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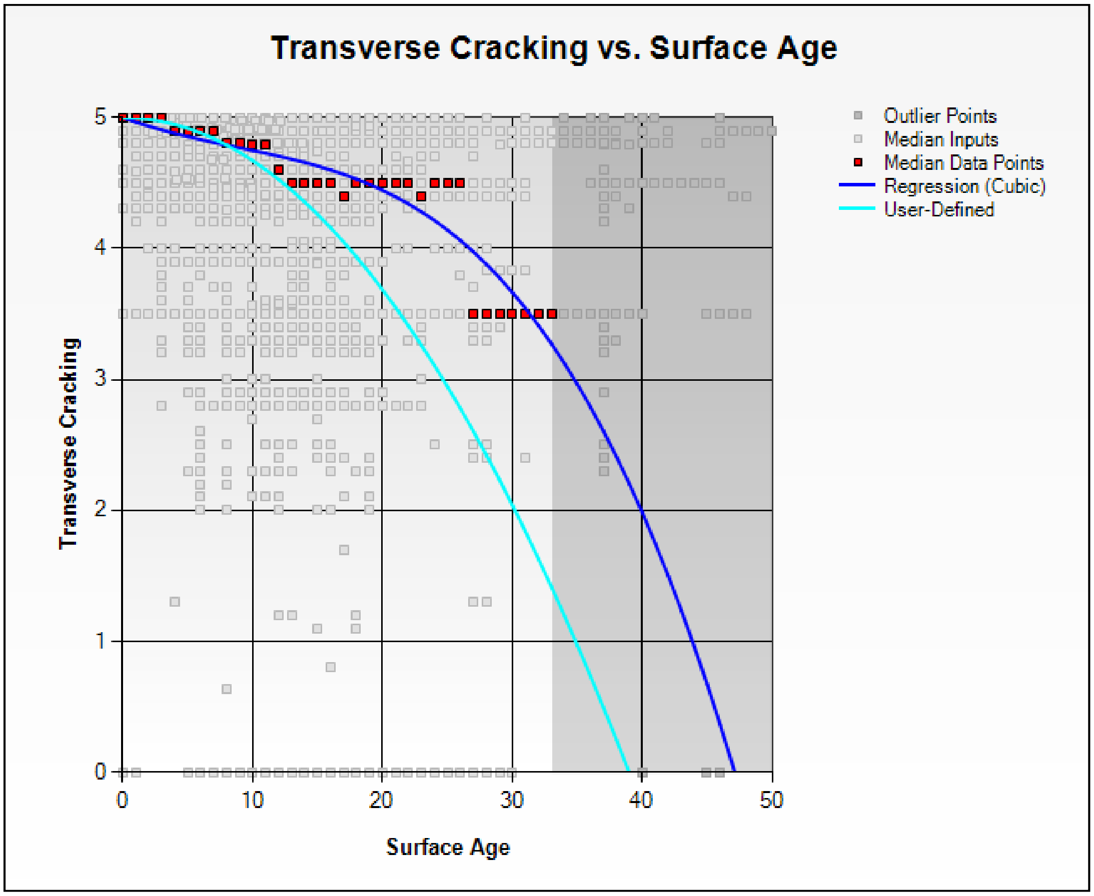

Updated Performance Curves for SDDOT's Pavement Management System

Study SD2011-04
Final Report

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16. Abstract

The South Dakota Department of Transportation (SDDOT) has used performance prediction models in their pavement management system since 1994. The performance prediction models are used to predict future pavement performance, estimate future maintenance and rehabilitation needs, and ultimately develop the statewide, multi-year optimized construction programs. The original 1994 performance prediction models were based on expert opinion. In 1997, SDDOT initiated a research project (SD1997-05, *Statistical Methods for Pavement Performance Curve Building, Historical Analysis, Data Sampling and Storage*) that developed performance prediction models using actual condition data and a more statistically-based approach. However, since 2004 SDDOT has encountered a number of issues that has made updating the performance prediction models impossible.

In 2011, SDDOT initiated this project to revise the 1997 approach for performance prediction model development by updating the methodology for evaluating the pavement family definitions, to use 17 years of historical condition data to develop improved performance prediction models; to develop a new stand-alone performance prediction modeling (PPM) tool; and to produce a final data model set that can be incorporated into the current pavement management process. In addition, guidance has been provided on how to use the pavement management data or the developed performance prediction models in the calibration of the American Association of State Highway and Transportation Officials (AASHTO) *Mechanistic-Empirical Pavement Design Guide* (*MEPDG*) to South Dakota conditions.

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TABLE OF ACRONYMS

Acronym	Definition
AADTT	Average Annual Daily Truck Traffic
AASHTO	American Association of State Highway and Transportation Officials
ADT	Average Daily Traffic
ANOVA	Analysis of Variance
AONC	Asphalt on Concrete (pavement family)
BIT	Bureau of Information & Telecommunications
BLOT	Base and Blotter (pavement family)
CRCP	Continuously Reinforced Concrete Pavement (pavement family)
DCV	Data Collection Vehicle
DOT	Department of Transportation
dTIMS	Deighton Total Infrastructure Management System
EI	Engineering Index
ESAL	Equivalent Single Axle Load
FD	Full Depth Asphalt (pavement family)
FHWA	Federal Highway Administration
GRAV	Gravel (pavement family)
HPMS	Highway Performance Monitoring System
IP	Internet Protocol
IRI	International Roughness Index
LAN	Local Area Network
LTPP	Long Term Pavement Performance
ME	Mechanistic-Empirical
MEPDG	Mechanistic-Empirical Pavement Design Guide
MESH	Mesh Reinforced Concrete Pavement (pavement family)
MRM	Mileage Reference Marker
NTIS	National Transportation Information Service
PCC	Portland Cement Concrete
PG	Performance Graded
PPM	Performance Prediction Modeling
RAP	Recycled Asphalt Pavement
R^2	Coefficient of Determination
RES	Roadway Environment System
SCI	Surface Condition Index
SDCL	South Dakota Codified Law
SDDOT	South Dakota Department of Transportation
SQL	Structured Query Language
THK	Thick Asphalt (pavement family)
TKSJD	Thick Short-Jointed Doweled Concrete Pavement (pavement family)
TKSJ	Thick Short-Jointed Concrete Pavement (pavement family)
TNSJ	Thin Short-Jointed Concrete Pavement (pavement family)
TONS	Thin Asphalt on Strong Base (pavement family)
TONW	Thin Asphalt on Weak Base (pavement family)
TRID	Transport Research International Documentation
TRB	Transportation Research Board
VMT	Vehicle Miles Traveled
WIM	Weigh-In-Motion

Executive Summary

Introduction

Since 1994, the South Dakota Department of Transportation (SDDOT) has used performance prediction models based on either expert opinion or measured condition data to predict future pavement performance, estimate future maintenance and rehabilitation needs, and ultimately develop the statewide, multi-year optimized construction programs. In 1997, SDDOT initiated a research project (SD1997-05, *Statistical Methods for Pavement Performance Curve Building, Historical Analysis, Data Sampling and Storage*) that resulted in the development of computer software for determining pavement performance prediction models using measured condition data and a statistically-based approach; however, since 2004, SDDOT has encountered a number of issues that have made updating of the performance prediction models difficult.

This project was initiated to revise the 1997 approach by updating the method for evaluating pavement family definitions, using 17 years of historical condition data in the development of the performance prediction models, developing a new stand-alone performance prediction modeling (PPM) tool, and recommending performance prediction models for incorporation into the pavement management process. In addition, this project provides guidance on how the developed performance prediction models can be used in the calibration of the American Association of State Highway and Transportation Officials (AASHTO) *Mechanistic-Empirical Pavement Design Guide* (*MEPDG*) (AASHTO 2008) to South Dakota conditions.

Method for Developing Performance Prediction Models

The first step in developing the performance prediction model method was to assess the limitations of the current model building process and the environment in which the new software was to be used. Requirements of the pavement performance modeling (PPM) tool include development in the Windows operating system environment, ability to access the data contained in the Deighton's Total Infrastructure Management System (dTIMS), and a process for exporting the recommended performance prediction models (and companion virtual age models) from the PPM tool back into dTIMS. The next step was to understand and document the desired functionality of the new model development process, any issues that may need to be resolved before software development can begin, and any business rules and policies that might affect the application. Understanding and documenting operation and functional software needs ensures that SDDOT expectations are based on a completely defined set of requirements. Having such clear requirements and a well-thought-out approach has allowed for the most efficient development of the final software product.

Based on information obtained during the kick-off meeting, the literature search, and the interviews with SDDOT and industry pavement management stakeholders, the research team defined the method for using historical condition data to create/update performance prediction models. At a minimum, the resulting method:

- Provides a process for importing an exported dTIMS data file into the PPM tool.
- Provides the ability to evaluate the current pavement family tree based on the data contained within an exported dTIMS database file (in .xml format).

- Includes the ability to evaluate the condition data and generate performance prediction models using five regression model forms (i.e., linear, quadratic, cubic, power, and exponential) and provides an assessment of the goodness of fit using the R^2 (coefficient of determination) statistic.
- Provides a graphical comparison of the existing performance prediction models to the newly developed models. Also includes tabular information related to the R^2 statistic, the number of data points, the number of outliers, and the performance prediction equations.
- Includes the ability to constrain the condition data used in the regression analysis according to the years of data (inclusive) and the minimum segment length.
- Includes the ability to constrain the regression model development according to an x-and y-range boundary condition, x-axis intercept (i.e., fixing the condition indicator value at x = 0), and y-axis intercept (i.e., fixing the age for y = 0). For the y-range boundary condition, the available options include (1) defining the range of y-axis values, (2) using the median condition index values for each year of data, or (3) specifying the use of a confidence interval.
- Allows for a user-specified fixed endpoint for the y-intercept (fixed y at x = 0).
- Provides a process for exporting the performance prediction models (and companion virtual age equations) to a Microsoft Excel comma-separated values (.csv) file which can be imported into Excel and then into dTIMS.
- Provides practical step-by-step guidance on the operation and functionality of the PPM tool through the developed user manual.
- Recommends a methodology for using the condition data/performance prediction models in the calibration of the *MEPDG*.

Performance Prediction Modeling Software

The PPM tool was developed to generate, analyze, and compare performance prediction models using data contained within the dTIMS database. The PPM tool contains features and capabilities that:

- Automates the processing of pavement data to generate performance prediction models.
- Includes a user-friendly interface for establishing and updating the pavement family definitions.
- Provides feedback to help the user determine when the current pavement family definitions may need to be changed.
- Evaluates different regression model types and provides useful graphical and tabular feedback to the user.
- Provides user-interface for filtering the condition data points and identifying data outliers.
- Compares current or previously saved model sets to newly developed models.
- Provides a method for the user to override a recommended regression equation with an engineering judgment-based model (if deemed necessary).
- Provides useful output data (e.g., tables, charts, reports) to best meet SDDOT needs.

Update Performance Prediction Models

The PPM tool was used to develop and update performance prediction models for the existing SDDOT pavement families (i.e., for condition indices in currently defined SDDOT pavement families) using the 17 years of available historical condition information. Based on a statistical analysis of the existing pavement family tree as well as the evaluation of whether or not the current pavement families can be further subdivided, the research team developed a recommended family tree and the associated performance prediction models.

Develop User Manual and Provide Training

A PPM tool user manual has been prepared as a separate document and submitted along with the final report and executive summary. The research team presented the findings of the research to the SDDOT Research Review Board on August 19, 2013 and provided on-site training for SDDOT personnel involved in the use of the PPM tool on August 20, 2013.

Use in Calibrating the Mechanistic-Empirical Pavement Design Guide

For this evaluation, five SDDOT identified case studies were evaluated using the AASHTOWare *Pavement ME Design*™ (formerly known as DARWin-ME) and compared to applicable performance prediction models developed using the PPM tool. This evaluation indicated that the AASHTOWare *Pavement ME Design*™ tended to under-predict, on average, the International Roughness Index (IRI) by 26 percent, asphalt rut depth by 53 percent, fatigue cracking by 81 percent, and faulting by 99 percent (although the latter is based on only one case study). In addition, the AASHTOWare *Pavement ME Design*™ tends to over-predict transverse cracking in asphalt pavements by 19 percent. However, it was also determined that the resulting PPM tool performance prediction models can be used as a starting point in the calibration of the prediction equations in the AASHTOWare *Pavement ME Design*™ software. In addition, data contained within the dTIMS database could be used to verify the SDDOT calibrated prediction equations.

Recommendations

The following provides implementation recommendations for consideration by the Technical Panel.

1. Adopt the PPM tool for developing and evaluating performance prediction models.
2. Review the recommended performance prediction models to verify acceptability to SDDOT conditions and knowledge of pavement performance.
3. Evaluate and update the performance prediction models on an annual basis or as necessary.
4. Evaluate the family tree definitions every 5 to 10 years or as sufficient data is available to define new pavement types.
5. Use the performance prediction models determined from the PPM tool as a starting point in the calibration of the *MEPDG*.
6. Consider revising distress measurement to meet *MEPDG* requirements.

1 PROBLEM DESCRIPTION

Beginning in 1994, SDDOT has used performance prediction models in its pavement management system to predict pavement performance, estimate future maintenance and rehabilitation needs, and ultimately develop the statewide, multi-year optimized construction programs. The original performance prediction models developed in 1994 were simply based on expert opinion. However, in an effort to transition from expert opinion models to performance prediction models based on actual historical pavement condition data, SDDOT initiated research in 1997 (SD1997-05, *Statistical Methods for Pavement Performance Curve Building, Historical Analysis, Data Sampling and Storage*) that focused on developing a more statistical-based approach. The primary results of that 1997 research were a set of procedures for collecting and screening historical condition data and a performance prediction modeling tool that depended on the S-Plus commercial statistics software. Using the outlined procedures and developed S-Plus tool, SDDOT personnel updated performance prediction models in 2001, 2003, and 2004.

Since 2004, SDDOT has encountered a number of issues with the current pavement modeling process that has made the updating of performance prediction models difficult. Because condition data are collected annually on the entire statewide network and incorporated into the SDDOT pavement management database, the volume of historical condition data has continued to grow each year. With 17 years of historical condition data to consider, the sheer volume of data has rendered the original data screening and sorting processes impractical (i.e., using the entire data file exceeds the Microsoft Excel data limit). There have also been documented issues with the S-Plus tool itself, which include:

- The performance prediction model building data set has become too large for the S-Plus tool to handle.
- The tool has a limited number of available performance prediction model forms (only linear, quadratic, and cubic are currently used).
- The tool can only produce one model at a time.
- The SDDOT has encountered Windows operating system compatibility issues with the tool.

Therefore, SDDOT initiated the research documented in this report to address these concerns and to update the pavement performance models used in its pavement management system.

In addition, in 2008 the American Association of State Highway and Transportation Officials (AASHTO) released the *Mechanistic-Empirical Pavement Design Guide* (*MEPDG*) and in 2010, the accompany pavement design and analysis software. One requirement prior to adopting the *MEPDG* is for agencies to evaluate and compare the *MEPDG* predicted pavement performance to actual in-field conditions. Therefore, along with the development of pavement performance modeling (PPM) tool, guidance has been provided on how SDDOT can use the pavement management data and/or the developed pavement performance curves in the calibration of the *MEPDG* performance prediction models.

2 OBJECTIVES

Five 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: Develop a methodology for creating, updating, and assessing the quality of pavement performance curves from historical data on the South Dakota state highway network.

A thorough literature review was conducted to summarize information about the performance prediction model-building processes being used by other state agencies. A summary of the results of the literature review is provided in Appendix A. After conducting the literature review, the research team met with the SDDOT Technical Panel and interviewed SDDOT and industry stakeholders to determine the needed features for the new modeling tool. Based on the compiled information, the research team developed a performance prediction model evaluation methodology that is capable of meeting current and future SDDOT model building needs.

Objective 2: Develop software for creating and updating pavement performance curves from historical data.

Based on the developed methodology, the research team created a stand-alone Windows operating system-based software program that incorporates the features and functions necessary to develop, evaluate, and update pavement performance prediction models.

Objective 3: Update South Dakota's pavement performance curves using the developed methodology and software.

After development of the performance prediction modeling (PPM) tool was complete, the research team demonstrated the capabilities of the tool by developing models for three pavement families. The results of the three pavement families were presented to the Technical Panel, who then approved the proposed approach for updating the SDDOT performance prediction models. In addition, the research team also assessed the appropriateness of the current SDDOT pavement family definitions.

Objective 4: Develop a user manual and provide training to SDDOT employees on the use of the methodology and software.

The research team has prepared a user manual that documents the functionality and use of the PPM tool. The user manual was developed as a stand-alone document and is submitted along with this final report and executive summary. In addition, the research team developed and will conduct on-site training on August 20, 2013 for SDDOT personnel involved in the performance prediction model development process.

Objective 5: Describe the relationship and potential application of historical pavement data and pavement performance curves to Mechanistic-Empirical Pavement Design.

As part of this study, the research team evaluated five SDDOT identified pavement case studies using the AASHTOWare *Pavement ME Design*™ software. The results of the design analysis, for comparable pavement types, were then evaluated against the performance prediction models developed using the PPM tool. For the International Roughness Index (IRI) and faulting, the *MEPDG*, on average, tended to under-predict the results from the performance prediction models developed using the PPM tool, while for asphalt rutting, asphalt fatigue cracking, and asphalt transverse cracking, the *MEPDG* tended to over-predict the results from the performance equations developed using the PPM tool. However, the distress over-prediction (or under-prediction in some cases) is not unexpected and can be resolved through the local calibration process. The performance prediction models developed using the PPM tool reflect actual pavement performance patterns in South Dakota, adjustment of the calibration coefficients until the *MEPDG* predicted distress match the distress determined from the PPM tool predicted models is recommended. In addition, once the calibration process has been completed, applicable *MEPDG* performance prediction models should be verified using twenty to thirty site-specific pavement segments. The results of the *MEPDG* analysis and comparison with the performance prediction models developed using the PPM tool are summarized in Section 4 (task 13) of this report.

3 TASK DESCRIPTION

The project objectives were achieved through the completion of fifteen tasks. This chapter describes each task separately, detailing how each task was completed under this study.

Task 1: Attend Kick-Off Meeting

Meet with the project's technical panel in Pierre, SD to review the project scope and work plan.

The first project task included attending a project kick-off meeting at the SDDOT office in Pierre, South Dakota. The intent of the kick-off meeting was to meet with the Technical Panel as well as additional SDDOT and industry personnel with knowledge of the current process for determining SDDOT performance prediction models. The specific goals of the project kick-off meeting included the following:

- To provide an opportunity for the project team to discuss the details of the project scope.
- To confirm the Technical Panel's expectations for the project.
- To discuss the proposed approach for meeting the project objectives and to clarify any outstanding issues.
- To provide the proposed project schedule and dates for the project deliverables.
- To establish the project team's expectations for SDDOT assistance with data extraction activities and procedures for reviewing the updated models.

The project kick-off meeting was held on March 20, 2012, in Pierre, South Dakota. During the meeting, the research team discussed their understanding of the problem, reviewed the project objectives, and presented the approach for completing each project task. In addition, the research team provided a brief discussion of the different model types that can be used in pavement management and a short discussion on the use of individual versus family models in the state highway agency pavement management systems.

Immediately following the kick-off meeting, the research team met with representatives from the SDDOT Field Offices, Materials and Surfacing, Transportation Inventory Management, Operations, Pavement Management, Planning and Engineering, Project Development, Finance, and Research offices, the South Dakota Bureau of Information and Telecommunications, and industry to conduct the stakeholder interviews documented in task 3.

Task 2: Perform Literature Review

Review and summarize literature pertinent to developing performance curves, including information about how other state DOTs are using automated curve-building procedures.

A formal literature search was conducted for this project by querying the Transport Research International Documentation (TRID) database managed by the Transportation Research Board (TRB), the National Transportation Information Service (NTIS), the Engineering Index (EI Compendex) databases, the internet, and conference websites and/or CD-ROMs where significant attention was focused on performance prediction modeling within pavement management activities. The research team also reviewed papers and presentations provided at the TRB's Annual meetings and at the International Conferences on Managing Pavement Assets.

The development of reliable performance prediction models is a critical element in pavement management systems. Specifically, performance prediction models are used to:

- Estimate future pavement conditions.

- Identify the appropriate timing for pavement maintenance and rehabilitation actions.
- Identify the most cost-effective treatment strategy for pavements in the network.
- Estimate statewide pavement needs required to address agency-specified goals, objectives, and constraints.
- Demonstrate the consequences of different pavement investment strategies and funding scenarios.

In essence, the performance prediction models serve as the cornerstone in guiding highway agencies to make more informed decisions regarding the maintenance and rehabilitation of the pavement network. Thus, it is important that the performance prediction models are not only reliable but also represent the actual deterioration trends exhibited by the agency's pavements. The more accurately the performance prediction models reflect agency-specific deterioration patterns, the less likely the system is to misrepresent future condition levels or the impacts of various construction programs.

The literature review summarizes the performance prediction modeling and data collection practices in state highway agencies. Looking back at past efforts is important because practices can often be improved by examining what approaches and processes have worked well in the past and which have not been successful. The literature review also allowed for the comparison of SDDOT's pavement condition data collection practices with the data collection needs associated with the *MEPDG*. The results of the literature review for this project are contained in Appendix A of this report.

Task 3: Conduct Interviews

Interview SDDOT and pavement industry personnel recommended by the panel.

Interviews of both SDDOT internal and external pavement management stakeholders were conducted to identify current and anticipated needs for performance prediction model building, for conducting future performance prediction model updates, and for potentially using both the pavement management data and developed performance prediction models in the calibration of the *MEPDG* to South Dakota conditions. During the interviews, the research team was interested in discerning specific information on:

- Limitations of the current performance prediction model building process.
- Issues associated with historical changes in data collection technologies.
- Desired functionality for building and updating performance prediction models in the future.
- Issues and functionality associated with the import/export process of data and models from the dTIMS pavement management software.
- Guidance on relevance of other pavement families, in addition to currently defined pavement families.
- Information technology requirements for software development.
- Current status and short-term goals for the implementation of the *MEPDG*.
- Expected performance characteristics from the industry perspective.

The research team developed specific questions for each interview group, but also approached the interviews as an open conversation with SDDOT staff and industry representatives to exchange any issues, concerns, and requirements related to performance, modeling, and software functionality that may not have been fully captured by the specific interview questions.

The primary goal of these interviews was to develop an understanding of SDDOT's current procedures, as well as future needs in performance prediction modeling. Therefore, a significant part of the interviews focused on understanding the many details of the current process, including the import and export of pavement condition data and models, technical aspects of the model-building process, current use of the *MEPDG*, and software development requirements. From these interviews, the research team was able to determine the required functionality of the PPM tool.

The following provides a summary of the interview results.

Pavement Management Cycle and Process

During the stakeholder interview, Pavement Management staff indicated that the tool developed during this project could not have a detrimental impact on the current pavement management cycle, which includes:

- May to August—Data collection and preservation programming. Two forms of data collection are conducted, roughness and rut depth data using a Distress Collection Van (DCV), which is described in the next section, and a visual survey of pavement (surface) condition. Student interns are trained on how to conduct the visual pavement condition survey. Raters conduct windshield surveys for the entire length of all sections of the state highway network, driving on the shoulder at about 15 mph. The Pavement Management Engineer also identifies projects for chip seals, minor joint repair, microsurfacing, and so on, and performs what-if scenarios for upper management.
- August to November—Data quality control. The Pavement Management group checks the pavement condition survey data and performs data clean-up and collects missed sections as needed.
- December to January—Load pavement management system and Roadway Environment System (RES) data into dTIMS, and perform roadway segmentation. The RES contains data collected by the Office of Transportation Inventory Management, and includes information related to roadway location, functional class, roadway geometry, pavement structure, traffic, and so on. The Pavement Management Engineer uploads the pavement management system data, while the Bureau of Information Technology (BIT) conducts the RES upload. dTIMS dynamically segments the network, and the Pavement Management Engineer makes manual adjustments and combines segments into projects as needed.
- January—Load traffic and accident data and run analyses. The first dTIMS analysis is conducted using the previous year's traffic and accident data. The second analysis is run once the new data has been received.
- February to March—Field inspection of project prioritized by the pavement management system or recommended by the SDDOT Region managers. Recommendations are sent out to the Regions, and 2-day inspection trips are performed. Projects to be reviewed include those with data anomalies or those that are requested by the district.
- April—Review and refine program. Pavement Management staff meet with Pavement Design staff to discuss projects and consider input from field trips. Scope and cost estimates are adjusted at this time.
- May—Programming meeting, final pavement management system analysis, needs report, and Highway Performance Monitoring System (HPMS) submittal. Upper management meets to

approve projects for the State Transportation Improvement Program (STIP) program, the final pavement management system analysis is run, and the Needs Report and HPMS submittal are completed.

The pavement management software used by the SDDOT is the Deighton Associates Total Infrastructure Management System (dTIMS).Within dTIMS, six separate pavement management system analyses are run, one for each functional class. SDDOT's version of dTIMS currently utilizes about 180 deterioration models for twenty-eight pavement families. A different model is used to predict performance if the applied treatment is different from the previously-applied surface. However, new models are not used for new chip seal or microsurfacing applications.

The pavement management analyses are used to recommend projects to the STIP. Pavement management is the most significant factor in identifying new projects and drives project selection and programming. Pavement management is also used to demonstrate to the legislature what the impacts of funding changes would be on the network pavement condition.

Historical Changes in Data Collection Technology

Since the 1980s, SDDOT has used four generations of data collection vehicle (DCV) technology. A timeline of these devices includes:

- 1980s to 1995: South Dakota road profiler.
- 1996 to 2003: Roadware ARAN.
- 2004 to 2010: Pathway Services, Inc., PathRunner (first generation).
- 2011 to current: Pathway Services, Inc., PathRunner (second generation).

Faulting is currently not collected due to limitations of the current DCV. The current DCV has a 128-point rut bar, but only 3 points are used so that the data will be consistent with previous years' results. Video images are collected using the DCV, but distress information is not collected from these images. SDDOT purchased a new DCV in 2013 which is capable of measuring transverse and longitudinal profile (from which roughness, rut depth and faulting can be determined), as well as surface distress. Transverse profile is determined using a 4,000 point measurement system over a width of 13 feet. SDDOT will incorporate the new transverse profile measurement system in 2014. Longitudinal profile is measured similarly to the current SDDOT method; however, pavement laser sensors project a 4 inch line oriented at 45 degrees to minimize the effects of transverse and longitudinal tining or grooving on concrete pavement surfaces. The new DCV also measures a continuous 3-D surface which enables cracks to be detected and measured. The changes to profile, rut, and distress measurements are expected to affect the future performance prediction models (i.e., models may require updating after several years of data collection using the new DCV).

Pavement condition data are collected from April to October, with annual pavement condition data available from 1995 to the current year.

Pavement Performance

SDDOT has made a number of asphalt and concrete pavement design- and construction- related changes over the last several years. The following provides a summary of the impact of these changes on the overall pavement performance.

Asphalt Pavements

- Performance grade (PG) binders have been used in asphalt pavements since the late 1990s. SDDOT noted that rutting is becoming less of an issue than in the past. Cracking in full-depth asphalt pavements also appears to be declining.
- Around 2007, SDDOT implemented the use of the gyratory compactor for developing asphalt mix designs.
- From 2009 to 2012, SDDOT modified construction specifications to allow up to 20 percent recycled asphalt pavement (RAP) in the asphalt pavement layer. Today, many projects, often for economic reasons, incorporate RAP in the asphalt layer, frequently with polymer modified binders.
- Class S overlays (i.e., open graded friction courses) are placed on many higher-volume asphalt-surfaced paving projects.
- SDDOT anticipates that more warm mix asphalt (WMA) and hot and cold in-place recycling will be conducted in the future.
- The primary distress leading to a need for treatment of asphalt pavements includes fatigue and environmental cracking (e.g., block and transverse cracking). Preventive maintenance is performed regularly with a chip seal at year 3, and then every 5 to 7 years until the roadway requires an overlay. In recent years, the primary focus has been on timely application of maintenance treatments. As a result of this systematic approach, the first asphalt overlay can often be delayed for approximately 16 years.

Concrete Pavements

- Dowel bars have been used at all transverse construction joints in concrete pavements since 1987.
- The majority of base layers under the concrete layer are untreated aggregate.
- Skewed joints in plain jointed concrete pavements are no longer built and there is a move to shorten the transverse joint spacing to 15 feet.
- SDDOT constructed a number of continuously reinforced concrete pavements (CRCP) in the 1970s, and again more recently, but is not using this pavement type now due to initial cost.
- There have been a few projects using bonded and unbonded overlays and whitetopping.
- SDDOT reported that there was previously a major issue with alkali-silica reactivity (ASR) and D-cracking distress, but specification changes have eliminated most of those problems.
- Joint spalling is the primary distress leading to a need for treatment.

Composite Pavements

- The underlying concrete often continues to deteriorate and tends to heave at the underlying joints.
- SDDOT saws and seals the asphalt over the underlying joints of long-jointed concrete pavements.

Oilfield traffic, hay hauling, and ethanol plants have impacted the performance of pavements in recent years. Corn is now hauled year-round instead of only in the fall. Recent flooding has impacted adjacent or nearby roadways, and environmental factors, in general, have the greatest impact on performance for the majority of the state-maintained roadways. Where allowed, it is also believed that super single tires will have an impact on pavement performance. For the most part, the group believed that the current performance prediction models seem to reliably estimate predicted pavement performance.

Limitations of Current Model Building Process/Software

The limitations of the current model building process/software include the following:

- A reliance on using Microsoft Excel to import the data into the S-Plus tool. Microsoft Excel has a file size limitation that is currently being exceeded due to the many years of data at 1/4-mile increments. With 17 years of condition data, the volume of data has also overwhelmed the functionality of the S-Plus tool.
- Prior to inputting data into the S-Plus tool, the system data requires cleanup to eliminate conflicts between pavement type and distress type (e.g., concrete distresses recorded on asphalt pavements). This is more a function of the data input process and not that of the existing tool.
- The S-Plus tool generates a limited number of performance prediction model types (only linear, quadratic, and cubic model forms).
- The S-Plus tool produces one model at a time, making it challenging to evaluate multiple models. In addition, there is no automated approach for recommending the "best" model to include.
- The S-Plus tool is not compatible with Windows 7 operating system.
- New or changed equations are currently hand-entered into dTIMS. Also, a companion equation for virtual age must be calculated and hand entered. Therefore, unless a performance prediction model significantly changed, the new model would not be included in dTIMS.
- The model building process, from data export to data clean-up to model generation to updating dTIMS, is extensive and time prohibitive.

Import and Export of Data and Models

Details for exporting pavement management data and importing the resulting performance prediction models from/into dTIMS include:

- **Data Filtering—**Any data contained in the dTIMS database that may be suspect should be identified prior to initiating the export process. Suspect data may be based on known errors in the pavement condition survey, outdated condition data, inaccurate surface age, or other issues identified by SDDOT Pavement Management staff. A number of records contained in the dTIMS data base were known to be suspect or identified for exclusion in the analysis. Therefore, SDDOT Pavement Management staff added an exclusion code into the dTIMS database that would be used to identify records (database rows) and data elements (database columns) that should be excluded from the PPM tool analysis. A software script was written to identify the exclusion code on the exported data file and the associated pavement condition rating scores were changed to a value of 9.99. The revised exported data file was then uploaded into the PPM tool. Within the PPM tool, the user defines the range of applicable pavement condition scores, and all condition scores outside this range (i.e., 0 to 5) are excluded from the analysis.
- **Data Loading—**The condition data is in 1/4-mile increments and is exported from dTIMS. Each new year of data is stored in a separate dTIMS perspective. A perspective is a table in the dTIMS database that holds information about different aspects of the roadway network (e.g., road section data, bridge data, and traffic data). A data view is created in dTIMS and then a perspective query executed to export the new years' worth of data in .xml format. All variable names are the same structure as previous years; however, many of the variables contain the year within the name. For example, IRI from the 2008 collection is stored as RUFF_2008.

- **Model Forms—**In addition to the performance prediction equations, dTIMS also requires the use of a virtual age equation. The virtual age equation is the inverse of the performance prediction equation in that it uses pavement condition to predict age, while the performance prediction equation uses pavement age to predict pavement condition. dTIMS uses the virtual age equation to predict future pavement condition. For this reason, each performance prediction model requires a matching virtual age equation. All new models created by the PPM tool must also have the companion virtual age equation created, both of which are imported back into dTIMS. Performance prediction models need to reference both the variable name and the perspective in which it is contained. All condition variables have a range of 0 to 5, and a value of 9.99 means that the variable does not apply to the pavement segment (e.g., faulting on asphalt-surfaced pavements, rutting on concrete-surfaced pavements).
- **Model Import/Export—**dTIMS has the functionality to import and export multiple models at a time. This allows for importing all performance prediction models and virtual age equations at once rather than manually editing each existing equation within dTIMS.

Use of the New PPM Tool

Due to limitations of the previous performance prediction modeling tool, SDDOT Pavement Management has not updated the performance prediction models since 2004. The expectations of the new PPM tool include:

- Models will be checked in the summer every few years for use in developing the next year's project and treatment recommendations.
- Pavement family definitions will not be revisited unless there is a compelling reason to do so.
- Performance equations will not be revised in dTIMS unless the model changes significantly.
- Statistical tests, such as R^2 or some other appropriate measure, are desired to judge whether the model has a good fit and has changed significantly.

The performance prediction models are used almost exclusively by SDDOT Pavement Management, but there is some interest from other areas to have access to the performance prediction models. For example, the SDDOT Field Offices would like to explore different scenarios related to maintenance treatment timing, while SDDOT Pavement Design would like to know if PG binders and edge drains result in improved pavement performance and are cost-effective.

Besides using the PPM tool to update performance prediction models, there is interest in possibly using the tool to model other asset performance. Assets discussed included bridges, culverts, and signs. Another major use of the tool is to support implementation of the *MEPDG* (see the following section). The general process for developing performance models using the PPM tool includes:

1. Identify the asset for which performance will be measured.
2. Identify which factors could affect asset performance (e.g., age, type, location).
3. Identify which data elements need to be collected.
4. Collect data elements over a period of time, inputting data into a database or spreadsheet.
5. Filter data any known errors or exclusions.
6. Export the data into the PPM tool.
7. Develop performance models.

8. Import the developed performance models into the asset management program.

Use of the PPM Tool with *MEPDG* Implementation

SDDOT has an implementation plan for the *MEPDG* and has been proceeding slowly towards eventual implementation. For the last several years, SDDOT has been working with the South Dakota School of Mines & Technology for material characterization. Pavement structure information is available in the SDDOT Surfacing Log and other information (e.g., traffic) is in RES. Trenching studies have not been conducted to assist in characterizing the extent of rutting in the asphalt, base, or subgrade layers. IRI is collected as part of the annual condition survey and for construction acceptance on asphalt pavements. Profilograph with a zero blanking band is used for construction acceptance of concrete pavements; however SDDOT is considering the use of IRI for concrete acceptance.

SDDOT will be purchasing an AASHTOWare *Pavement ME Design*™ software license and would like to fully implement the design process within 2 to 3 years (2014 to 2015), but this may be optimistic. It is desirable to have a feedback loop between the PPM tool and the *MEPDG* to determine the need to calibrate the performance prediction model coefficients in the *MEPDG*.

