Enhancement of the Pavement Health Track (PHT) Analysis Tool

Final Report

Executive Summary

Technical Information

Federal Highway Administration

Office of Asset Management

U.S. Department of Transportation
Federal Highway
Adminstration

Sept 2013

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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle **Pavement Health Track (PHT) Analysis Tool, Summary Report**		5. Report Date September 27, 2013 6. Performing Organization Code 100007469
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12. Sponsoring Agency Name and Address Federal Highway Administration Office of Asset Management Washington, D.C.		13. Type of Report and Period Covered Summary Report (10/11 – 9/13) 14. Sponsoring Agency Code
15. Supplementary Notes COTM: Nastaran Saadatmand		

16. Abstract

The objective of this study was to enhance and develop the Pavement Health Track (PHT) Analysis Tool for the FHWA to provide improved performance, recalibrated analysis models, and modeling of maintenance treatments on the pavement remaining service life (RSL), and to improve the graphical user interface and reporting features.

The PHT Analysis Tool is an engineering software application for determining and reporting the health of pavement networks in terms of the pavement's RSL. The PHT Analysis Tool uses performance models recently developed by FHWA for the Highway Economic Requirements System (HERS) and the National Pavement Cost Model (NAPCOM). These pavement models are based on concepts developed under National Cooperative Highway Research Program (NCHRP) Projects 1-37A and 1-40D and included in the Interim American Association of State Highway and Transportation Officials (AASHTO) Mechanistic-Empirical Pavement Design Guide (MEPDG), making them a simplified version of the more complex mechanistic-empirical (ME) set of models and procedures used in the Interim AASHTO MEPDG.

This report presents an overview of the simplified MEPDG models incorporated into the PHT Analysis Tool along with a detailed description of PHT Analysis Tool approaches to determining pavement RSL, a description of the maintenance model, guidance on setting up the PHT Analysis Tool input database from HPMS and other databases, and guidance on setting key parameters for determining overall RSL.

17. Key Words Pavement performance, mechanistic-empirical, PHT, RSL, HMA, PCC.		18. Distribution Statement	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 158	22. Price

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Executive Summary

The Pavements Health Track Analysis Tool (PHT) sponsored by the FHWA Office of Asset Management is an engineering software application for determining and reporting the health of pavement networks in terms of pavements remaining service life (RSL.) This application uses performance models recently developed by FHWA for the Highway Economic Requirements System (HERS) and the National Pavement Cost Models (NAPCOM). These pavement models are the simplified version of the more complex mechanistic-empirical (ME) set of models and procedures used in the Pavement Design Guide (PDG). In addition, the PHT also offers state-of-practice maintenance options to estimate the benefits of each pavement section improvement quantified in terms extended service life. The PHT maintenance model is implemented into the PHT graphical user interface as an integrated feature of the PHT that allows to measure the pavement performance under a maximum Benefit/Cost ratio or under constrained funds. The Pavements Health Track analysis tool has been developed by the Battelle/Maks/ARA team for FHWA using an off-the-shelf engineering analysis software interface.

The tool allows users to determine pavement health in terms of pavement life, ride-ability, or distress by pavement types under various environmental and administrative conditions—e.g., climate, functional classification, or rural/urban environment—on projects, corridors within a state or crossing state lines, and networks. The pavement life in this application is simply the time in years or number of load applications it takes to reach one or more recommended terminal levels of distresses as shown in Exhibit 1.

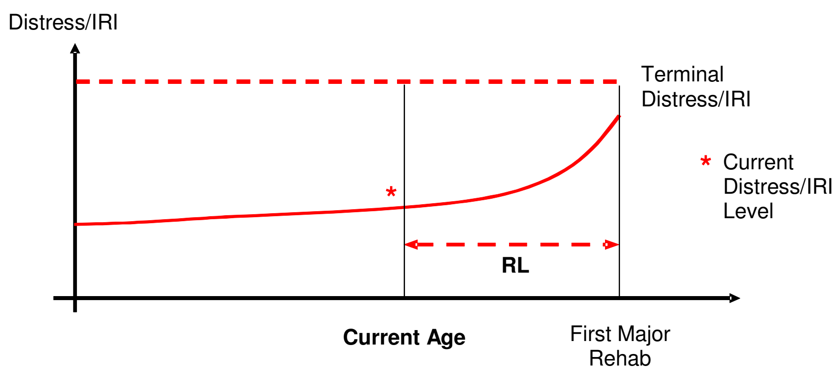

Exhibit 1. Distress/IRI and RSL Relationship

The primary input is HPMS 2010 data with an extension for the State Pavement Management System (PMS) database. The software comes with nationally calibrated matrix parameters and level 3 (policy and planning) default values currently available through ME-PDG design software with the option for custom adjustment.

The primary PHT outputs are the predicted distresses/IRI by pavement types, load applications, and weighted RSL. The results are tabulated in spreadsheet or document formats or illustrated in charts or map graphics by pavement type, RSL group (5, 10, 15 years, etc.), geographic locations, functional class, or along a particular corridor (illustrated in exhibit 2) using smart wizards built into PHT.

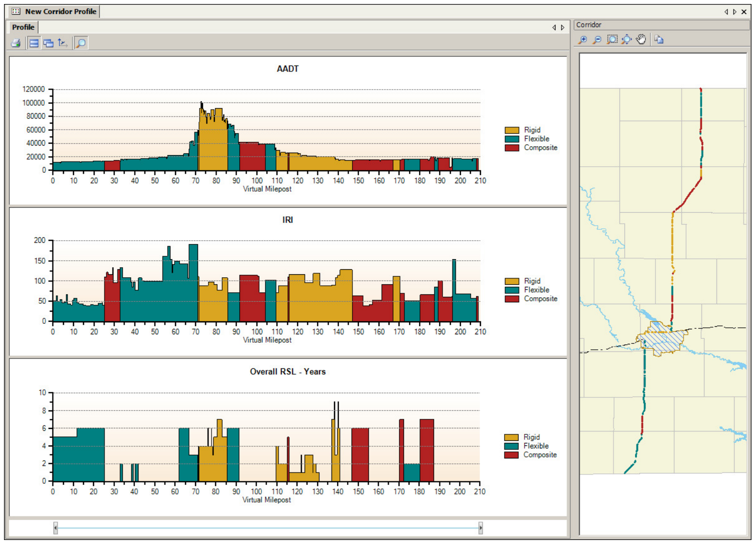

Exhibit 2. PHT Corridor Interface

The options of multiple parameter and data capture interfaces along with built-in query and Geographical Information System (GIS) tools also support “what if” scenario analyses under various pavement design parameters, traffic, and/or recommended terminal distresses or performance indicators. The modular design of PHT allows future expansion for estimating pavement asset values, impact on RSL under various M&R action plans, reconstruction needs, detection of uneven distribution of RSL (uneven workload and preventive maintenance), integrating HERS benefit/cost models, and incorporating state-specific pavement models or calibrated pavement performance coefficients.

Purpose

Background

In 2003, a contract entitled *Modification of FHWA Highway Performance Data Collection System and Pavement Performance Models* was awarded to a contractor to research methods to develop improved but simplified pavement performance models for the Highway Economic Requirements System (HERS). The project was a multi-year effort and resulted in the recommendation to use the Mechanistic-Empirical Pavement Design Guide (MEPDG) performance models. As part of that contract, the research team also evaluated the methods used to estimate Remaining Service Life (RSL) and made recommendations to make it more compatible with Mechanistic-Empirical Design.

During the development of the simplified MEPDG models for HERS, another project was initiated to reassess the components of the Highway Performance Monitoring System (HPMS) database. Since the proposed pavement models are dependent on HPMS data, a high level of cooperation was developed between the two project teams. The result of the HPMS reassessment project was a recommendation to add several new data items to support the simplified pavement models for HERS. These two projects provide a great opportunity for estimating pavement RSL using simplified MEPDG Mechanistic-Empirical models and the HPMS2010 data.

The FHWA has recently developed the Pavement Health Track (PHT) Analysis Tool that can help determine the health of a road network in terms of Remaining Service Life. The tool can determine the health of different pavement types under various conditions, such as rural or urban environments or various climates, and a range of applications, including individual projects, highway networks, and corridors within a State or crossing State lines. The tool requires pavement data inputs from the HPMS2010 or a State can input data from its pavement management system. The PHT Analysis Tool has already been tested by a few States. These tests resulted in several recommendations for further enchantment of the tool. As a result, the FHWA is undertook this effort to enhance the PHT Analysis Tool.

Project Objectives

The primary objective of this project was to enhance the capabilities and the Graphical User Interface (GUI) of the PHT Analysis Tool to allow US DOT as well as State DOT planners and policy makers to predict both the network and regional level health of the pavement so that preventive action can be put in place and maximum pavement life can be realized within a set of budgetary constraints.

This project investigated the extent to which improvements between versions 0.8 and 1.0 of the MEPDG forecasting models impact the results of the PHT Analysis Tool and implemented those improvements into the PHT forecasting models along with other models that account for maintenance activities and provide a reliability index for the RSL predictions.

Recommendations obtained from pilot users included providing a set of validation rules for the HPMS2010 source data and an enhanced mechanism to read pavement condition information from existing State pavement management systems. General enhancements for usability included the development a log system, custom HPMS data and corridor profile viewers, customizable chart templates, and expanded report wizard features. The PHT analysis engine run-time performance has also been optimized.

Sensitivity Analysis between MEPDG version 0.8 and 1.0

Introduction

The PHT Analysis Tool version 1.1 pavement performance prediction models were developed based on the simplified MEPDG version 0.8 models. Significant improvements have been made to the MEPDG models and algorithms used for computing fundamental pavement responses and the performance models as a whole has been recalibrated to reflect both changes in both computational algorithms and improved and more extensive LTPP calibration data. The objective of this task was to investigate whether there is significant differences between MEPDG versions 0.8 (PHT Tool) and DARWin-ME 1.0 pavement performance predictions and how possible differences do impact the results of the PHT Analysis Tool. This investigation involved conducting a sensitivity analysis to develop RSL estimates under different scenarios using the PHT Tool and the DARWin-ME pavement performance models and performing a statistical comparison of RSL outputs from each application.

The test experiment used a total of 40 LTPP unique sites from 20 states with 4 climate zones, 3 base type and four pavement surface types. The complete summary of the projects selected for the sensitivity analysis is provided in Appendix A of this document.

Sensitivity Analysis Methodology

The test methodology for statistical comparison is presented below.

Methodology:

1. Develop a matrix of projects adapted after in-service LTPP pavement projects for use in conducting sensitivity analysis. Criteria for developing the matrix of projects was as follows:
    a. Include all pavement types of interest (new flexible, asphalt overlaid flexible pavement, new jointed plain concrete pavement (JPCP), and asphalt overlaid JPCP).
    b. Cover all four LTPP climate zones (wet-freeze, wet-nofreeze, dry-freeze, dry-nofreeze).
    c. Based on the criteria (a) & (b) there was a total of 16 super cells in the proposed matrix. Each super cell will contain on average 2 to 3 projects representing a mix of AC and PCC thicknesses, sub-grade type, and highway functional class/traffic level.
2. Develop RSL computation parameters as follows:
    a. Terminal distress and smoothness.
    b. Maximum service life.
    c. Analysis types of interest:
    d. First to critical distress.
    e. Weighted average (equal weights for all distress and smoothness)
    f. Create PHT Tool and DARWin-ME input files.
    g. Run PHT Tool and DARWin-ME for all the projects included in the matrix.
    h. Obtain PHT estimates of RSL for all analysis types of interest.
3. Use the DARWin-ME predictions of future distress and smoothness to estimate RSL for all analysis types of interest.
4. Perform a statistical analysis to compare RSL output from the PHT Analysis Tool and the DARWin-ME 1.0 estimated RSL for goodness of fit, bias, t-test, etc.

This methodology was designed to ensure that both PHT Analysis Tool and the DARWin-ME pavement RSL estimates were based on the respective tools pavement performance model. Thus usual constraints in estimating pavement RSL such as maximum service life depending on pavement types were relaxed. Details of the analysis framework are presented in the following sections. Internal calibration of predicted distress/IRI using measured pavement performance data was not utilized.

The criteria for PHT Analysis Tool and the DARWin-ME model pavement RSL estimates include establishing performance thresholds that define the terminal distress and smoothness values that indicate the end of the pavements service life as well as establishing the maximum service life for each surface type. The terminal values for the smoothness and each distress type are shown in Table 1 and the maximum service life is shown in Table 2.

Table 1. Terminal Distress/Smoothness Values

Suggested Performance Criteria for Use in Pavement Design			
Pavement Type	**Performance Criteria**	**Maximum Value at End of Design Life**	
AC pavement and AC/PCC overlays	AC alligator cracking	Interstate: Primary: Local:	10 percent lane area 20 percent lane area 45 percent lane area
	Rutting	Interstate: Primary:	0.75 inch mean 1 inch mean
	Transverse cracking	Interstate: Primary/Secondary:	Crack length < 1000-ft/mile Crack length < 1,500-ft/mile
	IRI	Interstate: Primary: Secondary:	150 inch/mile 175 inch/mile 200 inch/mile
New JPCP	Mean joint faulting	Interstate: Primary: Secondary:	0.10 inch mean all joints 0.15 inch mean all joints 0.25 inch mean all joints
	Percent slabs with transverse cracking	Interstate: Primary: Secondary:	10 percent 15 percent 20 percent
	IRI	Interstate: Primary: Secondary:	150 inch/mile 175 inch/mile 200 inch/mile

Table 2. Maximum Service Life

Surface Type	Maximum Service Life, years
New HMA	30
New PCC	40
Thick AC Overlay of AC Pavement	15
Thin AC Overlay of AC Pavement	10
Thick AC Overlay of PCC Pavement	25
Unbonded PCC Overlay of PCC Pavement	30
Bonded PCC Overlay of PCC Pavement	15
Thin AC Overlay of AS/PCC Pavement	25

There are two analysis types that include a critical distress that determines the RSL until the first distress or smoothness threshold, and a weighted average that averages the critical distress for each distress type and smoothness together using an equal weight for each.

For analysis, pavement original or overlay construction date was assumed to be 2011. This was done to ensure that RSL estimates was mostly computed based on predicted future pavement condition rather than based on constraints of typical service life.

Statistical Analysis

Statistical analyses were performed to determine if pavement RSL predicted from the PHT Analysis Tool and from the DARWin-ME are sufficiently similar or significantly different and if a bias exists in the PHT Analysis Tool RSL predictions.

The goodness of fit between DARWin-ME and PHT Tool estimates of RSL was assessed by performing linear regression using DARWin-ME and PHT Tool estimates of RSL and determining diagnostic statistics including coefficient of determination (R^2) and standard error of the estimate (SEE). Engineering judgment was then used to determine the practical reasonableness of both diagnostic statistics. Models exhibiting a poor R^2 of less than 50 percent or excessive SEE of an RSL estimate greater than 3 years were deemed to be inadequate. If this occurs, it implies that statistically the PHT Analysis Tool is inadequately predicting RSL as defined by DARWin-ME. However, the magnitude of the difference in RSL must also be assessed on the basis of what is the practical importance of the difference.

Bias is defined as the consistent under or over prediction of pavement RSL. Bias is determined by performing linear regression using DARWin-ME and PHT Analysis Tool estimates of RSL and performing the following two hypothesis tests. A significance level of 5% was assumed for all hypothesis testing. This level of significance is often used in similar analyses and gives a relatively low probability of making a false judgment on bias of the RSL estimates.

Hypothesis One:

A paired t-test was done to determine whether the DARWin-ME and PHT Tool estimates of RSL represented the same population of RSL. The paired t-test was performed as follows:

1. Assume the following null and alternative hypothesis
    a. H0: Mean DARWin-ME RSL = mean PHT Tool RSL
    b. HA: Mean DARWin-ME RSL ≠ mean PHT Tool RSL
2. Compute test p-value
3. Compare computed p-value to predetermined level of significance for this test. Note a significance level of 5 percent was adopted for this analysis

Note:

A rejection of the null hypothesis (p-value < 0.05) would imply DARWin-ME and PHT Tool estimates of RSL are from different populations. This indicates that for the range of RSL used in analysis, the PHT Analysis Tool will produce biased predictions of RSL defined by DARWin-ME.

Hypothesis Two:

Determine whether the linear regression model developed using DARWin-ME and PHT Tool estimates of RSL has an intercept of 0 and a slope of 1.0:

1. Using the results of the linear regression analysis, test the following null and alternative hypotheses to determine if the fitted linear regression model has an slope of 1.0:
    a. Intercept
        i. H01: Model intercept = 1.0
        ii. HA1: Model intercept ≠ 1.0
    b. Slope
        i. H02: Model slope = 1.0
        ii. HA2: Model slope ≠ 1.0
2. Compute test p-values
3. Compare computed p-value to predetermined level of significant for this test. Note a significance level of 5 percent was adopted for this analysis.

Note:

A rejection of the null hypothesis 1 & 2 (p-value < 0.05) would imply that the linear model has an intercept significantly different from 0 and a slope significantly different from 1.0 at the 5 percent significance level. This indicates that using the PHT Analysis Tool could produce biased estimates of RSL defined by DARWin-ME.

The presence of bias does not necessarily imply that the PHT Analysis Tool is inadequate; rather it basically means that there is statistical bias in estimates of pavement RSL. The significance of the bias (over or under prediction) can also be judged on an engineering practical basis. If the PHT Analysis Tool RSL estimate is deemed to be biased or with an inadequate goodness of fit, and the differences are deemed to be too large for practical usage, recalibration of the PHT Analysis Tool will be needed.

Sensitivity Analysis

Comparisons of PHT Analysis Tool and DARWin-ME estimates of RSL are presented graphs below in Figure 1 and Figure 2. For the PHT Tool analysis, RSL was computed as described in the software user guide and other reference documents. For DARWin-ME, RSL was computed using relevant predicted pavement distress and IRI following the guidelines in appropriate PHT guide documents and analysis criteria; such as terminal distress/IRI and maximum service life.

A preliminary review of the comparison plots shows the following:

- Correlation between PHT Tool and DARWin-ME estimates of RSL was poor, ranging from 2.6 to 4.3 percent.
- PHT Tool estimates of RSL were generally far higher than DARWin-ME.
- Error in RSL estimates was considerably high (ranging from 8.7 to 11 years).
- Coefficient of variation (COV) ranged from 35 to 53 percent which is also high.

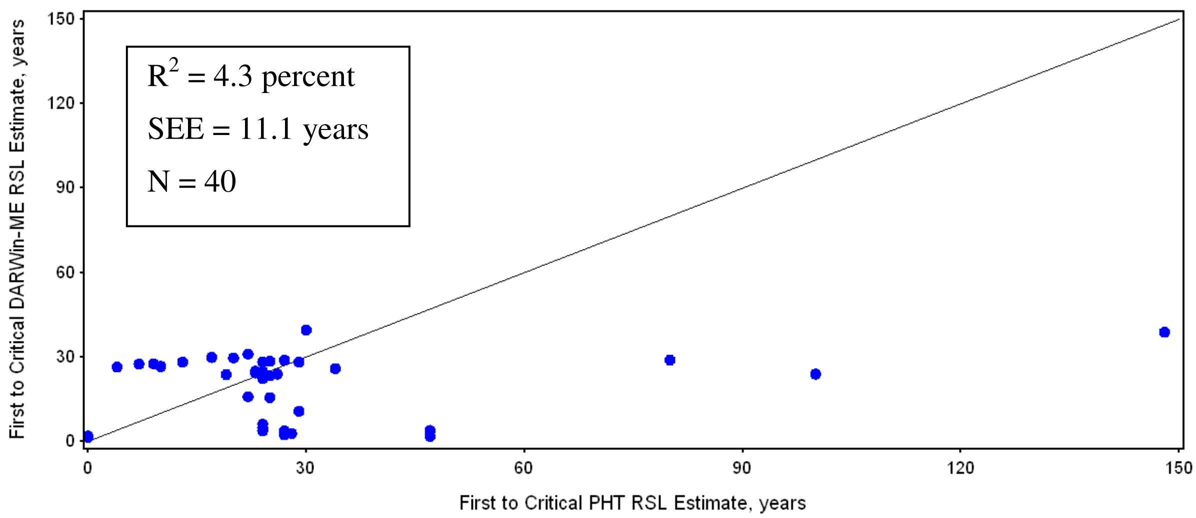

Figure 1. Comparison of PHT and DARWin-ME RSL Estimates, Critical Failure

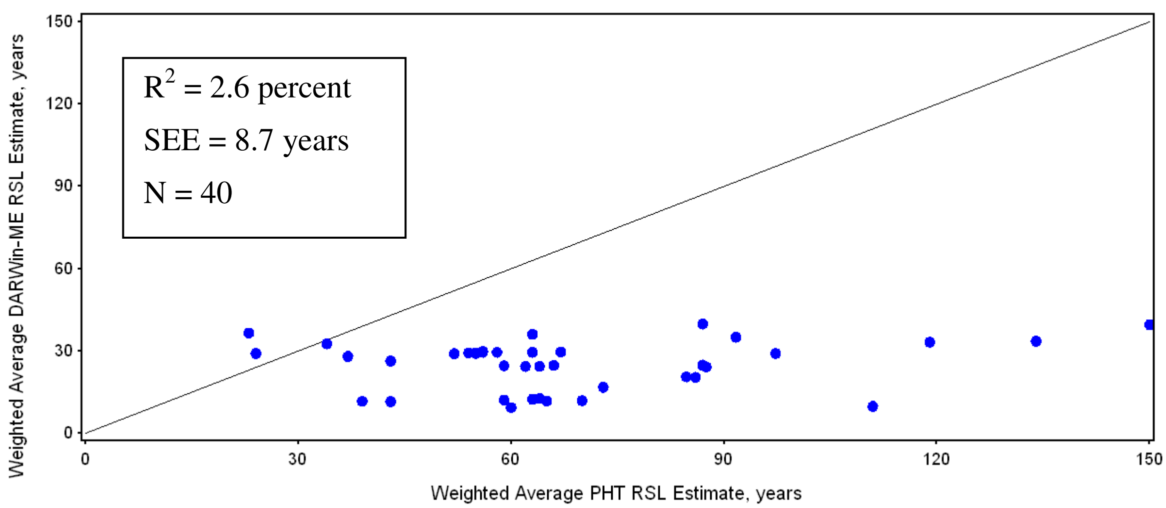

Figure 2. Comparison of PHT and DARWin-ME RSL Estimates, Weighted Average

A more detailed statistical evaluation of PHT Analysis Tool and DARWin-ME RSL estimates was performed and the results are presented in Table 3 that shows the following:

- For first to critical threshold analysis, PHT estimates of pavement RSL was mostly significantly different from that estimated from DARWin-ME. The slopes of the lines indicated significant bias for over prediction of RSL. The only parameter not significantly differently was the mean RSL (17.97 versus 21.4 years) and this was barely not significant (paired t-test p-value was 0.0594).
- For weighted average analysis, PHT estimates of pavement RSL was significantly different from that estimated from DARWin-ME for all parameters.

Table 3. Statistical Test Results Comparing PHT and DARWin-ME RSL Estimates

Analysis Type	Statistical Hypothesis Test	Mean Intercept Value, years	95 Percent Confidence Limits	p-Value
Critical (First distress or IRI)	Intercept = 0	17.97	12.7 to 23.2	< 0.0001
	Slope = 1	0.43	0.29 to 0.56	< 0.0001
	Paired t-test			0.0594
Weighted Average (Equal weights for all distress and IRI)	Intercept = 0	21.4	13.7 to 29.1	< 0.0001
	Slope = 1	0.322	0.27 to 0.37	< 0.0001
	Paired t-test			< 0.0001

Finally, a more detailed review of individual distress types and IRI was done to determine which of the individual PHT models produced estimates of RSL significantly different from that from DARWin-ME. The results are presented in Table 4.

Table 4. Statistical Test Results for each Distress/IRI and Pavement Type

Pavement Type	AC Fatigue Cracking	AC Rutting	AC Transverse Cracking (Thermal Reflection)	JPCP Slab Transverse Cracking	JPCP Faulting	IRI
New AC	<0.0001	0.1871	0.0035	Not applicable	Not applicable	0.0710
AC/AC	<0.0001	0.0318	0.3493	Not applicable	Not applicable	0.0343
New JPCP	Not applicable	Not applicable	Not applicable	0.0539	<0.0001	0.0029
AC/JPCP	Not applicable	Not applicable	0.6845	Not applicable	Not applicable	<0.0001

Note: The highlighted cells indicate distress/IRI based RSL estimates from PHT Tool are significantly different from that computed using DARWin-ME predicted distress/IRI.

