set 1
Traffic growth rate (%)	TGR	4	—	8	4
Tire pressure, psi	TPRESS	120		140	120
AC DESIGN FEATURES AND MATERIAL INPUTS					
AC layer thickness	HAC	3	4	5	4
AC mix gradation information (Percent retained on sieve, %)	ACGRAD	3/4”: 0 3/8”: 23 #4: 42 #200: 5.3	3/4”: 0 3/8”: 18 #4: 34 #200: 4.3	3/4”: 0 3/8”: 24 #4: 35 #200: 3	3/4”: 0 3/8”: 18 #4: 34 #200: 4.3
AC binder grade	ACBIND	58-28	64-28	70-34	64-28
Effective binder content, %	Not included directly. Varies with binder grade.	For 58-28: 5.5	For 64-28: 5	For 70-34: 4.8	For 64-28: 5
Air voids, %		For 58-28: 9	For 64-28: 7	For 70-34: 6	For 64-28: 7
Total unit weight, pcf		For 58-28: 145	For 64-28: 148	For 70-34: 150	For 64-28: 148
AC creep compliance	ACCRIP	“PG58-28” values from Table C-1	“PG64-28” values from Table C-1	“PG70-34” values from Table C-1	“PG64-28” values from Table C-1
Coef. of thermal contraction (in/in/°F)	CTC	1E-07	1E-05	1E-04	1E-05
BASE INPUTS (GRAVEL CUSHION)					
Base layer thickness, in	HBASE	4	12	14	12
Base resilient modulus, psi	EB	15,000	21,000	30,000	21,000
Base plasticity index, PI	PIBASE	0	—	6	0
SUBGRADE INPUTS					
Subgrade type	SG	A-7-6	A-6	A-4	A-6
Subgrade resilient modulus, psi	ES	8,000	17,000	24,000	17,000
Subgrade plasticity index, PI	Not included directly. Varies with subgrade type.	For A-7-6: 33	For A-6: 17	For A-4: 8	For A-6: 17
Subgrade liquid limit, LL		For A-7-6: 58	For A-6: 34	For A-4: 25	For A-6: 34
Subgrade gradation information (upper and lower bounds)		For A-7-6: #200: 38.4,99.2 #40: 69.7, 99.8 #10: 80.2, 100 #4: 84.2, 100 3/8": 92.9, 100	For A-6: #200: 36.1, 98.2 #40: 54, 99.7 #10: 70.4, 100 #4: 76.7, 100 3/8": 86.6,100	For A-4: #200: 37.3, 69.2 #40: 44.2, 98.9 #10: 45.2, 99.9 #4: 51.6, 100 3/8": 70.8, 100	For A-6: #200: 36.1, 98.2 #40: 54, 99.7 #10: 70.4, 100 #4: 76.7, 100 3/8": 86.6, 100

Analysis of the Longitudinal (Top-Down Fatigue) Cracking Model for New AC Design

The longitudinal cracking data over time produced by the MEPDG software were analyzed to evaluate the significance of the effect of each model input on the longitudinal cracking model output. In order to compare the degree of the change in the longitudinal cracking caused by each investigated input, the predicted values at the chosen AC design life of 20 years were collected and plotted as shown in figures C-10 and C-11 for Brookings and Winner, respectively. In these figures, the predicted longitudinal cracking associated with the "standard" section is depicted by the horizontal line on each chart (i.e., the 20-year longitudinal cracking value predicted for Brookings is 1,320 ft/mile). The remaining plotted points help illustrate the expected range of longitudinal cracking associated with a typical value range of South Dakota input values. The definitions of variable abbreviations used on the charts are defined in table C-10. Some notable observations from the summary charts include:

- **Effect of climate-related inputs—**For the "standard" design, a higher level of longitudinal cracking was predicted for the Winner climate than for the Brookings climate (1,400 ft/mi versus 1,320 ft/mi). It is also interesting to note that the DWT had no impact on the development of longitudinal cracking in either climatic location.
- **Effect of traffic-related inputs—**The initial two-way AADTT is observed to have the largest effect of all traffic-related variables on longitudinal cracking for both locations. The effect of TGR is also notable in the charts, while the other traffic-related inputs (VHD, THD, TGR, and tire pressure [TPRESS]) show little or no effect. As expected, higher traffic volume result in higher levels of longitudinal cracking.
- **Effect of AC layer-related inputs—**While the AC layer thickness (HAC) is observed to be the most influential factor in both climates, it is worth noting that there appears to be a counterintuitive trend associated with this variable. That is, the longitudinal cracking value associated with an HAC of 5 in is greater than that cracking associated with an HAC of 4 in. A review of the MEPDG documentation (NCHRP 2004) finds that this trend is an expected trend for this model. While no in-depth explanation of this model trend is included in the MEPDG documentation, it is believed that this observed trend is the result of having two separate longitudinal cracking models (i.e., top-down and bottom-up). For thinner sections, developing longitudinal cracks would most likely be bottom-up cracks not reflected in this model.

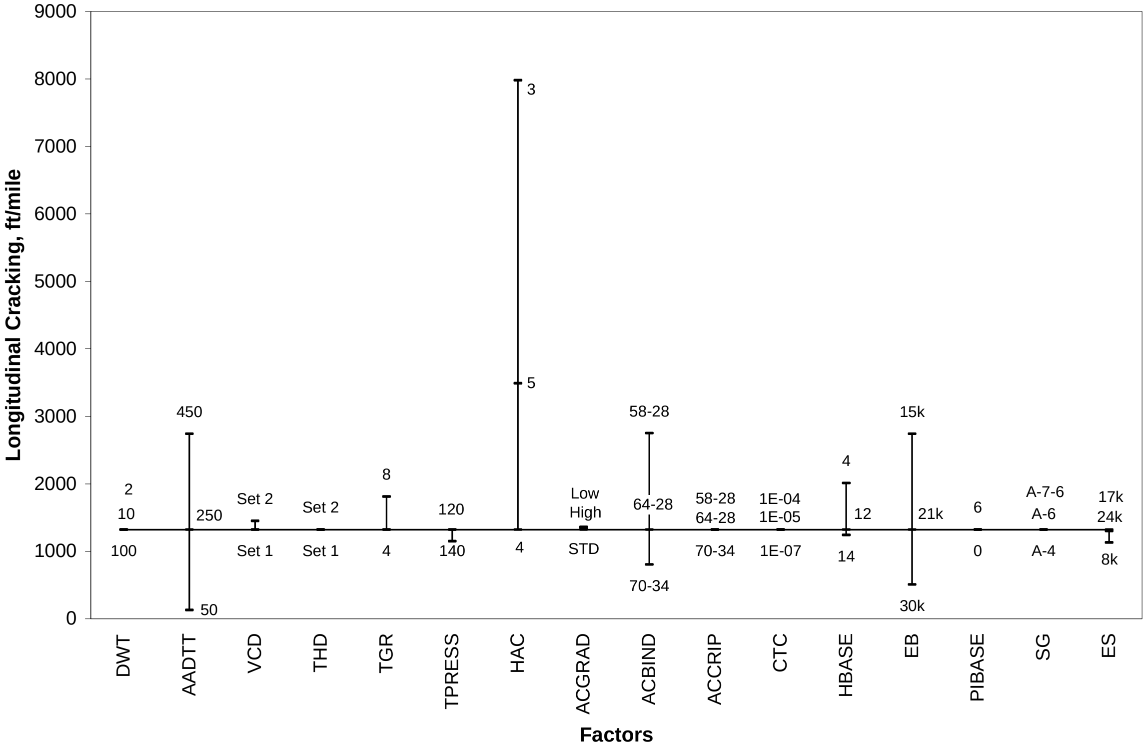

Figure C-10. Relative effect of variables on longitudinal cracking for new AC design (Location = Brookings).

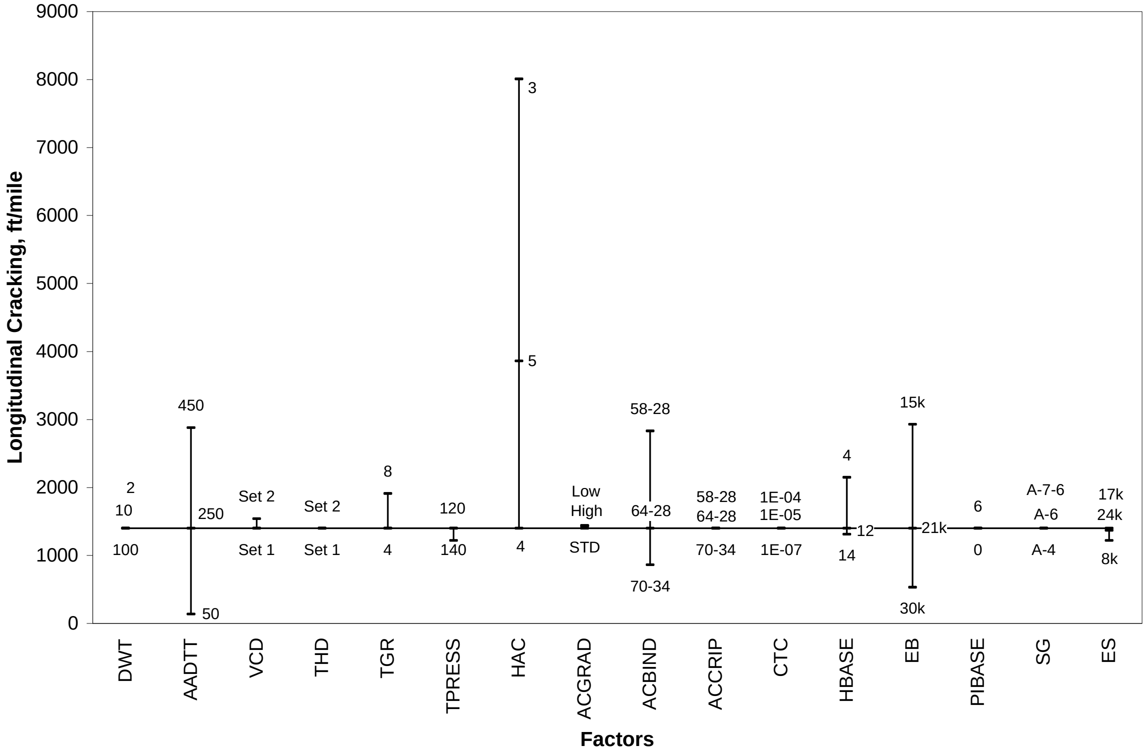

Figure C-11. Relative effect of variables on longitudinal cracking for new AC design (Location = Winner).

Another noticeable counterintuitive trend is that associated with TPRESS as both charts indicate a decrease in cracking as tire pressure increases. No explanation of this trend was found in the MEPDG documentation (NCHRP 2004).

Among the AC mix properties, only the AC binder grade (ACBIND) shows a noticeable impact on top-down longitudinal cracking. Also noteworthy is the fact that the AC creep compliance (ACCRIP) and coefficient of thermal contraction (CTC) variables have no effect on the top-down longitudinal cracking model.

- **Effect of base layer-related inputs—**The summary charts show a noticeable effect of base resilient modulus (EB) on longitudinal cracking with cracking increasing as EB decreases. This effect is comparable to the effect of AADTT and ACBIND. The HBASE variable also shows a noticeable effect on the level of longitudinal cracking, although this effect is not as great as that observed for EB. The base plasticity index (PIBASE) shows no impact on longitudinal cracking for either climatic location.
- **Effect of subgrade layer-related inputs—**A review of the subgrade-related variables finds that subgrade type (SG) shows no effect on longitudinal cracking while ES shows a minimal effect. It is also interesting to note that there appears to be a counterintuitive trend associated with ES (i.e., top-down longitudinal cracking decreases as the strength of the subgrade decreases). The MEPDG documentation explains that top-down longitudinal cracking increases as the foundation support increases because stiffer support conditions result in larger tensile strains at the surface (NCHRP 2004).

A subjective review of the ANOVA analysis results classifies HAC, AADTT, EB, and ACBIND as *Highly Significant,* and HBASE, TGR, TPRESS, VCD, ES, and CLIMATE as *Moderately Significant*. The complete ANOVA results are presented in table C-11.

Analysis of the Alligator (Bottom-Up Fatigue) Cracking Model for New AC Design

The results of the analysis of the new AC alligator (bottom-up) cracking model are presented in this section. For this analysis, 56 analysis runs were completed using the inputs defined in table C-10 above. The summary charts of relative effects summarizing the MEPDG run results are presented in figures C-12 and C-13 for Brookings and Winner, respectively. Some notable observations from the summary charts include:

Table C-11. ANOVA results for the AC longitudinal cracking model

Order No.	Factor Abbreviation	Factor Name	F	p-value	Model Significance (α=0.05)	Assessed Level of Significance
1	HAC	AC layer thickness	14210.31	0.000	Yes	Highly Significant
2	AADTT	Initial two-way average annual daily truck traffic	1739.84	0.000	Yes	
3	EB	Base resilient modulus	1345.87	0.000	Yes	
4	ACBIND	AC binder grade	1025.60	0.000	Yes	
5	HBASE	Base layer thickness	205.64	0.000	Yes	Moderately Significant
6	TGR	Traffic growth rate (%)	161.35	0.000	Yes	
7	TPRESS	Tire pressure	19.77	0.000	Yes	
8	VCD	Vehicle class distribution factors	11.76	0.002	Yes	
9	ES	Subgrade resilient modulus	11.53	0.000	Yes	
10	CLIMATE	Climatic characteristics (location)	8.49	0.007	Yes	
11	ACGRAD	AC mix gradation information	0.62	0.547	No	Not Significant
12	DWT	Depth of water table	0.03	0.968	No	
13	ACCRIP	AC creep compliance	0.00	1.000	No	
14	CTC	Coef. of thermal contraction	0.00	1.000	No	
15	PIBASE	Base plasticity index	0.00	1.000	No	
16	SG	Subgrade type	0.00	1.000	No	
17	THD	Truck hourly distribution factors	0.00	1.000	No	

Note: Shaded cells indicate those variables that were found to be insignificant.

- **Effect of climate-related inputs—**For the standard new AC design, there was very little difference between the alligator cracking predicted for both climatic locations (i.e., 26.6 percent for Brookings and 29.0 percent for Winner). The DWT variable also showed little or no impact on the development of alligator cracking in either climatic location.
- **Effect of traffic-related inputs—**A review of the summary charts shows that AADTT is the variable with the largest effect on alligator cracking in both climatic locations. The other traffic-related variables showing a noticeable impact on alligator cracking model are TGR, TPRESS, and VCD, in that order. THD did not show any effect on alligator cracking in either location.
- **Effect of AC layer-related inputs**—ACBIND and HAC are observed to be the most influential factors after AADTT. The asphalt mix gradation (ACGRAD) and the AC thermal properties (ACCRIP and CTC) showed little or no influence on the level of alligator cracking in both locations.

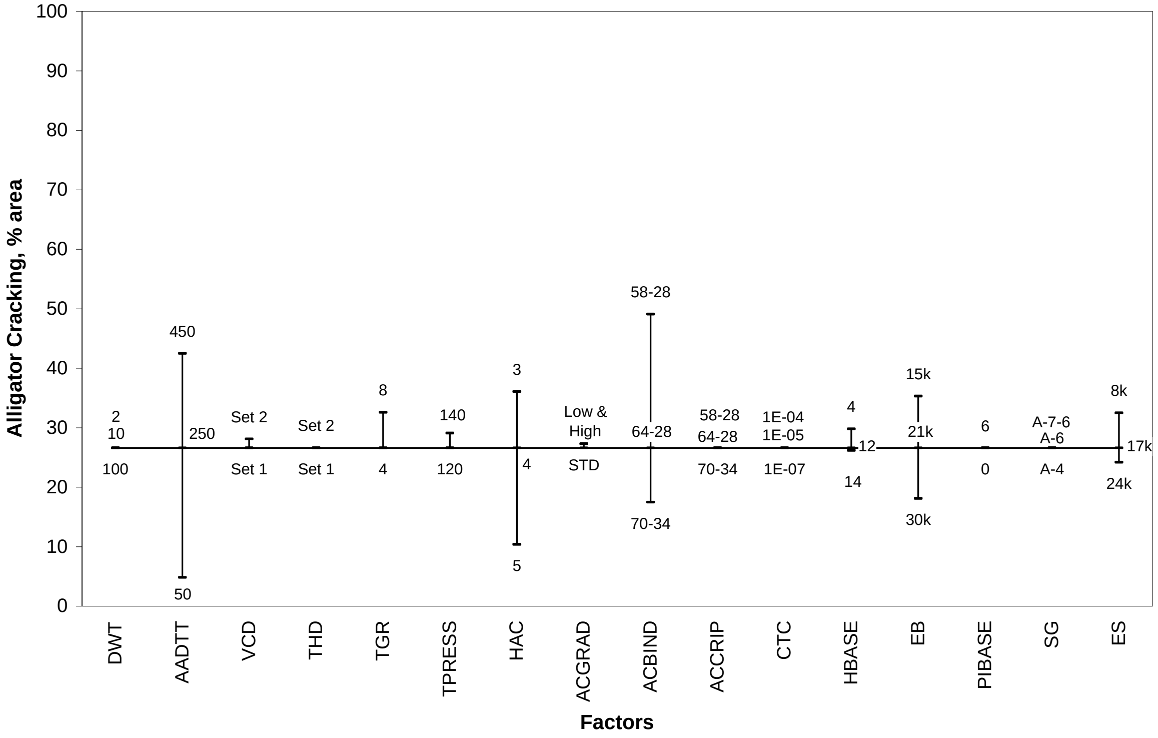

Figure C-12. Relative effect of variables on alligator cracking for new AC design (Location = Brookings).

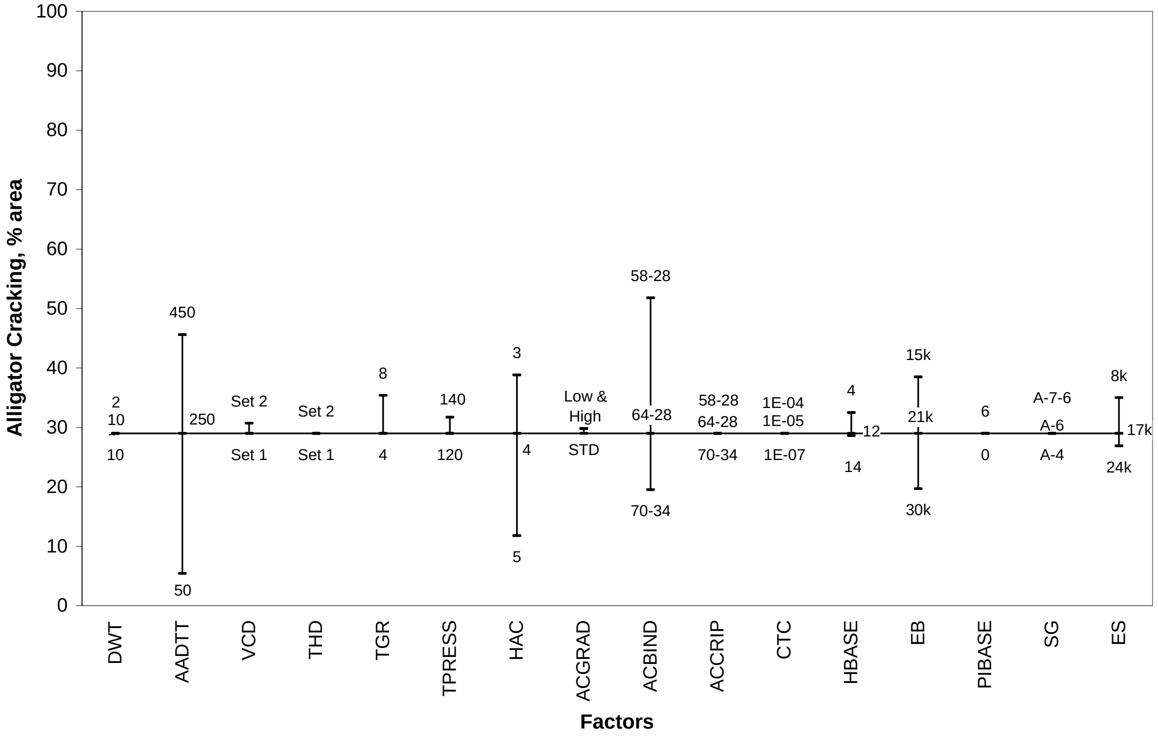

Figure C-13. Relative effect of variables on alligator cracking for new AC design (Location = Winner).

- **Effect of base layer-related inputs**—The summary charts do show a noticeable impact of EB and HBASE, in that order; however, PIBASE shows no impact on alligator cracking for either climatic location.
- **Effect of subgrade layer-related inputs**—A review of the subgrade-related variables finds that SG shows no effect on alligator cracking while ES shows a marginal effect. As expected, as ES decreases, the predicted alligator cracking increases.

A subjective review of the ANOVA analysis results classifies AADTT, ACBIND, HAC, and EB as *Highly Significant*, and TGR, ES, CLIMATE, HBASE, TPRESS, VCD, and ACGRAD as *Moderately Significant*. The complete ANOVA results are presented in table C-12.

Table C-12. ANOVA results for the AC alligator cracking model.

Order No.	Factor Abbreviation	Factor Name	F	p-value	Model Significance (α=0.05)	Assessed Level of Significance
1	AADTT	Initial two-way average annual daily truck traffic	6107.75	0.000	Yes	Highly Significant
2	ACBIND	AC binder grade	4408.00	0.000	Yes	
3	HAC	AC layer thickness	2856.18	0.000	Yes	
4	EB	Base resilient modulus	1286.84	0.000	Yes	
5	TGR	Traffic growth rate (%)	407.10	0.000	Yes	Mildly Significant
6	ES	Subgrade resilient modulus	294.23	0.000	Yes	
7	CLIMATE	Climatic characteristics (location)	110.71	0.000	Yes	
8	HBASE	Base layer thickness	73.13	0.000	Yes	
9	TPRESS	Tire pressure	71.59	0.000	Yes	
10	VCD	Vehicle class distribution factors	27.11	0.000	Yes	
11	ACGRAD	AC mix gradation information	4.47	0.021	Yes	
12	ACCRIP	AC creep compliance	0.00	1.000	No	Not Significant
13	CTC	Coef. of thermal contraction	0.00	1.000	No	
14	DWT	Depth of water table	0.00	1.000	No	
15	PIBASE	Base plasticity index	0.00	1.000	No	
16	SG	Subgrade type	0.00	1.000	No	
17	THD	Truck hourly distribution factors	0.00	1.000	No	

Note: Shaded cells indicate those variables that were found to be insignificant.

Analysis of the AC Layer Rutting (Permanent Deformation in AC Layer) Model for New AC Design

The results of the analysis of the AC layer rutting model for new AC design are presented in this section. For this analysis, 56 analysis runs were completed using the inputs defined in table C-10 above. The summary charts summarizing the MEPDG run results are presented in figures C-14 and C-15 for Brookings and Winner, respectively. Some notable observations from the summary charts include the following:

- **Effect of climate-related inputs**—For the standard new AC design, there was very little difference between the AC layer rutting predicted for both climatic locations (i.e., 0.102 in. for Brookings and 0.120 in. for Winner). The DWT variable also showed no impact on the development of AC layer rutting in either location.
- **Effect of traffic-related inputs—**Based on a review of the summary charts, AADTT is observed to be the variable with the largest impact on AC layer rutting in both climatic locations. The other traffic-related variables showing a noticeable impact on AC layer rutting model are TGR, TPRESS, and VCD, in that order. THD did not show any effect on AC layer rutting in either location.
- **Effect of AC layer-related inputs**—ACBIND and HAC are observed to be the most influential of all of the variables after AADTT. The thermal properties (ACCRIP and CTC) showed little or no influence on the level of AC layer rutting in both locations.
- **Effect of base layer-related inputs—**The summary charts do show small impacts of EB, HBASE, and PI on AC layer rutting, in that order. The observed trends show that for both locations, a decrease in EB results in an increase in AC layer rutting; a decrease in HBASE results in an increase in AC layer rutting; and an increase in PIBASE results in a very slight decrease in AC layer rutting.
- **Effect of subgrade layer-related inputs**—A review of the subgrade-related variables finds that SG shows no effect on AC layer rutting while ES shows a minimal effect. As expected, as ES decreases, the AC layer rutting increases.

A subjective review of the ANOVA analysis results classifies AADTT, HAC, ACBIND, and CLIMATE as *Highly Significant*, and TGR, TPRESS, EB, and VCD as *Moderately Significant*. The complete ANOVA results are presented in table C-13.

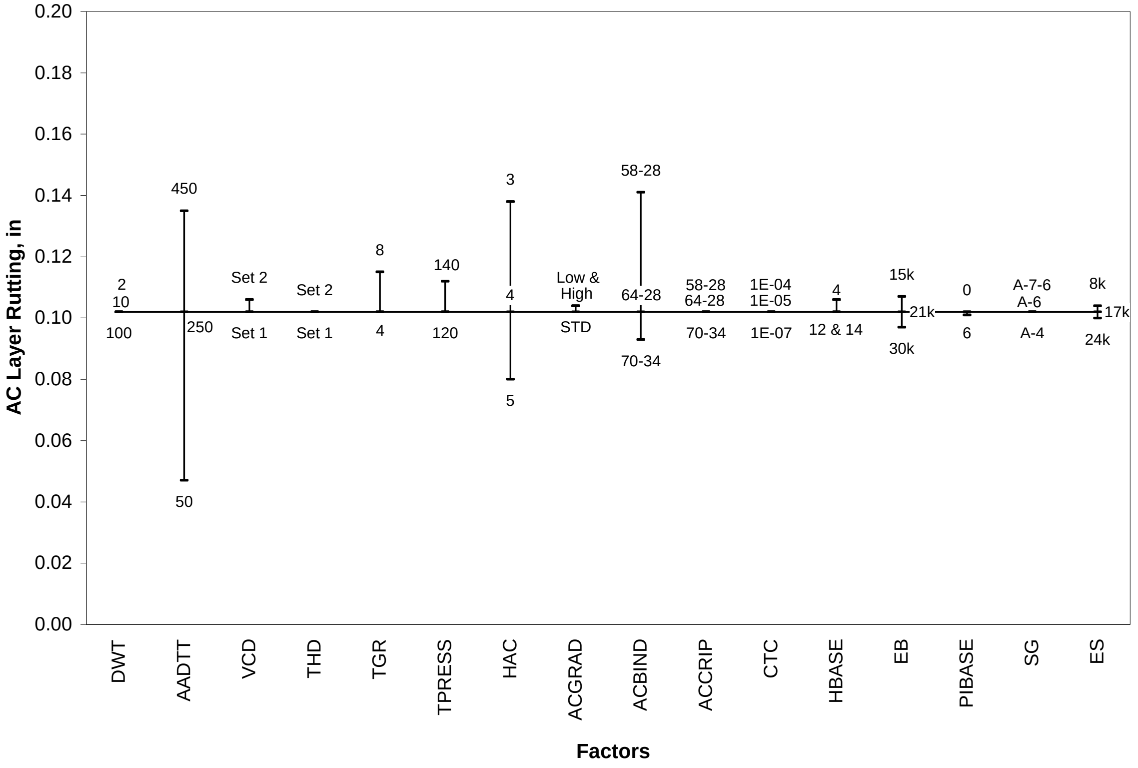

Figure C-14. Relative effect of variables on AC rutting for new AC design (Location = Brookings).

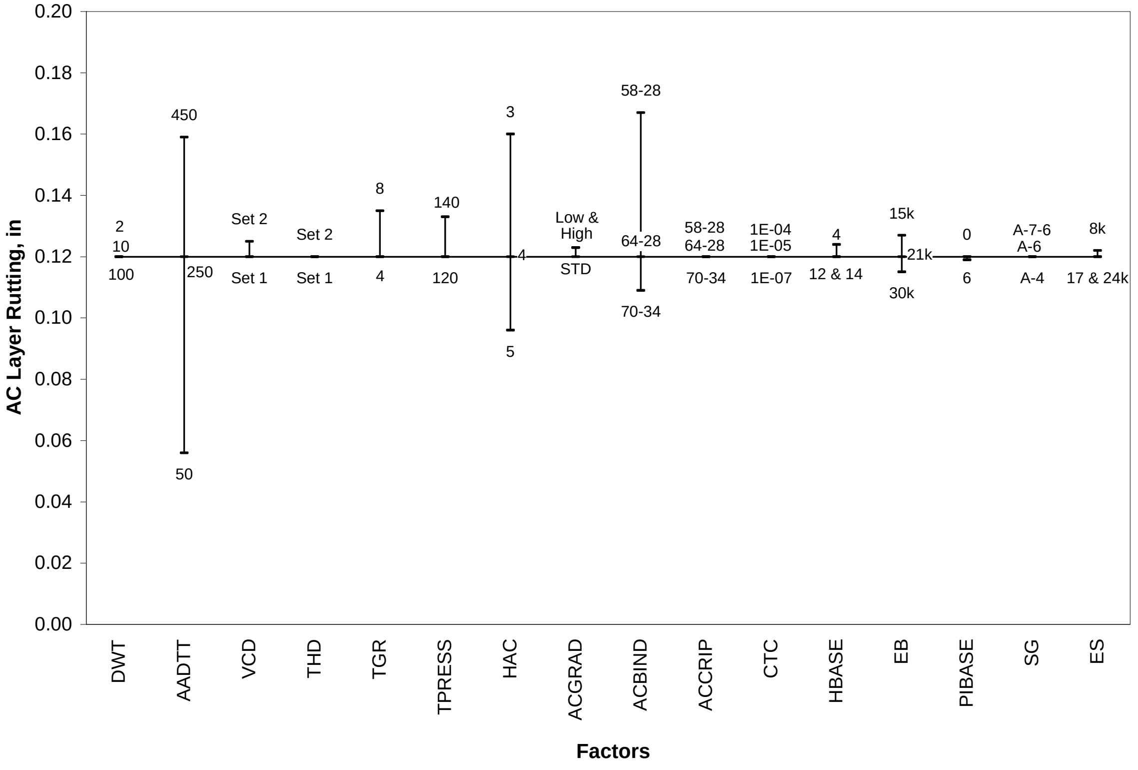

Figure C-15. Relative effect of variables on AC rutting for new AC design (Location = Winner).

Table C-13. ANOVA results for the AC layer rutting model.

Order No.	Factor Abbreviation	Factor Name	F	p-value	Model Significance (α=0.05)	Assessed Level of Significance
1	AADTT	Initial two-way average annual daily truck traffic	1163.93	0.000	Yes	Highly Significant
2	HAC	AC layer thickness	474.86	0.000	Yes	
3	ACBIND	AC binder grade	415.40	0.000	Yes	
4	CLIMATE	Climatic characteristics (location)	200.38	0.000	Yes	
5	TGR	Traffic growth rate (%)	64.74	0.000	Yes	Mildly Significant
6	TPRESS	Tire pressure	43.69	0.000	Yes	
7	EB	Base resilient modulus	15.05	0.000	Yes	
8	VCD	Vehicle class distribution factors	6.69	0.015	Yes	
9	HBASE	Base layer thickness	2.97	0.068	No	Not Significant
10	ACGRAD	AC mix gradation information	1.55	0.231	No	
11	ES	Subgrade resilient modulus	1.18	0.324	No	
12	PIBASE	Base plasticity index	0.33	0.570	No	
13	DWT	Depth of water table	0.04	0.957	No	
14	ACCRIP	AC creep compliance	0.00	1.000	No	
15	CTC	Coef. of thermal contraction	0.00	1.000	No	
16	SG	Subgrade type	0.00	1.000	No	
17	THD	Truck hourly distribution factors	0.00	1.000	No	

Note: Shaded cells indicate those variables that were found to be insignificant.

Analysis of the Total Rutting (Permanent Deformation) Model for New AC Design

The results of the analysis of the AC total rutting model for new AC design are presented in this section. For this analysis, 56 analysis runs were completed using the inputs defined in table C-10 above. The summary charts of relative effects summarizing the MEPDG run results are presented in figures C-16 and C-17 for Brookings and Winner, respectively. Some notable observations from the summary charts include the following:

- **Effect of climate-related inputs**—For the standard new AC design, the total rutting at the age of 20 years was noticeably higher for the Winner climate (0.57 in) than in the Brookings climate (0.49 in). Additionally, the DWT variable was observed to have a reasonably large impact on total rutting. However, the observed rutting trend associated with DWT was counterintuitive in that the charts showed that total rutting increased as DWT increased.

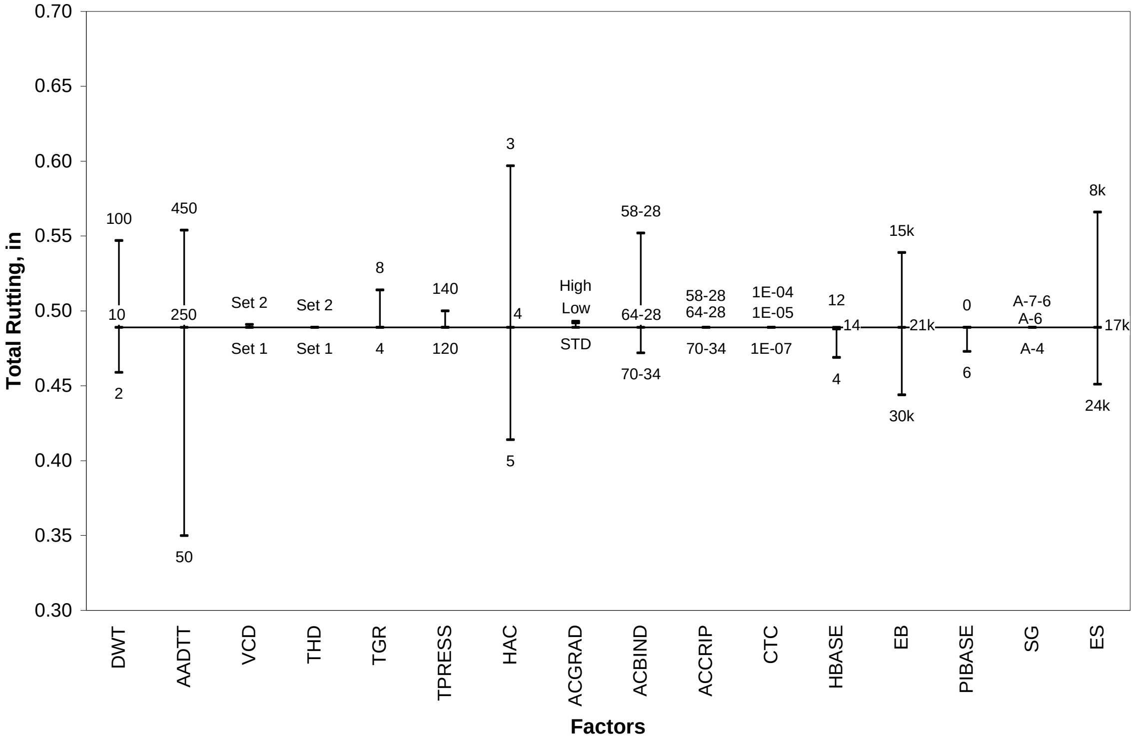

Figure C-16. Relative effect of variables on total rutting for new AC design (Location = Brookings).

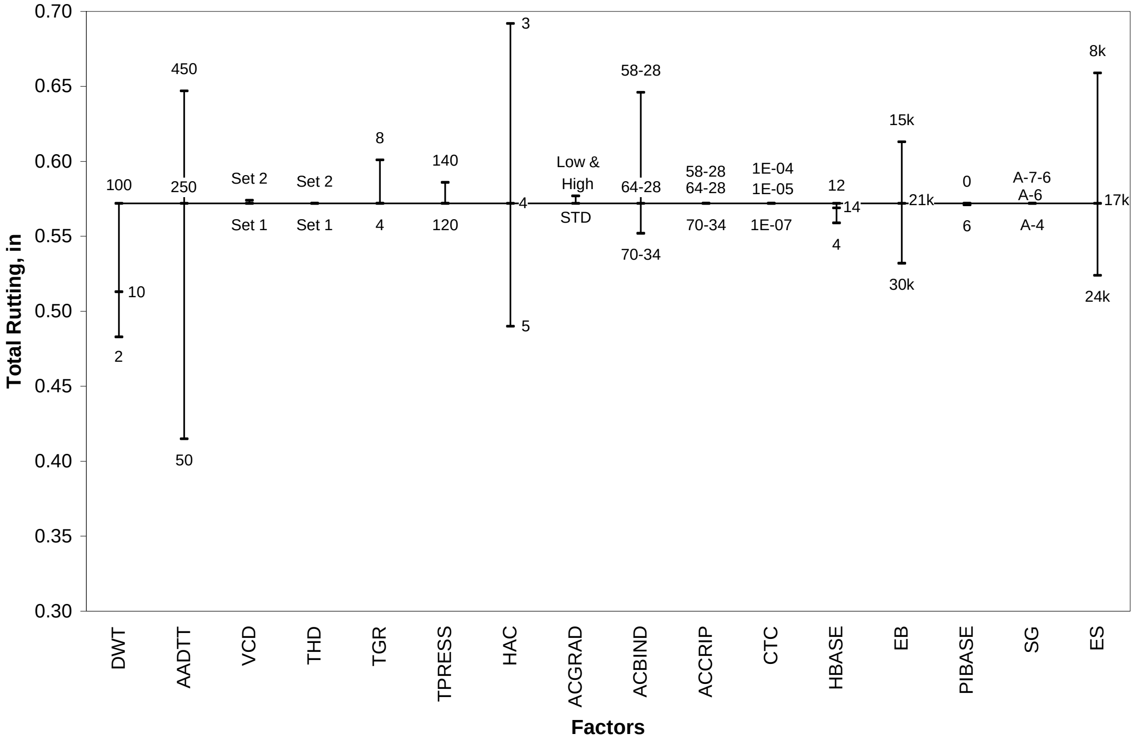

Figure C-17. Relative effect of variables on total rutting for new AC design (Location = Winner).