Software Requirements

The PPM tool should comply with applicable state Bureau of Information and Telecommunication (BIT) requirements and standards which include:

- Windows 7 operating system, Office 2010, SQL Server 2008 R2, and Windows Server 2008 R2.
- Software must be installed by BIT LAN technicians, and software must have an administrator for installation purposes.
- BIT recommends the software be installed on a network drive and access to the .exe file be provided to users over the network.
- The research team was requested to use caution when hard coding IP addresses since these may change in the future.
- BIT does not have any preference about programming language used to develop the tool and would only take over maintenance of the tool should the research team no longer be able to maintain it.
- BIT would like to see a high-level architecture and process flow for the tool prior to proceeding too far into developing the tool.

Task 4: Develop Methodology for Updating Performance Curves

Develop the methodology that will be used to update performance curves.

The PPM software methodology is defined and presented in this section. The first part of this section presents details associated with many of the primary software features and characteristics including a discussion of the dTIMS data export/import process, defining or editing the pavement family tree, and the performance prediction model development process. The second part of this section includes a step-by-step procedure that SDDOT can use to update the performance prediction models.

Software Features and Characteristics

Based on the findings of the literature search, stakeholder interviews, and knowledge of the previous performance prediction model development tool, the research team has developed the PPM tool to contain the following features and capabilities:

- An automated process for importing dTIMS data into the PPM tool and exporting performance prediction models and virtual age equations.
- The ability to develop and/or update the pavement family definitions through an easy to use interface.
- Feedback to help the user determine when the current pavement family definitions may need to be changed (according to R^2).
- Inclusion of five regression model forms (linear, quadratic, cubic, power, and exponential) for evaluating the data set.
- Data outlier identification using user interface tools.
- A user-defined fixed endpoint (y-intercept at x = 0) for any performance prediction model.
- Comparison of the current models to new models.
- The inclusion of an engineering judgment-based model.
- Graphical and tabular data of regression model results and color-coded graphical display based on data point density.
- Companion virtual age equation for each performance prediction model.
- A provision for reporting output data.

The general functionality and typical data flow through the software is outlined in figure 4-1.

Components of the PPM Tool

The PPM tool has been developed to provide the user with a sequential approach for evaluating, identifying, and selecting performance prediction models. The PPM tool consists of six tabular screens that include (presented in the recommended order of analysis):

1. **Home**—the **Home** tab is the first tab of the PPM tool and provides a brief introduction to each tab of the tool.
2. **Data Definition**—the **Data Definition** tab is used to import the pavement data from the previously created dTIMS exported data file (in .xml format). The user has the option to select the exported dTIMS file. The PPM tool will import data contained in the dTIMS file. The **Data Definition** tab is also used to define data inputs related to status, field name, and field type of each column contained in the exported dTIMS data file.
3. **Family Tree Building**—the **Family Tree Building** tab allows the user to define and review the pavement families according to elements contained within the dTIMS download file. The first step of performance model development process is the definition of meaningful pavement family definitions. This process is important because it determines how the historical pavement condition data should be divided so that the most appropriate and reasonable models can be developed to predict pavement performance. The general process for defining the pavement family include:

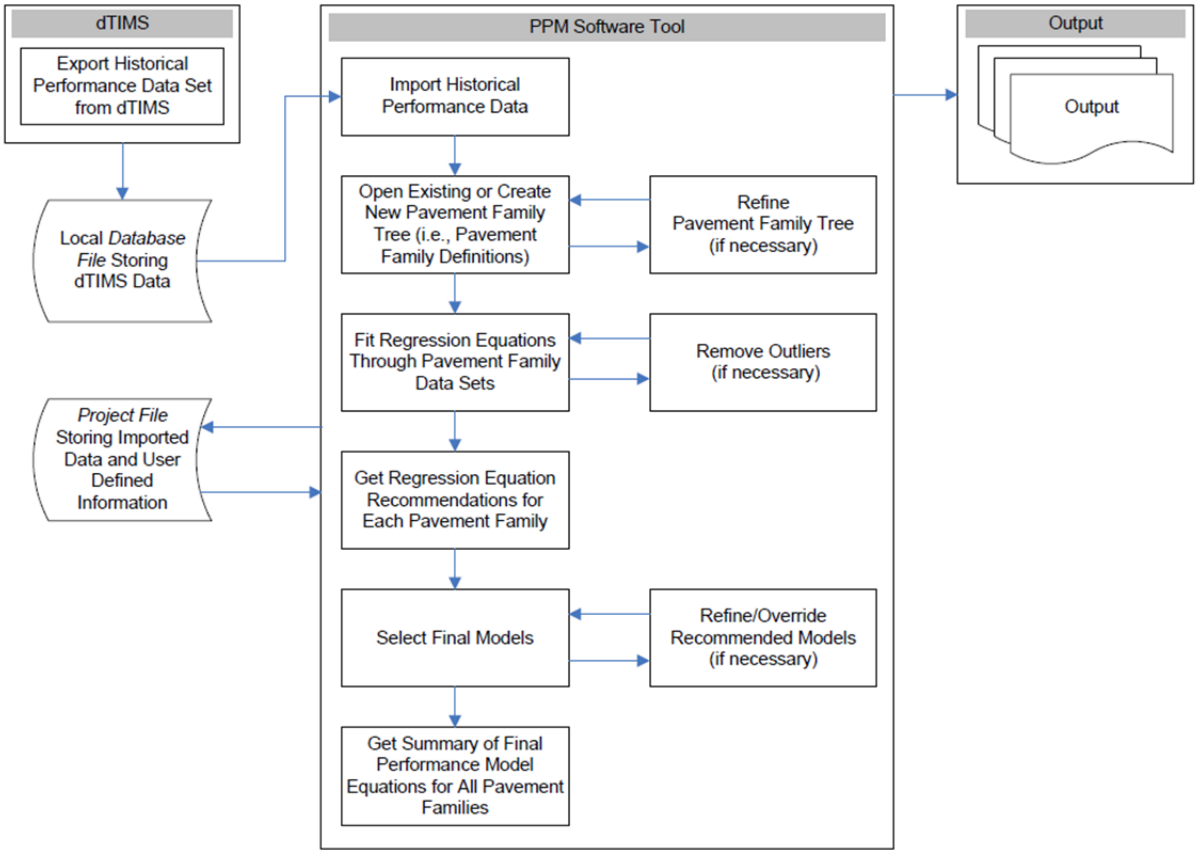


Figure 4-1. General functionality and data workflow of the PPM tool.

a. Select the pavement characteristics (database variables) that are most important to pavement performance (e.g., pavement type).

b. Select the pavement characteristic values (or value ranges) that define significant differences within a given pavement characteristic (e.g., thick, short-jointed concrete pavement, full-depth asphalt concrete).

c. Determine the order in which the chosen pavement characteristics are used to divide the database (e.g., first divide the database by pavement type, then treatment type, then by location, and so on).

When applying this approach, it is important to note that the process of dividing and subdividing the historical pavement condition into smaller sub data sets (i.e., pavement families) can be easily represented by the commonly used ordered directed tree data structure in which nodes and branches are used to describe data variable relationships (a sample pavement family tree is presented in figure 4-2).

For a pavement family tree, the following concepts apply:

- The nodes on the tree represent unique historical pavement condition data.
- The node at the root level represents the entire historical pavement condition data from dTIMS.

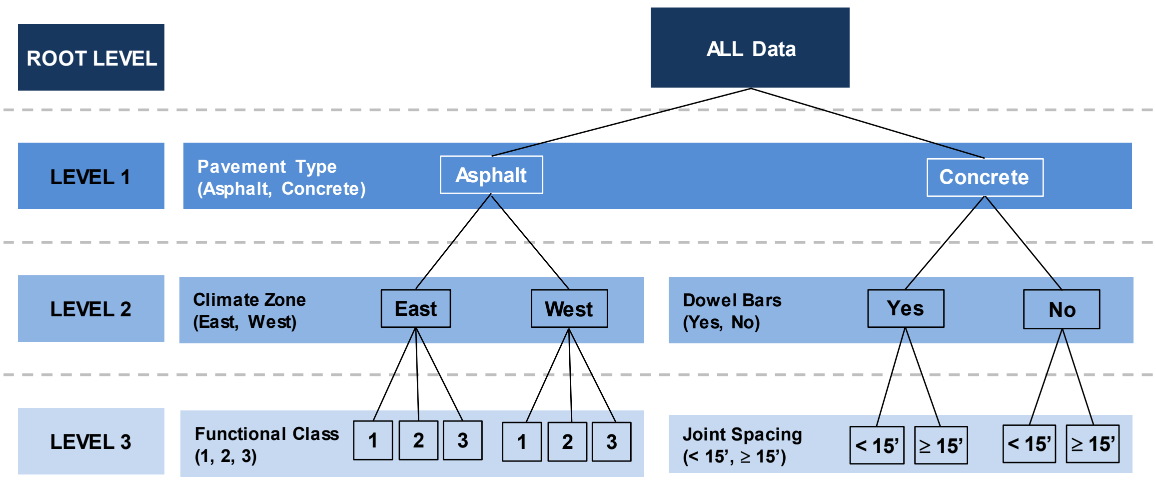


Figure 4-2. Example of a pavement family tree.

- New levels are created in the tree (from top to bottom) every time a new variable is used to split an existing data set into smaller sub data sets.
- Each node on the tree has one parent node (the linked node on the level above), and can have zero or more child nodes (the linked nodes on the level below).
- The number of child nodes under any given parent reflects the number of groups into which the parent node data set is being divided.
- Each node on the tree could be a potential pavement family for which performance curves can be developed. The quantity and quality of the data set at each node needs to be assessed to determine if the data can or should be subdivided further.

In the sample pavement family tree shown in figure 4-2, the original All Data set is divided by introducing three different levels of variables. The boxes on the chart represent the nodes of the tree and the lines between the nodes represent the branches. For this example, the user has decided that the data are to be first divided by pavement type (e.g., asphalt and concrete). For asphalt pavements, it was decided to next break the data set by two climatic zones (east and west) and then by functional class (1, 2, and 3).

Therefore, the branches of the tree on the asphalt side result in six different pavement families (illustrated by the six functional class boxes at Level 3).On the concrete side of the tree, the data are next divided by whether the pavements have dowels or not, and then by joint spacing categories. Therefore, the branches of the tree on the concrete side result in four different pavement families (illustrated by the four joint spacing boxes at Level 3).

While the SDDOT pavement family tree is much more complicated than the simple example illustrated in figure 4-2, the concepts used to assess and/or update the SDDOT pavement family tree are the same.

Because new pavement condition data are being added every year to the performance modeling database, the defined pavement family tree should be reviewed on a regular basis to determine if all necessary variables are included, and to determine if the current pavement families are the most appropriate selections for the available data. Within the PPM tool, selecting each node of the family tree displays the elements of that node. Node elements include the variable that defines the subset (e.g., pavement type, treatment type, traffic, percent trucks), the node details (i.e., node name, level of the node within the family tree, summary of the sibling status, number of pavement segments included in the node, and the percent of total segments included in the node), and the number of data points, range in age for each condition indicator, and the value range for the condition indicator.

4. **Regression Analysis**—the **Regression Analysis** tab includes both a tabular and graphical representation of the five regression equation forms (i.e., linear, quadratic, cubic, power, and exponential). Information summarized on this tab includes the number of data points, the number of outliers removed from the analysis, the y-axis value at age zero (if used), and the regression equation R^2 value for each condition indicator. In addition, a corresponding graph that provides a plot of the performance prediction models by condition indicator is also displayed on the **Regression Analysis** tab.
5. **Model Selection**—the **Model Selection** tab is used to define which model form will be selected for each node of the pavement family by condition indicator. The **Model Selection** tab includes both a summary table and graphical representation of the current selected models.
6. **Final Model Summary**—the **Final Model Summary** tab provides a list of selected models for each condition indicator of the family tree.

The remainder of this section provides more details about some of the more significant software characteristics and functional features.

dTIMS Export and PPM Tool Import Process

The import/export process from dTIMS to the PPM tool includes the following capabilities:

1. **Export data into a dTIMS export data file** —The research team recommends that each year, inventory and time-series performance data associated with each pavement segment be exported from dTIMS for evaluation in the PPM tool so that the PPM tool database will be kept current with data necessary to complete the performance prediction modeling process at any time. However, it should be noted that because there is no connection back to the original dTIMS database, data fields that could possibly be used by SDDOT to divide the pavements into various families (e.g., pavement type, ADT, percent RAP, binder type, cement type) must be included in the data snapshots exported from each year's export of the dTIMS database. The dTIMS data should be exported in .xml format.
2. **Import the dTIMS generated data file**—After the current data snapshot has been successfully exported from dTIMS and placed into an exported dTIMS .xml file, the user will use controls within the PPM tool, under the *Data Definition* tab, to point to and import the dTIMS .xml file. As part of this process, the PPM tool will check the data file to make sure the data in the file matches with the expected data structure. If it does not, it will ask the user to fix the data file before importing. If the data import checks are successfully passed, the dTIMS .xml data file is imported into the PPM tool and used to create the PPM tool database file.
3. **Define data fields**—After the dTIMS .xml file has been successfully checked and imported into the PPM tool, the user should define the field type for each field name contained in the imported data file. The field name consists of the .xml data file column headings, while the field type includes a dropdown menu where the user selects the data type (e.g., subdivider, x-axis, condition indicator, segment length). During data definition, the user must identify at least one condition

indicator, at least one subdivider, the x-axis, and segment length variables. Refer to the PPM tool user manual for more details.

The PPM tool will not at any time be linked to the dTIMS database. Although this export/import procedure adds an additional step to the data access process, it provides some necessary separation between the dTIMS pavement management database and the PPM tool. That is, since the PPM tool does not talk directly to the dTIMS database, the PPM tool will not be impacted if the dTIMS database structure changes, or if SDDOT changes pavement management system vendors. By using this planned separation, as long as the data are exported into the expected file format, the PPM tool will have no problem reading and importing the data.

Define Pavement Family Tree

This feature of the PPM tool allows the user to develop the pavement family using the variables that were identified as subdividers. The user is required to determine the subdivider sequence for defining the pavement family tree. For example, if pavement type and curve flag (treatment type associated with each pavement type, for example, diamond grinding, asphalt overlay, mill and asphalt overlay) are determined to be subdividers, the user must first define the pavement family tree using pavement type and then within each pavement type node, specify the applicable curve flags.

Regression Model Fitting

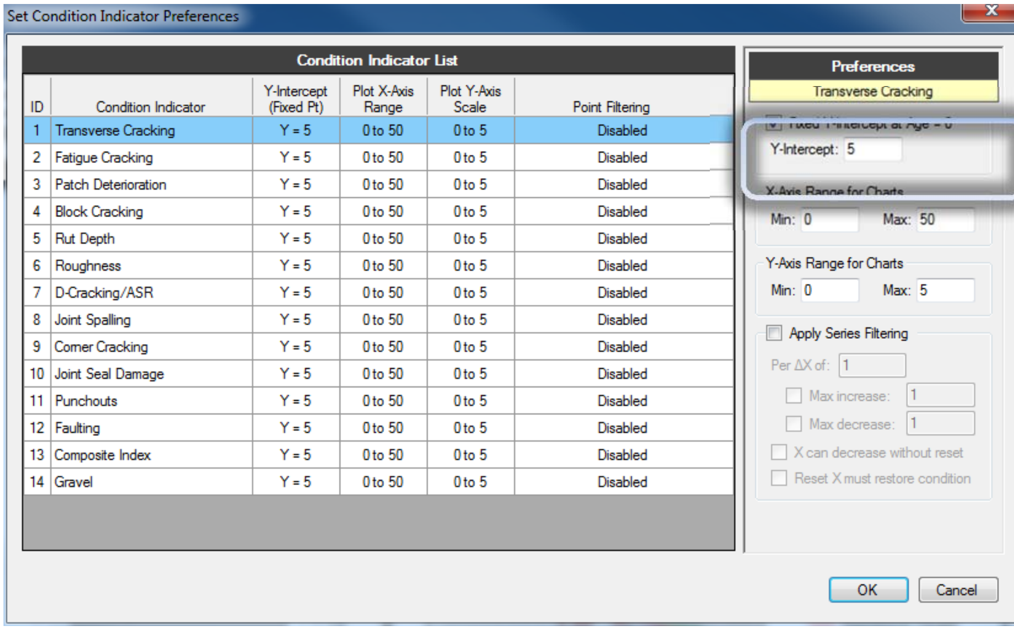
The next step in the typical data flow is to fit different regression equation types through the sub data sets defined in the pavement family tree. By fitting regression models through the sub data sets at a particular node on the tree, assessments can be made on whether the models associated with sub data sets (*child*) for that node are better or worse than the models associated with the *parent* data set. A total of five model types have been programmed into the PPM tool and include linear, quadratic, cubic, power, and exponential. The software allows easy access to condition-versus-age plots that display the data set points, tried regression models, and the previous SDDOT defined pavement family model (if applicable), presented on the same chart.

Outlier Identification and Resolution Tools

One of the primary parts of the PPM tool user interface is the ability to view condition data versus age plots with trial regression models fit through the data. When viewing these plots, it is very common to observe individual data *outliers* that either deviate significantly from the other points, or deviate significantly from expected data trends. Because outliers can be expected in every data set, the PPM tool features allow the user to identify outliers within a particular data plot and remove them from the final data set (if desired).

To aid in outlier identification, the PPM tool user interface allows user-defined outlier identification and removal. The first level involves the use of user-specified boundaries that when defined automatically mark data points outside of the boundaries as outliers. The PPM tool graphically illustrates identified outliers (i.e., shade outlier data points). The available boundary conditions include:

- **Segment length**—Excludes pavement segments that are shorter than a specified length. This applies to entire family tree (global level).
- **Constrain years of data**—Defines the consecutive years of data to be used in the analysis at the global level.
- **Fixed y-intercept**—Defines the point on the y-axis where x=0 (figure 4-3) at the global level.



ID	Condition Indicator	Y-Intercept (Fixed Pt)	Plot X-Axis Range	Plot Y-Axis Scale	Point Filtering
1	Transverse Cracking	Y = 5	0 to 50	0 to 5	Disabled
2	Fatigue Cracking	Y = 5	0 to 50	0 to 5	Disabled
3	Patch Deterioration	Y = 5	0 to 50	0 to 5	Disabled
4	Block Cracking	Y = 5	0 to 50	0 to 5	Disabled
5	Rut Depth	Y = 5	0 to 50	0 to 5	Disabled
6	Roughness	Y = 5	0 to 50	0 to 5	Disabled
7	D-Cracking/ASR	Y = 5	0 to 50	0 to 5	Disabled
8	Joint Spalling	Y = 5	0 to 50	0 to 5	Disabled
9	Corner Cracking	Y = 5	0 to 50	0 to 5	Disabled
10	Joint Seal Damage	Y = 5	0 to 50	0 to 5	Disabled
11	Punchouts	Y = 5	0 to 50	0 to 5	Disabled
12	Faulting	Y = 5	0 to 50	0 to 5	Disabled
13	Composite Index	Y = 5	0 to 50	0 to 5	Disabled
14	Gravel	Y = 5	0 to 50	0 to 5	Disabled

Figure 4-3. Define the years of data to include in the analysis.

- **Exclude specific years of data**—Allows the user to define which calendar years of data are included in the current pavement family's data set (figure 4-4a). Specifying years of data to exclude will be applied to the entire data set (global level).
- **X-range boundaries**—Defines the range in x-axis values (figure 4-4b) at the node level.
- **Y-range boundaries**—Defines the y-range boundary conditions (figure 4-4c) at the node level and includes three options:
  - Set confidence interval (figure 4-5).
  - Define y-range by points—Y-range at a specified x-value (figure 4-6).
  - Use medians only—Use the median y-value, for each year of data (figure 4-7).
- X-range and y-range values can be used in combination; however, only one y-range value is available at a time.
- **Fixed pass-through points**—Specifies both the y- and x-intercept for the performance prediction model (figure 4-4d) at the node level.

The PPM tool also includes the ability to export a summary .csv file that contains the data points used in each model analysis (figure 4-8). The exported summary file includes the x- and y-values, element ID, year, and identification of data elements that were excluded by the user (e.g., confidence interval, median, y-intercept).

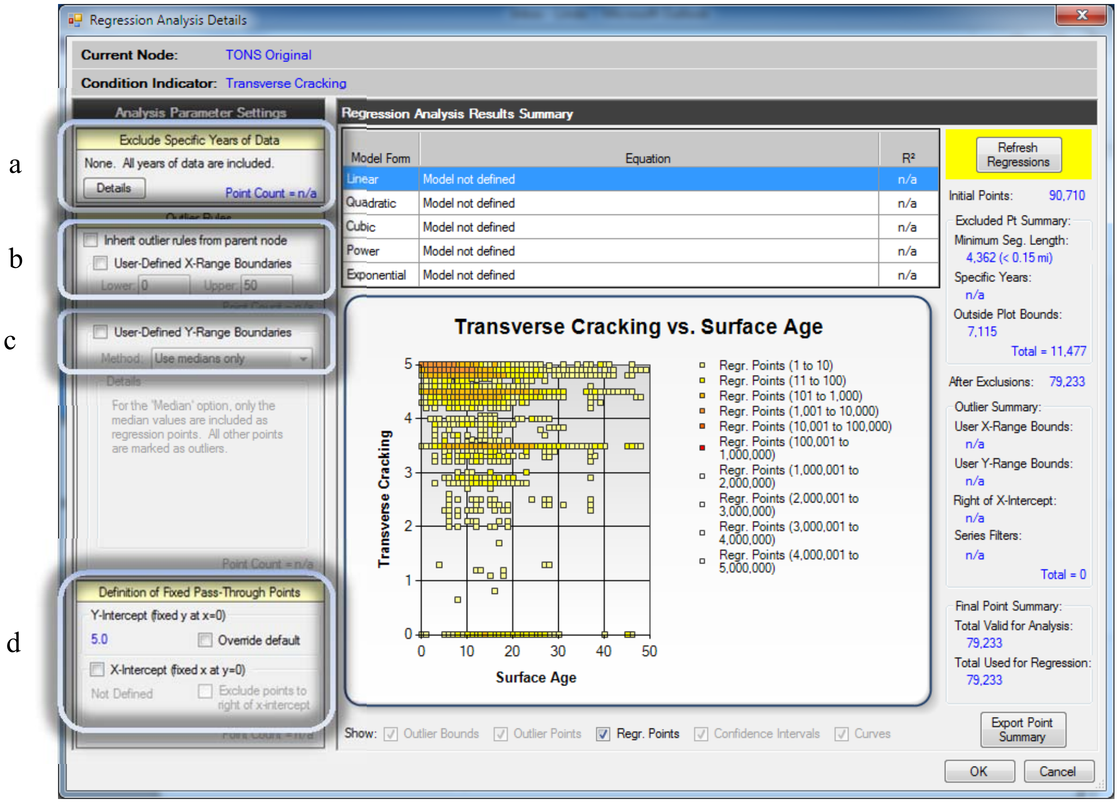


Figure 4-4. Node level outlier definitions.

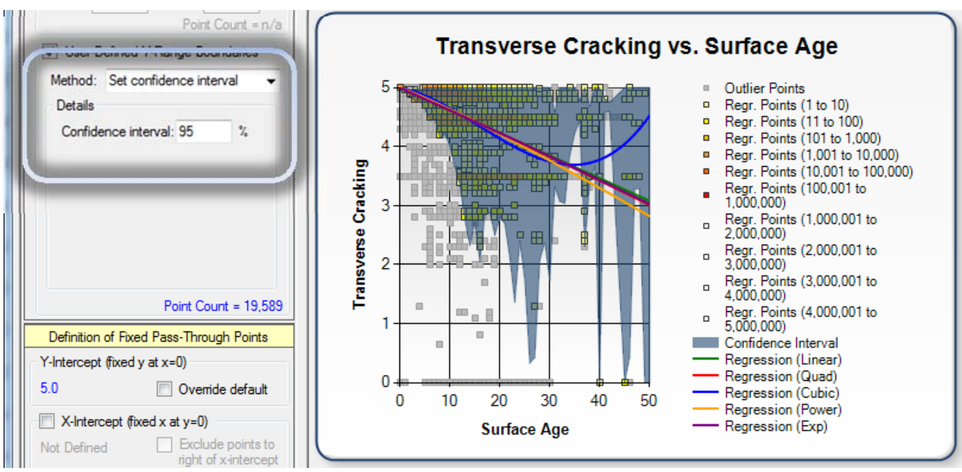


Figure 4-5. Define y-range boundary by confidence interval.

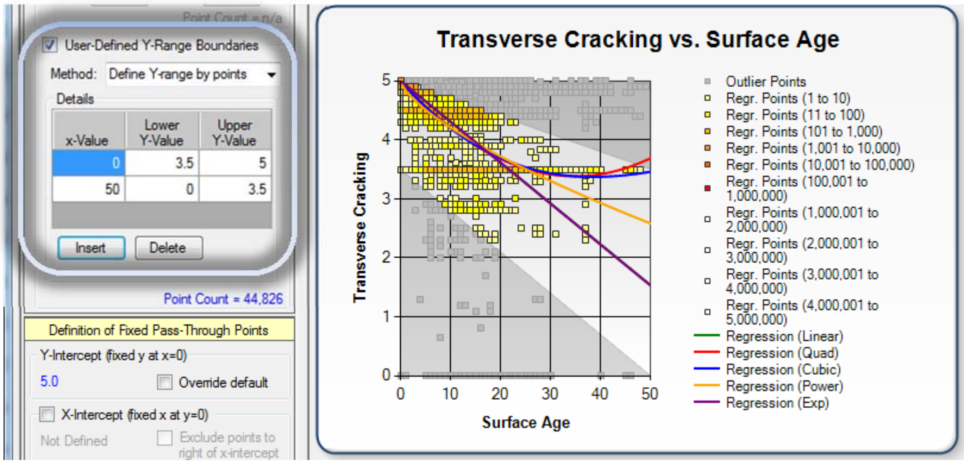


Figure 4-6. Define y-range boundary by points.

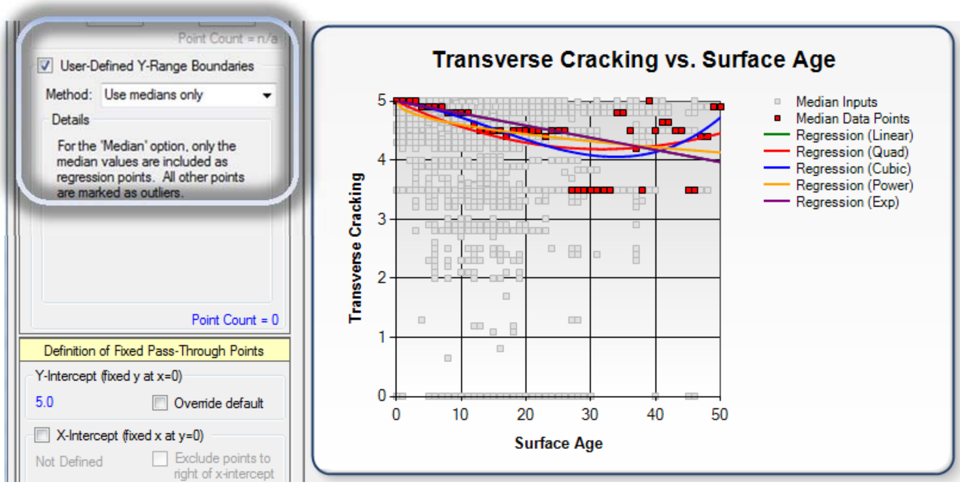


Figure 4-7. Define y-range boundary by median values.

Performance Prediction Model Recommendations

After the pavement family tree has been defined and outliers have been identified, the recommended model form can be selected. At a minimum, the model recommendations should be based on the following:

- **General assessment of model shape**. As a first step, the *general* quality of each tried model can be graphically assessed. For example, if a condition index is supposed to be always decreasing, but a particular model form results in the model predicting increasing values over a particular age range, this model shape is readily shown in the graphical display.
- **Statistical analysis of the quality of each tried model type**. The goodness-of-fit for each tried model form is assessed by computing the R^2 statistic. In addition, feedback (e.g., number of data points, number of outliers) on model forms is provided to the user in tabular format.

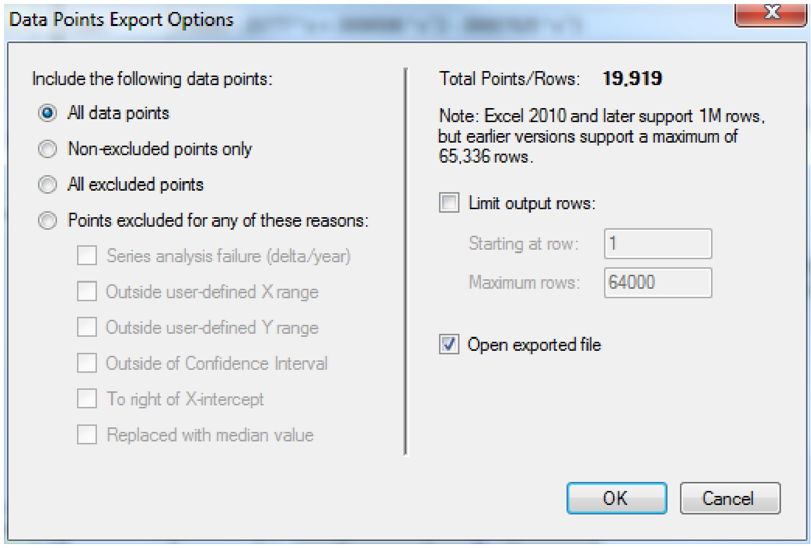


Figure 4-8. Generate report of data points used in the analysis.

Final Model Selection

Once the user obtains feedback about the recommended models for each sub data set, decisions will still need to be made regarding what models are incorporated into the final recommended pavement management model set. Because it would be very difficult to take the human element out of this model selection process and completely automate the process, the software provides the user with the necessary feedback (e.g., performance prediction model regression summary and condition versus age plots) so that the final model set can be easily defined. In using this feedback, the user will "select" the final performance prediction model associated with each condition indicator for each pavement family. There will undoubtedly be scenarios where the user will either want to refine or completely override a recommended regression equation with an engineering judgment-based model. Therefore, the ability to override the models developed with the PPM tool with a user-defined model has also been incorporated into the software.

Final List of User-Selected Models

After the user completes the final model selection/refinement process, the result will be a final table where each row contains final model information associated with each unique combination of pavement family, curve flag, and condition indicator. Relevant model-specific information (e.g., model form, performance equation, R^2) will be presented in tabular form in the user interface and can be exported in .csv file format to Excel and then to dTIMS.

Task 5: Submit Technical Memorandum and Make Presentation

Submit a technical memorandum and make a presentation to the technical panel summarizing the interviews and literature search and proposing the methodology for approval.

A draft Technical Memorandum summarizing Tasks 1 through 4 was developed and submitted to the SDDOT Project Manager on June 13, 2012 and presented to the Technical Panel on June 15, 2012 in Pierre, South Dakota. A revised Technical Memorandum, which incorporated responses to Technical Panel comments, was submitted on July 3, 2012 and accepted by the Project Manager on July 13, 2012.

Task 6: Develop Software

Upon the technical panel's approval of the methodology, develop the software that will be used to generate pavement performance curves.

The PPM tool has been developed as a stand-alone Windows .NET application that runs under the Windows XP operating system (Service Pack 3), as well as Windows 7.The PPM tool software complies with BIT software requirements. The PPM tool software has been installed on a network drive and can be accessed by multiple users.

Task 7: Demonstrate Software and Submit Technical Memo

Demonstrate the software on a small number of curves and submit a technical memorandum to the technical panel for approval.

A web-based PPM tool software demonstration was provided on October 25, 2012 via conference call and Join.Me meeting technology. The draft Technical Memorandum summarizing the features and capabilities of the PPM tool was submitted to the SDDOT Project Manager on October 29, 2012. Comments received on the draft Technical Memorandum were incorporated into the final Technical Memorandum, which was submitted on November 7, 2012.

Task 8: Develop Performance Models

Develop performance curves for all of SDDOT's pavement families and distress types using historical pavement data.

The 17 years (1995 to 2011) of data was extracted from dTIMS by SDDOT's Office of Project Development and provided to the research team in .xml format. The research team imported the .xml files (due to file size, data was exported into two files, one containing data from 1995 to 2003 and the other containing data from 2004 to 2011) into the PPM tool. In addition, the Office of Project Development provided the research team with the existing performance prediction models for each pavement type and curve flag combination. The research team used these performance equations to define the current family trees. The current SDDOT pavement families are shown in table 4-1. A complete list of the existing SDDOT performance prediction equations are provided in Appendix C.

Review of dTIMS Database

Upon review and use of the extracted dTIMS data, the research team noted the following discrepancies in the database file:

- A number of pavement segments had unreasonably high condition indices at a very high surface age (e.g., condition index greater than 4.0 at surface ages greater than 30 years). After discussing this issue with SDDOT Pavement Management, it was determined that a number of pavement segments should be excluded from the analysis. To address this issue, the SDDOT inserted a data exclusion code into dTIMS and exported a revised data file for use the by the research team. The data exclusion codes and the action taken for cleansing the database are shown in table 4.2. Rather than removing the data from the exported dTIMS database, the current condition indicator value was replaced with a value of 9.99.
- In some instances the RUFF index was not reset to "5" with the other condition indices after treatment application.
- Several pavement segments were found to have an inconsistent curve flag definition (a treatment type designation that is not typically associated with the specified pavement type, for example,

TONW-P, MESH-M) or a pavement type or curve flag was found to lack a performance model. Segments with inconsistent curve flags are identified as the cross-hatched cells in table 4-3. The shaded cells indicate a pavement type and curve flag designation that currently does not have performance models.

Table 4-1. Current family tree definition—asphalt-surfaced and gravel pavements.

	Pavement Type Code	Curve Flag Code	Description
Asphalt	AONC	O	Asphalt on concrete – original construction
		A	Asphalt on concrete – asphalt overlay
		M	Asphalt on concrete – mill and asphalt overlay
	BLOT	O	Blotter – original construction
	FD	O	Full-depth asphalt – original construction
		A	Full-depth asphalt – asphalt overlay
		F	Full-depth asphalt – full-depth mill and asphalt overlay
	THK	O	Thick asphalt – original construction
		A	Thick asphalt – asphalt overlay
		M	Thick asphalt – mill and asphalt overlay
	TONS	O	Thin asphalt on strong base – original construction
		A	Thin asphalt on strong base – asphalt overlay
		M	Thin asphalt on strong base – mill and asphalt overlay
	TONW	O	Thin asphalt on weak base – original construction
		A	Thin asphalt on weak base – asphalt overlay
		M	Thin asphalt on weak base – mill and asphalt overlay
Concrete	CRCP	O	Continuously reinforced concrete – original construction
	MESH	O	Mesh reinforced concrete – original construction
		J	Mesh reinforced concrete – minor joint and spall repair
		P	Mesh reinforced concrete – major joint and spall repair
		G	Mesh reinforced concrete – ground concrete
	TKSJD	O	Thick, short jointed, doweled concrete
		J	Thick, short jointed, doweled concrete – minor joint and spall repair
		P	Thick, short jointed, doweled concrete – major joint and spall repair
		G	Thick, short jointed, doweled concrete – ground concrete
	TKSJ	O	Thick, short jointed concrete
		J	Thick, short jointed concrete – minor joint and spall repair
		P	Thick, short jointed concrete – major joint and spall repair
		G	Thick, short jointed concrete – ground concrete
	TNSJ	O	Thin, short jointed concrete – minor joint and spall repair
		J	Thin, short jointed concrete – major joint and spall repair
		P	Thin, short jointed concrete – ground concrete
	GRAV	O	Gravel

Table 4-2. Data exclusion codes and database action.