The AC rutting model coefficients adapted from the original MEPDG version 0.8 were modified during PHT Tool development to reduce bias and enhance precision. Thus, this version of the rutting model was developed using more recent versions of the MEPDG; after the original 2004 NCHRP 1-37A submissions. This is why this version of the PHT Analysis Tool rutting model was found to be adequate.

The data shown above illustrates that 8 of the 13 distress/IRI and pavement type combination exhibited PHT Analysis Tool RSL estimates significantly different from those estimated by the DARWin-ME tool.

Bias and Precision

Any pavement distress/IRI and RSL prediction tool should be a representation of reality. How well reality is represented is dependent upon factors such as reasonableness of the input data, validity of the underlying mathematical algorithms, and the model bias and precision.

Having been used and tested over many years, the DARWin-ME mathematical algorithms and the LTPP data have proven to be reasonable and robust. Thus a good match between the PHT Analysis Tool and DARWin-ME output would indicate that the PHT Analysis Tool also has good sound mathematical formulations and have been calibrated to reflect the same reality that the DARWin-ME tool does. However, an imperfect match does indicate some type of defect exists that will need to be rectified through changes in mathematical formulations and/or recalibration to make the PHT Analysis Tool reflect the DARWin-ME reality.

Of utmost importance for such a comparative analysis is the definition of an adequate match between the outputs. The statistics commonly used to characterize how well a tools output adequately reflects reality is bias and precision.

Bias is the systematic difference that arises between the observed and predicted values as illustrated in Figure 3. Specific to this analysis, bias is when PHT estimates of RSL are systematically over or under predicting DARWin-ME RSL estimates.

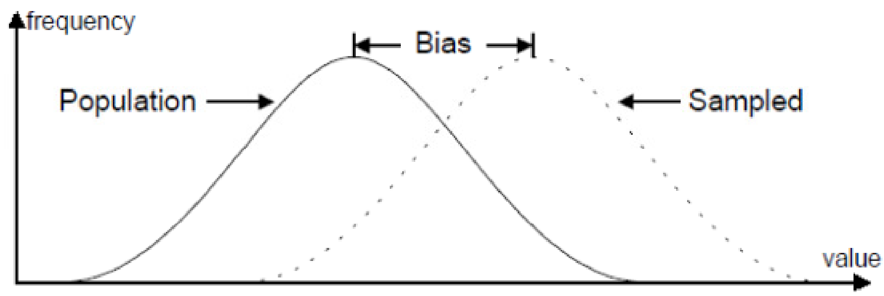

Figure 3. Bias in Sampled Data [1]

Precision is the measure of how closely the observed and predicted data are related to each other as illustrated in Figure 4. Specific to this analysis, precision will be how closely PHT estimates of RSL relate to DARWin-ME RSL estimates.

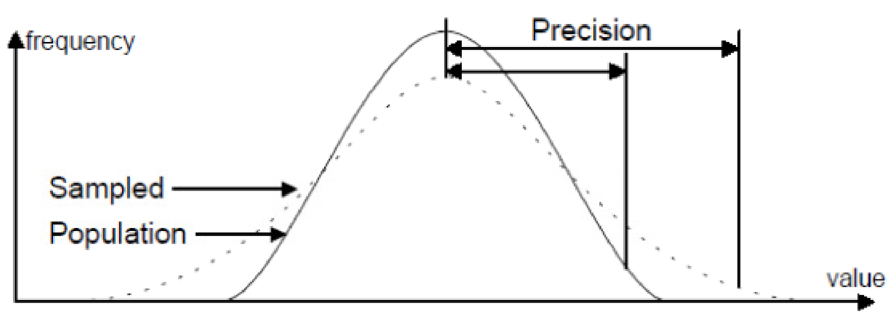

Figure 4. Precision in Sampled Data [1]

[1] Bennett and Paterson, 2000

The four scenarios illustrated in Figure 5 show how bias and precision fit into the context of adequacy when comparing observed and predicted data. Specific to this analysis, the outputs from the PHT Analysis Tool will be compared to a baseline reality RSL as estimated from the DARWin-ME tool.

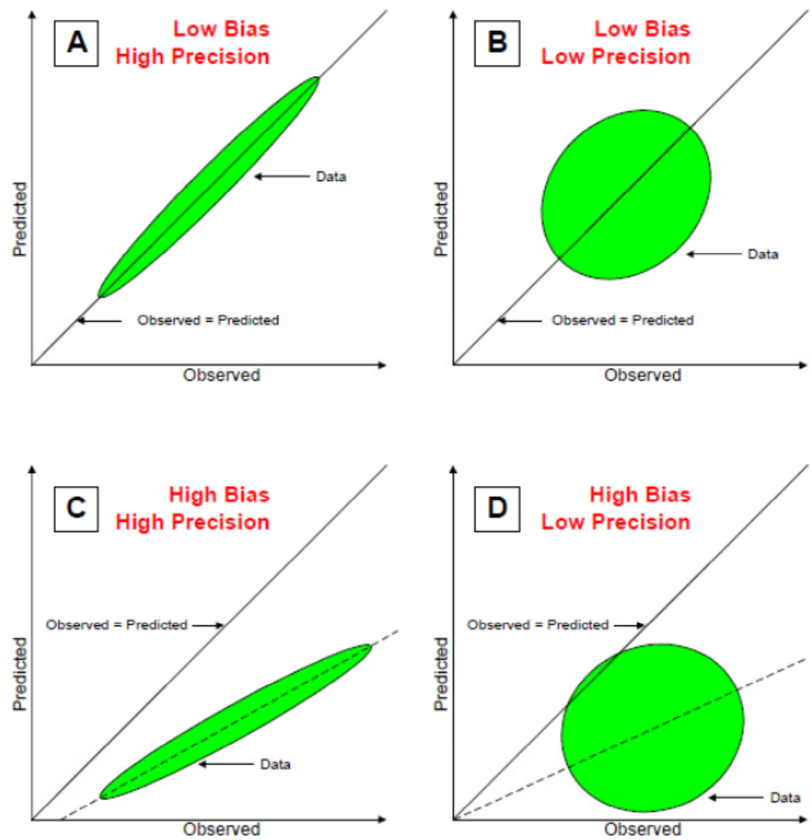

Figure 5. Bias and Precision for four Scenarios [1]

In the figure above, the shaded ellipse represents DARWin-ME estimated RSL which has been plotted against PHT Analysis Tool estimated RSL. The solid line at 45 degrees is the line of equality, where DARWin-ME and PHT estimated RSL are supposed to be equal. Each chart above is described in more detail in Table 5.

A pavement management and planning tool such as PHT must, as a minimum, satisfy the requirements of a model exhibiting low bias and low precision illustrated in Figure 5B to be described as adequate. The PHT sensitivity analysis results shown in Figure 1 and Figure 2 illustrate an outcome closer to that of Figure 5C with high bias and high precision. High bias and high precision implies that even though there is a relationship between the RSL estimates from DARWin-ME and PHT, the outputs from the two tools represents two very different populations.

Table 5. Bias and Precision Scenarios for Pavement Analysis

Distress/IRI Prediction Scenario	Description	Applicability	Needed Enhancement
Low bias & high precision (see Figure 5A)	This is the best case scenario for distress/IRI prediction. Low bias and high precious is characteristic of well calibrated mechanistic-empirical (cause and effect) pavement models. Such models employ a large input dataset that describes and characterizes key pavement structure, materials, design, and site properties. The detailed input data combined with complex mathematical equations forms the basis for distress/IRI prediction	**Pavement Design and Analysis** For such analysis, the goal is to obtain best estimate of pavement performance for a specific section under design/analysis. Extensive recourses can thus be employed to obtain data needed for the models. A reliability factor is added when used for design	None
Low bias - low precision (see Figure 5B)	This is the second best case scenario for distress/IRI prediction. Low bias and high precious is characteristic of empirical pavement models requiring limited amounts of input data for characterizing pavement structure, materials, design, and site properties	**Pavement Management & Planning** For such analysis, the goal is to obtain an overall best estimate of pavement condition across a pavement network or corridor. Thus the accuracy of pavement distress/IRI prediction for each pavement section does not matter as much as accuracy of overall network/corridor condition.	None
High bias - high precision (see Figure 5C)	Although distress/IRI is predicted with high precision, the magnitude of distress/IRI is significantly different from "reality." High precision typically implies that although underlying model assumptions and algorithms may be reasonable, the models calibration factors are inadequate leading to the presence of significant bias	**Not Suitable for Any Kind of Analysis** Models exhibiting high bias cannot be used for pavement design, forensic, management, or planning purposes.	Apply needed translation or rotation correction factors through calibration of models (see Figure 6)
High bias - low precision (see Figure 5D)	Distress/IRI prediction with low precision and high bias basically indicates a flawed model.	**Not Suitable for Any Kind of Analysis** Models exhibiting high bias and low precision cannot be used for pavement design, forensic, management, or planning purposes.	Apply needed translation or rotation correction factors through calibration of models (see Figure 6) Basic model formulation may have to be revised

The reasons for high bias and high precision include the following:

- The PHT Analysis Tool models were developed based on original DARWin-ME technology and outputs.
- Since original development, there have been significant changes to the DARWin-ME models and recalibration using practically new enhanced datasets with over 10 years of additional performance data and 5 years of additional climate data.

There was a need to develop correction factors that can be used to make necessary adjustments to the existing PHT models to make them more compatible with DARWin-ME. The corrections factors are typically obtained through calibration. Examples of needed correction factors for the different situations are illustrated in Figure 6.

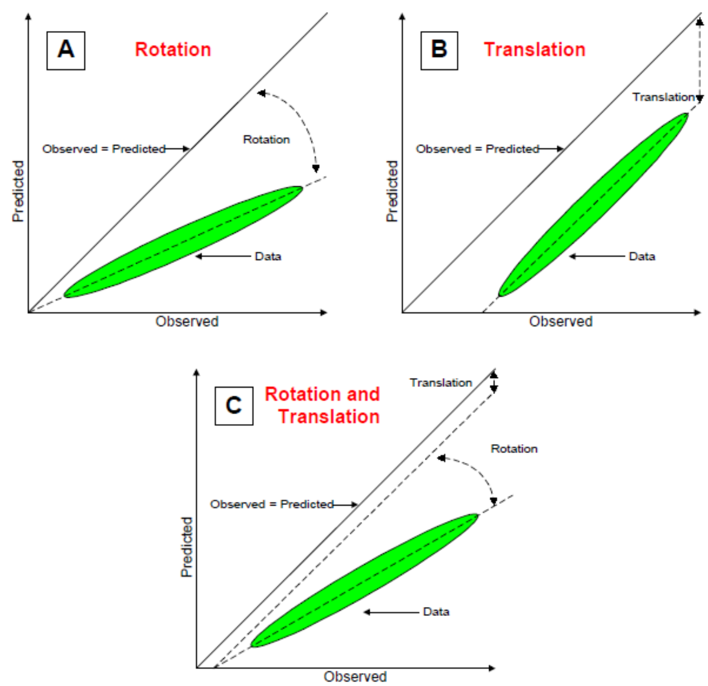

Figure 6. Correction Factors to Reduce Bias and Increase Precision [1]

Recommendations

Based on the statistical comparison results presented, it can be concluded that the PHT Tool pavement performance models mostly produce RSL estimates that are different from that from DARWin-ME. There is therefore a great need to recalibrate the PHT Tool pavement models to make them more comparable to that from DARWin-ME

The exact cause of differences in PHT Tool and DARWin-ME RSL estimates was further investigated by performing a t-test on individual distress/IRI RSL obtained from the PHT Tool and DARWin-ME as it from the individual distress/IRI RSL estimates that overall first to critical or weighted average RSL is computed. The results of the t-test showered the following models exhibiting significant bias at the 0.05 level of significance:

- New AC
    - Alligator cracking
    - Transverse “thermal” cracking
- AC overlaid AC pavement
    - Alligator cracking
    - Rutting
    - IRI
- New JPCP
    - Transverse cracking
    - Faulting
    - IRI
- AC overlaid AC
    - IRI

Thus, it is recommended that:

- All the distress/IRI models listed above be recalibrated to make their prediction more line with predictions from DARWin-ME. Even the few models that were not biased could be made better through recalibration. The many changes made between MEPDG Version 0.8 in 2005 and the 2011 DARWin-ME software require a recalibration of the models.
- The recalibrated distress/IRI models must be verified using a limited selection of LTPP and HPMS projects.

The reason for this verification is to further ensure that PHT Tool estimates of RSL are reasonable. By enhancing precision and reducing bias for the models listed above, the PHT Tool will improve individual distress/IRI based RSL predictions and produce overall RSL estimates with high precision and low bias.

In practical terms, use of the current PHT Analysis Tool to predict RSL may result in over prediction of RSL. The magnitude of over prediction depends on the pavement design and site conditions. Recalibration of the models is required to bring the models into unbiased predictions.

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PHT Version 1.1 Output Validity Test

Introduction

In addition to the sensitivity analysis, an experimental test was developed to observe the distress propagation under a set of incremental loading conditions, pavement surface thickness, base type and four climate zones using a total of 40 LTPP unique sites from 20 states. This experiment predicts the distress values at the time of critical failure or at the time when it reports the maximum remaining service life. A complete summary of the projects selected for the analysis is provided in Appendix A of this document.

Experimental Design

The following steps are carried out before running the PHT tool for a visual data quality analysis to identify any obvious anomalies.

a. New or recently rehabilitated pavement sections but showing at least one distress type with very high values or approaching to critical condition.
b. Pavement has already went through 30 to 40 years of service life but with little or no sign of distress propagation over time or no rehabilitation activities during this time period
c. Wrong distress units.
d. Reported year of last improvement but no reported improvement.
e. Group pavement sections that passes the visual inspection

The analysis results are summarized in three general areas.

a. PHT sensitivity in predicting distress propagation under a set of incremental traffic loading condition as expressed by cumulative ESALs at the time of failure.
b. PHT sensitivity in predicting distress propagation over time; and
c. PHT sensitivity when applied to the sample data under national default conditions.

To validate the model sensitivity to loads and aging factor for each of the distress model of PHT tool, the following test assumptions and associated model run parameter designs were established.

Design One:

The purpose of this design is to test the distress propagation due to pavement loading.

1. For a given pavement type, base design, and thickness the truck traffic load was increased using 5% growth per year and run the model under “no critical” distress constraints. The model runtime is 60 years. The 60 years is based on the observed maximum pavement overall life in the USA (interstate) that was built in the mid-50s and still in operation.
2. The analysis assumed NO maintenance over the analysis period (60 years).
3. Under the assumptions 1 and 2, create a set of experimental data points (or pavement section) by keeping all design variable fix but change only the following:
    a. Pavement thickness. For rigid pavement use 8, 10 and 12 inches; for new asphalt use 4, 6, and 8 inches; for composite overlay use 2, 3, and 4 inches.
    b. For each of these, change the design section by increasing the initial truck load by 5% and prepare 29 additional sections by repeating the first section but changing the truck loading by 5% from first section to next section. This process results 30 sections with a common pavement design and climate but with incremental loading.
    c. Reset initial distress data as null or assume a new pavement.
4. Change the distress critical value to its maximum domain value so that pavement does not fails by PHT tool due to critical trigger value rather it last for entire analysis period (60 years)
5. Prepare charts showing the pavement distress propagation under various pavements loading condition measured in terms of ESAL.

Design Two:

The purpose of this design is to test the distress propagation over time with constant loading.

1. Use the samples developed under Design One.
2. Run a unique sample with fixed loading, fixed design and climate by changing the analysis period in an increment of 5 years up to a maximum of 60 years. This analysis will generate distress value at the end of each analysis period for a total of 12 observations.
3. Use three fixed loading conditions; truck volume 2,000/day; truck volume 5,000/day; and truck volume 20,000/day.

New HMA Evaluation

The diagrams shown in Figure 7 illustrate distress propagation as reported by PHT tool at the end of the 60 years of pavement service life assuming no rehabilitation and or maintenance were performed during the analysis period. The charts also show the contribution of loading effect on distress propagation by HMA thickness, by base type (Base 2 and 3), and by four climatic zones. Each data point represent the final distress value for a given pavement section for a given load after 60 years of pavement life. To estimate the multiple data points for a given section, all parameter matrices, pavement properties, climate zone are assumed constant except the truck volume that was increased by 5% for each data point.

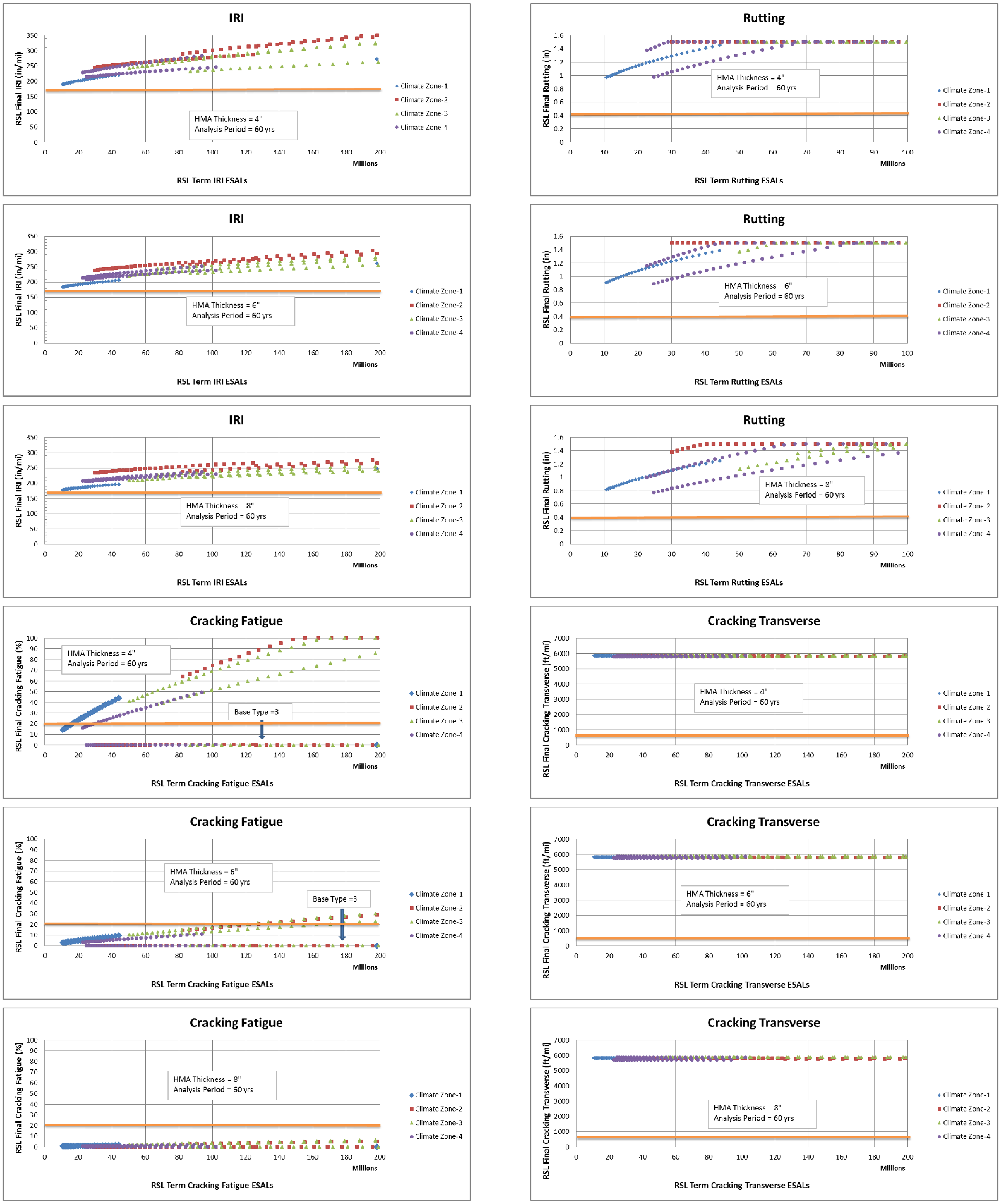

Figure 7. New HMA Distress Propagation Due to Incremental Traffic Loading

IRI

Assuming an IRI critical trigger value of 170 in/mile, all test pavements regardless of thickness, design and the climate condition will exceed the critical value at 60 years. The charts also show that for every million of ESAL, the rate of IRI deterioration for 4" HMA pavement is 300% higher for then the 8" pavement and 180% higher than the 6" pavement. The average rate of IRI deterioration for per million ESAL loading is approximately 0.75 in/mile, 0.4 in/mile, and 0.25 in/mile for 4", 6" and 8" pavement respectively. Form mechanistic point of view, the model sensitivity is reasonable but in reality, the pavement construction is not perfect and neither are the causes that accumulate the IRI for a given pavement section. The PHT model demonstrates low sensitivity on IRI propagation as a function of traffic loading and therefore reporting a higher RSL forecast.

This behavior of IRI models confirms that model parameters are more tied to pavement's mechanistic properties and hardly any effect on empirical properties and reporting low IRI as a function of cumulative ESAL loading. This observation is also consistent with low statistical parameter reported in Table 4.

Fatigue Cracking

By definition fatigue cracking is a series of interconnected cracks caused by fatigue failure of the HMA surface under repeated traffic loading. In thin pavements, cracking initiates at the bottom of the HMA layer where the tensile stress is the highest then propagates to the surface as one or more longitudinal cracks. This is commonly referred to as "bottom-up" or "classical" fatigue cracking. In thick pavements, the cracks most likely initiate from the top in areas of high localized tensile stresses resulting from tire-pavement interaction and asphalt binder aging referred to as "top-down" cracking. This mechanistic behavior of forming fatigue crack may explain some degree of such a variation. However, based on the in-service-pavement in the United States, the fatigue cracks developed earlier than what PHT tool predicting under such a high load condition.

The fatigue cracking charts shown in Figure 7 show high sensitivity of distress propagation due to pavement thickness and type of base used. The PHT Analysis Tool reports that for a typical HMA pavement with 6-inch asphalt thickness, more than 140 million ESAL are needed before the pavement reaches its critical value. The rate of distress propagation from a 4-inch pavement to 8-inch pavement with aggregate base is also extremely sensitive. When under a low traffic condition, it may take more than 60 years before pavement can show any sign of fatigue cracking. For HMA with an asphalt and cement treated base, the distress is non-responsive to traffic load. In an ideal, pure mechanistic condition it can be said that due to the cement treated base, bottom up cracking is completely checked thus become non-responsive to loading; however, for thick pavement this theory does not hold and some degree of top-down cracking must appears as loading increases due to localized tensile stresses as well as binder aging. This observation confirms significant biased on mechanistic material properties and stress and strain relationship and lack of empirical adjustment to the model. Calibrating the model coefficient with empirical data can bring the model that is more aligned with the observed in-service pavement conditions.

Transverse Cracking

Distress propagation of transverse cracking is independent of loading. The charts shown in Figure 7 show that most of the pavement will experience significant transverse cracks over the analysis period. Out of the four distresses, transverse cracking is the critical distresses that will prevent the pavement from have a service life more than 60 years.

Rutting

The rutting charts shown in Figure 7 show that, regardless of base type and traffic loading, each pavement section will experience significant rutting during the 60 years of the pavement service life. The model also shows the difference in the rate of distress propagation under different climate, pavement thickness and base type. The lowest rate of distress propagation is observed for 8-inch pavement in under dry non-freeze climate condition. The PHT tools response to rutting under the different loading conditions is more aligned with the empirical evidence as observed in the site condition and performing reasonably compare to the IRI and Fatigue cracking distresses. The data results generated using the PHT tool also demonstrates that the new calibrated models carried out under MEPDG version 1.0 can significantly improve the PHT predictive capability. The charts show distress propagations with loading that are very consistence with in-service pavement.

Conclusion

The PHT analysis on for new HMA pavement shows that out of the four HMA models analyzed under this research, both the Transverse Cracking and Rutting models are more likely aligned with the in-service pavement. However both the Fatigue Cracking and IRI model shows very slow distress propagation over a long analysis period and less responsible to loading specifically for fatigue cracking. Therefore, both the IRI and Fatigue Cracking models need to be calibrated with empirical data to establish the creditability of the PHT tool's application.

New JPCP Evaluation

The chart diagrams shown in Figure 8 illustrates distress propagation of new JPCP as reported by PHT tool at the end of the 60 years of pavement service life assuming no rehabilitation and or maintenance were performed during the analysis period. The charts also show the contribution of loading effect on distress propagation by rigid pavement thickness, by base type, and by the four climatic zones.