- **Effect of traffic-related inputs—**Similar to other models, AADTT is observed to be the variable with the largest effect on total rutting in both climatic locations. The other traffic-related variables showing noticeable impacts on total rutting are TGR, TPRESS, and VCD, in that order. THD did not show any effect on total rutting for either location.
- **Effect of AC layer-related inputs—**Of all the variables investigated, HAC was observed to have the second-largest impact on total rutting after AADTT. ACBIND was observed to have a relatively large impact on total rutting, while ACGRAD showed a very small effect in both climate locations. The thermal properties (ACCRIP and CTC) showed little or no impact on the level of total rutting in both locations.
- **Effect of base layer-related inputs—**The summary charts do show a moderate impact of EB, and small impacts of HBASE and PIBASE on total AC rutting. It is interesting to note that the total rutting ranges associated with the three base-related variables are noticeably larger for the Brookings location. Also, a noncontinuous trend was observed to be associated with HBASE (i.e., the total rutting value associated with a 14-in HBASE falls between the values associated with 4-in and 12-in HBASE layers).
- **Effect of subgrade layer-related inputs—**A review of the subgrade-related variables finds that SG shows no effect on total rutting while ES shows a fairly large effect. As expected, as ES decreases, the total rutting increases. It is also interesting to note that the total rutting value range associated with the Winner location is noticeably larger than the value range shown in the Brookings chart.

A subjective review of the ANOVA analysis results classifies AADTT, HAC, ES, DWT, ACBIND, and EB as *Highly Significant*, and CLIMATE, TGR, TPRESS, and HBASE as *Moderately Significant*. The complete ANOVA results are presented in table C-14.

Analysis of the IRI Model for New AC Design

In the MEPDG approach, IRI (an indicator of smoothness) for new AC pavements is predicted as a function of the initial as-constructed IRI and the predicted longitudinal cracking, alligator cracking, and total rutting. The model also includes a site factor for adjusting to the local subgrade and climate. Therefore, the IRI model in this study was evaluated in terms of its correlation with the main performance indicators (longitudinal cracking, alligator cracking, and

Table C-14. ANOVA results for the total rutting model.

Order No.	Factor Abbreviation	Factor Name	F	p-value	Model Significance (α=0.05)	Assessed Level of Significance
1	AADTT	Initial two-way average annual daily truck traffic	1029.23	0.000	Yes	Highly Significant
2	HAC	AC layer thickness	768.03	0.000	Yes	
3	ES	Subgrade resilient modulus	334.17	0.000	Yes	
4	DWT	Depth of water table	262.94	0.000	Yes	
5	ACBIND	AC binder grade	180.15	0.000	Yes	
6	EB	Base resilient modulus	157.87	0.000	Yes	
7	CLIMATE	Climatic characteristics (location)	61.13	0.000	Yes	Mildly Significant
8	TGR	Traffic growth rate (%)	40.34	0.000	Yes	
9	TPRESS	Tire pressure	8.83	0.006	Yes	
10	HBASE	Base layer thickness	7.58	0.002	Yes	
11	PIBASE	Base plasticity index	3.70	0.065	No	Not Significant
12	ACGRAD	AC mix gradation information	0.83	0.447	No	
13	VCD	Vehicle class distribution factors	0.27	0.604	No	
14	ACCRIP	AC creep compliance	0.00	0.998	No	
15	CTC	Coef. of thermal contraction	0.00	0.998	No	
16	SG	Subgrade type	0.00	0.998	No	
17	THD	Truck hourly distribution factors	0.00	0.954	No	

Note: Shaded cells indicate those variables that were found to be insignificant.

rutting). Although the visual IRI trends were assessed subjectively based on the same set of inputs as the fatigue, cracking, and rutting trends, the statistical analysis included only performance indicators as variables to evaluate their contribution to the IRI prediction model.

Figures C-18 and C-19 show the relative effects of the detailed variable inputs on predicted IRI (Note that the IRI values plotted in these figures are the predicted values at the end of the 20-year analysis period). A comparison of these figures finds that although the predicted IRI for the standard design was different between the two climates (134 in/mile for Brookings and 140 in/mile for Winner), the overall difference between these two values is relatively small on the IRI scale.

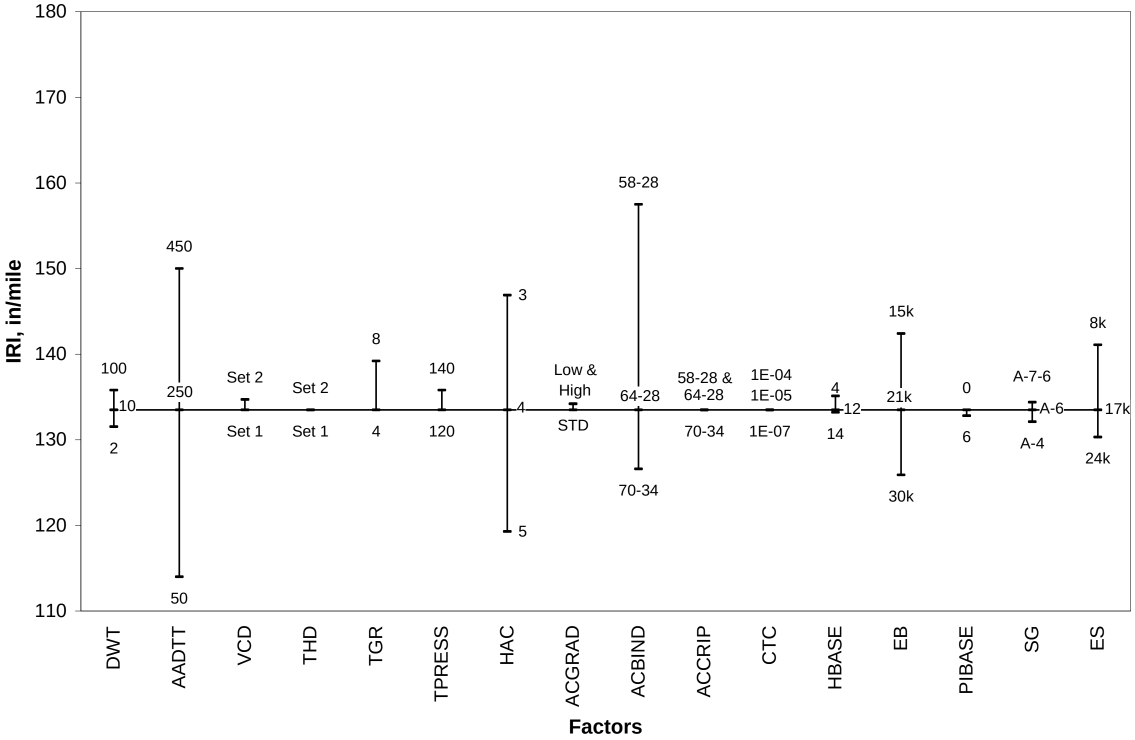

Figure C-18. Relative effect of variables on IRI for new AC design (Location = Brookings).

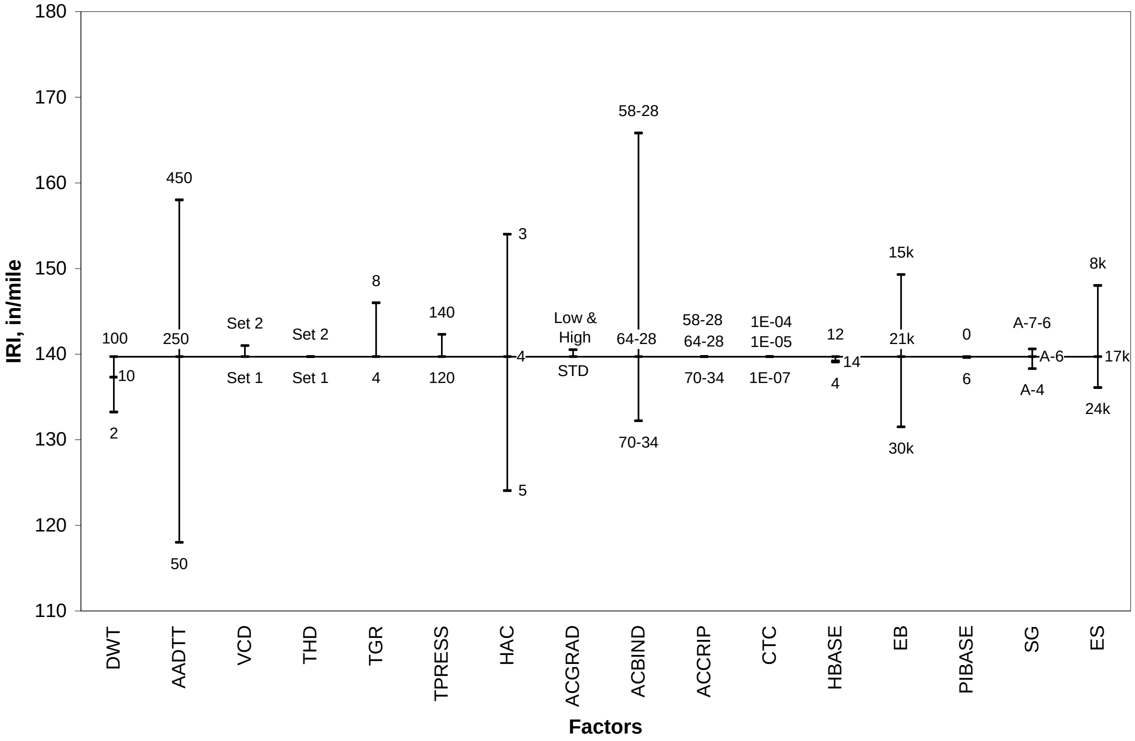

Figure C-19. Relative effect of variables on IRI for new AC design (Location = Winner).

A review of the ANOVA results for the new AC IRI model finds that only alligator cracking (ALLIGCRACK) and total rutting (TOTRUT) appear to have significant F-ratios. Based on these results, it can be concluded that for the given South Dakota data set, the change in mean IRI was affected mostly by the variation in alligator cracking and total rutting. A summary of the complete ANOVA results is presented in table C-15.

Table C-15. ANOVA results for the new AC IRI model

Order No.	Factor Abbreviation	Factor Name	F	p-value	Model Significance (α=0.05)
1	ALLIGCRACK	Alligator cracking (bottom-up)	259.75	0.000	Significant
2	TOTRUT	Total rutting	56.43	0.000	Significant
3	LONGCRACK	Longitudinal cracking (top-down)	1.34	0.253	Non-Significant
4	ACRUT	AC layer rutting	0.19	0.666	Non-Significant

Note: Shaded cells indicate those variables that were found to be insignificant.

Overall Assessment of Significant Variables for New AC (Rural Design)

The predicted performance of the newly designed rural AC pavements was evaluated based on 56 MEPDG software simulations. The sensitivity of the prediction models for those performance indicators to the change in design inputs was assessed by reviewing visual trends and conducting a statistical analysis of significance. The outcomes of the statistical analysis were used to *rank* the investigated model inputs from most significant to least significant in terms of how they influence the predicted performance of each individual performance model. Because the IRI model is dependent on the other performance indicator models, it is not considered in the overall ranking of most significant variables. Also, because total rutting and AC layer rutting are correlated, only total rutting (and not AC layer rutting) is considered in determining the overall rankings.

Table C-16 presents the input parameters found to be most significant for each performance indicator model. The parameters are placed in decreasing order of their significance for each investigated performance indicator. A ranking summary of each input parameter for a new rural AC design is also provided in table C-17. The ranking is based on the results of the analysis of variance for each performance indicator.

Table C-16. Summary of significance for new AC (rural design).

Performance Indicator	Input Parameter/Predictor
Top-down fatigue (longitudinal cracking)	• AC layer thickness • Initial two-way average annual daily truck traffic • Base resilient modulus • AC binder grade
Bottom-up fatigue (alligator cracking)	• Initial two-way average annual daily truck traffic • AC binder grade • AC layer thickness • Base resilient modulus
Permanent deformation in AC layer (AC rutting)	• Initial two-way average annual daily truck traffic • AC layer thickness • AC binder grade • Location (climate)
Total permanent deformation (total rutting)	• Initial two-way average annual daily truck traffic • AC layer thickness • Subgrade resilient modulus • Depth of water table • AC binder grade • Base resilient modulus
Smoothness (IRI)	• Bottom-up fatigue (alligator cracking) • Total permanent deformation (rutting)

All conclusions about the importance and the order of significance of the inputs are valid for the given range of inputs provided by the SDDOT, and are based on local South Dakota conditions.

Analysis Results: New CRCP—Interstate Design

For the sensitivity analysis of the new CRCP interstate design, the pavement performance is expressed in terms of the following performance indicators:

- Punchouts.
- IRI.

This section provides the details of the analysis of sensitivity performed for the new CRCP pavement design. Specifically it includes a summary of the investigated inputs, detailed descriptions of the model-by-model analyses of significance, and a ranking of variables in terms of their significance for a “standard” CRCP interstate pavement design in typical South Dakota conditions.

Table C-17. Ranking summary of significance of each input parameter on the performance indicator for new AC (rural design).

Input Parameter/Predictor	Rankings for Individual Performance Indicators			Overall Order of Significance
	Longitudinal Cracking	Alligator Cracking	Total Rutting	
Average annual daily truck traffic	2	1	1	1
AC layer thickness	1	3	2	2
AC binder grade	4	2	5	3
Base resilient modulus	3	4	6	4
Subgrade resilient modulus	9	6	3	5
Traffic growth rate	6	5	8	6
Base layer thickness	5	8	10	7
Climatic characteristics (location)	10	7	7	8
Tire pressure	7	9	9	9
Depth of water table	12	14	4	10
Vehicle class distribution	8	10	13	11
AC mix gradation	11	11	12	12
AC creep compliance	13	12	14	13
Base plasticity index	15	15	11	14
Coef. of thermal contraction	14	13	15	15
Subgrade type	16	16	16	16
Truck hourly distribution factors	17	17	17	17

Note: Shaded cells indicate those variables that were found to be insignificant.

Summary of Investigated Inputs

In the first stage of the analysis the input variables and their range for analysis were determined. Based on these inputs, 78 MEPDG software simulations were run to predict the development of punchouts and IRI in the two climatic locations (Brookings and Winner). The analysis period used for this design was chosen to be 40 years (i.e., all predicted performance values presented in the charts are the values predicted at the end of 40 years). Each run included in the sensitivity analysis represented a scenario when one varying input value was changed to a value other than the standard value (i.e., a high or low value). A summary of all of the inputs varied in the CRCP sensitivity analysis is provided in table C-18.

Analysis of the CRCP Punchouts Model

The results of the analysis of the CRCP punchouts model for new AC design are presented in this section. For this analysis, 78 analysis runs were completed using the inputs defined in table C-18. The summary charts of relative effects summarizing the MEPDG run results are

Table C-18. List of inputs for new CRCP design.

Name	**Abbreviation in Analysis**	**Input Values**			***Standard* Value**
		Low	**Med**	**High**	
CLIMATIC INPUTS					
Climatic characteristics (location)	CLIMATE	—	Brookings	Winner	—
Depth of water table (ft)	DWT	2	10	100	—
TRAFFIC INPUTS (RURAL TRAFFIC)					
Initial two-way average annual daily truck traffic	AADTT	800	1600	2400	1600
Vehicle class distribution factors[1]	VCD	Set 1	—	Set 2	Set 1
Truck hourly distribution factors[2]	THD	Set 1	—	Set 2	Set 1
Traffic growth rate (%)	TGR	4	—	8	4
CRCP DESIGN FEATURES AND PCC MATERIAL INPUTS					
Minimum Crack LTE%	CRACKLTE	50	70	90	90
Percent steel, %	%STEEL	0.6	0.7	0.8	0.7
Steel depth, in	STDEPTH	3	3.5	4	3.5
Bar diameter, in	BARD	0.625		0.75	0.625
Base/slab friction coefficient	BSFRIC	0.5	2.5	4	2.5
Shoulder type	SHOULD	Tied-Separate		Tied-Monolithic	Tied-Monolithic
PCC slab thickness, in	HPCC	8	9	10	9
Coefficient of thermal expansion (per °F x 10^{-6})	COTE	3.8	4.6	6.8	6.8
Cementitious material content, lb/yd^3	CC	550	600	660	600
Aggregate type	AGG	Limestone	Quartzite	Granite	Quartzite
PCC zero-stress temperature[3], °F	ZST	80	100	120	100
PCC 28-day modulus of rupture, psi	MR	550	650	750	650
BASE INPUTS (GRAVEL CUSHION)					
Base layer thickness, in	HBASE	3	5	7	5
Base resilient modulus, psi	EB	15,000	21,000	30,000	21,000
Base plasticity index, PI	PIBASE	0	—	6	0
SUBGRADE INPUTS					
Subgrade type	SG	A-7-6	A-6	A-4	A-6
Subgrade resilient modulus, psi	ES	8,000	17,000	24,000	17,000
Subgrade plasticity index, PI	Not included directly. Varies with subgrade type.	For A-7-6: 33	For A-6: 17	For A-4: 8	For A-6: 17
Subgrade liquid limit, LL		For A-7-6: 58	For A-6: 34	For A-4: 25	For A-6: 34
Subgrade gradation information (upper and lower bounds)		For A-7-6: #200: 38.4,99.2 #40: 69.7, 99.8 #10: 80.2, 100 #4: 84.2, 100 3/8": 92.9, 100	For A-6: #200: 36.1, 98.2 #40: 54, 99.7 #10: 70.4, 100 #4: 76.7, 100 3/8": 86.6,100	For A-4: #200: 37.3, 69.2 #40: 44.2, 98.9 #10: 45.2, 99.9 #4: 51.6, 100 3/8": 70.8, 100	For A-6: #200: 36.1, 98.2 #40: 54, 99.7 #10: 70.4, 100 #4: 76.7, 100 3/8": 86.6, 100

presented in figures C-20 and C-21 for Brookings and Winner, respectively. Some notable observations from the summary charts include:

- **Effect of climate-related inputs**—For the standard new CRCP design, there was a slightly larger number of punchouts predicted for Winner (i.e., 64 per mile for Winner and 55 per mile for Brookings). The DWT variable showed very little impact on the development of punchouts in either location.
- **Effect of traffic-related inputs—**Based on a review of the summary charts, AADTT is observed to have a relatively large impact on punchouts in both climatic locations. A review of the other traffic-related variables, finds TGR to have a moderate impact on punchouts, whereas VCD and THD show very little impact.
- **Effect of CRCP design feature inputs**—Of all the investigated variables, the percent steel in CRCP (%STEEL) and HPCC show two of the largest effects on punchouts. For both climatic locations, all of the remaining design-related inputs show a noticeable difference in punchouts. Based on the observed range of punchout values, the remaining variables are ranked (largest to smallest observed range) in the order of base/slab friction coefficient (BSFRIC), steel depth (STDEPTH), bar diameter (BARD), and shoulder type (SHOULD).
- **Effect of PCC material-related inputs—**MR was observed to have one of the largest impacts on punchouts of all investigated variables. PCC thermal-related variables such as ZST and COTE were the next most influential variables in the PCC material-related category. Finally, the mix-related variables of CC and AGG were found to have a minimal impact on the punchouts model.
- **Effect of base layer-related inputs**—All of the base-related variables (HBASE, EB, and PIBASE) were observed to have very small impacts on the punchouts model.
- **Effect of subgrade layer-related inputs**—A review of the subgrade-related variables finds that SG shows a minimal influence on punchouts, while ES shows a marginal impact. As expected, as ES decreases, the number of punchouts increases.

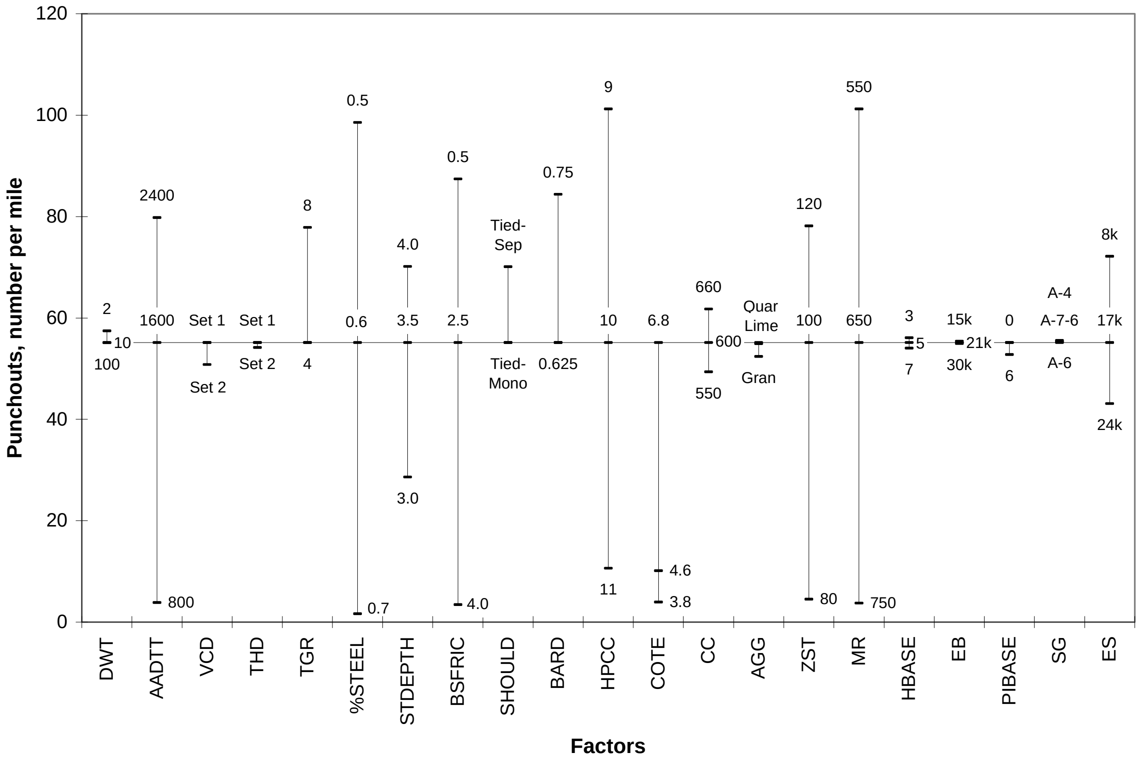

Figure C-20. Relative effect of variables on punchouts for new CRCP design (Location = Brookings).

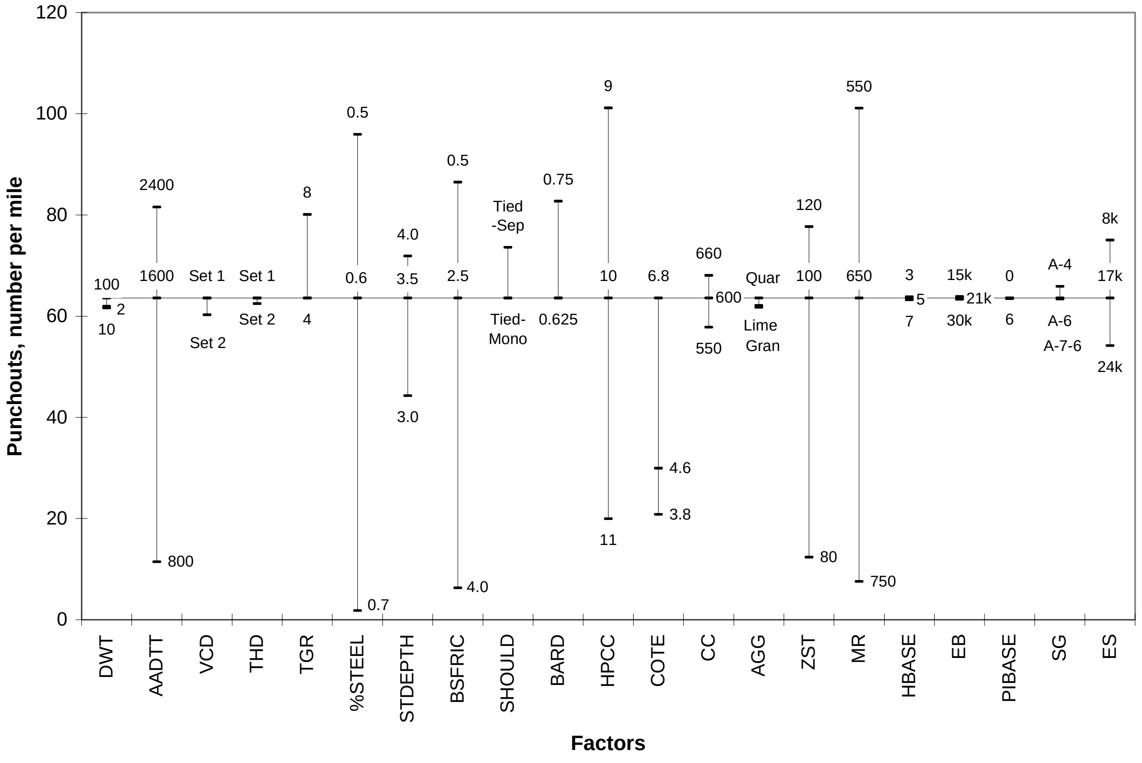

Figure C-21. Relative effect of variables on punchouts for new CRCP design (Location = Winner).

A subjective review of the ANOVA analysis results classifies %STEEL, MR, HPCC, BSFRIC, AADTT, ZST, and COTE as *Highly Significant*, and BARD, STDEPTH, TGR, ES, SHOULD, CLIMATE, and CC as *Moderately Significant*. The complete ANOVA results are presented in table C-19.

Table C-19. ANOVA results for the CRCP punchout model.

Order No.	**Factor Abbreviation**	**Factor Name**	**F**	**p-value**	**Model Significance (α=0.05)**	**Assessed Level of Significance**
1	%STEEL	Percent steel	360.21	0.000	Yes	Highly Significant
2	MR	PCC 28-day modulus of rupture	355.68	0.000	Yes	
3	HPCC	PCC slab thickness	285.80	0.000	Yes	
4	BSFRIC	Base/slab friction coefficient	273.77	0.000	Yes	
5	AADTT	Initial two-way average annual daily truck traffic	223.27	0.000	Yes	
6	ZST	PCC zero-stress temperature	206.07	0.000	Yes	
7	COTE	Coefficient of thermal expansion	143.38	0.000	Yes	
8	BARD	Bar diameter	62.90	0.000	Yes	Mildly Significant
9	STDEPTH	Steel depth	48.29	0.000	Yes	
10	TGR	Traffic growth rate (%)	41.78	0.000	Yes	
11	ES	Subgrade resilient modulus	24.56	0.000	Yes	
12	SHOULD	Shoulder type	17.40	0.000	Yes	
13	CLIMATE	Climatic characteristics (location)	7.01	0.012	Yes	
14	CC	Cementitious material content	4.96	0.012	Yes	
15	VCD	Vehicle class distribution factors	1.16	0.289	No	Not Significant
16	SG	Subgrade type	0.18	0.838	No	
17	AGG	Aggregate type	0.17	0.844	No	
18	HBASE	Base layer thickness	0.08	0.921	No	
19	PIBASE	Base plasticity index	0.06	0.809	No	
20	DWT	Depth of water table (ft)	0.05	0.954	No	
21	EB	Base resilient modulus	0.03	0.970	No	
22	THD	Truck hourly distribution factors	0.03	0.861	No	

Note: Shaded cells indicate those variables that were found to be insignificant.

Analysis of the CRCP IRI Model

In the MEPDG approach, IRI for CRCP is predicted as a function of the initial as-constructed IRI and the predicted punchouts. The model also includes a site factor for adjusting to the local subgrade and climate. Therefore, the IRI model in this study was evaluated in terms of its correlation with punchouts rather than with the detailed software inputs. Although the visual IRI trends were assessed subjectively based on the same set of inputs as the punchout trends, the statistical analysis included only punchouts to evaluate their contribution to the IRI prediction model.

Figures C-22 and C-23 show the relative effects of the detailed variable inputs on predicted IRI (Note that the IRI values plotted in these figures are the predicted values at the end of the 20-year analysis period). A comparison of these figures finds that although the predicted IRI for the standard design was different between the two climates (243 in/mile for Brookings and 232 in/mile for Winner), the overall difference between these two values is relatively small on the IRI scale. Because the IRI model is only a function of one performance indicator (punchouts), a more detailed statistical analysis of this model was unnecessary (i.e., it is known that the IRI model is directly correlated with predicted punchouts).

Overall Assessment of Significant Variables for New CRCP (Interstate Design)

The predicted performance of the newly designed interstate CRCP pavements was evaluated based on the total of 78 MEPDG software simulations. The sensitivity of the prediction models for those performance indicators to the change in design inputs was assessed by reviewing visual trends and conducting a statistical analysis of significance. The outcomes of the statistical analysis were used to *rank* the investigated model inputs from most significant to least significant in terms of how they influence the predicted performance of each individual performance model. Because the IRI model is dependent on the punchout model, only the punchout model is considered in the overall ranking of most significant variables.

Table C-20 presents the input parameters that were found to be most significant for each performance indicator model. The parameters are placed in decreasing order of their significance for each investigated performance indicator. A ranking summary of each input parameter for a new CRCP design is also provided in table C-21. As indicated previously, the punchout model is the controlling model for CRCP pavement performance.

All conclusions about the importance and the order of significance of the inputs are valid for the given range of inputs provided by the SDDOT, and are based on local South Dakota conditions.

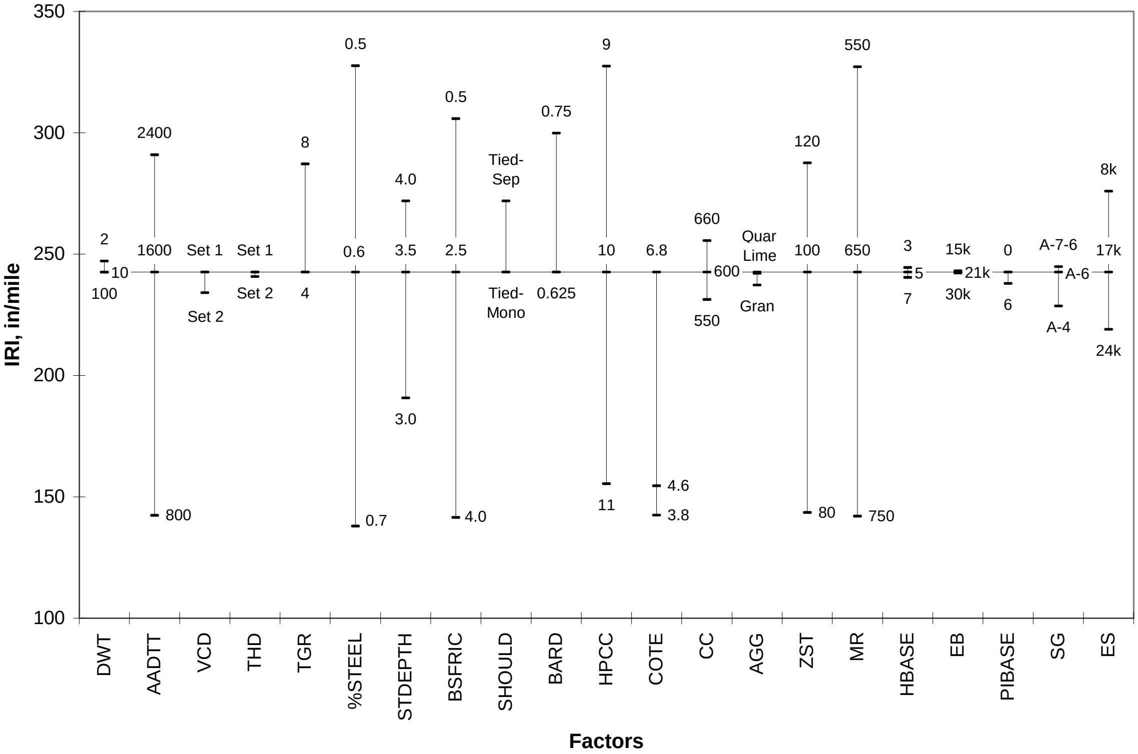

Figure C-22. Relative effect of variables on IRI for new CRCP design (Location = Brookings).

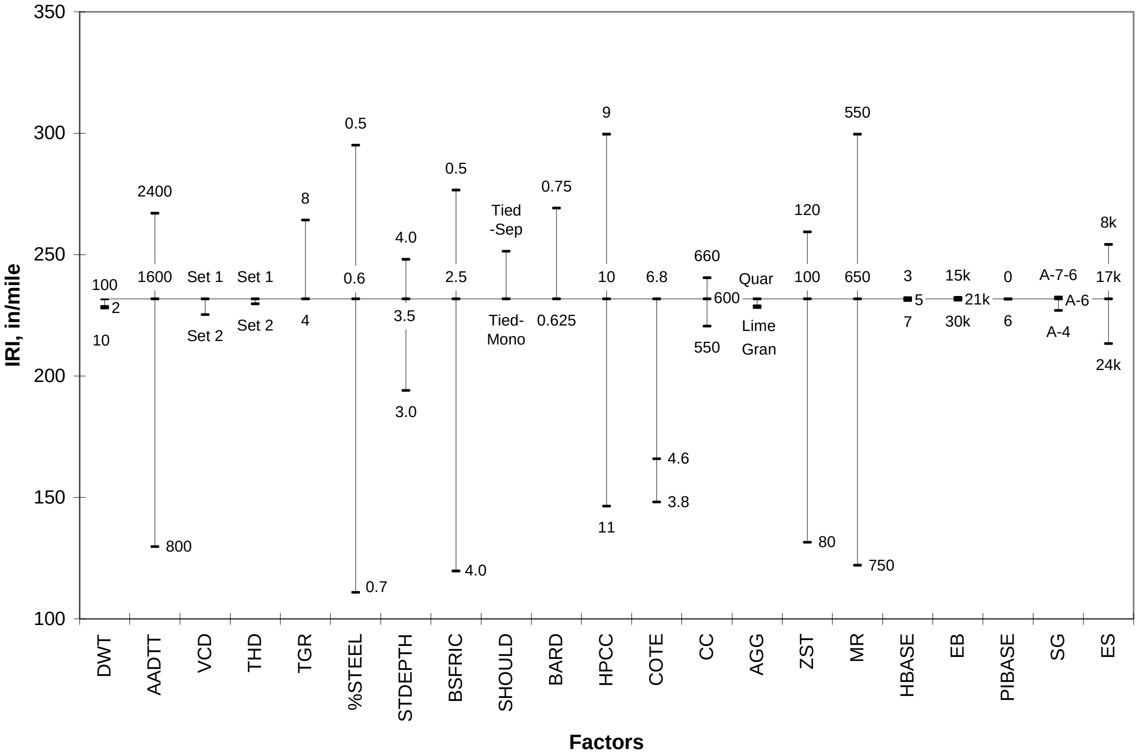

Figure C-23. Relative effect of variables on IRI for new CRCP design (Location = Winner).

Table C-20. Summary of significance for new CRCP (Interstate design).

Performance Indicator	Input Parameter/Predictor
Punchouts	• Percent steel • PCC 28-day modulus of rupture • PCC thickness • Base/slab friction coefficient • Initial annual average two-way truck traffic • PCC zero-stress temperature • PCC coefficient of thermal expansion
Smoothness(IRI)	• Punchouts

Table C-21. Ranking summary of significance of each input parameter on the performance indicator for new CRCP (interstate design).

Input Parameter/Predictor	Punchouts	Overall Order of Significance
Percent Steel, %	1	1
PCC 28-day modulus of rupture	2	2
PCC slab thickness	3	3
Base/slab friction coefficient	4	4
Average annual daily truck traffic	5	5
PCC zero-stress temperature	6	6
Coefficient of thermal expansion	7	7
Bar diameter	8	8
Steel depth	9	9
Traffic growth factor	10	10
Subgrade resilient modulus	11	11
Shoulder type	12	12
Climatic characteristics (location)	13	13
Cementitious material content	14	14
Vehicle class distribution factors	15	15
Subgrade type	16	16
Aggregate type	17	17
Base layer thickness	18	18
Base plasticity index	19	19
Depth of water table	20	20
Base resilient modulus	21	21
Truck hourly distribution factor	22	22

Note: Shaded cells indicate those variables that were found to be insignificant.

Analysis Results: ACOL on Rubblized JPCP—Rural Design

For the sensitivity analysis of the ACOL on rubblized JPCP rural design, the pavement performance is expressed in terms of the following performance indicators:

- Longitudinal cracking (top-down fatigue).
- Alligator cracking (bottom-up fatigue).
- Permanent deformation (rutting) in AC layer.
- Total permanent deformation.
- IRI.

As stated previously in the new AC pavement design section, although it is recognized that transverse cracking is also an important performance indicator for AC-surfaced pavements, a problem with the transverse cracking model was encountered when conducting the sensitivity analysis with version 0.9 of the MEPDG software. When reviewing the results from the sensitivity analysis runs, it was discovered that the transverse cracking model consistently predicted 20-year (AC design life) transverse cracking values equal to “0” when the runs were completed using a computer running the Windows XP operating system. Conversely, the same runs completed on computers running Windows NT2000 yielded nonzero results that were typically near the allowable model maximum of 2,110 ft/mi at 20 years. Due to the inability of this model to predict consistent nonzero values for the investigated runs, it was decided to ignore this model in the current sensitivity analysis. However, it is recommended that this model be revisited when version 1.0 of the MEPDG software is released.

This section provides the details of the analysis of sensitivity performed for the ACOL on rubblized JPCP rural design. Specifically it includes a summary of the investigated inputs, detailed descriptions of the model-by-model analyses of significance, and a ranking of variables in terms of their significance for a “standard” ACOL on rubblized JPCP rural design in typical South Dakota conditions.