Exclusion Code	Reason	Database Action Taken[1]	Fields Replaced[2]
1	Section length less than 0.15 miles	Exclude TRCR, FTCR, PTCH, BLCR, DASR, JTSP, CRCR, JTSL, POUT, FLTG, RUT, RUFF	184,041
2	Badlands and Wind Cave National Parks Highways	Exclude TRCR, FTCR, PTCH, BLCR, DASR, JTSP, CRCR, JTSL, POUT, FLTG, RUT, RUFF	18,648
3	Black Hills Highways	Exclude TRCR, FTCR, PTCH, BLCR, DASR, JTSP, CRCR, JTSL, POUT, FLTG, RUT, RUFF	959,000
4	Any spur route less than 1.2 miles long	Exclude TRCR, FTCR, PTCH, BLCR, DASR, JTSP, CRCR, JTSL, POUT, FLTG, RUT, RUFF	3,343
5	Any route designated as a "do-nothing" segment	Exclude TRCR, FTCR, PTCH, BLCR, DASR, JTSP, CRCR, JTSL, POUT, FLTG, RUT, RUFF	58,121
6	Inaccurate surface age or grade age	Exclude TRCR, FTCR, PTCH, BLCR, DASR, JTSP, CRCR, JTSL, POUT, FLTG, RUT, RUFF	0
7	Outdated visual data only for the rated year	Exclude TRCR, FTCR, PTCH, BLCR, DASR, JTSP, CRCR, JTSL, and POUT	48,582
8	Outdated profile data only for the rated year	Exclude RUFF, RUT, and FLTG	35,961
9	Outdated visual and profile data.	Exclude TRCR, FTCR, PTCH, BLCR, DASR, JTSP, CRCR, JTSL, POUT, FLTG, RUT, RUFF	95,751
10	All concrete visual data in 2005 where JRo rated.	Exclude TRCR, FTCR, PTCH, BLCR, DASR, JTSP, CRCR, JTSL, and POUT	45,918
11	Faulting data from 2008 to 2013.	Exclude FLTG	7,634
12	Rutting data in 2009.	Exclude RUT	24,785
13	Segment ends at an intersection	Exclude TRCR, FTCR, PTCH, BLCR, DASR, JTSP, CRCR, JTSL, POUT, FLTG, RUT, RUFF	0
14	All visual data rated by BB in 2011.	Exclude TRCR, FTCR, PTCH, BLCR, DASR, JTSP, CRCR, JTSL, and POUT	35,154
15	Reserved for future use.	Do nothing	0

[1] See Table 4-4 for performance indicator abbreviation description.
[2] Total number of fields replaced with a value of 9.99.

Table 4-3. Number of pavement segments by pavement type and curve flag.

Pavement Type	Curve Flag (from table 4-1)											Total
	A	F	G	J	M	O	P	U[1]	BRDG	OTHR	???	
AONC	636			2	792	3,238						4,668
BLOT						979						979
FD	575	813			18	362						1,768
THK	9,389	3		2	8,013	3,122					2	20,531
TONS	7,516				2,294	8,724						18,534
TONW	3,815	1	1		998	2,666	1					7,482
CRCP			72	281		2,508	17					2,878
MESH			790	2,651	1	301	317	21				4,081
TKSJ	5		305	1,356		1,204	9	460				3,339
TKSJD	10		308	1,492	1	4,373	8	36				6,228
TNSJ			33	532		555	13	208				1,341
BRDG									64			64
GRAV						411						411
OTHR										2,549		2,549
???											1,133	1,133
Total	21,946	817	1,509	6,316	12,117	28,443	365	725	64	2,549	1,135	75,986

[1] Underseal.

Note: Cross-hatched cells indicate potentially inconsistent curve flag designation, and shaded cells indicate performance curves not included in 2004 performance model update.

Steps for Determining Recommended Models

The following provides a brief summary of the steps that were used to determine the recommended performance prediction models. Detailed information related to PPM tool functionality is provided in the user manual submitted separately.

1. **Data Definition.** The first step involved importing the dTIMS data file, and defining the data contained in each column of the database (table 4-4).

Table 4-4. PPM tool data definitions.

dTIMS Column Name	Field Name	Field Type[1]	Annual Data
BLCR	Block Cracking	Condition Indicator	Yes
CRCR	Corner Cracking	Condition Indicator	Yes
DASR	D-Cracking/ASR	Condition Indicator	Yes
FLTG	Faulting	Condition Indicator	Yes
FTCR	Fatigue Cracking	Condition Indicator	Yes
GRVL	Gravel	Condition Indicator	Yes
JTSL	Joint Seal Damage	Condition Indicator	Yes
JTSP	Joint Spalling	Condition Indicator	Yes
POUT	Punchouts	Condition Indicator	Yes
PTCH	Patch Deterioration	Condition Indicator	Yes
RUFF	Roughness	Condition Indicator	Yes
RUT	Rut Depth	Condition Indicator	Yes
SCI	Composite Index	Condition Indicator	Yes
TRCR	Transverse Cracking	Condition Indicator	Yes
AREA_CODE	Area Name	Retain	
BEGIN_MRM	Begin MRM	Retain	
CUR_ADT	Traffic	Retain	
Elem_Id	Element ID	Retain	
FROM_ROAD	From	Retain	
GRVL_	Gravel Road	Retain	Yes
HWY	Highway	Retain	
PCT_TRUCK	Percent Trucks	Retain	
Road	Road	Retain	
SINCE_IMPR	Years Since Last Improvement	Retain	
To	To	Retain	
YEAR_INTL	Year of Initial Construction	Retain	
YR_LST_IMP	Year of Last Improvement	Retain	
Length	Length	Segment length	
CRV_FLG	Curve Flag	Subdivider	
PVTP	Pavement Type	Subdivider	Yes
SURF_AGE	Surface Age	X-Axis Value	Yes

[1] Refer to PPM tool user guide.

2. **Family Tree Building.** Next, each node, sub node, and associated condition indicator was defined. During this step, the research team used the current SDDOT pavement family definition, which are shown in tables 4-5 and 4-6 for asphalt- and concrete-surfaced pavements, respectively.
3. **Regression Analysis.** The following steps were used in the development of the regression models:
    a. Performance prediction models were evaluated using the 17 years of condition data, and then reviewed in relation to performance prediction model shape and resulting R^2 values. If a reasonable model shape (as expected for pavement management use) and R^2 value (greater than 0.60, in most cases) was determined, the performance prediction model with the best model shape and R^2 was selected. If a reasonable model was not obtained, the use of the median values only was evaluated (see next step).

Table 4-5. Current SDDOT asphalt-surfaced pavement families (SDDOT 2012a).

Pavement Type	Curve Flag	FTCR	TRCR	BLCR	PTCH	RUFF	RUT
AONC	O	✓	✓	✓	✓	✓	✓
	A	✓	✓	[1]	[1]	[1]	✓
	M	✓	✓	✓	✓	[1]	✓
BLOT	O	✓	✓	✓	✓	✓	✓
FD	O	✓	✓	✓	✓	✓	✓
	A	✓	✓	✓	[2]	[2]	✓
	F	✓	✓	✓	[2]	[2]	✓
THK	O	✓	✓	✓	✓	✓	✓
	A	✓	✓	✓	✓	✓	✓
	M	✓	✓	✓	✓	✓	✓
TONS	O	✓	✓	✓	✓	✓	✓
	A	✓	✓	✓	✓	✓	✓
	M	✓	✓	✓	✓	✓	✓
TONW	O	✓	✓	✓	✓	✓	✓
	A	✓	✓	✓	✓	✓	✓
	M	✓	✓	✓	✓	✓	✓

[1] Use AONC-O.
[2] Use FD-O.

Table 4-6. Current SDDOT concrete-surfaced pavement families (SDDOT 2012a).

Pavement Type	Curve Flag	CRCR	DASR	JPSP	JTSL	POUT	FLTG	RUFF
CRCP	O	✓	✓	✓	n/a	✓	n/a	✓
MESH	G	[1]	[1]	✓	✓	n/a	✓	✓
	P	✓	✓	✓	✓	n/a	✓	[2]
	J	✓	✓	✓	✓	n/a	✓	✓
	O	✓	✓	✓	✓	n/a	✓	✓
TKSJD	G	[3]	[3]	[3]	[3]	n/a	✓	✓
	P	[3]	✓	✓	✓	n/a	[3]	✓
	J	[3]	✓	✓	✓	n/a	[3]	✓
	O	✓	✓	✓	✓	n/a	✓	✓
TKSJ	G	[4]	[4]	[4]	[4]	n/a	✓	✓
	P	✓	[5]	✓	[6]	n/a	✓	[7]
	J	✓	✓	✓	✓	n/a	✓	✓
	O	✓	✓	✓	✓	n/a	✓	✓
TNSJ	P	[8]	✓	✓	[9]	n/a	✓	[8]
	J	✓	✓	✓	[7]	n/a	✓	✓
	O	✓	✓	✓	✓	n/a	✓	✓

[1] Use mesh concrete, new construction.
[2] Use mesh concrete, minor joint and spall repair.
[3] Use thick, short jointed, doweled, new construction.
[4] Use thick, short jointed, undoweled, new construction.
[5] Use thick, short jointed, undoweled, minor joint and spall repair.
[6] Use thick, short jointed, doweled, major joint and spall repair.
[7] Use thick, short jointed, doweled, minor joint and spall repair.
[8] Use thin, short jointed, undoweled, new construction.
[9] Use thick, short jointed, doweled, major joint and spall repair.

b. Sub data sets were evaluated using only the median values for each year of condition data. If a reasonable model shape and R^2 value was determined, the performance prediction model with the best model shape and R^2 was selected; if not, then a user-defined x-range boundary was evaluated (see next step).

c. Using the median value approach, a user-defined x-range boundary that resulted in the desirable model shape was determined. This was an iterative process; however, in some cases the data appeared to have a break in pavement condition from a surface age of 20 to 30 years. The break in condition was noted as a steady decline in condition over the first

20 to 30 years, a couple of years with no condition data, followed by higher condition indices than expected. In these instances, the selected x-range boundary coincided with the break in condition data; otherwise the surface age was reduced until the expected performance prediction model shape was obtained.

d. If none of the above resulted in a reasonable performance prediction model, the x- and y-range boundaries were adjusted until a reasonable model was obtained.

Figures 4-9 through 4-18 further illustrate this process. Figure 4-9 shows a screenshot of the roughness condition indicator for TONS-A. As shown, there is a very large dispersion of data both in relation to the roughness index value and the surface age (i.e., roughness index value ranges from 0 to 5 over the majority of surface ages). However, there is a larger concentration of data points, shown as the orange data points, which may result in a reasonably shaped performance prediction model and R2 value.

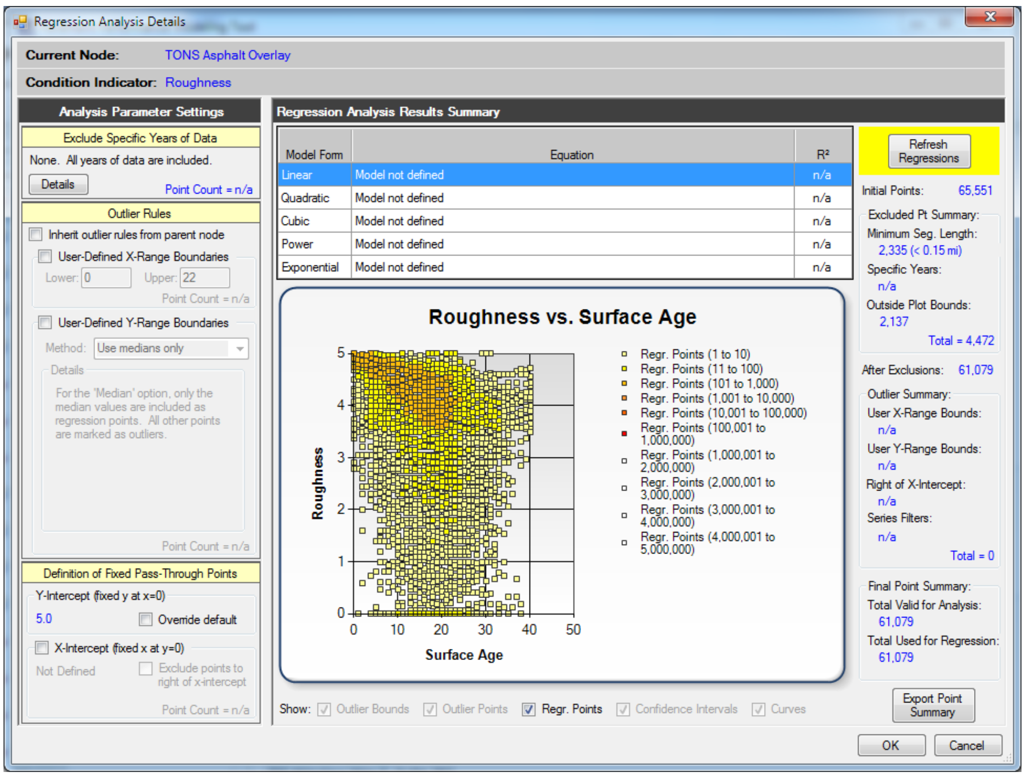


Figure 4-9. All condition data (TONS-A).

Using the available data, a regression analysis was conducted and the results are shown in figure 4-10. Five regression equations were included in the analysis, which show that none of the models result in the expected performance prediction model shape. As illustrated in the upper table of figure 4-10, the resulting R^2 values are low, ranging from 0.1845 (exponential model) to 0.1907 (cubic model).

The next analysis included the determination of the performance prediction models based on the median values of the condition indicator. The results of this analysis are shown in figure 4-11. The performance predication models using only the median values still do not result in the expected performance prediction model shape; however, the R^2 values, as expected, have increased and range from 0.6452 (exponential model) to 0.9600 (cubic model). It should also be noted that the cubic model results in an unrealistic model shape (i.e., decreases from a surface age of 0 to approximately 30 years, and then increases beyond year 30) and would not be selected for pavement management purposes since the same pavement condition could be obtained at multiple surface ages.

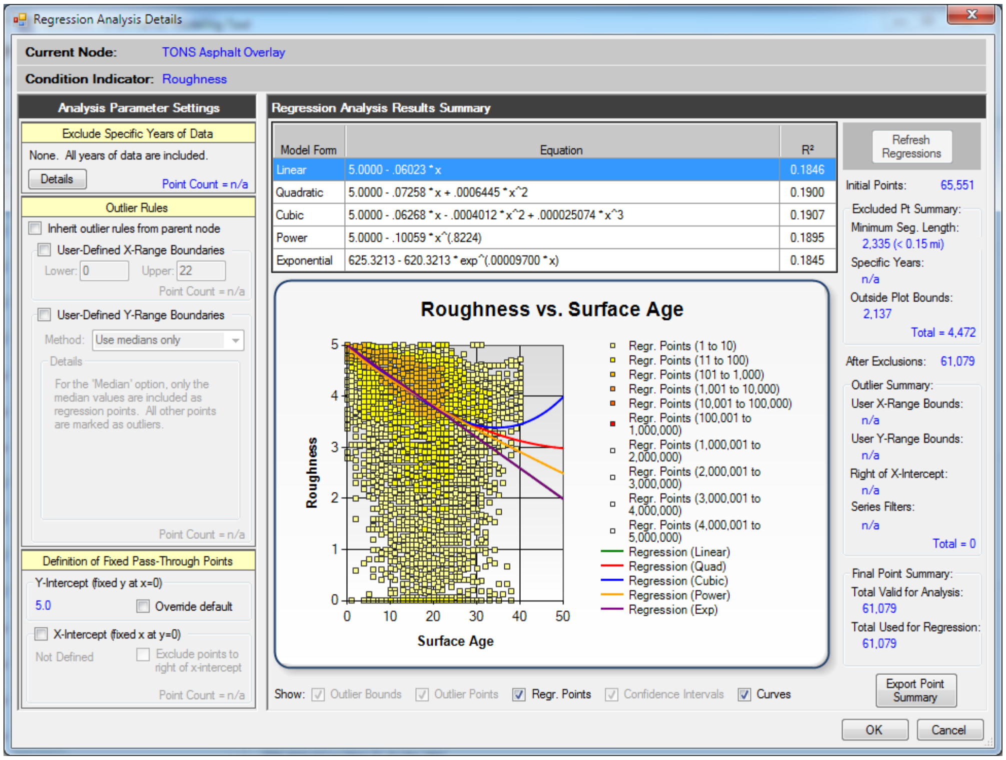


Figure 4-10. Performance prediction models using all condition data (TONS-A).

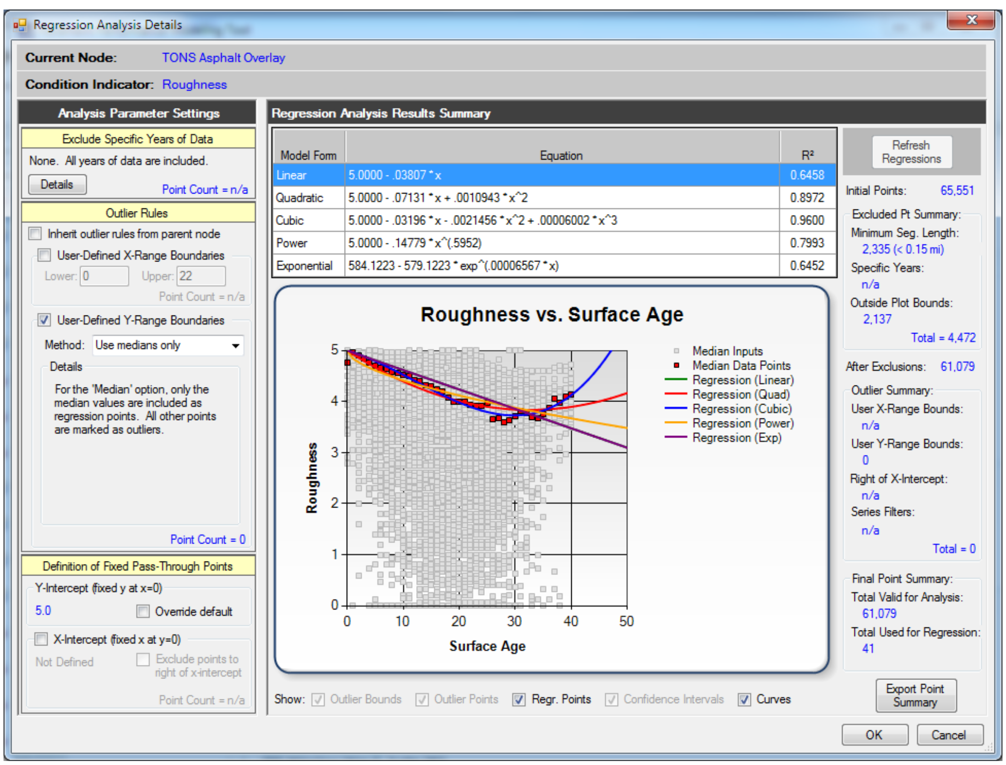


Figure 4-11. Performance prediction models using median condition values (TONS-A).

To determine if one of the performance prediction models can result in the expected performance prediction model shape, the user-defined x-range boundaries were adjusted (x-range boundary was reduced from an initial value of 50) until at least one of the performance prediction models resulted in the expected performance prediction model shape. This is an iterative process and should be based on knowledge of the pavement family and progression of pavement condition. At a surface age of 22 years the cubic performance prediction model met the expected performance prediction model shape (figure 4-12). The resulting R^2 value also improved to 0.9630.

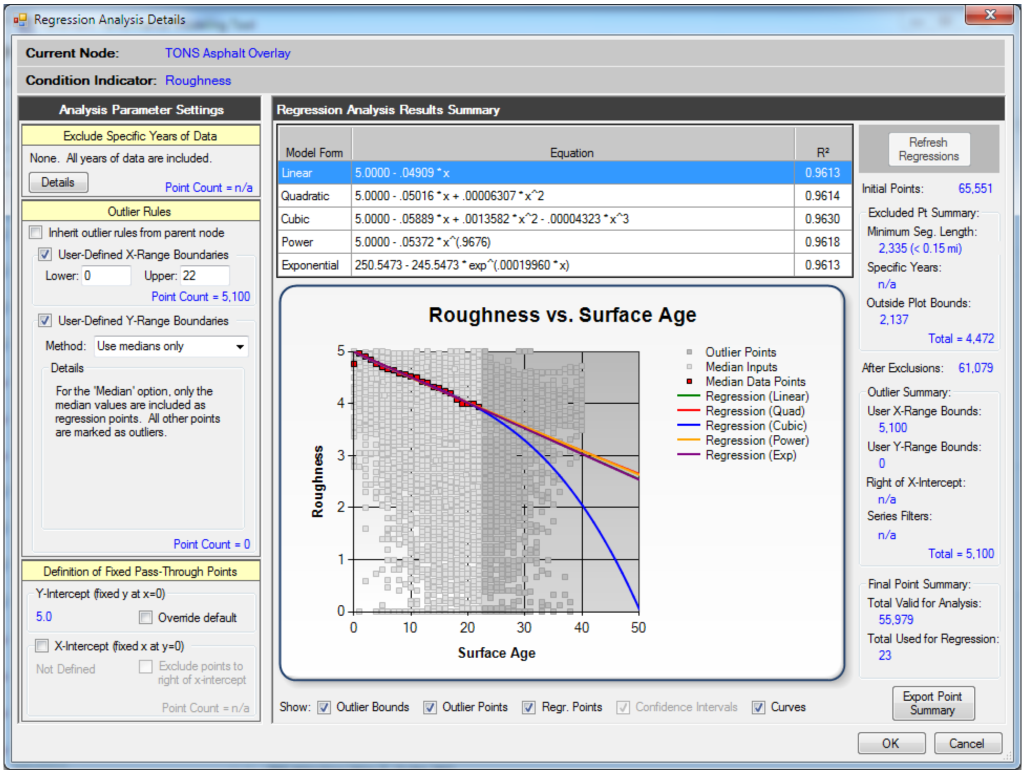


Figure 4-12. Performance prediction models using median condition values and x-range boundary (TONS-A).

The next example shows the rut depth for the AONC-O (figure 4-13). Using all of the condition data, there does not appear to be any obvious performance trends. Actually, the rut depth data appears to be concentrated at three condition values ranging from a surface age of 0 to 20 (as noted by the orange colored data points). There also appears to be a number of pavement sections with a relatively high rut depth index (i.e., greater than 4.0) at a surface age greater than 30 years.

Since there are no obvious performance trends, the pavement condition median values were selected for determining the performance prediction model, as shown in figure 4-14. The resulting median values appear to have two distinct groupings: surface age 0 to 27 and surface age 34 to 47. Although the exact cause of the latter grouping is unknown, this set of data seems to be unreasonable and was therefore excluded from the analysis. As shown in figure 4-15, a user-defined x-range boundary of 27 years was used to develop the performance prediction models. Specifying an x-range boundary of 27 years resulted in reasonably shaped exponential and quadratic models with R^2 values of 0.5803 and 0.3624, respectively. Since the exponential model results in a slightly higher R^2 value it would be selected as the recommended model.

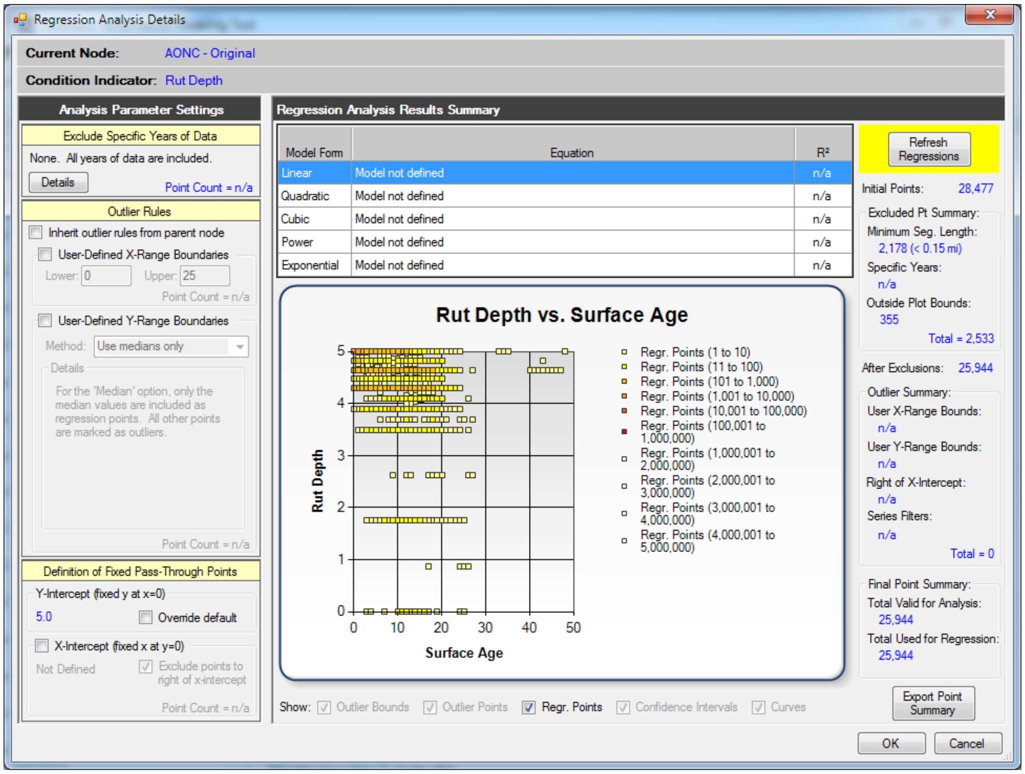


Figure 4-13. Example of all condition data (AONC-O).

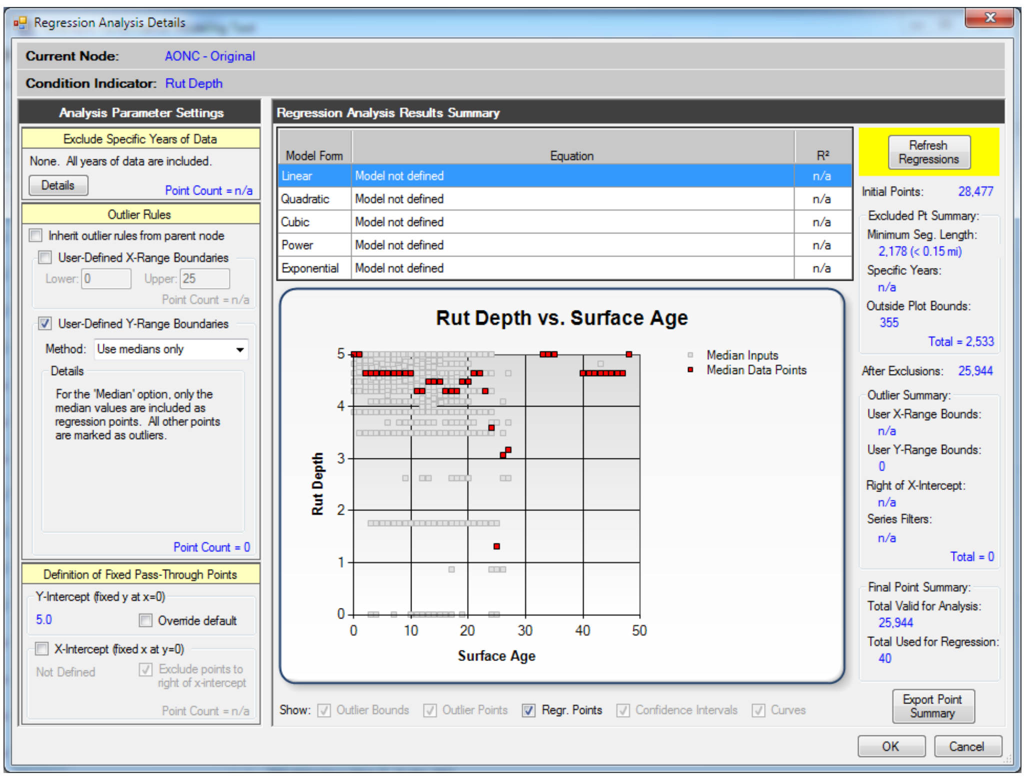


Figure 4-14. Example of median data (AONC-O).

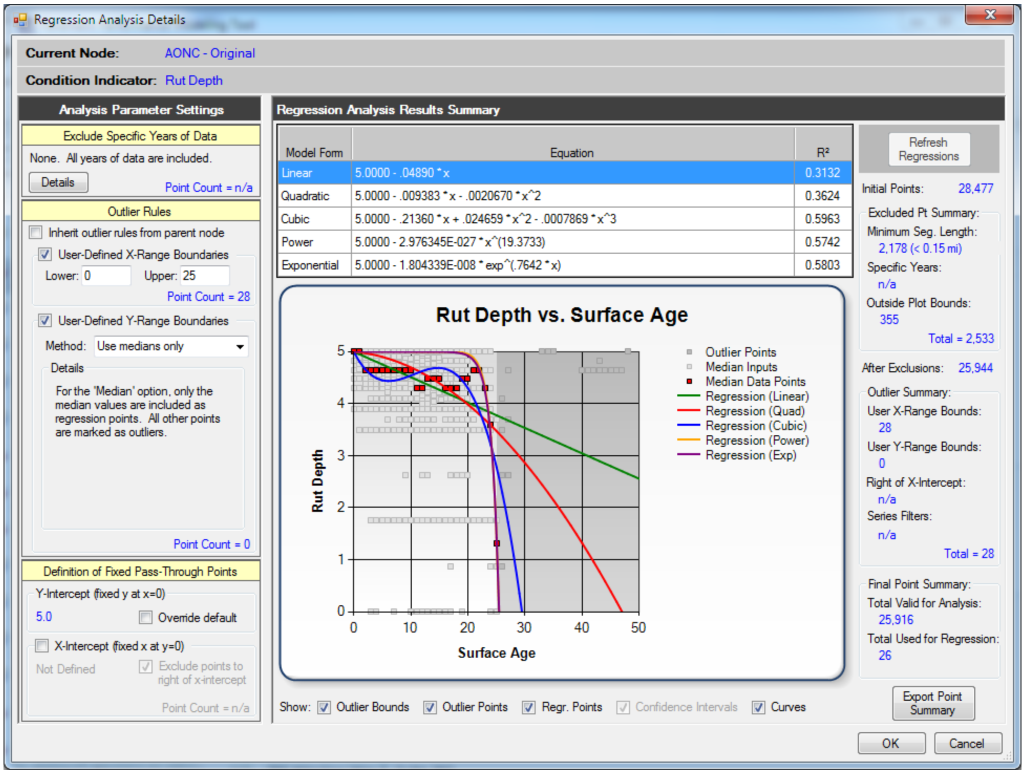


Figure 4-15. Example of x-range boundary and median value data (AONC-O).

Finally, figure 4-16 through figure 4-19 illustrate an example of the TKSJ-J pavement family where using neither all of the condition data nor the median values resulted in a reasonable performance prediction model shape. Figure 4-16 illustrates that there is a relatively low density of data points at any given surface age. There is a higher concentration of data at a faulting index of 5.0 between approximately 15 to 20 years, as well as a faulting index of 3.0 to 5.0 at a surface age of approximately 20 to 35 years. In this case, none of the performance prediction models result in an expected model shape.

Selecting the median values generated similar results (figure 4-17). In addition, changing the user-defined x-range boundary provided little improvement due to the large variation in the median values over the 50 year period. Specifically, there is a fairly broad range in the faulting index for the first 20 years, then a consistent downward trend in the faulting index from year 20 to 44, and then a broader faulting index range beyond year 44. The five performance prediction models resulted in very low R^2 values (0.0697 to 0.2023).

Further investigation would be warranted to determine the potential reasons for the broad range in the faulting index from zero to 20 years. In addition, the high faulting indices at a surface age greater than 40 years were determined to be outliers (although this should also be verified). Although the research team is experienced in pavement performance and performance prediction model development, outlier determination should be validated and/or reviewed by SDDOT prior to accepting any performance prediction model.

For the purpose of demonstrating the PPM tool capabilities and for this example, it was determined that faulting indices below 4.0 at year 20, and all data points beyond year 36 should be identified as outliers (figure 4-18). This results in reasonably shaped performance curves; however, the R^2 values are still relatively low and range from 0.1800 (linear) to 0.2717 (cubic).

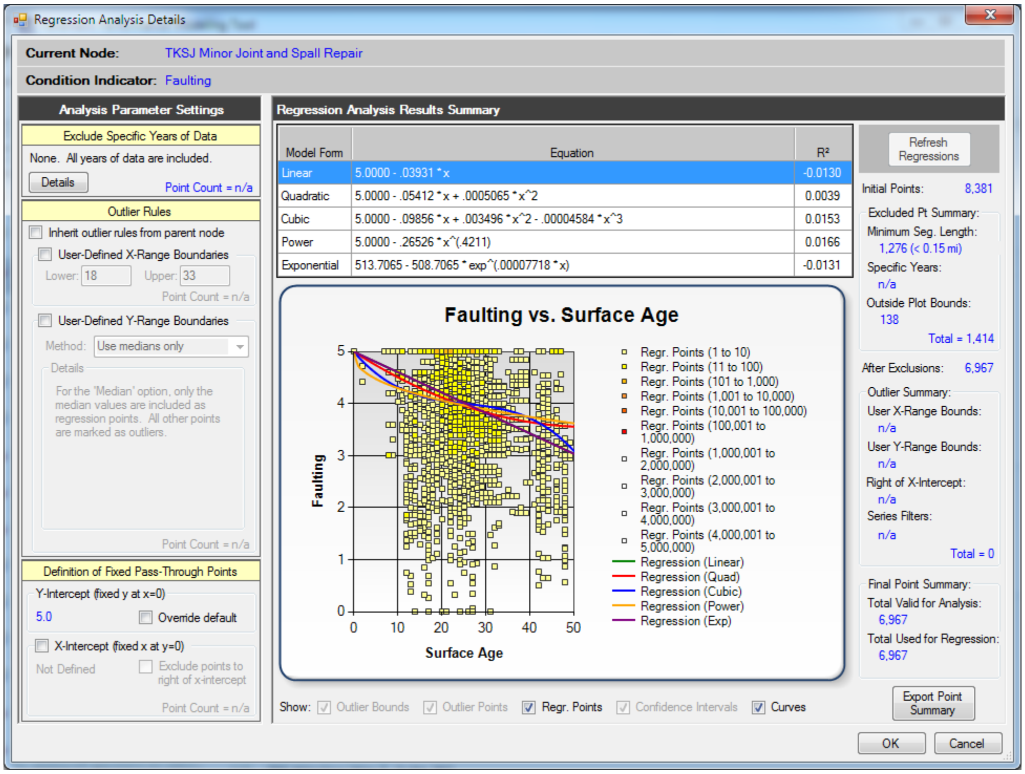


Figure 4-16. Example of all condition data (TKSJ-J).