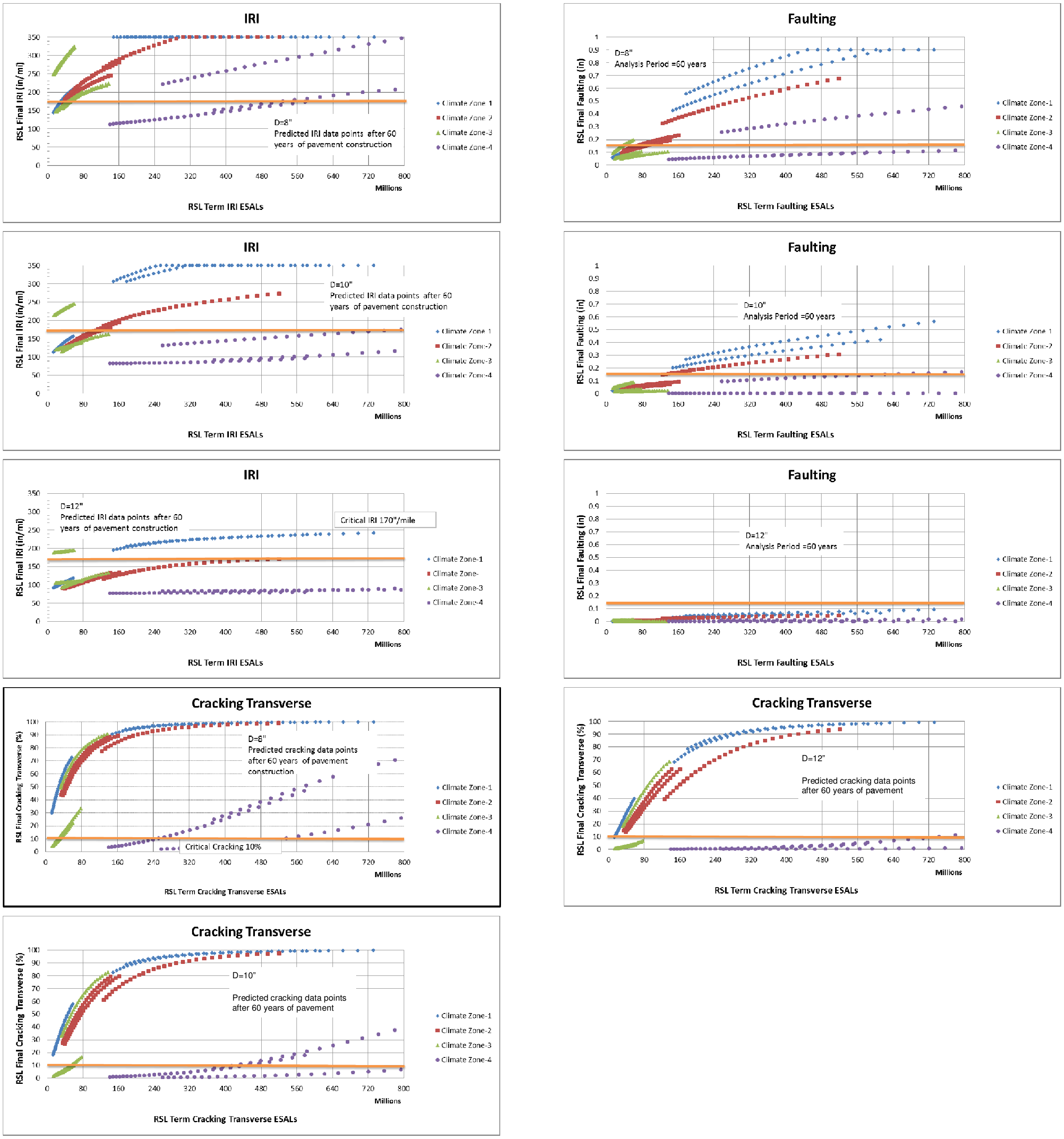

Figure 8. New JPCP Distress Propagation Due to Incremental Traffic Loading

IRI

The analysis shows accelerated distress propagation for climatic zone 1 and slower propagation in other climatic zones. For the other three climatic zones with a traffic loading less than a cumulative ESAL of 40 million over an analysis period of 60 years, the IRI distresses for most of the test pavement sections remain below the critical distress of 170 inches/mile.

The IRI propagation charts in Figure 8 also demonstrate a comparatively slow deterioration rate for typical 10-inch pavement for climatic zone 2 and 3, and little or no sign of distress propagation for pavement located in zone 4. The IRI remains below the critical distress for a cumulative ESAL loading equivalent to 35,000 trucks/day over a 60 year pavement life for the 12-inch rigid pavement for all climatic zones except for the wet-freeze zone 1.

Faulting

The faulting analysis assumed dowel bars at the joints. Except for the climatic zone 4, most of the pavement shows faulting at or above critical distress over the 60 years analysis period with cumulative ESAL in excess of 100 million ESAL.

Since the cause of faulting is mainly due to the difference in elevation across a joint or crack usually associated with undoweled joint construction as well as base and subbase strength, a non- stabilized aggregate base, as shown in the chart, is more sensitive to developing faulting than a cement or asphalt stabilized base.

The overall distress propagation shown in the faulting charts in Figure 8 is mostly aligned with a typical in-service 8-inch and 10-inch JPCP pavement with similar design properties in climatic zones 1 and 2. Additional calibration of this model should be able to eliminate any observed noises in the charts for pavement sections in the climatic zone 3 and 4.

Cracking

The distress propagation of percent of slab cracking as reported by the PHT tools shows it is highly responsive to traffic loading and reaches beyond the critical distress value at the end of the analysis period. The exception is those pavement sections located in the climatic zone 4where the distress propagation is comparatively slow and does not reach at the critical point until the pavement section experiences a cumulative loading of 240 million ESAL. Overall, the cracking distress is responsive to traffic load.

Conclusion

The PHT results show a slower overall distress propagation due to traffic loading and have little effect in pavement sections located in the climatic zone 4. The slower progression of reported distresses is also consistence with the sensitivity analysis and the IRI is shown to be less sensitive to loading. The result outcome is very consistent with low statistical parameter reported in Table 4.

AC/AC Evaluation

The chart diagrams shown in Figure 8 illustrate distress propagation as reported by PHT under a cumulative ESAL loading of 60 years of pavement service life. The charts also show the contribution of loading effect on distress propagation by AC/AC pavement thickness and by the four climatic zones.

Conclusion

The charts show the similar distress propagation pattern as of HMA pavement

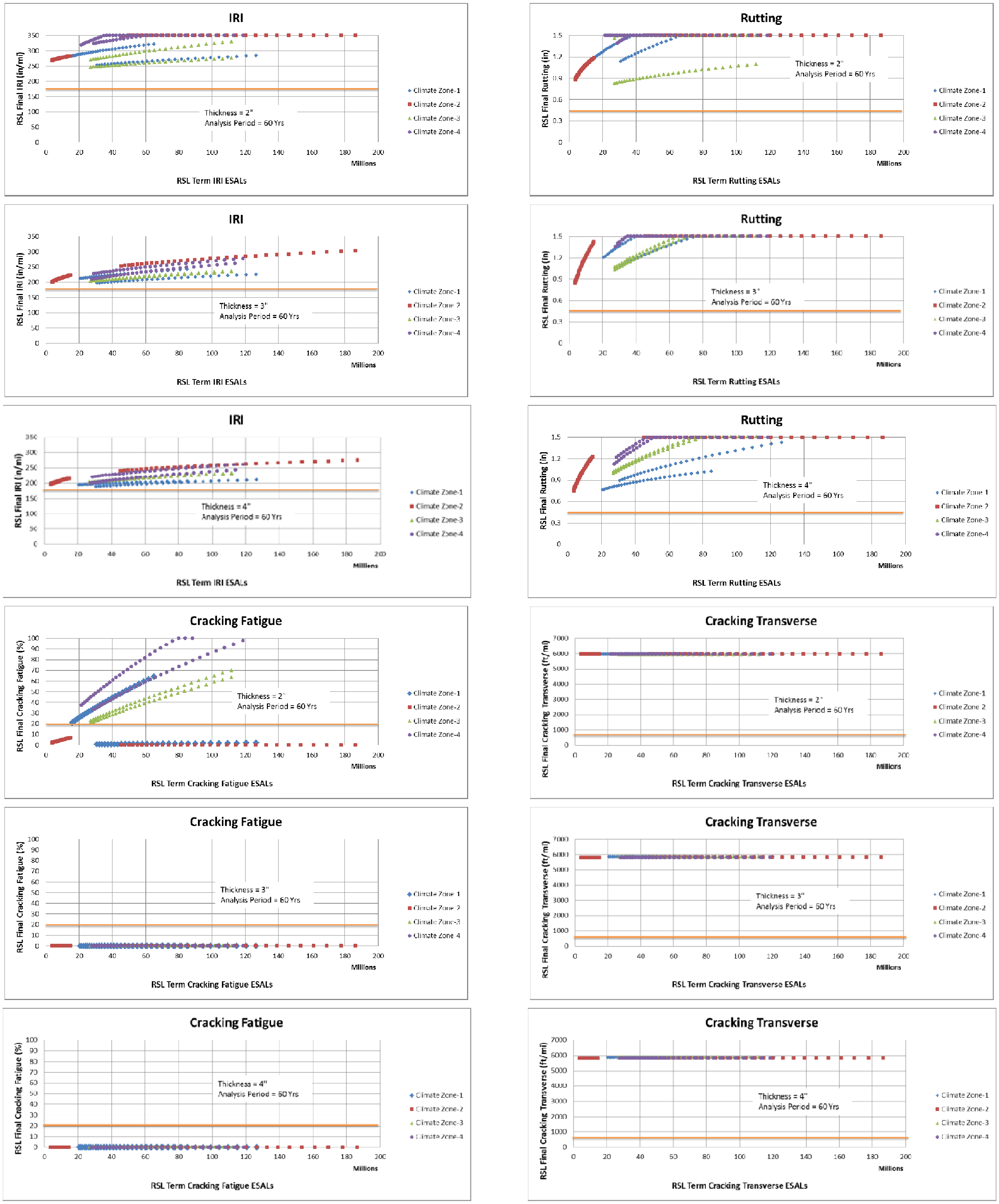

Figure 9. AC/AC Distress Propagation Due to Incremental Traffic Loading

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Update Pavement Forecasting Models and Reliability Index

Introduction

Sensitivity analysis produced a prioritized list of recommendations for improving the pavement distress/smoothness forecasting models used by the PHT analysis tool. This tasks objective of was to implement the improvements to enhance the PHT forecasting models to make them compatible with MEPDG version 1 and the AASHTO MEPDG manual of practice.

Along with updating the forecasting models, this task objective also included developing a reliability index that can be applied to the forecast RSL estimate to enable policy makers and engineers to model various uncertainties into the analysis. Pavement condition forecasting tools depend on many major assumptions such as climate, traffic growth, etc. Practically every input associated with forecasting the future pavement condition is variable in nature. The combined effect of variability in key inputs used for forecasting future pavement condition is variability and uncertainty in forecasted pavement condition and remaining service life. It is common to incorporate reliability into pavement condition forecasting tools for pavement design and management so as to consider these uncertainties and variations.

MEPDG Technology Development

Since the completion of version 0.8 of the MEPDG software in 2004, the NCHRP has initiated and conducted several research projects to review the product, recommend improvements, and implement the recommended improvements. This led to considerable change in the MEPDG. Examples of key changes are as follows:

- Improvement in pavement analysis algorithms (errors and deficiencies found in the original computational algorithms have been identified and corrected).
- Improvement to climate models used to model temperature and moisture profiles within the pavement structure (the original climate models have been enhanced based on work conducted at Arizona State University (ASU)).
- Recalibration of all MEPDG models in 2007 with update LTPP project information (additional materials test data, up to 8 years of additional performance and traffic data).Identification and correction of systematic error in PCC CTE data and recalibration of all rigid pavement performance prediction models in 2011.

PHT Analysis Tool Approach

The flexible, rigid, and composite simplified pavement performance prediction models developed for the Pavement Health Track (PHT) Analysis Tool were done using MEPDG version 0.8 software (i.e., the models were calibrated using predicted distress/IRI from the MEPDG software). Since then significant changes has been done to the MEPDG. Under this FHWA contract, Battelle/ARA investigated the reasonableness of the PHT Analysis Tool pavement models (Task 2) and found the following:

- Observed trends in PHT Analysis Tool distress/IRI predictions are similar to trends in version 0.8 of the MEPDG. Thus inherent anomalies in version 0.8 of the MEPDG are apparent in PHT Analysis Tool distress/IRI predictions.
- Goodness of fit for the PHT Analysis Tool distress/IRI pavement performance prediction models was mostly inadequate.
- PHT Analysis Tool estimates of RSL without internal calibration were mostly biased.
- Internal PHT Analysis Tool calibration of models in general does reduce bias.

The general consensus from all of the observations and findings presented is that although the version 0.8 of the MEPDG and thus the PHT Analysis Tool pavement performance prediction models are a vast improvement on current pavement technology there was the need for further improvement in order to make it a practical and useable pavement condition forecasting tool.

Also, as pavement condition forecasting tools depend on many major assumptions such as climate, traffic growth, etc. and inputs for the PHT Tools were mostly guesstimates, there need for incorporating reliability into the PHT pavement condition forecasting methodology to account for this high level of reliability. Incorporating reliability allows policy makers and engineers to model various kinds of uncertainty into remaining service life estimates and analysis.

Enhancement of MEPDG in the PHT Analysis Tool

Calibration of the existing pavement models comprised of the following steps:

- Select pavement types of interest.
- Identify input data (source and data items).
- Assemble data and establish project database.
- Review assembled data for completeness and accuracy.
- Develop algorithms and parameters required for calibration.
- Calibrate models by maximizing goodness of fit and minimizing error between measured and predicted distress.
- Perform sensitivity analysis to determine calibrated models reasonableness. Modify model parameters as needed.
- Finalize new calibrated models.

Select Pavement Types of Interest

All the four pavement types considered by the PHT tool were considered of interest and selected for models calibration.

- Bituminous Pavement.
- Jointed Plain Concrete Pavement (JPCP).
- Asphalt Concrete (AC) Overlay on Existing AC Pavement.
- Asphalt Concrete Overlay on Existing JPCP Pavement.

Identify Input Data Items

Data items of interest for developing the project calibration database are the HPMS2010 data items currently imported by the PHT analysis tool. No additional fields were required.

Assemble Data and Establish Project Database

A total of 504 LTPP projects were assembled for establishing a project database for the calibration analysis. A description of the projects and key pavement features are described in the following paragraphs

<u>Pavement Locations</u>

The selected projects are well distributed within the continental U.S. The good geographical distribution implies that data assembled form these projects will collectively represent site, design, and construction practices throughout the U.S. given the calibrated models a national character.

<u>Pavement Type</u>

A breakdown of the distribution of pavement type for the selected projects is listed below, which shows that each pavement type and base type of interest is well represented.

- Bituminous pavement:
    - Conventional AC over granular base: 32
    - Full-depth AC over asphalt treated base: 112
    - Semi-rigid AC over cement treated base: 25
- Jointed plain concrete pavement: 155
- Asphalt concrete overlay over existing AC pavement: 104
- Asphalt concrete overlay over existing jointed concrete pavement:18

<u>Pavement Type</u>

Highway functional class distribution is predominantly rural principal arterials. This is typical of pavements on the national highway system (NHS) and thus represents the type of pavements typical found in HPMS and State highway databases used for policy and asset management decision making.

<u>Truck Traffic</u>

New construction or AC overlay placement base year two-way average annual daily truck traffic and future volumes were used to characterize traffic for pavement forecasting. Historical truck AADT estimates was obtained from the LTPP and used to determine base year truck volumes and growth rates. The base year and growth rates were used to determine future truck AADT for 20 years after original construction or AC overlay placement. The truck AADT growth rate was determined by fitting a linear curve to the historical truck AADT data.

Climate Zone

The selected projects have an adequate distribution among the four LTPP climate regions. The good climate distribution implies that data assembled from these projects will collectively represent climate conditions across the U.S.

- Dry, Freeze: 67
- Dry, Non-Freeze: 80
- Wet, Freeze: 201
- Wet, Non-Freeze: 135

Sub-Grade Soil Type

The selected projects have an adequate distribution of projects among the two soil types. The good distribution implies that data assembled from these projects will collectively represent soil conditions across the U.S.

- Fine: 200
- Granular: 294

Design Features

The design features of interest are the AC overlay thickness, existing surface layer thickness, and the base type. The selected projects have the following design features, illustrated in Figure 10.

- PCC thickness represents typical U.S. practice ranging from 7 to 13 inches
- AC overlays were thicker for existing AC pavements when compared to existing PCC.
- All typical base types were represented.

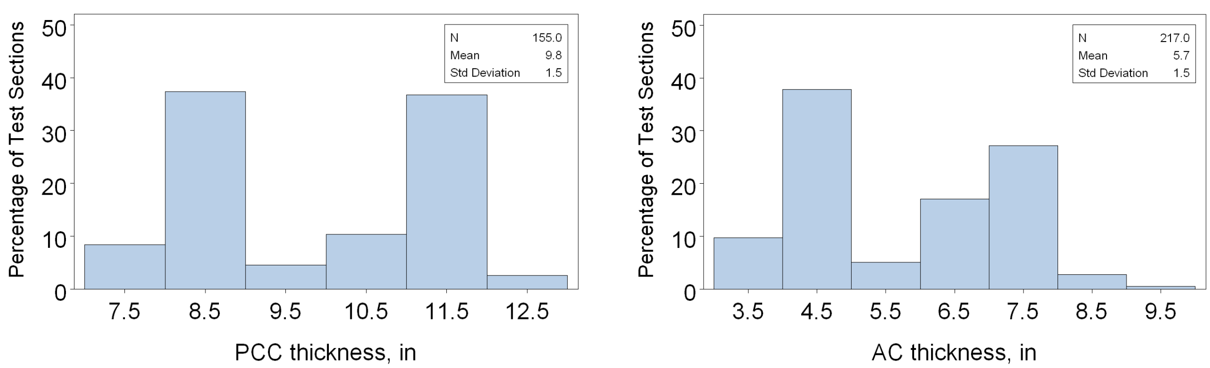

Figure 10. Pavement Thickness Distribution for LTPP Projects

Distress/Smoothness

Measured distress (cracking, rutting, and faulting) along with smoothness (IRI) data was assembled for all the 504 selected projects.

Review Assembled Data for Completeness and Accuracy

The assembled data was reviewed for completeness and accuracy. Data review was done by computing the mean, standard deviation, and range statistics to identify outliers and developing distress/IRI versus age plots to determine reasonableness of trends. Key issues identified and resolved were outliers in data, inconsistencies with AC overlay thickness for new JPCP pavements, and atypical trends. The anomalies were resolved as needed.

Develop Algorithms and Parameter Required for Calibration

The assembled data was used to compute the input variables and clusters required for forecasting pavement condition. The input variables and clusters were different for each pavement type and distress/IRI. A detailed description of the models input variables and clusters are summarized PHTv1.1 Forecasting Models Technical Information document.

Calibrate Models by Minimizing Error between Measured and Predicted Distress

Calibration comprised of the following steps:

- For all the projects, using the appropriate model inputs, execute models and equations and predict distress and smoothness. Distress/IRI predictions were done for a 40-year analysis period.
- Extracting relevant outputs, including inputs, clusters, predicted distress and IRI for each selected project.
- Reviewing the extracted data for accuracy and reasonableness.
- Matching the extracted predicted distress values with field-measured values and comparing the predicted distress with the measured values.
- Determine reasonableness of goodness of fit and bias.
- For models found to be inadequate, recalibrate prediction models as necessary to produce unbiased predictions.

Note that due to the nature of inputs, goodness of fit is not expected to be a good as the AASHTO MEPDG models. The goodness of it is expected to be as low as that reported for pavement management models (typically ranges from 10 to 30 percent). The goal thus was to meet this threshold of goodness of fit and eliminate bias between measured and predicted distress/IRI values.

Perform Sensitivity Analysis to Determine Model Reasonableness

The recalibrated pavement forecasting models were validated by performing a comprehensive sensitivity analyses. Sensitivity analysis comprised of the following steps:

- Develop typical “baseline” pavement sections for the four pavement types of interest.
- Determine key models inputs variables and the range of their typical values (e.g., PCC thickness ranges from 7 to 13 in).
- Predict distress/IRI for the baseline pavement sections and vary key inputs as needed within the range of typical values.

- Determine the impact of change in input variable values on predicted distress/IRI.
    - Are changes in distress/IRI in accordance with engineering expectations (e.g., thicker PCC implies less distress).
    - Is the magnitude of change reasonable (10 percent change in PCC thickness results in 5 to 15 percent change in distress/IRI within a 25 year analysis period).
- If the sensitivity analysis outcome is reasonable then the new recalibrated models are deemed as adequate. Otherwise, the models are modified as needed until an adequate outcome is obtained.

Finalize New Calibrated Models

The final new improved recalibrated PHT Tool models was documented and incorporated into the existing PHT analysis software. This required modifications to the analysis engine dynamic link library (DLL) file as well as the PHT graphical user interface (GUI) application to support the improved models.

Incorporation of Reliability into Pavement Condition Forecasting

Practically every input associated with forecasting the future pavement condition is variable in nature. Perhaps the most obviously uncertain of all is future levels of truck traffic, material properties, and climate. Furthermore, pavements have been known to exhibit significant variation in condition along their length. The combined effect of variability in key inputs used for forecasting future pavement condition is variability and uncertainty in forecasted pavement condition/life as shown in Figure 11. Thus, it is common to incorporate reliability into pavement condition forecasting tools for pavement design and management so as to consider the uncertainties and variations in inputs when forecasting future pavement condition/life.

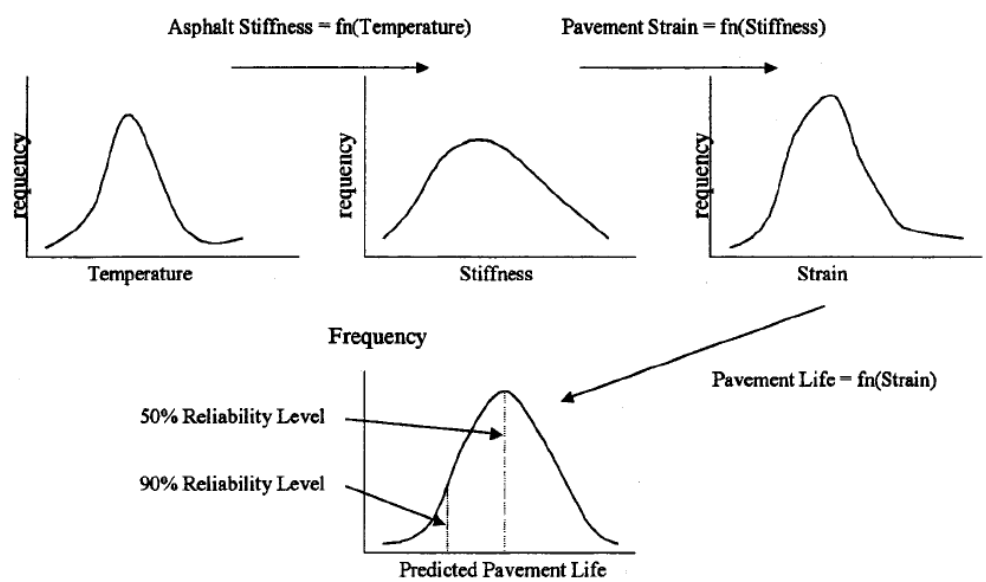

Figure 11. Example of Effect of Variability in Key Pavement Models

For pavement analysis, reliability has been described in many ways over the years.

- The probability that a pavement design will perform satisfactorily under prescribed traffic and environmental conditions over anticipated design period.
- The probability that a pavement system will perform its intended function over its design life (or time) and under the conditions (or environment) encountered during operation
- The probability that serviceability will be maintained at adequate levels from a user's point of view, throughout the design life of the facility

In the strictest sense reliability is defined as one minus the probability of failure:

$$R = 1 - Pfailure \tag{1}$$

Traditionally pavement failure has been defined using serviceability loss (a subjective measure of pavement performance). The 1993 AASHTO Pavement Design Guide define reliability mathematically in terms of the number of predicted equivalent single axle loads to terminal serviceability (N) being less than the number of equivalent single axle loads actually applied (n) to the pavement.

$$R = P[N < n] \tag{2}$$

The 1993 AASHTO Guide approach produced results that indicated that thicker pavements always increased design reliability. This assumption, however, is not always be true as several design features other than thickness (e.g., HMAC mixture design, dowels for jointed plain concrete pavements, and subgrade improvement for all pavement types) do influence reliability. Thus for AASHTO's MEPDG, reliability was incorporated in a consistent and uniform fashion for all pavement types, allowing users to select a desired level of reliability for each distress type and smoothness. Design reliability was defined as the probability that each of the key distress types and smoothness will be less than a selected critical level over the analysis period (see equation 3).

$$R = P[\text{Distress at Give Time during Design Period} < \text{Critical Distress Level}] \tag{3}$$

The diagram in Figure 12 illustrates the AASHTO MEPDG approach using a probability distribution for IRI. This diagram shows that the probability, R, that IRI is greater than its associated user-defined failure criteria can be computed over the entire analysis period.