Summary of Investigated Inputs

In the first stage of the analysis the input variables and their range for analysis were determined. Based on these inputs, 68 MEPDG software simulations were run to predict the development of longitudinal and alligator cracking, AC and total rutting, and IRI in the two climatic locations (Brookings and Winner). The analysis period used for this design was chosen to be 20 years (i.e., all predicted performance values presented in the charts are the values predicted at the end of 20 years). Each run included in the sensitivity analysis represented a scenario when one varying input value was changed to a value other than the standard value (i.e., a high or low value). A summary of all of the inputs varied in the sensitivity analysis is provided in table C-22.

Analysis of the Longitudinal (Top-Down Fatigue) Cracking Model for the ACOL on Rubblized JPCP Design

The results of the analysis of the AC longitudinal (top-down) cracking model are presented in this section. For this analysis, 68 analysis runs were completed using the inputs defined in table C-22 above. The summary charts of relative effects summarizing the MEPDG run results are presented in figures C-24 and C-25 for Brookings and Winner, respectively.

One general observation from a review of the summary charts is that the overall amount of longitudinal cracking predicted for the range of inputs is very small (i.e., between 0 and 12 ft/mi at 20 years). Therefore, the results of these sensitivity runs indicate that longitudinal cracking is not expected to be a major factor in the overall performance of this pavement design. Other notable observations from the summary charts include:

- **Effect of climate-related inputs**—For the standard ACOL on rubblized JPCP design, there was virtually no difference between the longitudinal cracking predicted for both climatic locations (i.e., 1.5 ft/mi for Brookings and 1.6 ft/mi for Winner). The DWT variable also showed no impact on longitudinal cracking in either location.
- **Effect of traffic-related inputs—**Based on a review of the summary charts, AADTT is the traffic variable with the largest effect on longitudinal cracking in both climatic locations. As expected, an increase in AADTT results in an increase in predicted cracking. The other traffic-related variables showing a noticeable impact on alligator cracking model include TPRESS, TGR, and VCD, in that order. THD did not show any effect on longitudinal cracking in either location. The only counterintuitive trend is that associated with TPRESS, as both charts indicate a decrease in cracking as tire pressure increases. No explanation of this trend was found in the MEPDG documentation (NCHRP 2004).

Table C-22. List of inputs for ACOL on rubblized JPCP design.

Name	**Abbreviation in Analysis**	**Input Values**			***Standard* Value**
		Low	**Med**	**High**	
CLIMATIC INPUTS					
Climatic characteristics (location)	CLIMATE	—	Brookings	Winner	—
Depth of water table (ft)	DWT	2	10	100	—
TRAFFIC INPUTS (RURAL TRAFFIC)					
Initial two-way average annual daily truck traffic	AADTT	50	250	450	250
Vehicle class dist. factors[1]	VCD	Set 1	—	Set 2	Set 1
Truck hourly dist. factors[2]	THD	Set 1	—	Set 2	Set 1
Traffic growth rate (%)	TGR	4	—	8	4
Tire pressure, psi	TPRESS	120		140	120
AC OVERLAY DESIGN FEATURES AND MATERIAL INPUTS					
Pavement rating	PR	Poor	Fair	Good	Fair
Existing fractured JPCP thickness, in	HPCC	8	9	10	9
Elastic resilient modulus of the fractured slab, psi	EPCC	100,000	150,000	200,000	150,000
AC overlay thickness, in	HACOL	4	4.5	5	4.5
AC overlay mix gradation information (percent retained on sieve, %)	ACOLGRAD	3/4”: 0 3/8”: 23 #4: 42 #200: 5.3	3/4”: 0 3/8”: 18 #4: 34 #200: 4.3	3/4”: 0 3/8”: 24 #4: 35 #200: 3	3/4”: 0 3/8”: 18 #4: 34 #200: 4.3
AC overlay binder grade	ACOLBIND	58-28	64-28	70-34	64-28
Effective binder content, %	Not included directly. Varies with binder grade.	For 58-28: 5.5	For 64-28: 5	For 70-34: 4.8	For 64-28: 5
Air voids, %		For 58-28: 9	For 64-28: 7	For 70-34: 6	For 64-28: 7
Total unit weight, pcf		For 58-28: 145	For 64-28: 148	For 70-34: 150	For 64-28: 148
AC overlay creep compliance	ACOLCRIP	“PG58-28” values from Table C-1	“PG64-28” values from Table C-1	“PG70-34” values from Table C-1	“PG64-28” values from Table C-1
Coef. of thermal contraction (in/in/°F)	CTC	1E-07	1E-05	1E-04	1E-05
BASE INPUTS (GRAVEL CUSHION)					
Base layer thickness, in	HBASE	3	5	7	5
Base resilient modulus, psi	EB	15,000	21,000	30,000	21,000
Base plasticity index, PI	PIBASE	0	—	6	0
SUBGRADE INPUTS					
Subgrade type	SG	A-7-6	A-6	A-4	A-6
Subgrade resilient modulus, psi	ES	8,000	17,000	24,000	17,000
Subgrade plasticity index, PI	Not included directly. Varies with subgrade type.	For A-7-6: 33	For A-6: 17	For A-4: 8	For A-6: 17
Subgrade liquid limit, LL		For A-7-6: 58	For A-6: 34	For A-4: 25	For A-6: 34
Subgrade gradation information (lower and upper bounds)		For A-7-6: #200: 38.4,99.2 #40: 69.7, 99.8 #10: 80.2, 100 #4: 84.2, 100 3/8": 92.9, 100	For A-6: #200: 36.1, 98.2 #40: 54, 99.7 #10: 70.4, 100 #4: 76.7, 100 3/8": 86.6,100	For A-4: #200: 37.3, 69.2 #40: 44.2, 98.9 #10: 45.2, 99.9 #4: 51.6, 100 3/8": 70.8, 100	For A-6: #200: 36.1, 98.2 #40: 54, 99.7 #10: 70.4, 100 #4: 76.7, 100 3/8": 86.6, 100

- **Effect of existing PCC slab-related inputs**—The modulus of elasticity for the rubblized JPCP layer (EPCC) was the variable with the second largest observed impact on longitudinal cracking (second only to the asphalt overlay layer thickness [HACOL]). As expected, longitudinal cracking increased as EPCC decreases. The thickness of the existing JPCP slab (HPCC) had a moderate effect on longitudinal cracking. Finally, as expected, the performance rating (PR) of the existing JPCP pavement had no effect on longitudinal cracking.
- **Effect of ACOL layer-related inputs**—The HACOL variable was observed to be the variable with the single most influence on the longitudinal cracking prediction. It is, however, important to note again that this model trend has a parabolic shape as thickness HACOL changes from 4 in to 5 in. As explained previously for the new AC design, a review of the MEPDG documentation (NCHRP 2004) finds that this trend is an expected trend for this model. It is believed that this observed trend is the result of having two separate longitudinal cracking models (i.e., top-down and bottom-up).

  Of the remaining ACOL-related inputs, the ACOL binder grade (ACOLBIND) showed a moderate effect on longitudinal cracking, while the ACOL mix gradation showed a very small influence. The thermal properties (ACOL creep compliance [ACOLCRIP] and CTC) showed absolutely no influence on the longitudinal cracking model.

- **Effect of base layer-related inputs**—The summary charts show that although two of the three base-related inputs have a minimal impact on longitudinal cracking, the overall impact of base-related inputs is relatively small. The two inputs showing some influence on the development of longitudinal cracking are EB and HBASE, in that order. PIBASE showed virtually no impact on longitudinal cracking.
- **Effect of subgrade layer-related inputs**—A review of the subgrade-related variables finds that SG shows no effect on longitudinal cracking while ES shows a marginal effect. However, it is important to note that while the trend associated with ES initially appears counterintuitive (i.e., as ES increases, so does longitudinal cracking), a review of the MEPDG documentation finds that this observed trend is consistent with the inherent trends in the top-down longitudinal cracking model (NCHRP 2004). Specifically, the MEPDG documentation explains that “any variable that tends to increase the foundation

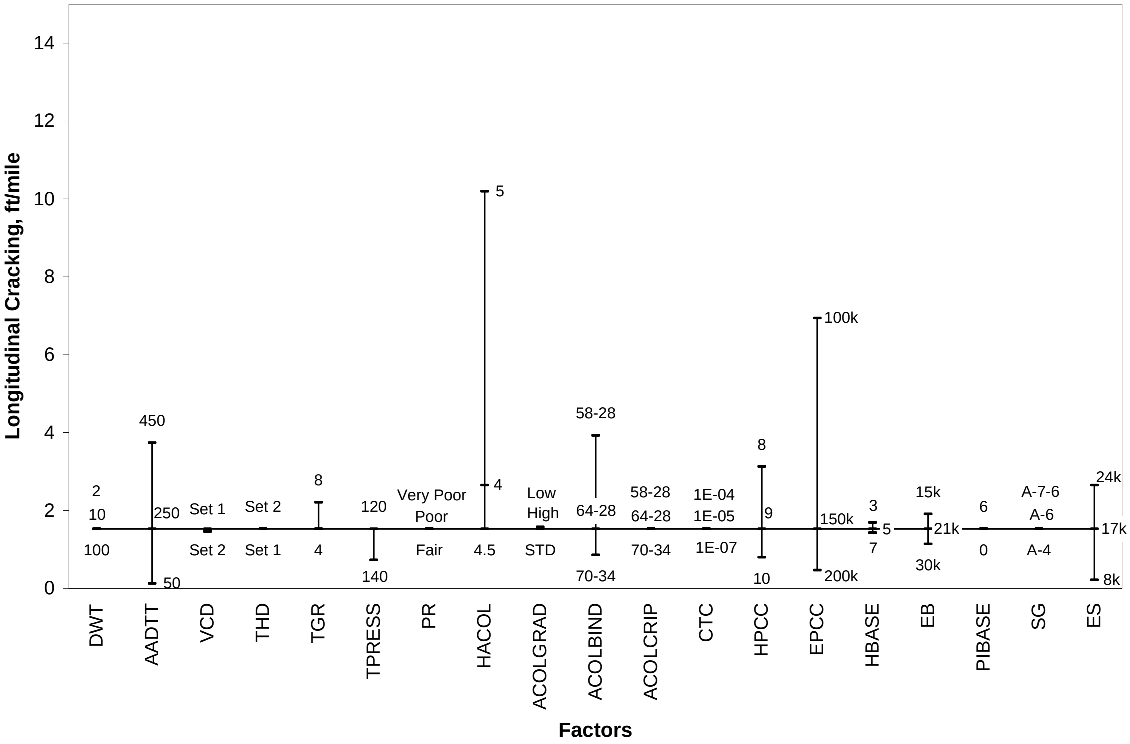

Figure C-24. Relative effect of variables on longitudinal cracking for ACOL on Rubblized JPCP design (Location = Brookings).

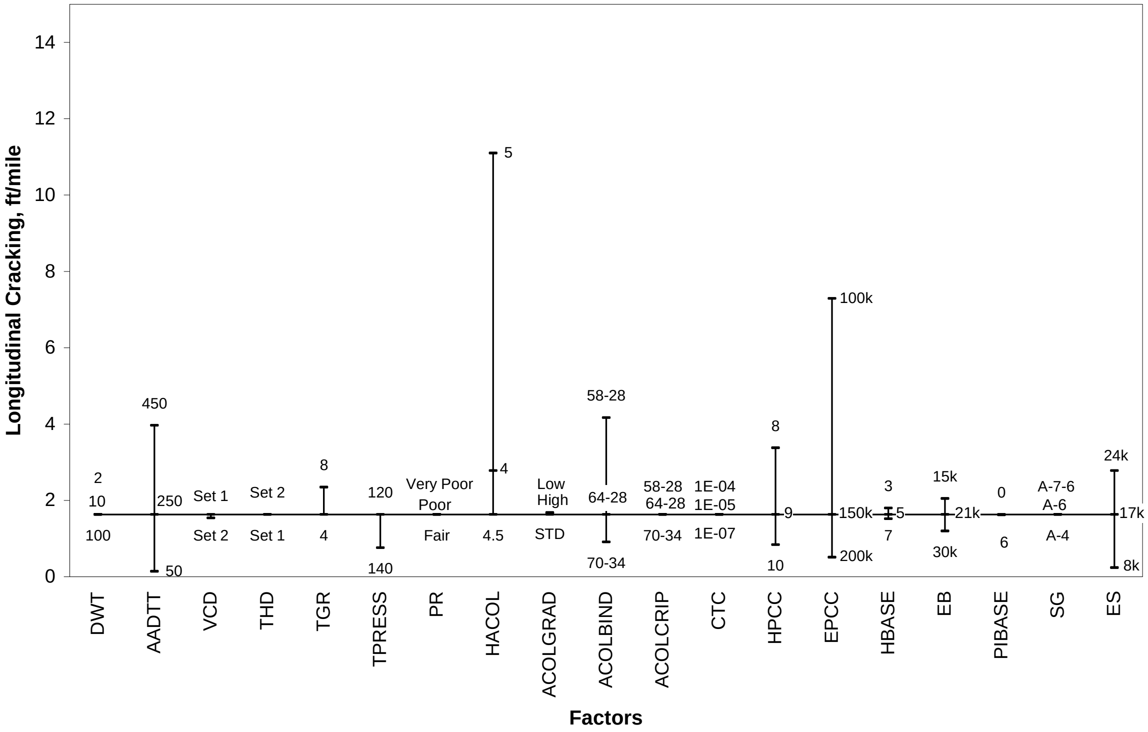

Figure C-25. Relative effect of variables on longitudinal cracking for ACOL on Rubblized JPCP design (Location = Winner).

> support (stiffer subgrade, stabilized base/subbase, very low ground water table location, presence of bedrock near the surface) will tend to cause a larger tensile strain at the surface layer and tend to increase longitudinal surface cracking" (NCHRP 2004).

A subjective review of the ANOVA analysis results classifies HACOL and EPCC as *Highly Significant,* and AADTT, ACOLBIND, HPCC, and ES as *Moderately Significant*. The complete ANOVA results are presented in table C-23.

Table C-23. ANOVA results for the ACOL on rubblized JPCP longitudinal cracking model.

Order No.	**Factor Abbreviation**	**Factor Name**	**F**	**p-value**	**Model Significance (α=0.05)**	**Assessed Level of Significance**
1	HACOL	ACOL layer thickness	2899.62	0.000	Yes	Highly Significant
2	EPCC	Elastic resilient modulus of the fractured slab	1355.00	0.000	Yes	
3	AADTT	Initial two-way average annual daily truck traffic	357.41	0.000	Yes	Moderately Significant
4	ACOLBIND	AC overlay binder grade	292.13	0.000	Yes	
5	HPCC	Existing fractured JPCP thickness	159.97	0.000	Yes	
6	ES	Subgrade resilient modulus	156.20	0.000	Yes	
7	TGR	Traffic growth rate (%)	32.93	0.000	Yes	Mildly Significant
8	EB	Base resilient modulus	16.54	0.000	Yes	
9	TPRESS	Tire pressure	10.75	0.003	Yes	
10	CLIMATE	Climatic characteristics (location)	1.91	0.176	No	Not Significant
11	HBASE	Base layer thickness	1.88	0.168	No	
12	VCD	Vehicle class distribution factors	0.43	0.517	No	
13	ACOLGRAD	AC overlay mix gradation	0.10	0.901	No	
14	DWT	Depth of water table	0.08	0.921	No	
15	ACOLCRIP	ACOL creep compliance	0.00	1.000	No	
16	CTC	AC coef. of thermal contraction	0.00	1.000	No	
17	PIBASE	Base plasticity index	0.00	0.968	No	
18	PR	Pavement rating	0.00	1.000	No	
19	SG	Subgrade type	0.00	1.000	No	
20	THD	Truck hourly distribution factors	0.00	1.000	No	

Note: Shaded cells indicate those variables that were found to be insignificant.

Analysis of the Alligator (Bottom-Up Fatigue) Cracking Model for the ACOL on Rubblized JPCP Design

The results of the analysis of the AC alligator (bottom-up) cracking model are presented in this section. For this analysis, 68 analysis runs were completed using the inputs defined in table C-22 above. The summary charts of relative effects summarizing the MEPDG run results are presented in figures C-26 and C-27 for Brookings and Winner, respectively.

One general observation from a review of the summary charts is that the overall amount of alligator cracking predicted for the range of inputs is very small (i.e., between 0 and 2 percent of the area). Therefore, the results of these sensitivity runs indicate that alligator cracking is not expected to be a major factor in the overall performance of this pavement design. Other notable observations from the summary charts include:

- **Effect of climate-related inputs—**For the standard ACOL on rubblized JPCP design, there was virtually no difference between the alligator cracking predicted for both climatic locations (i.e., 0.72 percent for Brookings and 0.73 percent for Winner). The DWT variable also showed no impact on the development of alligator cracking in either climatic location.
- **Effect of traffic-related inputs—**Based on a review of the summary charts, AADTT is observed to be the variable with the second-largest effect on alligator cracking (second only to EPCC) in both climatic locations. As expected, an increase in AADTT results in an increase in predicted cracking. The other traffic-related variables showing a noticeable impact on the alligator cracking model include TGR, TPRESS, and VCD, in that order. THD did not show any effect on longitudinal cracking in either location.
- **Effect of existing PCC slab-related inputs—**The EPCC variable was observed to be the single most influential variable in the summary charts. As expected, longitudinal cracking increased as EPCC decreases. With regard to the other PCC slab-related inputs, HPCC showed a minimal influence on alligator cracking while PR showed no effect.
- **Effect of ACOL layer-related inputs**—Of all of the ACOL layer-related inputs, the binder type (ACOLBIND) was observed to have the largest impact on alligator cracking. The HACOL variable was also observed to have a small impact on the predicted cracking, with an expected trend that showed that cracking increases as HACOL decreases. Finally, while the ACOL gradation properties (ACOLGRAD) showed a very small effect, the thermal property-related inputs (ACOLCRIP and CTC) showed absolutely no influence on the alligator cracking model.
- **Effect of base layer-related inputs—**All three of the base-related inputs (HBASE, EB, and PIBASE) show very little or no impact on the alligator cracking.

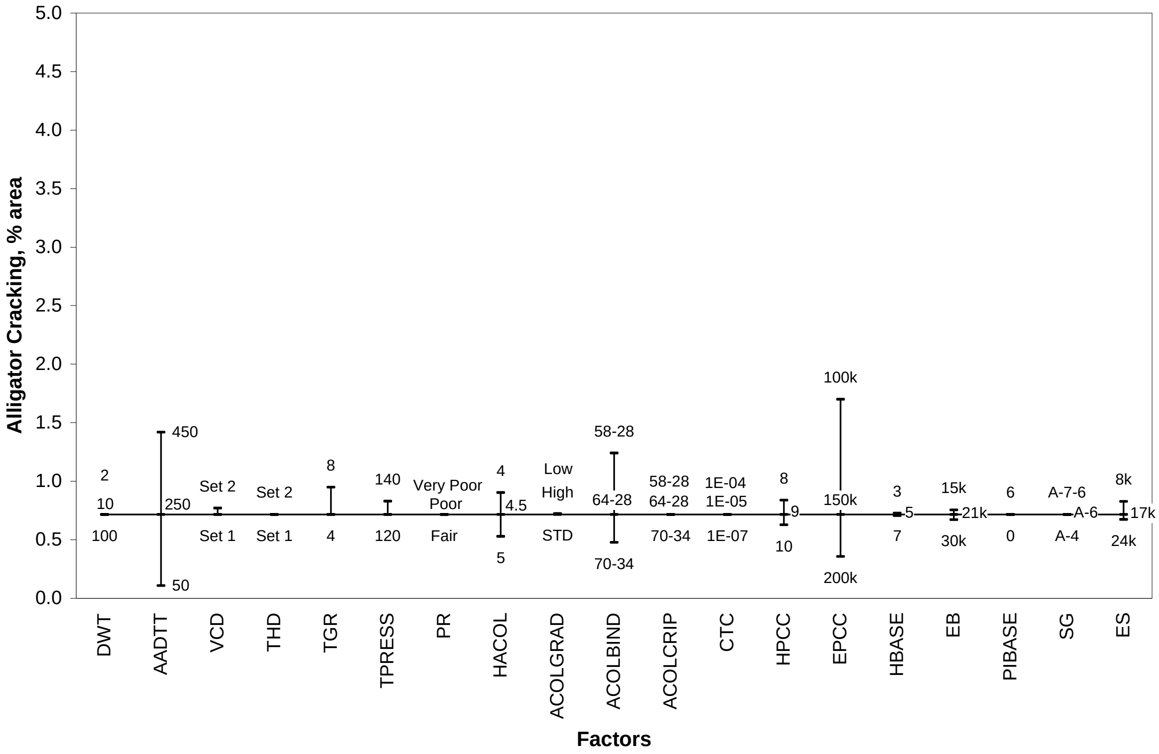

Figure C-26. Relative effect of variables on alligator cracking for ACOL on Rubblized JPCP design (Location = Brookings).

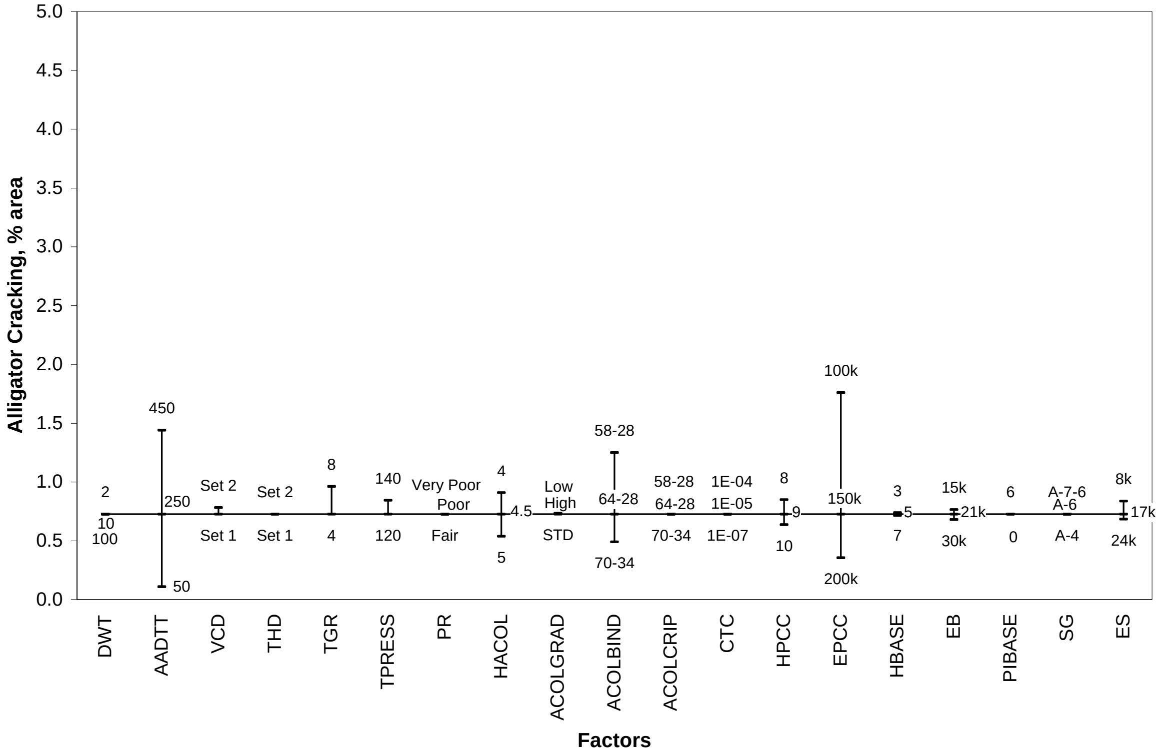

Figure C-27. Relative effect of variables on alligator cracking for ACOL on Rubblized JPCP design (Location = Winner).

- **Effect of subgrade layer-related inputs**—A review of the subgrade-related variables finds that SG shows no effect on alligator cracking while ES shows a minimal effect. As expected, as ES decreases, the predicted alligator cracking increases.

A subjective review of the ANOVA analysis results classifies EPCC, AADTT, and ACOLBIND as *Highly Significant,* and TGR and HACOL as *Moderately Significant*. However, because of extremely small range of predicted 20-year alligator cracking values obtained in this analysis (i.e., 0 to 2 percent), these statistical results should be viewed with extreme caution. The complete ANOVA results are presented in table C-24.

Table C-24. ANOVA results for the ACOL on Rubblized JPCP alligator cracking model.

Order No.	Factor Abbreviation	Factor Name	F	p-value	Model Significance (α=0.05)	Assessed Level of Significance
1	EPCC	Elastic resilient modulus of the fractured slab	4403.76	0.000	Yes	Highly Significant
2	AADTT	Initial two-way average annual daily truck traffic	3678.42	0.000	Yes	
3	ACOLBIND	AC overlay binder grade	1302.87	0.000	Yes	
4	TGR	Traffic growth rate (%)	309.33	0.000	Yes	Moderately Significant
5	HACOL	ACOL layer thickness	293.81	0.000	Yes	
6	HPCC	Existing fractured JPCP thickness	95.21	0.000	Yes	Mildly Significant
7	ES	Subgrade resilient modulus	54.71	0.000	Yes	
8	TPRESS	Tire pressure	18.20	0.000	Yes	
9	VCD	Vehicle class distribution factors	17.88	0.000	Yes	
10	EB	Base resilient modulus	14.32	0.000	Yes	
11	HBASE	Base layer thickness	1.07	0.355	No	Not Significant
12	CLIMATE	Climatic characteristics (location)	0.88	0.354	No	
13	ACOLGRAD	AC overlay mix gradation	0.19	0.831	No	
14	DWT	Depth of water table	0.01	0.987	No	
15	ACOLCRIP	ACOL creep compliance	0.00	1.000	No	
16	CTC	AC coef. of thermal contraction	0.00	1.000	No	
17	PIBASE	Base plasticity index	0.00	0.970	No	
18	PR	Pavement rating	0.00	1.000	No	
19	SG	Subgrade type	0.00	0.998	No	
20	THD	Truck hourly distribution factors	0.00	1.000	No	

Note: Shaded cells indicate those variables that were found to be insignificant.

Analysis of the AC Layer Rutting (Permanent Deformation in AC Layer) Model for the ACOL on Rubblized JPCP Design

The results of the analysis of the AC layer rutting model for the ACOL on rubblized JPCP design are presented in this section. For this analysis, 68 analysis runs were completed using the inputs defined in table C-22 above. The summary charts of relative effects summarizing the MEPDG run results are presented in figures C-28 and C-29 for Brookings and Winner, respectively. Some notable observations from the summary charts include:

- **Effect of climate-related inputs**—For the standard ACOL on rubblized JPCP design, there was virtually no difference between the AC layer rutting predicted for both climatic locations (i.e., 0.08 in for Brookings and 0.10 in for Winner). The DWT variable also showed no impact on the development of AC layer rutting in either climatic location.
- **Effect of traffic-related inputs—**Based on a review of the summary charts, AADTT is observed to be the variable with the largest effect on the AC layer rutting model in both climatic locations. As expected, an increase in AADTT results in an increase in rutting. The other traffic-related variables showing a noticeable impact on AC layer rutting model include TPRESS, TGR, and VCD, in that order. THD did not show any effect on AC layer rutting in either location.
- **Effect of existing PCC slab-related inputs**—Overall, the existing PCC slab-related inputs showed virtually no effect on the AC layer rutting model. Of the three inputs in this category, only the HPCC variable showed a very small impact on the rutting model. Conversely, EPCC and PR appeared to show no effect on AC layer rutting.
- **Effect of ACOL layer-related inputs**—Of all of the ACOL layer-related inputs, only binder type (ACOLBIND) was observed to have more than a minimal impact on AC layer rutting. Regarding the other ACOL layer-related inputs, only ACOLGRAD and HACOL showed any effect. The thermal property-related inputs (ACOLCRIP and CTC) showed absolutely no impact on the AC layer rutting model.
- **Effect of base layer-related inputs**—All three of the base-related inputs (HBASE, EB, and PIBASE) show very little or no impact on the development of AC layer rutting.
- **Effect of subgrade layer-related inputs**—A review of the subgrade-related variables finds that SG shows no effect on AC layer rutting while ES shows a minimal effect.

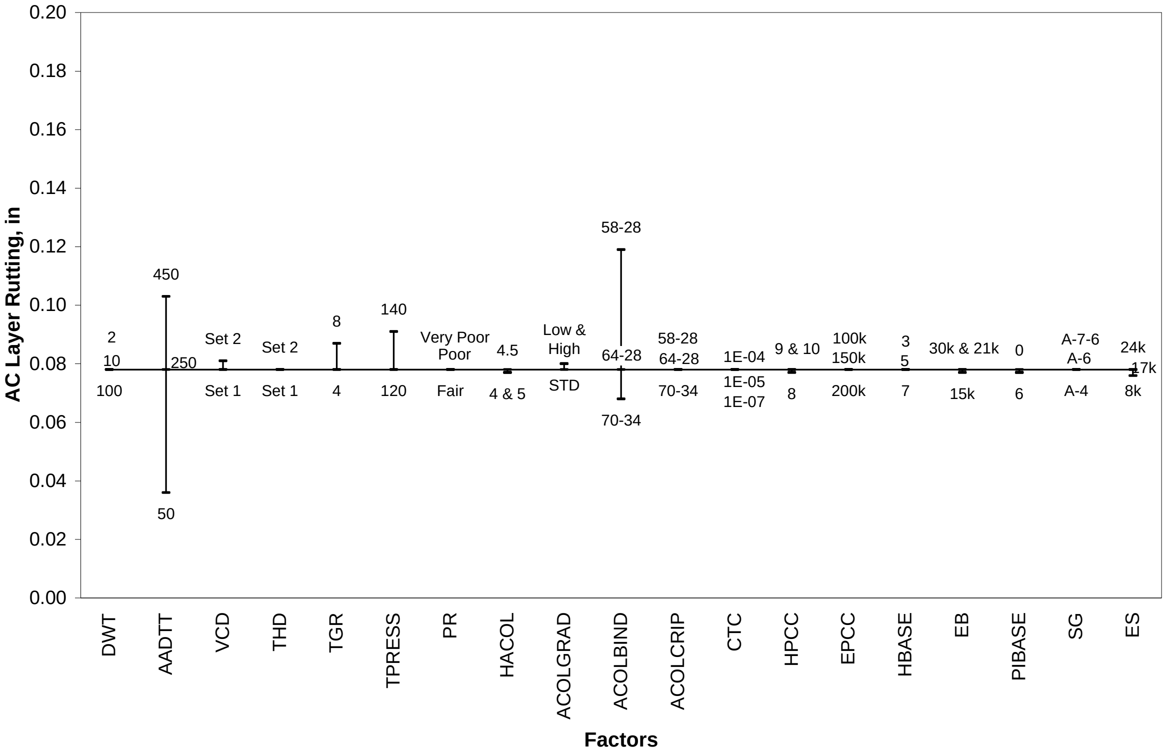

Figure C-28. Relative effect of variables on AC layer rutting for ACOL on Rubblized JPCP design (Location = Brookings).

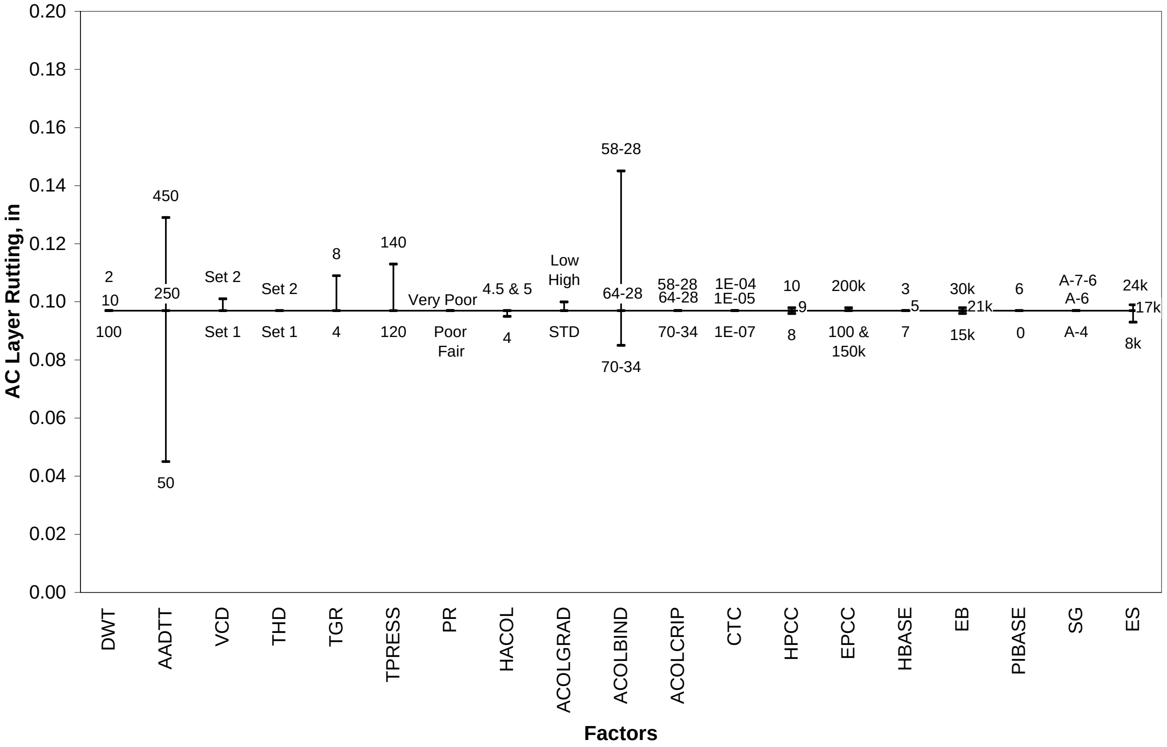

Figure C-29. Relative effect of variables on AC layer rutting for ACOL on Rubblized JPCP design (Location = Winner).

A subjective review of the ANOVA analysis results classifies AADTT, ACOLBIND, and CLIMATE as *Highly Significant,* and TGR and TPRESS as *Moderately Significant*. The complete ANOVA results are presented in table C-25.

Analysis of the Total Rutting Model for the ACOL on Rubblized JPCP Design

The results of the analysis of the total rutting model for the ACOL on rubblized JPCP design are presented in this section. For this analysis, 68 analysis runs were completed using the inputs defined in table C-23 above. The summary charts of relative effects summarizing the MEPDG run results are presented in figures C-30 and C-31 for Brookings and Winner, respectively. Some notable observations from the summary charts include:

- **Effect of climate-related inputs—**The difference in temperature and moisture between the Brookings and Winner locations resulted in noticeably different levels of total rutting (i.e., 0.29 in for Brookings and 0.35 in for Winner). Additionally, the change in DWT significantly affected the predicted total rutting; however, the observed trends for this variable were found to be counterintuitive (i.e., total rutting increases as DWT increases). This observed trend is opposite of what is expected in practice.
- **Effect of traffic-related inputs—**Based on a review of the summary charts, AADTT is observed to be the variable with the single largest impact on total rutting in both climatic locations. As expected, an increase in AADTT results in an increase in predicted rutting. The other traffic-related variables showing a noticeable impact on the total rutting model include TGR, TPRESS, and VCD, in that order. THD did not show any effect on total rutting in either location.
- **Effect of existing PCC slab-related inputs—**Overall, the existing PCC slab-related inputs (PR, HPCC, and EPCC) showed very small effects on the total rutting model. All three inputs had similar impacts on the total rutting model, and all showed expected trends.
- **Effect of ACOL layer-related inputs—**Of all of the ACOL layer-related inputs, only binder type (ACOLBIND) was observed to have more than a minimal impact on the total rutting model. Regarding the other ACOL layer-related inputs, only HACOL and ACOLGRAD showed any effect. The thermal property-related inputs (ACOLCRIP and CTC) showed absolutely no impact on the total rutting model.

Table C-25. ANOVA results for the ACOL on Rubblized JPCP AC rutting model.

Order No.	Factor Abbreviation	Factor Name	F	p-value	Model Significance (α=0.05)	Assessed Level of Significance
1	AADTT	Initial two-way average annual daily truck traffic	488.09	0.000	Yes	Highly Significant
2	ACOLBIND	AC overlay binder grade	302.71	0.000	Yes	
3	CLIMATE	Climatic characteristics (location)	146.22	0.000	Yes	
4	TGR	Traffic growth rate (%)	24.44	0.000	Yes	Mildly Significant
5	TPRESS	Tire pressure	9.37	0.004	Yes	
6	VCD	Vehicle class distribution factors	2.72	0.109	No	Not Significant
7	ES	Subgrade resilient modulus	1.50	0.239	No	
8	ACOLGRAD	AC overlay mix gradation	1.04	0.365	No	
9	HACOL	AC layer thickness	0.25	0.781	No	
10	EB	Base resilient modulus	0.20	0.822	No	
11	HPCC	Existing fractured JPCP thickness	0.20	0.822	No	
12	PIBASE	Base plasticity index	0.06	0.815	No	
13	EPCC	Elastic resilient modulus of the fractured slab	0.03	0.969	No	
14	ACOLCRIP	ACOL creep compliance	0.00	1.000	No	
15	CTC	AC coef. of thermal contraction	0.00	1.000	No	
16	DWT	Depth of water table	0.00	1.000	No	
17	HBASE	Base layer thickness	0.00	1.000	No	
18	PR	Pavement rating	0.00	1.000	No	
19	SG	Subgrade type	0.00	1.000	No	
20	THD	Truck hourly distribution factors	0.00	1.000	No	

Note: Shaded cells indicate those variables that were found to be insignificant.