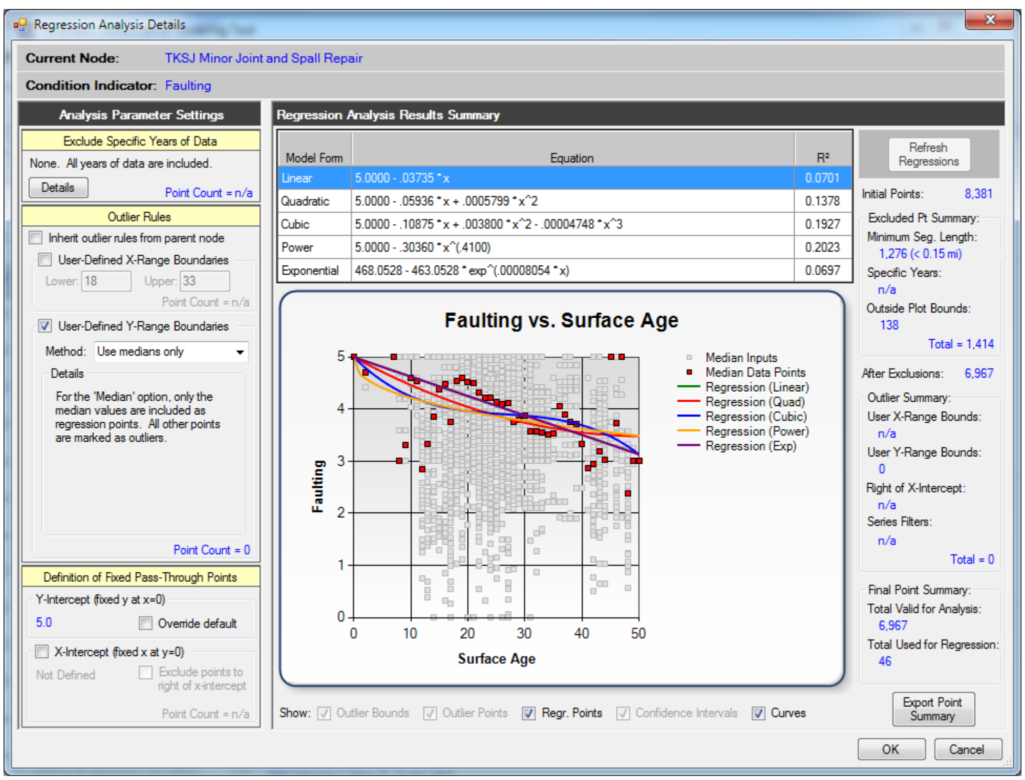


Figure 4-17. Example of all median values (TKSJ-J).

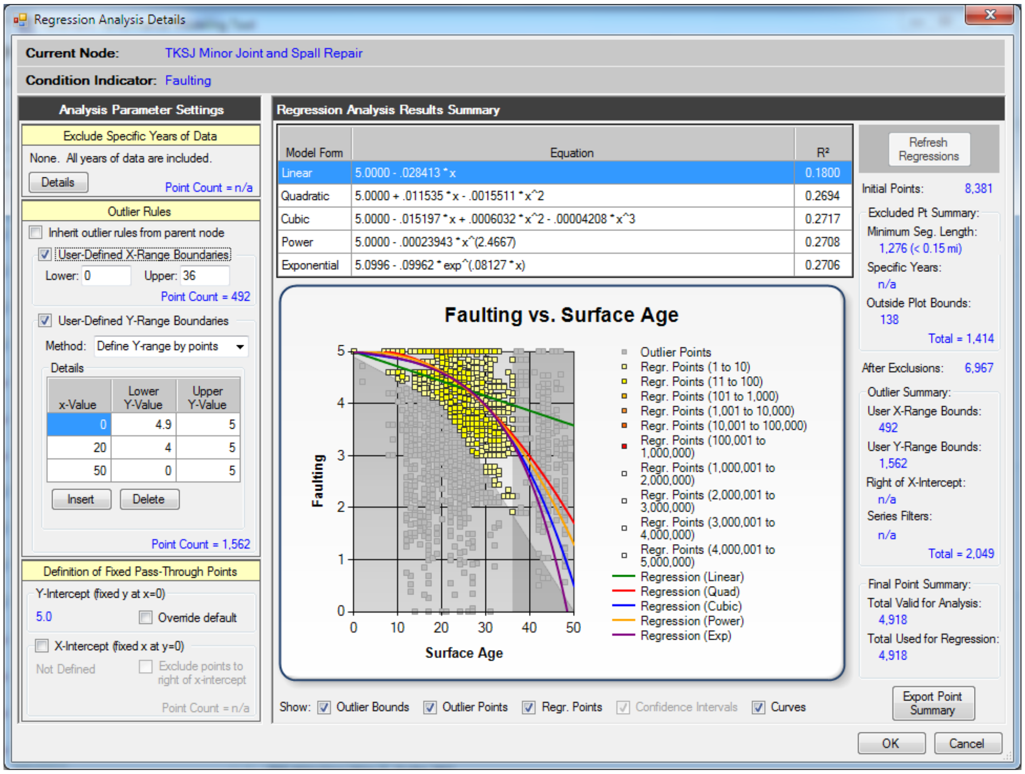


Figure 4-18. Example of x- and y-range boundaries (TKSJ-J).

Appendix E contains the PPM tool screenshots showing the results of the regression analysis for each pavement type in the SDDOT family tree (including "parent" performance curves) using all years of pavement condition data. Appendix E is arranged according to pavement type and curve flag and each screenshot shows both the revised performance model and, when applicable, the 2004 SDDOT determined performance model (shown as "User-Defined"). Appendix F contains the resulting update performance prediction model equations.

It should be noted that the performance prediction models for many of the pavement families show a significant difference from the existing SDDOT models. The impact of these differences should be evaluated prior to adopting the recommended models for use in the dTIMS pavement management software.

Task 9: Recommend Additional Families

Recommend additional families of curves and perform analysis on additional families of curves approved by the technical panel.

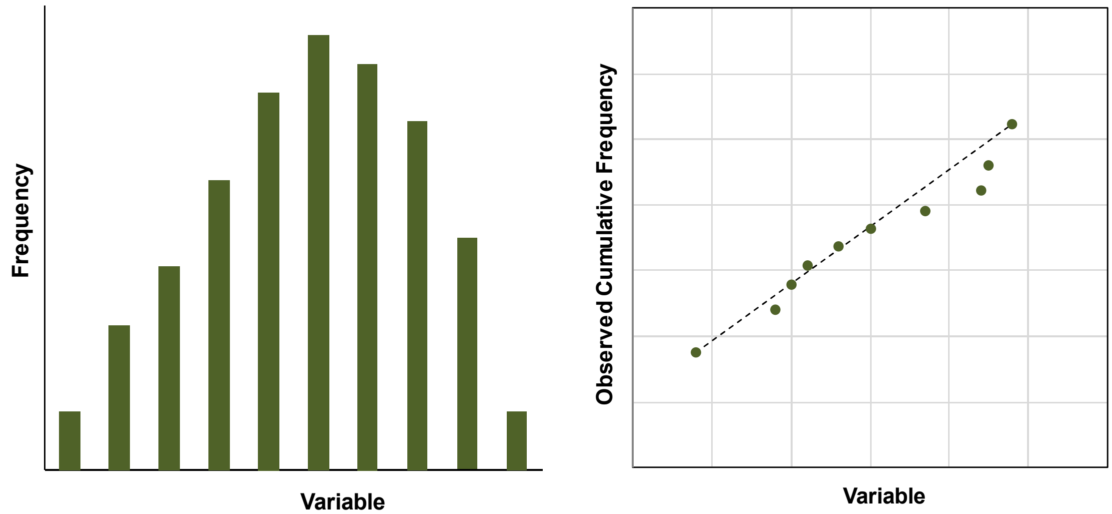
A statistical analysis of the data contained within the dTIMS database was conducted to determine if the current SDDOT definition of the pavement family tree by pavement type and curve flag is appropriate. Since asphalt and concrete pavements perform differently and are characterized by different distress types (except for IRI), the initial node of the family tree should be split into asphalt pavements and concrete pavements. From there, it also makes sense to further split the asphalt pavement and concrete pavements by pavement type, and by curve flag. However, what is unclear, and is the intent of this statistical analysis, is to determine if the current pavement type and curve flag definitions are appropriate or if they could be combined and/or further split.

The general approach used to conduct the "family tree statistical analysis" consists of the following activities:

1. Export asset data (e.g., asset type, age, treatment type and timing, condition indicator) to statistical software applicable file format. Many statistical analysis programs (e.g., Minitab, SAS, SPSS) are able to import data using Microsoft Excel spreadsheets.
2. Determine data reduction requirements. Evaluate the number of segments that can be analyzed based on the statistical software capabilities (i.e., the data set may require reduction to meet the maximum number of observations that can be analyzed with the statistical software). Data reduction may include limiting the number of years of data, averaging data for similar asset segments, or condensing other data elements.
3. Conduct data checks. Data checks may include:
    a. Identifying and removing asset types with insufficient data.
    b. Grouping data into applicable categories if performance is different for each asset type (e.g., asphalt pavements and concrete pavements).
    c. If multiple condition indicators are used (e.g., rutting, roughness, cracking for asphalt pavement), selecting one condition indicator that is more predominant in defining asset performance. Having multiple condition indicators will unnecessarily complicate the statistical analysis and reduce the ability to interpret the results.
4. Review and adjust the data set to ensure it meets the statistical analysis criteria. For example, the Analysis of Variance (ANOVA) (and other statistical methods) requires that the data be normally distributed. Statistical analysis programs, such as Minitab, SAS, and SPSS, as well as Microsoft Excel, include the functionality to evaluate the data set for normality. Common normality tests include histograms (figure 4-19a) and normal probability plots (figure 4-19b). Figure 4-19 represents the same data set presented as a histogram and as a probability distribution plot. The histogram graphically illustrates the data measurement scale (variable range) and counts (frequency). The normal probability plot graphically represents how well the data conforms to a hypothesized distribution. If the data is normally distributed it will plot along a straight line. For this example data set, the determination of normality is a subjective determination and looking at figure 4-19, the data appears to be normally distributed.
5. Develop the statistical model. The statistical model defines what variables (and their interaction) will be analyzed in the statistical analysis software.
6. Analyze the results.

Current Pavement Family Tree and dTIMS Database Structure

The current SDDOT pavement family tree is shown in figure 4-20. The first level of the pavement family tree is divided into two pavement groups, asphalt and concrete. The asphalt group includes five pavement types (BLOT, AONC, FD, TONS, and TONW), and the associated curve flag designations (O, A, F, and M). The concrete group also consists of five pavement types (MESH, TKSJD, TKSJ, TNSJ, CRCP), and the associated curve flag designation (O, G, J, and P).



a.Histogram b. Normal probability plot.

Figure 4-19. Graphical methods for testing data normality.

Prior to initiating the statistical analysis, a review of the dTIMS database was conducted to gain a better understanding of the database structure and its contents. The dTIMS database has several data levels and consists of both class and continuous variables. Class variables are data elements that are non-numerical (e.g., pavement type, Highway Region) or are numerical values that have been grouped into categories (e.g., surface age < 5 years, 5 to 10 years, and > 10 years). At the highest level are Area Code, Highway Region, and functional class. At the next level are highway and current ADT, followed by highway section with characteristics that vary along each individual highway. Within each highway section, data are arranged according to the year of data collection, pavement type, curve flag, and the associated condition indicator variables. The dTIMS data file structure is shown in figure 4-21.

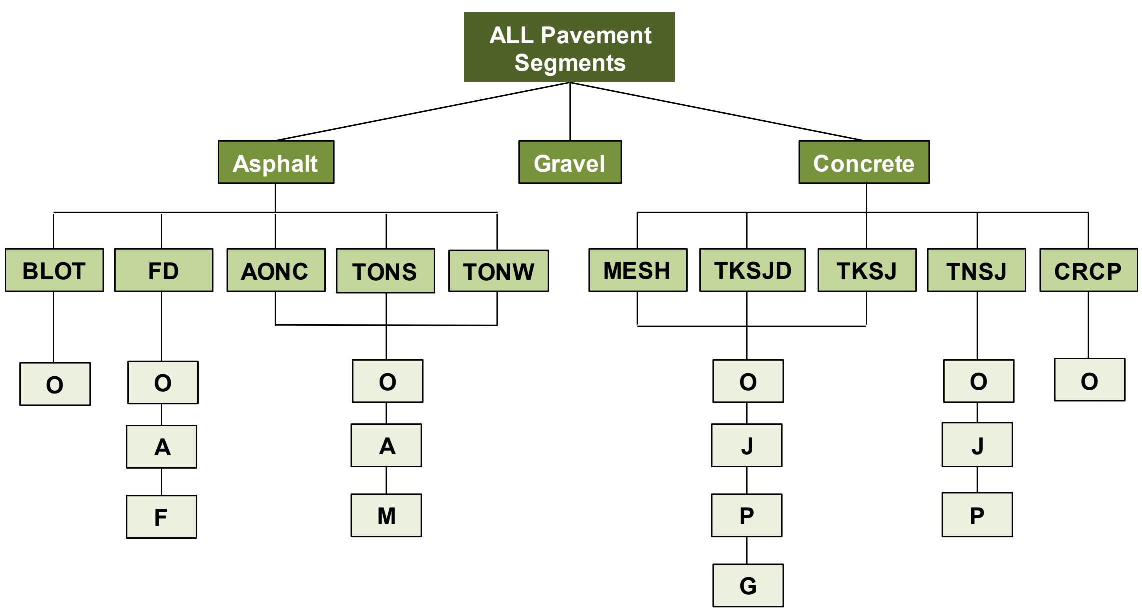


Figure 4-20. SDDOT current pavement family tree.

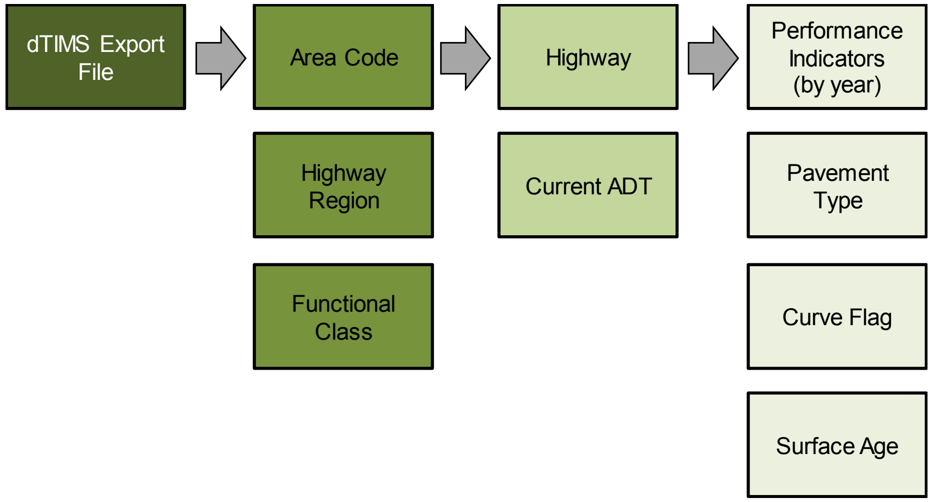


Figure 4-21. dTIMS database structure.

The following sections describe the process and results of the statistical analysis conducted in the evaluation of the current SDDOT pavement family tree definition.

Export Data

SDDOT Pavement Management provided an export of the dTIMS database in Microsoft Excel format. Due to the Microsoft Excel record length limitation, three spreadsheets were received containing data from 1995 to 1998, 1999 to 2003, and 2004 to 2008. Due to the large volume of data, the analysis of the family tree was based only on the data obtained from 2004 to 2008. Although that reflects only a 5-year subset of the 17 years of available data, pavement segments of all ages, pavement types, and curve flags were included in the statistical analysis. The use of all 17 years of data, or more than 600,000 records, is too extensive to be analyzed by even the more robust statistical analysis programs (e.g., Minitab, SAS, SPSS). The use of only 5 years of data is believed to have no significant impact on the results of the statistical analysis (i.e., the statistically significant variables would be the same regardless of the number of years of data used in the analysis, as long as sufficient data are available for each pavement type and curve flag combinations). Each year of the data set has a total of 36,327 observations and, if this is expanded to include all 5 years (2004 to 2008), then there are a total of 181,635 observations, which is still too extensive to manage within a statistical analysis program.

Data Reduction

In order to perform the statistical analysis using an appropriate, but rather complicated approach, it is necessary to first reduce the data set to a more reasonable number of observations. The data set was first reduced by removing any condition indices containing a value of 9.99 (indicating that the condition indicator is not applicable to the pavement type or was identified for exclusion by SDDOT Pavement Management). Next, the condition indices data were averaged over a one-mile length for each year, highway section, but only for like pavement types for each surface age. With these two reductions, the data set was reduced from 181,635 to 47,413 observations, which is much more manageable within a statistical analysis program. A summary of the resulting number of pavement segments for each pavement type and curve flag combination is shown in table 4-7.

Table 4-7. Revised number of pavement segments by pavement type and curve flag.

	Pavement Type	Curve Flag							Subtotal	Total
		O	A	M	F	J	P	G		
Asphalt	AONC	2,273	191	450		14			2,928	21,942
	FD	168	257	5	731				1,161	
	THK	2,324	6,321	6,745					15,390	
	TONS	8,146	4,527	970					13,643	
	TONW	1,679	2,077	454					4,210	
Concrete	MESH	47				720	218	6	991	24,184
	CRCP	1,466				215	40	36	1,757	
	TKSJ	398	1			579	10	138	1,126	
	TKSJD	3,543	7	10		486	8	213	4,267	
	TNSJ	351				273	25	4	653	
Other	BLOT	463	28						491	1,287
	BRDG	105							105	
	GRAV	421	1						422	
	OTHR	230	38	1					269	
	Total	21,614	13,448	8,635	731	2,287	301	397	47,413	

Based on the results shown in table 4-7, a number of pavement segments were excluded from the statistical analysis or modified as follows:

- GRAV and BLOT pavement types were excluded from the statistical analysis due to a limited number of pavement segments (422 and 491 pavement segments, respectively). In addition, GRAV and BLOT pavement types are considered unique, in that they would not necessarily be grouped with other pavement types (i.e., asphalt or concrete).
- CRCP was excluded from the statistical analysis due to the unique performance indicator for this pavement type (i.e., punchouts) compared to those for other concrete pavement types (i.e., faulting, joint spalling).
- All OTHR pavement types were excluded from the statistical analysis because the pavement type cannot be determined.
- All BRDG segments were excluded from the statistical analysis since they are not pavements.
- Pavement segments designated as FD-F were relabeled to FD-M. Although the depth of milling and the asphalt overlay thickness of a full-depth mill and asphalt overlay (F) and a mill and asphalt overlay (M) may be different, the application of the treatment was considered to be the similar (i.e., a mill and asphalt overlay of an existing asphalt pavement).

Since asphalt and concrete pavements perform differently and are evaluated using different distress types (except for IRI), each pavement segment was then grouped into two categories: asphalt-surfaced and concrete-surfaced.

Import Data into Statistical Program

The pavement data was imported into the SAS program using Microsoft Excel file format.

Conduct Data Checks

The minimum, maximum, mean value, and total number of pavement segments (or observations) for each performance indicator was determined (table 4-8). From this evaluation only roughness and surface condition index (SCI) were selected to represent common performance indicators across all pavement segments. Since the SCI is calculated from a combination of the other distresses, it was determined to be the best condition indicator to use in the evaluation of the pavement family tree. This does not imply that the other distress types (and IRI) are not important; however, evaluating the family tree using multiple variables would only confound the analysis and greatly reduce the interpretation of the results.

Table 4-8. Performance indicator summary.

	Performance Indicator	Definition	Range	Mean	No. of Observations
Asphalt	BLCR	Block cracking	0.00 – 5.00	4.58	38,300
	CRCR	Corner cracking	1.80 – 5.00	4.91	8,936
	FTCR	Fatigue cracking	0.00 – 5.00	4.57	38,300
	RUT	Rutting index	0.00 – 5.00	4.45	38,300
	TRCR	Transverse cracking	0.00 – 5.00	4.46	38,300
Concrete	DASR	D-Cracking/ASR	0.00 – 5.00	4.61	8,936
	FLTG	Faulting	0.00 – 5.00	4.45	7,179
	JTSL	Joint seal damage	0.00 – 5.00	3.99	8,936
	JTSP	Joint spalling	0.00 – 5.00	4.02	8,936
	PTCH	Patch deterioration	0.00 – 5.00	4.81	38,300
	POUT	Punchout	2.29 – 5.00	4.98	8,936
	RUFF	Roughness index	0.00 – 5.00	4.25	47,413
	SCI	Surface condition index	0.00 – 5.00	3.91	47,413

The data was also reviewed according to functional class. This evaluation was conducted since pavement performance can be significantly different across functional classes due to the level of truck traffic. In general, functional class can be used to represent a level of ADT (i.e., interstate typically has higher traffic levels than principal arterials; principal arterials typically have higher traffic levels than minor arterials; and so on). Table 4-9 summarizes the number and percent of total pavement segments by functional class. Since the majority of pavement segments are on functional classes 01, 02, 06, and 07, only these roadway segments were used in the statistical analysis.

Table 4-9. Functional class distribution.

Functional Class Code	Description	Number Pavement Segments	Percent of Pavement Segments
01	Rural Principal Arterial – Interstate	783	8.3
02	Rural Principal Arterial – Other	3,084	32.5
06	Rural Minor Arterial	3,906	41.1
07	Rural Major Collector	1,321	13.9
09	Rural Local Roads	10	0.1
11	Urban Principal Arterials – Interstate	108	1.1
12	Urban Principal Arterial – Freeway	18	0.2
14	Urban Other Principal Arterial	180	1.9
16	Urban Minor Arterial	78	0.8
17	Urban Collector	7	0.1

A hierarchical mixed model ANOVA, using a significance level of 0.10, was the statistical analysis approach selected for evaluating the definition of the pavement family tree. The ANOVA model includes factors for evaluating random effects, fixed effects, and the error structures at different levels. The ANOVA is used to get an overall picture of how the different effects explain the variation in the data and where the differences in the levels of effects happen. Fixed effects are the variables that represent the variable of interest. On the other hand, the random effects includes variables were the value of the variable is not of particular interest, just interesting as a representative of other variables or not interesting at all (i.e., a nuisance variable). For example, if in the evaluation of pavement performance curves the Highway Region is of specific interest, then the Highway Region would be the fixed effect. However, if the variable of interest is functional class, pavement type, and curve flag, regardless of Highway Region, then Highway Region would become a random effect.

From the ANOVA results, an F-test is conducted to identify if the standard deviations are the same across pavement families and the p-value determined to indicate the likeliness of the observed result. If the p value is less than the significance level (α, chance of incorrectly rejecting the null hypothesis when it is true for $\leq \alpha$), the null hypothesis (H_o: $\mu_1 = \mu_2$) is rejected, meaning that there are differences in performance between the pavement families. If the adjusted p value is greater than α, the null hypothesis cannot be rejected (i.e., no evidence to conclude that another hypothesis is preferred over the null hypothesis, and there are no differences in performance between the pavement families).

The ANOVA was identified to be the best approach for evaluating the variation among and between the pavement type and curve flag designations within each pavement group (i.e., asphalt and concrete). The ANOVA provides a statistical test that can be used to infer whether the pavement condition means of each pavement type and curve flag designation are likely to come from the same population (or data set); if this is demonstrated, then it may imply that pavement type and curve flag designations can be combined. Thus, it is the method that is used to help determine whether a fledgling pavement family should be combined with other families (if there are no significant observed differences) or whether it should be kept separate (if there are significant observed differences).

Prior to conducting the ANOVA, the following assumptions must be met:

- Independent observations. The occurrence of one observation doesn't affect another.
- Standard deviations of data groups (e.g., condition data from year to year) are equal.
- Normality of residuals. Residuals are the difference between the observed value and the estimated value, and can be thought of as the error in the fitted model. A close look at the residuals can help to determine if the statistical assumptions are reasonable and if the selected statistical model is appropriate. The residuals should occur in a random fashion and the level of the error should be independent of when the observation occurred, the number of the observations being predicted, or in the factors used to make the prediction (NIST 2012). The histogram of residuals should be similar to a bell-shaped pattern (NIST 2012).

In order to satisfy the last assumption, variables that are not normally distributed should be transformed to meet the requirement for normality. As an example of a non-normal distribution, figure 4-22 illustrates the histogram for SCI that depicts a skewed distribution, with an upper bound of 5.0 and a lower bound of 0.

When the histogram is skewed towards a maximum value other than 0, the first step of the transformation process is to subtract the observed values from the maximum value, which in this case equals 5.0. Next, the data are adjusted by taking the log, square root, quadratic root, or cubic root of the data values (i.e., data transformations) to determine which would result in a more normally distributed SCI variable. The cubic root transformation was found to results in the most normal distribution (based on a visual perception of the data) for the SCI variable. Finally, the transformed data is subtracted from the cubed root of the maximum value (Equation 4-1).

$$trfSCI = 5.0^{1/3} - (5.0 - SCI_{observed})^{1/3} \quad (4\text{-}1)$$

where:

$trfSCI$ = Transformed SCI variable.

$SCI_{observed}$ = SCI value for each pavement segment for each year.

```
                   Histogram                           #  Boxplot
 5.1+***                                             440     |
    .********************************               5293     |
    .************************************************ 7960  +-----+
    .*************************************          6016  |     |
    .****************************                   4601  *-----*
 4.1+**********************                         3525  |     |
    .*******************                            3117  |  +  |
    .*****************                              2819  |     |
    .***************                                2433  +-----+
    .************                                   1853     |
 3.1+**********                                     1591     |
    .********                                       1316     |
    .********                                       1192     |
    .******                                          955     |
    .*****                                           745     |
 2.1+****                                            605     |
    .****                                            552     |
    .***                                             473     0
    .***                                             430     0
    .***                                             414     0
 1.1+***                                             334     0
    .**                                              255     0
    .*                                               163     0
    .*                                               103     0
    .*                                               111     0
 0.1+*                                               141     0
     ----+----+----+----+----+----+----+----+----+---
     * may represent up to 166 counts
```

Figure 4-22. SCI histogram—untransformed.

The histogram of the transformed SCI data is shown in figure 4-23. ADT and surface age variables were also very skewed and required transformation. For both of these variables, the log transformation provided the best results (see figures 4-24 through 4-27).

```
                   Histogram                           #  Boxplot
 1.75+****                                           440     0
     .*****                                          535     |
     .*                                               72     |
     .***                                            271     |
     .**********                                    1156     |
     .**********************************            4103     |
     .**********************************************  5535  +-----+
     .************************************************ 5844  |     |
     .*********************************************  5430  |     |
     .*****************************************     4973  *--+--*
     .*****************************************     4971  |     |
     .*************************************         4482  +-----+
     .*****************************                 3458     |
     .**********************                        2601     |
     .***************                               1727     |
     .***********                                   1285     |
 0.05+*****                                          554     |
      ----+----+----+----+----+----+----+----+----+---
      * may represent up to 122 counts
```

Figure 4-23. SCI histogram—cubed transformation.

```
                          Histogram                          #  Boxplot
29000+*                                                      5     *
     .*                                                     55     *
     .*                                                     27     *
     .*                                                     37     *
     .*                                                     95     *
     .*                                                     94     *
     .*                                                    228     *
15000+*                                                    276     *
     .*                                                    278     *
     .*                                                    384     *
     .**                                                  1031     *
     .**                                                  1462     0
     .****                                                3294     0
     .***********                                         9985  +-----+
 1000+************************************************   43752  *--+--*
      ----+----+----+----+----+----+----+----+----+---
      * may represent up to 912 counts
```

Figure 4-24. ADT—untransformed.

```
                          Histogram                          #  Boxplot
10.25+*                                                    119     0
     .****                                                 778     0
     .*******                                             1577     |
 8.75+*************                                       3001     |
     .*************************                           6190     |
     .*****************************                       7137  +-----+
 7.25+******************************************         10349  |     |
     .************************************************   11949  *--+--*
     .**************************************              9232  +-----+
 5.75+***********************                             5709     |
     .***********                                         2719     |
     .******                                              1482     |
 4.25+***                                                  747     |
     .*                                                      4     0
     .*                                                      5     0
 2.75+*                                                      5     0
      ----+----+----+----+----+----+----+----+----+---
      * may represent up to 249 counts
```

Figure 4-25. ADT histogram—log transformation.

```
                        Histogram                          #  Boxplot
82.5+*                                                    10     *
    .*                                                     5     *
    .*                                                    30     *
    .*                                                     7     *
    .
    .*                                                     7     0
    .**                                                  434     0
    .***                                                 945     0
42.5+****                                               1049     0
    .****                                               1079     0
    .****                                               1085     |
    .******                                             2025     |
    .***************                                    4959     |
    .*************************                          8501  +-----+
    .*******************************                   10412  |  +  |
    .******************************************        14111  *-----*
 2.5+************************************************  16444  +-----+
     ----+----+----+----+----+----+----+----+----+---
     * may represent up to 343 counts
```

Figure 4-26. Surface age histogram—untransformed.

```
                      Histogram                            #  Boxplot
4.5+*                                                      8     |
   .*                                                     42     |
   .*                                                     62     |
   .************                                        1579     |
   .*************                                       1709     |
   .************                                        1547     |
   .*****************                                   2270     |
   .********************************                    4424     |
   .************************************************    6656  +-----+
   .*******************************************         5973  |     |
   .*******************************                     4270  |     |
2.3+********************************                    4370  *-----*
   .*****************************************           5578  |  +  |
   .***********************                             3075  |     |
   .*********************************************       6238  +-----+
   .**                                                   161     |
   .**********************                              2977     |
   .***********************                             3066     |
   .*                                                     62     |
   .**********************                              2979     |
   .*                                                     52     |
   .*                                                      7     |
0.1+*****************************                       3998     |
    ----+----+----+----+----+----+----+----+----+---
    * may represent up to 139 counts
```

Figure 4-27. Surface age histogram—log transformation.

Develop Statistical Model

The statistical model is used to evaluate how one or more random variables are related to one or more other variables. The first step in developing the statistical model is to identify the fixed and the random effects. For this analysis, the fixed effects include the condition indicator and surface age. The random effects include highway number since it represents a label that is associated with other measures specific to a roadway segment. The Highway Region by Area Code is also treated as a random effect to account for the proper error structure. Asphalt and concrete pavements were analyzed separately. The analyses were also performed separately for each functional class. Table 4-10 provides a list of the class variables, and fixed and random effects used in the statistical model. In table 4-10, the fixed and random effect variables are grouped as a way of assessing the effects of those variables when combined.

Table 4-10. Statistical model variable definitions.

Class Variables	Fixed Effects[1]	Random Effects[1]
• AREA_CODE • ADTclass(0 – 100, 100 – 500, 500 – 2500, and > 2500) • CRV_FLG • Functional class (FC) • HWY • Highway region (HR) • PVTP • SURF_AGEclass (0 – 4, 4 – 10, 10 – 17, and > 17 years) • YR_LST_IMP	• HR • AREA_CODE(HR) • YR_LST_IMP • PVTP • PVTP * YR_LST_IMP • CRV_FLG(PVTP) • YR_LST_IMP * PVTP * CRV_FLG • ADTclass • ADTclass * YR_LST_IMP • ADTclass * PVTP • ADTclass * CRV_FLG * PVTP • SURF_AGEclass • SURF_AGEclass * YR_LST_IMP • PVTP * SURF_AGEclass • PVTP * CRV_FLG * SURF_AGEclass	• AREA_CODE * HR * HWY • AREA_CODE * HR * HWY * YR_LST_IMP

* indicates the interaction of the variables; variables in parenthesis indicate the first variable, plus the interaction of the first variable and the variable within the parenthesis (e.g., AREA_CODE(HR) = AREA_CODE + the interaction of AREA_CODE and HR).

Variable combinations shown in table 4-10 were included to fully capture the relationship between the variables contained within the dTIMS database. All variables are included in the statistical model and the ANOVA is used to identify possible interactions between variables and purge interactions that are not of interest. In addition, although not all variables have significance to assessment of the pavement family tree, some variables are used to obtain other variables in the SAS analysis. For example, highway number by itself has no significance on pavement condition; however, it is needed in the analysis to obtain the correct error terms.

Analyze the Results

The results of the ANOVA are shown in tables 4-11 and 4-12 for the asphalt and concrete pavement groups, respectively.

Table 4-11. Summary of the statistical analysis–asphalt pavement group.

Effect	FC = 1		FC = 2		FC = 6		FC = 7	
	F value	p value	F value	p value	F value	p value	F value	p value
HR	0.75	0.6687	0.45	0.7188	5.58	0.0015	0.66	0.5793
HR+ AREA_CODE	0.57	0.7450	0.52	0.8798	3.16	0.0003	0.58	0.7889
YR_LST_IMP	0.52	0.7252	4.98	0.0008	6.03	0.0001	0.03	0.9985
PVTP	20.42	<0.0001	12.82	<0.0001	7.30	<0.0001	14.83	<0.0001
PVTP + YR_LST_IMP	1.54	0.1386	2.16	0.0046	2.94	<0.0001	1.45	0.1088
PVTP + CRV_FLG	15.60	<0.0001	5.73	<0.0001	4.28	<0.0001	3.74	0.0001
YR_LST_IMP + PVTP + CRV_FLG	9.39	<0.0001	4.21	<0.0001	3.68	<0.0001	4.60	<0.0001
ADTclass	1.84	0.1586	42.20	<0.0001	31.85	<0.0001	[1]	[1]
YR_LST_IMP + ADTclass	8.30	<0.0001	8.77	<0.0001	4.84	<0.0001	[1]	[1]
ADTclass + PVTP	8.95	<0.0001	5.58	<0.0001	9.50	<0.0001	[1]	[1]
ADTclass + PVTP + CRV_FLG	19.17	<0.0001	5.05	<0.0001	22.20	<0.0001	[1]	[1]
SURF_AGEclass	99.39	<0.0001	415.90	<0.0001	299.22	<0.0001	146.62	<0.0001
SURF_AGEclass + YR_LST_IMP	5.30	<0.0001	9.15	<0.0001	10.19	<0.0001	6.33	<0.0001
SURF_AGEclass + PVTP	2.81	0.0386	17.58	<0.0001	3.35	<0.0001	8.05	<0.0001
SURF_AGEclass + PVTP + CRV_FLG	37.80	<0.0001	19.69	<0.0001	14.59	<0.0001	18.91	<0.0001
Number of Observations Used	1,143		11,007		18,711		5,751	

[1] Insufficient number of different ADT classes.

Table 4-12. Summary of the statistical analysis–concrete pavement group.

Effect	FC = 1		FC = 2		FC = 6		FC = 7	
	F value	p value	F value	p value	F value	p value	F value	p value
HR	15.36	0.1849	0.58	0.6368	2.62	0.0760	[1]	[1]
HR+ AREA_CODE	14.35	0.1835	0.34	0.9506	0.64	0.6739	[1]	[1]
YR_LST_IMP	2.35	0.0831	19.81	<0.0001	3.52	0.0094	1.74	0.1853
PVTP	10.51	<0.0001	39.63	<0.0001	12.06	<0.0001	0.01	0.9279
PVTP + YR_LST_IMP	2.88	0.0036	[1]	[1]	1.98	0.0260	[1]	[1]
PVTP + CRV_FLG	30.34	<0.0001	27.64	<0.0001	6.95	<0.0001	[1]	[1]
YR_LST_IMP + PVTP + CRV_FLG	1.64	0.0579	[1]	[1]	[1]	[1]	[1]	[1]
ADTclass	25.63	<0.0001	8.28	0.0003	17.94	<0.0001	[1]	[1]
YR_LST_IMP + ADTclass	4.89	0.0006	[1]	[1]	2.14	0.0324	[1]	[1]
ADTclass + PVTP	11.84	0.0006	16.73	<0.0001	28.55	<0.0001	[1]	[1]
ADTclass + PVTP + CRV_FLG	[1]	[1]	28.55	<0.0001	[1]	[1]	[1]	[1]
SURF_AGEclass	83.99	<0.0001	9.00	<0.0001	9.64	<0.0001	[1]	[1]
SURF_AGEclass + YR_LST_IMP	4.72	<0.0001	6.66	<0.0001	[1]	[1]	[1]	[1]
SURF_AGEclass + PVTP	[1]	[1]	1.72	0.1127	5.28	0.0004	1.24	0.3129
SURF_AGEclass + PVTP + CRV_FLG	[1]	[1]	11.88	<0.0001	[1]	[1]	[1]	[1]
Number of Observations Used	1,180		4,206		478		28	

[1] Insufficient number of different ADT classes.