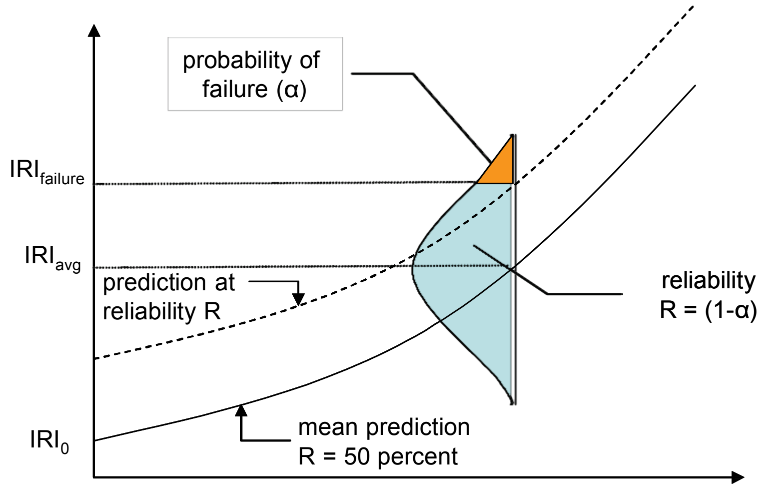

Figure 12. Design Reliability Concept for Smoothness

Reliability was incorporated into MEPDG predicted distress/IRI as follows:

- Calibrate distress/IRI model using field measured distress/IRI data. Typically each distress/IRI model was calibrated using LTPP and other field performance data.
- Plot predicted distress/IRI (horizontal axis) versus residual error of prediction (i.e., difference of predicted distress/IRI and measured distress/IRI results for all sections used in calibration) (vertical axis). The residual error characterizes how the prediction model fails to properly explain the observed distress/IRI.
- Divide predicted distress/IRI into reasonably spaced increments and assume a distribution of residual error for each distress/IRI. Typically a normal distribution is assumed.
- For each increment, estimate mean predicted distress/IRI and mean standard error of estimate for measured distress/IRI.
- Develop a mathematical relationship to predict distress/IRI standard error from mean predicted distress/IRI. The standard error is determined as a function of the predicted distress/IRI.
- An illustration for JPCP slab cracking and JPCP slab cracking at various reliability levels is shown in Figure 13 and Figure 14 respectively. Estimate cracking at the desired reliability level using the following relationship:

$$\text{Distress / IRI} = \text{Distress / IRI\_mean} + \text{STDmeas} \times Zp \qquad (4)$$

WHERE

Distress/IRI _P	=	Distress/IRI level corresponding to the reliability level p
Distress/IRI _mean	=	Distress/IRI predicted using the deterministic model with mean inputs (corresponding to 50 percent reliability)
STDmeas	=	Standard deviation of distress/IRI corresponding to distress/IRI predicted using the deterministic model with mean inputs
Zp	=	Standardized normal deviate (mean 0 and standard deviation 1) corresponding to reliability level p.

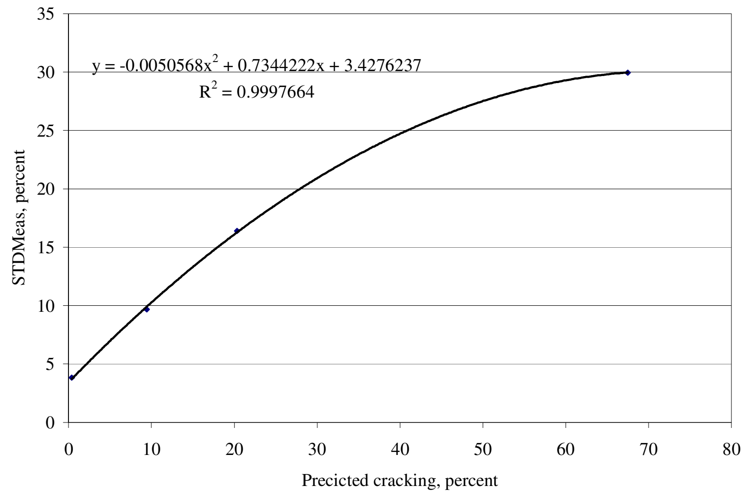

Figure 13. Standard Deviation of Measured Cracking vs. Predicted Cracking

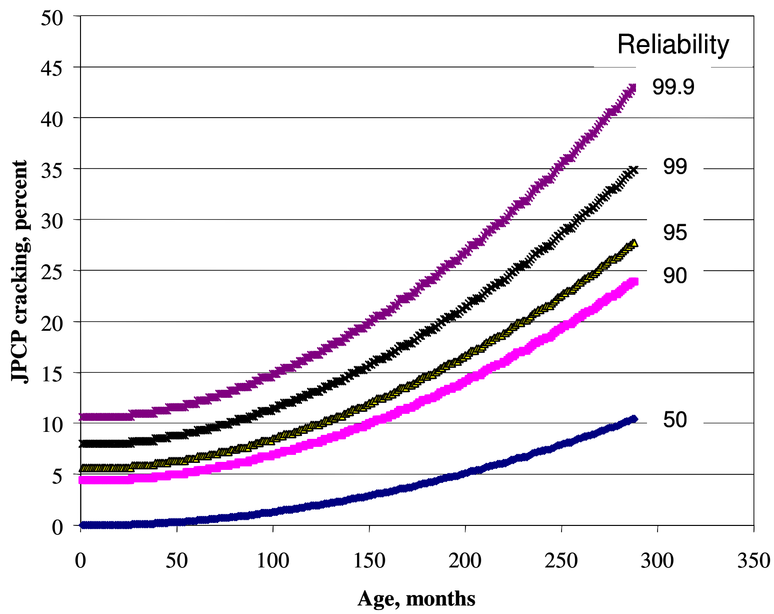

Figure 14. Cracking Estimation at Different Levels of Reliability

The procedure described above was used for incorporating reliability/risk into PHT Tool pavement condition forecasting. This enables users to forecast pavement condition at a given reliability level/index and then estimate RSL based on that reliability level. The reliability index incorporated was a decimal value between 50 and 100 percent that describes the reliability percentage of the RSL forecast as reported by the PHT tool. Note that the existing PHT determines RSL at 50 percent reliability, mean value.

Calibration of Bituminous and AC Overlays on Existing AC Pavement

Alligator Cracking

Measured alligator cracking data at different ages was available for most of the sections. The PHT Analysis Tool computed parameters that are inputs to the alligator cracking model were extracted for ages corresponding to field alligator cracking data measurements. The predicted alligator cracking was compared against the measured field data to compute the residual error for each age.

Plots of measured/predicted alligator cracking versus computed PHT Tool estimated fatigue damage was prepared and examined. Outliers were further examined for erroneous inputs and when found they were rerun in the PHT Tool. The updated data were then used to develop revised calibration coefficients and model that resulted in unbiased alligator cracking prediction. Unbiased prediction means that the model does not on average over all of the data over predict or under predict the measured data.

The new PHT Tool alligator cracking model developed from the S-shaped curve model relating cracking to fatigue damage for new bituminous pavements is as presented below:

$$ACRK = \frac{100}{1 + C0(FDAM)^{C1}} \tag{5}$$

WHERE

ACRK	=	predicted alligator cracking, percent lane area
FDAM	=	fatigue damage
C0	=	calibration coefficients = 0.115
C1	=	calibration coefficients = -1.25

The C0 and C1 coefficients were determined to minimize the prediction error of the model and reduce bias. The model was developed with 1095 data points and has an R^2 of 17.14 percent and an RMSE of 8.7 percent. The new model goodness of fit statistics indicates the level of accuracy typical for pavement management type models. A plot of predicted and measured cracking versus fatigue damage is shown in Figure 15 for the entire dataset used for model calibration development. This data plot illustrates the S-Shaped curve typically used in modeling cracking versus fatigue damage.

The new alligator cracking model was further evaluated for bias. Bias was defined as the consistent under or over estimation of cracking. Bias was determined by performing a statistical paired t-test to determine if measured and predicted alligator cracking was similar:

- Develop null and alternative hypothesis:
  - Null hypothesis H0: PHT Tool cracking = LTPP measured cracking.
  - Alternate hypothesis HA: PHT Tool cracking ≠ LTPP measured cracking.
- Perform statistical analysis to determine and evaluate test p-value.
  - A rejection of the null hypothesis (p-value < 0.05) would imply cracking from the PHT Tool and measured LTPP cracking are from different populations. This indicates bias in PHT Tool alligator cracking estimates for the range of typical inputs used in analysis.

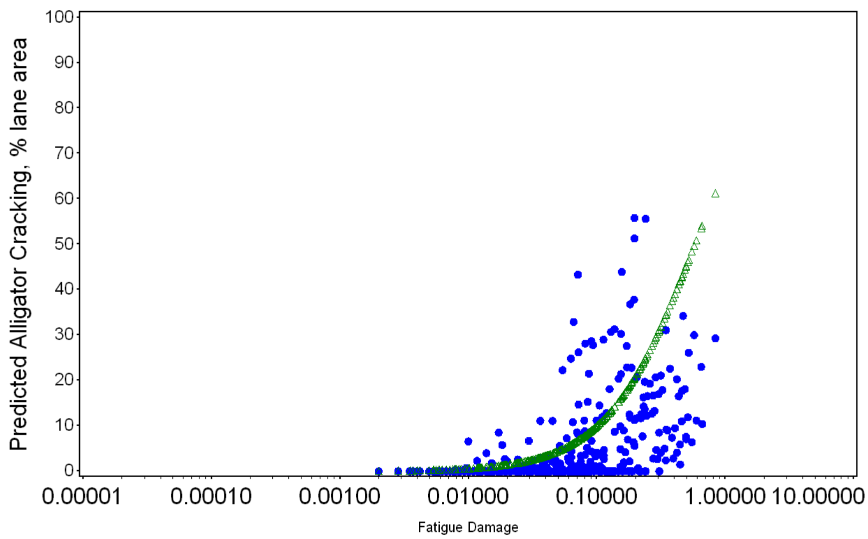

Figure 15. Predicted vs. Measured Alligator Cracking

Note that a significance level, α, of 0.05 or 5 percent was assumed for all hypothesis testing. The outcome of the paired t-test was a p-value of 0.8587. The p-value showed that there was not significant bias in predicted alligator cracking.

The new bituminous pavement alligator cracking model can be used to predict future alligator cracking in AC overlay of existing AC pavements. The reflection of existing AC cracking for such pavements was considered as the HPMS and state PMS databases do not provide information on existing pavement past/historical distress and the extent of repairs done to the existing pavement prior to AC overlay placement. The nationally calibrated MEPDG alligator cracking reflection model was recommended. Default existing alligator cracking post repairs and AC overlay placement was determine using historical data from the LTPP database as shown below in Table 6.

Table 6. Default Existing Alligator Cracking Post Repairs

Pavement Age at AC Overlay Placement, years	Alligator Cracking Post Repairs (ICRK), percent lane area
0 to 5	5
5 to 10	10
10 to 15	15
> 15	20

Reliability Model

Risk associated with alligator cracking prediction or the reliability of the alligator cracking is defined as the one-tail confidence interval at a predefined reliability level around a given alligator cracking prediction. Specifically, the one-tailed confidence interval is as defined in equation 4. For this study, confidence interval was determined as follows:

- Use new PHT Tool alligator cracking model to estimate the distress (over typical range of cracking, i.e., 0 to 100 percent).
- Divided the typical range of the distress into subsets (e.g., 0 to 10, 10 to 20, etc.).
- For each subset of predicted alligator cracking, estimate the standard error of the mean prediction (i.e., standard deviation of measured – predicted distress (i.e., std. error of the estimate, SEE) for all individual data points that falls within the subset).
- Develop a relationship between the SEE and predicted alligator cracking.

The relationship developed was used in the PHT Tool to determine SEE for any predicted alligator cracking. SEE will be used to estimate predicted alligator cracking at any desired reliability level as shown in Table 7. The design reliability procedure described above requires the estimation of variability in the form of standard deviation at any given level of predicted alligator cracking. Predicted alligator cracking standard deviation was determined as follows:

- Divide predicted alligator cracking to five or more intervals.
- For each interval, determine mean predicted alligator cracking and standard error (i.e., standard variation of predicted – measured alligator cracking for all the predicted alligator cracking that falls within the given interval).
- Develop a non linear model to fit mean predicted alligator cracking and standard error for each interval.

Table 7. Reliability Level and Corresponding Standardized Normal Deviate

Reliability Level P (One Sided Confidence Interval), percent	Standardized Normal Deviate (Mean 0 and Standard Deviation 1) Corresponding To Reliability Level P
75	0.674
80	0.842
85	1.036
90	1.282
95	1.645

The resulting standard error prediction model developed for the PHT Tool is presented below:

$$Stderr(ACRK) = 7.24 + \left(0.65 \times MPACRK^{0.417}\right) \quad (6)$$

WHERE

Stderr(ACRK) = cracking standard error of the estimate, percent
ACRK = predicted alligator cracking, percent lane area
MPACRK = mean predicted alligator cracking

The diagram in Figure 16 presents a plot of standard deviation versus predicted alligator cracking developed using the data presented in Table 8 which was obtained through analysis of predicted alligator cracking data. The region of predicted cracking that triggers maintenance and rehabilitation is in the range of 5 to 30 percent, and reported predicted alligator cracking SEE for this range was found to be reasonable.

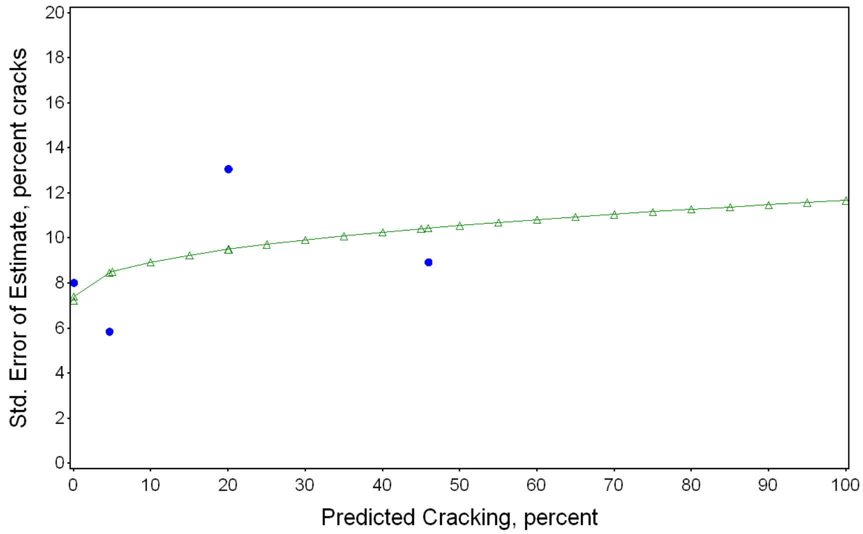

Figure 16. Predicted Cracking vs. Cracking SEE

Table 8. Predicted Cracking Data for Standard Deviation Model

Mean Cracking, percent	Standard Deviation of Predicted Cracking, percent
0	7.2
10	8.9
20	9.5
30	9.9
40	10.3
50	10.6
60	10.8
70	11.1
80	11.3
90	11.5
100	11.7

Rutting

Measured rutting data for a wide range of ages and truck traffic application was available for most of the sections. PHT Tool computed parameters that are inputs to the rutting model. The rutting model input parameters were extracted for ages corresponding to field rutting measurements. The PHT predicted rutting was compared against the measured field rutting data to compute the residual error for each age.

Plots of field measured and PHT Tool predicted rutting versus age was prepared and examined. Outliers were further examined for erroneous inputs. Errors in inputs were corrected as needed and the PHT Tool was rerun for those sections to obtain new corrected predictions of rutting. The updated measured/predicted rutting dataset was then used to revise the existing PHT Tool rutting model algorithm and calibration coefficients as needed to increase goodness of fit, minimize error in measured and predicted rutting, and minimize bias.

The new PHT Tool rutting model developed for new bituminous pavements is as presented below:

$$\text{TRUT} = \text{ACRUT} + \text{BASERUT} + \text{SUBGRUT} \tag{7}$$

$$\text{ACRUT} = C0 \times MAAT^{0.792} \times \left(\varepsilon_{HMA-V} \times CESALS^{0.527285}\right) \tag{8}$$

$$\text{BASERUT} = C1 \times BASETHK \times \left(\varepsilon_{BASE-V} \times CESALS^{0.1307}\right) \tag{9}$$

$$\text{SUBGRUT} = (C2 \times PRECIP + C3 \times FI)\left(\frac{\varepsilon_o}{\varepsilon_r}\right)^{1.30692} e^{-\left(\frac{\rho}{CESAL}\right)^{\beta}} \left(\varepsilon_{vSUBG}\right)^{0.1116} \tag{10}$$

WHERE

TRUT	=	predicted total rutting in all layers
ACRUT	=	predicted rutting in the AC layer
BASERUT	=	predicted rutting in the base layer
SUBGRUT	=	predicted rutting in the sub-grade layer
MAAT	=	mean annual air temperature, °F
CESAL	=	cumulative 18-kip ESALs since last improvement or original construction
PRECIP	=	mean annual precipitation/rainfall, in
C0	=	0 .01038
C1	=	0 .112531
C2	=	0 .000476
C3	=	0 .0000221

The revised rutting models coefficients were determined to minimize total rutting prediction error and reduce bias. The model was developed with 592 data points and has an R^2 of 20.0 percent and an RMSE of 0.104 in. The new model goodness of fit statistics is typical for pavement management type models. The diagram in Figure 17 present plot of predicted versus measured rutting for the entire dataset used for model development.

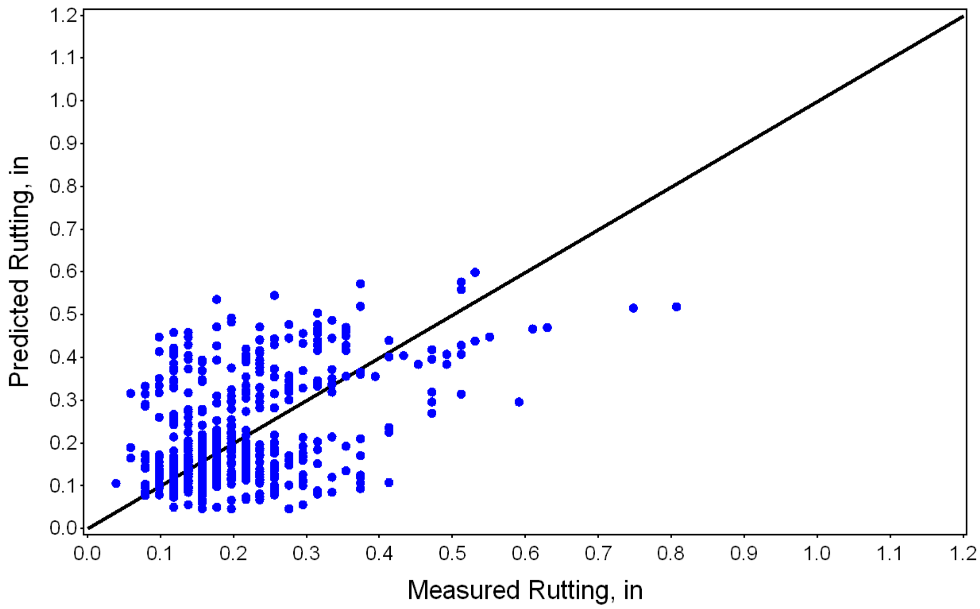

Figure 17. Predicted vs. Measure Rutting

The new rutting model was further evaluated for bias. Bias was defined as the consistent under- or over-estimation of rutting. Bias was determined by performing a statistical paired t-test to determine is measured and predicted rutting was similar (i.e., essentially from the same population). The paired t-test was performed as follows:

- Develop null and alternative hypothesis:
  - Null hypothesis H0: PHT Tool rutting = LTPP measured rutting.
  - Alternate hypothesis HA: PHT Tool rutting ≠ LTPP measured rutting.
- Perform statistical analysis to determine and evaluate test p-value.
  - A rejection of the null hypothesis (p-value < 0.05) would imply rutting from the PHT Tool and measured LTPP rutting are from different populations. This indicates bias in PHT Tool rutting estimates for the range of typical inputs used in analysis.

Note that a significance level, α, of 0.05 or 5 percent was assumed for all hypothesis testing. The outcome of the paired t-test was a p-value of 0.0509. The p-value showed that there was not significant bias in predicted rutting.

<u>Reliability Model</u>

Risk associated with rutting prediction or the reliability of the rutting is defined as the one-tail confidence interval at a predefined reliability level around a given rutting prediction. For this study, confidence interval was determined as follows:

- Use new PHT Tool rutting model to estimate the distress over typical range of rutting from 0.0 to 1.0 inches.
- Divided the typical range of the distress into subsets (e.g., 0 to 0.10, 0.10 to 0.20, etc.).
- For each subset of predicted rutting, estimate the standard error of the mean prediction (i.e., standard deviation of measured – predicted distress (i.e., std. error of the estimate, SEE) for all individual data points that falls within the subset).
- Develop a relationship between the SEE and predicted rutting.

The relationship developed was used in the PHT Analysis Tool to determine SEE for any predicted rutting. SEE will be used to estimate predicted rutting at any desired reliability level as shown in Table 7. The design reliability procedure described above requires the estimation of variability in the form of standard deviation at any given level of predicted rutting. Predicted rutting standard deviation was determined as follows:

- Divide predicted rutting to five or more intervals.
- For each interval, determine mean predicted rutting and standard error (i.e., standard variation of predicted – measured rutting for all the predicted rutting that falls within the given interval).
- Develop a non linear model to fit mean predicted rutting and standard error for each interval.

The resulting standard error prediction model developed for the PHT Tool is presented below:

$$Stderr(TRUT) = 0.0186 + \left(0.0729 \times MPRUT^{0.1}\right) \quad (11)$$

WHERE

Stderr(TRUT)	=	rutting standard error of the estimate, inches
TRUT	=	predicted rutting, inches
MPRUT	=	mean predicted rutting

The diagram in Figure 18 presents a plot of standard deviation versus predicted rutting developed using the data presented in Table 9 which was obtained through analysis of predicted rutting data. The region of predicted rutting that triggers maintenance and rehabilitation is 0.4 to 0.90 inches, and reported predicted rutting SEE for this range was found to be reasonable.

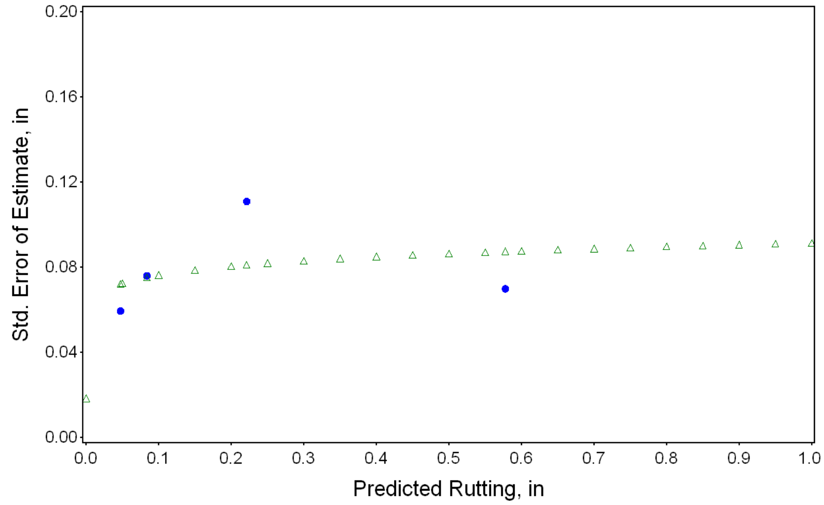

Figure 18. Predicted Rutting vs. Rutting SEE

Table 9. Predicted Rutting Data for Standard Deviation Model

Mean Rutting**, inches**	**Standard Deviation of Predicted Rutting, inches**
0	0.018
0.1	0.076
0.2	0.080
0.3	0.083
0.4	0.085
0.5	0.086
0.6	0.087
0.7	0.088
0.8	0.089
0.9	0.090
1	0.091

Transverse Cracking

Measured transverse cracking data was available for most of the sections for a wide range of pavement ages. PHT Tool was used to compute parameters that are inputs to the transverse cracking model. For each pavement section and for the ages for which measured transverse cracking data was available, relevant input computed parameters and corresponding field measured transverse cracking data was extracted and used to develop a project database for model evaluation and calibration. The input PHT Tool and output computed parameters and predicted transverse cracking was evaluated to identify errors and outlines in the input database. The outcome of this examination was to correct anomalies and errors. The PHT Tool was rerun using the corrected input database.