- **Effect of base layer-related inputs—**All three of the base-related inputs (HBASE, EB, and PIBASE) show very little or no impact on the total rutting model.
- **Effect of subgrade layer-related inputs—**A review of the subgrade-related variables finds that SG shows virtually no effect on total rutting while ES shows a fairly large impact. The impact of the ES variable was observed to be the second largest of all investigated inputs. As expected, total rutting increases as ES decreases.

A subjective review of the ANOVA analysis results classifies AADTT, ES, DWT, and ACOLBIND as *Highly Significant*, and CLIMATE, TGR, EPCC, HPCC, HACOL, TPRESS, and EB as *Moderately Significant*. The complete ANOVA results are presented in table C-26.

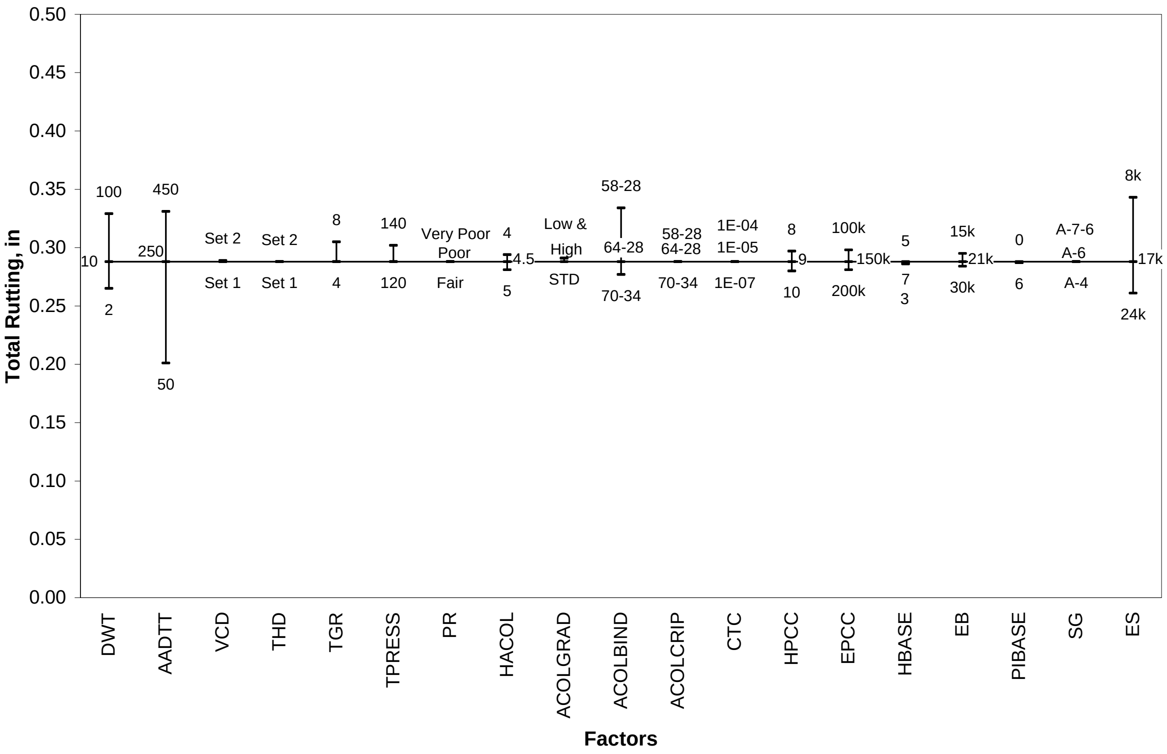

Figure C-30. Relative effect of variables on total rutting for ACOL on Rubblized JPCP design (Location = Brookings).

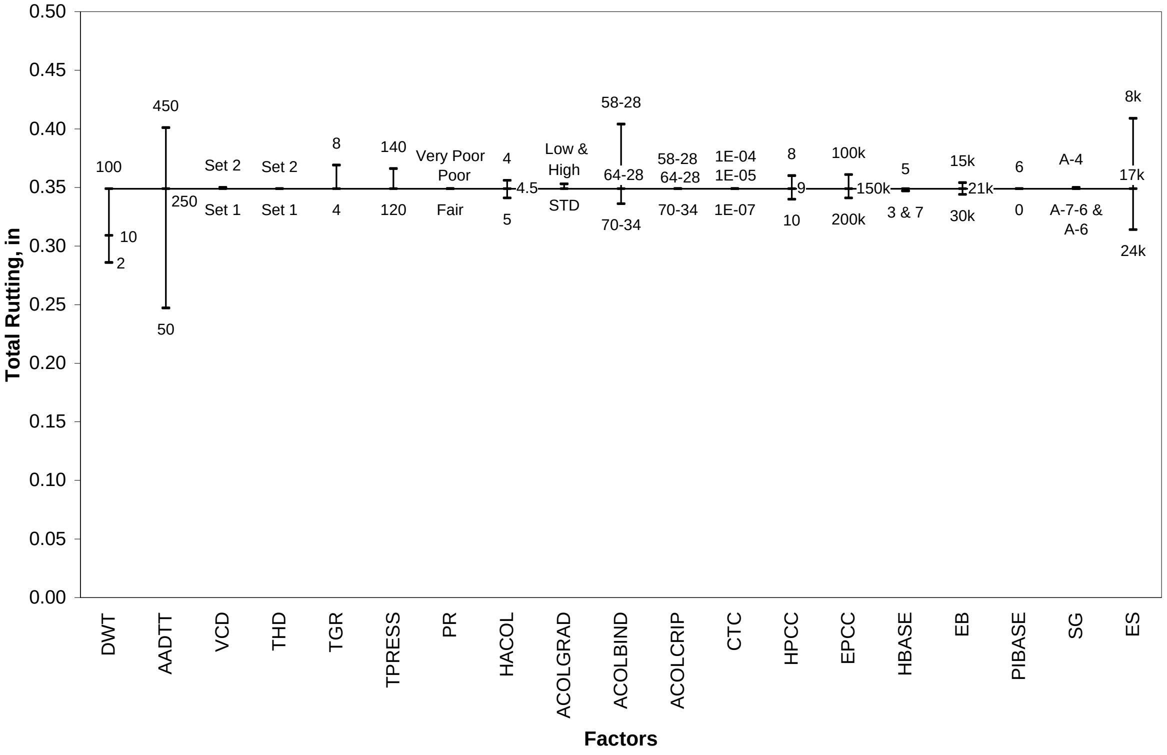

Figure C-31. Relative effect of variables on total rutting for ACOL on Rubblized JPCP design (Location = Winner).

Table C-26. ANOVA results for the ACOL on Rubblized JPCP total rutting model.

Order No.	**Factor Abbreviation**	**Factor Name**	**F**	**p-value**	**Model Significance (α=0.05)**	**Assessed Level of Significance**
1	AADTT	Initial two-way average annual daily truck traffic	997.96	0.000	Yes	Highly Significant
2	ES	Subgrade resilient modulus	382.94	0.000	Yes	
3	DWT	Depth of water table	296.22	0.000	Yes	
4	ACOLBIND	AC overlay binder grade	216.93	0.000	Yes	
5	CLIMATE	Climatic characteristics (location)	95.78	0.000	Yes	Mildly Significant
6	TGR	Traffic growth rate (%)	41.63	0.000	Yes	
7	EPCC	Elastic resilient modulus of the fractured slab	16.25	0.000	Yes	
8	HPCC	Existing fractured JPCP thickness	16.06	0.000	Yes	
9	HACOL	ACOL layer thickness	9.24	0.001	Yes	
10	TPRESS	Tire pressure	5.69	0.023	Yes	
11	EB	Base resilient modulus	5.19	0.011	Yes	
12	ACOLGRAD	AC overlay mix gradation	0.99	0.382	No	Not Significant
13	HBASE	Base layer thickness	0.39	0.682	No	
14	PIBASE	Base plasticity index	0.07	0.793	No	
15	VCD	Vehicle class distribution factors	0.07	0.793	No	
16	ACOLCRIP	ACOL creep compliance	0.01	0.994	No	
17	CTC	AC coef. of thermal contraction	0.01	0.994	No	
18	PR	Pavement rating	0.01	0.994	No	
19	SG	Subgrade type	0.01	0.988	No	
20	THD	Truck hourly distribution factors	0.01	0.930	No	

Note: Shaded cells indicate those variables that were found to be insignificant.

Analysis of the IRI Model for the ACOL on Rubblized JPCP Design

In the MEPDG approach, IRI for ACOL projects is predicted as a function of the initial as-constructed IRI and the predicted longitudinal cracking, alligator cracking, and total rutting. The model also includes a site factor for adjusting to the local subgrade and climate. Therefore, the IRI model in this study was evaluated in terms of its correlation with the main performance indicators (longitudinal cracking, alligator cracking, and rutting). Although the visual IRI trends were assessed subjectively based on the same set of inputs as the fatigue, cracking, and rutting trends, the statistical analysis included only performance indicators as variables to evaluate their contribution to the IRI prediction model.

Figures C-32 and C-33 show the relative effects of the variable inputs on predicted IRI (Note that the IRI values plotted in these figures are the predicted 20-year values). A comparison of these figures finds that although the predicted IRI for the standard design was different between the

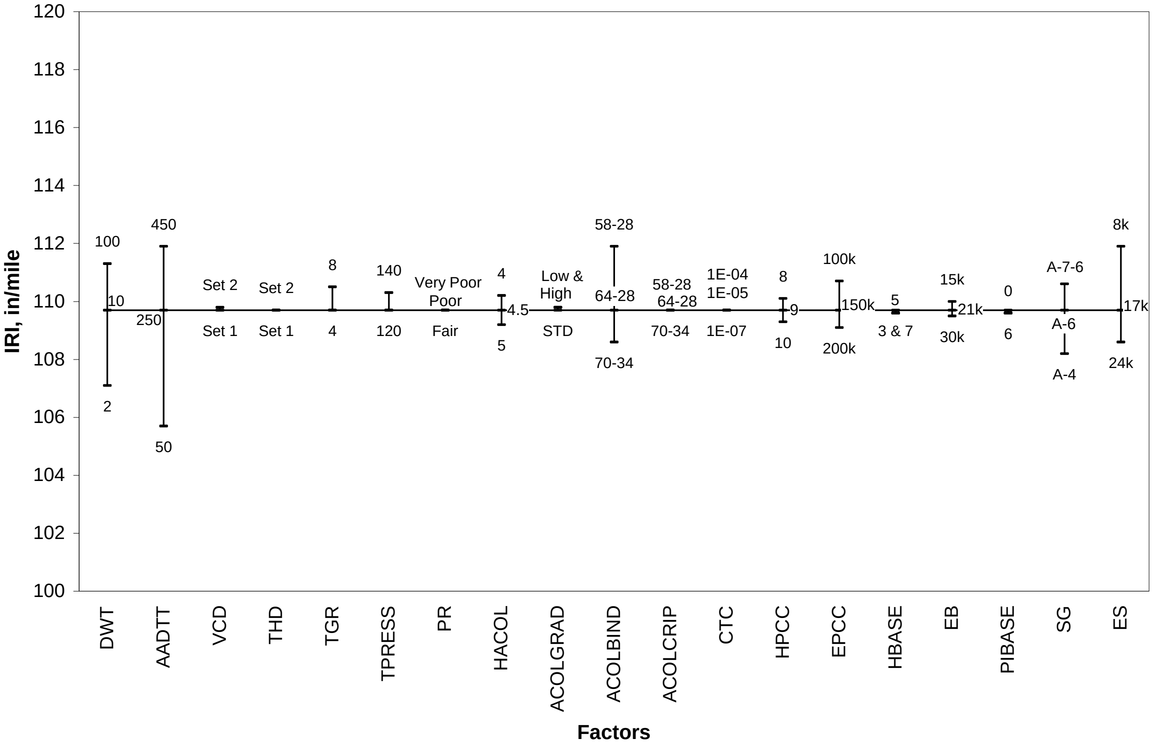

Figure C-32. Relative effect of variables on IRI for ACOL on Rubblized JPCP design (Location = Brookings).

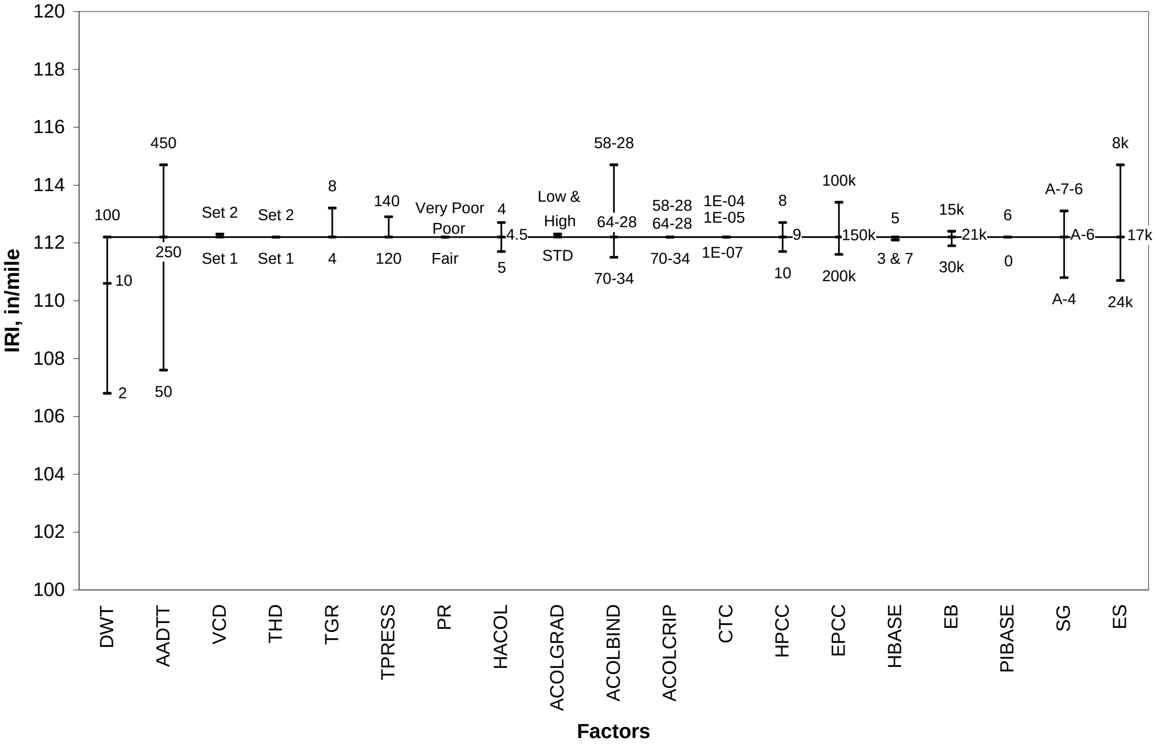

Figure C-33. Relative effect of variables on total IRI for ACOL on Rubblized JPCP design (Location = Winner).

two climates (109.7 in/mile for Brookings and 112.2 in/mile for Winner), the overall difference between these two values is extremely small on the IRI scale.

A review of the ANOVA results for the ACOL on rubblized JPCP IRI model finds that only total rutting (TOTRUT) appears to have a significant F-ratio. A summary of the ANOVA results is presented in table C-27.

Table C-27. ANOVA results for the ACOL on rubblized JPCP IRI model.

Order No.	Factor Abbreviation	Factor Name	F	p-value	Model Significance (α=0.05)
1	TOTRUT	Total rutting	54.58	0.000	Significant
2	ALLIGCRACK	Alligator cracking (bottom-up)	2.30	0.134	Non-Significant
3	LONGCRACK	Longitudinal cracking (top-down)	0.23	0.631	Non-Significant
4	ACRUT	AC layer rutting	0.09	0.771	Non-Significant

Note: Shaded cells indicate those variables that were found to be insignificant.

Overall Assessment of Significant Variables for the ACOL on Rubblized JPCP Design

The predicted performance for ACOL on rubblized JPCP pavements was evaluated based on the total of 68 MEPDG software simulations. The sensitivity of the prediction models for those performance indicators to the change in design inputs was assessed by reviewing visual trends and conducting a statistical analysis of significance. The outcomes of the statistical analysis were used to *rank* the investigated model inputs from most significant to least significant in terms of how they influence the predicted performance of each individual performance model. Because the IRI model is dependent on the other performance indicator models, it is not considered in the overall ranking of significant variables. Also, because total rutting and AC layer rutting are correlated, only total rutting is considered in determining the overall rankings.

Table C-28 presents the input parameters found to be most significant for each performance indicator model. The parameters are placed in decreasing order of their significance for each investigated performance indicator. A ranking summary of each input parameter for the ACOL of rubblized JPCP design is also provided in table C-29. The ranking is based on the results of the analysis of variance for each performance indicator. Note that because the predicted values of longitudinal and alligator cracking were found to be relatively insignificant to overall performance, it is the total rutting ranking that controls the overall ranking of variable significance for this design.

Table C-28. Summary of significance for ACOL on rubblized JPCP (rural design).

Performance Indicator	Input Parameter/Predictor
Top-down fatigue (longitudinal cracking)	• ACOL thickness • Elastic modulus of the rubblized JPCP • Annual average daily truck traffic • ACOL binder grade • Thickness of the rubblized JPCP • Subgrade resilient modulus
Bottom-up fatigue (alligator cracking)	• Elastic modulus of the rubblized JPCP • Annual average daily truck traffic • ACOL binder grade • Traffic growth rate • ACOL thickness
Permanent deformation in AC layer (AC rutting)	• Annual average daily truck traffic • AC overlay binder grade • Location (climate) • Traffic growth rate • Tire pressure
Total permanent deformation (total rutting)	• Annual average daily truck traffic • Subgrade resilient modulus • Depth of water table • ACOL binder grade • Location (climate) • Traffic growth rate
Smoothness (IRI)	• Total permanent deformation (total rutting)

All conclusions about the importance and the order of significance of the inputs are valid for the given range of inputs provided by the SDDOT, and are based on local South Dakota conditions.

Analysis Results: ACOL on Existing AC—Rural Design

For the sensitivity analysis of the ACOL on existing AC rural design, the pavement performance is expressed in terms of the following performance indicators:

- Longitudinal cracking (top-down fatigue).
- Alligator cracking (bottom-up fatigue).
- Reflective cracking.
- Permanent deformation (rutting) in AC layer.
- Total permanent deformation.
- IRI.

Table C-29. Ranking summary of significance of each input parameter on the performance indicator for ACOL on rubblized JPCP (rural design).

Input Parameter/Predictor	Rankings for Individual Performance Indicators			Overall Order of Significance
	Longitudinal Cracking	Alligator Cracking	Total Rutting	
Annual average daily truck traffic	3	2	1	1
Subgrade resilient modulus	6	7	2	2
Depth of water table	14	14	3	3
AC overlay binder grade	4	3	4	4
Location (climate)	10	12	5	5
Traffic growth rate	7	4	6	6
Elastic resilient modulus of the fractured slab	2	1	7	7
Existing fractured JPCP thickness	5	6	8	8
AC overlay thickness	1	5	9	9
Tire pressure	9	8	10	10
Base resilient modulus	8	10	11	11
AC overlay mix gradation	13	13	12	12
Base layer thickness	11	11	13	13
Base plasticity index	17	17	14	14
Vehicle class distribution factors	12	9	15	15
AC overlay creep compliance	15	15	16	16
Coefficient of thermal contraction	16	16	17	17
Pavement rating	18	18	18	18
Subgrade type	19	19	19	19
Truck hourly distribution	20	20	20	20

Note: Shaded cells indicate those variables that were found to be insignificant.

As stated previously, although it is recognized that transverse cracking is also an important performance indicator for AC-surfaced pavements, a problem with the transverse cracking model was encountered when conducting the sensitivity analysis with version 0.9 of the MEPDG software. When reviewing the results from the sensitivity analysis runs, it was discovered that the transverse cracking model consistently predicted 20-year (AC design life) transverse cracking values equal to “0” when the runs were completed using a computer running the Windows XP operating system. Conversely, the same runs completed on computers running Windows NT2000 yielded nonzero results that were typically near the allowable model maximum of 2,110 ft/mi at 20 years. Due to the inability of this model to predict consistent nonzero values for the investigated runs, it was decided to ignore this model in the current sensitivity analysis. However, it is recommended that this model be revisited when version 1.0 of the MEPDG software is released.

This section provides the details of the analysis of sensitivity performed for the ACOL on existing AC rural design. Specifically it includes a summary of the investigated inputs, detailed descriptions of the model-by-model analyses of significance, and a ranking of variables in terms of their significance for a "standard" ACOL on existing AC rural design in typical South Dakota conditions.

Summary of Investigated Inputs

In the first stage of the analysis the input variables and their range for analysis were determined. Based on these inputs, 78 MEPDG software simulations were run to predict the development of longitudinal cracking, alligator cracking, AC layer rutting, total rutting, and IRI in the two climatic locations (Brookings and Winner). The analysis period used for this design was chosen to be 20 years (i.e., all predicted performance values presented in the charts are the values predicted at the end of 20 years). Each run included in the sensitivity analysis represented a scenario when one varying input value was changed to a value other than the standard value (i.e., a high or low value). A summary of all of the inputs varied in the sensitivity analysis is provided in table C-30.

Analysis of the Longitudinal (Top-Down Fatigue) Cracking Model for the ACOL on Existing AC Design

The results of the analysis of the AC longitudinal (top-down) cracking model are presented in this section. For this analysis, 78 analysis runs were completed using the inputs defined in table C-30 above. The summary charts of relative effects summarizing the MEPDG run results are presented in figures C-34 and C-35 for Brookings and Winner, respectively.

One general observation from a review of the summary charts is that the overall amount of longitudinal cracking predicted for the range of inputs is very small (i.e., between 0 and 37 ft/mi at 20 years). Therefore, the results of these sensitivity runs indicate that longitudinal cracking is not expected to be a major factor in the overall performance of this pavement design. Other notable observations from the summary charts include:

Table C-30. List of inputs for ACOL on existing AC rural design.

Name	**Abbreviation in Analysis**	**Input Values**			***Standard* Value**
		Low	**Med**	**High**	
CLIMATIC INPUTS					
Climatic characteristics (location)	CLIMATE	—	Brookings	Winner	—
Depth of water table (ft)	DWT	2	10	100	—
TRAFFIC INPUTS (RURAL TRAFFIC)					
Initial two-way average annual daily truck traffic	AADTT	50	250	450	250
Vehicle class dist. factors[1]	VCD	Set 1	—	Set 2	Set 1
Truck hourly dist. factors[2]	THD	Set 1	—	Set 2	Set 1
Traffic growth rate (%)	TGR	4	—	8	4
Tire pressure, psi	TPRESS	120		140	120
AC OVELAY DESIGN FEATURES AND MATERIAL INPUTS					
Milled thickness, in	HMILL	0.5	1	2	1
Pavement rating	PR	Poor	Fair	Good	Fair
Total rutting in existing AC layer, in	TOTRUTEXIST	0	0.125	0.25	0.125
AC overlay thickness, in	HACOL	2	3	4	3
AC overlay mix gradation information (percent retained on sieve, %)	ACOLGRAD	3/4”: 0 3/8”: 23 #4: 42 #200: 5.3	3/4”: 0 3/8”: 18 #4: 34 #200: 4.3	3/4”: 0 3/8”: 24 #4: 35 #200: 3	3/4”: 0 3/8”: 18 #4: 34 #200: 4.3
AC overlay binder grade	ACOLBIND	58-28	64-28	70-34	64-28
Effective binder content, %	Not included directly. Varies with binder grade.	For 58-28: 5.5	For 64-28: 5	For 70-34: 4.8	For 64-28: 5
Air voids, %		For 58-28: 9	For 64-28: 7	For 70-34: 6	For 64-28: 7
Total unit weight, pcf		For 58-28: 145	For 64-28: 148	For 70-34: 150	For 64-28: 148
AC overlay creep compliance	ACOLCRIP	“PG58-28” values from Table C-1	“PG64-28” values from Table C-1	“PG70-34” values from Table C-1	“PG64-28” values from Table C-1
Coef. of thermal contraction (in/in/°F)	CTC	1E-07	1E-05	1E-04	1E-05
EXISTING AC DESIGN FEATURES AND MATERIAL INPUTS					
AC layer thickness, in	HAC	3	4	5	4
AC mix gradation information (percent retained on sieve, %)	ACGRAD	3/4”: 0 3/8”: 23 #4: 42 #200: 5.3	3/4”: 0 3/8”: 18 #4: 34 #200: 4.3	3/4”: 0 3/8”: 24 #4: 35 #200: 3	3/4”: 0 3/8”: 18 #4: 34 #200: 4.3
AC binder grade	ACBIND	58-28	64-28	70-34	64-28
Effective binder content, %	—	For 58-28: 5.5	For 64-28: 5	For 70-34: 4.8	For 64-28: 5
Air voids, %	—	For 58-28: 9	For 64-28: 7	For 70-34: 6	For 64-28: 7
Total unit weight, pcf	—	For 58-28: 145	For 64-28: 148	For 70-34: 150	For 64-28: 148

Table C-30. List of inputs for ACOL on AC design (continued).

Name	Abbreviation in Analysis	Input Values			*Standard* Value
		Low	Med	High	
BASE INPUTS (GRAVEL CUSHION)					
Base layer thickness, in	HBASE	4	12	14	12
Base resilient modulus, psi	EB	15,000	21,000	30,000	21,000
Base plasticity index, PI	PIBASE	0	—	6	0
SUBGRADE INPUTS					
Subgrade type	SG	A-7-6	A-6	A-4	A-6
Subgrade resilient modulus, psi	ES	8,000	17,000	24,000	17,000
Subgrade plasticity index, PI	Not included directly. Varies with subgrade type.	For A-7-6: 33	For A-6: 17	For A-4: 8	For A-6: 17
Subgrade liquid limit, LL		For A-7-6: 58	For A-6: 34	For A-4: 25	For A-6: 34
Subgrade gradation information (lower and upper bounds)		For A-7-6: #200: 38.4,99.2 #40: 69.7, 99.8 #10: 80.2, 100 #4: 84.2, 100 3/8": 92.9, 100	For A-6: #200: 36.1, 98.2 #40: 54, 99.7 #10: 70.4, 100 #4: 76.7, 100 3/8": 86.6,100	For A-4: #200: 37.3, 69.2 #40: 44.2, 98.9 #10: 45.2, 99.9 #4: 51.6, 100 3/8": 70.8, 100	For A-6: #200: 36.1, 98.2 #40: 54, 99.7 #10: 70.4, 100 #4: 76.7, 100 3/8": 86.6, 100

- **Effect of climate-related inputs—**For the standard ACOL on existing AC design, there was virtually no difference between the longitudinal cracking predicted for both climatic locations (i.e., 8.5 ft/mi for Brookings and 12.5 ft/mi for Winner). The DWT variable also showed virtually no impact on the development of longitudinal cracking in either climatic location.
- **Effect of traffic-related inputs—**Based on a review of the summary charts, AADTT is observed to be the variable with the second-largest impact on the longitudinal cracking model in both climatic locations. As expected, an increase in AADTT results in an increase in longitudinal cracking. The other traffic-related variables showing a noticeable impact on the longitudinal cracking model include TGR, TPRESS, and VCD, in that order. THD did not show any effect on longitudinal cracking in either location. It is interesting to note that the trend associated with TPRESS was counterintuitive, as both charts indicate a decrease in cracking as tire pressure increases. No explanation of this trend was found in the MEPDG documentation (NCHRP 2004).

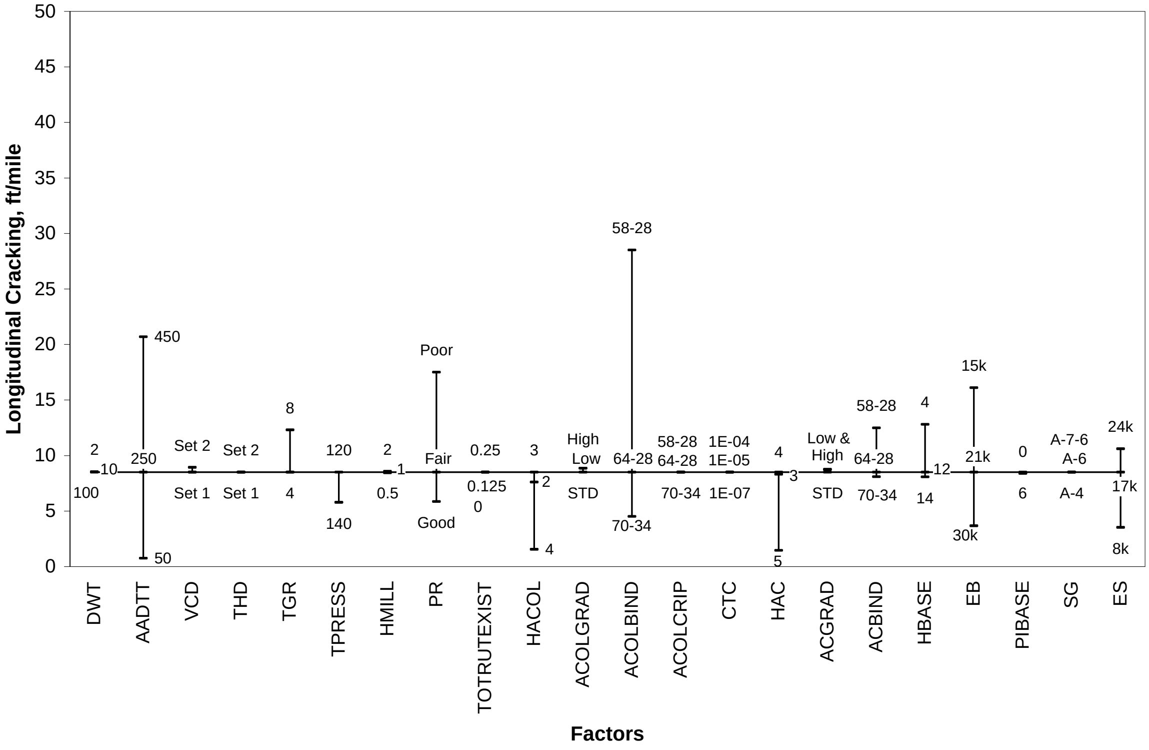

Figure C-34. Relative effect of variables on longitudinal cracking for ACOL on AC design (Location = Brookings).

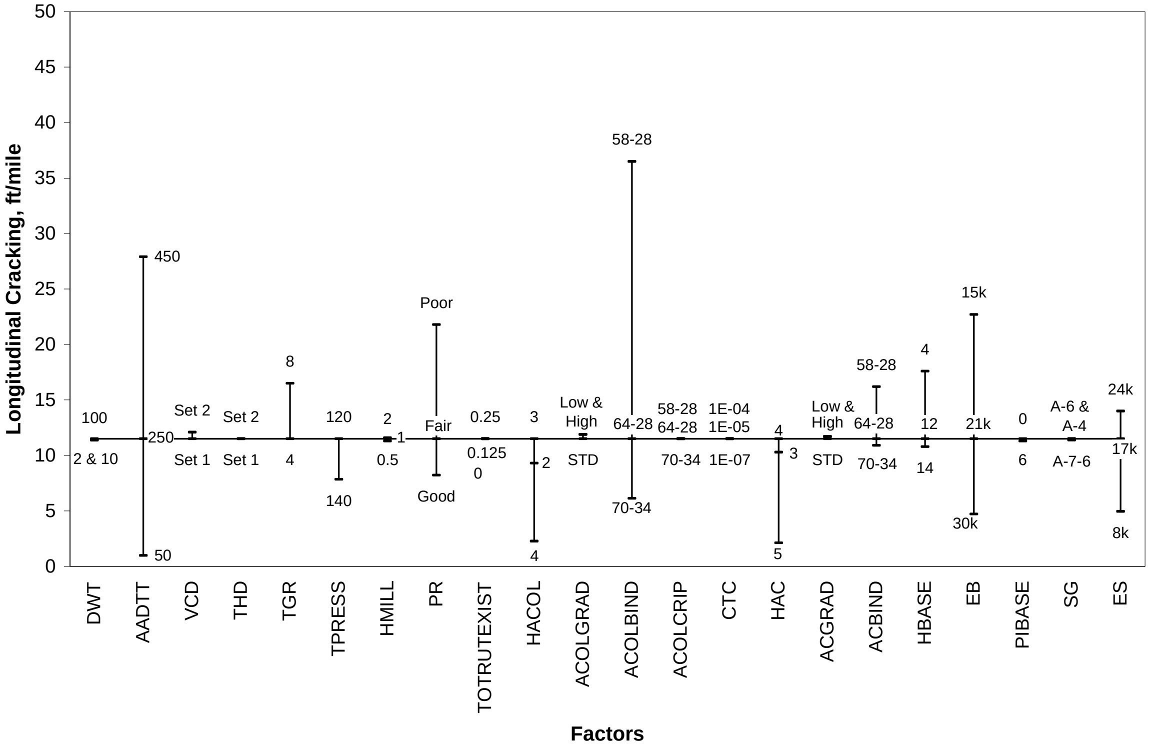

Figure C-35. Relative effect of variables on longitudinal cracking for ACOL on AC design (Location = Winner).

- **Effect of existing AC layer-related inputs—**Within the existing AC layer-related inputs, a number of variables were observed to have a large to marginal impact on the longitudinal cracking model. One variable observed to have a large impact on longitudinal cracking was the current pavement rating (i.e., PR) for the existing AC pavement. Two variables found to have marginal impacts on the longitudinal cracking model are the thickness of the existing AC layer (HAC) and the existing AC binder type (ACBIND). It is, however, important to note that once again, the resulting model trend associated with HAC was parabolic in shape. Finally, the existing AC gradation (ACGRAD), selected milling thickness (HMILL), and total rutting in the existing AC pavement (TOTRUTEXIST) variables were observed to have very little impact on the longitudinal cracking model.
- **Effect of ACOL layer-related inputs—**A review of the summary charts indicates that ACOLBIND has the largest impact on longitudinal cracking out of all of the investigated variables. While HACOL does show a marginal impact on the longitudinal cracking model, the observed trend for this variable is parabolic in form. Finally, ACOLGRAD shows a very small impact, while the thermal property-related inputs (ACOLCRIP and CTC) showed no impact on the longitudinal cracking model.
- **Effect of base layer-related inputs—**For the ACOL of existing AC design type, the EB variable has a fairly large impact on the predicted longitudinal cracking. Next, the HBASE variable has a marginal effect on the model output, while the PIBASE variable was observed to have virtually no impact.
- **Effect of subgrade layer-related inputs—**A review of the subgrade-related variables finds that SG shows no effect on longitudinal cracking while ES shows a marginal effect. As observed for the ACOL on rubblized JPCP design type, the trend associated with ES initially appears counterintuitive (i.e., as ES increases, so does longitudinal cracking). A review of the MEPDG documentation finds that this observed trend is consistent with the inherent trends in the top-down longitudinal cracking model (NCHRP 2004).

A subjective review of the ANOVA analysis results classifies ACOLBIND, AADTT, EB, and PR as *Highly Significant,* and HAC, ES, TGR, HBASE, CLIMATE, HACOL, ACBIND, and TPRESS as *Mildly Significant*. The complete ANOVA results are presented in table C-31.

Table C-31. ANOVA results for the ACOL on existing AC longitudinal cracking model.

Order No.	Factor Abbreviation	Factor Name	F	p-value	Model Significance (α=0.05)	Assessed Level of Significance
1	ACOLBIND	ACOL binder grade	222.95	0.000	Yes	Highly Significant
2	AADTT	Initial two-way average annual daily truck traffic	139.73	0.000	Yes	
3	EB	Base resilient modulus	59.05	0.000	Yes	
4	PR	Pavement rating	45.13	0.000	Yes	
5	HAC	Existing AC layer thickness	23.81	0.000	Yes	Mildly Significant
6	ES	Subgrade resilient modulus	17.61	0.000	Yes	
7	TGR	Traffic growth rate (%)	12.94	0.001	Yes	
8	HBASE	Base layer thickness	10.96	0.000	Yes	
9	CLIMATE	Climatic characteristics (location)	10.07	0.003	Yes	
10	HACOL	AC overlay thickness	8.42	0.001	Yes	
11	ACBIND	Existing AC binder grade	7.73	0.002	Yes	
12	TPRESS	Tire pressure	6.65	0.014	Yes	
13	VCD	Vehicle class distribution factors	0.19	0.666	No	Not Significant
14	ACOLGRAD	ACOL mix gradation	0.08	0.925	No	
15	ACGRAD	Existing AC mix gradation	0.03	0.972	No	
16	HMILL	Milled thickness	0.01	0.989	No	
17	PIBASE	Base plasticity index	0.01	0.910	No	
18	ACOLCRIP	ACOL creep compliance	0.00	1.000	No	
19	CTC	AC coef. of thermal contraction	0.00	1.000	No	
20	DWT	Depth of water table	0.00	1.000	No	
21	SG	Subgrade type	0.00	0.999	No	
22	THD	Truck hourly distribution factors	0.00	0.987	No	
23	TOTRUTEXIST	Total rutting in existing AC	0.00	1.000	No	

Note: Shaded cells indicate those variables that were found to be insignificant.

Analysis of the Alligator (Bottom-Up Fatigue) Cracking Model for the ACOL on Existing AC Design

The results of the analysis of the AC alligator (bottom-up) cracking model are presented in this section. For this analysis, 78 analysis runs were completed using the inputs defined in table C-30 above. The summary charts of relative effects summarizing the MEPDG run results are presented in figures C-36 and C-37 for Brookings and Winner, respectively.

One general observation from a review of the summary charts is that the overall amount of alligator cracking predicted for the range of inputs is very small (i.e., between 0 and 0.5 percent of the area). Therefore, the results of these sensitivity runs indicate that alligator cracking is not expected to be a major factor in the overall performance of this pavement design. Other notable observations from the summary charts are described below.