The statistical analysis included further evaluation of the pavement family tree using an adjusted p-value of less than 10 percent and the step-down-Bonferroni method. The step-down-Bonferroni method adjusts the determined p-values by multiplying each probability by the total number of tests minus 1 for each effect evaluated. The step-down-Bonferroni method is used to minimize the probability of drawing one or more false conclusions based on pure chance and not true differences (e.g., separating families when they really should be combined). The process for conducting the step-down-Bonferroni method is described below. In addition, the data for functional class 01 from table 4-11 were used as an example to further illustrate the step-down-Bonferroni method. The results of this example are shown in table 4-13.

1. Select an appropriate level of significance (use $\alpha = 0.10$).
2. Establish the null hypothesis. The null hypothesis is the basis for what will be tested in the statistical analysis, and in this case, confirms that there are no differences in pavement performance.
3. Determine the number of comparisons to be checked, k (from table 4-11, FC = 1, there are 12 effects, use k = 12).
4. Rank the p-value of each group member from the smallest to the largest, $p_1, \dots, p_k$.
5. Multiply the first p-value by the number of effects. If the adjusted p_1 is less than α, the null hypothesis (H_o: $\mu_1 = \mu_2$) is rejected, meaning that there are differences in pavement performance. If the adjusted p_1 is greater than α, the null hypothesis cannot be rejected (i.e., no evidence to conclude that another hypothesis is preferred over the null hypothesis, and there are no differences in performance between the families).
6. Multiply the second p-value by the number of effects minus 1. If the adjusted p_2 is less than α, the null hypothesis is rejected. If the adjusted p_2 is greater than α, the null hypothesis cannot be rejected.
7. Multiply the third p-value by the number of effects minus 2. If the adjusted p_3 is less than α, the null hypothesis is rejected. If the adjusted p_3 is greater than α, the null hypothesis cannot be rejected.
8. Repeat the process until the null hypothesis fails to be rejected. If the null hypothesis is rejected, then the effect is considered to be statistically significant.

Table 4-13. Example calculation of step-down-Bonferroni method.

k	p-value	k – i	Adjusted p_i	Action
1	0.0001	12	0.0012	Reject the null hypothesis
2	0.0001	11	0.0011	Reject the null hypothesis
3	0.0001	10	0.0010	Reject the null hypothesis
4	0.0001	9	0.0009	Reject the null hypothesis
5	0.0001	8	0.0008	Reject the null hypothesis
6	0.0006	7	0.0042	Reject the null hypothesis
7	0.0006	6	0.0036	Reject the null hypothesis
8	0.0036	5	0.0180	Reject the null hypothesis
9	0.0579	4	0.2316	Fail to reject the null hypothesis
10	0.0831	3	0.2493	Fail to reject the null hypothesis
11	0.1835	2	0.3670	Fail to reject the null hypothesis
12	0.1849	1	0.1849	Fail to reject the null hypothesis

In evaluation of the family tree, the results of the step-down Bonferroni method for the asphalt pavement group indicated that except for functional class 06, there was no statistical significance for Highway Region and Area Code (i.e., pavement condition was not statistically different across Highway Regions and Area Codes, except for functional class 06). For functional class 06, Highway Regions 2 and 3 are different from Highway Region 4. In Highway Region 1, Area Codes A, B, H, and M are different from Area Code S, for Highway Region 2, Area Codes H, M, S, and Y are different from W, and for Highway Region 3, Area Code M differs from Area Code W. For the concrete pavement group, there was no statistical significance between Highway Regions and Area Codes.

Surface age is an overwhelming important effect for asphalt pavements, and only functional class 01 for concrete pavements. The ADT class is the next important effect for asphalt pavements and functional classes 06 and 07, as well with some modification for concrete pavements and functional classes 01 and 06 (modification due to very significant interactions with other factors). Pavement type is the next significant factor, followed by curve flag, except for concrete pavements and functional class 01 (again, with modifying effects from interactions with other factors).

Table 4-14 provides a summary of the differences between pavement types for each functional class. This analysis indicates differences with several pavement types; however, the differences are not consistent for all functional classes.

Table 4-14. Step-down-Bonferroni method results—pavement type and curve flag.

Functional Class	Asphalt Pavements					Concrete Pavements			
	AONC	FD	THK	TONS	TONW	MESH	TKSJ	TKSJD	TNSJ
01	None	N/A	O~M	N/A	N/A	J~P	None	J~O	N/A
02	A, O~M	None	A, O~M	None	None	N/A	None	G, O~J	J~O
06	None	None	A~M, O	None	None	N/A	None	None	N/A
07	None	None	None	A, O~M	A, M~O	N/A	N/A	N/A	N/A

Note: ~ indicates different at the 10 percent level; None indicates no differences in the means, and N/A indicates insufficient data to conduct comparisons. Pavement type and curve flag combinations not shown indicate insufficient data available to conduct analysis

An evaluation was also conducted to determine the statistical significance of combining pavement types within each pavement group, and combining curve flags within each pavement type. Evaluated pavement type and curve flag combinations are listed in table 4-15. Pavement type and curve flag combinations not listed in table 4-15 were excluded due to insufficient data.

Table 4-15. Pavement type and curve flag combinations.

Pavement Type	Curve Flag
• TONS and TONW • TONS, TONW, and THK • TONS, TONW, THK, and FD • TKSJ and TKSJD • TKSJ and TNSJ • TKSJ, TNSJ, and TKSJD	• O and A • A and O • O and M • O and G

Table 4-16 provides the results of the pavement type combinations and table 4-17 provides the results of the curve flag combinations. As with the previous analysis, differences existing between some of the pavement type and curve flag combinations; however, these differences are not consistent across all functional classes

Table 4-16. Step-down-Bonferroni method results—pavement type combinations.

Functional Class	Asphalt Pavements			Concrete Pavements		
	O	A	M	O	G	J
01	AONC~THK	N/A	None	N/A	None	MESH~TKSJD
02	None	None	AONC, TONW~THK	None	None	None
06	AONC~THK	None	None	None	N/A	N/A
07	None	None	None	None	N/A	N/A

Note: ~ indicates different at the 10 percent level; None indicates no differences in the means, and N/A indicates no comparisons.

Table 4-17. Step-down-Bonferroni method results—curve flag combinations.

Functional Class	Asphalt Pavements			Concrete Pavements		
	O	A	M	O	G	J
01	AONC~THK	N/A	None	N/A	None	MESH~TKSJD
02	None	None	AONC, TONW~THK	None	None	None
06	AONC~THK	None	None	None	N/A	N/A
07	none	None	None	None	N/A	N/A

Note: ~ indicates different at the 10 percent level; None indicates no differences in the means, and N/A indicates no comparisons.

The above analysis indicates that while there differences in some of the pavement type and curve flag groupings, the differences are not consistent for all functional classes. Therefore, the analysis would not support combining pavement types or curve flags within each of the pavement groups (i.e., current family tree definition is appropriate).

There are a number of potential ways to define an asset family tree. As discussed previously and supported by the ANOVA and the step-down-Bonferroni method evaluation, the current SDDOT pavement family tree definition is appropriate. However, if the impact of other features (e.g., traffic volume) is of interest, an analysis similar to that described above would be conducted outside of the PPM tool. However, the PPM tool can be used as an initial evaluation of the potential impact of other pavement (or asset) features on the development of the performance models. For example, a preliminary analysis was conducted using one pavement type to evaluate the potential improvement in pavement performance prediction by using the ADT class in the family tree definition. As long as the feature in question is available in the exported dTIMS database, the feature can be added using the *Family Tree Building* tab. The resulting analysis indicated that using ADT did not appear to improve the performance prediction models, as the resulting R^2 for many of the performance models decreased. Although this process is not as rigorous as that of the ANOVA, the PPM tool does provide the ability to at least evaluate the potential outcomes (i.e., performance models) of changes to the family tree definition.

Task 10: Recommend Most Acceptable Curves

Compare the old and newly generated curves and recommend the most acceptable curves.

This project introduces a different way for establishing pavement families using "parent" and "children." A "parent" includes all subsets, and the "child" is defined as the subset. One benefit of evaluating the relationship between the "parent" and the "child" is when there is insufficient data to support unique pavement performance models for the "child" the "parent" models can be used. However, this approach does not preclude developing a "child" as additional performance data becomes available.

The "parent" and "child" definition was incorporated into the PPM tool analysis. Performance models were developed for each "parent" condition indicator (the "children" were developed under task 8). The next step in the process was to evaluate whether or not the pavement performance models for the "parent" better represented the predicted distress for each "child." In addition, pavement performance models were generated for those pavement segments that were not included in the 2004 performance model, specifically, TNSJ-G, TNSJ-U, MESH-U, CRCP-G, CRCP-J, and CRCP-P (see shaded cells in table 4-3).

Tables 4-18 and 4-19 provide a comparison of the resulting R^2 values for each pavement type and curve flag combination for asphalt- and concrete-surfaced pavements, respectively. Shaded cells indicate that the R^2 value for the "parent" is higher than the R^2 value for the "child."

Table 4-18. Comparison of R^2—asphalt-surfaced pavements.

Pavement Type	Condition Indicator	R^2			
		Parent	O	A	M (or F)
GRAVEL	Gravel	—	—	—	—
Blotter	Transverse Cracking	—	0.80	—	—
	Fatigue Cracking	—	0.50	—	—
	Patch Deterioration	—	0.94	—	—
	Block Cracking	—	0.79	—	—
	Rut Depth	—	0.73	—	—
	Roughness	—	0.74	—	—
TONS	Block Cracking	0.75	0.81	0.76	0.82
	Fatigue Cracking	0.84	0.93	0.88	0.95
	Patch Deterioration	0.81	0.69	0.83	0.83
	Roughness	0.99	0.98	0.96	0.86
	Rut Depth	0.85	0.89	0.78	0.87
	Transverse Cracking	0.83	0.87	0.86	0.89
TONW	Block Cracking	0.72	0.75	0.70	0.80
	Fatigue Cracking	0.92	0.85	0.94	0.88
	Patch Deterioration	0.81	0.87	0.80	0.68
	Roughness	0.96	0.96	0.96	0.93
	Rut Depth	0.70	0.82	0.82	0.92
	Transverse Cracking	0.74	0.84	0.85	0.62
AONC	Block Cracking	0.88	0.92	0.83	0.59
	Fatigue Cracking	0.71	0.76	0.84	0.76
	Patch Deterioration	0.84	0.84	0.64	0.81
	Roughness	0.95	0.97	0.66	0.90
	Rut Depth	0.66	0.58	0.76	0.64
	Transverse Cracking	0.82	0.83	0.90	0.81
FD	Block Cracking	0.90	0.83	0.90	0.58
	Fatigue Cracking	0.85	0.94	0.89	0.67
	Patch Deterioration	0.74	0.93	0.67	0.81
	Roughness	0.84	0.92	0.99	0.90
	Rut Depth	0.80	0.62	0.73	0.73
	Transverse Cracking	0.95	0.90	0.81	0.85
THK	Block Cracking	0.73	0.74	0.58	0.79
	Fatigue Cracking	0.87	0.76	0.80	0.84
	Patch Deterioration	0.85	0.87	0.90	0.99
	Roughness	0.96	0.77	0.95	0.91
	Rut Depth	0.80	0.78	0.78	0.82
	Transverse Cracking	0.88	0.81	0.87	0.87

Note: shaded cells indicate "parent" has higher R^2 than the "child."

The research team recommends that SDDOT review the recommended performance prediction models developed as part of this project prior to inclusion into dTIMS. Performance prediction models should be verified to ensure the predicted performance trends reflect expected performance for each pavement type, curve flag, and distress combination. For those pavement types where the "parent" R^2 value is higher than that of the "child," the research team also recommends that the "parent" performance model be evaluated for use as the "child" performance model. The list of recommended models is provided in Appendix G.

Task 11: Develop User Manual

Develop a user manual that explains how to screen historical data, generate curves and use the software, determine the validity of curves, determine when to add new families of curves, and generate new families of curves.

A User Manual was developed and submitted as a separate document with the final report. The User Manual summarizes the operational and functional features of the PPM tool.

Table 4-19. Comparison of R^2—concrete-surfaced pavements.

Pavement Type	Condition Indicator	R^2					
		Parent	O	G	J	P	U
CRCP	Corner Cracking	0.87	0.42	0.18	0.26	0.09	—
	D-Cracking/ASR	0.86	0.94	0.77	0.68	0.80	—
	Joint Spalling	0.57	0.63	0.88	0.68	0.60	—
	Punchouts	0.79	0.21	0.49	0.72	0.79	—
	Roughness	0.83	0.86	0.55	0.82	0.99	—
MESH	Corner Cracking	0.59	0.70	0.42	0.61	0.99	0.00
	D-Cracking/ASR	0.91	0.68	0.32	0.54	0.51	0.03
	Faulting	0.82	0.66	0.21	0.46	0.65	0.00
	Joint Seal Damage	0.84	0.86	0.80	0.73	0.76	0.22
	Joint Spalling	0.73	0.83	0.86	0.58	0.76	0.23
	Roughness	0.69	0.62	0.48	0.82	0.75	0.28
TKSJ	Corner Cracking	0.82	0.70	0.93	0.84	0.93	0.60
	D-Cracking/ASR	0.93	0.71	0.66	0.86	0.77	0.41
	Faulting	0.87	0.72	0.67	0.95	0.34	0.78
	Joint Seal Damage	0.81	0.90	0.89	0.64	0.79	0.70
	Joint Spalling	0.84	0.89	0.87	0.61	0.70	0.67
	Roughness	0.87	0.94	0.92	0.59	0.89	0.88
TKSJD	Corner Cracking	0.84	0.96	0.77	0.62	0.66	—
	D-Cracking/ASR	0.94	0.83	0.83	0.91	0.00	—
	Faulting	0.70	0.76	0.62	0.62	0.94	—
	Joint Seal Damage	0.90	0.90	0.92	0.85	0.86	—
	Joint Spalling	0.92	0.94	0.93	0.88	0.86	—
	Roughness	0.53	0.73	0.77	0.93	0.67	—
TNSJ	Corner Cracking	0.82	0.97	0.10	0.65	0.68	0.67
	D-Cracking/ASR	0.81	0.90	0.60	0.85	0.94	0.94
	Faulting	0.95	0.79	0.79	0.81	0.76	0.73
	Joint Seal Damage	0.81	0.78	0.52	0.80	0.81	0.70
	Joint Spalling	0.80	0.79	0.62	0.91	0.73	0.77
	Roughness	0.92	0.86	0.62	0.88	0.61	0.79

Note: shaded cells indicate "parent" has higher R^2 than the "child."

Task 12: Provide Training to SDDOT Staff

Provide training to SDDOT staff involved in the use of the pavement management system.

A 1/2-day training course on the operation and use of the PPM tool was conducted at the SDDOT Office in Pierre, South Dakota on August 20, 2013. The training included a PowerPoint and hands-on demonstration of the operation and use of the PPM tool. The training course included software demonstration and discussion of each required step for determining the recommended performance prediction models.

Task 13: Explain Historical Data / Performance Curve Use in MEPDG Calibration / Software

Explain how historical data and performance curves could be used in calibration or use of the new Mechanistic Empirical Pavement Design Guide (MEPDG) software.

The *MEPDG* and accompanying AASHTOWare Pavement ME Design™ software, represents a significant advancement in pavement design. The design approach considers the development of key pavement distresses that are computed by using a structural response model and transfer functions. The structural response model calculates the critical pavement responses through mechanistic models embedded within the software. Empirical transfer functions convert these critical pavement responses into performance indicators that are evaluated over the anticipated design life of the pavement.

For asphalt pavements, the distress indicators in the *MEPDG* include longitudinal (surface or top-down) cracking, fatigue (bottom-up or alligator) cracking, transverse (thermal fracture) cracking, and rutting. Fatigue fracture is also included for chemically stabilized layers. For concrete pavements, the distress indicators include punchouts for continuously reinforced concrete pavements (CRCP) and mean joint faulting and load-related transverse slab cracking for jointed plain concrete pavements. Functional performance for pavements is defined by time-dependent pavement roughness expressed in terms of the IRI. The IRI is predicted using a regression equation that is based on the predicted distress, the initial IRI, and site/climatic factors.

The performance prediction models contained within the *MEPDG* have been nationally calibrated using data contained within the Long-Term Pavement Performance (LTPP) database and other site specific pavement studies. Prior to fully implementing the *MEPDG*, calibration of the performance prediction models should be conducted when necessary to ensure that the predicted distress (and IRI) reflects actual field performance. However, one challenge facing many state highway agencies (SHAs) is the availability of site specific data related to materials, traffic, climate, and performance for use in the local calibration effort. One of the many benefits of a pavement management system is the availability of data for potential use in the *MEPDG* calibration effort.

SDDOT has conducted or is conducting a number of studies/efforts in support of the *MEPDG* calibration. Though the effort conducted under this project did not attempt to calibrate the *MEPDG* performance prediction models, the performance prediction models developed in the PPM tool may provide value in the *MEPDG* calibration effort. To assist in demonstrating how the performance prediction models developed in the PPM tool can be used to assist with the *MEPDG* calibration, SDDOT Pavement Design identified five case studies:

- New asphalt pavement (TONW-O or TONS-O).
- New jointed plain concrete pavement (TKSJD-O).
- Asphalt overlay of an existing asphalt pavement (TONW-A or TONS-A).
- Asphalt overlay of an existing concrete pavement (AONC-O).
- Unbonded concrete overlay of an existing concrete pavement (this section has no applicable SDDOT pavement type designation).

As part of SD2005-01, *Mechanistic-Empirical Pavement Design Guide Implementation Plan*, an appendix of input values was generated for use in the sensitivity analysis. These same input values were used for the evaluation of the five case studies. It should be noted that the SD2005-01 project was based on the rudimentary software program developed as part of the National Cooperative Highway Research Program (NCHRP) Project 1-37A, *Development of the 2002 Guide for the Design of New and Rehabilitated Pavement Structures: Phase II* (NCHRP 2004). The current version of the AASHTOWare Pavement ME Design™ software incorporates the majority of inputs used in the NCHRP 1-37A software; however, there are slight differences. Appendix B contains a summary of revised SDDOT default values applicable to the current version of the *MEPDG*. Unless otherwise noted, SDDOT default input values were used for inputs in all case studies.

To provide a direct comparison of the *MEPDG* to the PPM tool distress predictions, the latter required conversion from a condition indicator (ranging from 0 to 5) to an actual measure (e.g., length of cracking, depth of rutting). For asphalt pavements, this includes conversion of IRI, fatigue cracking, asphalt rut depth, and transverse cracking, while for concrete pavements, conversions include IRI and faulting.

Although additional distresses are predicted in the *MEPDG*, the noted distresses are the only comparable distress types collected by SDDOT. Additional distress types predicted in the *MEPDG* but not collected/quantified by SDDOT include total rut depth and longitudinal cracking for asphalt pavements and percent cracked slabs for concrete pavements. Table 4-20 provides a comparison of SDDOT measured distress and those used in the *MEPDG*.

Table 4-20. Comparison of SDDOT and *MEPDG* distress types (adapted from Hoerner et al. 2007; SDDOT 2012)

Pavement Type	*MEPDG* Distress Type	SDDOT Distress Type	Modifications to Conform to the *MEPDG*
Asphalt	Longitudinal cracking (ft/mi)	No equivalent distress measurement	Report longitudinal cracking in the wheel path
	Fatigue cracking (% of length)	Fatigue cracking (% wheel path by severity level)	Convert to or measure as percent of cracking per mile
	Transverse cracking (ft/mi)	Transverse cracking (crack spacing)	Convert to length of cracking per mile
	Rut depth, asphalt layer (in)	No equivalent distress measurement	Evaluate/estimate percent of total rut due to asphalt layer
	Rut depth, total (in)	Rut depth, total (severity level)	Report average total rut depth (in)
	IRI (in/mi)	IRI (in/mi by severity level)	Report average value (in/mi)
Plain Jointed Concrete	Mean joint faulting (in.)	Faulting (% slabs by severity level)	Report average faulting (in)
	Transverse cracking (ft/mile)	No equivalent distress measurement	Report number of cracked slabs per mile
	IRI (in/mi)	IRI (in/mi by severity level)	Report average value (in/mi)

Conversion from the SDDOT performance indicator to an actual measure is based on the deduct value equations and distress extent levels provided by SDDOT Pavement Management. The SDDOT distress extent levels are provided in table 4-21.

Table 4-21. Distress extent levels (SDDOT 2007)

Distress	Measure	Low	Moderate	High	Extreme
Transverse cracking	Distance between adjacent cracks (ft)	> 50	25 – 50	< 25	n/a
Fatigue cracking	Percent of wheel path	1 – 9	10 – 24	25 – 49	≥ 50
Faulting	Percent of slabs	1 – 9	10 – 24	25 – 49	≥ 50

The corresponding SDDOT deduct value equations include (SDDOT 2007):

- IRI

  If IRI ≤ 50.0 in/mi, deduct value = 0.0

  If IRI ≥ 225.0 in/mi, deduct value = 5.0

  IF IRI > 50 and ≤ 110.0 in/mi, deduct value = 0.0083 x IRI – 0.4167

  If IRI > 110 and ≤ 170.0 in/mi, deduct value = 0.01667 x IRI – 1.333

  If IRI > 170 and ≤ 195.0 in/mi, deduct value = 0.06 x IRI – 8.7

  If IRI > 195 and < 225 in/mi, deduct value = 0.0667 x IRI – 10.0

- Asphalt rut depth

  If rut depth ≤ 0.2 in, deduct value = 3.5 x rut depth

  If rut depth > 0.2 and ≤ 0.4 in, deduct value = 4.0 x rut depth – 0.1

If rut depth > 0.4 and ≤ 0.6 in, deduct value = 17.5 x rut depth – 5.5

If rut depth > 0.6 in, deduct value = 5.0

- Fatigue cracking

For fatigue cracking, SDDOT uses the deduct values shown in table 4-22.

Table 4-22. Fatigue cracking deduct values.

Severity	Extent			
	Low	Moderate	High	Extreme
Low	0.4	0.8	1.4	2.0
Medium	0.8	1.7	3.1	5.0
High	1.1	2.7	5.0	5.0

To estimate fatigue cracking, the moderate severity range was used to develop the following equation to relate the deduct value to the percent fatigue cracking:

$$Fatigue\ cracking\ (\%) = \frac{Deduct\ Value}{0.973}$$

- Transverse cracking

For transverse cracking, SDDOT uses the deduct values shown in table 4-23. Similar to fatigue cracking, transverse cracking was estimated using the moderate severity range. The developed conversion equation is:

$$Transverse\ cracking\ (ft) = -412.12(Deduct\ Value)^2 + 2046.8\ (Deduct\ Value)$$

Table 4-23. Transverse cracking deduct values.

Severity	Extent		
	Low	Moderate	Extreme
Low	0.1	0.2	0.5
Medium	0.2	0.6	1.5
High	1.0	2.2	5.0

- Faulting

The deduct values for faulting are dependent on low (< 0.2 in), medium (0.2 to 0.3 in), and high (≥ 0.3 in) severity. The total deduct value is determined by the percent of faulting in each severity level. The SDDOT deduct value equation for faulting includes:

Low: deduct value = 0.02 x percent faulting

Medium: Fault ≤ 25.0 percent, deduct value = 0.04 x percent faulting

Fault ≤ 92.0 percent, deduct value = 0.06 x percent faulting – 0.5

Fault > 92 percent, deduct value = 5.0

High: Fault ≤ 25.0 percent, deduct value = 0.056 x percent faulting

Fault ≤ 50.0 percent, 0.104 x percent faulting – 1.2

Fault ≤ 60.0 percent, 0.1 x percent faulting – 1.0

Fault > 60 percent, deduct value = 5.0

However, the fault prediction in the *MEPDG* is based on the average fault depth. Using the fault equations shown above and the associated fault depth value at each severity level (i.e., 0.2 in for low, 0.25 in for medium, and 0.3 in for high severity), an estimated average depth of faulting was determined. Specifically, figure 4-28 illustrates the relationship between the extent of faulting and the SDDOT deduct value. Using figure 4-28, the percent contribution of each severity level at a given deduct value was determined and the associated fault depth calculated as the sum of each severity level (figure 4-29).

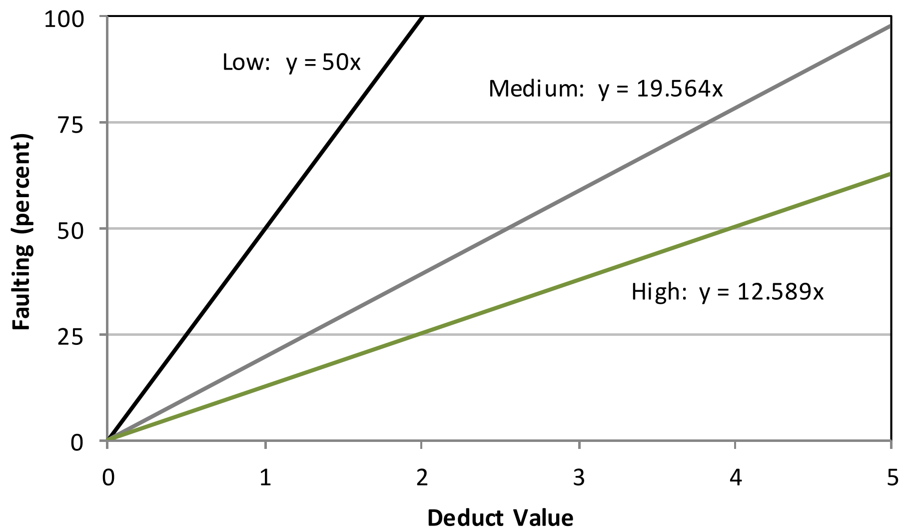


Figure 4-28. Percent of faulting and deduct value.

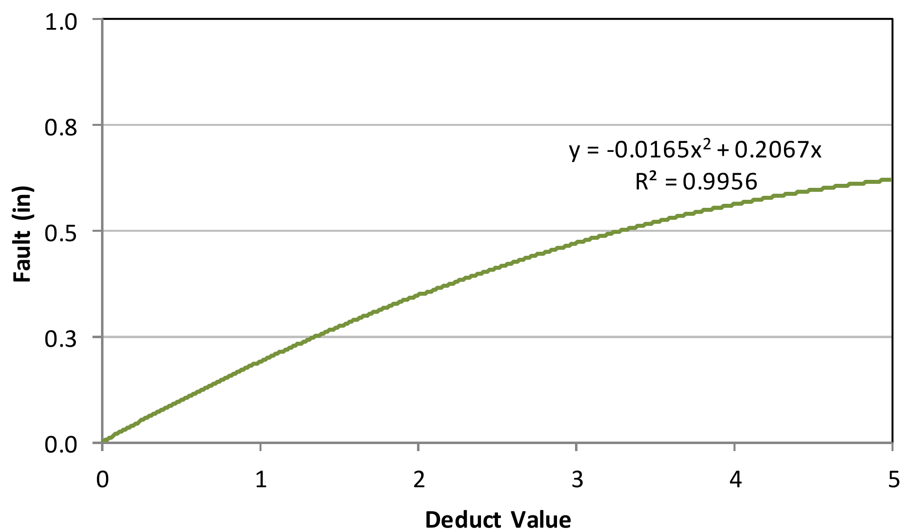


Figure 4-29. Fault depth and deduct value.

The following includes a summary of each case study and the *MEPDG* results, as well as tabular and graphical comparisons of these results to the applicable pavement family performance prediction model determined using the PPM tool. The evaluated pavement sections for each case study are based on the standard SDDOT layer thicknesses provided in Appendix B.

Pavement Design Case Study 1 – New Asphalt Pavement

Project Title: SD73, Jackson County, Bennett County Line N to SD44

Project Limits: MRM 37.65 + 0.000 to MRM 53.00 + 0.100

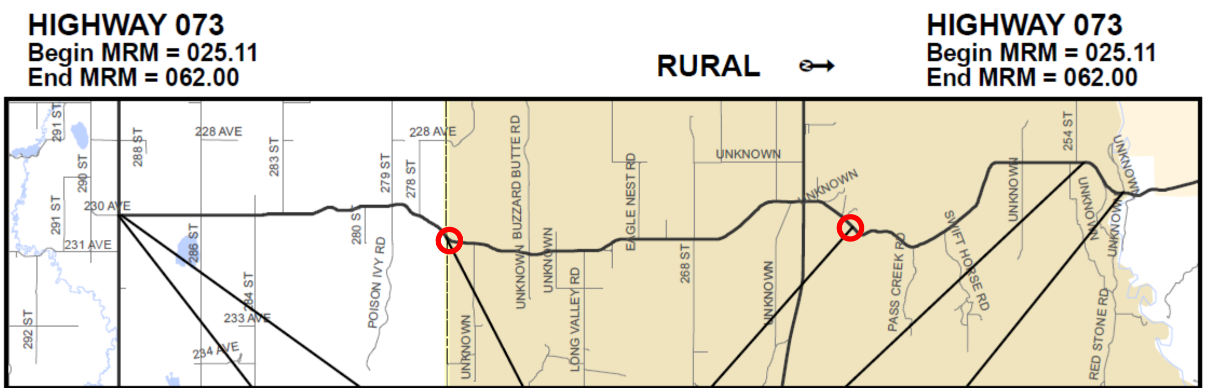
Vicinity: Martin, South Dakota

Functional Class: Rural Minor Arterial

No. of lanes: 2

Location

Case Study 1 is located in Jackson County, between Bennett County Line and Highway 44, and is approximately 24 miles northeast of Martin, South Dakota (figure 4-30).



IDENTIFICATION							
Federal Aid System	STP	STP	STP	STP	STP		
Funding Category	MAJA	MAJA	MAJA	MAJA	MAJA		
Functional Classification	R-MI A	R-MI A	R-MI A	R-MI A	R-MI A		
Direction							
Beginning MRM	025.11	025.12	037.65	053.00	062.00		
MRM Displacement	0.000	0.089	0.000	0.100	0.670		
Segment Length	0.112	12.166	15.396	9.542	1.740		
Year Built	1971	2007	1953	1985	1955		
Year Last Improved	2010	2010	1983	1997	1997		
Year Last Sealed			1986	2000	2000		

Figure 4-30. Location—Case Study 1 (SDDOT 2012b).

Pavement Structure Evaluated

The pavement section evaluated for this case study included 4.0 in of asphalt over 12.0 in of crushed gravel base. This pavement structure is classified as TONS. The analysis period for this case study is 20 years.

Materials

Default material properties were used for all pavement layers (see Appendix B).

Subgrade

The majority of the soil samples obtained at this case study ranged from A-2-4 to A-7-6. Due to the propensity of the A-7-6 subgrade soil type, this soil classification was used in the analysis.

Climate

The closest weather station to this project is located in Pine Ridge, South Dakota. An elevation of 999 ft and a depth to water table of 100 ft was used in the analysis.

Traffic

- AADTT (2012): 72
- Trucks in design direction: 52 percent
- Trucks in design lane: 100 percent
- Growth rate: 0.7 percent
- Operational speed: 65 mph

Table 4-24 provides project specific data related to the number of axles per truck, AADTT distribution, and monthly distribution. Table 4-25 includes the hourly traffic distribution.

Table 4-24. Traffic data—Case Study 1.

Vehicle Class	No. of Axles per Truck			AADTT Distribution (percent)
	Single	Tandem	Tridem	
4	0.90	0.00	0.00	1.18
5	1.75	0.00	0.00	34.43
6	0.96	0.96	0.00	10.46
7	0.50	0.00	0.25	1.06
8	2.40	0.40	0.00	6.46
9	1.21	1.75	0.00	31.36
10	0.90	1.14	0.61	5.88
11	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00
13	1.68	1.42	0.91	9.17

Month	Distribution Factor[1]
January	1.14
February	1.17
March	1.09
April	0.97
May	0.85
June	0.87
July	0.87
August	0.94
September	0.95
October	0.75
November	1.04
December	1.33

[1] Monthly distribution factors differ slightly from those provided by SDDOT; the monthly distribution factors were adjusted so that the sum of the factors equal 12.0.

Table 4-25. Hourly traffic distribution—Case Study 1.

Hour	Distribution (percent)
12 AM	1.47
1 AM	0.95
2 AM	0.85
3 AM	0.53
4 AM	0.96
5 AM	1.52
6 AM	2.04
7 AM	3.44
8 AM	4.41
9 AM	6.12
10 AM	6.77
11 AM	7.88

Hour	Distribution (percent)
12 PM	8.14
1 PM	7.19
2 PM	6.68
3 PM	6.11
4 PM	6.06
5 PM	5.61
6 PM	5.44
7 PM	4.79
8 PM	4.25
9 PM	3.91
10 PM	2.95
11 PM	1.92

Results

A summary of the *MEPDG* results for this case study are provided in table 4-26 (the detailed output report is provided in Appendix G). Table 4-26 includes the predicted distress at a reliability of 50 percent (mean value) and 90 percent at the end of the performance period (20 years), and an estimate of the year when the target value at 90 percent reliability will be reached. For the pavement section evaluated, all predicted distresses, excluding transverse cracking and longitudinal cracking, are below the *MEPDG* 90 percent reliability target values. The *MEPDG* predicted significant transverse and longitudinal cracking by the end of the 20-year analysis period.

The comparison of transverse crack prediction between the PPM tool developed performance equations and the *MEPDG* are shown in figure 4-31 (all comparison figures include the *MEPDG* results at 50 percent reliability). Although there is significant difference in the progression of transverse cracking between the *MEPDG* prediction model and PPM tool developed performance equation, by the end of the 20-years the *MEPDG* slightly over predicts the PPM tool developed performance equation by 9 percent (PPM tool – 1,773 feet; *MEPDG* – 1,928 feet).

Table 4-26. Summary of *MEPDG* results—Case Study 1.

Distress Type	Distress at 50 percent Reliability[1]	Distress at 90 percent Reliability[1]		Target Reached[2] (years)
		Target	Predicted	
Terminal IRI (in/mi)	127	178	172	—
Asphalt rut depth (in)	0.06	0.43	0.09	—
Total rut depth (in)	0.31	0.43	0.40	—
Fatigue cracking (%)	5	25	23	—
Transverse cracking (ft/mi)	1,928	1,000	2,935	2.5
Longitudinal cracking (ft/mi)	2,290	1,000	5,263	< 1

[1] At the end of the 20-year analysis period.
[2] Number of years after construction that the predicted distress reaches the target value.

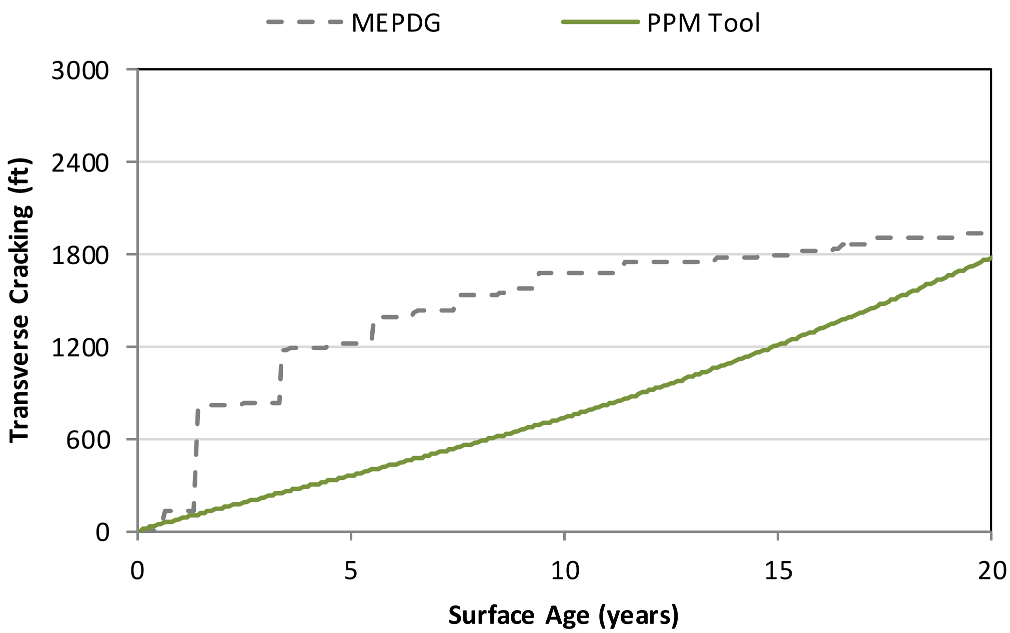


Figure 4-31. Predicted transverse cracking—Case Study 1.