Plots of measured versus predicted transverse cracking was prepared and evaluated. Evaluation comprised of comparing measured field and PHT Tool predicted transverse cracking to assess goodness of fit and bias. The outcome of this evaluation was a determination that current PHT Tool transverse cracking model produced biased predictions. Thus there was a need for recalibration to improve goodness of fit and minimize bias. Unbiased prediction means that the model does not on average over all of the data over predict or under predict the measured data.

The new PHT Tool transverse cracking model developed from the S-shaped curve model relating a pseudo damage parameter to transverse cracking. The new bituminous pavement transverse cracking model is as presented below:

$$TCRK = \frac{8000}{1 + C0 \times \left(Log_{10}(FACTOR)\right)^{C1}} \tag{12}$$

$$FACTOR = AGE / (62.5 + 14.9986{*}HMATHK - 409967{*}\text{loglog}(\eta) - 6.9433{*}VA - 0.4584{*}PCT34 - 3.3029{*}FTCYC) \tag{13}$$

WHERE

TCRK	=	predicted transverse cracking, feet/mile
AGE	=	pavement age, years
HMATHK	=	HMA thickness, inches
VA	=	as-constructed HMA mix air void content, percent
PCT34	=	cumulative percent retained on the ¾ in sieve for the HMA
FTCYC	=	mean annual air freeze-thaw cycles
C0	=	WF: 4.61, WNF: 1053, Dry: 223.6
C1	=	WF: -3.327, WNF: -4.5, Dry: -4.5

The model was developed with 700 data points and has an R^2 of 53.5 percent and an RMSE of 502 ft/mi. The new model goodness of fit statistics indicates the level of accuracy typical for pavement management type models. The diagram in Figure 19 presents the plot of predicted versus measured transverse cracking for the entire dataset used for model development. The diagram in Figure 20 presents a plot of predicted transverse cracking versus FACTOR. This plot shows considerably higher predictions of transverse cracking for Freeze and Dry regions compared to Wet/No-freeze.

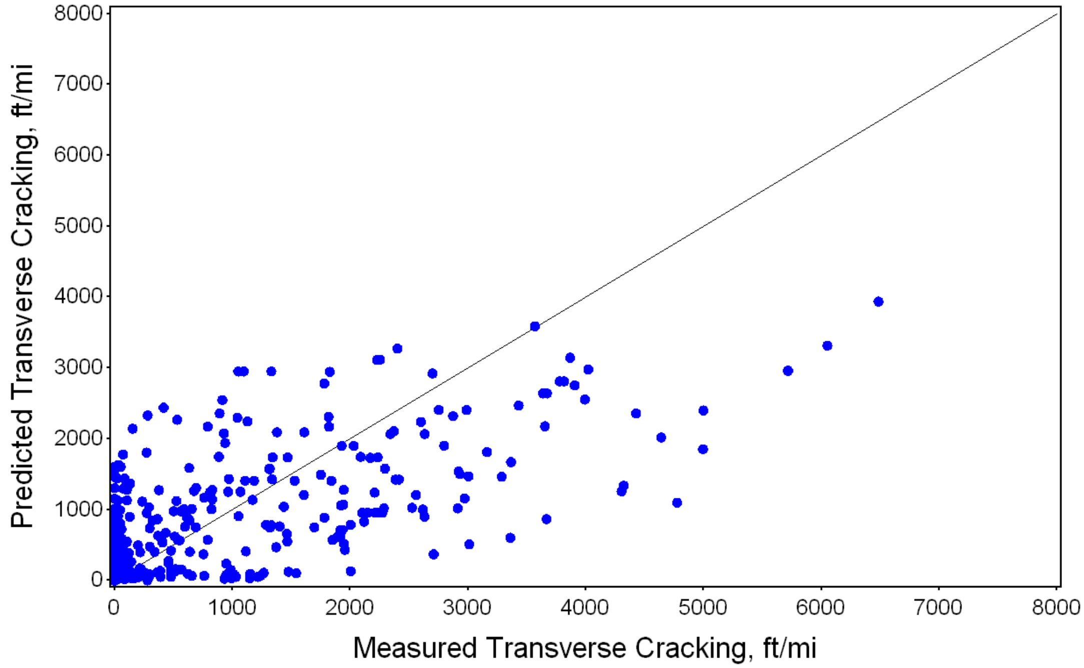

Figure 19. Predicted vs. Measured Transverse Cracking

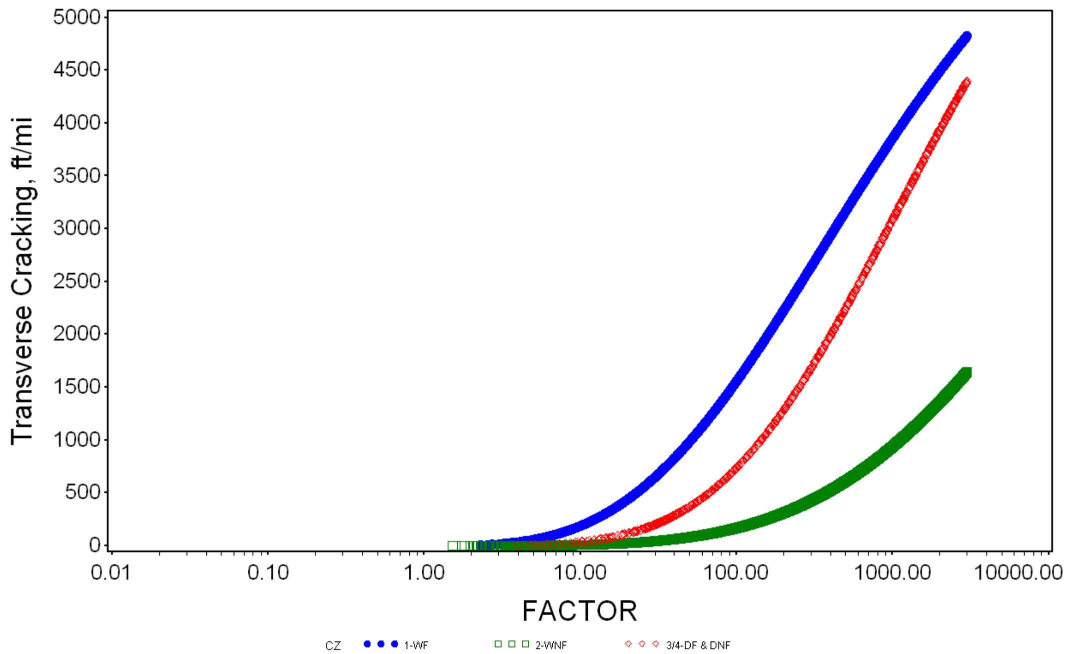

Figure 20. Predicted Transverse Cracking vs. FACTOR

The new transverse cracking model was further evaluated for bias. Bias was defined as the consistent under or over estimation of cracking. Bias was determined by performing a statistical paired t-test to determine is measured and predicted transverse cracking was similar. The paired t-test was performed as follows:

- Develop null and alternative hypothesis:
    - Null hypothesis H0: PHT Tool cracking = LTPP measured cracking.
    - Alternate hypothesis HA: PHT Tool cracking ≠ LTPP measured cracking.
- Perform statistical analysis to determine and evaluate test p-value.
    - A rejection of the null hypothesis (p-value < 0.05) would imply cracking from the PHT Tool and measured LTPP cracking are from different populations. This indicates bias in PHT Tool transverse cracking estimates for the range of typical inputs used in analysis.

Note that a significance level, α, of 0.05 or 5 percent was assumed for all hypothesis testing. The outcome of the paired t-test was a p-value of 0.7902. The p-value showed that there was not significant bias in predicted transverse cracking.

Reliability Model

Risk associated with transverse cracking prediction or the reliability of the transverse cracking prediction was defined as the one-tail confidence interval at a predefined reliability level around a given transverse cracking prediction. The confidence interval was determined as follows:

- Use new PHT Tool transverse cracking model to estimate the distress over typical range of cracking of 0 to 5000 ft/mi.
- Divided the typical range of the distress into subsets (e.g., 0 to 1000, 1000 to 2000, etc.).
- For each subset of predicted transverse cracking, estimate the standard error of the mean prediction (i.e., standard deviation of measured – predicted distress (i.e., std. error of the estimate, SEE) for all individual data points that falls within the subset).
- Develop a relationship between the SEE and predicted transverse cracking.

The relationship developed was used in the PHT Analysis Tool to determine SEE for any predicted transverse cracking. SEE will be used to estimate predicted transverse cracking at any desired reliability level as shown in Table 7. The design reliability procedure described above requires the estimation of variability in the form of standard deviation at any given level of predicted transverse cracking. Predicted transverse cracking standard deviation was determined as follows:

- Divide predicted transverse cracking to five or more intervals.
- For each interval, determine mean predicted transverse cracking and standard error (i.e., standard variation of predicted – measured transverse cracking for all the predicted transverse cracking that falls within the given interval).
- Develop a non linear model to fit mean predicted transverse cracking and standard error for each interval.

The resulting standard error prediction model developed the PHT Tool is presented below:

$$Stderr(TCRK) = 1.0 + \left(59.23 \times MPTCRK^{0.3953}\right) \tag{14}$$

WHERE

Stderr(TCRK)	=	cracking standard error of the estimate, feet/mile
TCRK	=	predicted transverse cracking, feet/mile
MPTCRK	=	mean predicted transverse cracking

The diagram in Figure 21 presents a plot of standard deviation versus predicted transverse cracking developed using the data presented in Table 10 which was obtained through analysis of predicted transverse cracking data. The region of predicted cracking that triggers maintenance and rehabilitation is 1000 to 3000 ft/mi, and reported predicted transverse cracking SEE for this range was found to be reasonable.

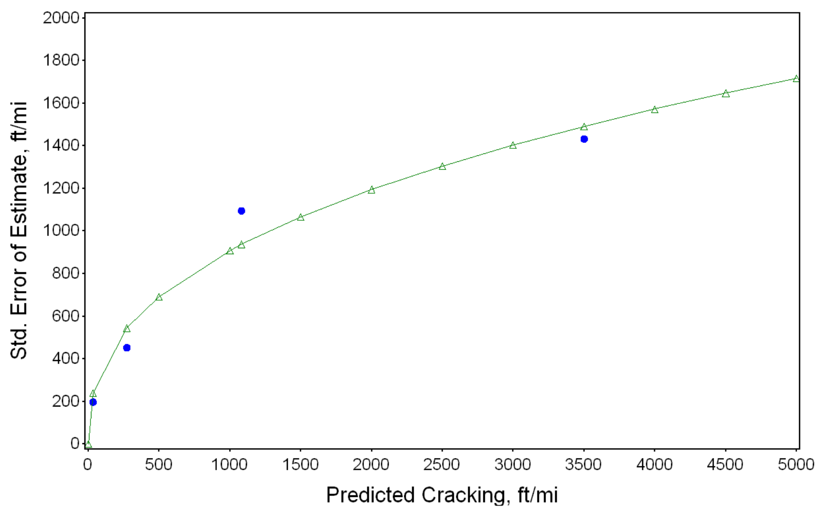

Figure 21. Predicted Transverse Cracking vs. Cracking SEE

Table 10. Predicted Transverse Cracking Data for Standard Deviation Model

Mean Transverse Cracking, ft/mi	Standard Deviation of Predicted Transverse Cracking, ft/mi
0	1
500	691.83
1000	909.59
1500	1067.54
2000	1195.99
2500	1306.19
3000	1403.73
3500	1491.87
4000	1572.67
4500	1647.58
5000	1717.61

Pavement Smoothness

Measured smoothness data was available for most of the sections for a wide range of pavement ages. PHT Tool was used to compute parameters that are inputs to the smoothness model such as alligator cracking, rutting, transverse cracking, and site factors. The initial IRI is a key smoothness model input and was estimated using historical field measured IRI available in the LTPP database.

For each LTPP section and for the ages for which measured smoothness data was available, the required smoothness inputs were estimated and used along with measured IRI to develop a project database for PHT Tool IRI model evaluation and calibration.

Current model evaluation began by reviewing the IRI calibration database for reasonableness and to identify errors and outliers. The outcome of this examination was to correct identified anomalies and errors. The PHT Tool was rerun using the corrected input database to develop a final IRI calibration database.

Next, plots of measured versus predicted smoothness was prepared and evaluated. Evaluation comprised of comparing measured field and PHT Tool predicted smoothness king to assess goodness of fit and bias. The outcome of this evaluation was a determination that current PHT Tool smoothness model produced biased IRI predictions. Thus there was a need for recalibration to improve goodness of fit and minimize bias. Unbiased prediction means that the model does not on average over all of the data over predict or under predict the measured data.

The new PHT Tool smoothness model was thus developed which was essentially recalibration of the existing IRI model to obtain new model coefficients that produce a better fit of measured and predicted IRI. The new bituminous pavement smoothness model is as presented below:

$$IRI = IRI0 + (C0 \times TCRK) + (C1 \times TRUT) + (C2 \times ACRK) + (C3 \times FACTOR) \quad (15)$$

$$FACTOR = FROSTH + SWELLP \times AGE^{1.5} \quad (16)$$

$$FROSTH = LN((PRECIP + 1) \times FINES \times (FI + 1)) \quad (17)$$

$$SWELLP = LN((PRECIP + 1) \times CLAY \times (PI + 1)) \quad (18)$$

WHERE

IRI	=	predicted IRI value
IRI0	=	initial IRI value
TCRK	=	predicted transverse cracking, feet/mile
TRUT	=	predicted rutting, inches
ACRK	=	predicted alligator cracking, percent
AGE	=	pavement age, years
PRECIP	=	mean annual precipitation, inches
FINES	=	amount of fine sand and silt particles in sub-grade, percent
CLAY	=	amount of clay particles in sub-grade, percent
FI	=	mean annual freezing index
PI	=	sub-grade soil plasticity index
C0	=	0.000592
C1	=	8.5571
C2	=	0.8676
C3	=	0.0175

The model was developed with 1507 data points and has an R^2 of 72.7 percent and an RMSE of 7.54 in/mi. The new model goodness of fit statistics indicates the level of accuracy typical for pavement management type models. The diagram in Figure 22 presents the plot of predicted versus measured IRI for the entire dataset used for model development.

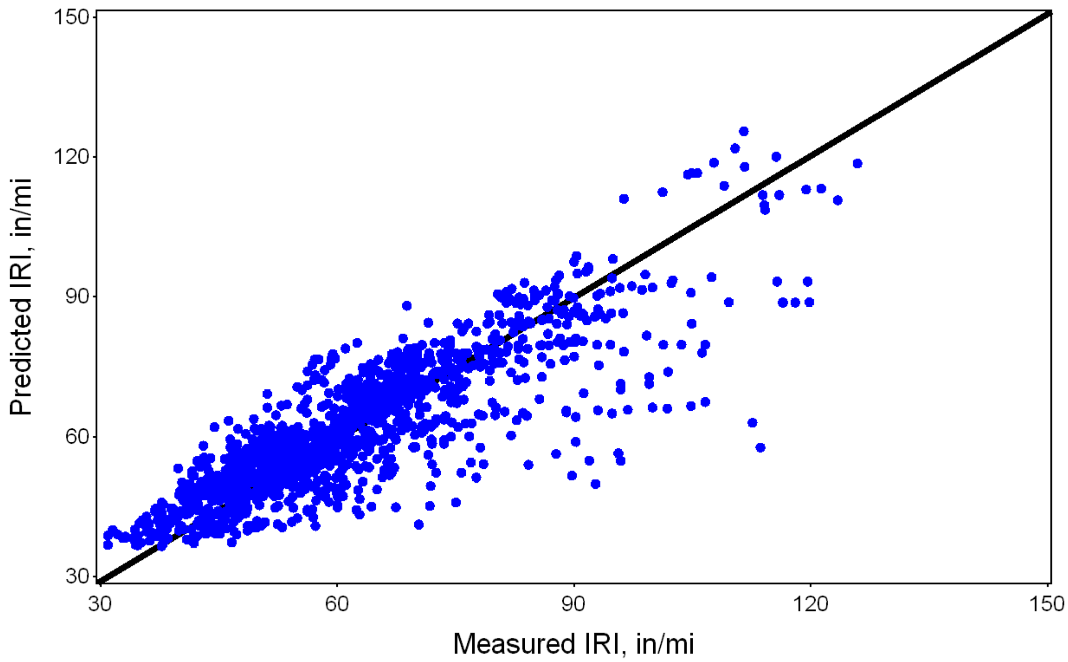

Figure 22. Predicted vs. Measured IRI

The new IRI model was further evaluated for bias. Bias was defined as the consistent under or over estimation of IRI. Bias was determined by performing a statistical paired t-test to determine is measured and predicted IRI was similar. The paired t-test was performed as follows:

- Develop null and alternative hypothesis:
    - Null hypothesis H0: PHT Tool mean IRI = LTPP measured IRI.
    - Alternate hypothesis HA: PHT Tool mean IRI ≠ LTPP measured IRI.
- Perform statistical analysis to determine and evaluate test p-value.
    - A rejection of the null hypothesis (p-value < 0.05) would imply IRI from the PHT Tool and measured LTPP IRI are from different populations. This indicates bias in PHT Tool IRI estimates for the range of typical inputs used in analysis.

Note that a significance level, α, of 0.05 or 5 percent was assumed for all hypothesis testing. The outcome of the paired t-test was a p-value of 0.0780. The p-value showed that there was not significant bias in predicted IRI.

Reliability Model

Risk associated with IRI prediction or the reliability of the IRI prediction was defined as the one-tail confidence interval at a predefined reliability level around a given IRI prediction. Specifically, the one-tailed confidence interval is as defined in equation 4. For this study, confidence interval was determined as follows:

- Use new PHT Tool IRI model to estimate the distress over typical range of IRI ranging from 30 to 300 inches/mile.
- Divide the typical range of the distress into subsets (e.g., 30 to 60, 60 to 90, etc.).
- For each subset of predicted IRI, estimate the standard error of the mean prediction (i.e., standard deviation of measured – predicted distress (i.e., std. error of the estimate, SEE) for all individual data points that falls within the subset).
- Develop a relationship between the SEE and predicted IRI.

The relationship developed was used in the PHT Analysis Tool to determine SEE for any predicted IRI. SEE will be used to estimate predicted IRI at any desired reliability level as shown in Table 7. The design reliability procedure described above requires the estimation of variability in the form of standard deviation at any given level of predicted IRI. Predicted IRI standard deviation was determined as follows:

- Divide predicted IRI to five or more intervals.
- For each interval, determine mean predicted IRI and standard error (i.e., standard variation of predicted – measured IRI for all the predicted IRI that falls within the given interval).
- Develop a non linear model to fit mean predicted IRI and standard error for each interval.

The resulting standard error prediction model developed for the PHT Tool is presented below:

$$Stderr(IRI) = 0.001 + \left(1.5827 \times MPIRI^{0.3809}\right) \tag{19}$$

WHERE

Stderr(IRI)	=	IRI standard error of the estimate, inch/mile
IRI	=	predicted IRI, inch/mile
MPIRI	=	mean predicted IRI

The diagram in Figure 23 presents a plot of standard deviation versus predicted IRI developed using the data presented in Table 11 which was obtained through analysis of predicted IRI data. The region of predicted IRI that triggers maintenance and rehabilitation is 150 to 250 in/mi, and reported predicted IRI SEE for this range was found to be reasonable.

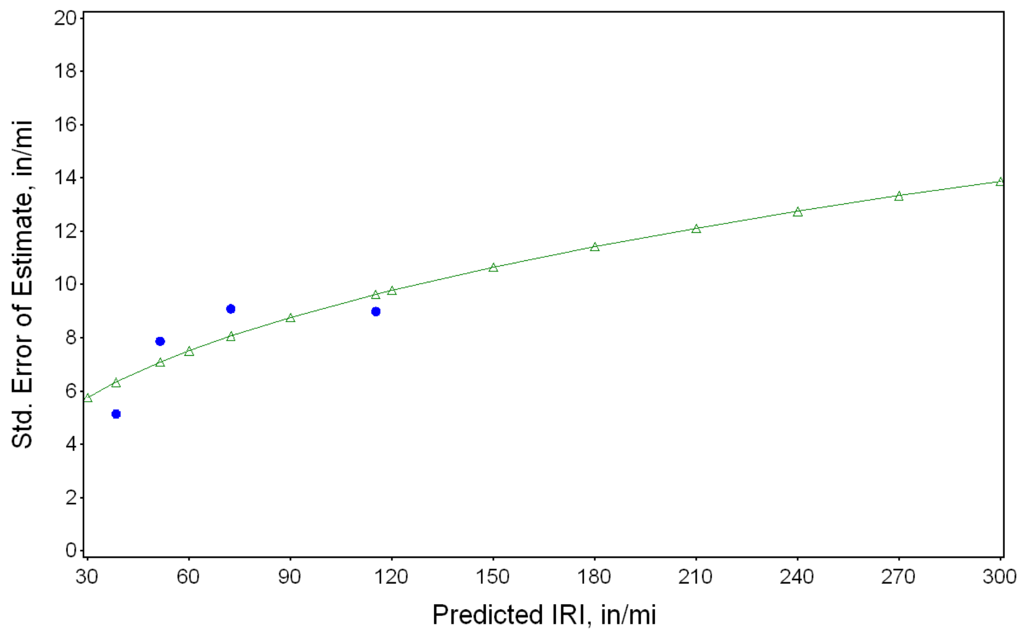

Figure 23. Predicted IRI vs. IRI SEE

Table 11. Predicted IRI Data for Standard Deviation Model

Mean IRI, in/mi	Standard Deviation of Predicted IRI, in/mi
30	5.8
60	7.5
90	8.8
120	9.8
150	10.7
180	11.4
210	12.1
240	12.8
270	13.4
300	13.9

Calibration of Jointed Plain Concrete Pavement

Slab Cracking

Measured transverse cracking data was available for most of the sections for a wide range of pavement ages. PHT Tool was used to compute parameters that are inputs to the transverse cracking model such as edge support, climate, PCC compressive strength, and PCC elastic modulus. For each pavement section and for the ages for which measured slab cracking data was available, all required inputs along with field measured slab cracking data was assembled into a project database for model evaluation and calibration. The assembled data was reviewed to identify errors and outliers. The outcome of this examination was to correct identified anomalies and errors. The PHT Tool was rerun using the corrected input database to develop the final project database.

Plots of measured versus predicted slab cracking was prepared and evaluated. Evaluation comprised of comparing measured field and PHT Tool predicted slab cracking to assess goodness of fit and bias. The outcome of this evaluation was a determination that current PHT Tool slab cracking model produced biased predictions. Thus there was a need for recalibration to improve goodness of fit and minimize bias. Unbiased prediction means that the model does not on average over all of the data over predict or under predict the measured data.

The new PHT Tool slab cracking model developed from the S-shaped curve model relating a pseudo damage parameter to slab cracking. The new JPCP slab cracking model is below:

$$TCRK = \left(\frac{AGE}{AGE+1}\right)\left(\frac{100}{1+1.006^{(-18.6*CESALS+0.965*FACTOR)}}\right) \tag{20}$$

$$\begin{aligned} FACTOR \quad = \quad & \mathrm{C0}*EDGSUP + \mathrm{C1}*EPCC + \mathrm{C2}*CTB + \mathrm{C3}*ATB + \\ & \mathrm{C4}*PCC\_COMP + \mathrm{C5}*PCCTHK + \mathrm{C6}*SUBGCOAR + \\ & \mathrm{C7}*CLIMWF + \mathrm{C8}*CLIMWNF + \mathrm{C9}*CLIMDNF \end{aligned} \tag{21}$$

WHERE

TCRK	=	predicted transverse cracking, feet/mile
AGE	=	pavement age, years
CESALS	=	mean annual precipitation, inches

Coefficient	Value	Description
C0	200	EDGSUP = (1 if a tied PCC shoulder or widened slab , otherwise 0)
C1	-0.0039	EPCC = 28-day PCC slab elastic modulus in psi
C2	-20	CTB = (1 if base type is cement treated material, otherwise 0)
C3	752.4	ATB = (1 if base type is asphalt treated material, otherwise 0)
C4	1.9799	PCCCOMP = 28-day PCC compressive strength in psi
C5	730	PCCTHK = PCC slab thickness in inches
C6	-315	SUBGCOAR = (1 if sub-grade soil type is coarse grained, otherwise 0)
C7	1000	CLIMWF = (1 if pavement is located in a wet-freeze climate, otherwise 0)
C8	100	CLIMWNF = (1 if pavement is located in a wet-no-freeze climate, otherwise 0)
C9	100	CLIMDNF = (1 if pavement is located in a dry-no-freeze climate, otherwise 0)

The model was developed with 618 data points and has an R^2 of 67.8 percent and an RMSE of 6.8 percent. The new model goodness of fit statistics indicates the level of accuracy typical for pavement management type models. The diagram in Figure 24 present plot of predicted versus measured transverse cracking for the entire dataset used for model development.