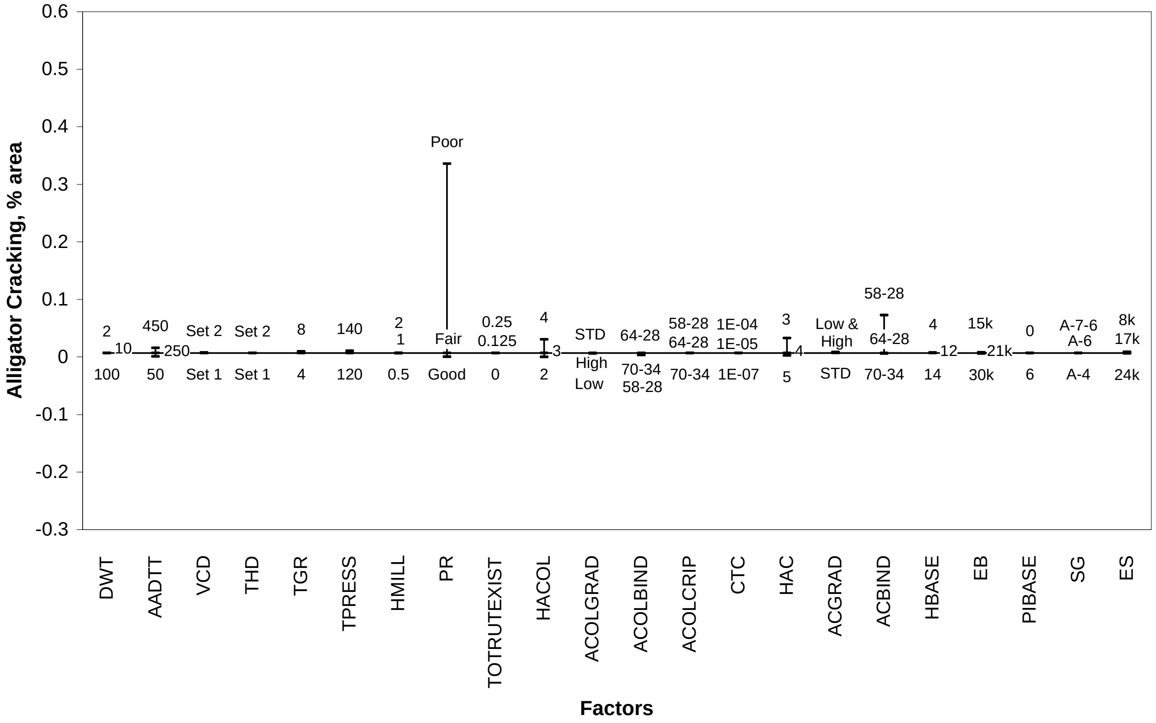

Figure C-36. Relative effect of variables on alligator cracking for ACOL on AC design (Location = Brookings).

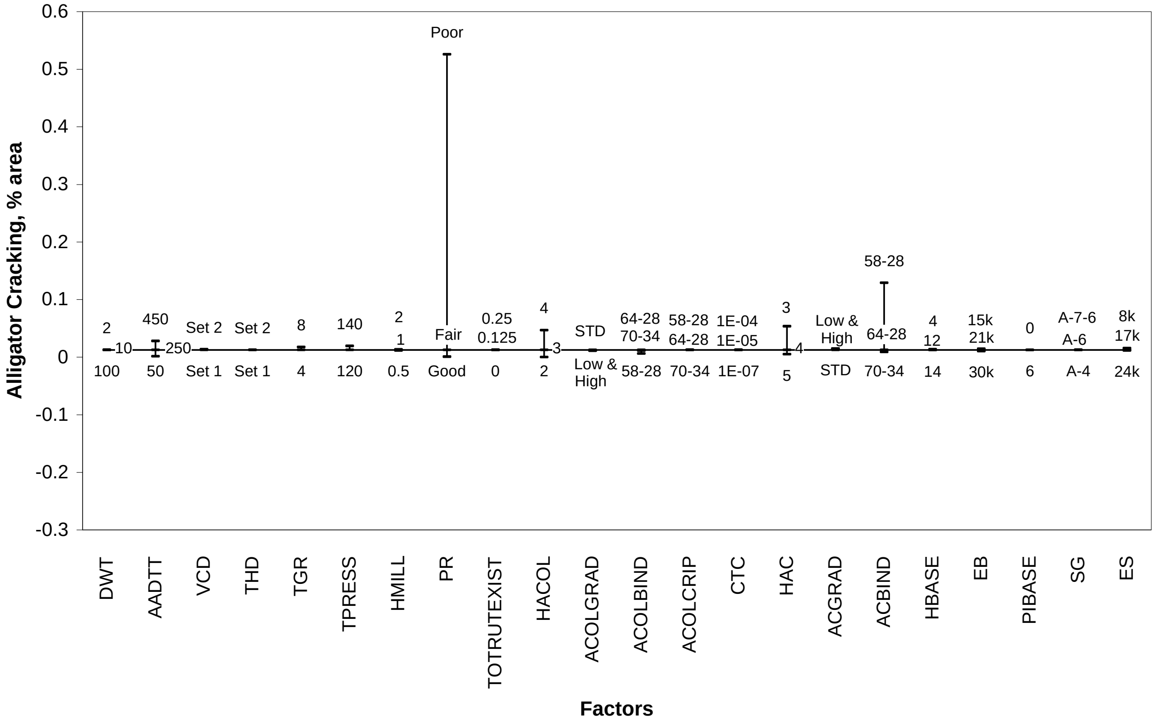

Figure C-37. Relative effect of variables on alligator cracking for ACOL on AC design (Location = Winner).

- **Effect of climate-related inputs—**For the standard ACOL on existing AC design, there was no practical difference between the alligator cracking predicted for both climatic locations (i.e., 0.007 percent area for Brookings and 0.013 percent area for Winner). The DWT variable also showed virtually no impact on the development of alligator cracking in either climatic location.
- **Effect of traffic-related inputs—**Based on a review of the summary charts, all of the traffic-related inputs showed very little or no impact on the alligator cracking model.
- **Effect of existing AC layer-related inputs—**By far, the only variable showing a significant influence on the development of alligator cracking on the ACOL of existing AC pavement design is the current pavement rating (i.e., PR). However, even though this variable showed the largest relative impact of all of the investigated variables, it is important to note that the overall observed alligator cracking range was just over 0.5 percent of the total area.

  Of the remaining AC layer-related inputs, ACBIND and HAC showed a noticeable impact on the alligator cracking model. Variables such as HMILL, TOTRUTEXIST, and ACGRAD showed virtually no impact on the prediction of alligator cracking.

- **Effect of ACOL layer-related inputs—**A review of the summary charts indicates that with the exception of HACOL, all of the ACOL layer-related variables have virtually no impact on the alligator cracking model. While the HACOL variable does show some impact on the prediction of alligator cracking, the impact is minimal. It is also important to note that the trend associated with the HACOL variable is counterintuitive to the expected trend. That is, the observed trend indicates that as HACOL increases, so does alligator cracking.
- **Effect of base layer-related inputs—**All three of the base-related variables (HBASE, EB, and PIBASE) were observed to have very little or no impact on the prediction of alligator cracking.
- **Effect of subgrade layer-related inputs—**Similar to the base-related variables, both SG and ES were observed to have very little or no impact on the prediction of alligator cracking.

A subjective review of the ANOVA analysis results classifies PR as *Highly Significant* and ACBIND as *Mildly Significant*. The complete ANOVA results are presented in table C-32.

Table 32. ANOVA results for the ACOL on AC alligator cracking model.

Order No.	Factor Abbreviation	Factor Name	F	p-value	Model Significance (α=0.05)	Assessed Level of Significance
1	PR	Pavement rating	297.01	0.000	Yes	Highly Significant
2	ACBIND	Existing AC binder grade	13.91	0.000	Yes	Mildly Significant
3	HAC	Existing AC layer thickness	2.12	0.133	No	Not Significant
4	HACOL	AC overlay thickness	1.86	0.169	No	
5	AADTT	Initial two-way average annual daily truck traffic	0.49	0.618	No	
6	CLIMATE	Climatic characteristics (location)	0.36	0.550	No	
7	TPRESS	Tire pressure	0.08	0.774	No	
8	TGR	Traffic growth rate (%)	0.05	0.830	No	
9	ACOLBIND	ACOL binder grade	0.04	0.962	No	
10	DWT	Depth of water table	0.04	0.960	No	
11	ACGRAD	Existing AC mix gradation	0.01	0.993	No	
12	EB	Base resilient modulus	0.01	0.991	No	
13	ES	Subgrade resilient modulus	0.01	0.987	No	
14	ACOLCRIP	ACOL creep compliance	0.00	1.000	No	
15	ACOLGRAD	ACOL mix gradation	0.00	0.998	No	
16	CTC	AC coef. of thermal contraction	0.00	1.000	No	
17	HBASE	Base layer thickness	0.00	0.999	No	
18	HMILL	Milled thickness	0.00	0.998	No	
19	PIBASE	Base plasticity index	0.00	0.991	No	
20	SG	Subgrade type	0.00	1.000	No	
21	THD	Truck hourly distribution factor	0.00	1.000	No	
22	TOTRUTEXIST	Total rutting in existing AC	0.00	1.000	No	
23	VCD	Vehicle class distribution factors	0.00	0.961	No	

Note: Shaded cells indicate those variables that were found to be insignificant.

Analysis of the Reflective Cracking Model for the ACOL on Existing AC Design

The results of the analysis of the AC reflective cracking model are presented in this section. For this analysis, 78 analysis runs were completed using the inputs defined in table C-30 above. The summary charts of relative effects summarizing the MEPDG run results are presented in figures C-38 and C-39 for Brookings and Winner, respectively.

One general observation from a review of the summary charts is that the overall amount of reflective cracking was large for both climates (i.e., between 17 and 51 percent area at 20 years). Therefore, the results of these sensitivity runs indicate that reflective cracking is expected to be a major factor in the overall performance of this design. Other notable observations from the summary charts include:

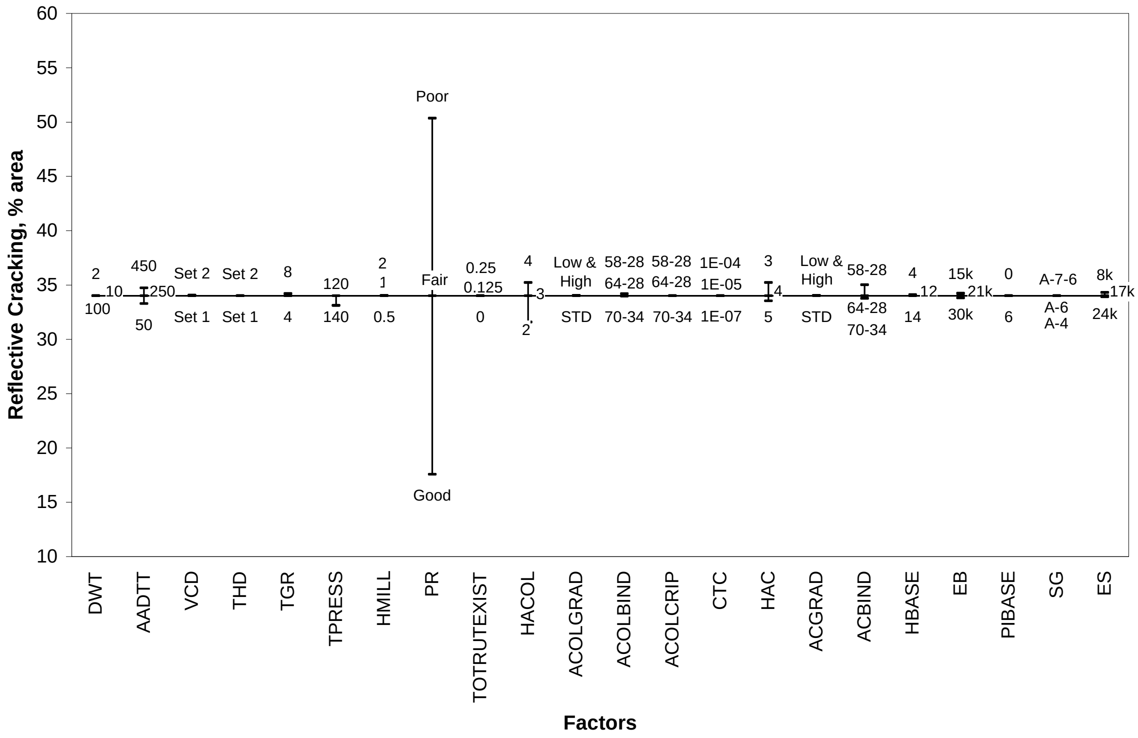

Figure C-38. Relative effect of variables on reflective cracking for ACOL on AC design (Location = Brookings).

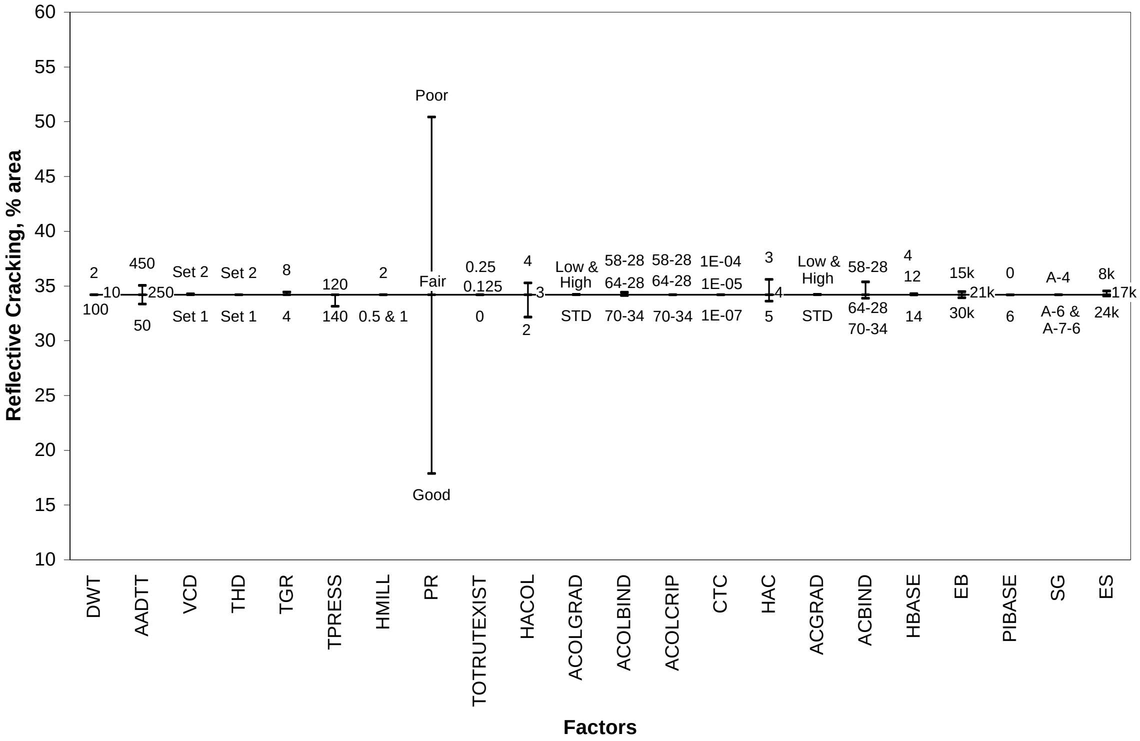

Figure C-39. Relative effect of variables on reflective cracking for ACOL on AC design (Location = Winner).

- **Effect of climate-related inputs**—For the standard ACOL on existing AC design, there was no practical difference between the reflective cracking predicted for both climatic locations (i.e., 34.0 percent area for Brookings and 34.2 percent area for Winner). The DWT variable also showed virtually no impact on the development of alligator cracking in either climatic location.
- **Effect of traffic-related inputs**—Based on a review of the summary charts, all of the traffic-related showed very little or no impact on the reflective cracking model.
- **Effect of existing AC layer-related inputs—**By far, the only variable showing a significant influence on the development of reflective cracking on the ACOL of existing AC pavement design is the current pavement rating (i.e., PR). The observed range of reflective cracking associated with PR was observed to be very large (i.e., a range of approximately 35 percent for both climates). Of the remaining AC layer-related inputs, ACBIND and HAC showed a noticeable impact on the reflective cracking model. Variables such as HMILL, TOTRUTEXIST, and ACGRAD showed virtually no impact on the prediction of reflective cracking.
- **Effect of ACOL layer-related inputs—**With the exception of HACOL, all of the ACOL layer-related variables have virtually no impact on the reflective cracking model. While the HACOL variable does show a noticeable impact on the reflective cracking model, the impact is only marginal. It is also important to note that the trend associated with the HACOL variable is counterintuitive to the expected trend. That is, the observed trend indicates that as HACOL increases, so does reflective cracking.
- **Effect of base layer-related inputs—**All three of the base-related variables (HBASE, EB, and PIBASE) were observed to have very little or no impact on the prediction of reflective cracking.
- **Effect of subgrade layer-related inputs—**Similar to the base-related variables, both SG and ES were observed to have very little or no impact on the prediction of reflective cracking.

A subjective review of the ANOVA analysis results classifies PR as *Highly Significant,* HACOL as *Moderately Significant*, and HAC, TPRESS, AADTT, ACBIND, EB, ES, CLIMATE, TGR, and ACOLBIND as *Mildly Significant*. The complete ANOVA results are presented in table C-33.

Table C-33. ANOVA results for the ACOL on AC reflective cracking model.

Order No.	Factor Abbreviation	Factor Name	F	p-value	Model Significance (α=0.05)	Assessed Level of Significance
1	PR	Pavement rating	118307.73	0.000	Yes	Highly Significant
2	HACOL	AC overlay thickness	1328.24	0.000	Yes	Moderately Significant
3	HAC	Existing AC layer thickness	405.05	0.000	Yes	Mildly Significant
4	TPRESS	Tire pressure	281.08	0.000	Yes	
5	AADTT	Initial two-way average annual daily truck traffic	271.57	0.000	Yes	
6	ACBIND	Existing AC binder grade	242.71	0.000	Yes	
7	EB	Base resilient modulus	27.18	0.000	Yes	
8	ES	Subgrade resilient modulus	22.00	0.000	Yes	
9	CLIMATE	Climatic characteristics (location)	16.91	0.000	Yes	
10	TGR	Traffic growth rate (%)	16.33	0.000	Yes	
11	ACOLBIND	ACOL binder grade	9.12	0.001	Yes	
12	HBASE	Base layer thickness	1.62	0.210	No	Not Significant
13	VCD	Vehicle class distribution factors	1.45	0.236	No	
14	ACGRAD	Existing AC mix gradation	0.14	0.871	No	
15	ACOLGRAD	ACOL mix gradation	0.05	0.951	No	
16	DWT	Depth of water table	0.03	0.975	No	
17	HMILL	Milled thickness	0.03	0.974	No	
18	PIBASE	Base plasticity index	0.03	0.864	No	
19	ACOLCRIP	ACOL creep compliance	0.00	1.000	No	
20	CTC	AC coef. of thermal contraction	0.00	1.000	No	
21	SG	Subgrade type	0.00	0.996	No	
22	THD	Truck hourly distribution factor	0.00	1.000	No	
23	TOTRUTEXIST	Total rutting in existing AC	0.00	1.000	No	

Note: Shaded cells indicate those variables that were found to be insignificant.

Analysis of the AC Layer Rutting (Permanent Deformation in AC Layer) Model for the ACOL on Existing AC Design

The results of the analysis of the AC layer rutting model for the ACOL on existing AC design are presented in this section. For this analysis, 78 analysis runs were completed using the inputs defined in table C-30 above. The summary charts of relative effects summarizing the MEPDG run results are presented in figures C-40 and C-41 for Brookings and Winner, respectively. Some notable observations from the summary charts include:

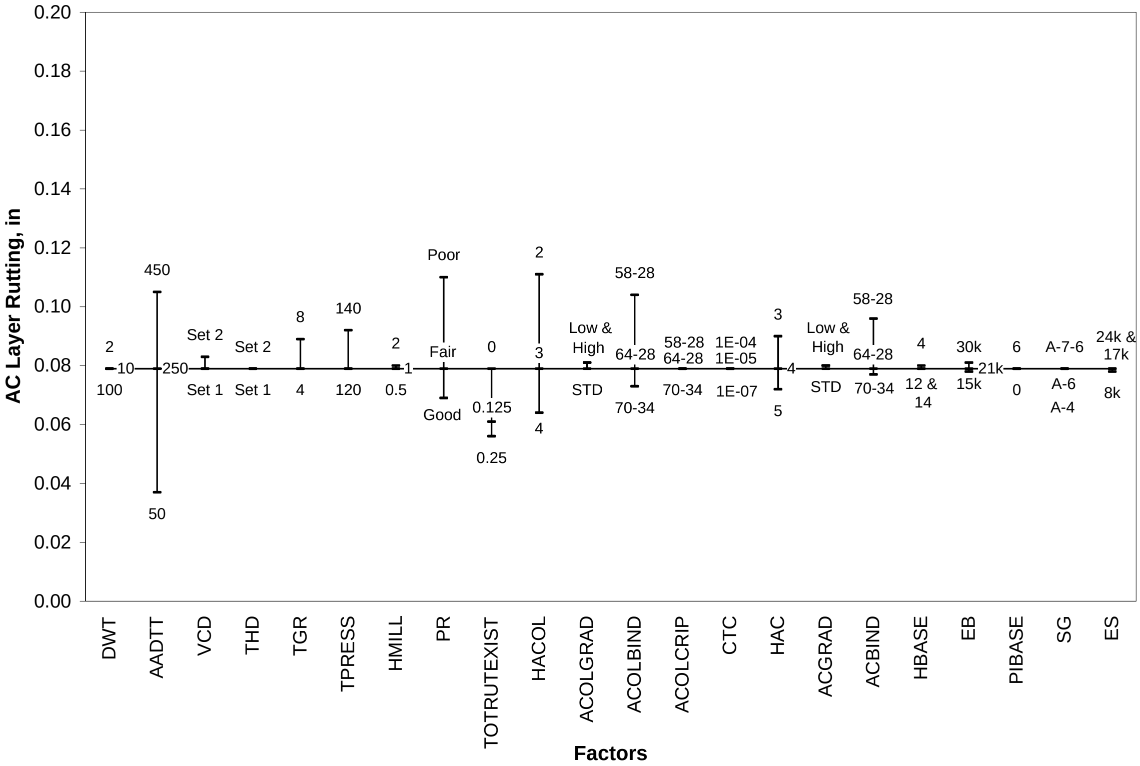

Figure C-40. Relative effect of variables on AC layer rutting for ACOL on AC design (Location = Brookings).

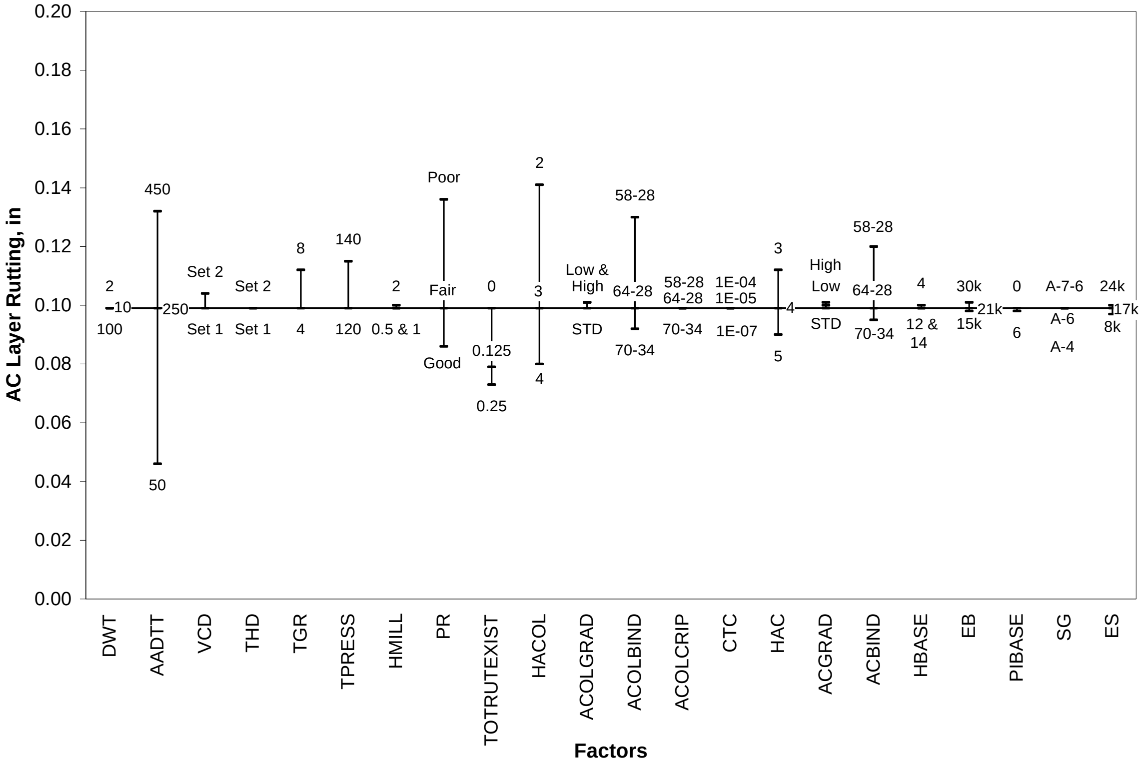

Figure C-41. Relative effect of variables on AC layer rutting for ACOL on AC design (Location = Winner).

- **Effect of climate-related inputs**—For the "standard" section for the ACOL on existing AC design, there was little difference between the AC layer rutting predicted for both climatic locations (i.e., 0.08 in for Brookings and 0.10 in for Winner). The DWT variable also showed virtually no impact on the development of longitudinal cracking in either climatic location.
- **Effect of traffic-related inputs—**Based on a review of the summary charts, AADTT is observed to be the variable with the largest impact on the AC layer rutting model in both climatic locations. As expected, an increase in AADTT results in an increase in AC layer rutting. The other traffic-related variables showing a noticeable impact on the AC layer rutting model include TPRESS, TGR, and VCD, in that order. THD did not show any effect on AC layer rutting in either location. It is interesting to note that the trend associated with TPRESS was counterintuitive, as both charts indicate a decrease in AC layer rutting as tire pressure increases. No explanation of this trend was found in the MEPDG documentation (NCHRP 2004).
- **Effect of existing AC layer-related inputs—**Within the existing AC layer-related inputs, a number of variables were observed to have a large to marginal impact on the AC layer rutting model. One variable observed to have a large impact on AC layer rutting is the current pavement rating (i.e., PR) for the existing AC pavement. Three variables found to have marginal impacts on the AC layer rutting model are TOTRUTEXIST, HAC, and ACBIND, in that order. Finally, the ACGRAD and HMILL variables were observed to have very little impact on the AC layer rutting model. It is interesting to note that the observed AC layer rutting trend associated with the TOTRUTEXIST variable is counterintuitive (i.e., the predicted AC layer rutting decreases as the existing rutting value increases). No explanation for this trend was found in the MEPDG documentation (NCHRP 2004).
- **Effect of ACOL layer-related inputs—**A review of the summary charts indicates that HACOL has the second-largest impact on AC layer rutting out of all of the investigated variables (only second to AADTT). Another variable that has a marginal impact on the AC layer rutting model is ACOLBIND. Finally, ACOLGRAD shows a very small impact, while the thermal property-related inputs (ACOLCRIP and CTC) showed absolutely no impact on the AC layer rutting model.

- **Effect of base layer-related inputs**—All three of the base-related variables (HBASE, EB, and PIBASE) were observed to have very little or no impact on the prediction of AC layer rutting.
- **Effect of subgrade layer-related inputs**—Similar to the base-related variables, both SG and ES were observed to have very little or no impact on the prediction of AC layer rutting.

A subjective review of the ANOVA analysis results classifies AADTT, HACOL, PR, CLIMATE, ACOLBIND, and TOTRUTEXIST as *Highly Significant*, and ACBIND, TPRESS, HAC, TGR, and VCD as *Moderately Significant*. The complete ANOVA results are presented in table C-34.

Table C-34. ANOVA results for the ACOL on existing AC ACOL layer rutting model.

Order No.	Factor Abbreviation	Factor Name	F	p-value	Model Significance (α=0.05)	Assessed Level of Significance
1	AADTT	Initial two-way average annual daily truck traffic	556.49	0.000	Yes	Highly Significant
2	HACOL	AC overlay thickness	284.69	0.000	Yes	
3	PR	Pavement rating	212.27	0.000	Yes	
4	CLIMATE	Climatic characteristics (location)	181.61	0.000	Yes	
5	ACOLBIND	ACOL binder grade	129.86	0.000	Yes	
6	TOTRUTEXIST	Total rutting in existing AC	89.20	0.000	Yes	
7	ACBIND	Existing AC binder grade	55.91	0.000	Yes	Moderately Significant
8	TPRESS	Tire pressure	51.22	0.000	Yes	
9	HAC	Existing AC layer thickness	37.28	0.000	Yes	
10	TGR	Traffic growth rate (%)	32.22	0.000	Yes	
11	VCD	Vehicle class distribution factors	4.93	0.032	Yes	
12	EB	Base resilient modulus	0.87	0.428	No	Not Significant
13	ACOLGRAD	ACOL mix gradation	0.73	0.488	No	
14	ES	Subgrade resilient modulus	0.41	0.666	No	
15	ACGRAD	Existing AC mix gradation	0.31	0.736	No	
16	HBASE	Base layer thickness	0.14	0.872	No	
17	HMILL	Milled thickness	0.14	0.872	No	
18	PIBASE	Base plasticity index	0.06	0.806	No	
19	DWT	Depth of water table	0.01	0.990	No	
20	ACOLCRIP	ACOL creep compliance	0.00	1.000	No	
21	CTC	AC coef. of thermal contraction	0.00	1.000	No	
22	SG	Subgrade type	0.00	1.000	No	
23	THD	Truck hourly distribution factor	0.00	1.000	No	

Note: Shaded cells indicate those variables that were found to be insignificant.

Analysis of the Total Rutting (Permanent Deformation) Model for the ACOL on Existing AC Design

The results of the analysis of the total rutting model for the ACOL on existing AC design are presented in this section. For this analysis, 78 analysis runs were completed using the inputs defined in table C-30 above. The summary charts of relative effects summarizing the MEPDG run results are presented in figures C-42 and C-43 for Brookings and Winner, respectively.

One general observation from a review of the summary charts is that the overall amount of total rutting was large for both locations (i.e., between 0.11 and 0.51 in at 20 years). Therefore, the results of these sensitivity runs indicate that total rutting is expected to be a major factor in the overall performance of this design. Other notable observations from the summary charts include:

- **Effect of climate-related inputs—**For the standard ACOL on existing AC design, there was a noticeable difference between the total rutting predicted for both climatic locations (i.e., 0.36 in for Brookings and 0.43 in for Winner). The DWT variable also showed a marginal impact on the development of total rutting in both climatic locations. However, similar to other models, the observed model trend associated with the DWT variable was the opposite of what is expected (i.e., the summary charts indicate that as DWT increases, so does total rutting).
- **Effect of traffic-related inputs—**Based on a review of the summary charts, AADTT is observed to be the variable with the second-largest impact on the total rutting model in both climatic locations (second only to TOTRUTEXIST). As expected, an increase in AADTT results in an increase in total rutting. The other traffic-related variables showing a noticeable impact on the total rutting model include TGR and TPRESS, in that order. THD and VCD did not show any effect on total rutting in either location.
- **Effect of existing AC layer-related inputs—**By far, the variable with the largest impact on total rutting was the total existing rutting (i.e., TOTRUTEXIST). Similar to the trend shown for the AC layer rutting, the observed total rutting trend associated with the TOTRUTEXIST variable is counterintuitive (i.e., the predicted total rutting decreases as the existing rutting value increases). No explanation for this trend was found in the MEPDG documentation (NCHRP 2004). Two variables found to have marginal impacts

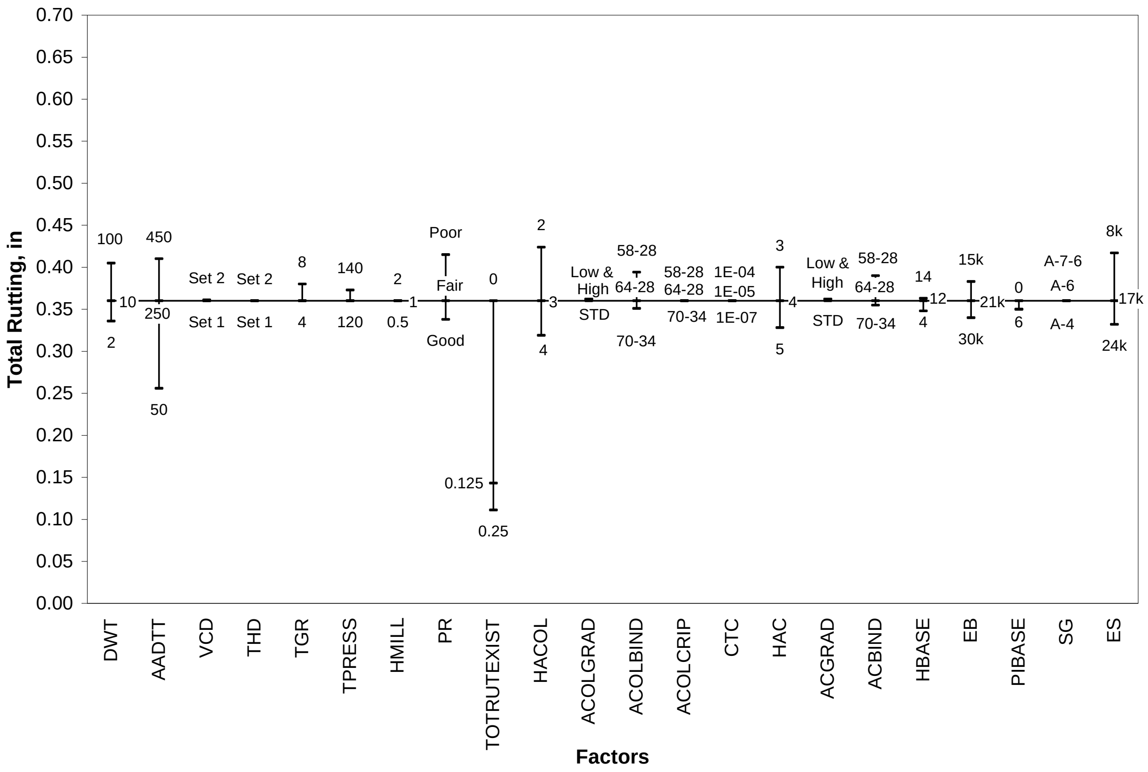

Figure C-42. Relative effect of variables on total rutting for ACOL on AC design (Location = Brookings).

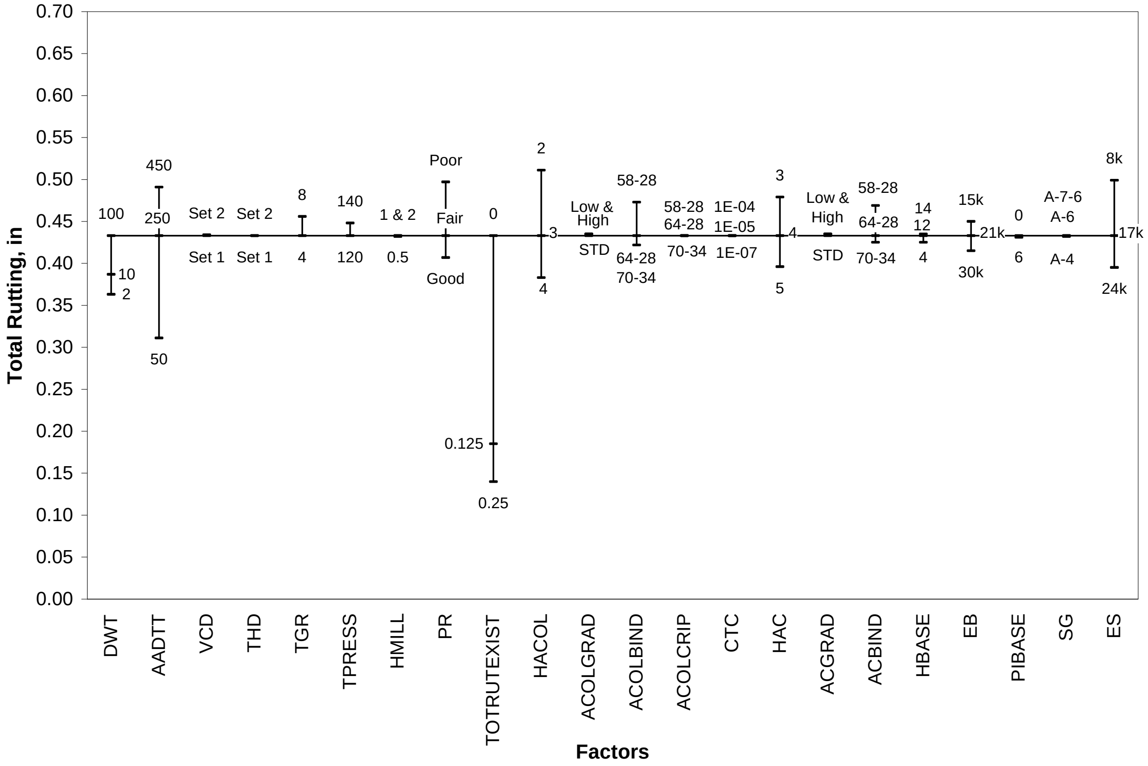

Figure C-43. Relative effect of variables on total rutting for ACOL on AC design (Location = Winner).

on the total rutting model are PR and HAC. Finally, the ACBIND, ACGRAD, and HMILL variables were observed to have very little impact on the total rutting model.