The comparison of fatigue crack prediction between the PPM tool developed performance equations and the *MEPDG* is shown in figure 4-32. The *MEPDG* fatigue cracking prediction, by the end of the 20-year analysis period is slightly lower than that predicted by the performance equations developed using the PPM tool. At the end of the analysis period the *MEPDG* under-predicts fatigue cracking by 43 percent when compared to the PPM tool developed performance prediction equations (PPM tool – 9 percent; *MEPDG* – 5 percent).

Since SDDOT does not measure the rut depth for each of the pavement layers (asphalt, unbound base, and subgrade layers), it is assumed that the majority of the measured rut depth is confined within the asphalt layer(s), which is a reasonable assumption for the majority of highways. The comparison plot shown in figure 4-33 illustrates the PPM tool developed prediction results for surface rutting and the *MEPDG* predicted asphalt layer rutting. At the end of the 20-year analysis period, the *MEPDG* under-predicts the PPM tool predicted rut depth by 72 percent (PPM tool – 0.20 in; *MEPDG* 0.06 in).

The total rut depth predicted by the *MEPDG* is shown in figure 4-34. The total rut depth predicted by the *MEPDG* at the end of the analysis period is 0.31 in. In addition, the *MEPDG* predicts that the rutting in the base and subgrade layers is approximately 80 percent of the total predicted rut depth by the end of the analysis period (asphalt layer – 0.06 in; all layers – 0.31 in).

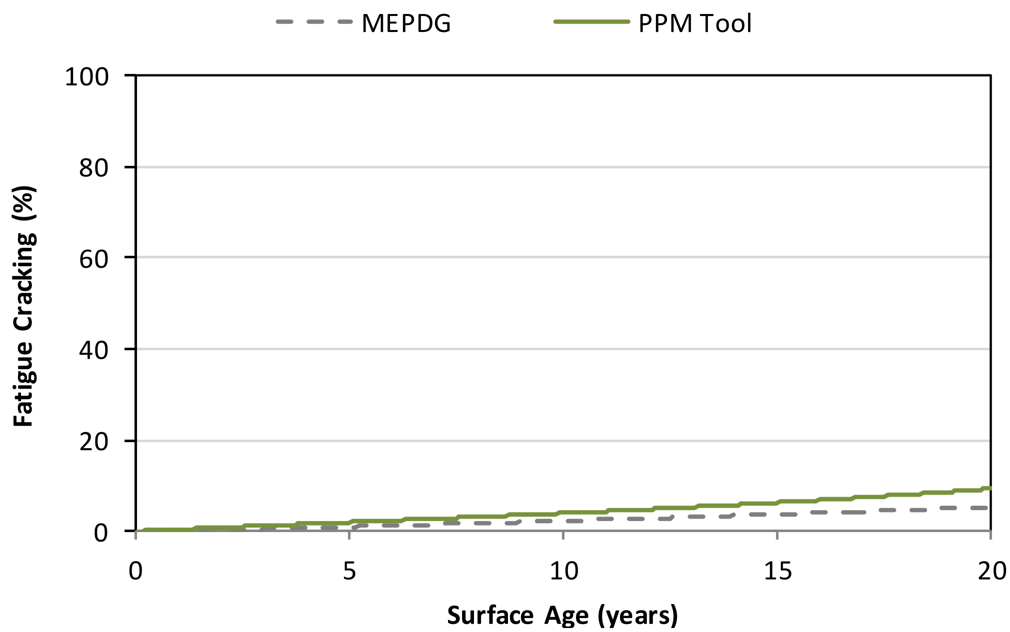


Figure 4-32. Predicted fatigue cracking—Case Study 1.

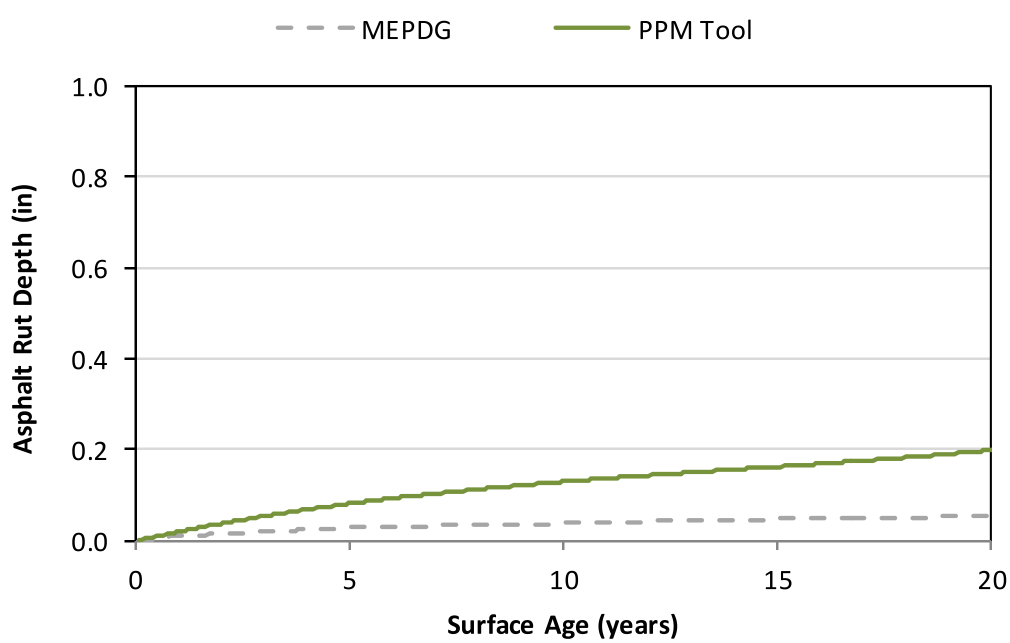


Figure 4-33. Predicted asphalt rut depth—Case Study 1.

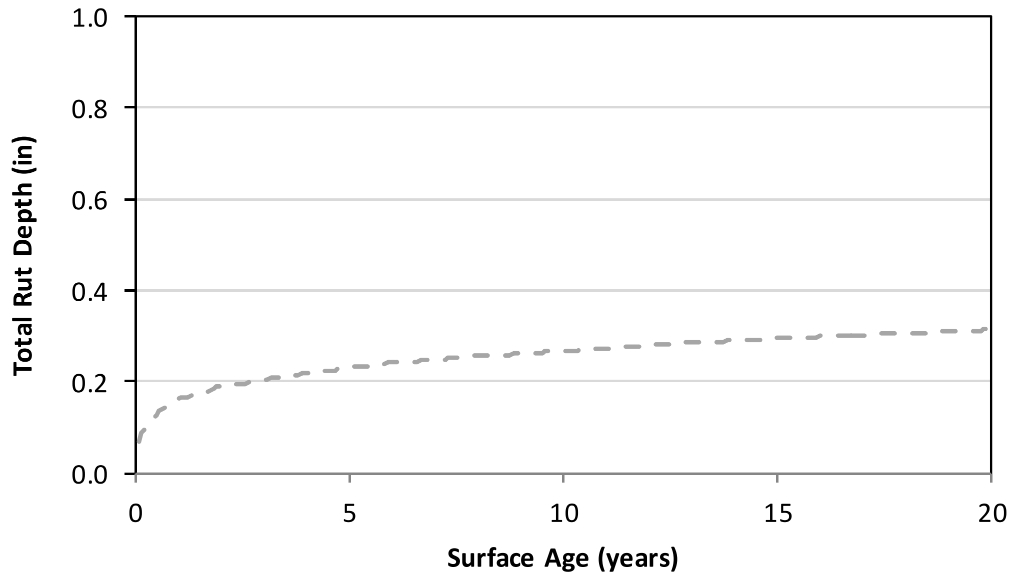


Figure 4-34. *MEPDG* predicted total rut depth—Case Study 1.

The IRI prediction comparison is provided in figure 4-35 and shows reasonable agreement over the entire analysis period. At the end of the analysis period, the performance equation developed using the PPM tool and the *MEPDG* IRI predication are within 10 percent (PPM tool – 142 in/mi; *MEPDG* – 127 in/mi).

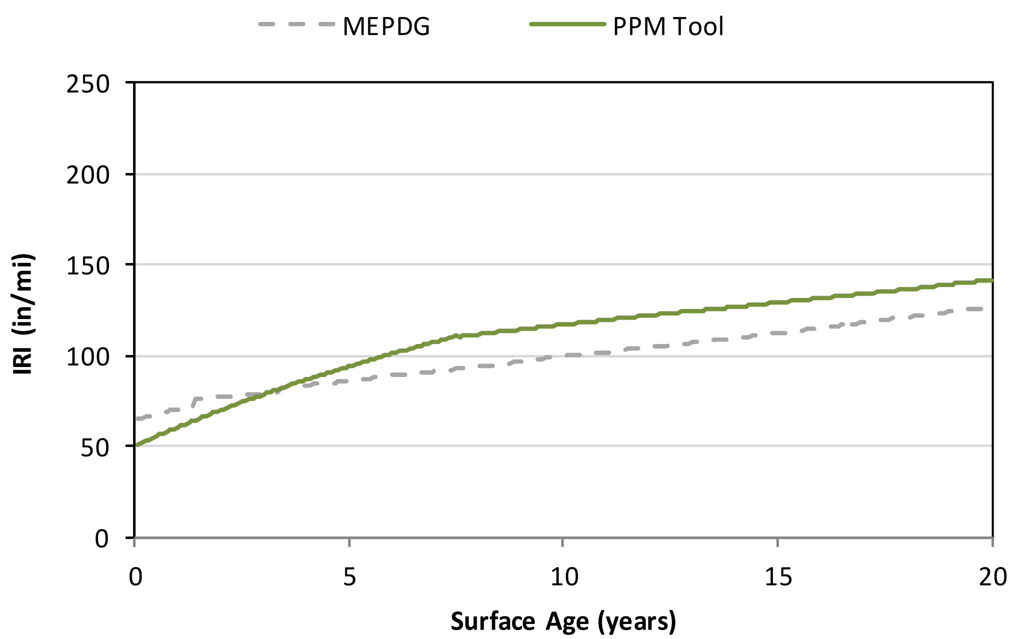


Figure 4-35. Predicted IRI—Case Study 1.

Although longitudinal cracking is not measured by the SDDOT during the pavement condition survey, figures 4-36 illustrates the *MEPDG* prediction for longitudinal cracking.

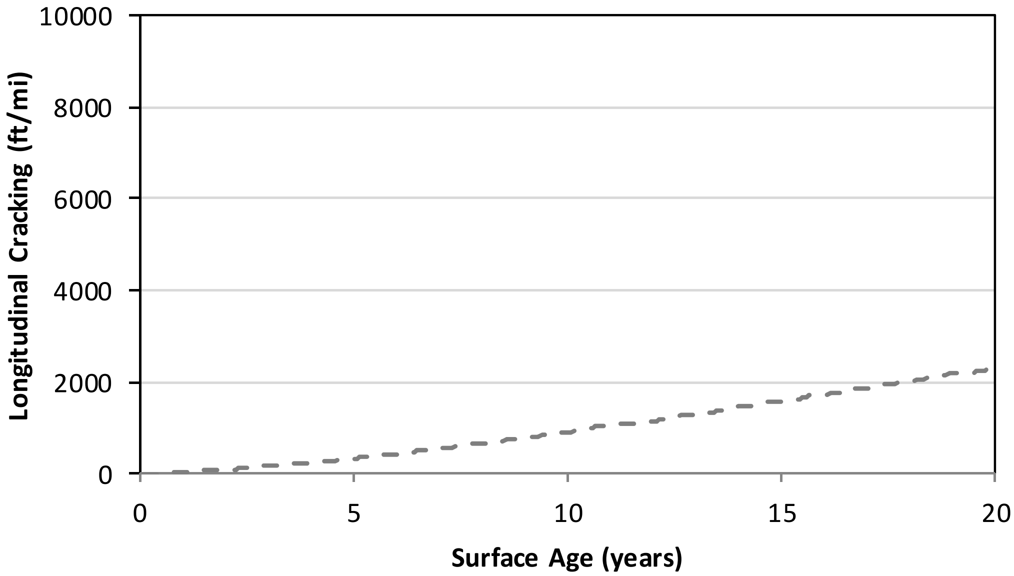


Figure 4-36. *MEPDG* predicted longitudinal cracking—Case Study 1.

Table 4-27 provides a summary comparison of the *MEPDG* and PPM tool predicted condition indicators at the end of the 20-year analysis period.

Table 4-27. Comparison of PPM tool and *MEPDG* predicted condition—Case Study 1.

Predicted Condition	PPM Tool	*MEPDG*	Percent Difference
Terminal IRI (in/mi)	142	127	10
Asphalt rut depth (in)	0.20	0.06	72
Total rut depth (in)	—	0.31	—
Fatigue cracking (%)	9	5	43
Transverse cracking (ft/mi)	1,773	1,928	-9
Longitudinal cracking (ft/mi)	—	2,290	—

Pavement Design Case Study 2 – New Jointed Concrete Pavement

Project Title: I90E, Lawrence County, Exit 10 E to Exit 17

Project Limits: MRM 10.08 + 0.000 to MRM 18.48 + 0.163

Vicinity: Spearfish, South Dakota

Functional Class: Urban Interstate

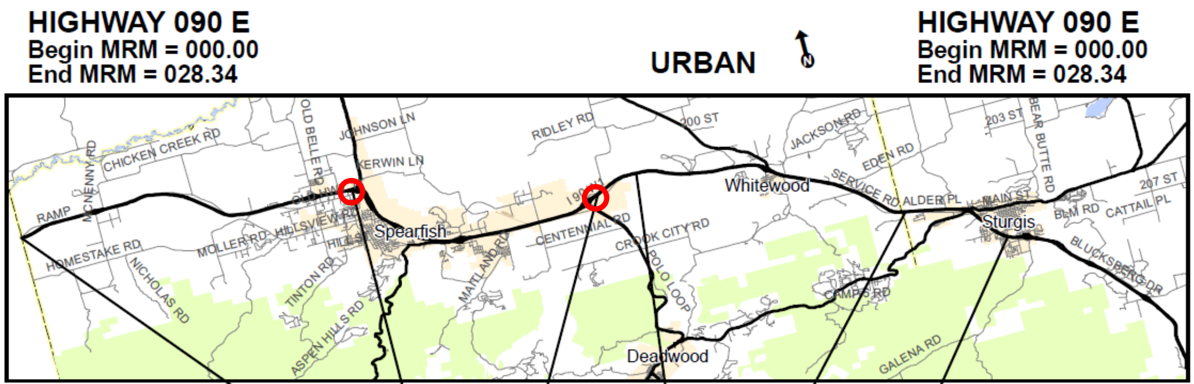
No. of lanes: 2

Location

Case Study 2 is located on Interstate 90E in Lawrence County in the vicinity of Spearfish, South Dakota (figure 4-37).

Pavement Structure Evaluated

The pavement structure for this case study included 9 in of short-jointed doweled concrete pavement over 5 in of crushed gravel base. This pavement structure is classified as TKSJD. The analysis period for this case study is 40 years.



IDENTIFICATION							
Federal Aid System	NHS-IN	NHS-IN	NHS-IN	NHS-IN	NHS-IN		
Funding Category	INT	INT	INT	INT	INT		
Functional Classification	R-INT	U-INT	R-INT	R-INT	U-INT		
Direction	E	E	E	E	E		
Beginning MRM	000.00	010.08	018.48	019.42	028.34		
MRM Displacement	0.000	0.000	0.163	0.496	0.078		
Segment Length	10.003	8.453	1.276	8.502	3.486		
Year Built	1976	1973	1973	1968	1964		
Year Last Improved	2004	2005	2001	2001	2010		
Year Last Sealed							

Figure 4-37. Location—Case Study 2 (SDDOT 2012b).

Subgrade

The soil types for this case study consist of silty clay, clay silt, gravelly silty sand, and sandy silt. Loose soil samples were classified as A-6, A-3, or A-4 (AASHTO Classification). An A-6 soil was used in the analysis.

Traffic

- AADTT (2012): 818
- Trucks in the design direction: 50 percent
- Trucks in the design lane: 87.1 percent
- Growth rate: 0.8 percent
- Operational speed: 75 mph

Table 4-28 provides project specific data related to the number of axles per truck, AADTT distribution, monthly distribution, and the hourly truck distribution is shown in table 4-29.

Materials

Default material properties were used for all pavement layers (see Appendix B).

Results

The results of *MEPDG* analysis are summarized in table 4-30 (the detailed output report is provided in Appendix G). For the pavement section evaluated, the *MEPDG* estimates that all distress criteria will be exceed prior to the end of the 40-year analysis period. In addition, the target values for IRI and transverse slab cracking appear to be excessive in that the target IRI level is reached approximately 1 year after construction, and the target percent of transverse cracking is reached in less than 1 year.

Table 4-28. Traffic data—Case Study 2.

Vehicle Class	No. of Axles per Truck			AADTT Distribution (percent)
	Single	Tandem	Tridem	
4	1.47	0.46	0.00	1.35
5	1.75	0.00	0.00	47.15
6	0.99	0.99	0.00	3.26
7	0.77	0.09	0.50	0.19
8	2.61	0.37	0.00	4.98
9	1.24	1.76	0.00	33.53
10	0.98	1.29	0.68	2.51
11	4.81	0.00	0.00	0.08
12	3.93	0.67	0.00	0.06
13	1.58	2.25	0.58	6.89

Month	Distribution Factor[1]
January	1.20
February	1.09
March	1.10
April	1.20
May	1.05
June	0.96
July	0.90
August	0.81
September	0.96
October	0.89
November	0.93
December	0.91

[1] Monthly distribution factors differ slightly from that provided by SDDOT; sum of monthly distribution factors should equal 12.0.

Table 4-29. Hourly distribution—Case Study 2.

Hour	Distribution (percent)
12 AM	1.50
1 AM	1.15
2 AM	1.02
3 AM	0.98
4 AM	1.29
5 AM	1.68
6 AM	2.39
7 AM	3.63
8 AM	4.66
9 AM	5.85
10 AM	6.44
11 AM	6.68

Hour	Distribution (percent)
12 PM	6.74
1 PM	6.87
2 PM	7.20
3 PM	7.04
4 PM	6.68
5 PM	6.21
6 PM	5.53
7 PM	4.68
8 PM	4.00
9 PM	3.29
10 PM	2.63
11 PM	1.86

Table 4-30. Summary of *MEPDG* results—Case Study 2, new construction.

Distress Type	Distress at 50 percent Reliability[1]	Distress at 90 percent Reliability[1]		Target Reached[2] (years)
		Target	Predicted	
Terminal IRI (in/mi)	153	178	210	21.5
Mean joint faulting (in)	0.01	0.15	0.04	—
Transverse cracking (% slabs)	91	15	109	3

[1] At the end of the 40-year analysis period.
[2] Number of years after construction that the predicted distress reaches the target value.

Figures 4-38 through 4-40 illustrate the results from the PPM tool developed models and the *MEPDG* prediction models. The fault prediction is provided in figure 4-38 and shows that the *MEPDG* significantly under-predicts faulting when compared to the performance model developed using the PPM tool for this pavement type (PPM tool – 0.62 in; *MEPDG* – 0.01 in). Based on SDDOT condition measurement rules, a maximum faulting index of 5.0 equates to 0.62 in, which is obtained in year 36 of the 40-year analysis period.

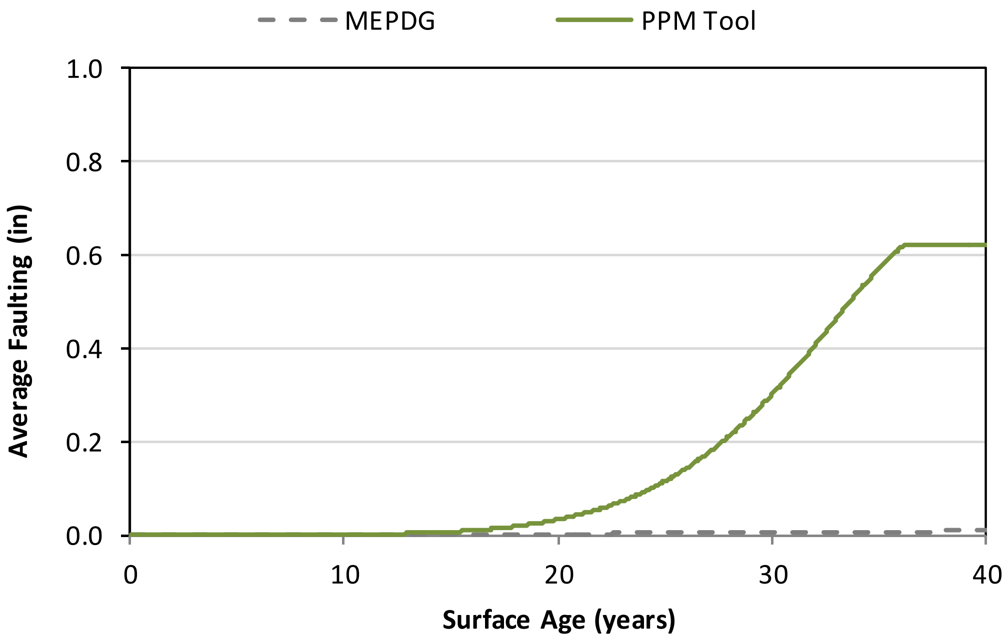


Figure 4-38. Predicted faulting—Case Study 2.

For IRI prediction, shown in figure 4-39, the *MEPDG* over-predicts IRI by approximately 19 percent at the end of the 40-year analysis period (PPM tool – 189 in/mi; *MEPDG* – 153 in/mi).

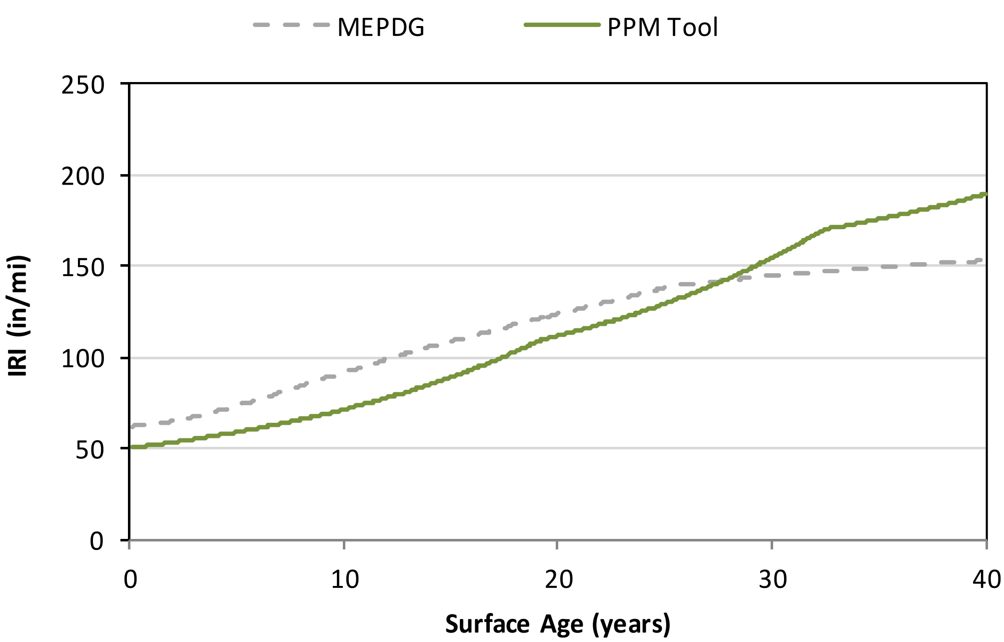


Figure 4-39. Predicted IRI—Case Study 2.

Figure 4-40 shows the *MEPDG* predicted percent of slabs with transverse cracking. Since this distress type is not measured by the SDDOT, a comparison with the PPM tool is not appropriate. However, it is interesting to note that by the end of the 40-year analysis period, the *MEPDG* predicts that 91 percent of all slabs will contain a transverse crack. Based on SDDOT experience (interviews with stakeholders indicated that spalling was the predominant distress requiring treatment), this prediction appears to be excessive for this pavement type.

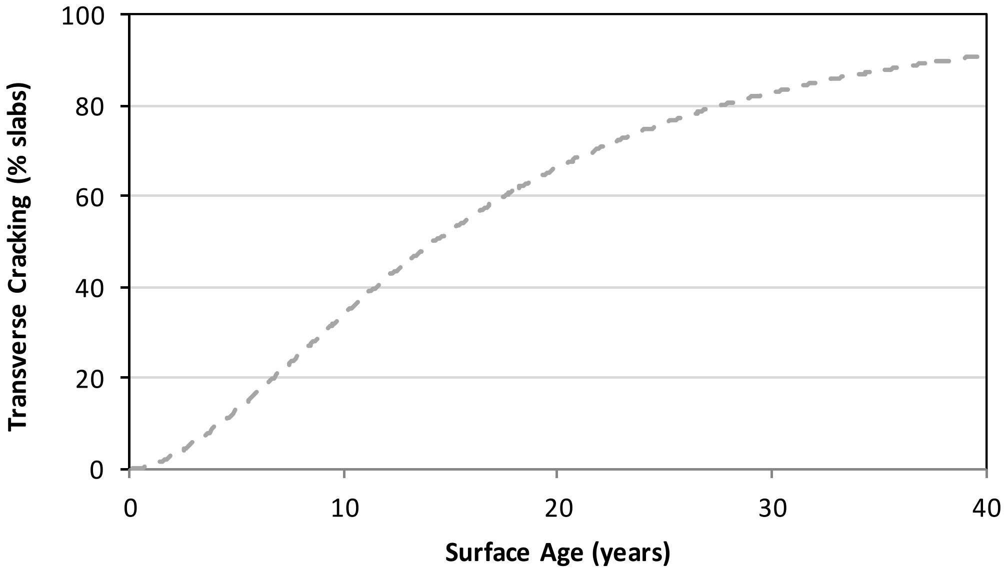


Figure 4-40. *MEPDG* predicted transverse cracking—Case Study 2.

Table 4-31 provides a summary comparison of the *MEPDG* and PPM tool predicted condition indicators at the end of the 40-year analysis period.

Table 4-31. Comparison of PPM tool and *MEPDG* predicted condition —Case Study 2.

Predicted Condition	PPM Tool	*MEPDG*	Percent Difference
Terminal IRI (in/mi)	189	153	19
Faulting (in)	0.62	0.01	99
Transverse Cracking (percent slabs)	—	91	—

Pavement Design Case Study 3 – Asphalt Overlay of an Asphalt Pavement

Project Title:	SD45, McPherson County, Edmunds County Line N to SD10 at Leola
Project Limits:	MRM 193.00 + 0.028 to MRM 201.51 + 0.000
Vicinity:	Leola, South Dakota
Functional Class:	Rural Minor Arterial
No. of lanes:	2

Location

Case Study 3 is located in McPherson County, between Edmunds County Line North and Highway 10 (figure 4-41). The project is located just south of Leola, South Dakota.

Pavement Structure Evaluated

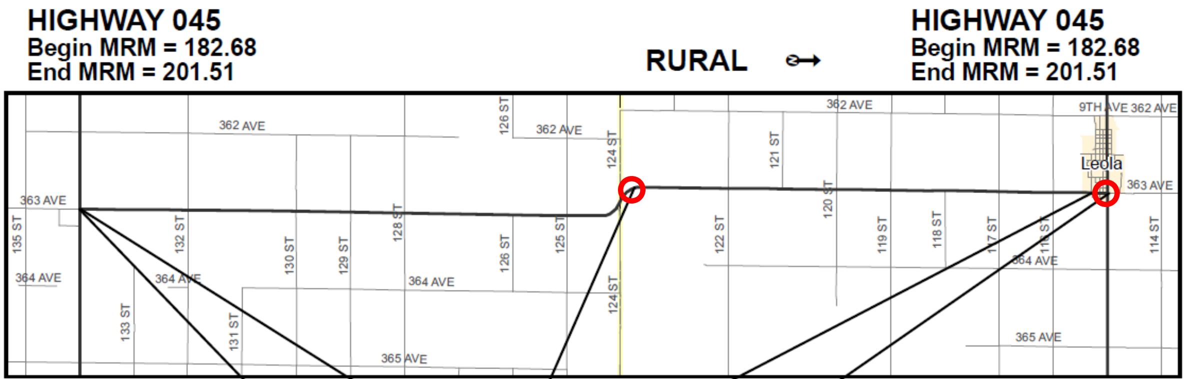
The pavement structure evaluated included a 3-in asphalt overlay of an existing 3-in asphalt pavement over 10 in of crushed aggregate base. This pavement structure is classified as a TONS-A.

Materials

Default material properties were used for all layers (see Appendix B).

Subgrade

The soils for this case study are classified as A-7-6 or A-6 (AASHTO Classification). An A-6 soil type was used in the analysis.



IDENTIFICATION								
Federal Aid System	STP	STP	STP	STP				
Funding Category	MINA	MINA	MINA	MUNI				
Functional Classification	R-MI A	R-MI A	R-MI A	R-MI A				
Direction								
Beginning MRM	182.68	182.70	193.00	201.51				
MRM Displacement	0.000	0.003	0.028	0.000				
Segment Length	0.023	10.350	8.485	0.271				
Year Built	1977	1992	1996	1996				
Year Last Improved	1992	2005	1997	1997				
Year Last Sealed		2008	2008	2008				

Figure 4-41. Location—Case Study 3 (SDDOT 2012b).

Climate

The closest weather station to this project is located in Aberdeen, South Dakota. An elevation of 999 ft and a depth to water table of 100 ft was used in the analysis.

Traffic

- AADTT (2012): 135
- Trucks in design direction: 51 percent
- Trucks in design lane: 100 percent
- Growth rate: 0.8 percent
- Operational speed: 65 mph

Table 4-32 provides project specific data related to the number of axles per truck, AADTT distribution, and monthly distribution and table 4-33 includes the hourly traffic distribution.

Table 4-32. Traffic data—Case Study 3.

Vehicle Class	No. of Axles per Truck			AADTT Distribution (percent)
	Single	Tandem	Tridem	
4	0.40	0.00	0.20	0.63
5	2.06	0.00	0.10	24.74
6	0.86	0.86	0.08	3.52
7	0.50	0.00	0.50	0.40
8	2.61	0.20	0.07	3.81
9	1.19	1.79	0.08	45.91
10	0.94	1.41	0.51	8.19
11	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00
13	1.86	1.67	0.48	12.80

Month	Distribution Factor[1]
January	1.07
February	1.20
March	1.13
April	0.99
May	1.01
June	0.93
July	0.90
August	0.97
September	1.02
October	0.84
November	0.96
December	0.97

[1] Monthly distribution factors differ slightly from that provided by SDDOT; sum of monthly distribution factors should equal 12.0.

Table 4-33. Hourly distribution—Case Study 3.

Hour	Distribution (percent)	Hour	Distribution (percent)
12 AM	1.23	12 PM	7.30
1 AM	0.86	1 PM	7.10
2 AM	0.68	2 PM	7.22
3 AM	0.67	3 PM	7.15
4 AM	0.71	4 PM	7.09
5 AM	0.96	5 PM	6.39
6 AM	1.66	6 PM	5.48
7 AM	3.13	7 PM	4.68
8 AM	4.88	8 PM	4.00
9 AM	6.05	9 PM	3.35
10 AM	7.14	10 PM	2.90
11 AM	7.47	11 PM	1.90

Results

A summary of the *MEPDG* results is provided in table 4-34 (the detailed output report is provided in Appendix G). As with Case Study 1, the *MEPDG* analysis under-predicts IRI, asphalt rut depth, and fatigue cracking, and significantly over-predicts the amount of transverse cracking when compared to the performance equations developed using the PPM tool.

Table 4-34. Summary of *MEPDG* results—Case Study 3, new construction.

Distress Type	Distress at 50 percent Reliability[1]	Distress at 90 percent Reliability[1]		Target Reached[2] (years)
		Target	Predicted	
Terminal IRI (in/mi)	129	178	174	—
Asphalt rut depth (in)	0.08	0.43	0.12	—
Total rut depth (in)	0.33	0.43	0.42	—
Fatigue cracking (%)	0	25	1	—
Transverse cracking (ft/mi)	2,112	1,000	3,213	< 1
Longitudinal cracking (ft/mi)	2,820	1,000	5,826	< 1
Total cracking (percent)[3]	36	100	36	—

[1] At the end of the 20-year analysis period.
[2] Number of years after construction that the predicted distress reaches the target value.
[3] Reflective cracking + fatigue cracking

Figures 4-42 through 4-48 illustrate the performance prediction models determined using the PPM tool and the *MEPDG* predicted distresses. In addition, the SDDOT measured condition values for this project location are also provided.

Figure 4-42 illustrates the comparison of the percent of predicted transverse cracking from the *MEPDG* and PPM tool analysis. Interestingly, the *MEPDG* predicts that the maximum percent of transverse cracking will be achieved within the first 6 months while the prediction model developed with the PPM tool indicates a more gradual increase in transverse cracking over the 20-year analysis period. However, both methods predict similar levels of transverse cracking at the end of the 20-year analysis period (PPM tool – 1,770 ft; *MEPDG* – 2,112 ft). As shown in figure 4-42 the prediction model developed with the PPM tool for this pavement segment reasonably reflects the actual measured performance.

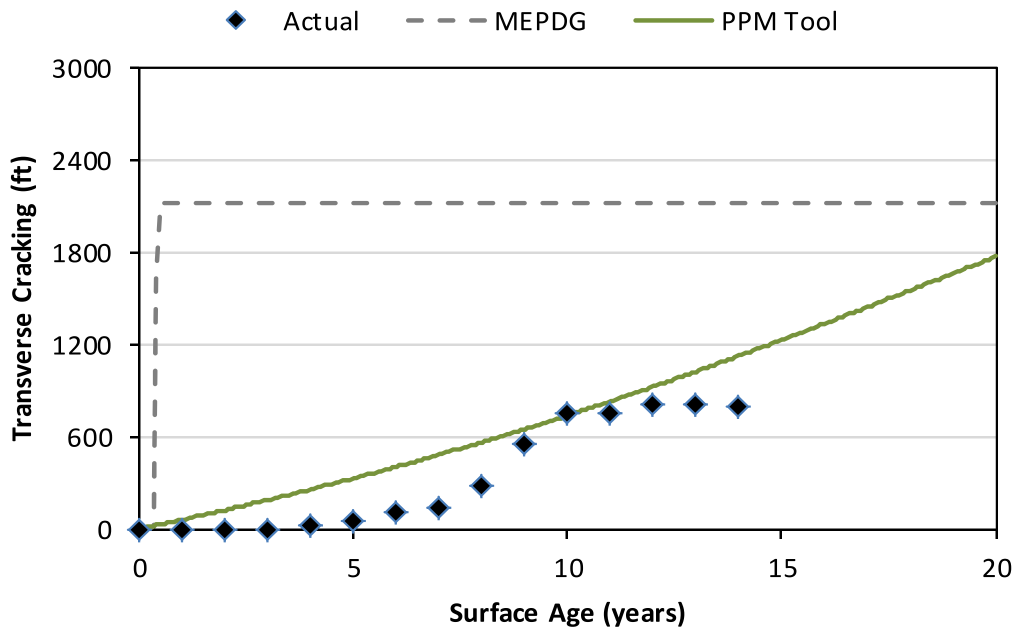


Figure 4-42. Predicted transverse cracking—Case Study 3.