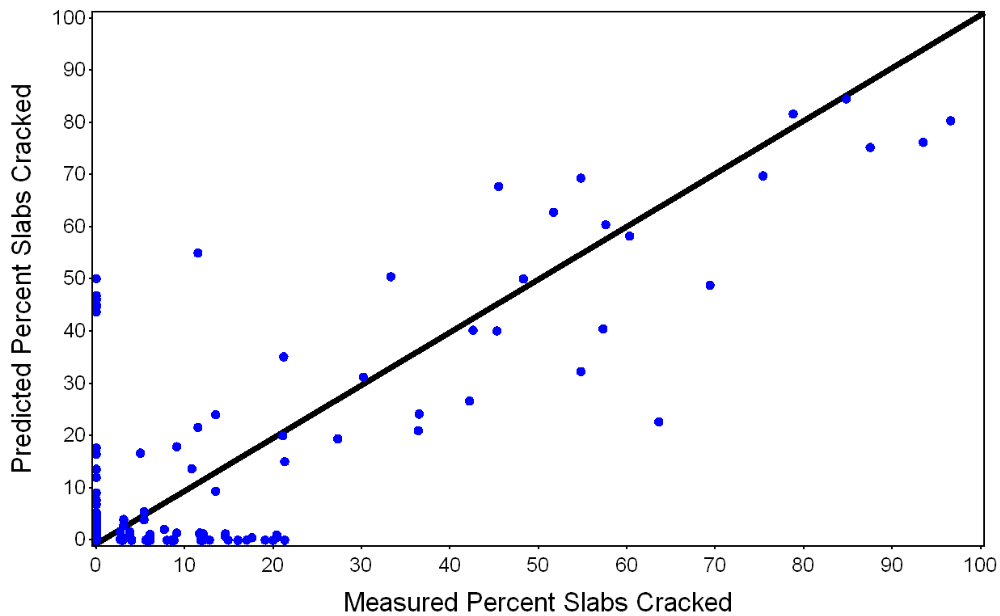

Figure 24. Predicted vs. Measured Slab Cracking

The new slab cracking model was further evaluated for bias. Bias was defined as the consistent under or over estimation of slab cracking. Bias was determined by performing a statistical paired t-test to determine is measured and predicted slab cracking was. The paired t-test was performed as follows:

- Develop null and alternative hypothesis:
    - Null hypothesis H0: PHT Tool slab cracking = LTPP measured cracking.
    - Alternate hypothesis HA: PHT Tool slab cracking ≠ LTPP measured cracking.
- Perform statistical analysis to determine and evaluate test p-value.
    - A rejection of the null hypothesis (p-value < 0.05) would imply cracking from the PHT Tool and measured LTPP cracking are from different populations. This indicates bias in PHT Tool slab cracking estimates for the range of typical inputs used in analysis.

Note that a significance level, α, of 0.05 or 5 percent was assumed for all hypothesis testing. The outcome of the paired t-test was a p-value of 0.0575. The p-value showed that there was not significant bias in predicted slab cracking.

Reliability Model

Risk associated with slab cracking prediction or the reliability of the slab cracking prediction was defined as the one-tail confidence interval at a predefined reliability level around a given slab cracking prediction. For this study, confidence interval was determined as follows:

- Use new PHT Tool slab cracking model to estimate the distress over typical range of slab cracking of 0 to 100 percent.
- Divided the typical range of the distress into subsets (e.g., 0 to 10, 10 to 20, etc.).
- For each subset of predicted slab cracking, estimate the standard error of the mean prediction (i.e., standard deviation of measured – predicted distress (i.e., std. error of the estimate, SEE) for all individual data points that falls within the subset).
- Develop a relationship between the SEE and predicted slab cracking.

The relationship developed was used in the PHT Analysis Tool to determine SEE for any predicted slab cracking. SEE was used to estimate predicted slab cracking at any desired reliability level as shown in Table 7. The design reliability procedure described above requires the estimation of variability in the form of standard deviation at any given level of predicted slab cracking. Predicted slab cracking standard deviation was determined as follows:

- Divide predicted slab cracking to four or more intervals.
- For each interval, determine mean predicted slab cracking and standard error (i.e., standard variation of predicted – measured slab cracking for all the predicted slab cracking that falls within the given interval).
- Develop a non linear model to fit mean predicted slab cracking and standard error for each interval.

The resulting standard error prediction model developed for the PHT Tool is presented below:

$$Stderr(TCRK) = 0.2227 + \left(4.0127 \times MPTCRK^{0.3691}\right) \tag{22}$$

WHERE

Stderr(TCRK)	=	slab cracking standard error of the estimate, percent
TCRK	=	predicted slab cracking, percent
MPTCRK	=	mean predicted slab cracking

The diagram in Figure 25 presents a plot of standard deviation versus predicted slab cracking. The region of predicted cracking that triggers maintenance and rehabilitation is 10 to 30 percent, and reported predicted slab cracking SEE for this range was found to be reasonable.

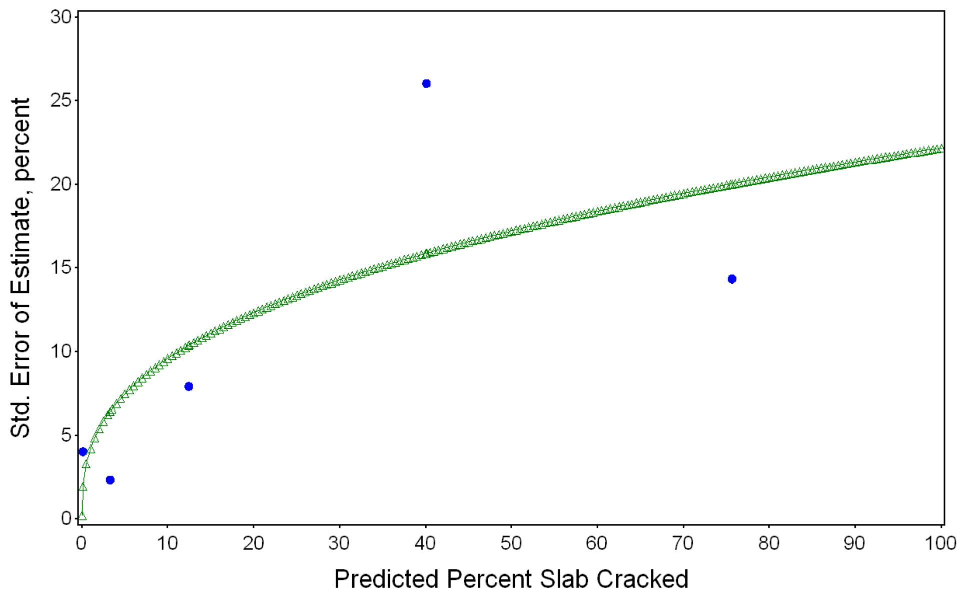

Figure 25. Predicted Slab Cracking vs. Slab Cracking SEE

Transverse Joint Faulting

Measured transverse joint faulting data was available for most of the sections for a wide range of pavement ages. The PHT Tool was used to compute parameters that are inputs to the joint faulting model such as edge support, climate, and joint spacing. For each pavement section and for the ages for which measured transverse joint faulting data was available, all required inputs along with field measured joint faulting data was assembled into a project database for model evaluation and calibration. The assembled data was reviewed to identify errors and outliers. The outcome of this examination was to correct identified anomalies and errors. The PHT Tool was rerun using the corrected input database to develop the final project database.

Plots of measured versus predicted transverse joint faulting was prepared and evaluated. Evaluation comprised of comparing measured field and PHT Tool predicted transverse joint faulting to assess goodness of fit and bias. The outcome of this evaluation was a determination that current PHT Tool transverse joint faulting model produced biased predictions. Thus there was a need for recalibration to improve goodness of fit and minimize bias. Unbiased prediction means that the model does not on average over all of the data over predict or under predict the measured data.

The new PHT Tool transverse joint faulting model developed from the S-shaped curve model relating a pseudo damage parameter to joint faulting. The new JPCP transverse joint faulting model is as presented below:

$$TJFLT = \left(\frac{AGE}{AGE+5}\right)\left(\frac{0.4}{1+1.009^{(-3.0*CESALS+0.4323*FACTOR)}}\right) \quad (23)$$

$$\begin{aligned} FACTOR \quad = \quad & \text{C0}*DOWDIA + \text{C1}*ATB + \text{C2}*CTB + \\ & \text{C3}*EDGESUP + \text{C4} + \text{C5}*WET + \text{C6}*PCCTHK + \\ & \text{C7}*SUBGCOAR \end{aligned} \quad (24)$$

WHERE

TJFLT = predicted transverse joint faulting, inches
AGE = pavement age, years

Coefficient	Value	Description
C0	652.9	DOWDIA = dowel diameter, 0 for non doweled pavements and PCC thickness or 8 for doweled pavements
C1	122.6	ATB = 1 if base type is asphalt treated or permeable asphalt treated
C2	441.7	CTB = 1 if base type is cement treated or lean concrete
C3	760.7	EDGESUP (Edge support), 1 if a tied PCC shoulder (HPMS Shoulder_Type = 3) or widened slab (lane width > 12 ft) is used, otherwise 0
C4	703.3	Site factor constant
C5	-501.8	WET = 1 if mean annual precipitation > 20 in., else 0
C6	-20.9	PCCTHK = PCC slab thickness in inches
C7	-290.8	SUBGCOAR = 1 if sub-grade soil type is coarse grained, otherwise 0

The model was developed with 527 data points and has an R^2 of 66.3 percent and an RMSE of 0.028 inches. The new model goodness of fit statistics indicates the level of accuracy typical for pavement management type models. The diagram in Figure 26 presents the plot of predicted versus measured transverse joint faulting for the entire dataset used for model development.

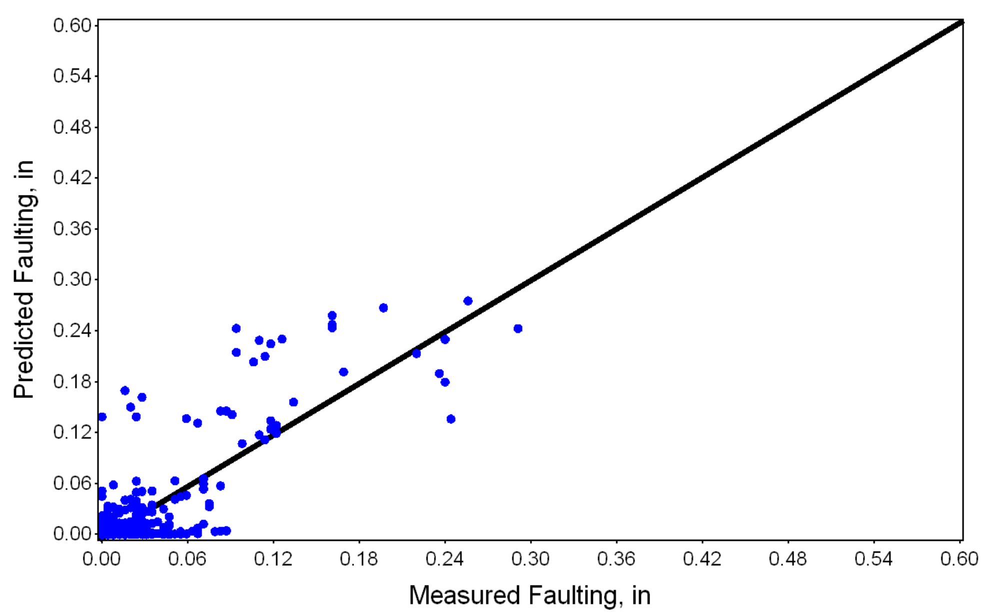

Figure 26. Predicted vs. Measured Transverse Joint Faulting

The new transverse joint faulting model was further evaluated for bias. Bias was defined as the consistent under or over estimation of joint faulting. Bias was determined by performing a statistical paired t-test to determine is measured and predicted transverse joint faulting was similar. The paired t-test was performed as follows:

- Develop null and alternative hypothesis:
    - Null hypothesis H0: PHT Tool joint faulting = LTPP measured faulting.
    - Alternate hypothesis HA: PHT Tool joint faulting ≠ LTPP measured faulting.
- Perform statistical analysis to determine and evaluate test p-value.
    - A rejection of the null hypothesis ($p\text{-value} < 0.05$) would imply faulting from the PHT Tool and measured LTPP faulting are from different populations. This indicates bias in PHT Tool transverse joint faulting estimates for the range of typical inputs used in analysis.

Note that a significance level, α, of 0.05 or 5 percent was assumed for all hypothesis testing. The outcome of the paired t-test was a p-value of 0.4558. The p-value showed that there was not significant bias in predicted transverse joint faulting.

<u>Reliability Model</u>

Risk associated with transverse joint faulting prediction or the reliability of the transverse joint faulting prediction was defined as the one-tail confidence interval at a predefined reliability level around a given transverse joint faulting prediction. For this study, confidence interval was determined as follows:

- Use new PHT Tool transverse joint faulting model to estimate the distress over typical range of joint faulting of 0 to 0.5 inches.
- Divided the typical range of the distress into subsets (e.g., 0 to 0.10, 0.10 to 0.20, etc.).
- For each subset of predicted transverse joint faulting, estimate the standard error of the mean prediction (i.e., standard deviation of measured – predicted distress (i.e., std. error of the estimate, SEE) for all individual data points that falls within the subset).
- Develop a relationship between the SEE and predicted transverse joint faulting.

The relationship developed was used in the PHT Analysis Tool to determine SEE for any predicted transverse joint faulting. SEE was used to estimate predicted transverse joint faulting at any desired reliability level as shown in Table 7. The design reliability procedure described above requires the estimation of variability in the form of standard deviation at any given level of predicted transverse joint faulting. Predicted transverse joint faulting standard deviation was determined as follows:

- Divide predicted transverse joint faulting into four or more intervals.
- For each interval, determine mean predicted transverse joint faulting and standard error (i.e., standard variation of predicted – measured transverse joint faulting for all the predicted transverse joint faulting that falls within the given interval).
- Develop a non linear model to fit mean predicted transverse joint faulting and standard error for each interval.

The resulting standard error prediction model developed for the PHT Tool is presented below:

$$Stderr(TJFLT) = 0.0042 + \left(0.1363 \times MPTJFLT^{0.5}\right) \quad (25)$$

WHERE

Stderr(TJFLT)	=	joint faulting standard error of the estimate, inches
TJFLT	=	predicted transverse joint faulting, inches
MPTJFLT	=	mean predicted transverse joint faulting

The diagram in Figure 27 presents a plot of standard deviation versus predicted transverse joint faulting. The region of predicted transverse joint faulting that triggers maintenance and rehabilitation is 0.1 to 0.3 inches, and reported predicted joint faulting SEE for this range was found to be reasonable.

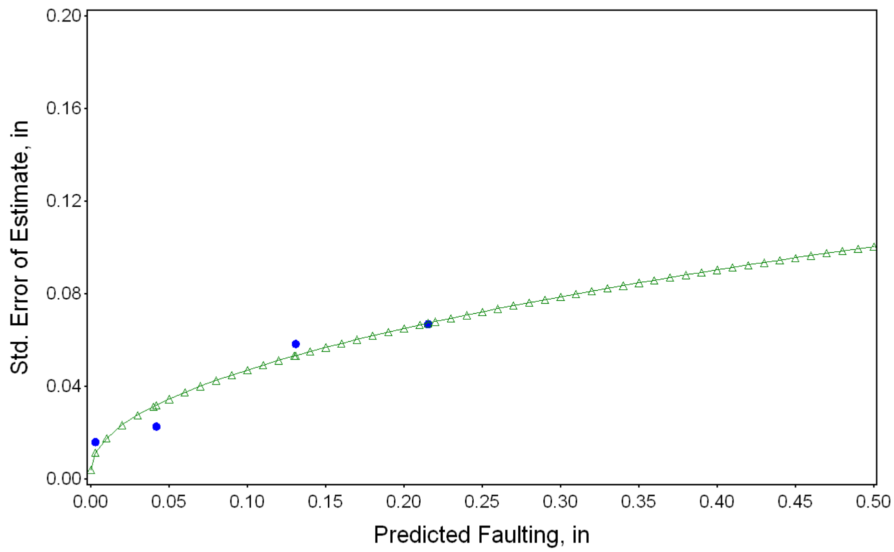

Figure 27. Predicted Joint Faulting vs. Joint Faulting SEE

Smoothness

Measured smoothness data was available for most of the sections for a wide range of pavement ages. PHT Tool was used to compute parameters that are inputs to the smoothness model including slab cracking, transverse joint faulting, spalling, and site factors. The initial IRI is a key smoothness model input and was estimated using historical field measured IRI available in the LTPP database. For each LTPP section and for the ages for which measured smoothness data was available, the required smoothness inputs were estimated and used along with measured IRI to develop a project database for PHT Tool IRI model evaluation and calibration.

Current model evaluation began by reviewing the IRI calibration database for reasonableness and to identify errors and outliers. The outcome of this examination was to correct identified anomalies and errors. The PHT Tool was rerun using the corrected input database to develop a final IRI calibration database.

Next, plots of measured versus predicted smoothness was prepared and evaluated. Evaluation comprised of comparing measured field and PHT Tool predicted smoothness to assess goodness of fit and bias. The outcome of this evaluation was a determination that current PHT Tool smoothness model produced biased IRI predictions. Thus there was a need for recalibration to improve goodness of fit and minimize bias. Unbiased prediction means that the model does not on average over all of the data over predict or under predict the measured data.

The new PHT Tool smoothness model was thus developed which was essentially recalibration of the existing IRI model to obtain new model coefficients that produce a better fit of measured and predicted IRI. The new JPCP smoothness model is as presented below.

$$IRI = IRI_0 + (C0 \times TCRK) + (C1 \times TJFLT) + (C2 \times TJSPALL) + (C3 \times FACTOR) \tag{26}$$

$$FACTOR = AGE \times (1 + 0.5556 \times FI) \times (1 + P_{200}) \times 10^{-6} \tag{27}$$

WHERE

IRI	=	predicted IRI value
IRI0	=	initial IRI value
TCRK	=	predicted slab cracking, percent
TJFLT	=	predicted transverse joint faulting, inches
TJSPALL	=	predicted transverse joint spalling, percent
AGE	=	pavement age, years
FI	=	mean annual freezing index
C0	=	0.4
C1	=	21.2
C2	=	1.52
C3	=	18.16

The model was developed with 777 data points and has an R^2 of 73.35 percent and an RMSE of 15.02 in/mi. The new model goodness of fit statistics indicates the level of accuracy typical for pavement management type models. The diagram in Figure 28 presents the plot of predicted versus measured IRI for the entire dataset used for model development.

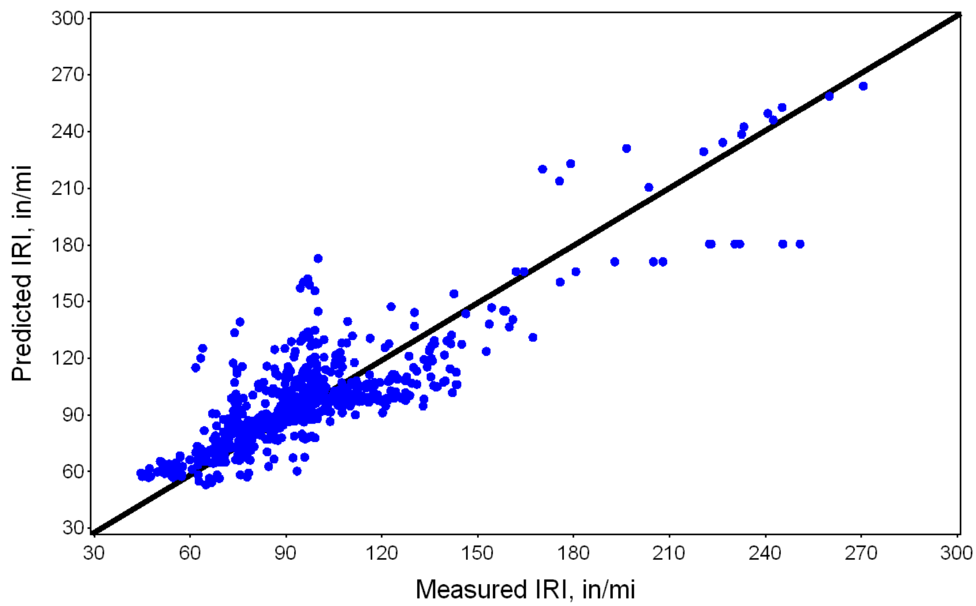

Figure 28. Predicted vs. Measured JPCP Smoothness IRI

The new JPCP IRI model was further evaluated for bias. Bias was defined as the consistent under or over estimation of cracking. Bias was determined by performing a statistical paired t-test to determine is measured and predicted IRI was similar. The paired t-test was performed as follows:

- Develop null and alternative hypothesis:
    - Null hypothesis H0: PHT Tool IRI = LTPP measured IRI.
    - Alternate hypothesis HA: PHT Tool IRI ≠ LTPP measured IRI.
- Perform statistical analysis to determine and evaluate test p-value.
    - A rejection of the null hypothesis (p-value < 0.05) would imply IRI from the PHT Tool and measured LTPP IRI are from different populations. This indicates bias in PHT Tool IRI estimates for the range of typical inputs used in analysis.

Note that a significance level, α, of 0.05 or 5 percent was assumed for all hypothesis testing. The outcome of the paired t-test was a p-value of 0.1108. The p-value showed that there was not significant bias in predicted IRI.

<u>Reliability Model</u>

Risk associated with IRI prediction or the reliability of the IRI prediction was defined as the one-tail confidence interval at a predefined reliability level around a given IRI prediction. For this study, confidence interval was determined as follows:

- Use new PHT Analysis Tool IRI model to estimate the distress over the typical range of IRI of 30 to 300 in/mi.
- Divide the typical range of the distress into subsets (e.g., 30 to 60, 60 to 90, etc.).

- For each subset of predicted IRI, estimate the standard error of the mean prediction (i.e., standard deviation of measured – predicted distress (i.e., std. error of the estimate, SEE) for all individual data points that falls within the subset).
- Develop a relationship between the SEE and predicted IRI.

The relationship developed was used in the PHT Analysis Tool to determine SEE for any predicted smoothness IRI. SEE was used to estimate predicted IRI at any desired reliability level as shown in Table 7. The design reliability procedure described above requires the estimation of variability in the form of standard deviation at any given level of predicted IRI. Predicted IRI standard deviation was determined as follows:

- Divide predicted IRI to five or more intervals.
- For each interval, determine mean predicted IRI and standard error (i.e., standard variation of predicted – measured IRI for all the predicted IRI that falls within the given interval).
- Develop a non linear model to fit mean predicted IRI and standard error for each interval.

The resulting standard error prediction model developed for the PHT Tool is presented below:

$$Stderr(IRI) = 0.001 + \left(3.793 \times MPIRI^{0.2952}\right) \tag{28}$$

WHERE

Stderr(IRI)	=	IRI standard error of the estimate, inches/mile
IRI	=	predicted IRI value, inches/mile
MPIRI	=	mean predicted IRI

The diagram in Figure 29 presents a plot of standard deviation versus predicted IRI. The region of predicted IRI that triggers maintenance and rehabilitation is 150 to 250 in/mi, and reported predicted IRI SEE for this range was found to be reasonable.