- **Effect of ACOL layer-related inputs—**A review of the summary charts indicates that HACOL is the only variable in this category with a marginal impact on the total rutting model. Another variable with a small impact on the model is binder type (i.e., ACOLBIND). The remaining ACOL layer-related variables (i.e., ACOLGRAD, ACOLCRIP, and CTC) showed virtually no impact on the total rutting model.
- **Effect of base layer-related inputs—**EB, HBASE, and PIBASE all showed a very small impact on the total rutting model. It is interesting to note that the total rutting trend was counterintuitive (i.e., total rutting increases as HBASE increases).
- **Effect of subgrade layer-related inputs—**A review of the subgrade-related variables finds that SG shows no effect on total rutting while ES shows a marginal effect. As expected, as ES decreases, the total rutting increases.

A subjective review of the ANOVA analysis results classifies TOTRUTEXIST, AADTT, and HACOL as *Highly Significant*, and ES, DWT, PR, HAC, CLIMATE, ACOLBIND, ACBIND, EB, TGR, and TPRESS as *Mildly Significant*. The complete ANOVA results are presented in table C-35.

Analysis of the IRI Model for ACOL on Existing AC Design

In the MEPDG approach, IRI (an indicator of smoothness) for ACOL on existing AC projects is predicted as a function of the initial as-constructed IRI and the predicted longitudinal cracking, alligator cracking, reflective cracking, AC layer rutting, and total rutting. The model also includes a site factor for adjusting to the local subgrade and climate. Therefore, the IRI model in this study was evaluated in terms of its correlation with the performance indicators. Although the visual IRI trends were assessed subjectively based on the same set of inputs as the other performance indicators, the statistical analysis included only performance indicators as variables to evaluate their contribution to the IRI prediction model.

Table C-35. ANOVA results for the ACOL on existing AC total rutting model.

Order No.	Factor Abbreviation	Factor Name	F	p-value	Model Significance (α=0.05)	Assessed Level of Significance
1	TOTRUTEXIST	Total rutting in existing AC	1236.72	0.000	Yes	Highly Significant
2	AADTT	Initial two-way average annual daily truck traffic	286.02	0.000	Yes	
3	HACOL	AC overlay thickness	134.41	0.000	Yes	
4	ES	Subgrade resilient modulus	90.36	0.000	Yes	Mildly Significant
5	DWT	Depth of water table	74.26	0.000	Yes	
6	PR	Pavement rating	73.63	0.000	Yes	
7	HAC	Existing AC layer thickness	58.43	0.000	Yes	
8	CLIMATE	Climatic characteristics (location)	33.99	0.000	Yes	
9	ACOLBIND	ACOL binder grade	25.00	0.000	Yes	
10	ACBIND	Existing AC binder grade	18.60	0.000	Yes	
11	EB	Base resilient modulus	14.71	0.000	Yes	
12	TGR	Traffic growth rate (%)	12.19	0.001	Yes	
13	TPRESS	Tire pressure	5.23	0.028	Yes	
14	HBASE	Base layer thickness	1.75	0.188	No	Not Significant
15	PIBASE	Base plasticity index	0.85	0.362	No	
16	ACGRAD	Existing AC mix gradation	0.10	0.907	No	
17	ACOLGRAD	ACOL mix gradation	0.10	0.907	No	
18	VCD	Vehicle class distribution factors	0.04	0.842	No	
19	ACOLCRIP	ACOL creep compliance	0.00	0.999	No	
20	CTC	AC coef. of thermal contraction	0.00	0.999	No	
21	HMILL	Milled thickness	0.00	0.998	No	
22	SG	Subgrade type	0.00	0.999	No	
23	THD	Truck hourly distribution factor	0.00	0.968	No	

Note: Shaded cells indicate those variables that were found to be insignificant.

Figures C-44 and C-45 show the relative effects of the detailed variable inputs on predicted IRI (Note that the IRI values plotted in these figures are the predicted values at the end of the 20-year analysis period). A comparison of these figures finds that although the predicted IRI for the standard design was different between the two climates (112 in/mile for Brookings and 115 in/mile for Winner), the overall difference between these two values is extremely small on the IRI scale.

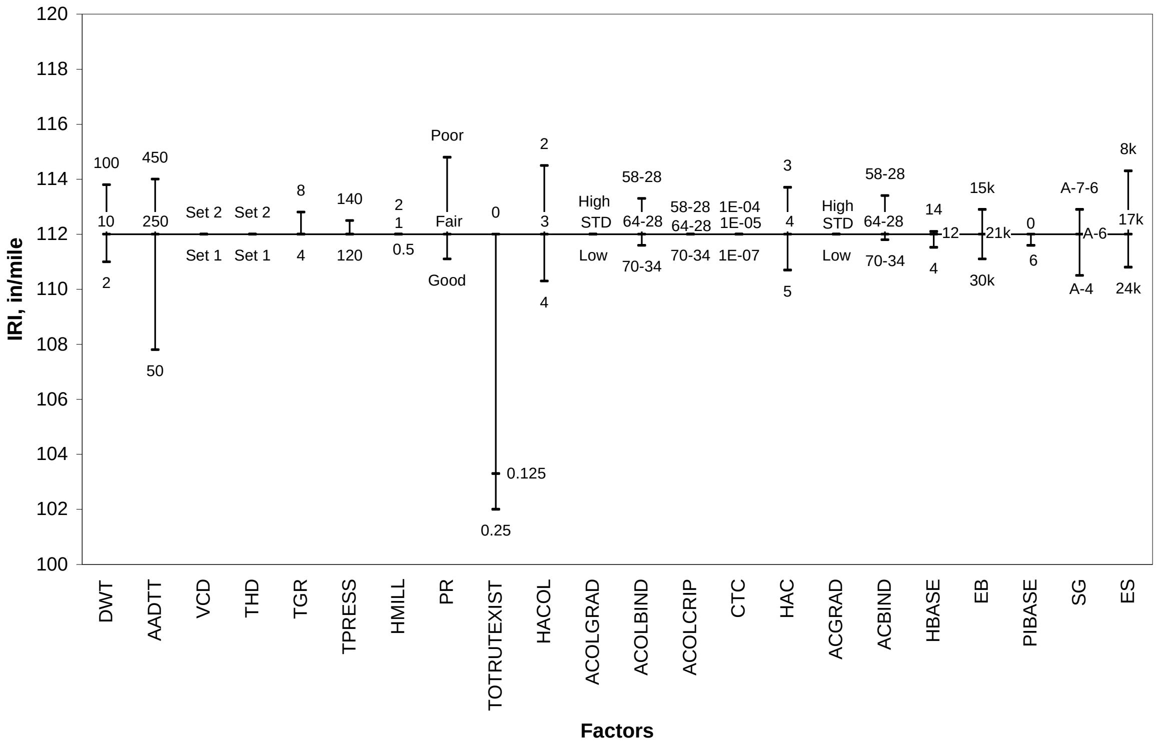

Figure C-44. Relative effect of variables on IRI for ACOL on AC design (Location = Brookings).

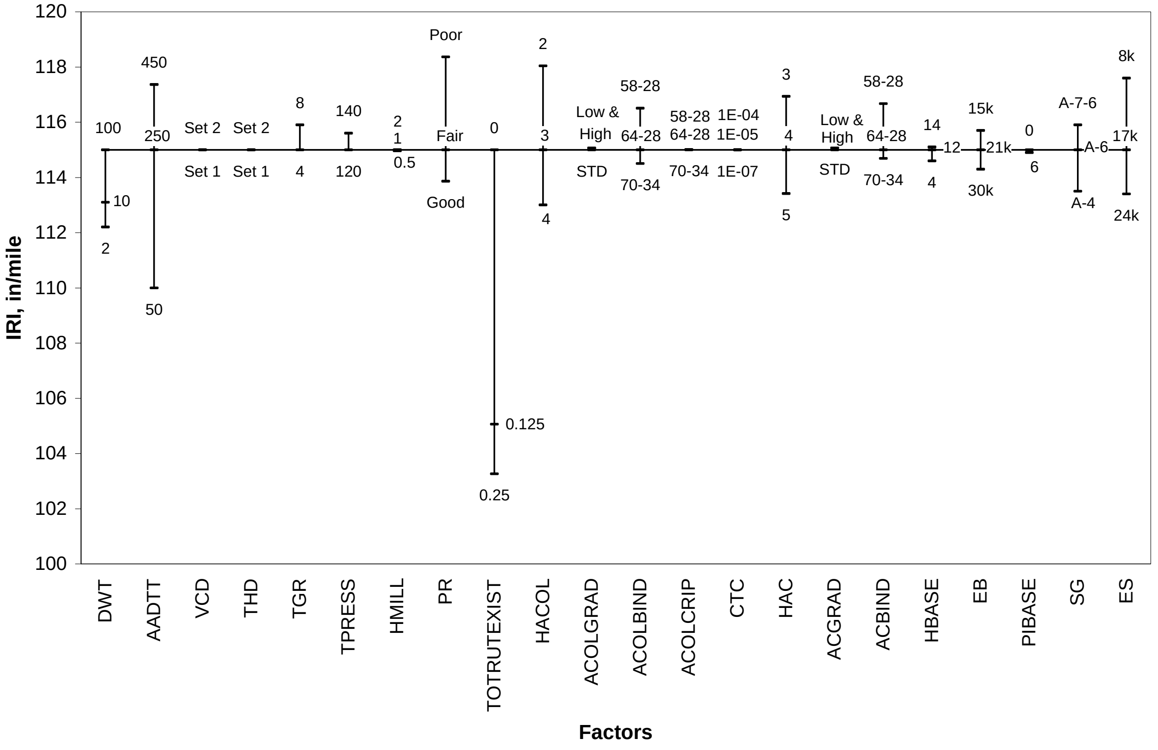

Figure C-45. Relative effect of variables on IRI for ACOL on AC design (Location = Winner).

A review of the F-test results for the ACOL on existing AC IRI model finds that only total rutting (TOTRUT) appears to have a significant F-ratio. A summary of the F-test results is presented in table C-36.

Table C-36. F-test results for the ACOL on existing AC IRI model.

Order No.	Factor Abbreviation	Factor Name	F	p-value	Model Significance (α=0.05)
1	TOTRUT	Total rutting	2382.9	0	Significant
2	ALLIGCRACK	Alligator cracking (bottom-up)	6.21	0.0149	Non-Significant
3	LONGCRACK	Longitudinal cracking (top-down)	0.03	0.8724	Non-Significant
4	ACRUT	AC layer rutting	0.02	0.8984	Non-Significant
5	REFCRACK	Reflective cracking	0	0.9788	Non-Significant

Note: shaded cells indicate those variables that were found to be insignificant.

Overall Assessment of Significant Variables for the ACOL on Existing AC Design

The predicted performance for ACOL on existing AC pavements was evaluated based on the total of 78 MEPDG software simulations. The sensitivity of the prediction models for those performance indicators to the change in design inputs was assessed by reviewing visual trends and conducting a statistical analysis of significance. The outcomes of the statistical analysis were used to *rank* the investigated model inputs from most significant to least significant in terms of how they influence the predicted performance of each individual performance model. Because the IRI model is dependent on the other performance indicator models, it is not considered in the overall ranking of significant variables. Also, because total rutting and AC layer rutting are correlated, only total rutting is considered in determining the overall rankings.

Table C-37 presents the input parameters found to be most significant for each performance indicator model. The parameters are placed in decreasing order of their significance for each investigated performance indicator. A ranking summary of each input parameter for the ACOL of existing AC design is also provided in table C-38. The ranking is based on the results of the analysis of variance for each performance indicator. Note that because the predicted values of longitudinal and alligator cracking were found to be relatively insignificant to overall performance, the reflective cracking and total rutting rankings control the overall ranking of variable significance for this design.

Table C-37. Summary of significance for ACOL on existing AC (rural design).

Performance Indicator	Input Parameter/Predictor
Top-down fatigue (longitudinal cracking)	• AC overlay binder grade • Annual average daily truck traffic • Base resilient modulus • Pavement rating of the existing AC pavement
Bottom-up fatigue (alligator cracking)	• Pavement rating of the existing AC pavement • Existing AC binder grade
Reflective cracking	• Pavement rating of the existing AC pavement • AC overlay thickness
Permanent deformation in AC layer (AC rutting)	• Annual average daily truck traffic • AC overlay thickness • Pavement rating of the existing AC pavement • Climate (location) • AC overlay binder grade • Total rutting in existing pavement
Total permanent deformation (total rutting)	• Total rutting in existing AC pavement • Annual average daily truck traffic • AC overlay thickness
Smoothness (IRI)	• Total permanent deformation (total rutting)

Table C-38. Ranking summary of significance of each input parameter on the performance indicator for ACOL on existing AC (rural design).

	Rankings for Individual Performance Indicators				
Input Parameter/Predictor	**Longitudinal Cracking**	**Alligator Cracking**	**Reflective Cracking**	**Total Rutting**	**Overall Order of Significance**
Pavement rating	4	1	1	6	1
Annual average daily truck traffic	2	5	5	2	2
Existing AC layer thickness	5	3	3	7	3
AC overlay thickness	10	4	2	3	4
Existing AC binder grade	11	2	6	10	5
AC overlay binder grade	1	9	11	9	6
Subgrade resilient modulus	6	13	8	4	7
Location (climate)	9	6	9	8	8
Base resilient modulus	3	12	7	11	9
Tire pressure	12	7	4	13	10
Traffic growth rate	7	8	10	12	11
Depth of water table	20	10	16	5	12
Base layer thickness	8	17	12	14	13
AC mix gradation	15	11	14	16	14
AC overlay mix gradation	14	15	15	17	15
Vehicle class distribution factors	13	23	13	18	16
Total rutting in existing AC layer	23	22	23	1	17
Base plasticity index	17	19	18	15	18
AC overlay creep compliance	18	14	19	19	19
Milled thickness	16	18	17	21	20
Coefficient of thermal contraction	19	16	20	20	21
Subgrade type	21	20	21	22	22
Truck hourly distribution	22	21	22	23	23

Note: Shaded cells indicate those variables that were found to be insignificant.

All conclusions about the importance and the order of significance of the inputs are valid for the given range of inputs provided by the SDDOT, and are based on local South Dakota conditions.

APPENDIX D: SUMMARY OF MEPDG HIERARCHICAL INPUT LEVELS

Introduction

This appendix summarizes the data requirements for MEPDG inputs at each MEPDG hierarchical input level (i.e., Level 1, Level 2, and Level 3). Note that all variables in an analysis do not have to be set to the same hierarchical input level. The input-related information presented in the remainder of this appendix is presented by input type category.

General MEPDG Inputs

Table D-1. Summary of input levels for climate-related variables (NCHRP 2004).

Heading in MEPDG Software	**Variable**	**LEVEL 1**	**LEVEL 2**	**LEVEL 3**
Climate	**Depth of Water Table (ft)**	Determined from profile characterization boring prior to design.	None	A potential source to obtain Level 3 estimates is the county soil reports.
	Climatic Data	Hierarchical levels not appropriate here. Generate new climate data file by selecting climatic data for a specific weather station or interpolating climatic data between weather stations. Data needed includes hourly air temperature, hourly precipitation, hourly wind speed, hourly percentage sunshine, and hourly relative humidity (a minimum of 24 months of data is needed).		

Note: Shaded cells indicate levels not currently supported by the MEPDG software or Guide.

Table D-2. Summary of input levels for traffic-related variables (NCHRP 2004).

Heading in MEPDG Software	Variable	LEVEL 1	LEVEL 2	LEVEL 3
Traffic	**Initial Two-Way AADTT**	Estimated from site-specific WIM, AVC, vehicle count data or site calibrated traffic forecasting and trip generation models.	Estimated from regional/statewide WIM, AVC, or vehicle count data or from regional traffic forecasting and trip generation models.	Estimated from AADT obtained from traffic count data and estimates of percent trucks, or local experience.
	Number of Lanes in Design Direction	Hierarchical levels are not appropriate for this design variable.		
	Percent Trucks in Design Direction	Site-specific values determined from WIM, AVC, and vehicle count data.	Regional/statewide values from WIM, AVC, and vehicle count data.	National average value or an estimate based on local experience.
	Percent Trucks in Design Lane	Site-specific values determined from WIM, AVC, and vehicle count data.	Regional/statewide lane distribution factors determined from WIM, AVC, and vehicle count data.	National average value, an estimate obtained from traffic forecasting and trip generation models, or based on local experience.
	Operational speed	Hierarchical levels are not appropriate for this design variable.		
Traffic Volume Adjustment Factors	**Monthly Adjustment Factors (MAF)**	Site- or segment-specific MAFs for each vehicle class computed from WIM, AVC, and vehicle count data or trip generation models.	Regional/statewide MAFs for each vehicle class computed from WIM, AVC, or vehicle count data or trip generation models.	MAFs determined from national data or local experience.
	Vehicle Class Distribution	Data obtained from site- or segment-specific WIM, AVC, or vehicle counts.	Data from regional/statewide WIM, AVC, or vehicle counts.	Distribution factors determined from national data or local experience.
	Truck Hourly Distribution Factors	Site-specific hourly distribution factors determined from WIM, AVC, and vehicle count data.	Regional/statewide distribution factors determined from WIM, AVC, and vehicle count data.	Distribution factors determined from national data or local experience.
	Traffic Growth Factors	Site-specific traffic growth factor information.	Regional/statewide traffic growth factor information.	Values based on national data or local information.
Axle Load Distribution Factors	**Axle Factors by Axle Type**	Axle load distribution factors based on an analysis of site- or segment-specific WIM data.	Axle load distribution factors based on an analysis of regional/statewide WIM data.	Default axle load distribution factors computed from a national database such as LTPP.
General Traffic Inputs	**Mean Wheel Location**	Determined through direct measurement on site-specific segments (not applicable to new alignments).	Regional/statewide averages determined from measurements on roadways with similar traffic characteristics and site conditions.	National average value or estimates based on local experience.
	Traffic Wander Standard Deviation	Determined through direct measurement on site-specific segments (not applicable to new alignments).	Regional/statewide averages determined from measurements on roadways with similar traffic characteristics and site conditions.	National average value or estimates based on local experience.
	Design Lane Width	Hierarchical levels are not appropriate for this design variable.		
	Number of Axle Types per Truck Class	Values determined through direct analysis of site-specific traffic data (AVC, WIM, or traffic counts).	Values determined through direct analysis of regional/statewide traffic data (AVC, WIM, or traffic counts).	Default values based on analysis of national databases such as the LTPP databases.
	Axle Configuration	Hierarchical levels are not appropriate for these inputs which include *average axle width*, *dual tire spacing*, *tire pressure*, and *axle spacings* for Tandem, Tridem, and Quad axles. These data elements can be obtained directly from manufacturers' databases or measured directly in the field.		
	Wheelbase	Hierarchical levels are not appropriate for these inputs. These inputs include *average axle spacing* and *percent trucks* associated with short, medium, and long axle spacings. Note that this wheelbase information is needed for the JPCP top-down cracking model and is applicable to only truck tractors (Class 8 and above). These data elements can be obtained directly from manufacturers' databases or measured directly in the field.		

HMA Layer-Related MEPDG Inputs

Table D-3. Summary of input levels for HMA material-related variables for NEW HMA layers (NCHRP 2004).

Heading in MEPDG Software	Variable	LEVEL 1	LEVEL 2	LEVEL 3
General	**HMA Layer Thickness**	Hierarchical levels are not appropriate for this design variable.		
Structure	**Surface Shortwave Absorptivity**	Laboratory testing; however, there are currently no AASHTO standards for measuring this variable.	Correlations are not available. Use Level 3 default values.	Use default values in guide. 0.8 to 0.9 for weathered asphalt (gray); 0.9 to 0.98 for fresh asphalt (black).
Asphalt Mix	**Dynamic Modulus or Gradation Data**	Enter dynamic modulus (E*) frequency sweep test data for a minimum of five temperatures and four frequencies (NCHRP 1-28A). This data is used to develop master stiffness curves.	Aggregate gradation information (i.e., percent retained on 3/4”, 3/8”, and #4 sieves, and the percent passing #200).	
Asphalt Binder	**Binder Properties**	Option 1—Superpave binder test data. Measure Complex Shear Modulus (G*) and Phase Angle (δ) at different temperatures with a Dynamic Shear Rheometer (DSR) in accordance with AASHTO T 315. Mixture testing should be performed after Rolling Thin Film Oven Test (RTFO) aging in accordance with AASHTO R30. Option 2—Conventional binder test data. For this option, the binder may be characterized using conventional binder tests. This process involves measuring viscosities (AASHTO T 201, T 202, T 316 or ASTM D4402), penetration (AASHTO T 49), specific gravity (ASTM D70), and softening point (ASTM D36).		Select a Superpave binder grading, conventional viscosity grade, or conventional penetration grade. Software uses default viscosity-related parameters (A and VTS) associated with the chosen binder grade to define the temperature-viscosity relationship (i.e., no testing is required).
Asphalt General	**Reference Temperature**	Hierarchical levels are not appropriate for this input. A standard temperature of 70° F is typically used.		
	Volumetric Properties As Built	Hierarchical levels are not appropriate for these mix design inputs. Volumetric properties of the HMA are defined by entering the Effective Binder Content (%), Air Voids (%), and Total Unit Weight (pcf) for the chosen mix.		
	Poisson’s Ratio	For dense-graded HMA only, estimate from laboratory testing. Note: This method is currently not practical.	For dense-graded HMA, estimate from equations that are a function of E_{AC} at a particular temperature OR select from default value ranges. Select from default value ranges for open-graded mixes and cold-mix asphalt.	Use typical values included in Guide.
	Thermal Conductivity, K	Measure directly from laboratory testing (ASTM E 1952).	No correlations available. Use Level 3 default values.	Select value based on agency historical data or from typical values of 0.44 to 0.81 Btu/(ft)(hr)(°F).
	Heat Capacity, Q	Measure directly from laboratory testing (ASTM D 2766).	No correlations available. Use Level 3 default values.	Select value based on agency historical data or from typical values of 0.22 to 0.40 Btu/(lb)(°F).

Note: Shaded cells indicate levels not currently supported by the MEPDG software or Guide.

Table D-4. Summary of input levels for HMA creep compliance-related variables for HMA layers (NCHRP 2004).

Heading in MEPDG Software	**Variable**	**LEVEL 1**	**LEVEL 2**	**LEVEL 3**
Thermal Cracking	**Creep Compliance**	Laboratory test data for HMA creep compliance is required (AASHTO T322). Specifically, testing data for the combination of seven loading types and three temperatures (-1, 14, and 32 °F) are required.	Similar to Level 1, laboratory test data for HMA creep compliance is required (AASHTO T322), but only for the intermediate 14 °F temperature.	At Level 3, typical test values as recommended by the agency or recommended by the Design Guide can be used. The software Help shows suggested creep compliance values based on binder type.
	Tensile Strength	At Level 1 laboratory test data for HMA tensile strength at 14 °F is required. Testing should be done in accordance with AASHTO T322.	At Level 2, the tensile strength at 14 °F would be derived from correlations with other AC properties. The Guide states that "no correlations are recommended at this time."	At Level 3, typical test values as recommended by the agency or recommended by the Design Guide can be used. A table included in the MEPDG Software Help contains values suggested based on binder type.
	Coefficient of Thermal Contraction	Hierarchical levels are not appropriate for these mix design inputs. There are no AASHTO or ASTM standard tests for determining the coefficient of thermal contraction (CTC) of HMA materials. The Design Guide software computes CTC internally using the HMA volumetric properties such as VMA and the thermal contraction coefficient for the aggregates. Table 2.2.39 in the Guide contains thermal contraction coefficient values for different aggregate types.		

Note: Shaded cells indicate levels not currently supported by the MEPDG software or Guide.

Table D-5. Summary of input levels for HMA material-related variables for EXISTING HMA layers (NCHRP 2004; Loulizi, Flintsch, and McGhee 2006).

Heading in MEPDG Software	Variable	LEVEL 1	LEVEL 2	LEVEL 3
General	**Existing HMA Layer Thickness**	Hierarchical levels are not appropriate for this design input. Existing HMA layer thickness should be determined as accurately as possible through coring or another accepted method.		
Structure	**Flexible Rehabilitation**	A Level 1 pavement evaluation for rehabilitation requires the following: 1. Estimate damage in existing layers through materials testing and FWD testing. Note that the current software user interface does not support the entering of FWD results. 2. Trenching is used to determine the permanent rutting in each layer. Rutting data is entered for each layer in the "Structure" dialog box.	A Level 2 pavement evaluation for rehabilitation requires the following: 1. Estimate damage by entering the amount of observed fatigue cracking in the existing pavement. Fatigue cracking data is entered for the existing HMA layer as in the "Structure" dialog. 2. Rutting for each individual layer is estimated. Rutting data is entered for each layer in the "Structure" dialog box.	A Level 3 pavement evaluation for rehabilitation requires that a subjective "Pavement Rating" be selected. Available pavement rating choices are *Excellent*, *Good*, *Fair*, *Poor*, and *Very Poor*. Initial damage factors provided in the Guide are associated with these pavement ratings (see table on p. 3.6.43).
Asphalt Mix	**Dynamic Modulus or Gradation Data**	Obtain field cores to establish mix volumetric parameters (air voids, asphalt volume, gradation, and asphalt viscosity parameters) to determine undamaged master curve. The current MEPDG interface requires the same gradation for all three Levels (i.e., percent retained on 3/4", 3/8", and #4 sieves, and the percent passing #200). This gradation information is used in the estimation of a dynamic modulus for the existing HMA layer. Although Version 0.9 of the MEPDG software does not support the direct entering of FWD data for Level 1 or additional Mr testing for Level 2, the documentation defines the following methods for estimating asphalt dynamic modulus for rehabilitation design. Level 1 *1. Backcalculate average HMA modulus (E_f) from FWD testing.* *2. Extract cores to obtain HMA volumetric parameters.* *3. Develop undamaged-HMA dynamic modulus (E*) master curve using Witczak equation.* *4. Estimate damage, d_j as a function of E_f and predicted dynamic modulus (E*).* *5. Compute fitting parameter α' as function of d_j and fitting parameter α.* 6. *Determine field-damaged HMA master curve by using α' instead of α.* Level 2 *Same procedure used for Level 1, but no FWD testing. Some additional cores are extracted and subjected to resilient modulus (Mr) testing. Damage, dj, is then computed as a function of Mr rather than Ef. The field damaged master curve is generated using the steps 5 and 6 described in the Level 1 procedure.*		Use "typical estimates" of mix volumetric parameters (mix volumetric, gradation and binder type) to develop the undamaged master curve with aging for site layer. The current MEPDG interface requires the same gradation for all three levels (i.e., percent retained on 3/4", 3/8", and #4 sieves, and the percent passing #200). This gradation information is used in the estimation of a dynamic modulus for the existing HMA layer. For Level 3, no FWD or laboratory testing required. The undamaged HMA master curve is generated from typical mix parameters while damage is estimated from range of values associated with on pavement condition categories (i.e., Excellent, Good, Fair, Poor, and Very Poor).
Asphalt Binder	**Binder Properties**	Conduct coring and test those samples using one of the two options described under the Level 1 option for new HMA layers.		Select a Superpave binder grading, conventional viscosity grade, or conventional penetration grade that represents the in-place HMA material. Default viscosity-related parameters associated with the chosen binder grade are used to define the temperature-viscosity relationship. No testing is required.

Table D-5. Summary of input levels for HMA material-related variables for EXISTING HMA layers (NCHRP 2004; Loulizi, Flintsch, and McGhee 2006) (continued).

Heading in MEPDG Software	Variable	LEVEL 1	LEVEL 2	LEVEL 3
Asphalt General	**Reference Temperature**	Hierarchical levels not appropriate for this input. A standard temperature of 70° F is typically used.		
	Volumetric Properties As Built	Hierarchical levels are not appropriate for these mix-related inputs. Extract cores and conduct laboratory testing to determine volumetric properties of the HMA (i.e., Effective Binder Content, Air Voids, and Total Unit Weight) for the chosen mix.		
	Poisson's Ratio	For dense-graded HMA only, estimate from laboratory testing. Note: This method is currently not practical.	For dense-graded HMA, estimated from equations that are a function of E_{AC} at a particular temperature <u>OR</u> selected from default value ranges. Selected from default value ranges for open-graded mixes and cold-mix asphalt.	Typical values included in guide.
	Thermal Conductivity, K	Direct measurement from testing of core samples (ASTM E 1952).	No correlations available. Use Level 3 default values.	Select value based on agency historical data or from typical values of 0.44 to 0.81 Btu/(ft)(hr)(°F).
	Heat Capacity, Q	Direct measurement from testing of core samples (ASTM D 2766).	No correlations available. Use Level 3 default values.	Select value based on agency historical data or from typical values of 0.22 to 0.40 Btu/(lb)(°F).

Note: Shaded cells indicate levels not currently supported by the MEPDG software or Guide.

PCC Layer-Related MEPDG Inputs

Table D-6. Summary of input levels for PCC-related materials for new JPCP and CRCP layers (NCHRP 2004).

Heading in MEPDG Software	Variable	LEVEL 1	LEVEL 2	LEVEL 3
Structure	**Surface Shortwave Absorptivity**	Laboratory testing; however, there are currently no AASHTO-certified standards for measuring this variable.	Correlations are not available. Use Level 3 default values.	Use default values in guide. 0.7 to 0.9 for PCC pavements.
Thermal – General Properties	**PCC Thickness**	Hierarchical levels are not appropriate for this design input.		
	Unit weight	Estimate value from laboratory testing (AASHTO T121).	Not applicable.	User selected value from historical data or typical values in Guide (140 to 160 lb/ft^3)
	Poisson's ratio (μ)	Determined simultaneously with elastic modulus laboratory testing (ASTM C 469).	Not applicable. Correlations are not available.	Typical value ranges included in Guide.
Thermal – Thermal Properties	**Coefficient of Thermal Expansion**	Direct measurement from laboratory testing (AASHTO TP 60). This is the procedure used for the LTPP program and all of the sections used for calibration of this Guide.	Weighted average of the constituent coefficient of thermal expansion (i.e., aggregate and paste) values based on the relative volumes of the constituents (see table 2.2.38 in the Guide).	Historical averages. It is highly recommended that an agency test its typical PCC mixes containing a range of aggregate types and cement contents to obtain typical values.
	Thermal Conductivity	Estimate using laboratory testing in accordance with ASTM E 1952.		Reasonable values range from 1.0 to 1.5 with a typical value of 1.25 Btu/(ft)(hr)(°F).
	Heat Capacity of PCC	Estimate using laboratory testing in accordance with ASTM D 2766.		Reasonable values range from 0.2 to 0.28 with a typical value of 0.28 Btu/(lb)(°F).
Mix – General	**Cement Type**	Hierarchical levels are not appropriate for this design input.		
	Cementitious Material Content	Hierarchical levels are not appropriate for this design input.		
	Water/Cement Ratio	Hierarchical levels are not appropriate for this design input.		
	Aggregate Type	Hierarchical levels are not appropriate for this design input.		
	PCC Zero-Stress Temperature	PCC zero-stress temperature, Tz, is defined as the temperature (after placement and during the curing process) at which the PCC becomes sufficiently stiff that it develops stress if restrained. This value may be 1) computed by the software based on cement content and the mean monthly ambient temperature during construction, or 2) entered directly. It is recommended that Tz be computed by the software.		
Mix - Shrinkage	**Ultimate Shrinkage at 40% Relative Humidity**	Determined from lab testing; however, no methods are currently available to extrapolate short-term shrinkage to ultimate shrinkage values. Therefore, agencies are encouraged to measure short-term shrinkage strains in the laboratory to develop confidence in the ultimate shrinkage strains estimated using the Level 2 and 3 approaches (AASHTO T160).	At input Level 2, ultimate shrinkage can be estimated from a standard correlation based on PCC mix parameters (cement type, cement content, and water-cement ratio), 28-day PCC compressive strength, and curing conditions.	The Level 3 method is the same as the Level 2 method with the only difference being that agency typical values are used for water content and compressive strength from historical records instead of mixture specific values as required in Level 2.
	Reversible Shrinkage (% of ultimate shrink.)	At all input levels, unless more reliable information is available, a value to 50 percent is recommended. This value was used in calibrating the pavement performance models.		
	Time required to develop 50% ultimate shrinkage	At all input levels, unless more reliable information is available, a value of 35 days, as recommended by the ACI Committee 209. This value was used in calibrating the pavement performance models.		
	Curing Method	Hierarchical levels are not appropriate for this design input.		

Table D-6. Summary of input levels for PCC-related materials for new JPCP and CRCP layers (NCHRP 2004) (continued).

Heading in MEPDG Software	**Variable**	**LEVEL 1**	**LEVEL 2**	**LEVEL 3**
Strength	**PCC Strength**	At Level 1, test data for flexural strength (Mr) and modulus of elasticity (E) at 7, 14, 28, and 90 days are required. In addition, the user is required to enter an estimate of the long-term strength (for both E and Mr) in terms of a 20-year to 28-day strength ratio. A value of 1.2 is recommended for this ratio for both E and Mr. The E and Mr values are determined using tests conducted in accordance with ASTM C 469 and the ASTM C 78 (AASHTO T 97) standards respectively.	At Level 2, the user provides test data for concrete compressive strength (f'c) at 7, 14, 28, and 90 days. In addition, the user is required to enter an estimate of the long-term strength in terms of a 20-year to 28-day strength ratio. A value of 1.44 is recommended for this ratio for f'c. The compressive strength is determined using tests conducted in accordance with ASTM C 39.	At Level 3, the MEPDG software requires a 28-day strength (either determined for the specific mix or an agency default). The user may specify this strength as either a 28-day Mr or f'c value. In addition, the user has the option of allowing the software to compute E or enter an E value directly. These values may be determined using standard tests (i.e., ASTM C 469, ASTM C 78, and the ASTM C 39 for E, Mr, and f'c, respectively) of agency-specific or mix-specific defaults can be used.

Notes:

- Shaded cells indicate levels not currently supported by the MEPDG software or Guide.
- JPCP design features such as joint spacing, sealant type, dowel information, edge support conditions, PCC base-interface friction, and base erodibility index are not included in this table as they are all design inputs with no hierarchical levels.
- CRCP design features such as shoulder type, steel reinforcement information, and crack spacing model information are not included in this table as they are all design-related inputs with no hierarchical levels.

Unbound Layer-Related MEPDG Inputs

Table D-7. Summary of input levels for soils and unbound layers (NCHRP 2004).

Heading in MEPDG Software	Variable	LEVEL 1	LEVEL 2	LEVEL 3
General	**Unbound Material**	Hierarchical levels are not appropriate for this input. In the MEPDG, unbound materials are classified using standard AASHTO or unified soil classification (USC) definitions. The AASHTO classification system is described in the test standard AASHTO M 145 while the USC system is described in the test standard ASTM D2487.		
	Layer Thickness	Hierarchical levels are not appropriate for this design input.		
Strength Properties - General	**Poisson's Ratio (μ)**	Laboratory testing. Direct measurement of Poisson's Ratio for unbound materials is not recommended due to its low sensitivity on structural responses.	There are appropriate models and correlations that can be used to estimate Poisson's Ratio. However, they are not recommended in this design procedure. Designers can, however, adopt models and correlations based on local knowledge and experience.	For Level 3, typical values shown in table 2.2.52 in the Guide can be used. Poisson's ratio for unbound granular materials and subgrades typically ranges between 0.2 and 0.45.
	Coefficient of Lateral Pressure	Hierarchical levels are not appropriate for this input. The coefficient of lateral pressure, k_o, is the ratio of the lateral earth pressure to the vertical earth pressure. For unbound granular, subgrade, and bedrock materials the in-situ typical k_o ranges from 0.4 to 0.6. Material-specific ranges of k_o values are shown in table 2.2.53 in the Guide.		
Strength Properties - Material Property	**Resilient Modulus**	The Guide discusses a Level 1 methodology in which resilient modulus values are determined from cyclic triaxial tests (NCHRP 1-28). However, the current user interface does not support Level 1 inputs.	In the Level 2 methodology, the software computes resilient modulus values using a correlation to one of the following: • CBR. • R-value. • Layer coefficient. • Penetration from DCP. • PI and gradation (entered on ICM screen).	For Level 3, only a representative resilient modulus value is required at optimum moisture content. EICM is used to modify the representative value for the seasonal effect of climate. Users have the option of specifying that the representative resilient modulus value be used without modification for climate by EICM. The recommended default values based on national calibration are given in table 2.2.51 in the Guide.
ICM	**Gradation Information**	Hierarchical levels are not appropriate for this input. Gradation information is determined by conducting a sieve analysis in accordance with AASHTO test standard AASHTO T27.		
	Plasticity index (PI) and Liquid Limit	Laboratory testing is recommended to determine appropriate plasticity index (PI) and liquid limit (LL) values for the unbound material. The AASHTO test standards used for determining PI, LL, and PL are AASHTO T90 and AASHTO T89.		

Note: Shaded cells indicate levels not currently supported by the MEPDG software or Guide.

References

National Cooperative Highway Research Program (NCHRP). 2004. *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures*. Web documents at http://www.trb.org/mepdg/guide.htm. Transportation Research Board, Washington, DC.

Loulizi, A., G. Flintsch, and K. McGhee. 2006. *Determination of the In-Place Hot-Mix Asphalt Layer Modulus for Rehabilitation Projects Using a Mechanistic-Empirical Procedure*. Report No. FHWA/VTRC 07-CR1, Virginia Tech Transportation Institute, Blacksburg, VA.