Figure 4-43 illustrates that the *MEPDG* predicts no fatigue cracking over the 20-year analysis period, while the PPM tool prediction model indicates approximately 11 percent fatigue cracking by the end of the analysis period. However, since this case study is an asphalt overlay of an existing asphalt pavement, the *MEPDG* includes a prediction model for reflective cracking. Although the *MEPDG* does not predict any fatigue cracking, it does predict approximately 36 percent reflective cracking (figure 4-44).

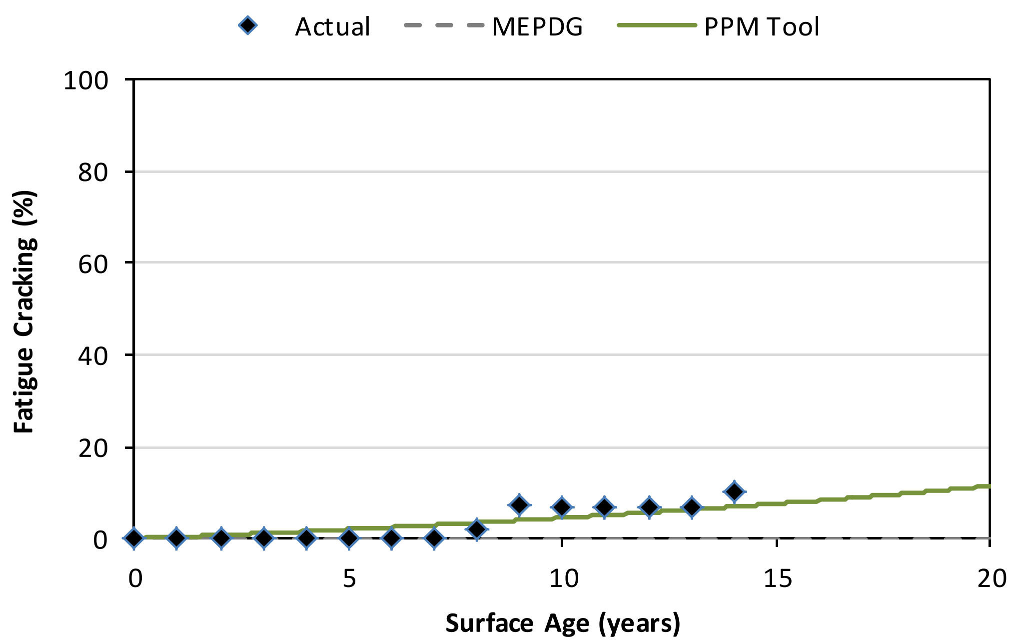


Figure 4-43. Predicted fatigue cracking—Case Study 3.

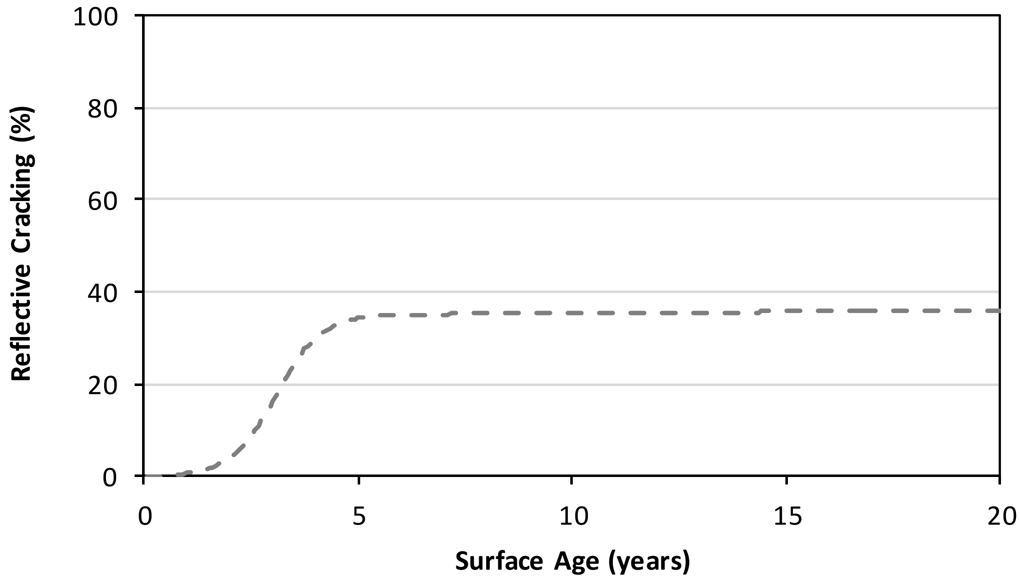


Figure 4-44. *MEPDG* predicted reflective cracking—Case Study 3.

Figure 4-45 illustrates the predicted asphalt rut depth for the PPM tool and the *MEPDG*, as well as the SDDOT measured values. For this case study, the *MEPDG* under-predicts the asphalt rut depth by 0.15 in as compared to the PPM tool performance model (PPM tool – 0.23 in; *MEPDG* – 0.08 in). In addition, the measured values tend to indicate a more rapid increase in the asphalt rut depth, especially from year 12 to year 14. The total *MEPDG* predicted rut depth is shown in figure 4-46. The *MEPDG* predicted total rut depth is 0.33 in, with approximately 75 percent of the rut depth due to rutting in the base and subgrade layers (asphalt rut depth – 0.08 in; total rut depth – 0.33 in).

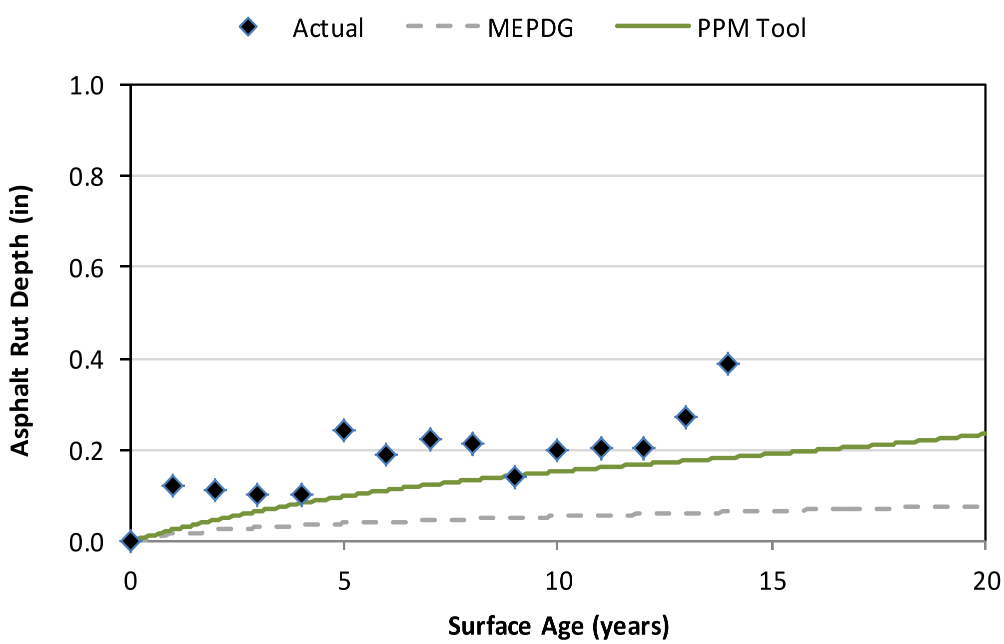


Figure 4-45. Predicted asphalt rut depth—Case Study 3.

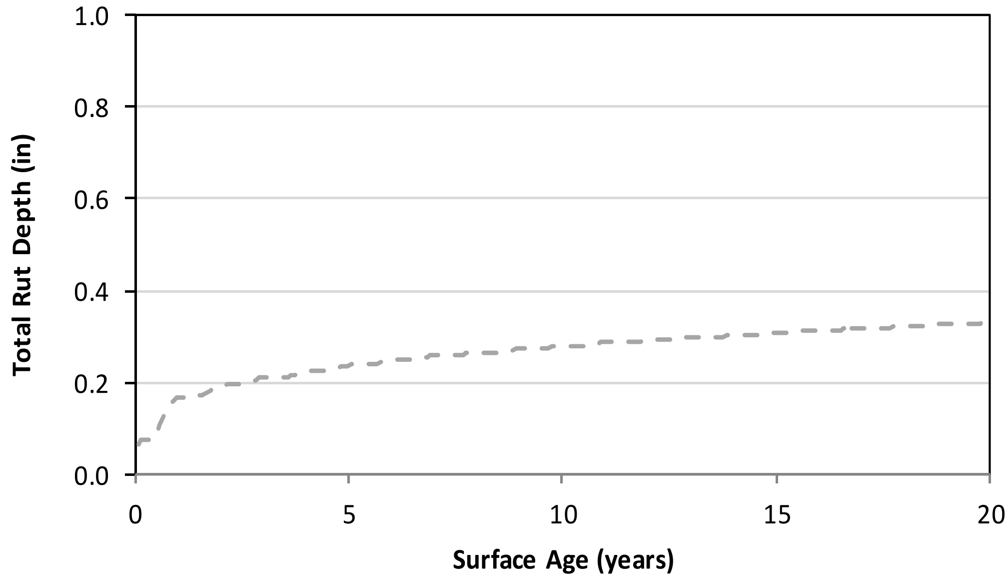


Figure 4-46. *MEPDG* predicted total rut depth—Case Study 3.

For IRI prediction, the *MEPDG* and PPM tool results in very similar results from year 8 to the end of the analysis period (PPM tool – 139 in/mi; *MEPDG* – 129 in/mi) (figure 4-47).The increase in IRI level from year 0 to year 8 is due in part to the predicted increase in total rut depth and reflective cracking over this same time period.

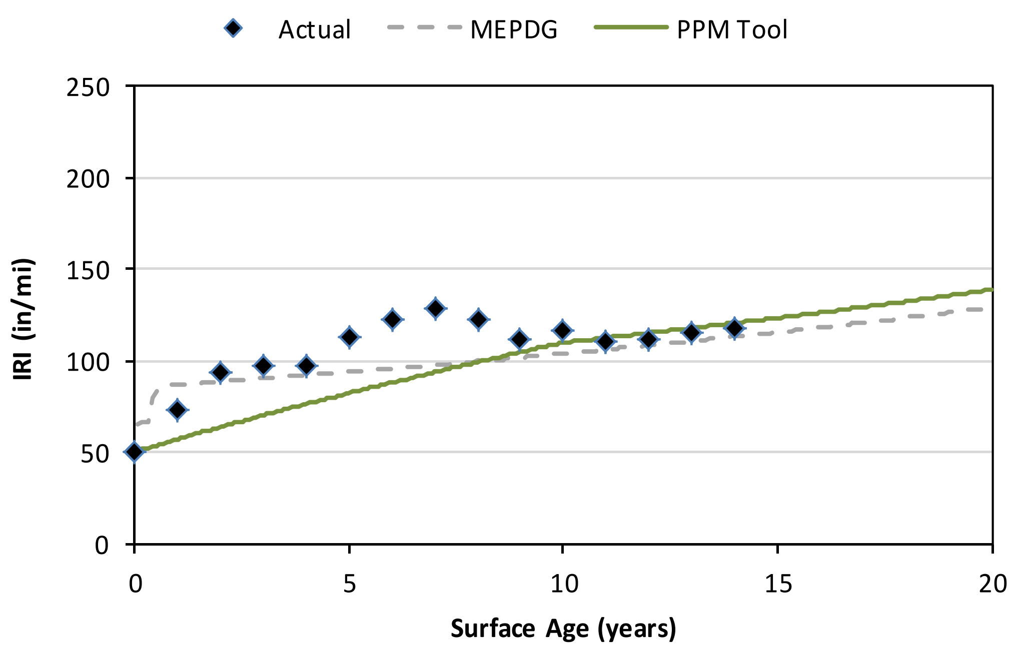


Figure 4-47. Predicted IRI—Case Study 3.

Figures 4-48 shows the *MEPDG* predicted longitudinal cracking for this case study.

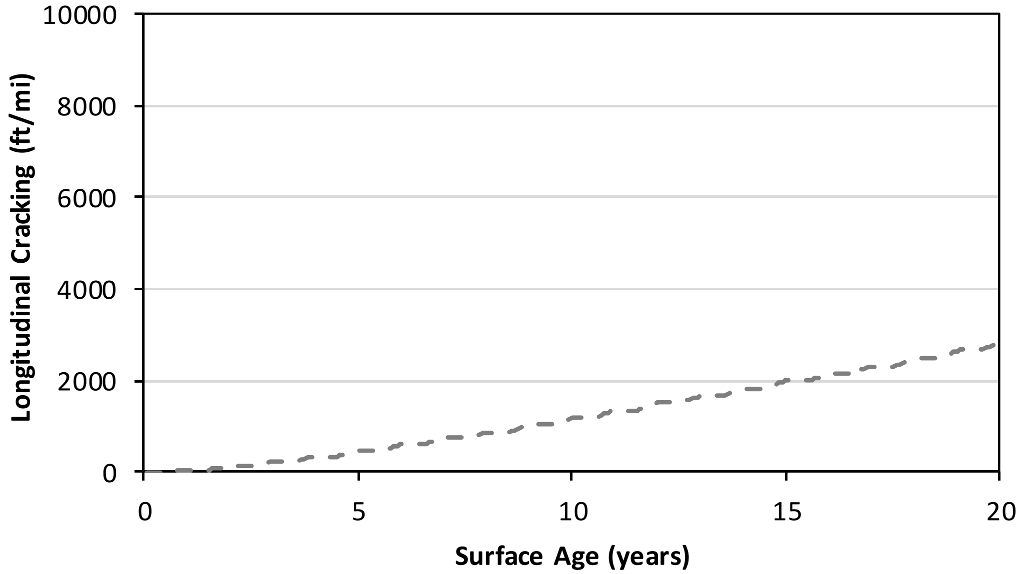


Figure 4-48. ***MEPDG*** **predicted longitudinal cracking—Case Study 3.**

Table 4-35 provides a summary comparison of the *MEPDG* and PPM tool predicted condition indicators at the end of the 20-year analysis period.

Table 4-35. Comparison of PPM tool and ***MEPDG*** **predicted condition —Case Study 3.**

Predicted Condition	PPM Tool	*MEPDG*	Percent Difference
Terminal IRI (in/mi)	139	129	7
Asphalt rut depth (in)	0.23	0.08	67
Total rut depth (in)	—	0.33	—
Fatigue cracking (%)	11	0	100
Transverse cracking (ft/mi)	1,770	2,112	-19
Longitudinal cracking (ft/mi)	—	2,820	—

Pavement Design Case Study 4 – Asphalt Overlay of Existing Concrete Pavement

Project Title: US14, Hughes County, Pierre East – 5.8 miles

Project Limits: MRM 233.95 + 0.000 to MRM 239.00 + 0.725

Vicinity: Pierre, South Dakota

Functional Class: Rural Principal Arterial

No. of lanes: 2

Location

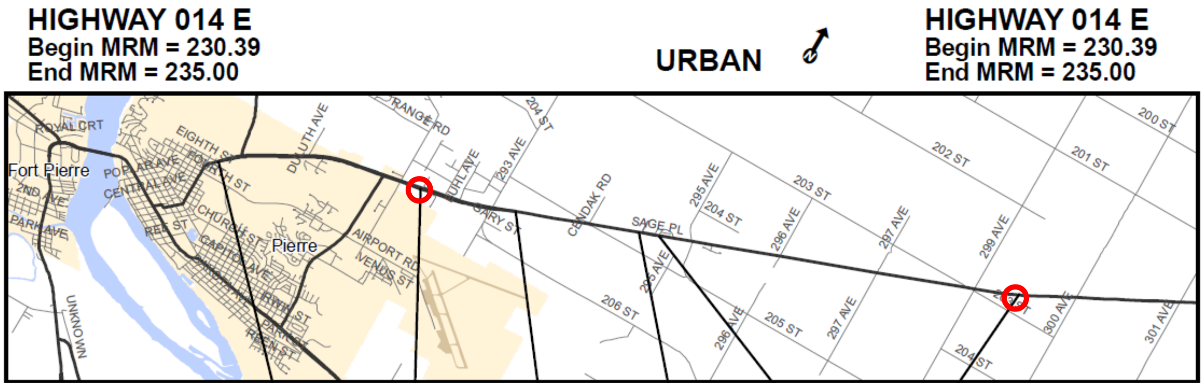
Case Study 4 is located in Hughes County, between North Airport Road and west of 293rd Avenue (figure 4-49). The project is in the vicinity of Pierre, South Dakota.

Pavement Structure Evaluated

This pavement structure was evaluated using a 4.5-in asphalt overlay of an existing 7.5-in plain-jointed concrete pavement over 4.5 in of crushed aggregate base. This pavement structure is classified as an AONC.

Materials

Default material properties were used for all layers (see Appendix B).



IDENTIFICATION							
Federal Aid System	STP	NHS-NI	NHS-NI	NHS-NI	NHS-NI		
Funding Category	URB	MAJA	MAJA	MAJA	MAJA		
Functional Classification	U-P A	R-P A	R-P A	R-P A	R-P A		
Direction	E	E					
Beginning MRM	230.39	232.58	233.95	235.00	235.00		
MRM Displacement	0.000	0.221	0.000	0.323	0.571		
Segment Length	2.400	1.101	1.418	0.248	4.150		
Year Built	1961	1979	1979	1979	1979		
Year Last Improved	2004	1999	1999	1999	1999		
Year Last Sealed	2007						

Figure 4-49. Location—Case Study 4 (SDDOT 2012b).

Subgrade

Soil types encountered in the loose subgrade samples are silty clay, clay silt, clay sand, clay, and sandy clay. The loose samples were classified as A-6, A-7-5, and A-7-6. An A-6 soil classification was used in the analysis.

Climate

The closest weather station to this project is located in Pierre, South Dakota. An elevation of 999 ft and a depth to water table of 100 ft was used in the analysis.

Traffic

- AADTT (2012): 397
- Trucks in design direction: 51 percent
- Trucks in design lane: 100 percent
- Growth rate: 0.7 percent
- Operational speed: 65 mph

Table 4-36 provides project specific data related to the number of axles per truck, AADTT distribution, and monthly distribution and table 4-37 includes the hourly traffic distribution.

Results

A summary of the *MEPDG* results for this case study are provided in table 4-38 (the detailed output report is provided in Appendix G). For the pavement section evaluated, all predicted distresses (excluding traverse cracking) are well below the target values. The amount of transverse cracking, at 90 percent reliability, is predicted to be exceeded within 5.5 years of construction.

Figures 4-50 through 4-55 illustrate the performance prediction models determined using the PPM tool and the *MEPDG*. As with previous case studies, the *MEPDG* over-predicts transverse cracking (figure 4-50) as compared to the performance model developed with the PPM tool (PPM tool – 1,413 ft/mi; *MEPDG* – 1,848 ft/mi).

Table 4-36. Traffic data—Case Study 4.

Vehicle Class	No. of Axles per Truck			AADTT Distribution (percent)
	Single	Tandem	Tridem	
4	0.92	0.00	0.08	0.93
5	1.76	0.00	0.06	26.61
6	0.95	0.95	0.05	4.84
7	1.00	0.00	0.81	0.81
8	2.35	0.52	0.07	6.76
9	1.19	1.79	0.07	43.36
10	0.97	1.35	0.59	3.91
11	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00
13	2.02	1.76	0.57	12.78

Month	Distribution Factor[1]
January	1.34
February	1.12
March	1.04
April	0.94
May	0.99
June	0.91
July	0.92
August	0.81
September	0.83
October	0.93
November	1.00
December	1.17

[1] Monthly distribution factors differ slightly from that provided by SDDOT; sum of monthly distribution factors should equal 12.0.

Table 4-37. Hourly distribution—Case Study 4.

Hour	Distribution (percent)
12 AM	0.73
1 AM	0.60
2 AM	0.60
3 AM	1.15
4 AM	1.85
5 AM	2.94
6 AM	4.48
7 AM	5.90
8 AM	6.81
9 AM	7.55
10 AM	8.04
11 AM	7.83

Hour	Distribution (percent)
12 PM	7.48
1 PM	7.50
2 PM	7.07
3 PM	6.59
4 PM	5.60
5 PM	4.65
6 PM	3.64
7 PM	2.66
8 PM	2.12
9 PM	1.84
10 PM	1.49
11 PM	0.89

Table 4-38. Summary of *MEPDG* results—Case Study 4.

Distress Type	Distress at 50 percent Reliability[1]	Distress @ Specified Reliability[1]		Target Reached[2] (years)
		Target	Predicted	
Terminal IRI (in/mi)	86	178	117	—
Asphalt rut depth (in)	0.08	0.43	0.12	—
Total rut depth (in)	0.08	0.43	0.12	—
Transverse cracking (ft/mi)	1,848	1,000	2,815	5.5
Fatigue cracking (%)	0	25	1	—
Longitudinal cracking (ft/mi)	0	1,000	398	—
Total cracking (percent)[3]	5	100	5	—
JPCP transverse cracking[4]	0	15	4	—

[1] At the end of the 20-year analysis period.
[2] Approximate number of years after construction that the predicted distress reaches the target value.
[3] Reflective cracking + fatigue cracking.
[4] Percent of transverse cracked slabs.

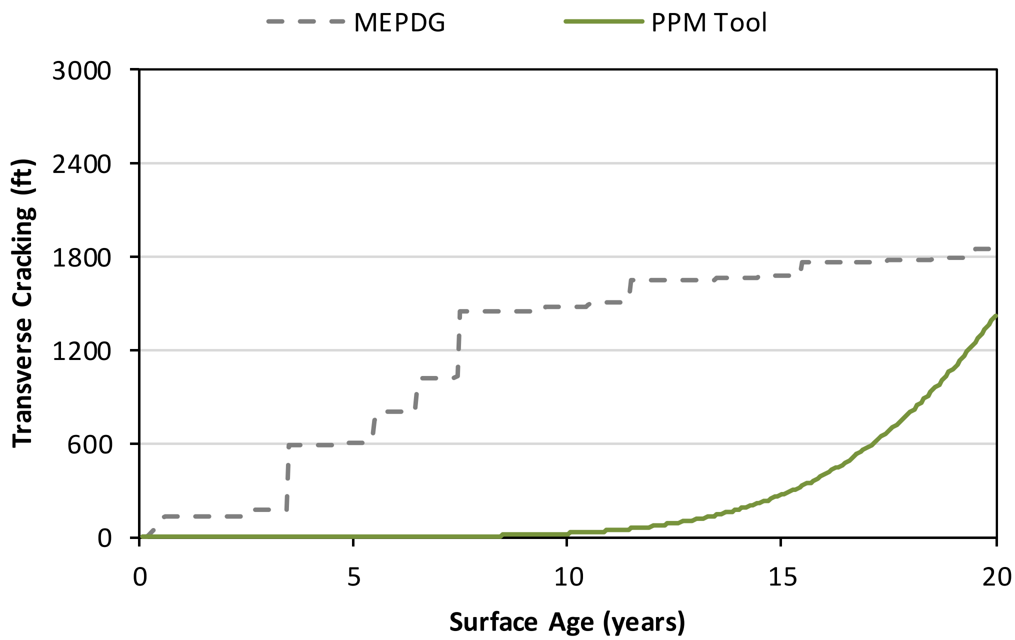


Figure 4-50. Predicted transverse cracking—Case Study 4.

The predicted fatigue cracking is shown in figure 4-51, and *MEPDG* reflective cracking is shown in figure 4-52. The *MEPDG* predicts 0 percent fatigue cracking and 5 percent reflective cracking, while the PPM tool predicts approximately 8 percent fatigue cracking over the analysis period.

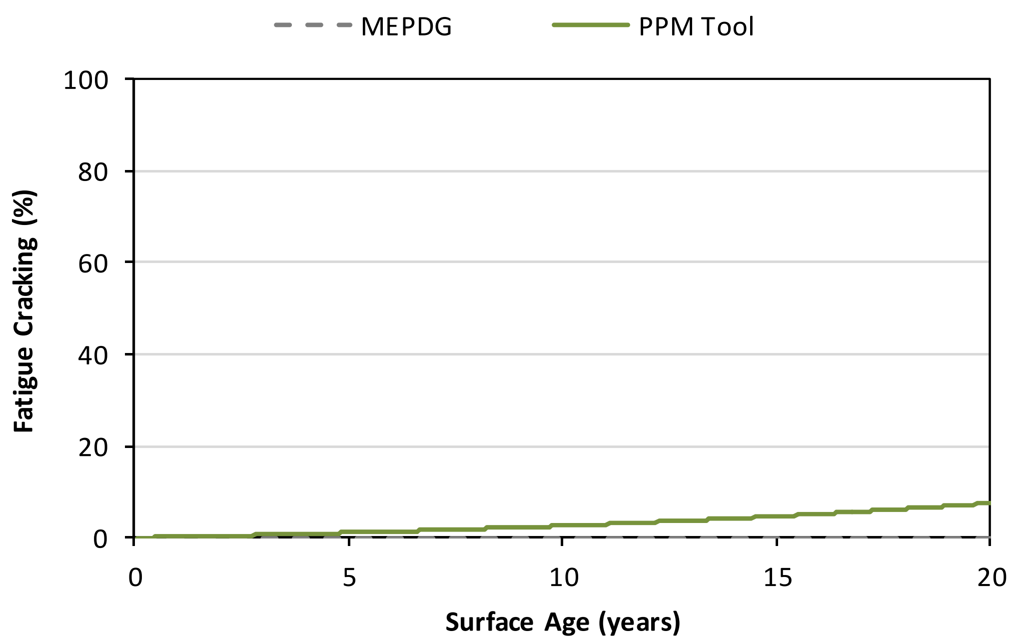


Figure 4-51. Predicted fatigue cracking—Case Study 4.

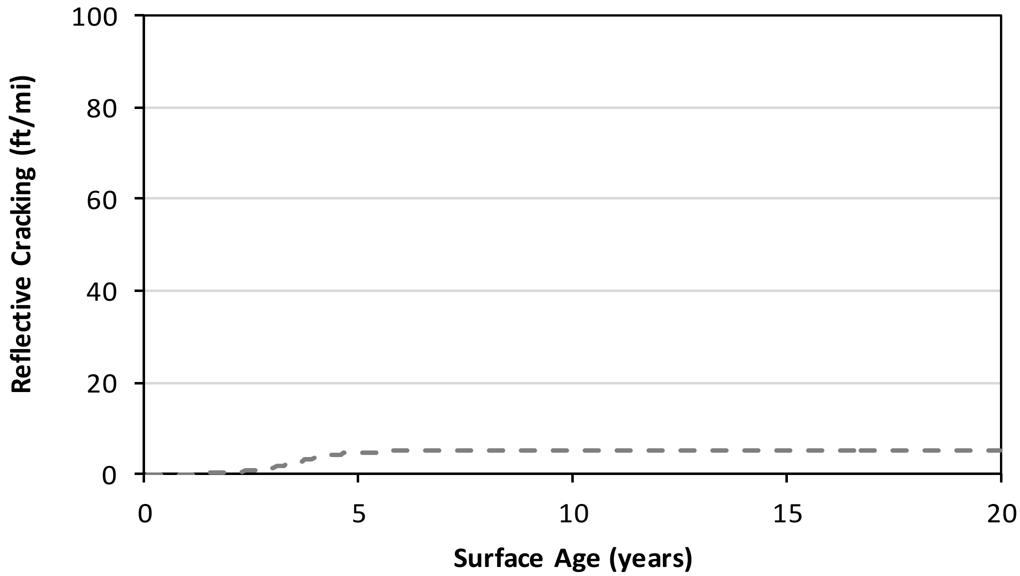


Figure 4-52. *MEPDG* predicted reflective cracking—Case Study 4.

For this pavement type, the PPM tool and the *MEPDG* predicts very little asphalt rutting (0.02 in and 0.08 in, respectively) over the analysis period (figure 4-53). The *MEPDG* also predicts very little total rutting (0.08 in), which is expected for this asphalt overlay of an existing concrete pavement (figure 4-54).

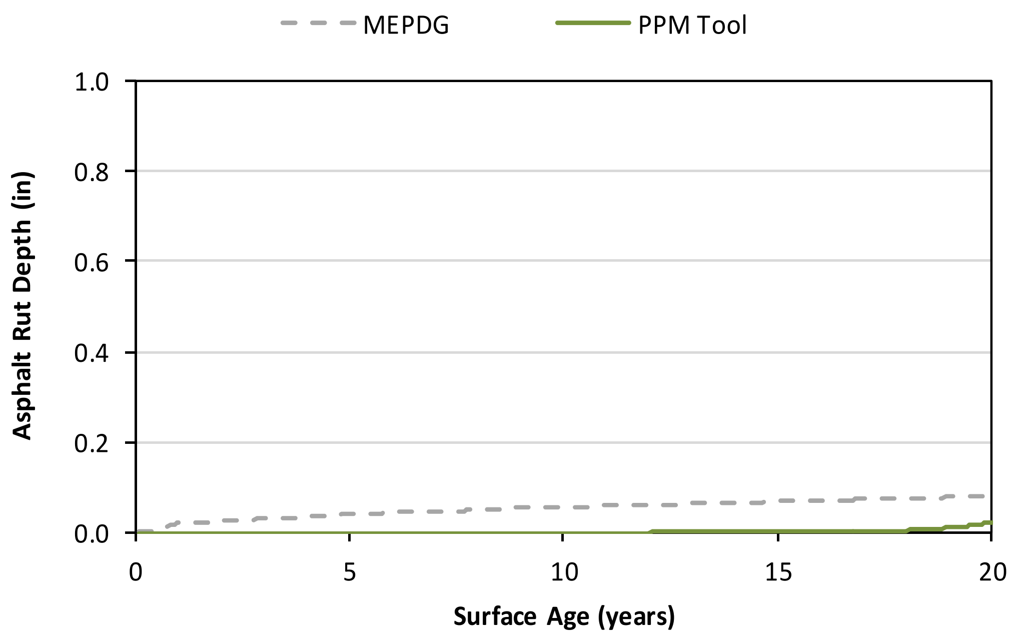


Figure 4-53. Predicted asphalt rut depth—Case Study 4.

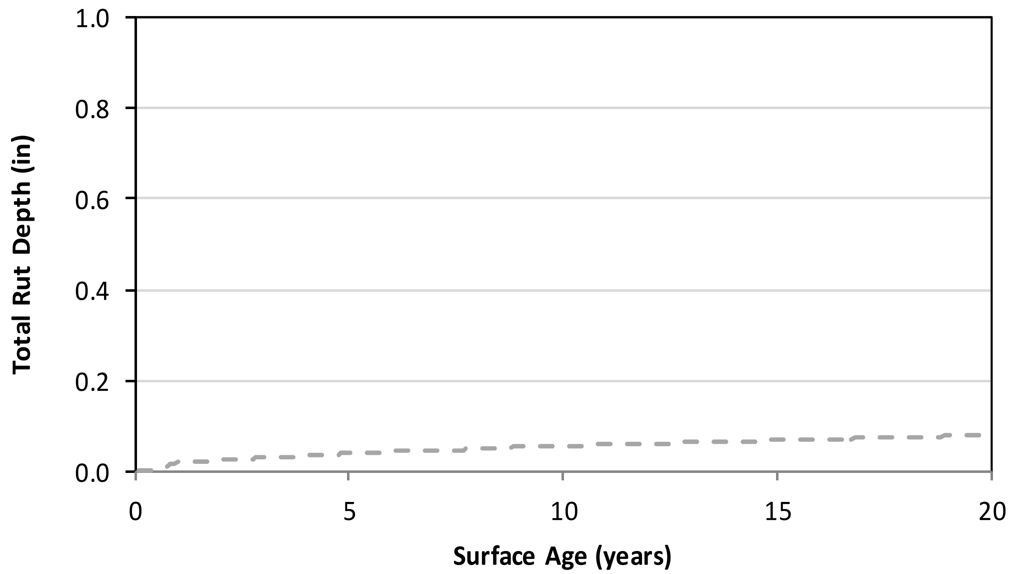


Figure 4-54. *MEPDG* predicted total rut depth—Case Study 4.

At the end of the analysis period, the *MEPDG*-predicted IRI level is approximately half of the IRI level predicted using the performance model developed with the PPM tool (PPM tool – 161 in/mi; *MEPDG* – 86 in/mi). The prediction model developed from the PPM tool has a much steeper slope than that determined from the *MEPDG* (figure 4-55).

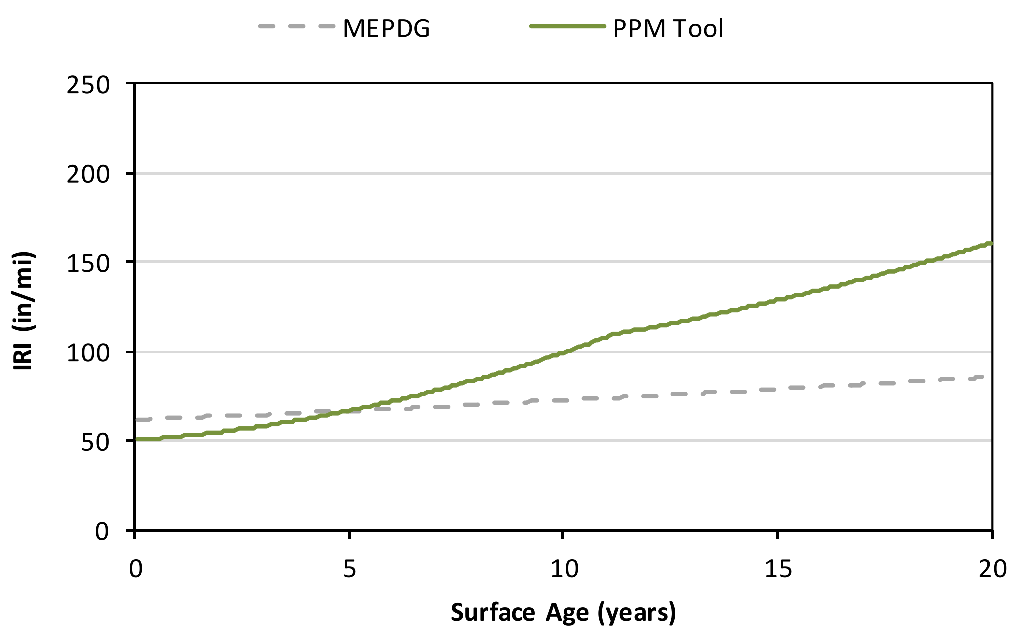


Figure 4-55. Predicted IRI—Case Study 4.

The *MEPDG* predicts that longitudinal cracking will not occur over the 20-year performance period.

Table 4-39 provides a summary comparison of the *MEPDG*- and PPM tool-predicted condition indicators at the end of the 20-year analysis period.

Table 4-39. Comparison of PPM tool and *MEPDG* predicted condition —Case Study 4.