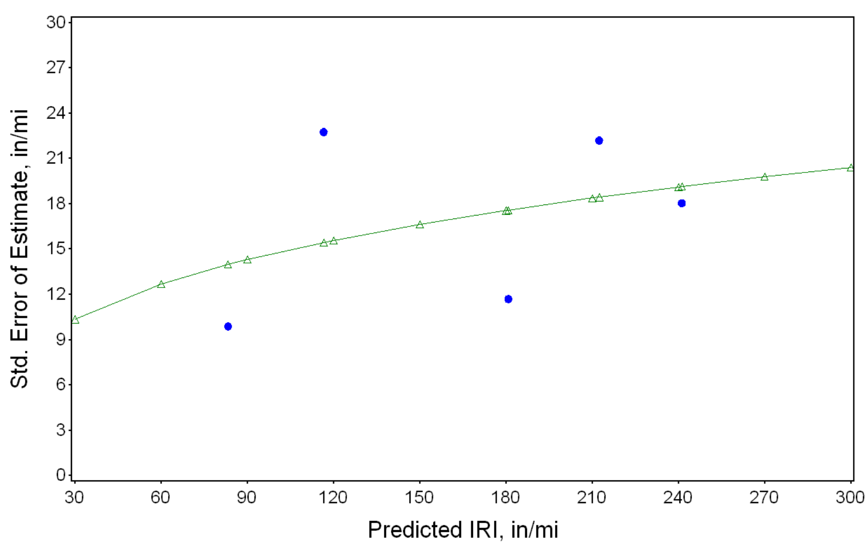

Figure 29. Predicted Smoothness IRI vs. IRI SEE

Calibration of AC Overlays on Existing JPCP Pavement

Transverse (Reflection) Cracking

Measured transverse cracking data was available for most of the sections for a wide range of pavement ages. PHT Tool was used to compute parameters that are inputs to the transverse cracking model. For each pavement section and for the ages for which measured transverse cracking data was available, relevant input computed parameters and corresponding field measured transverse cracking data was extracted and used to develop a project database for model evaluation and calibration. The input PHT Tool and output computed parameters and predicted transverse cracking was evaluated to identify errors and outlines in the input database. The outcome of this examination was to correct anomalies and errors. The PHT Tool was rerun using the corrected input database.

Plots of measured versus predicted reflection cracking was prepared and evaluated. Evaluation comprised of comparing measured field and PHT Tool predicted reflection cracking to assess goodness of fit and bias. The outcome of this evaluation was a determination that current PHT Tool reflection cracking model produced biased predictions. Thus there was a need for recalibration to improve goodness of fit and minimize bias. Unbiased prediction means that the model does not on average over all of the data over predict or under predict the measured data.

The new PHT Tool reflection cracking model developed from the S-shaped curve model relating age since overlay placement to reflection cracking. The AC overlaid JPCP reflection cracking model is as presented below:

$$RCRK = \frac{\text{C0} * \text{EXTCRK} * \text{LWIDTH}}{1 + 2.718^{C1(a)+C2(AGE)(b)}} \tag{29}$$

WHERE

RCRK	=	predicted reflection cracking, feet/mile
EXTCRK	=	number of pre-overlay transverse joints and cracks
LWIDTH	=	underlying slab or land width, feet
AGE	=	pavement age, years
C0	=	9.9639
C1	=	0.3896
C2	=	0.2826

The coefficients listed above were determined to minimize the prediction error of the model and reduce bias. The model was developed with 200 data points and has an R^2 of 54.0 percent and an RMSE of 862 ft/mi. The new model goodness of fit statistics indicates the level of accuracy typical for pavement management type models. The diagram in Figure 30 presents the plot of predicted versus measured reflection cracking for the entire dataset used for model development.

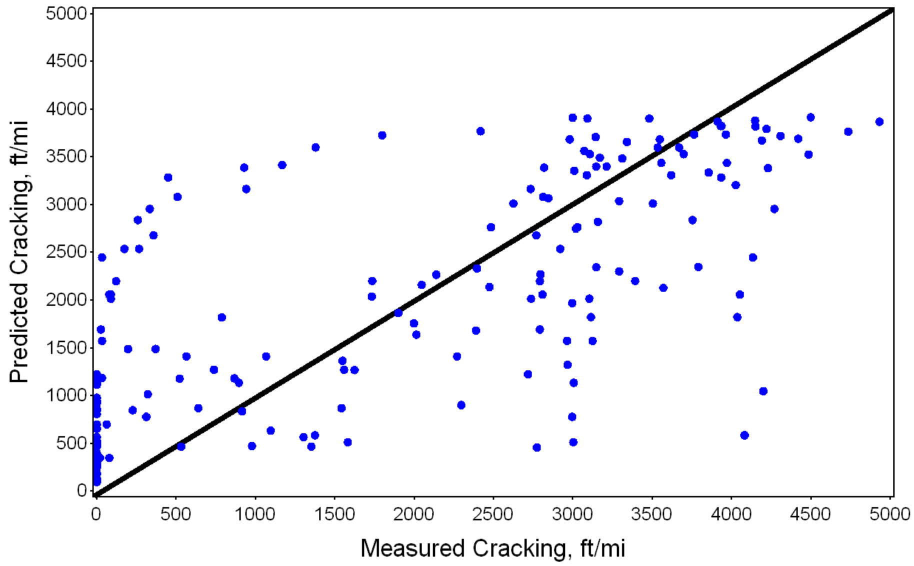

Figure 30. Predicted vs. Measured Reflection Cracking

The new reflection cracking model was further evaluated for bias. Bias was defined as the consistent under or over estimation of cracking. Bias was determined by performing a statistical paired t-test to determine is measured and predicted transverse cracking was similar. The paired t-test was performed as follows:

- Develop null and alternative hypothesis:
  - Null hypothesis H0: PHT Tool cracking = LTPP measured cracking.
  - Alternate hypothesis HA: PHT Tool cracking ≠ LTPP measured cracking.
- Perform statistical analysis to determine and evaluate test p-value.
  - A rejection of the null hypothesis (p-value < 0.05) would imply cracking from the PHT Tool and measured LTPP cracking are from different populations. This indicates bias in PHT Tool reflection cracking estimates for the range of typical inputs used in analysis.

Note that a significance level, α, of 0.05 or 5 percent was assumed for all hypothesis testing. The outcome of the paired t-test was a p-value of 0.8706. The p-value showed that there was not significant bias in predicted reflection cracking.

Reliability Model

Risk associated with transverse reflection cracking prediction or the reliability of the reflection cracking prediction was defined as the one-tail confidence interval at a predefined reliability level around a given reflection cracking prediction. For this study, confidence interval was determined as follows:

- Use new PHT Tool reflection cracking model to estimate the distress over typical range of cracking from 0 to 5000 ft/mi.
- Divided the typical range of the distress into subsets (e.g., 0 to 1000, 1000 to 2000, etc.).
- For each subset of predicted reflection cracking, estimate the standard error of the mean prediction (i.e., standard deviation of measured – predicted distress (i.e., std. error of the estimate, SEE) for all individual data points that falls within the subset).
- Develop a relationship between the SEE and predicted reflection cracking.

The relationship developed was used in the PHT Analysis Tool to determine SEE for any predicted reflection cracking. SEE was used to estimate predicted reflection cracking at any desired reliability level as shown in Table 7. The design reliability procedure described above requires the estimation of variability in the form of standard deviation at any given level of predicted reflection cracking. Predicted transverse reflection cracking standard deviation was determined as follows:

- Divide predicted reflection cracking to five or more intervals.
- For each interval, determine mean predicted cracking and standard error (i.e., standard variation of predicted – measured cracking for all the predicted reflection cracking that falls within the given interval).
- Develop a non linear model to fit mean predicted reflection cracking and standard error for each interval.

The resulting standard error prediction model developed for the PHT Tool is presented below.

$$Stderr(RCRK) = 1.0 + \left(134 \times MPRCRK^{0.2964}\right) \tag{30}$$

WHERE

Stderr(RCRK)	=	reflection cracking standard error of the estimate, feet/mile
RCRK	=	predicted reflection cracking, feet/mile
MPRCRK	=	mean predicted reflection cracking

The diagram in Figure 31 presents a plot of standard deviation versus predicted reflection cracking. The region of predicted reflection cracking that triggers maintenance and rehabilitation is 1000 to 3000 ft/mi, and reported predicted reflection cracking SEE for this range was found to be reasonable.

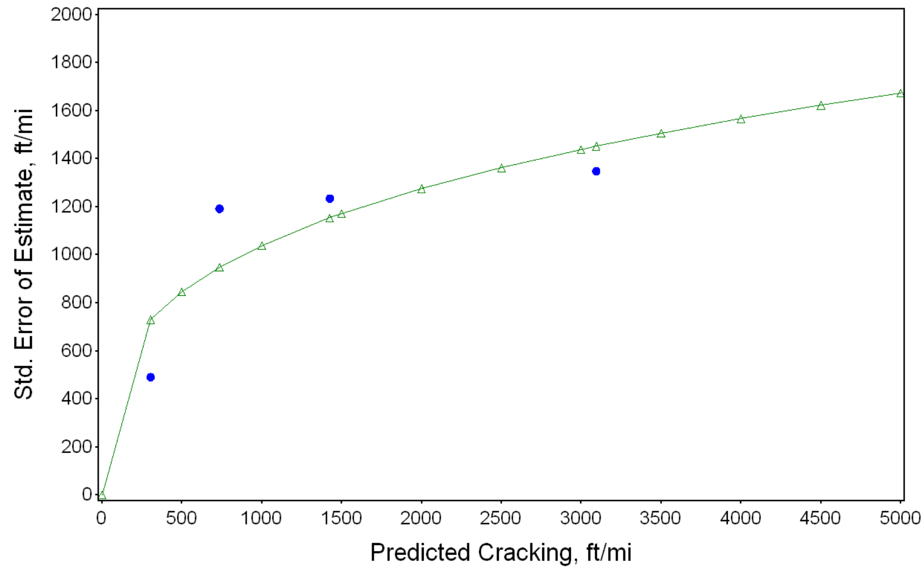

Figure 31. Predicted Reflection Cracking vs. Cracking SEE

Smoothness

Measured smoothness data was available for most of the sections for a wide range of pavement ages. PHT Tool was used to compute parameters that are inputs to the smoothness model such as initial IRI and transverse cracking. The initial IRI is a key smoothness model input and was estimated using historical field measured IRI available in the LTPP database. For AC overlaid existing JPCP, the effect of site factors on future IRI was deemed negligible while future rutting and alligator cracking was also minimal. Thus, they were not included in this model.

For each LTPP section and for the ages for which measured smoothness data was available, the required smoothness inputs were estimated and used along with measured IRI to develop a project database for PHT Tool IRI model evaluation and calibration. Current model evaluation began by reviewing the IRI calibration database for reasonableness and to identify errors and outliers. The outcome of this examination was to correct identified anomalies and errors. The PHT Tool was rerun using the corrected input database to develop a final IRI calibration database.

Next, plots of measured versus predicted smoothness was prepared and evaluated. Evaluation comprised of comparing measured field and PHT Tool predicted smoothness king to assess goodness of fit and bias. The outcome of this evaluation was a determination that current PHT Tool smoothness model produced biased IRI predictions. Thus there was a need for recalibration to improve goodness of fit and minimize bias. Unbiased prediction means that the model does not on average over all of the data over predict or under predict the measured data.

The new PHT Tool smoothness model was thus developed which was essentially recalibration of the existing IRI model to obtain new model coefficients that produce a better fit of measured and predicted IRI. The new composite pavement smoothness model is as presented below.

$$IRI = IRI0 \; + (C0 \times RCRK) \tag{31}$$

WHERE

IRI	=	predicted IRI smoothness, in/mile
IRI0	=	initial IRI smoothness, in/mile
RCRK	=	predicted reflection cracking, feet/mile
C0	=	0.00401

The coefficient listed above was determined to minimize the prediction error of the model and reduce bias. The model was developed with 264 data points and has an R^2 of 32.97 percent and an RMSE of 7.27 in/mi. The new model goodness of fit statistics indicates the level of accuracy typical for pavement management type models. The diagram in Figure 32 presents the plot of predicted versus measured IRI for the entire dataset used for model development.

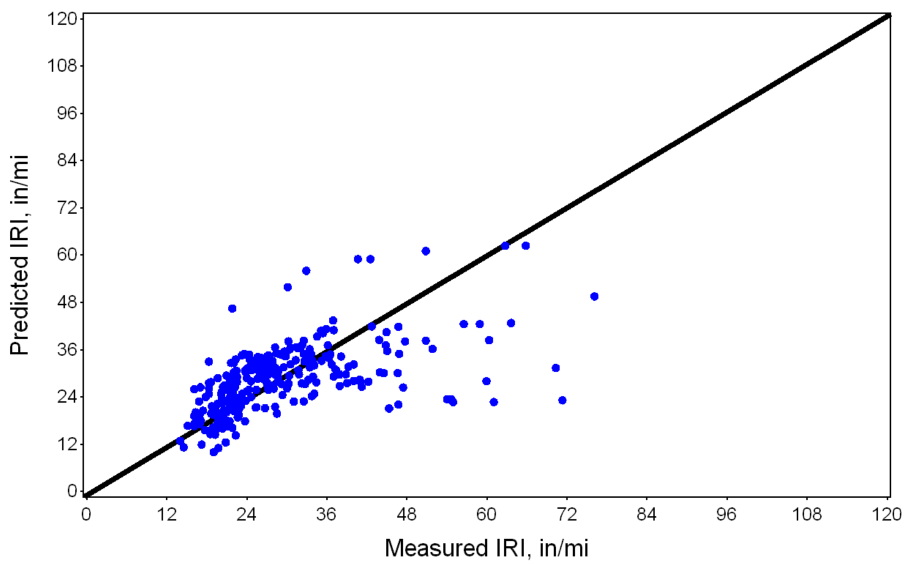

Figure 32. Predicted vs. Measured Smoothness IRI

The new IRI model was further evaluated for bias. Bias was defined as the consistent under or over estimation of IRI. Bias was determined by performing a statistical paired t-test to determine is measured and predicted IRI was similar. The paired t-test was performed as follows:

- Develop null and alternative hypothesis:
  - Null hypothesis H0: PHT Tool IRI = LTPP measured IRI.
  - Alternate hypothesis HA: PHT Tool IRI ≠ LTPP measured IRI.
- Perform statistical analysis to determine and evaluate test p-value.
  - A rejection of the null hypothesis (p-value < 0.05) would imply IRI from the PHT Tool and measured LTPP IRI are from different populations. This indicates bias in PHT Tool IRI estimates for the range of typical inputs used in analysis.

Note that a significance level, α, of 0.05 or 5 percent was assumed for all hypothesis testing. The outcome of the paired t-test was a p-value of 0.2688. The p-value showed that there was not significant bias in predicted IRI.

Reliability Model

Risk associated with IRI prediction or the reliability of the IRI prediction was defined as the one-tail confidence interval at a predefined reliability level around a given IRI prediction. For this study, confidence interval was determined as follows:

- Use new PHT Tool IRI model to estimate the distress over typical range of IRI ranging from 30 to 300 in/mi.
- Divide the typical range of the distress into subsets (e.g., 30 to 60, 60 to 90, etc.).
- For each subset of predicted IRI, estimate the standard error of the mean prediction (i.e., standard deviation of measured – predicted distress (i.e., std. error of the estimate, SEE) for all individual data points that falls within the subset).
- Develop a relationship between the SEE and predicted IRI.

The relationship developed was used in the PHT Analysis Tool to determine SEE for any predicted smoothness IRI. SEE was used to estimate predicted IRI at any desired reliability level as shown in Table 7. The design reliability procedure described above requires the estimation of variability in the form of standard deviation at any given level of predicted IRI. Predicted IRI standard deviation was determined as follows:

- Divide predicted IRI to five or more intervals.
- For each interval, determine mean predicted IRI and standard error (i.e., standard variation of predicted – measured IRI for all the predicted IRI that falls within the given interval).
- Develop a non linear model to fit mean predicted IRI and standard error for each interval.

The resulting standard error prediction model developed for the PHT Tool is presented below:

$$Stderr(IRI) = 6.43 + \left(0.56 \times MPIRI^{0.5}\right) \qquad (32)$$

WHERE

Stderr(IRI)	=	IRI standard error of the estimate, inches/mile
IRI	=	predicted IRI value, inches/mile
MPIRI	=	mean predicted IRI

The diagram in Figure 33 presents a plot of standard deviation versus IRI. The region of predicted smoothness IRI that triggers maintenance and rehabilitation is 150 to 250 in/mi, and reported predicted IRI SEE for this range was found to be reasonable.

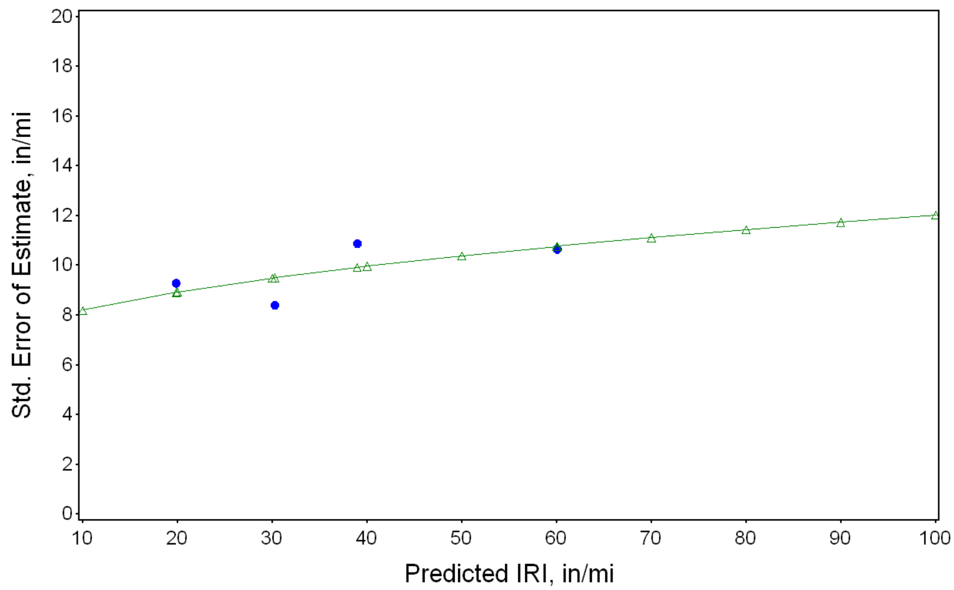

Figure 33. Predicted Smoothness IRI vs. IRI SEE

PHT Version 2.0 Output Validity Test

New HMA Evaluation

The new PHT version 2.0 with calibrated model predicts lower IRI value than that of previous version for all weather and pavement condition. This is an improvement over previous model with accelerated deterioration under same conditions. The IRI results by climate zone and HMA thickness are illustrated in Figure 34 through Figure 36.

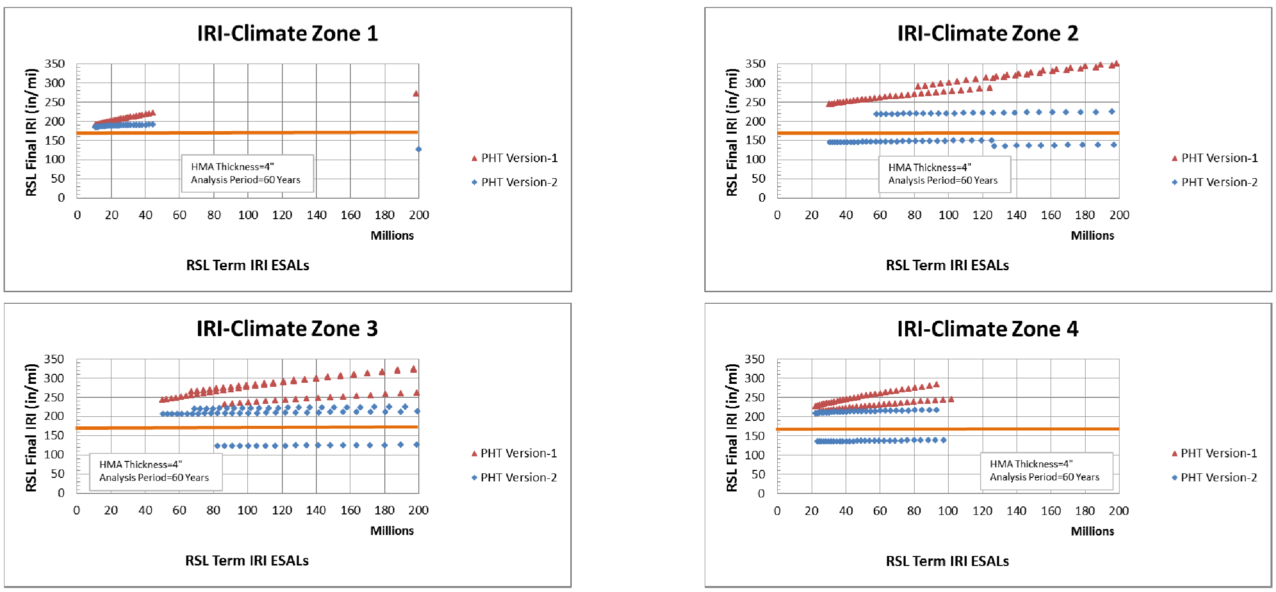

Figure 34. IRI by Climate Zone for HMA Thickness of 4 inches

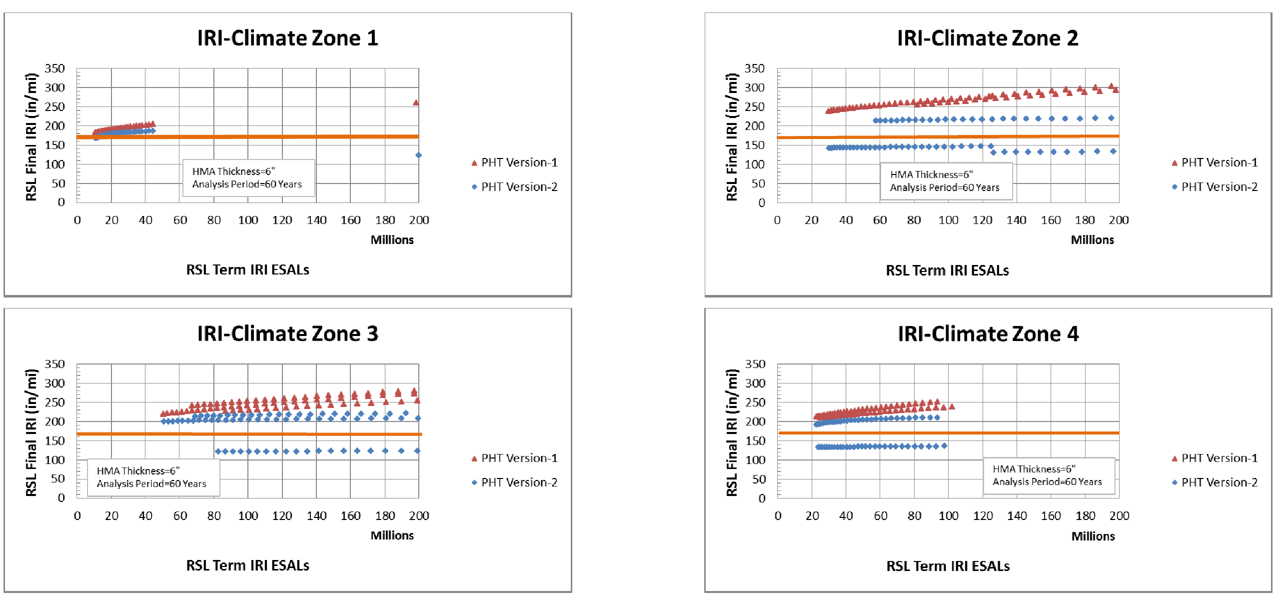

Figure 35. IRI by Climate Zone for HMA Thickness of 6 inches

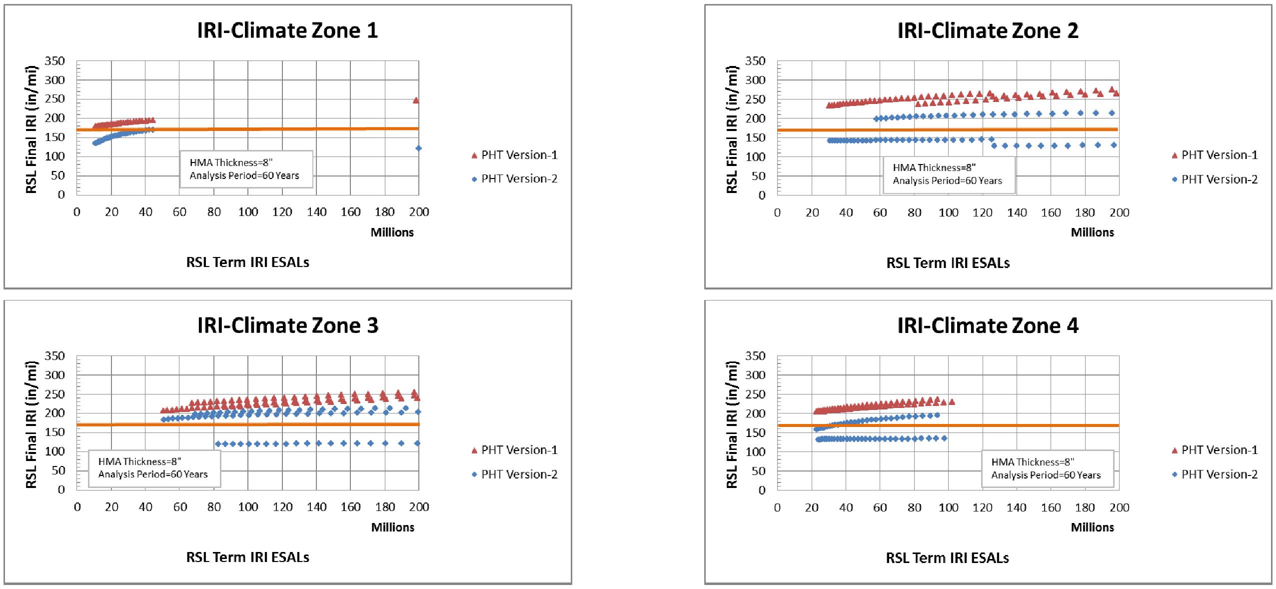

Figure 36. IRI by Climate Zone for HMA Thickness of 8 inches

Regardless of base type and traffic loading or climate zone, each pavement section has experienced lower rutting in the new version of PHT. This is an improvement as the rate of rutting decreased/increases as a function HMA thickness. The Rutting results by climate zone and HMA thickness are illustrated in Figure 37 through Figure 39.