APPENDIX E: SOUTH DAKOTA MEPDG IMPLEMENTATION PLAN

Introduction

The Mechanistic-Empirical Pavement Design Guide (MEPDG) is a new approach to pavement design that is currently being considered as a replacement for the 1993 AASHTO Guide. Under this new MEPDG approach, the principles of engineering mechanics are used to compute the internal material behaviors in a pavement structure (i.e., deflections, stresses, and strains) as it is subjected to predicted future traffic loadings and environmental conditions (e.g., moisture and temperature). Those predicted material behaviors are related to accumulated pavement damage through developed "transfer" functions, and then correlated with actual performance (distress) data. While this new approach to pavement design is a move in the right direction as the method is based on sound engineering principles, its adoption presents some new challenges for the South Dakota Department of Transportation (SDDOT).

Background

The development of the MEPDG and corresponding software began in 1996 when the American Association of State Highway and Transportation Officials (AASHTO) Joint Task Force on Pavements, the National Cooperative Highway Research Program (NCHRP), and the Federal Highway Administration (FHWA) co-sponsored research under NCHRP project 1-37A. The accumulation of this research reached its first milestones in 2004 with the completion of the Final Report in March 2004 and a beta version of the MEPDG software (version 0.7) in July 2004. Since the time of these initial submittals, improvements to the Guide and software have continued to be made under NCHRP Project 1-40, "Facilitating the Implementation of the Guide for Design of New and Rehabilitated Pavements." Under that project, the following significant tasks have either been completed or are ongoing:

- NCHRP 1-40, Task 3 (NCHRP 1-40A)—This task has the objective of conducting a thorough, independent review of the guide and software to objectively assess the material contained in the guide, identify deficiencies, and recommend corrective measures, including short-term research activities. A complete summary of the results of this independent review was published in September 2006 in NCHRP Research Results Digest 307 (NCHRP 2006).
- NCHRP 1-40, Task 4 (NCHRP 1-40B)—The objective of this task is to develop step-by-step procedures for use by state DOTs to refine the performance models in the Guide and software on the basis of local and regional conditions, materials, and practices. The

results of this task are being summarized into a final report titled "User Manual and Local Calibration Guide for the Mechanistic-Empirical Pavement Design Guide and Software." A final version of this document is expected to be released to the public in mid to late 2007.

- NCHRP 1-40, Task 6 (NCHRP 1-40D)—This task has the objective of refining and upgrading the design software on a continuing basis. Since the original release of version 0.7 of the software, the developers have solicited feedback and continued to make corrections and improvements to the MEPDG software under this contract. Specific software milestones include the release of version 0.8 in November 2005 and version 0.9 in July 2006. Version 1.0 is nearing completion and is expected to be released to the public in mid to late 2007.
- NCHRP 1-40, Task 8 (NCHRP 1-40J)—The objective of this ongoing task is to provide support for the Mechanistic Design Guide Lead States and related state DOT activities. The Lead States Group has a mission of promoting and facilitating the refinement, implementation, and evolution of the MEPDG in conjunction with AASHTO, NCHRP, and FHWA activities (VDOT 2007).

On April 10 and 11, 2007, a "MEPDG Roll Out Workshop" was held in Irvine, California. At this workshop, version 1.0 was introduced and specific inquiries among state participants were addressed by the development team. The workshop was structured as an outreach activity to familiarize practitioners in state highway agencies (SHAs) with the new software.

Because it appears that AASHTO will adopt the MEPDG in the near future, this implementation plan is focused on readying the SDDOT for this implementation process.

Implementation Plan Steps

The MEPDG Implementation Plan presented in this stand-alone document is provided as a "road map" that outlines the tasks that will need to be implemented by the SDDOT over the next 3 years to successfully implement the MEPDG. The basic implementation plan consists of 11 general steps, many of which will be completed concurrently. The 11 general implementation steps consist of:

1. Conduct sensitivity analysis of MEPDG inputs.
2. Recommend MEPDG input levels and required resources to obtain those inputs.

3. Obtain necessary testing equipment to implement the MEPDG at the target MEPDG input levels.
4. Review version 1.0 of the MEPDG software.
5. Form a SDDOT MEPDG Implementation Team and develop and implement a communication plan.
6. Conduct staff training.
7. Develop formal SDDOT-specific MEPDG-related documentation.
8. Develop and populate a central database(s) with required MEPDG input values.
9. Resolve differences between the MEPDG predicted distresses and those currently collected for the SDDOT pavement management system.
10. Calibrate and validate MEPDG performance prediction models to local conditions.
11. Define the long-term plan for adopting the MEPDG design procedure as the official SDDOT pavement design method.
12. Develop a design catalog.

In the preparation of this document, other available SHA-developed implementation plan documents were certainly not ignored (e.g., Iowa [Coree, Ceylan, and Harrington 2005], Texas [Uzan, Freeman, and Cleveland 2004], Indiana [Nantung et al. 2004], Minnesota [Khazanovich, Husain, and Yut 2006], Mississippi [Saeed and Hall 2003], Virginia [VDOT 2007], and so on). This document represents a combination of both new concepts and previously published ideas from the aforementioned published reports; however, the resulting information is customized to more closely address the current SDDOT needs. Each of these identified implementation steps is discussed in more detail below.

Step 1: Conduct Sensitivity Analysis of MEPDG Inputs

The new MEPDG has a large number of inputs (over 150) that need to be collected or assumed when conducting any analysis run. However, as with every model, some inputs have more of an impact on the answer than others. Therefore, one of the first questions any SHA needs to answer when evaluating the new MEPDG guide is, “What inputs have the most significant influence on the prediction of performance for my pavements?” To answer this question, a sensitivity analysis of the required inputs needs to be completed for each chosen pavement design. This sensitivity analysis has been completed for SDDOT (using version 0.9 of the software) by completing the following steps:

- Selecting the typical pavement design types to investigate.
- Determining the representative input ranges associated with the MEPDG inputs required by each typical design.
- Conducting a comprehensive sensitivity analysis of the inputs associated with the typical designs.
- Ranking the investigated inputs in order of most to least significance within each pavement design.

Those variables determined to have the largest impact on the predicted distress output are the variables for which SDDOT should be focusing on obtaining the most accurate input values as possible. Obtaining more accurate values for any input will require greater resources, whether it is new or improved testing equipment, increased training and outreach, and/or more personnel.

Step 2: Recommend MEPDG Input Levels and Required Resources to Obtain Those Inputs

After determining what variables are the most influential on the predicted distresses, the next tasks involve completing a series of steps that ultimately determine what resources are expected to be required to implement the MEPDG with the recommended input levels. Specifically, the completion of this goal requires the completion of the following tasks:

- Determine recommended MEPDG input levels for each input associated with the typical designs—This decision is based on assessing how significant each individual input is to the predicted output.
- Assessment of gaps between the current SDDOT data and testing/sampling protocols, and the required data and testing under for the recommended MEPDG input levels—After selecting the recommended input levels, the current SDDOT testing methods or data sources must be assessed to determine where data required for the recommended input levels might not be available (i.e., gaps between the required and available data).
- Assessment of SDDOT data sources or new sampling/testing procedures required to close these identified data and sampling/testing protocols gaps—To fill in the identified gaps in the required data, new data-collection or sampling/testing techniques could be deemed necessary. These required databases or processes are identified under this task.

- Identification of required SDDOT resources to move from current practices to the new recommended MEPDG input levels—The final step of this process is to estimate any new resources (i.e., personnel, equipment, IT department support, etc.) required to obtain all of the MEPDG inputs at their recommended input levels.

These tasks were accomplished under Tasks 4 and 5 of the current project.

Step 3: Obtain necessary testing equipment to implement the MEPDG at the target MEPDG input levels.

In Task 6 of the current project, the SDDOT sampling and testing procedures were reviewed to determine what additional sampling and testing equipment would be needed to implement the MEPDG at the "target" input levels. Because the "target" MEPDG input levels were carefully selected based on the significance of each input to the predicted distresses, under this step of the implementation plan it is recommended that the SDDOT focus on obtaining all sampling and testing equipment necessary for implementing the MEPDG at these target input levels. While the SDDOT currently owns most of the necessary sampling and testing equipment to accomplish this task, it has been identified that the SDDOT needs to purchase three additional pieces of equipment to be able to conduct all of the currently recommended MEPDG sampling and testing in-house. Table E-1 presents a summary of these three additional pieces of equipment, the MEPDG inputs that they are associated with, and estimates of their costs.

Step 4: Review Version 1.0 of the MEPDG Software

Because this research was conducted using a beta version of the MEPDG software (version 0.9), this step of the implementation process should review version 1.0 of the software to determine any user interface or input changes that might affect the initial results or input-related recommendations made under this contract.

Special attention should also be focused on documented model changes or updates between version 0.9 and 1.0. If it is documented that specific prediction models have changed significantly between versions 0.9 and 1.0, that could warrant rerunning sensitivity runs for those designs affected by the changes. One specific area of concern is associated with the asphalt-related designs, as they include the thermal cracking model. As documented in the body of the main report for this current exploratory project, the thermal cracking model results predicted

Table E-1. Recommended sampling and testing equipment for purchase in order to implement the MEPDG at the selected SDDOT "target" input levels.

Input Parameter	Design Type	Target Level	Test Description	Estimated Cost
PCC coefficient of thermal expansion	JPCP, CRCP	1	COTE testing is conducted on prepared PCC cylinders. All specimen preparation and testing should be conducted in accordance with AASHTO TP60. Specifically, the standard features of a COTE test set-up include the following: • Concrete saw for creating specimens. • Balance with capacity of 44 lbs and accuracy of 0.1%. • Caliper or other device to measure specimen length to nearest 0.004 in. • Water bath with temperature range of 50 to 122 °F, capable of controlling temperature to 0.2 °F. • Support frame that has minimal influence on length change measurements. • Temperature measuring devices with resolution of 0.2 °F and accurate to 0.4 °F. • Submersible LVDT gauge with minimum resolution of 0.00001 in and typical measuring range of ± 0.1 in. • Micrometer or other calibration device for LVDT with minimum resolution of 0.00001 in.	Approximately $15,000.
New AC or ACOL mix properties	New AC, AC/AC, AC/JPCP	1	For Level 1 designs, Dynamic Modulus (E*) testing is required. AASHTO TP62 requires the use of the Simple Performance Tester (SPT). To conduct these tests in-house, SDDOT will need to obtain the SPT equipment and a Superpave Gyratory Compactor required to prepare samples for SPT testing. Note: The Superpave Gyratory Compactor must be capable of compacting samples that are 170 mm in height.	The cost of the SPT is approximately $40,000 to $50,000. The cost of the Superpave Gyratory Compactor is approximately $25,000.

using version 0.9 were not included in the analysis as an inconsistency in the results was discovered when runs were conducted on computers with different operating systems. For those runs using the most modern Windows operating system, the transverse cracking values were typically predicted to be "0." Those same runs completed using computers with Windows 2000 operating systems exhibited nonzero thermal cracking values. Therefore, it is recommended that spot checking of the previously conducted sensitivity analysis results (i.e., with version 0.9) be conducted to assess the model output differences between versions 0.9 and 1.0 of the software. If significant changes between the model outputs do exist, steps 1 and 2 of this implementation should be repeated using version 1.0 of the software.

Step 5: Form a SDDOT MEPDG Implementation Team and Develop and Implement a Communication Plan

During the implementation effort, the most important goal is to maintain good communication among all personnel involved. As a means to this end, it is first recommended that the SDDOT establish a more formal SDDOT *MEPDG Implementation Team* that consists of both an overseeing *Steering Committee* to guide and monitor the progress of the implementation effort, and a *Technical Committee* in charge of executing the implementation plan. While it is recommended that the Steering Committee have one representative each from FHWA, the PCC industry, and the HMA industry, it is envisioned that the Technical Committee will be made up entirely of SDDOT personnel. It is recommended that the Technical Committee have an individual champion for each of the following MEPDG-related categories:

- Traffic.
- PCC-related materials characterization, sampling, and testing.
- HMA-related materials characterization, sampling, and testing.
- Unbound materials (base and subgrade) materials characterization, sampling, and testing.
- Environmental data.
- Rehabilitation design.
- Performance model calibration and validation.
- Training.

With the MEPDG Implementation Team in place, as a minimum, the following action items are recommended for the team:

- Determine a flow chart of MEPDG responsibilities within the SDDOT.
- Determine an approach and associated schedule for completing all of the additional recommended implementation steps.
- Determine an approach to deliver any necessary training to all personnel chosen to be involved with the MEPDG implementation or future use of the MEPDG.
- Hold bi-annual meetings to discuss all MEPDG-related activities and progress.

Step 6: Conduct Staff Training

Because the MEPDG design approach is vastly different from that used in the 1993 AASHTO design guide, it is imperative that all personnel involved in the implementation process be well trained on the background, usage, and data-collection efforts required by the MEPDG. When outlining a training approach, much can be learned from the previously published staff training plans (e.g., Texas [Uzan, Freeman, and Cleveland 2004], Iowa [Coree, Ceylan, and Harrington 2005], Indiana [Nantung et al. 2004]). While it is expected that the detailed training approaches will be determined by the SDDOT MEPDG Implementation Team, it is anticipated that the following two-tiered approach (similar to that recommended for the Texas Department of Transportation implementation) will best work in SDDOT (Uzan, Freeman, and Cleveland 2004):

1. <u>Training for the SDDOT MEPDG Implementation Team</u>—Where required, the first task should be to provide any necessary training for all members of the SDDOT MEPDG Implementation Team. It is recommended that any training deemed necessary be completed within 6 months after the appointment of members to the SDDOT MEPDG Implementation Team. The FHWA Design Guide Implementation Team (DGIT) has developed a number of training activities for state personnel, which include traditional workshops, as well as technology-enhanced training, such as web-available teleconferences. The National Highway Institute (NHI) also offers the following series of MEPDG-related training courses:
    - NHI #131109—"Analysis of New and Rehabilitated Pavement Performance with Mechanistic-Empirical Pavement Design Software" (Under Development - Pilot: Spring 2007).
    - NHI #131064—"Introduction to Mechanistic Design."
    - NHI #132040—"Geotechnical Aspects of Pavements."
    - NHI #151018—"Application of the Traffic Monitoring Guide."
2. <u>Training of all pavement engineers</u>—Within the first year after the formation of the MEPDG Implementation Team, it is recommended that the training focus switch to the Pavement Engineers who will be involved with all aspects of using the MEPDG. This training is expected to focus more on the operation of the software and the development

of inputs for the analysis. This training could consist of using the aforementioned available FHWA or NHI resources, or in-house training seminars conducted by members of the SDDOT MEPDG Implementation Team.

3. <u>Training of laboratory personnel</u>—Because a number of the recommended input levels require new laboratory testing equipment and protocols, laboratory staff will most likely require training (external or in-house) to learn the new testing procedures. The timing of this training will depend on when/if new equipment or testing procedures are adopted.
4. <u>Training of support personnel in other departments</u>—Because the collection of inputs for the MEPDG will impact many different departments in the SDDOT (i.e., materials, traffic, design, pavement management [PMS], information technology [IT], and so on) it could be beneficial to conduct simplified training sessions for personnel who might be considered to be on the "fringe" of the process. As an example, this could include the IT or pavement management staff. While the personnel in these departments won't be responsible for using the MEPDG, they will be asked to provide MEPDG-related data for either using or calibrating the MDPDG. In order to facilitate buy-in from all departments, it is recommended that in-house training for these personnel be conducted.
5. <u>External personnel who interact with or conduct business with the SDDOT</u>—Other published MEPDG implementation plans (e.g., Iowa, Indiana, and Texas) mention not limiting the training activities to DOT employees (Coree, Ceylan, and Harrington 2005; Nantung et al. 2004; Uzan, Freeman, and Cleveland 2004). Taking that approach, to facilitate buy-in of any design method changes being implemented by SDDOT, the SDDOT MEPDG Implementation Team should develop a strategy for conducing MEPDG training seminars for all non-SDDOT personnel that will be impacted by the implementation of the MEPDG. Participants in this training would most likely consist of consultants, contractors, county and city personnel, academia from local universities, and personnel from other impacted agencies (e.g., local FHWA officials, local industry representatives, etc.)

<u>Step 7: Develop Formal SDDOT-Specific MEPDG-Related Documentation</u>

Due to the complexity of the MEPDG process, the large number of data inputs required to complete an analysis, and the fact that the process is designed to be customized for a given agency, it is recommended that SDDOT develop some formal MEPDG-related documentation to facilitate the use and calibration of the MEPDG. Specifically, it is envisioned that SDDOT would benefit from the development of:

- <u>MEPDG Pavement Design Procedural Manual</u>—Because the process of determining a pavement design with the MEPDG is vastly different from using the 1993 AASHTO method, it is recommended that the SDDOT develop a MEPDG Pavement Design Procedural Manual. Such a manual would focus on outlining a step-by-step procedure a pavement engineer could easily follow to complete a pavement design with the MEPDG. It is envisioned that as a minimum, this document would include all of the detailed steps to follow when conducting a design, including:

    - Identifying the best climatic data for the given location.
    - Selecting the appropriate input levels and values. (This information would include many types of information, including which inputs are fixed, what levels to use for each input [when applicable], the sources to use to find the needed inputs, etc.)
    - Choosing layer thicknesses for the initial pavement structure trial (i.e., trial 1).
    - Comparing the performance results from trial 1 to the chosen acceptable performance levels and adjusting the layer thicknesses if necessary.
    - Conducting additional iterations with the software until a structural design is obtained that meets selected performance needs.
    - Conducting design optimization procedures (if developed) that take into account tradeoffs between different design features (e.g., slab thickness, base type, and dowel diameter for PCC pavements) and cost. The goal of this step would be to find the optimal combination of design features that maximizes performance while minimizing costs.

    Although the process for determining rehabilitation designs is similar to the procedure for determining new pavement designs, one main difference is the process that is used to assess the existing pavement. Because it is envisioned that falling weight deflectometer (FWD) testing data will eventually become the main focus in the assessment of an existing pavement's condition, the MEPDG Pavement Design Procedural Manual should define the specific testing procedures and protocols associated with assessing the condition of an existing pavement section.

- MEPDG Material Characterization Guidelines—Because the implementation of the MEPDG will most likely require a number of changes to the current material sampling and testing methods, it is recommended that separate MEPDG Material Characterization Guidelines be developed to outline how each material type is to be characterized for use as an input in the MEPDG process. As a minimum, these guidelines would document 1) the different acceptable MEPDG input levels associated with each material-related input; 2) the recommended MEPDG input level for each input; 3) the MEPDG level-specific laboratory- and field-testing protocols (if applicable), and 4) acceptable default values for some inputs. Such a document will not only be very helpful for the staff tasked with conducting the testing for the current MEPDG levels, but it will also clearly document the methods that would be required should the recommended level be changed.

Step 8: Develop and Populate a Central Database(s) with Required MEPDG Input Values

Because of the large number of inputs required by the MEPDG, it is recommended that a centralized database (or databases) be developed to facilitate the collection of the inputs during the design process. Any input that is determined to not be project-specific is a good candidate for storage in a central database. The following are some ideas for data types that are deemed good candidates for storage in a centralized location:

- Depth to water table (DWT)—Because of the uncertainty with depth to water table, it is recommended that default values be determined for this value. If DWT data are easily available from other existing records (e.g., geological survey data), then one idea would be able to pull all of that available data into a central database by larger logical borders (e.g., by county if applicable). Alternatively, perhaps all of the data could be plotted on a map, and visual interpolation could be used when selecting values for design runs.
- Traffic data—Based on the results of the sensitivity analysis, a number of traffic variables were found to have little significance on the predicted performance in both climatic locations tested. Any default values that are determined to be associated with a logical group (e.g., functional classes, locations within the state, etc.) could be stored in a central database.

- Default material property database—It is currently envisioned that default material properties associated with the typical paving materials (e.g., the granular base materials) will initially be used in the MEPDG. Based on this assumption, a central database of typical material properties is useful to store these default values. This database will include information about the typical material properties used around the state.
- Typical design inputs—Similar to the other inputs discussed above, typical values for any other inputs required by typical designs would also be good candidates for storage in a central location.

Step 9: Resolve Differences Between the MEPDG Predicted Distresses and Those Currently Collected for the SDDOT Pavement Management System

The calibration of the models incorporated into the MEPDG software requires the use of comparable pavement performance data for each distress type. Because the SDDOT PMS system is the most logical source for data to calibrate the MEPDG models, any discrepancies between the current PMS data and the required distress data for the MEPDG must be resolved before going forward. Therefore, one of the steps of the implementation process is to review the distress definitions and measurement protocols associated with both the MEPDG models and the current SDDOT PMS, and develop a plan for resolving any differences between the two.

The first step in this process involves matching the MEPDG distress types with the distress currently collected as part of SDDOT’s pavement management activities. The general differences between the included distress types for both flexible and rigid pavement types are presented in table E-2.

A comparison of the distress data in table E-2 shows the SDDOT pavement condition survey procedures include the majority of distress types incorporated into the MEPDG models. Notable exceptions where the distress measurement protocols differ include the measurement of fatigue cracking and rutting on flexible pavements, and the lack of measurement of transverse cracking on rigid pavements. Each of these discrepancies is discussed in more detail below.

Table E-2. Distress type comparison (FHWA 2003; SDDOT 2005).

MEPDG Distress Type	SDDOT Pavement Management Distress Type	Comments
Flexible Pavement Distress		
Fatigue Cracking (top-down and bottom-up)	Fatigue Cracking (assumed to be bottom-up)	No differentiation for top-down fatigue cracking in the current SDDOT measurement protocols; however, the identification of top-down cracking requires coring which is not practical on a network level.
Thermal Cracking	Transverse Cracking	Comparable, but SDDOT-measured transverse cracking may not be limited to thermal cracking
Permanent Deformation (rutting in AC layer and total rutting)	Rutting (total rutting)	SDDOT measurements are comparable to the MEPDG total rutting model. SDDOT does not currently measure AC layer rutting; however, this measurement is not practical on a network level.
IRI	IRI	Comparable
Rigid Pavement Distress		
Faulting	Faulting	Comparable
Transverse Cracking	No equivalent distress measurement	Not currently collected by SDDOT
Punchouts (CRCP only)	Punchouts	Comparable
IRI	IRI	Comparable

For fatigue cracking on flexible pavements, the MEPDG has separate models for top-down and bottom-up cracking that are not differentiated in the SDDOT pavement condition surveys. In the SDDOT procedure, fatigue cracking is representative of any longitudinal cracking in the wheel path. Because there is no easy way to determine if a longitudinal crack is a top-down crack (i.e., without coring), it is currently recommended that the SDDOT-measured fatigue cracking data be used to calibrate the MEPDG bottom-up fatigue cracking model only. It is also recommended that the MEPDG default top-down fatigue cracking model be used without calibration; however, the results of the top-down fatigue cracking model should be carefully monitored to judge the model's reasonableness. By taking this approach, no changes to the SDDOT flexible pavement fatigue cracking measurement protocols are deemed necessary.

For rutting on flexible pavements, the MEPDG has separate models for AC layer rutting and total rutting. Because there is no easy way to determine AC layer rutting (i.e., without coring), it is currently recommended that the SDDOT-measured rutting data be used to calibrate the MEPDG total rutting model only. It is also recommended that the MEPDG default AC layer rutting model be used without calibration; however, the results of this model should be carefully monitored to judge the model's reasonableness. By taking this approach, no changes to the SDDOT rutting measurement protocols are deemed necessary at this time.

For rigid pavements, while the MEPDG includes a transverse cracking model, the SDDOT does not currently measure this distress. However, because the transverse cracking model in the MEPDG approach is an important indicator of the pavement's structural condition, it is recommended that this model be calibrated with actual SDDOT data. If the SDDOT wants to use the pavement management data as the primary source for calibrating all included MEPDG models, it is recommended that the SDDOT consider changing the current PMS data collection protocols to include the measurement of transverse cracking on rigid pavements.

The second step in evaluating the appropriateness of the distress data for use in calibrating the MEPDG models is comparing the definitions used to define distress severity and extent. An initial comparison of the MEPDG and current SDDOT PMS distress measurement protocols does find some differences in the definitions used to describe distress severity and extent. While differences in the definitions of medium- and high-severity levels are not expected to be significant (because the MEPDG models combine all severity levels), the calibration process could be affected if there is a difference in how a low-severity distress is defined. That is, if there is a significant difference in the protocols, one protocol might identify an occurrence of a distress as being low severity, while another protocol might not yet classify that occurrence as a distress. Such a difference in protocols could have a significant impact on the amount of identified distress at any given time, and therefore, could cause difficulty during the calibration steps.

In this step of the implementation process, it is recommended that the differences between the MEPDG and SDDOT PMS distress types and measurement protocols be investigated in more detail. While some preliminary data collection-related recommendations were made under the current project, the goal of this step of the implementation plan will be to review those recommendations, and compile a final list of detailed recommendations for resolving any discrepancies between the distress types and measurement protocols used by the MEPDG and SDDOT PMS. The most likely solution options from this study are to 1) alter the PMS measured distress types or measurement procedures to better match those used in the MEPDG, or 2) continue to collect PMS data using current protocols and use the uncalibrated results for those

MEPDG models not currently supported by SDDOT procedures (e.g., transverse cracking for rigid pavements), or 3) ignore the use of selective MEPDG model results all together. As part of this implementation step, it is also recommended that the SDDOT MEPDG Implementation Team develop and adopt documentation that outlines the future role of PMS data in the calibration of MEPDG models.

Step 10: Calibrate and Validate MEPDG Performance Prediction Models to Local Conditions

One of the most important steps in the implementation plan is the calibration and validation of the MEPDG performance prediction models to South Dakota conditions. The term *calibration* refers to the mathematical process through which the total error or difference between observed and predicted values of distress is minimized (NCHRP 2003b). The term *validation* refers to the process to confirm that the calibrated model can produce robust and accurate predictions for cases other than those used for model calibration (NCHRP 2003b). Currently, the recommended method for calibrating and validating MEPDG performance models is the *split-sample jackknifing* approach as outlined in NCHRP Project 9-30 "Experimental Plan for Calibration and Validation of HMA Performance Models for Mix and Structural Design."

The split-sample jackknifing approach (a combination of the separate jackknifing and split-sample validation methods) is a statistical method that uses a single database to both calibrate and validate a given model. This is an important concept in the calibration and validation of pavement performance prediction models because actual distress data are expensive and time consuming to collect (NCHRP 2003b). More detailed information on the use of the split-sample jackknifing approach is available in two NCHRP Research Results Digests (NCHRP 2003a; NCHRP 2003b). More specific guidance on using these recommended calibration and validation procedures is expected to be outlined in the soon-to-be published "Local Calibration Guidance for the Recommended Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures" (NCHRP 1-40B).

Step 11: Define the Long-Term Plan for Adopting the MEPDG Design Procedure as the Official SDDOT Pavement Design Method

In order for the MEPDG to get to the point where the MEPDG procedure is fully accepted as the official design procedure, much experience with the calibrated/validated models must be obtained. After the MEPDG procedure is recognized by AASHTO as the official pavement design procedure, it is recommended that SDDOT begin evaluating the accuracy and consistency of the MEPDG output. Throughout this 3-year period, it is recommended that an MEPDG analysis be conducted alongside every pavement design conducted using the currently accepted pavement design procedure (i.e., the 1993 AASHTO guide). The primary goal of this exercise is to produce and review expected performance data for given pavement designs, with the ultimate goal of gaining confidence in the MEPDG predicted performance. All selected MEPDG inputs and collected performance data should be recorded and stored so it can be used in future calibration and validation efforts. The final decision to officially adopt the MEPDG design procedure as SDDOT's official pavement design procedure rests with the MEPDG Implementation Team. Such a decision should not be made until the MEPDG Implementation Team members have great confidence that the calibrated and validated MEPDG performance models are predicting distress values that are reasonable and considered to be acceptably accurate for South Dakota conditions.

Step 12: Develop a Design Catalog

Once the SDDOT MEPDG Implementation Team has gained considerable confidence that the calibrated MEPDG models are predicting reasonable performance for South Dakota conditions, it is recommended that SDDOT begin investigating the preparation of a *design catalog*. The concept of the design catalog is to simulate and document the results of many hypothetical pavement design situations in South Dakota. For example, in the development of such a catalog, MEPDG runs representing different combinations of site conditions (climate, traffic, and subgrade) and design features (layer thickness, slab geometry, dowel diameter, and so on) would be conducted ahead of time. Based on selected performance limits (e.g., 15 percent of fatigue cracking and 0.2 in of rutting), an expected pavement life would be computed for each hypothetical design. By compiling results associated with enough combinations of typical design inputs, it is envisioned that eventually, a pavement design engineer could use the information recorded in the design catalog to select a given design, rather than have to use the software to simulate a given scenario.

Projected Time Line

The implementation process for accepting the MEPDG as the primary pavement design method for the SDDOT is anticipated to occur over a 3-year time frame. Note that step 11 is not required to be done until after the MEPDG method becomes the accepted design method. Although it is recommended that the MEPDG Implementation Team develop the details of the time line, the general year-by-year milestones are outlined in table E-3 below.

Table E-3. General SDDOT MEPDG implementation plan time line.

Implementation Step	**Complete**	**Year**			**Future Activity**
		1	**2**	**3**	
1. Conduct sensitivity analysis of MEPDG inputs	✓				
2. Recommend MEPDG input levels and required resources to obtain those input	✓				
3. Obtain necessary testing equipment to implement the MEPDG at the target MEPDG input levels.		■	■	■	
4. Review version 1.0 of the MEPDG software		■			
5. Form a SDDOT MEPDG Implementation Team and develop and implement a communication plan		■			
6. Conduct staff training		■	■	■	
7. Develop formal SDDOT-specific MEPDG-related documentation			■	■	
8. Develop and populate central database(s) with required MEPDG input values		■	■	■	
9. Resolve differences between the MEPDG predicted distresses and those currently collected for the SDDOT PMS			■		
10. Calibrate and validate MEPDG performance prediction models to local conditions			■	■	
11. Define the long-term plan for accepting the MEPDG design procedure as the official SDDOT pavement design method		■			
12. Develop a design catalog					✓

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APPENDIX F:
SUMMARY OF MEPDG RESOURCES

Introduction

In April 2007, the mechanistic empirical pavement design guide (MEPDG) developers held a “Mechanistic-Empirical Pavement Design Guide Seminar” in Irvine, California, to discuss the changes incorporated into version 1.0 of the MEPDG software, and to address any State Highway Agency (SHA) MEPDG-related comments or concerns. As a courtesy to the seminar participants at this meeting, the MEPDG developers produced and distributed a document of useful MEPDG resources. This document titled “Mechanistic-Empirical Pavement Design Guide Bibliography, Research Projects, and Courses” is a comprehensive document that summarizes many of the current documents and available resources deemed useful to those interested in learning more about the current MEPDG procedure and software (ARA 2007). This summary document is presented verbatim in the first section of this Appendix.

During the conduct of the current South Dakota Department of Transportation (SDDOT) research project, the research team conducted its own literature search to provide a basis for the research and to take advantage of past MEPDG-related work. As a result of this project-specific literature search, an annotated bibliography was produced. This SDDOT project-specific annotated bibliography of useful MEPDG resources is included in the second section of this Appendix.

PART 1: SUMMARY DOCUMENT OF MEPDG BIBLIOGRAPHY, RESEARCH PROJECTS, AND COURSES

As mentioned previously, the MEPDG developers distributed a summary document of useful MEPDG resources at the April 2007 "Mechanistic-Empirical Pavement Design Guide Seminar" in Irvine, California. While some formatting changes have been made for presentation purposes, the contents of the document titled "Mechanistic-Empirical Pavement Design Guide Bibliography, Research Projects, and Courses" have been reproduced verbatim and are included as the first section of this Appendix (ARA 2007).

MECHANISTIC-EMPIRICAL PAVEMENT DESIGN GUIDE

BIBLIOGRAPHY, RESEARCH PROJECTS, AND COURSES

MAY 2007

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Active and Pending Research Projects—May 2007

1. NCHRP Project 1-41, Models for Predicting Reflection Cracking of Hot-Mix Asphalt Overlays (Texas A&M University; Scheduled Completion: April 2008)
2. NCHRP Project 1-42A, Models for Predicting Top-Down Cracking of Hot-Mix Asphalt Layers (University of Florida; Scheduled Completion: April 2008)
3. NCHRP Project 9-29, Simple Performance Tester for Superpave Mix Design (Advanced Asphalt Technologies, LLC; Scheduled Completion: August 2008)
4. NCHRP Project 9-30A, Calibration of Rutting Models for HMA Structural and Mix Design (Applied Research Associates, Inc.; Scheduled Completion: November 2008)
5. NCHRP Project 9-38, Endurance Limit of Hot Mix Asphalt Mixtures to Prevent Fatigue Cracking in Flexible Pavements (National Center for Asphalt Technology; Scheduled Completion: December 2007)
6. NCHRP Project 9-44, Developing a Plan for Validating an Endurance Limit for HMA Pavements (Advanced Asphalt Technologies, LLC; Scheduled Completion: April 2008)
7. SHRP 2 Project R-21, Composite Pavement Systems (Award Anticipated in 2007)
8. NCHRP Project 1-46, Development of an AASHTO Pavement Handbook (Award Anticipated in 2008)
9. NCHRP Project 9-47, Environmental and Engineering Properties of Warm Mix Asphalt Technologies (Award Anticipated in 2008)
10. NCHRP Project 10-75, Evaluation of Pavement Type Selection Processes Including Alternate Design/Alternate Bidding (Award Anticipated in 2008)

FHWA Courses and Workshops—May 2007

1. Analysis of New and Rehabilitated Pavement Performance with Mechanistic-Empirical Pavement Design Software. (National Highway Institute training course; planned, 2007)
2. Climatic Considerations for Mechanistic-Empirical Pavement Design. (FHWA workshop; first presented, 2006; webcast at http://www.ct.gov/dot/cwp/view.asp?a=1617&q=327668)
3. Executive Summary for Mechanistic-Empirical Pavement Design (FHWA webcast at mms://conndot-video.ct.gov/mediapoint/fhwa/john_dangelo.wmv)
4. Introduction to the Mechanistic-Empirical Pavement Design Guide. (FHWA workshop; first presented, 2004; webcast at www.ct.gov/dot.pavement101)
5. Local Calibration Considerations for Implementation of the Mechanistic-Empirical Pavement Design Guide. (FHWA workshop; planned, 2008)
6. Obtaining Materials Inputs for Mechanistic-Empirical Pavement Design. (FHWA workshop; first presented, 2005; webcast at http://www.ct.gov/dot/cwp/view.asp?a=1617&Q=300236&PM=l)
7. Traffic Inputs for Mechanistic-Empirical Pavement Design. (FHWA workshop; first presented, 2005; webcast at http://www.ct.gov/dot/cwp/view.asp?a=1617&q=327664)
8. Traffic Monitoring Enhancements Needed for New Mechanistic-Empirical Pavement Design Guide. (FHWA Web seminar; first presented, 2005)
9. Use of Pavement Management System Data to Calibrate Mechanistic-Empirical Pavement Design (FHWA workshop; first presented, 2006; webcast at http://www.ct.gov/dot/cwp/view.asp?a=1617&q=:327670)
10. Weighing the Impacts of Traffic for Mechanistic-Empirical Pavement Design. (FHWA workshop; first presented. 2007)

PART 2: RESEARCH TEAM ANNOTATED BIBLIOGRAPHY

In the early stages of the SDDOT project work, the research team conducted a literature review under Task A of the project. One product from that task is an annotated bibliography of relevant published reports that was presented to the Technical Panel at the project kick-off meeting. This SDDOT project-specific annotated bibliography of useful MEPDG resources is included in this section of this Appendix.

Ali, H.A. and S.D. Tayabji. 1998. “Evaluation of Mechanistic-Empirical Performance Prediction Models for Flexible Pavements.” *Transportation Research Record 1629*, Transportation Research Board, Washington, DC.

> Abstract: In recognition of the potential of mechanistic-empirical (M-E) methods in analyzing pavements and predicting their performance, pavement engineers around the country have been advocating the movement toward M-E design methods. In fact, the next AASHTO Guide for Design of Pavement Structures is planned to be mechanistically based. Because many of the performance models used in the M-E methods are laboratory-derived, it is important to validate these models using data from in-service pavements. The Long-Term Pavement Performance (LTPP) program data provide the means to evaluate and improve these models. The fatigue and rutting performances of LTPP flexible pavements were predicted using some well-known M-E models, given the loading and environmental conditions of these pavements. The predicted performances were then compared with actual fatigue cracking and rutting observed in these pavements. Although more data are required to arrive at a more conclusive evaluation, fatigue cracking models appeared to be consistent with observations, whereas rutting models showed poor agreement with the observed rutting. Continuous functions that relate fatigue cracking to fatigue damage were developed.

Attoh-Okine, Nii O. Mar., 2002. “Uncertainty Analysis in Structural Number Determination in Flexible Pavement Design - A Convex Model Approach.” *Construction and Building Materials, Volume 16, No. 2*. Elsevier Science Ltd.

> Abstract: The AASHTO Guide for Design of Pavement Structures uses a structural number as one of the major inputs for flexible pavement thickness design. Previous studies have shown that the layer coefficients, which are a component of the structural number, have variability. The use of these values without a strong consideration of their variability can influence the overall determination of the structural number, hence, the thickness of the pavement. This paper proposes to use convex models as a tool for addressing the variability and uncertainty in the structural number determination. The convex models provide a completely non-probabilistic representation of uncertainty. The uncertainty is treated as unknown-but-bounded. The approach is illustrated by an example. © 2002 Elsevier Science Ltd. All rights reserved.

Bendana, Luis Julian, Dan McAuliffe, and Wei-Shih Yang. 1994. “Mechanistic-Empirical Rigid Pavement Design for New York State.” *Transportation Research Record 1449*, Transportation Research Board, Washington, DC.