Predicted Condition	PPM Tool	*MEPDG*[1]	Percent Difference
Terminal IRI (in/mi)	161	86	47
Asphalt rut depth (in)	0.02	0.08	-257
Total rut depth (in)	—	0.08	—
Fatigue cracking (%)	8	0	100
Transverse cracking (ft/mi)	1,413	1,848	-31
Longitudinal cracking (ft/mi)	—	0	—

Pavement Design Case Study 5 – Concrete Overlay of Existing Concrete Pavement

Project Title: US14, Beadle County, Huron

Project Limits: MRM 338.00 + 0.515 to MRM 342.84 + 0.000

Vicinity: Huron, South Dakota

Functional Class: Rural Minor Arterial

No. of lanes: 2

Location

Case Study 5 is located in Beadle County, between 303rd Avenue and Mellette Avenue (figure 4-56). The project is located in the vicinity of Huron, South Dakota.

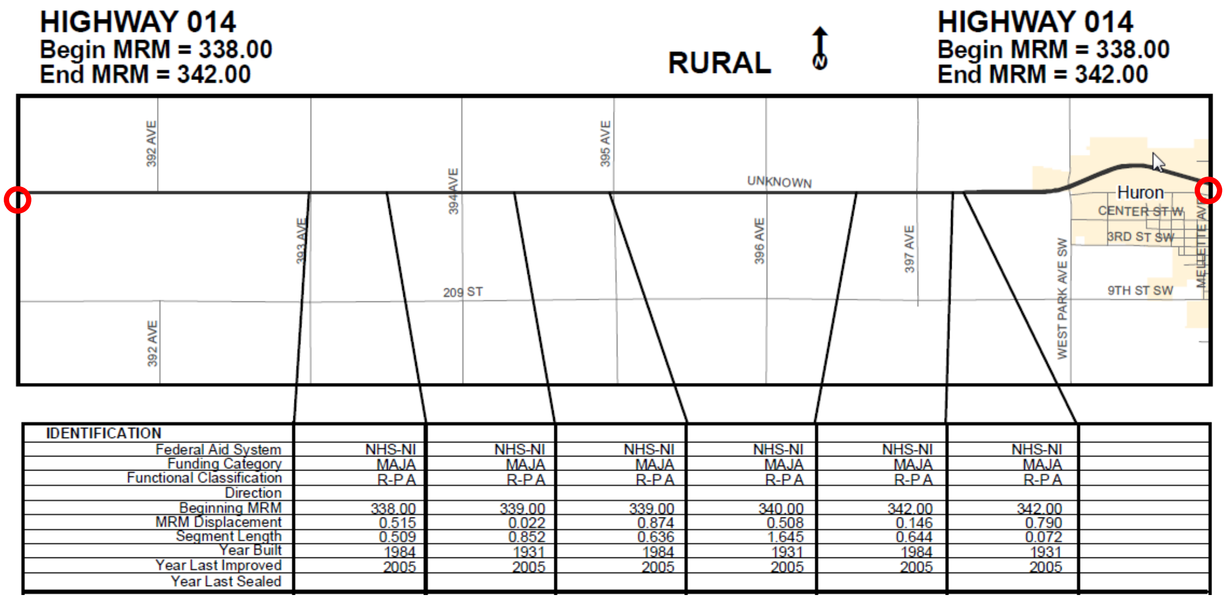


Figure 4-56. Location—Case Study 5 (SDDOT 2012b).

Pavement Structure Evaluated

The pavement section evaluated for this case study included a 6.0-in unbounded concrete overlay over 2.0 in of asphalt over an existing 8.0-in plain jointed concrete pavement and 7.5 in of crushed gravel base. The analysis period for this case study was 40 years.

Materials

Default material properties were used for all layers (see Appendix B).

Subgrade

The soil types encountered in the loose subgrade samples were clay sand, sandy clay, silty sand, and clay silt and classified as A-6 or A-7-6. An A-6 soil type was used in the analysis.

Climate

The closest weather station to this project is located in Aberdeen, South Dakota. An elevation of 999 ft and a depth to water table of 100 ft was used in the analysis.

Traffic

- AADTT (2012): 301
- Trucks in design direction: 50 percent
- Trucks in design lane: 100 percent
- Growth rate: 0.7 percent
- Operational speed: 65 mph

Table 4-40 provides project specific data related to the number of axles per truck, AADTT distribution, and monthly distribution, and table 4-41 provides the hourly traffic distribution.

Table 4-40. Traffic Data—Case Study 5.

Vehicle Class	No. of Axles per Truck			AADTT Distribution (percent)
	Single	Tandem	Tridem	
4	0.92	0.00	0.08	0.93
5	1.76	0.00	0.06	26.61
6	0.95	0.95	0.05	4.84
7	1.00	0.00	0.81	0.81
8	2.35	0.52	0.07	6.76
9	1.19	1.79	0.07	43.36
10	0.97	1.35	0.59	3.91
11	0.00	0.00	0.00	0.00
12	0.00	0.00	0.00	0.00
13	2.02	1.76	0.57	12.78

Month	Distribution Factor[1]
January	1.34
February	1.12
March	1.04
April	0.94
May	0.99
June	0.91
July	0.92
August	0.81
September	0.83
October	0.93
November	1.00
December	1.17

[1] Monthly distribution factors differ slightly from that provided by SDDOT; sum of monthly distribution factors should equal 12.0.

Table 4-41. Hourly distribution—Case Study 5.

Hour	Distribution (percent)
12 AM	0.73
1 AM	0.60
2 AM	0.60
3 AM	1.15
4 AM	1.85
5 AM	2.94
6 AM	4.48
7 AM	5.90
8 AM	6.81
9 AM	7.55
10 AM	8.04
11 AM	7.83

Hour	Distribution (percent)
12 PM	7.48
1 PM	7.50
2 PM	7.07
3 PM	6.59
4 PM	5.60
5 PM	4.65
6 PM	3.64
7 PM	2.66
8 PM	2.12
9 PM	1.84
10 PM	1.49
11 PM	0.89

Results

The results of the *MEPDG* analysis is shown in table 4-42. From this analysis, the 6-in unbonded concrete overlay meets all targeted distress and IRI values by the end of the 40-year analysis period. The predicted distresses for all conditions are well below the target values (at 90 percent reliability) except for transverse cracking. The percent of slabs with transverse cracks is predicted to reach the target value in approximately 34 years.

Table 4-42. Summary of *MEPDG* results—Case Study 5.

Distress Type	Distress at 50 percent Reliability[1]	Distress at 90 percent Reliability[1]		Target Reached[2] (years)
		Target	Predicted	
Terminal IRI (in/mi)	92	178	132	—
Mean joint faulting (in)	0.01	0.15	0.04	—
Transverse cracking (% slabs)	12	15	23	34

[1] At the end of the 40-year analysis period.
[2] Approximate number of years after construction that the predicted distress reaches the target value.

At this time, SDDOT does not define unbonded concrete overlays as a pavement family; therefore, comparison with a performance prediction model developed using the PPM tool is not applicable. This case study was provided for informational purposes only. The *MEPDG* predicted fault, IRI, and transverse slab cracking for this case study are shown in figures 4-57 through 4-59, respectively.

Figures 4-57 and 4-58 illustrate that the *MEPDG* predicts very low mean joint faulting and IRI over the analysis period, while figure 4-59 illustrates the rate of transverse cracking over the design period.

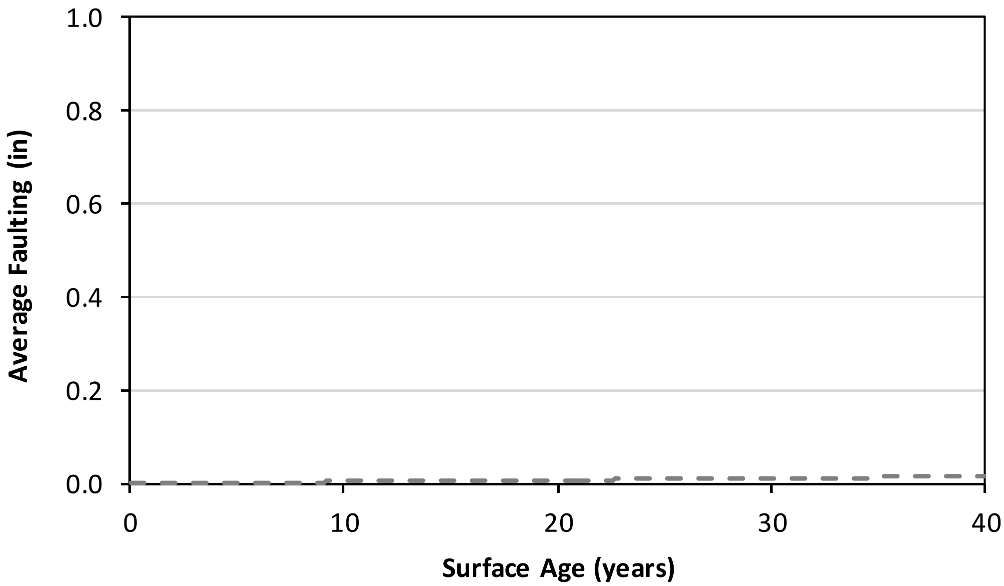


Figure 4-57. Predicted faulting—Case Study 5.

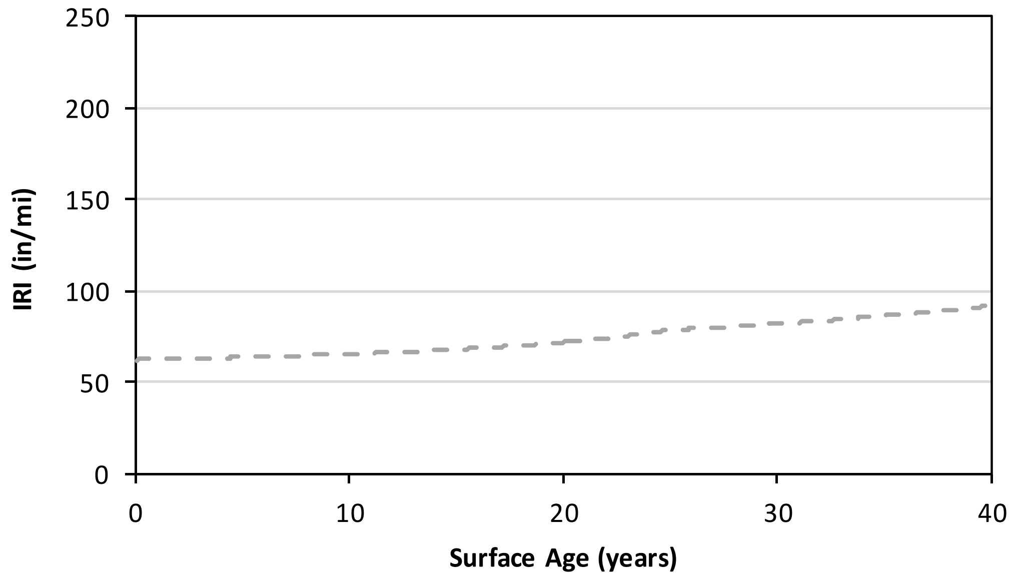


Figure 4-58. Predicted IRI—Case Study 5.

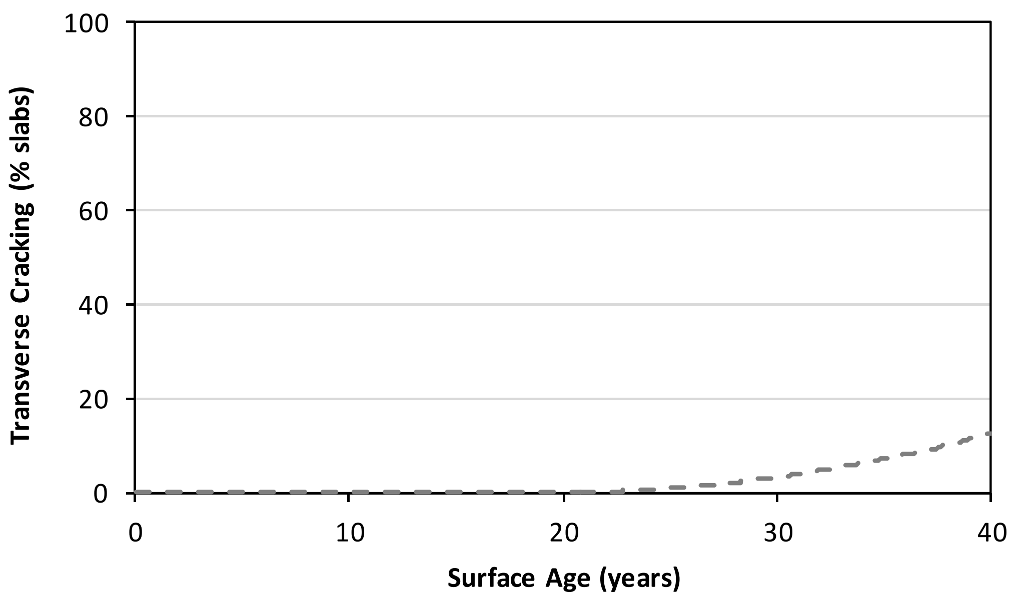


Figure 4-59. Predicted transverse slab cracking—Case Study 5.

Table 4-43 provides a summary of the *MEPDG* predicted condition at the end of the analysis period.

Table 4-43. Summary of *MEPDG* predicted condition —Case Study 5.

Predicted Condition	*MEPDG*
Terminal IRI (in/mi)	92
Faulting (in)	0.01
Transverse Cracking (percent slabs)	12

Relationship between AASHTOWare *Pavement ME Design*™ and Distress Prediction Using the PPM Tool

Based on the information provided from the case studies, the *MEPDG* asphalt pavement performance prediction models, on average, under-predict rut depth by 53 percent, under-predict fatigue cracking by approximately 81 percent, and over-predict transverse cracking by 19 percent compared to the distress prediction from models developed using the PPM tool. For concrete pavements, the *MEPDG* under-predicts faulting by 99 percent; however, the analysis was only based on one case study. Additional case studies should be conducted prior to assessing the prediction capabilities of the *MEPDG* and PPM tool performance prediction models. For both pavement types, the *MEPDG*, on average, under-predicts IRI by 26 percent when compared to the performance prediction models developed using the PPM tool. Table 4-44 provides a summary of the average difference of predicted distress values between *MEPDG* and PPM tool performance prediction models, as well as the number of case studies and range in value differences.

Table 4-44. Summary of PPM tool and *MEPDG* predicted condition.

Predicted Condition	Number of Case Studies	Range of Differences	Average Difference (%)[1]
Terminal IRI (in/mi)	4	7 to 47	26
Asphalt rut depth (in)	3	-257 to 72	53
Fatigue cracking (%)	3	43 to 100	81
Transverse cracking (ft)	3	-31 to -9	-19
Faulting (in)	1	99	99

[1] Average percent difference between PPM tool and *MEPDG* predicted condition. Negative values indicate *MEPDG* over-predicts condition compared to the PPM tool results.

Although there are differences between the predicted conditions using the PPM tool and the *MEPDG* software, the differences more than likely can be resolved through the local calibration process. Figures 4-60 through 4-63 compare the predicted distress quantities using the PPM tool and *MEPDG* models for transverse cracking, fatigue cracking, and IRI for all asphalt-surfaced case studies.

There appears to be significant difference in the rate of transverse cracking over the 20-year analysis period (as shown in figure 4-60). However, for the most part, there is relatively good agreement (the difference in transverse cracking at the end of the performance period ranges from 155 to 435 ft/mi for all three asphalt case studies) in the predicted amount of transverse cracking by the end of the analysis period.

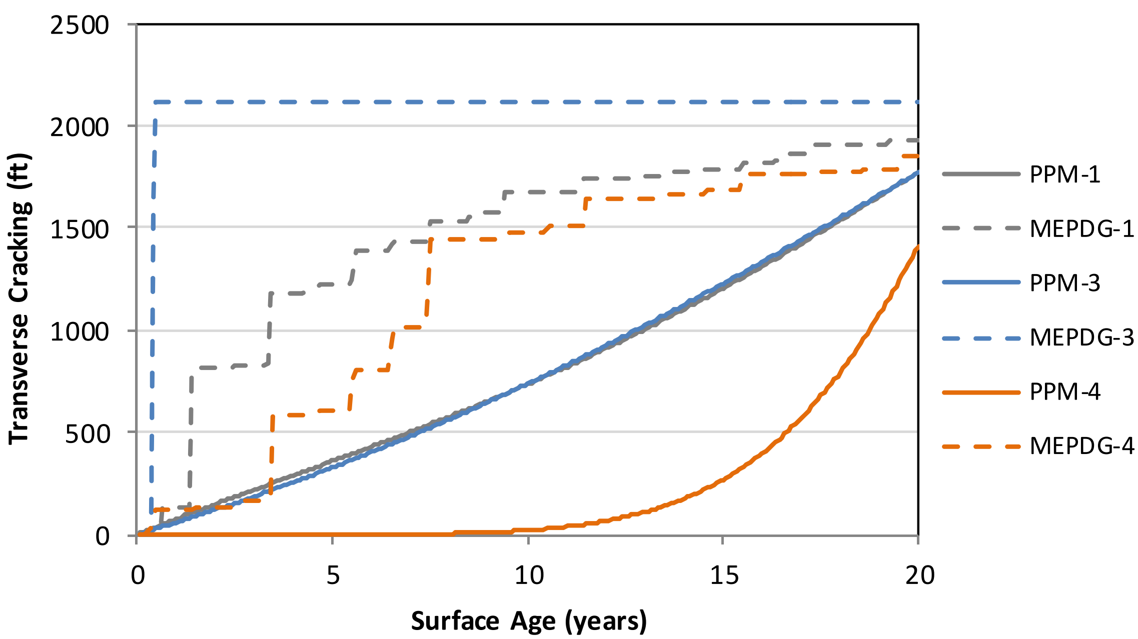


Figure 4-60. Predicted transverse cracking—all asphalt-surfaced case studies.

The predicted distress curves for fatigue cracking differ only in the slope of the curve, such that local calibration should be a relatively easy adjustment (shown in figure 4-61). The actual difference in the predicted percent of fatigue cracking between the *MEPDG* and PPM tool performance models is less than 11 percent (ranging from 4 to 11 percent). If the assumed wheel path area over 1 lane-mile is 31, 680 ft^2 (3 ft wide wheel path x 2 wheel paths x 5280 ft/mi), then the difference in the predicted length of fatigue cracking between the two prediction models is approximately 200 to 600 ft (both wheelpaths).

As with fatigue cracking, the asphalt rut depth prediction curve (figure 4-62) and the IRI prediction curve (figure 4-63), mostly only differ in the slope of the curve. The difference in predicted asphalt rut depth at the end of the performance period ranges from 0.06 to 0.15 in, and the difference between *MEPDG* total rut depth and the rut depth prediction using the PPM tool-developed performance model (surface rutting only) ranges from 0.06 to 0.11 in. Similarly, the difference in IRI prediction ranges from 10 in/mi to 75 in/mi. The local calibration effort should be a relatively easy adjustment for both of these *MEPDG* distress prediction models.

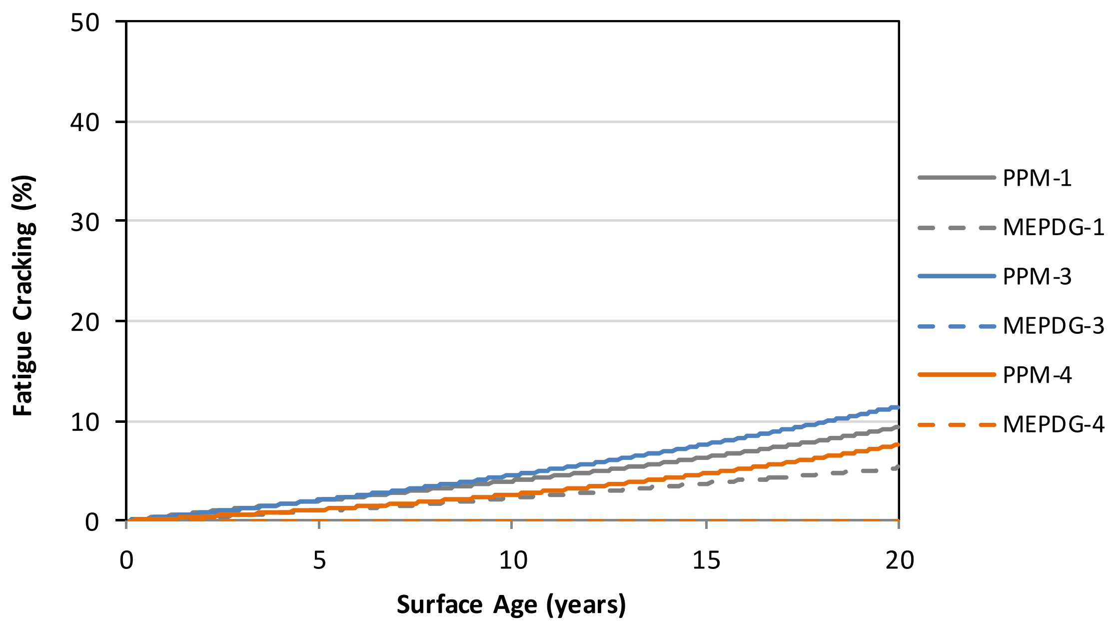


Figure 4-61. Predicted fatigue cracking— all asphalt-surfaced case studies.

Recommendations for Use in AASHTOWare *Pavement ME Design*™ Calibration

The performance prediction models developed using the PPM tool can be used to calibrate the performance prediction models contained within the *MEPDG* and accompanying AASHTOWare *Pavement ME Design*™ software. However, as noted previously, review of the PPM tool performance prediction models is highly recommended to ensure that they reflect expected performance. Once the performance prediction models have been accepted, they can be used to adjust the calibration coefficients within the AASHTOWare *Pavement ME Design*™ software. Guidelines on how to accomplish the calibration process are contained in the *Calibration Guide* (AASHTO 2010). Using the performance prediction models developed using the PPM tool, the *MEPDG* calibration coefficients for the various prediction models would be adjusted until there is agreement between the results. Adjustment of the calibration coefficients can either be performed by iterating applicable coefficients or through the use of a spreadsheet solver routine. As noted in the *Calibration Guide* (AASHTO 2010), the calibrated models should be validated before implementation. Validation would include the identification of several (i.e., 10 to 20) pavement segments, for each pavement type/distress combination, which would be evaluated based on the revised calibration coefficients. Also noted in the *Calibration Guide* (AASHTO 2010), a significant number of test sections will be needed to locally calibrate the IRI prediction models. Details of the validation process are also contained within the *Calibration Guide* (AASHTO 2010).

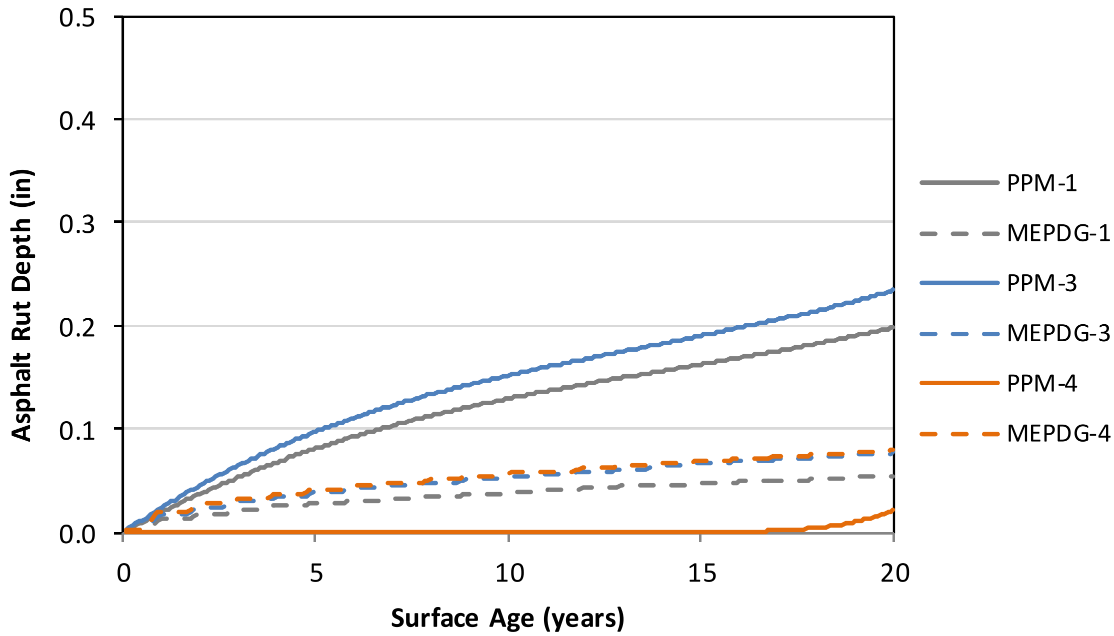


Figure 4-62. Predicted asphalt rut depth—all asphalt-surfaced case studies.

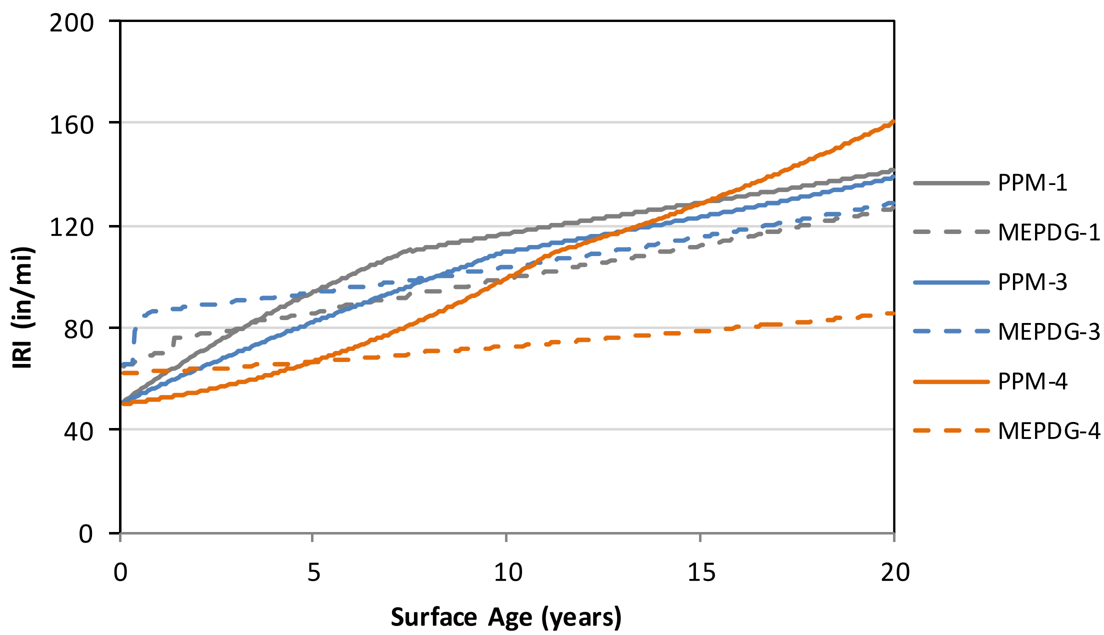


Figure 4-63. Predicted IRI—all asphalt-surfaced case studies.

Task 14: Prepare Final Report

Prepare a final report summarizing research methodology, findings, conclusions, and recommendations.

This document 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 15: Make Executive Presentation

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 19, 2013. The presentation included a summary of the project objectives, the technical approach, significant findings from the research, and final conclusions and recommendations.

4 FINDINGS AND CONCLUSIONS

Significant findings and conclusions from this study include the following:

- At a minimum, the software tool developed under this project needed to provide the following capabilities:
  - Automate as much of the performance prediction modeling and updating process as possible.
  - Generate more than one model at a time and provide recommendations on which model is the "best" model to incorporate into dTIMS.
  - Generate model types that include cubic, exponential, linear, power, and quadratic.
  - Include the ability to set a fixed endpoint in a performance prediction model.
  - Include built-in functionality to determine if new model is significantly different from the existing model.
  - Include the ability to generate companion virtual age equations for each performance prediction model.
  - Be compatible with the Windows 7 operating system.
- Comparing the models of the current SDDOT family tree to the revised models using 17 years of pavement condition data, resulted in model changes for the majority of condition indicators for all pavement type and curve flag combinations. A number of the recommended performance prediction models were different, in some cases significantly different, than the existing performance prediction model.
- A number of pavement segments had high condition indices at ages greater than 20 to 30 years; however, prior to conducting the analysis the research team worked with SDDOT Pavement Management to resolve this issue. Other data concerns include pavement segments with incorrect curve flag definitions, pavement segments where the RUFF index was not reset to 5.0 after treatment application, and pavement segments where 0.0 was entered due to roadway construction rather than a value greater than 5.0.
- The current SDDOT approach for establishing the pavement family tree (i.e., by pavement type and curve flag) is a valid approach for use in pavement management applications, therefore no significant changes are recommended.
- Slight changes were made to the current pavement family tree based on the results of the statistical analysis.
- The pavement performance equations determined from the PPM tool can be used as a starting point in the local calibration of the *MEPDG*. In order to use pavement condition results contained within the dTIMS database, the research team developed a process to convert SDDOT condition indices to actual measures of distress (e.g., area, length). However, these conversion equations should be validated using additional pavement segments. Although there are differences between the PPM tool and *MEPDG* predicted distress conditions, it appears that adjustment of the *MEPDG* calibration coefficients would effectively improve the *MEPDG* predictions.

5 IMPLEMENTATION RECOMMENDATIONS

This project was initiated to update and revise the current process for defining and evaluating the performance prediction models for the SDDOT pavement families, develop a tool that could be used by SDDOT to aid in the evaluation and updating of the performance prediction models, recommend performance prediction models for each pavement family, and evaluate how the developed tool could be used in the calibration of the *MEPDG* to South Dakota conditions. The following provides implementation recommendations for consideration by the Technical Panel.

1. **Adopt the PPM tool for the development and evaluation of performance prediction models**. The PPM tool has been developed based on the information obtained from the literature search, stakeholder interviews, and knowledge of the research team in performance prediction modeling and SDDOT practices. The PPM tool includes a customized user interface that allows for easy importing of the dTIMS database; establishing the pavement family tree, regression model development and evaluation for each node of the pavement family tree; reporting of regression information in both graphical and tabular formats, and exporting the recommended performance prediction models (and accompanying virtual age equations) for import back into the dTIMS software.
2. **Review the recommended performance prediction models**. The performance prediction models currently used in the dTIMS software were last established in 2004. During this project, 17 years of pavement condition data were imported into the PPM tool for evaluation and use in the development of the recommended models. Prior to importing the recommended performance prediction models into the dTIMS software, each model should be reviewed by SDDOT Pavement Management staff prior to acceptance and use.
3. **Evaluate and update the performance prediction models on an annual basis or as necessary**. Although it is not expected that the performance prediction models will change drastically from one year to the next, the research team recommends that the performance prediction models be evaluated annually. Much of the performance prediction model evaluation process has been automated, to the extent possible, resulting in an improved process than the previous SDDOT performance prediction model development tool. In addition, the research team also recommends that the dTIMS data (all inventory and time-series performance data associated with each pavement segment for each year of available data) be exported for use in the PPM tool. The PPM tool functionality will allow for the addition of a single (or more) year of data, but in order to maintain data consistency (both from dTIMS and the PPM tool), export of the entire dTIMS data is highly recommended. Using the last developed performance prediction model set, the PPM tool will conduct a statistical evaluation (based on R^2) of the new year's data set and notify the user whether or not the new data is within the user-defined change in the regression model R^2.
4. **Evaluate the family tree definitions**. The pavement family tree definitions should be evaluated every 5 to 10 years or as new pavement types are included in the SDDOT pavement system. The evaluation of family tree definitions has been conducted for this project and is described in chapter 4, task 9 of this final report. The required statistical analysis of the pavement family is an extensive process that requires significant data manipulation and evaluation. The evaluation of the family tree definitions should be conducted by a statistician.
5. **Use the performance prediction models as a starting point in the calibration of the *MEPDG***. As demonstrated in chapter 4, task 13, the PPM tool can be used to evaluate the *MEPDG* distress

prediction. The calibration coefficients for the *MEPDG* (2008) distress prediction models can be adjusted such that the resulting distress prediction is equivalent to the performance prediction determined from the PPM tool. The step-by-step process for adjusting the calibration coefficients is outlined in the *Calibration Guide* (AASHTO 2010). Once the calibrated models have been developed, they should be verified using existing SDDOT pavement segments. The verification process is also described in the *Calibration Guide* (AASHTO 2010).

6. **Consider revising distress measurement to meet *MEPDG* requirements**. Comparison of the performance prediction models developed using the PPM tool and the *MEPDG* distress prediction was based on equations, developed as part of this study, to convert SDDOT distress index ratings (0 to 5 scale) to an actual measure of distress (e.g., length of cracking, depth of rutting). Although the converted predicted distress appears to be reasonable, and in at least one case study closely matches the measured distress, using a conversion equation rather than measured distress is not ideal, especially during the calibration process. Many of the SDDOT distresses are based on a severity range rather than a measure of actual distress extent (e.g., length of cracking, depth of rutting). The implications of changing the manner in which the pavement distresses are collected to match that of the *MEPDG* predicted distresses should be evaluated.

6 ANALYSIS OF RESEARCH BENEFITS

Pavement performance prediction models are one of many important aspects of a pavement management system. The primary use of pavement performance prediction models is to determine pavement condition over time. The ability to predict pavement condition allows an agency to estimate future pavement condition on individual roadway segments, as well as the overall network, identify pavement preservation, rehabilitation, and reconstruction needs, select the appropriate timing of future treatments, estimate funding levels to achieve performance targets, and evaluate the consequences associated with various budgetary constraints. In order to accurately estimate these aspects of the pavement management system, it is critical that the pavement performance prediction models are as accurate as possible and reflect field pavement performance. Not only will accurate models provide improved prediction of pavement condition, applicable treatment selection and timing scenarios, and actual budgetary needs, but will also improve the reliability and the user confidence in the outputs of the pavement management system. However, the ability to provide accurate pavement performance prediction models is highly dependent on the accuracy of the pavement condition (and IRI) data. Accuracy of the pavement performance prediction models can only be as good as the accuracy of the condition data.

This study will provide a number of benefits to the SDDOT. These benefits include:

1. **Improved process for evaluating and updating pavement performance models**. The PPM tool provides a user-friendly process for importing the dTIMS database in the development, evaluation, and update of the pavement performance prediction models. The PPM tool includes a graphical user interface that provides direct feedback (tabular and graphical representation of curve shape, curve fit, and so on) for the performance prediction models. In addition, the PPM tool provides an improved process for exporting the developed performance prediction models (and accompany virtual age models) back into dTIMS.
2. **Shortened timeframe for evaluating and updating the pavement performance models**. In the past, updating of the pavement performance prediction models was a labor intensive process that required significant editing and file-handling to generate the final performance prediction model recommendations. In addition, determination of the virtual age equations required a significant amount of time since they were determined "by hand." The PPM tool, to the extent possible, has automated much of the time consuming tasks, in that the process of importing data from and exporting prediction models to dTIMS, as well as generating and exporting the virtual age equations, requires little to know effort and therefore, has drastically reduced the required amount of time to conduct these tasks.
3. **Structured process for evaluating pavement performance prediction models**. The PPM tool was developed to provide a step-by-step process for developing and updating the pavement family tree and the associated pavement performance prediction models.
4. **Provide a framework for prediction model development for other assets**. Although developed specifically for pavement performance prediction, the PPM tool can be used for other development of other agency assets as long as the necessary data is readily available.
5. **Provide performance prediction models for use in the calibration of the *MEPDG***. The pavement performance prediction models can be used in evaluating and calibrating the *MEPDG* to South Dakota conditions.

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