> Abstract: In 1993 New York published a new Thickness Design Manual for New and Reconstructed Pavements based on the 1986 AASHTO design guide. The AASHTO equation for rigid pavement performance was calibrated with performance data for 225-mm rigid pavements in New York, and the calibrated equation was then used to design rigid pavements. Because New York does not have experience with thicknesses greater than 225 mm, the modified AASHTO equation could not be verified for thicker pavements. The development of a mechanistic-empirical (M-E) design procedure for verifying the designs presented in the new thickness manual is described. First, a nondimensional fatigue model was established on the basis of New York's past pavement performance, environmental

conditions, and traffic loadings. The study was then extended to develop design curves for thicknesses of 225, 250, 275, 300, and 325 mm (5-m slab lengths for 225- to 275-mm thicknesses and 5.5-m slab lengths for 300- to 325-mm thicknesses). Finally, the M-E design curve was compared with the modified AASHTO equation. The results indicate that for thicknesses greater than 275 mm, AASHTO predicts up to 40 percent more equivalent single axle loads than the M-E approach.

Buchanan, M. S. Dec., 2004. *Load Spectra Development for the 2002 AASHTO Design Guide.* Mississippi Dept. of Transportation, Research Div., Jackson, MS.

Abstract: Accurate knowledge of traffic volumes and loading is essential to structural pavement design and performance. Underestimation of design traffic can result in premature pavement failures and excessive rehabilitation costs. Overestimation can result in overly conservative pavement designs that are not cost effective for the owner agency. Traffic input for the anticipated National Cooperative Highway Research Program (NCHRP) 1-37A Design Guide will be in terms of axle load spectra along with several other important traffic parameters. Axle load spectra consists of classifying traffic loading in terms of the number of load applications of various axles configurations (single, dual, and tridem) within a given weight classification range. Long term pavement performance (LTPP) data from Mississippi sites were extensively reviewed to determine vehicle class distribution, monthly and hourly distribution factors, and axle load spectra.

Burnham, T. R. and W. M. Pirkl. May, 1997. *Application of Empirical and Mechanistic-Empirical Pavement Design Procedures to Mn/ROAD Concrete Pavement Test Sections.* Minnesota Local Road Research Board, St. Paul, MN.

Abstract: Current pavement design procedures are based principally on empirical approaches. The current trend toward developing more mechanistic-empirical type pavement design methods led Minnesota to develop the Minnesota Road Research Project (Mn/ROAD), a long-term pavement testing facility. The project consists of 40 heavily instrumented test sections, 14 of which are jointed plain concrete (JPC) designs. Mn/ROAD researchers determine the predicted lives of the concrete test sections by applying design and as-built data to three currently accepted concrete pavement design methods: Minnesota Department of Transportation's rigid pavement design guidelines, AASHTO Guide for Design of Pavement Structures 1993, and the PCA Thickness Design for Concrete Highway and Street Pavements (1984). The analysis began with determining the applicable as-built parameter values for each respective design method. Applying the as-built parameters to the three methods resulted in widely varied predictions of pavement life. For the 1993 AASHTO design method, reliability levels of 50 percent and 95 percent were applied for comparison. An experimental procedure for converting PCA method fatigue and erosion results to AASHTO type CESALS demonstrated unsuitability. Validation of the predictions presented will occur as the test cells reach their terminal serviceability.

Chen, H.-J. L. J. Bendana, and D. E. McAuliffe. Oct., 1995. *Adapting the AASHTO Pavement Design Guide to New York State Conditions.* New York State Dept. of Transportation, Albany, NY.

> Abstract: This report summarizes New York's efforts to evaluate and adapt the 1986/1993 AASHTP Pavement Design Guide to the state's pavement design procedure for new and reconstructed pavements. Development of the Guide is briefly described from the original AASHTO Road Test to the greatly expanded 1993 edition. A sensitivity analysis was performed to identify design variables important in deciding design pavement thickness. The history of New York pavement performance is reviewed. Results of performance studies are presented for selected highways in relation to the AASHTO procedure. Based on sensitivity of the variables, New York's past pavement performance and on past and current practices involving these variables, values and/or procedures are recommended and discussed for each variable involving thickness design. Also presented is the revised rigid pavement design equation. Many concerns in adopting the AASHTO procedure are discussed such as design life and other issues. An example is provided of how to design pavements according to the adapted AASHTO procedure. Findings of this study were implemented by New York when New York State Thickness Design Manual for New and Reconstructed Pavements was published in 1993. It is recommended that comprehensive pavement performance data to be collectg4ed on pavements using the new design so that the design procedure can continuously be improved.

Corley-Lay, J. B. 1996. “Efforts by North Carolina Department of Transportation to Develop Mechanistic Pavement Design Systems.” *Transportation Research Record 1539*. Transportation Research Board. Washington, DC.

> Abstract: A first generation mechanistic empirical pavement design procedure was developed using falling weight deflectometer deflections taken over a 3-year period at 16 test sections in Siler City, North Carolina. Information available for use in developing the procedure included deflection data, surface and air temperature, coring thicknesses at each test location, pavement performance records regarding rate of cracking, and traffic records. Jung's method, based on the curvature of the deflection bowl, was used to calculate strain at the bottom of the asphalt layer as a measure of fatigue. This calculated strain was used to obtain a calculated number of load repetitions to failure. Comparison of actual loads to failure with calculated loads to failure resulted in a table of shift factors by pavement type.

Corley-Lay, J. B. and Y. Qian. 1997. “Progress and Pitfalls for a Lot-Developed Mechanistic Design Procedure.” *Proceedings*. Eighth International Conference on Asphalt Pavements. Aug. 10-14, 1997, Seattle, Washington.

> Abstract: Last year, North Carolina Department of Transportation reported on efforts to develop a mechanistic-empirical design procedure (Corley-Lay 1996). That initial effort was based on falling weight deflectometer (FWD) testing and pavement condition evaluations at 24 test sections taken over a three year period. Since the initial effort, additional work has been done to improve the procedure and to test whether the method selected to estimate the pavement response under loading is giving reasonable results. This paper describes the comparison of strain calculations from the earlier effort with several other methods. In

addition, work has been done on implementation of Miner's hypothesis to consider seasonal variations. Finally, some comments on the types and amounts of data required to develop a calibrated mechanistic-empirical pavement design procedure are provided to assist other agencies as they plan to implement mechanistic design. This result is particularly important in light of the current efforts by the American Association of State Highway and Transportation Officials to produce a mechanistic empirical design procedure for implementation in 2002.

Cottrell, B. H. Jr., T. O. Schinkel, and T. M. Clark. Oct., 2003. *A Traffic Data Plan for Mechanistic-Empirical Pavement Designs (2002 Pavement Design Guide)*. Virginia Dept. of Transportation, Richmond, VA.

Abstract: The Virginia Department of Transportation (VDOT) is preparing to implement the mechanistic-empirical pavement design methodology being developed under the National Cooperative Highway Research Program's Project 1-37A, commonly referred to as the 2002 Pavement Design Guide (2002 Guide). The developers of the 2002 Guide have stated that transportation agencies in compliance with the Federal Highway Administration’s “Traffic Monitoring Guide” will have the traffic data necessary to implement the new pavement design approach. The 2002 Guide is structured in a hierarchical manner with three pavement design levels. For Level 1 designs, all project-specific data will be collected, including axle load spectra information (and axle loadings by vehicle classification) and vehicle classification counts at the project location. For Level 2 designs, regional and project-specific data will be applied. For Level 3 designs, estimated project-specific and statewide average or default data will be used in the analysis. The purpose of this effort was to develop a plan to position VDOT to collect traffic and truck axle weight data to support Level 2 pavement designs. This report serves as the basis for implementing and maintaining the truck weigh program necessary for the new pavement design approach and provides data for the current pavement design process used in Virginia (i.e., the 1993 pavement design methodology of the American Association of State Highway and Transportation Officials). To keep program costs at a minimum, the proposed traffic data program for pavement design takes advantage of the flexibility permitted in the “Traffic Monitoring Guide” and the availability of weigh-in-motion data from the Virginia Department of Motor Vehicles. Truck weight Groups 1 and 2, which consist of interstate and arterial roads, where the majority of truck loading occurs, are the first priority for implementation. A traffic data plan and a phased approach to implement the plan were proposed.

Dai, S., and J. Zollars. 2002. “Resilient Modulus of Minnesota Road Research Project Subgrade Soil.” *Transportation Research Record 1786*. Transportation Research Board, Washington, DC.

Abstract: Laboratory remolded subgrade soil samples have been widely used to study subgrade resilient modulus (M sub r). But physical conditions, such as moisture content and density, of such specimens may not represent in situ conditions very well. Therefore, AASHTO and the Long-Term Pavement Performance program have recommended that undisturbed, thin-walled tube samples be used to study subgrade resilient behavior. The Minnesota Department of Transportation (MnDOT) is developing mechanistic-empirical pavement design approaches through the Minnesota Road Research project and has realized the importance of M sub r in the design approaches. Currently, MnDOT is making an effort

to study the M sub r of unbound pavement materials through laboratory experiments. Under a research project at MnDOT, several thin-walled tube samples of subgrade soil were obtained from six different pavement sections at the Minnesota Road Research project. Repeated loading triaxial tests were conducted on the soil specimens to determine the M sub r at the MnDOT laboratory. Also, some soil properties, such as resistance, R-value, and plasticity index, were obtained. R-value is an indicative value of performance when soil is placed in the subgrade of a road subjected to traffic. Two constitutive models (the Uzan-Witczak universal model and the deviator stress model) were applied to describe the M sub r. The objectives of the research were to compare these two well-known constitutive models in describing subgrade soil resilient behavior and to study the effects of material properties on the M sub r. From the specimens tested, the experimental results showed that the universal model described the subgrade M sub r slightly better than the deviator stress model, and the coefficients in these two constitutive models were found to have correlation to material properties. Also, no well-defined relationships between the R-value and the coefficients in the constitutive models were observed from the results of the tested specimens.

D'Angelo, J. S. Vanikar, and K. Petros. Sep., 2004. “Designing Tomorrow’s Pavements: The New Guide and Software May Become the National Approach for Creating and Rehabilitating Roadway Surfaces.” *Public Roads, Volume 68, No. 2.* Federal Highway Administration (FHWA), Washington, DC.

Abstract: In the early 1960s, the American Association of State Highway Officials (AASHO), the precursor to the American Association of State Highway and Transportation Officials (AASHTO), conducted the road tests that would become the basis for most pavement designs. Researchers are now incorporating the latest advances in pavement design into a new set of design procedures. This article describes the new guide, entitled Mechanistic-Empirical Pavement Design Guide, that was developed through the National Cooperative Highway Research Program (NCHRP Project 1-37A). The guide includes a user-friendly software package designed for flexibility, offering engineers three levels of input data from which to choose (depending on the amount of available data). The most significant change is the use of a more sophisticated design procedure that uses a mechanistic empirical approach that includes both experimental data and mathematical models to predict pavement performance. The new guide will also provide analysts with predictions for pavement performance rather than pavement thickness values. The authors stress that local validation and calibration of distress predictions are key to the successful implementation of mechanistic-empirical design. The new design guide also includes procedures for analyzing more pavement types than the existing guide and software. One sidebar describes the Design Guide Implementation Team (DGIT), a group established by the Federal Highway Administration (FHWA) to help implement the new guide. The article is illustrated with numerous full-color photographs.

Gucunski, N. Nov., 1998. *Development of a Design Guide for Ultra Thin Whitetopping (UTW).* Federal Highway Administration (FHWA), Trenton, NJ.

Abstract: Concrete overlay of deteriorated asphalt pavements (whitetopping) has been a viable alternative to improve the pavement's structural integrity for over six decades. The thickness of such overlay usually exceeds five (5) inches. In the last few years, however, a

newer technology has emerged which is commonly known as Ultra Thin Whitetopping (UTW). UTW is a construction technique, which involves placement of a thinner (than normal) thickness ranging from 2 to 4 inches. The application of UTW has been targeted to restore/rehabilitate deteriorated asphalt pavements with fatigue and/or rutting distresses.

Hajek, Jerry J., Olga Selezneva, Jane Y. Jiang, and Goran Mladenovic. 2002. "Improving Reliability of Pavement Loading Estimates with Pavement Loading Guide." *Transportation Research Record 1809*. Transportation Research Board, Washington, DC.

Abstract: The development of the Long-Term Pavement Performance (LTPP) Pavement Loading Guide (PLG) was initiated to improve the reliability of traffic load estimates for the LTPP sections that do not have measured axle load data. The PLG contains extensive traffic data obtained from the LTPP database that may constitute the best available source of traffic data at the national level, a user-friendly graphical interface, and guidelines intended to help the user with the development of axle load spectra. Because of these features, the PLG will also facilitate traffic projections for general pavement design and management purposes. The uncertainty associated with estimating annual axle load spectra was quantified by assuming that the measured data do not exist and must be estimated. The estimated data were obtained by using axle load spectra obtained at similar sites in the same jurisdiction and utilized prototype PLG software. The difference between the estimated and the measured traffic loads was quantified by expressing axle load spectra in terms of equivalent single-axle loads. The results show that reasonable traffic load estimates can be obtained by judiciously selecting replacement traffic data. Although the PLG can reduce uncertainty of traffic forecasts and facilitate traffic forecasting, surrogate data can never replace site-specific data.

Harichandran, Ronald S., Neeraj Buch, and Gilbert Y. Baladi. 2001. "Flexible pavement design in Michigan: Transition from empirical to mechanistic methods." *Transportation Research Record 1778*. Transportation Research Board, Washington, DC.

Abstract: Michigan is rapidly moving toward adopting and using a mechanistic-empirical design for flexible pavements. To facilitate the transition from empirical to mechanistic design methods, the Michigan Department of Transportation contracted the development of software called the Michigan Flexible Pavement Design System (MFPDS). This software provides a holistic framework for analyzing and designing flexible pavements. MFPDS includes modules for AASHTO design, linear and nonlinear mechanistic analysis, backcalculation, and mechanistic design (including overlay design). The software incorporates enhanced elastic layer and finite element models within an easy-to-use Windows user interface and can be used on a routine basis. New response models to predict fatigue life and rut depth also were developed as part of this effort and are included in MFPDS. New pavements and overlays may be designed to limit predicted distresses to user-specified threshold values. The features of the mechanistic analysis and design approaches used are presented.

Jackson, N. Mike, Abdallah Jubran, Robert E. Hill. and Gary D. Head. 2002. "The Road to Smooth Pavements in Tennessee." *ASTM Special Technical Publication 1433*. American Society for Testing and Materials, West Conshohocken, PA.

Abstract: Pavement smoothness directly affects the dynamics of moving vehicles, impacting the rate of deterioration of the pavement and the operation and safety of vehicles and occupants. Consequently, the FHWA and many state transportation agencies have taken measures to address pavement smoothness immediately following construction. The significance of smoothness is evidenced by the preliminary recommendations for the adoption of the International Roughness Index (IRI) in the forthcoming AASHTO 2002 Pavement Design Guide. The State of Tennessee Department of Transportation (TDOT) adopted the Mays meter for the measurement of HMA pavement smoothness in the early 1980s. At that time, Mays meter measurements of 55 to 65 inches per mile (868 to 1026 mm per km) were not uncommon on pavements throughout the state. Through the implementation of increasingly stringent, incentive-based specifications, annual Smooth Pavement Awards for top-performing contractors, and advances in paving equipment, Mays meter measurements as low as 10 inches per mile (158 mm per km) are quite common today. This paper documents the measures taken in Tennessee over the past 20 years to improve pavement smoothness.

Khazanovich, Lev, Michael I. Darter, and H. Thomas Yu. 2004. “Mechanistic-Empirical Model to Predict Transverse Joint Faulting.” *Transportation Research Record 1896*, Transportation Research Board, Washington, DC.

Abstract: A summary is presented of the procedures used to model the effects of transverse joint faulting in the design of jointed plain concrete pavements v in the 2002 Design Guide, which was developed under NCHRP Project 1-37A, Development of the 2002 Guide for Design of New and Rehabilitated Pavement Structures. The mechanistic-empirical 2002 guide procedure for rigid pavement design incorporates several key features that are expected to offer significant improvements in design accuracy. The 2002 Design Guide faulting model identifies the differential energy of subgrade deformation as the mechanistic parameter governing joint faulting development. This parameter reflects total pavement flexibility and the level of load transfer efficiency. The 2002 design procedure uses the incremental damage approach. It allows for direct consideration of changes in many factors throughout the entire design period and joint load transfer, including material properties (concrete strength and modulus), seasonal climatic conditions, traffic loadings, subgrade support, and others. Each analysis increment represents a specific combination of the preceding factors over a distinct period (month, season, etc.). The main concepts are described, the model overview presented, and the results of the model calibration provided. Several examples illustrating sensitivity of the 2002 Design Guide faulting prediction to the key design parameters (dowel diameter, slab width and edge support, built-in temperature gradient, and others) are also provided.

Lee, K. W.; A. S. Marcus, K. Mooney, S. Vajjhala, E. Kraus, and K. Park. Aug., 2003. *Development of Flexible Pavement Design Parameters for Use with the 1993 AASHTO Pavement Design Procedures.* Rhode Island Dept. of Transportation, Providence, RI.

Abstract: The American Association of State Highway and Transportation Officials published the Guide for Design of Pavement Structures (AASHTO Guide) in 1986, and updated in 1993. Design parameters for use in the flexible pavement design modules of the computer program, DARWin(trademark) 2.01, which is based on the 1993 AASHTO Guide were determined. Effective soil resilient modulus, layer coefficients, and drainage

coefficients have been identified as three parameters essential to use the AASHTO Guide in Rhode Island. Representative materials for the state of Rhode Island have been acquired and fundamental testing was done to determine their properties. All the materials showed good soil classification. A series of laboratory resilient modules tests were performed on two granular subgrade soils at four temperatures and three moisture contents using the AASHTO T292-91 testing procedure. Prediction equations were developed to determine the resilient moduli under Rhode Island environmental and field conditions. A procedure to estimate the cumulative 18-kip ESAL was developed utilizing the weigh-in motion (WIM) data in Rhode Island.

“Material Properties for Implementation of Mechanistic-Empirical (M-E) Pavement Design Procedures.” CD-ROM. 2004.

Abstract: A comprehensive study was conducted to compile mechanistic property data for pavement materials specified and utilized in Ohio. This product includes a CD-ROM consisting of three major components accompanied by a User's Guide. In the first component, background information on the new mechanistic-empirical (M-E) pavement design/analysis procedures was researched and presented. In the second component, each of the twenty-eight pavement-related research projects conducted for the ODOT within the last two decades was summarized with emphases placed on pavement material properties measured and pavement distress data recorded. In the third component reliability of the Asphalt Institute's Witczak equation was evaluated for asphalt concrete mixtures used in Ohio in light of the latest laboratory dynamic modulus test data collected by the authors. The end result of the project was a collection of recommended hierarchical material property values and prediction methods for both rigid and flexible pavements to aid highway engineers and researchers in Ohio to implement the M-E procedures.

Meininger, Richard C. Dec., 2004. “Pavement design basis is in the bases.” *Rock Products, Volume 107, No. 12*, Primedia Intertec Publishing Corp. Overland Park, KS.

Abstract: The development of a Pavement Design Guide, by the National Cooperative Highway Research Program, for new and rehabilitated pavement structures is discussed. The guide is intended to replace the older versions of the American Association of State Highway Transportation Officials Pavement Guides that are used in some form by most of the states. It is suggested that the basis of a good performing pavement design is to properly use quality aggregate base coarse layers in the structures. It is found that these layer can take as many forms depending on the need to support and protect the wearing surface on the subgrade under specific traffic and climatic conditions.

Perkins, S. W. B. R. Christopher, E. L. Cuelho, G. R. Eiksund, and I. Hoff. May, 2004. *Development of Design Methods for Geosynthetic Reinforced Flexible Pavements*. Federal Highway Administration (FHWA), Washington, DC.

Abstract: Base reinforcement in pavement systems using geosynthetics has been found under certain conditions to provide improved performance. Current design methods for flexible pavements reinforced with a geosynthetic in the unbound aggregate base layer are largely empirical methods based on a limited set of design conditions over which test sections have

been constructed. These design methods have been limited in use due to the fact that the methods are not part of a nationally recognized pavement design procedure, the methods are limited to the design conditions in the test sections from which the method was calibrated, and the design methods are often times proprietary and pertain to a single geosynthetic product. The first U.S. nationally recognized mechanistic-empirical design guide for flexible pavements is currently under development and review (NCHRP Project 1-37A, NCHRP 2003). The purpose of this project was to develop design methods for geosynthetic reinforced flexible pavements that are compatible with the methods being developed in NCHRP Project 1-37A. The methods developed in this project, while compatible with the NCHRP 1-37A Design Guide, are sufficiently general so as to allow the incorporation of these methods into other mechanistic-empirical design methods.

Perkins, S. W. Nov., 2002. *Evaluation of Geosynthetic Reinforced Flexible Pavement Systems Using Two Pavement Test Facilities.* Montana Dept. of Transportation, Research Management Unit. Helena, MT.

Abstract: The project was initiated to provide additional test section data to better define the influence of traffic loading type and geosynthetic reinforcement type. The loading provided to the test sections forming the basis of the models described above consisted of a cyclic load applied to a stationary plate. In this project, four full-scale test sections were constructed and loaded with a heavy vehicle simulator (HVS) located at the US Army Corp of Engineers facility in Hanover, NH. The for test sections used three geosynthetics identical to those used in previous test sections and pavement layer materials and thickness similar to previous sections. Additional test sections were constructed in the pavement test box used in previous studies to examine the influence of base aggregate type, base course thickness reduction level sand reinforcement type. A rounded pit run aggregate was used in test sections to evaluate the influence of geosynthetic-aggregate shear interaction parameters on reinforcement benefit. The 1993 AASHTO Design Guide was used to backcalculate the base course thickness reduction from previous test section results where a traffic benefit ratio (extension of life) was known. Sections were built to this base course thickness reduction to see if equivalent life to an unreinforced section was obtained. Finally, six different geosynthetic products were used in test sections to evaluate the influence of reinforcement type on pavement performance.

Saeed, A. and J. W. Hall. Sep., 2003. *Mississippi DOT's Plan to Implement the 2002 Design Guide.* Mississippi Dept. of Transportation, Jackson, MS.

Abstract: Applied Research Associates, Inc. is finalizing the development of the 2002 Guide For Design of New and Rehabilitated Structures through National Cooperative Highway Research Program (NCHRP) Project 1-37A. The Mississippi DOT is implementing the design guide in two phases. An implementation plan is developed in Phase I, and actual implementation of the Design Guide occurs in Phase II.

Sneddon, R. V. and J. Rohde. Jun., 1998. *Development of Drainage Coefficients and Loss of Support Values for Pavement Design in Nebraska*. Nebraska State Dept. of Roads, Roadway Design Div., Lincoln, NE.

> Abstract: A chart of drainage time to achieve 50 percent saturation for bases and subbases with edge drains was developed. Using this cart recommended values for drainage coefficients for portland cement concrete (PCC) and asphalt cement (AC) pavements can be determined from the 1993 American Association of State highway and Transportation officials (AASHTO) Design Guide. At the sites evaluated, pavement drainage in Nebraska is rated Poor to Very Poor. Therefore C(d) will range from 0.95 to 0.70 depending on topography of the right-of-way and climate. LS values of 1 to 1.5 are appropriate for design, unless highly permeable non-erodable subbases are designed so that pavement drainage can be rated Good. A computer model which incorporates the AASHTO 1993 Design equation of PCC concrete pavement is presented in a spreadsheet for mat that provides ease of design for evaluation of alternate criteria and material properties is presented. Two design examples representing conditions at one of the test sites are presented. The examples assume poor and good drainage for design assumptions comparison.

Sun, L., W. R. Hudson, and Z. Zhang. Mar., 2003. "Empirical-Mechanistic Method Based Stochastic Modeling of Fatigue Damage to Predict Flexible Pavement Cracking for Transportation Infrastructure Management." *Journal of Transportation Engineering, Volume 129, No. 2*. American Society of Civil Engineers, Reston, VA.

> Abstract: In the purely theoretical approach of pavement design, percentage fatigue cracking is related to damage in a probabilistic manner according to the Miner's law. Two methods that are currently widely in use are based on assumptions of damage distribution. One method assumes fatigue damage being normally distributed, while the other one assumes fatigue damage being lognormally distributed. Since mechanistic-empirical pavement design and pavement management require precise forecasting of pavement fatigue cracking, much effort should be taken to characterize and predict fatigue cracking in terms of damage distribution. In this paper, we formulate the probability density distribution of fatigue damage of flexible pavements according to the underlying structure of fatigue cracking equations so that pavement fatigue-cracking damage can be interpreted in a more meaningful way. Numerical computation is conducted for a case study. It is found that damage is neither normally nor lognormally distributed. It is therefore recommended that methodology and damage distribution model established in this paper be used in practice to predict damage distribution and percentage cracking so that a better estimation of fatigue cracking can be made.

Tam, W. O., and H. Von Quintus. 2003. "Use of Long-Term Pavement Performance Data to Develop Traffic Defaults in Support of Mechanistic-Empirical Pavement Design Procedures." *Transportation Research Record 1855*. Transportation Research Board, Washington, DC.

> Abstract: Traffic data are a key element for the design and analysis of pavement structures. Automatic vehicle-classification and weigh-in-motion (WIM) data are collected by most state highway agencies for various purposes that include pavement design. Equivalent single-axle loads have had widespread use for pavement design. However, procedures being developed under the National Cooperative Highway Research Program (NCHRP) require the use of

axle-load spectra. The Long-Term Pavement Performance database contains a wealth of traffic data and was selected to develop traffic defaults in support of NCHRP Project 1-37A as well as other mechanistic-empirical design procedures. Automated vehicle-classification data were used to develop defaults that account for the distribution of truck volumes by class. Analyses also were conducted to determine direction and lane-distribution factors. WIM data were used to develop defaults to account for the axle-weight distributions and number of axles per vehicle for each truck type. The results of these analyses led to the establishment of traffic defaults for use in mechanistic-empirical design procedures.

Thompson, M. R. 1996. "Mechanistic-Empirical Flexible Pavement Design: An Overview." *Transportation Research Record 1539*. Transportation Research Board, Washington, DC.

Abstract: Activities associated with the development of the revised AASHTO "Guide for the Design of Pavement Structures" (1986 edition) prompted the AASHTO Joint Task Force on Pavements (JTFOP) recommendation to immediately initiate research with the objective of developing mechanistic pavement analysis and design procedures suitable for use in future versions of the AASHTO guide. The mechanistic-empirical (M-E) principles and concepts stated in the AASHTO guide were included in the NCHRP 1-26 ("Calibrated Mechanistic Structural Analysis Procedures for Pavements") project statement. It was not the purpose of NCHRP Project 1-26 to devote significant effort to develop new technology but to assess, evaluate, and apply available M-E technology. Thus, the proposed processes and procedures were based on the best demonstrated available technology. NCHRP Project 1-26 has been completed and the comprehensive reports are available. M-E flexible pavement design is a reality. Some state highway agencies (Kentucky and Illinois) have already established M-E design procedures for new pavements. M-E flexible pavement design procedures have also been developed by industry groups (Shell, Asphalt Institute, and Mobil). The AASHTO JTFOP continues to support and promote the development of M-E procedures for pavement thickness design and is facilitating movement toward an M-E procedure. The successful and wide-scale implementation of M-E pavement design procedures will require cooperating and interacting with various agencies and groups (state highway agencies, AASHTO--particularly the AASHTO JTFOP, FHWA--particularly the Pavement Division and Office of Engineering, and many material and paving association industry groups). It is not an easy process, but it is an achievable goal.

Timm, D., B. Birgisson, and D. Newcomb. 1998. "Development of Mechanistic-Empirical Pavement Design in Minnesota." *Transportation Research Record 1629*. Transportation Research Board, Washington, Dc.

Abstract: The next AASHTO guide on pavement design will encourage a broader use of mechanistic-empirical (M-E) approaches. While M-E design is conceptually straightforward, the development and implementation of such a procedure are somewhat more complicated. The development of an M-E design procedure at the University of Minnesota, in conjunction with the Minnesota Department of Transportation, is described. Specifically, issues concerning mechanistic computer models, material characterization, load configuration, pavement life equations, accumulating damage, and seasonal variations in material properties are discussed. Each of these components fits into the proposed M-E design procedure for Minnesota but is entirely compartmentalized. For example, as better computer models are developed, they may simply be inserted into the design method to yield more accurate pavement response predictions. Material characterization, in terms of modulus, will rely on falling-weight deflectometer and laboratory data. Additionally, backcalculated values from the Minnesota Road Research Project will aid in determining the seasonal variation of moduli. The abundance of weigh-in-motion data will allow for more accurate load characterization in terms of load spectra rather than load equivalency. Pavement life equations to predict fatigue and rutting in conjunction with Miner's hypothesis of accumulating damage are continually being refined to match observed performance in Minnesota. Ultimately, a computer program that incorporates the proposed M-E design method into a user-friendly Windows environment will be developed.

Timm, David, Bjorn Birgisson, and David Newcomb. Nov., 1998. “Department of Mechanistic-Empirical Pavement Design in Minnesota.” *Transportation Research Record 1629*, Transportation Research Board, Washington, DC.

Abstract: The next AASHTO guide on pavement design will encourage a broader use of mechanistic-empirical (M-E) approaches. While M-E design is conceptually straightforward, the development and implementation of such a procedure are somewhat more complicated. The development of an M-E design procedure at the University of Minnesota, in conjunction with the Minnesota Department of Transportation, is described. Specifically, issues concerning mechanistic computer models, material characterization, load configuration, pavement life equations, accumulating damage, and seasonal variations in material properties are discussed. Each of these components fits into the proposed M-E design procedure for Minnesota but is entirely compartmentalized. For example, as better computer models are developed, they may simply be inserted into the design method to yield more accurate pavement response predictions. Material characterization, in terms of modulus, will rely on falling-weight deflectometer and laboratory data. Additionally, backcalculated values from the Minnesota Road Research Project will aid in determining the seasonal variation of moduli. The abundance of weigh-in-motion data will allow for more accurate load characterization in terms of load spectra rather than load equivalency. Pavement life equations to predict fatigue and rutting in conjunction with Miner's hypothesis of accumulating damage are continually being refined to match observed performance in Minnesota. Ultimately, a computer program that incorporates the proposed M-E design method into a user-friendly Windows environment will be developed.

Timm, D. H. and D. E. Newcomb. 2003. “Calibration of Flexible Pavement Performance Equations for Minnesota Road Research Project.” *Transportation Research Record 1853*. Transportation Research Board, Washington, DC.

Abstract: As mechanistic-empirical (M-E) pavement design gains wider acceptance as a viable design methodology, there is a critical need for a well-calibrated design system. Calibration of the pavement performance equations is essential to link pavement responses under load to observed field performance. A field calibration procedure for asphalt pavements that incorporates live traffic, environmental effects, observed performance, and in situ material characterization was developed. The procedure follows the M-E design process, iterating the transfer function coefficients until the performance equation accurately predicts pavement distress. Test sections from the Minnesota Road Research Project were used to demonstrate the calibration process, and fatigue and rutting performance equations were developed. It is recommended that further calibration studies be undertaken with this methodology, possibly by using sections from the Long-Term Pavement Performance project.

Timm, D. H., D. E. Newcomb, B. Birgisson, and T. V. Galambos. Jul., 1999. *Incorporation of Reliability Into the Minnesota Mechanistic-Empirical Pavement Design Method*. Minnesota Dept. of Transportation, St. Paul, MN.

Abstract: This report documents the research that incorporated reliability analysis into the existing mechanistic-empirical (M-E) flexible pavement design method for Minnesota. Reliability in pavement design increases the probability that a pavement structure will perform as intended for the duration of its design life. The report includes a comprehensive literature review of the state-of-the-art research. The Minnesota Road Research Project (Mn/ROAD) served as the primary source of data, in addition to the literature review. This research quantified the variability of each pavement design input and developed a rational method of incorporating reliability analysis into the M-E procedure through Monte Carlo simulation. Researchers adapted the existing computer program, ROADENT, to allow the designer to perform reliability analysis for fatigue and rutting. A sensitivity analysis, using ROADENT, identified the input parameters with the greatest influence on design reliability. Comparison designs were performed to check ROADENT against the 1993 AASHTO guide and the existing Minnesota granular equivalency methods. Those comparisons showed that ROADENT produced very similar design values for rutting. However, data suggest that the fatigue performance equation will require further modification to accurately predict fatigue reliability.

Timm, D. H., D. E. Newcomb, and T. V. Galambos. 2000. "Incorporation of Reliability Into Mechanistic-Empirical Pavement Design." *Transportation Research Record 1730.* Transportation Research Board, Washington, DC.

Abstract: Pavement thickness design traditionally has been based on empiricism. However, mechanistic-empirical (M-E) design procedures are becoming more prevalent, and there is a current effort by AASHTO to establish a nationwide M-E standard design practice. Concurrently, an M-E design procedure for flexible pavements tailored to conditions within Minnesota has been developed and is being implemented. Regardless of the design procedure type, inherent variability associated with the design input parameters will produce variable pavement performance predictions. Consequently, for a complete design procedure, the input variability must be addressed. To account for input variability, reliability analysis was incorporated into the M-E design procedure for Minnesota. Monte Carlo simulation was chosen for reliability analysis and was incorporated into the computer pavement design tool, ROADENT. A sensitivity analysis was conducted by using ROADENT in conjunction with data collected from the Minnesota Road Research Project and the literature. The analysis demonstrated the interactions between the input parameters and showed that traffic weight variability exerts the largest influence on predicted performance variability. The sensitivity analysis also established a minimum number of Monte Carlo cycles for design (5,000) and characterized the predicted pavement performance distribution by an extreme value Type I function. Finally, design comparisons made between ROADENT, the 1993 AASHTO

pavement design guide, and the existing Minnesota design methods showed that ROADENT produced comparable designs for rutting performance but was somewhat conservative for fatigue cracking.

Tutumluer, E. 2001. "A Validated Model for Predicting Field Performance of Aggregate Base Courses." *Proceedings.* International Center for Aggregates Research 9th Annual Symposium: Aggregates, Concrete, Bases, and Fines. Apr. 22-25, 2001, Austin, TX.

Abstract: The ICAR Research Project 502 has focused on determining structural considerations of unbound aggregate pavement layers for a proper representation in the new AASHTO Pavement Design Guide - 2002. The research team developed models for the resilient and permanent deformation behavior from the results of triaxial tests conducted at the Texas Transportation Institute (TTI) and at the University of Illinois. The studies have mainly indicated that the unbound aggregate base (UAB) material should be modeled as nonlinear and cross-anisotropic to account for stress sensitivity and the significant differences between vertical and horizontal moduli and Poisson's ratios. Field validation data were collected from a full-scale pavement test study conducted at Georgia Tech. The validation of the anisotropic modeling approach was accomplished by analyzing pavement test sections using GT-PAVE finite element program, predicting UAB responses, and comparing them to the measured ones. Laboratory testing of the aggregate samples was conducted at the University of Illinois and the characterization models were developed for the stress sensitive, cross-anisotropic aggregate behavior. With nonlinear anisotropic modeling of the UAB, the resilient behavior of pavement test sections was successfully predicted at the same time for a number of response variables. In addition, the stress sensitive, cross-anisotropic representation of the base was shown to greatly reduce the horizontal tension computed in the granular base when compared to a linear isotropic representation.

Von Quintus, Harold L., Ahmed Eltahan, and Amber Yau. 2001. "Smoothness Models for Hot-Mix Asphalt-Surfaced Pavements: Developed from Long-Term Pavement Performance Program Data. *Transportation Research Record 1764.* Transportation Research Board, Washington, DC.

Abstract: The results of a study conducted to determine the relationship between changes in the surface distress of flexible pavements and incremental changes in the international roughness index (IRI) or ride quality by using Long-Term Pavement Performance (LTPP) program data are presented. The results of the regression analyses completed to identify those distresses found to be important and related to incremental changes in the IRI were obtained under the sponsorship of NCHRP Project 1-37A (Development of the 2002 Guide for the Design of New and Rehabilitated Pavement Structures). The results from the study have shown that selected distresses do have a significant effect on incremental changes in IRI with time and traffic. The results summarized can be used for the management, design, or evaluation of pavement structures.

Wang, S.S., and H. P. Hong. Jun., 2004. "Partial Safety Factors for Designing and Assessing Flexible Pavement Performance." *Canadian Journal of Civil Engineering, Volume 31, No. 3.* National Research Council of Canada, Ottawa, Canada.

Abstract: In designing and assessing pavement performance, the uncertainty in material properties and geometrical variables of pavement and in traffic and environmental actions should be considered. A single factor is employed to deal with these uncertainties in the current American Association of State Highway and Transportation Officials (AASHTO) guide for design of pavements. However, use of this single factor may not ensure reliability-consistent pavement design and assessment because different random variables that may have different degrees of uncertainty affect the safety and performance of pavement differently. Similar problems associated with structural design have been recognized by code writers and dealt with using partial safety factors or load resistance factors. The present study is focused on evaluating a set of partial safety factors to be used in conjunction with the flexible pavement deterioration model in the Ontario pavement analysis of cost and the model in the AASHTO guide for evaluating the flexible pavement performance or serviceability. Evaluation and probabilistic analyses are carried out using the first-order reliability method and simple simulation technique. The results of the analysis were used to suggest factors that could be used, in a partial safety factor format, for designing or assessing flexible pavement conditions to achieve a specified target safety level. © 2004 NRC Canada.

References

Applied Research Associates, Inc., ERES Division (ARA). 2007. *Mechanistic-Empirical Pavement Design Guide Bibliography, Research Projects, and Courses*. Document presented at the April 2007, “Mechanistic-Empirical Pavement Design Guide Seminar” in Irvine, California.