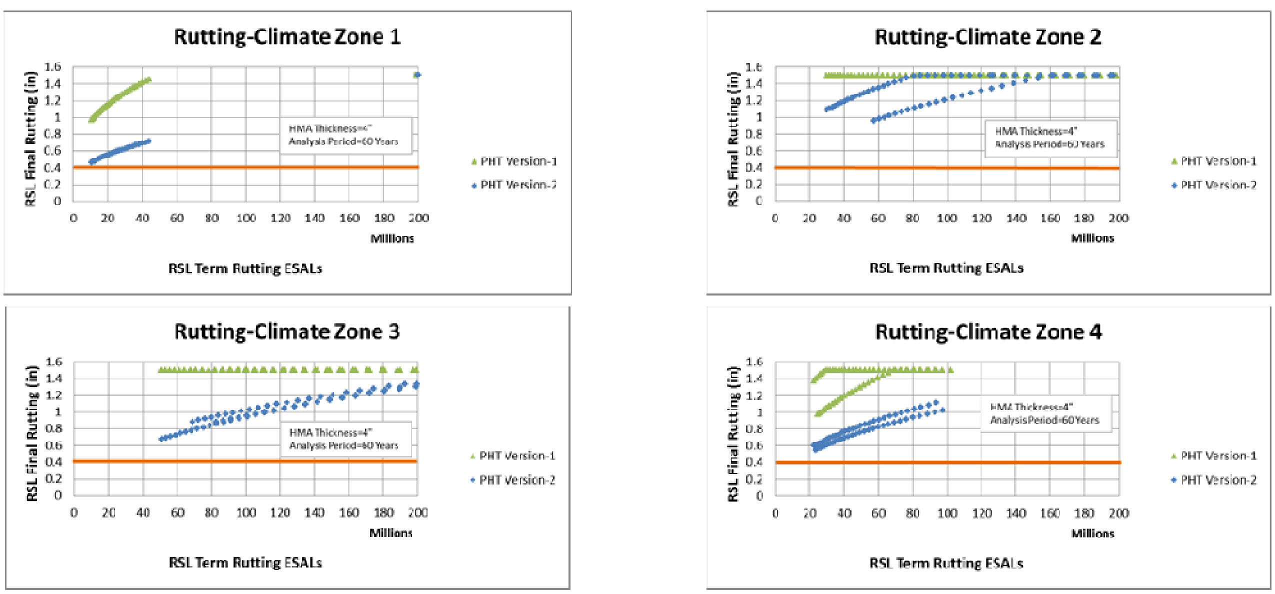

Figure 37. Rutting by Climate Zone for HMA Thickness of 4 inches

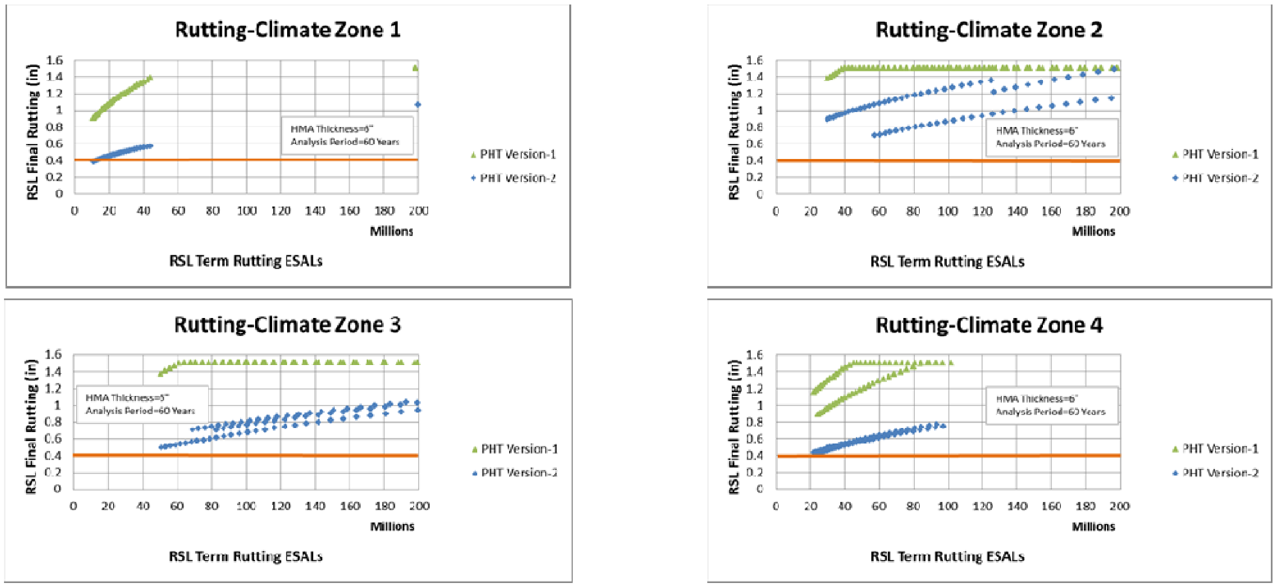

Figure 38. Rutting by Climate Zone for HMA Thickness of 6 inches

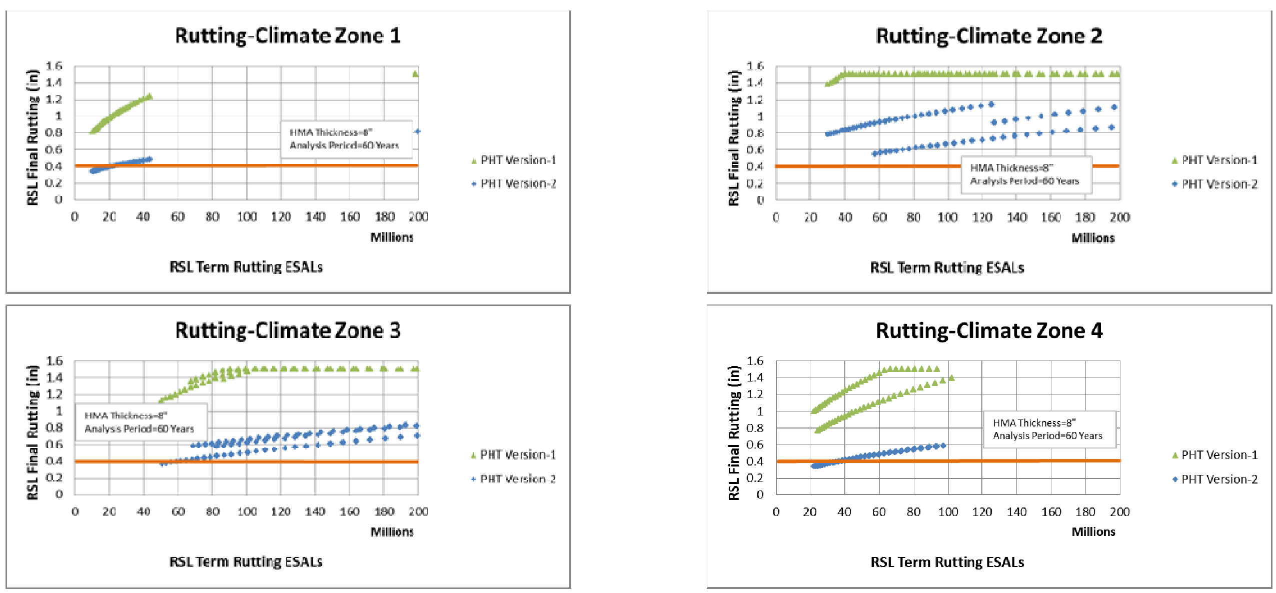

Figure 39. Rutting by Climate Zone for HMA Thickness of 8 inches

The new PHT models are predicting progressive fatigue cracking as a function of loads and are showing improved sensitivity to climate than the previous version except for the pavement with cement treated stabilized base. This is a significant improvement over the previous version of the PHT analysis tool. The Percent Cracking results by climate zone and HMA thickness are illustrated in Figure 40 through Figure 42.

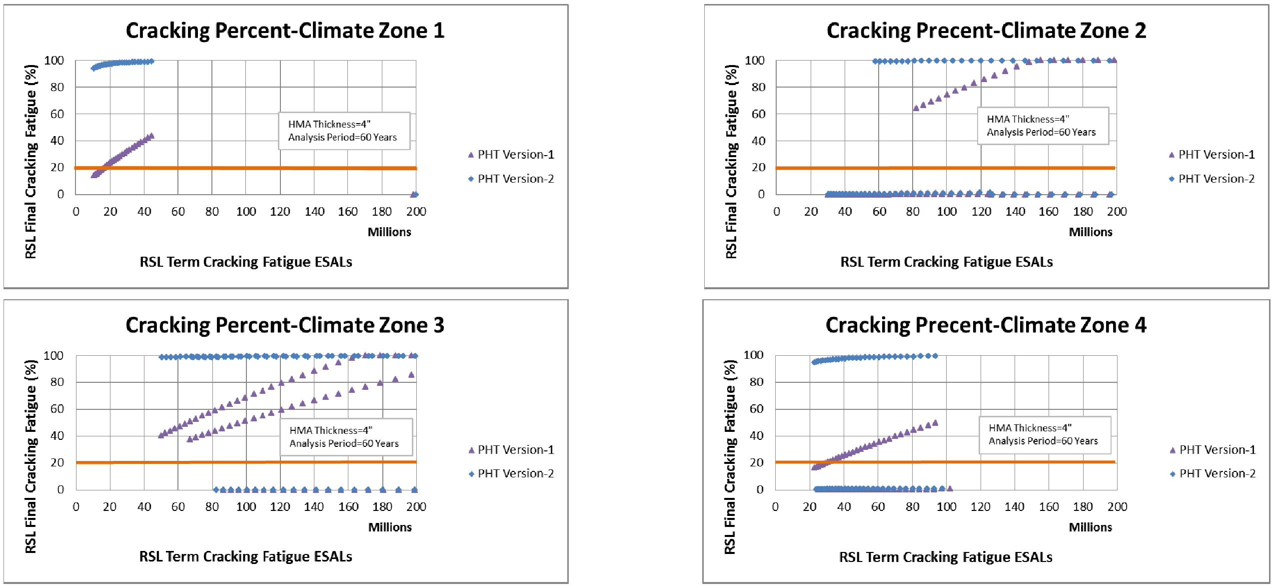

Figure 40. Cracking Percent by Climate Zone for HMA Thickness of 4 inches

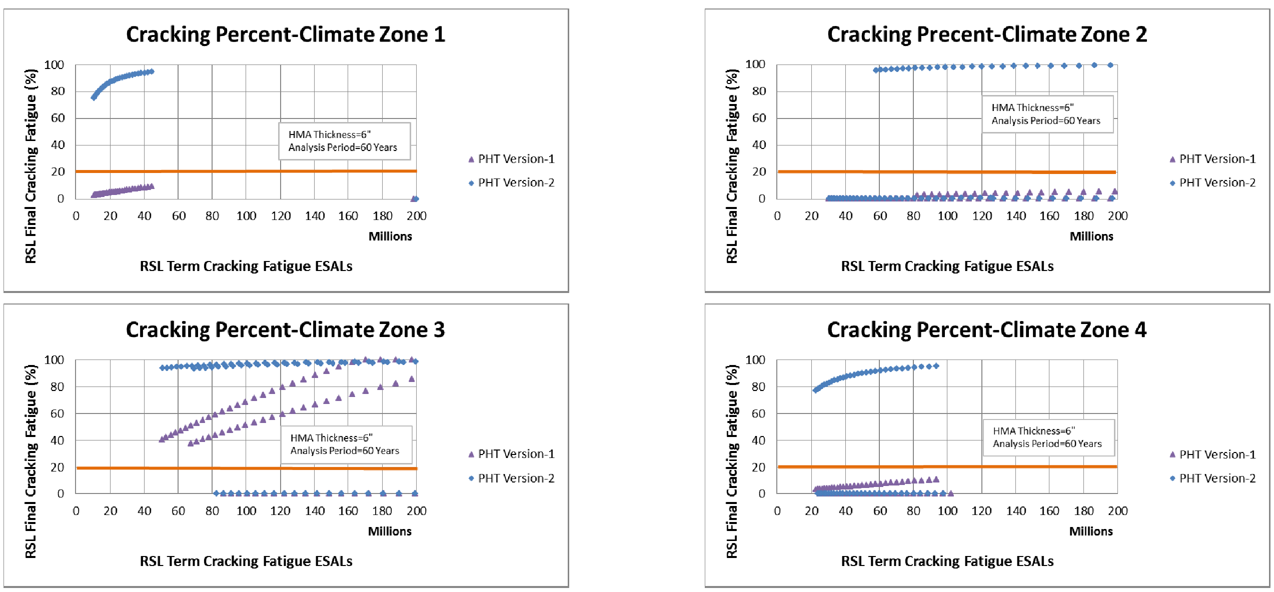

Figure 41. Cracking Percent by Climate Zone for HMA Thickness of 6 inches

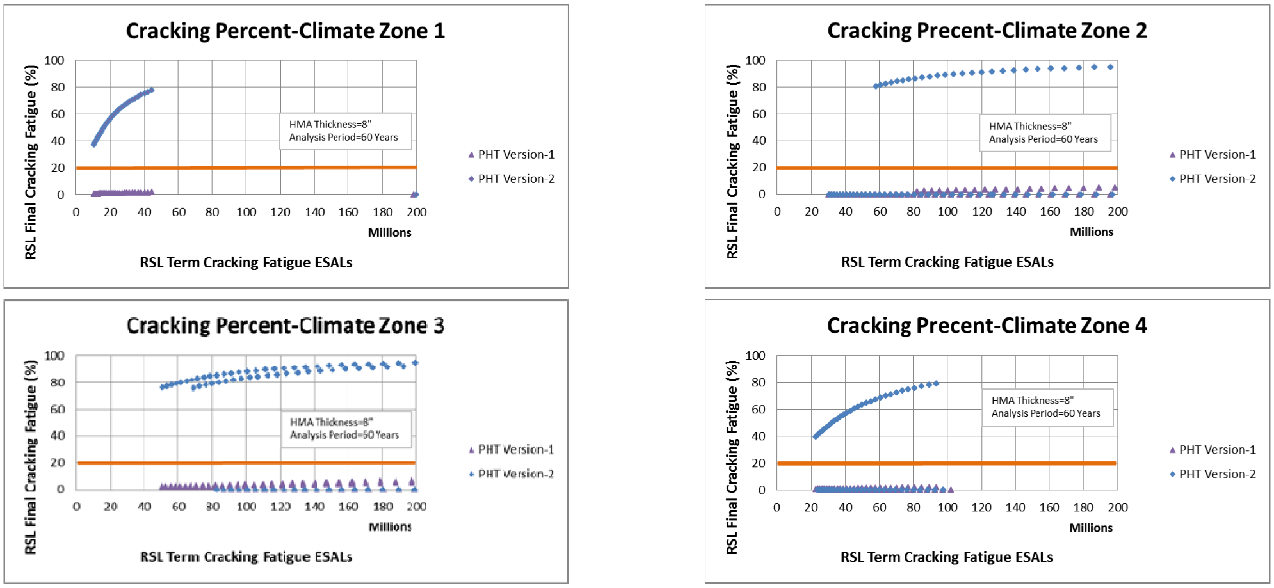

Figure 42. Cracking Percent by Climate Zone for HMA Thickness of 8 inches

Except for pavements under climate zone-1, all the pavements have experienced significantly lower Transverse cracking length than the previous PHT version. As distress propagation of transverse cracking is independent of loading, the models do not show any sensitivity regarding traffic loading. This is a significant improvement on the previous version. The Percent Cracking results by climate zone and HMA thickness are illustrated in Figure 43 through Figure 45.

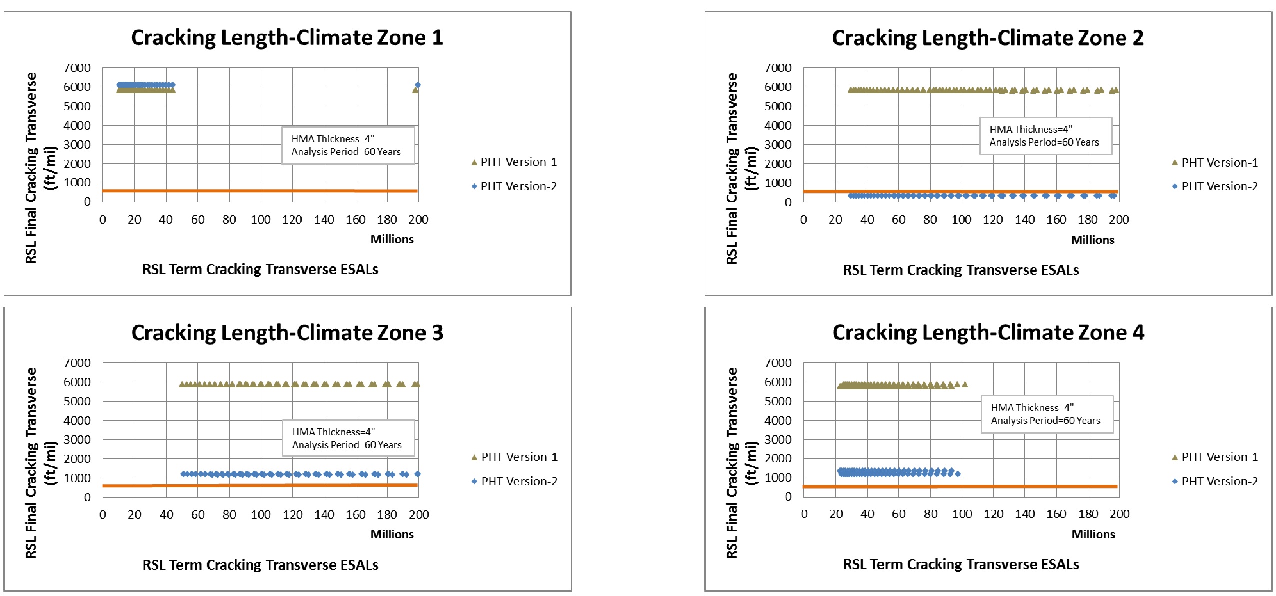

Figure 43. Cracking Length by Climate Zone for HMA Thickness of 4 inches

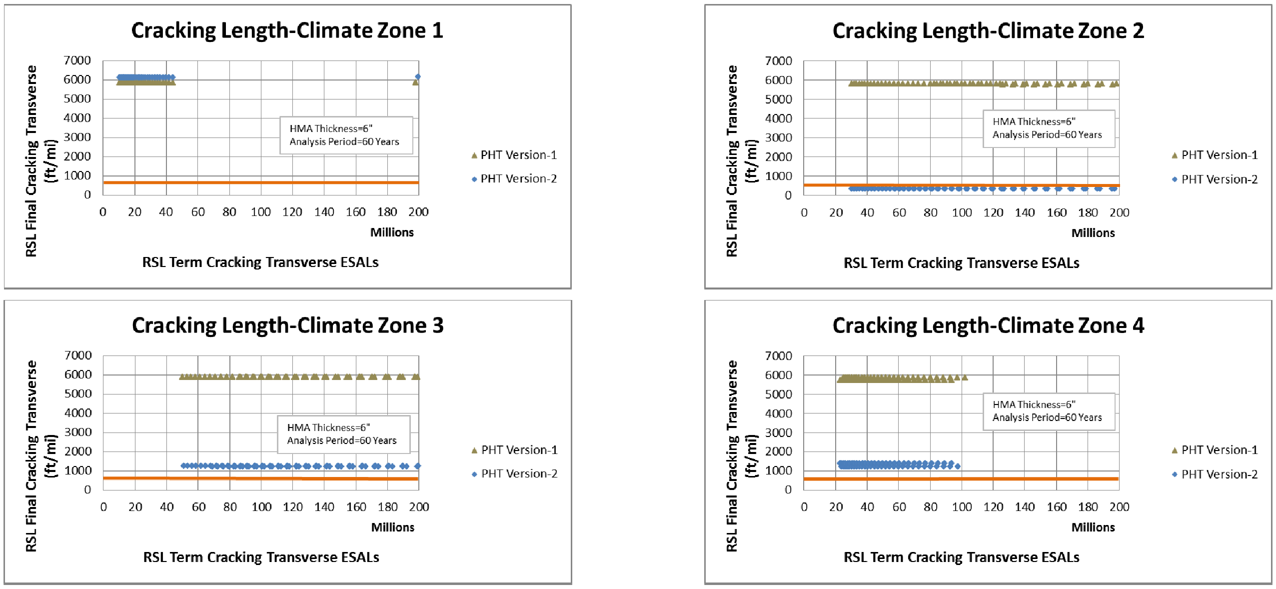

Figure 44. Cracking Length by Climate Zone for HMA Thickness of 6 inches

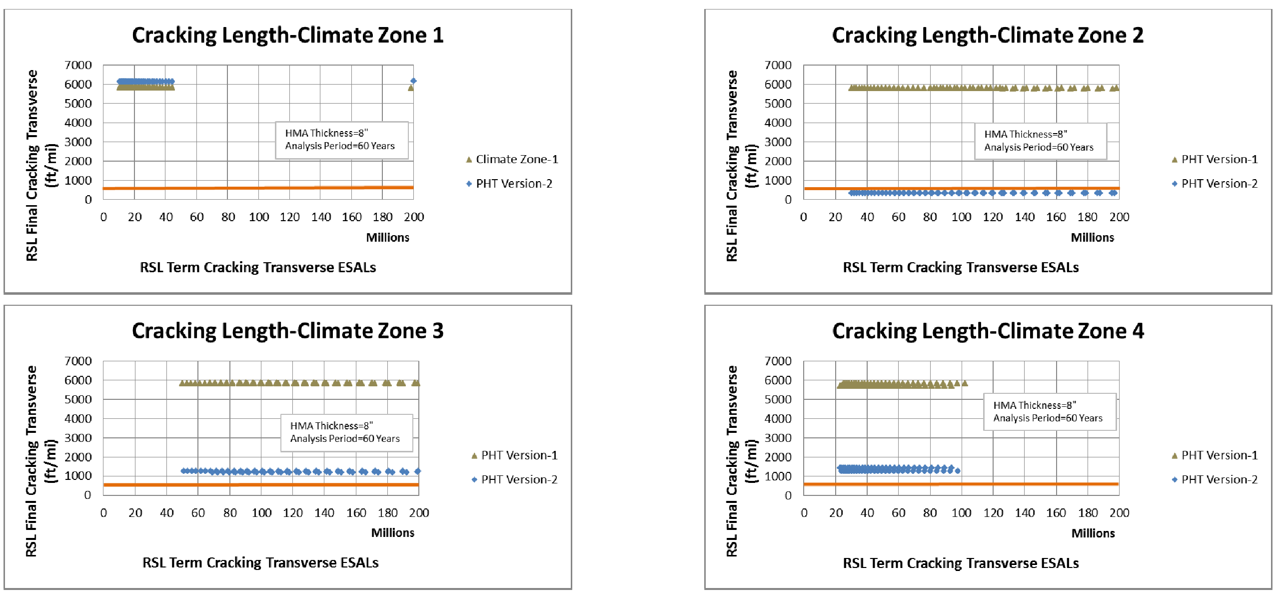

Figure 45. Cracking Length by Climate Zone for HMA Thickness of 8 inches

New JPCP Evaluation

Most of the pavement sections have predicted IRI value higher than the previous version of PHT. This is an improvement over previous version. One pavement in climate zone 3 and with low traffic load has experienced lower predicted IRI value than that of previous version. The IRI results by climate zone and JPCP thickness are illustrated in Figure 46 through Figure 48.

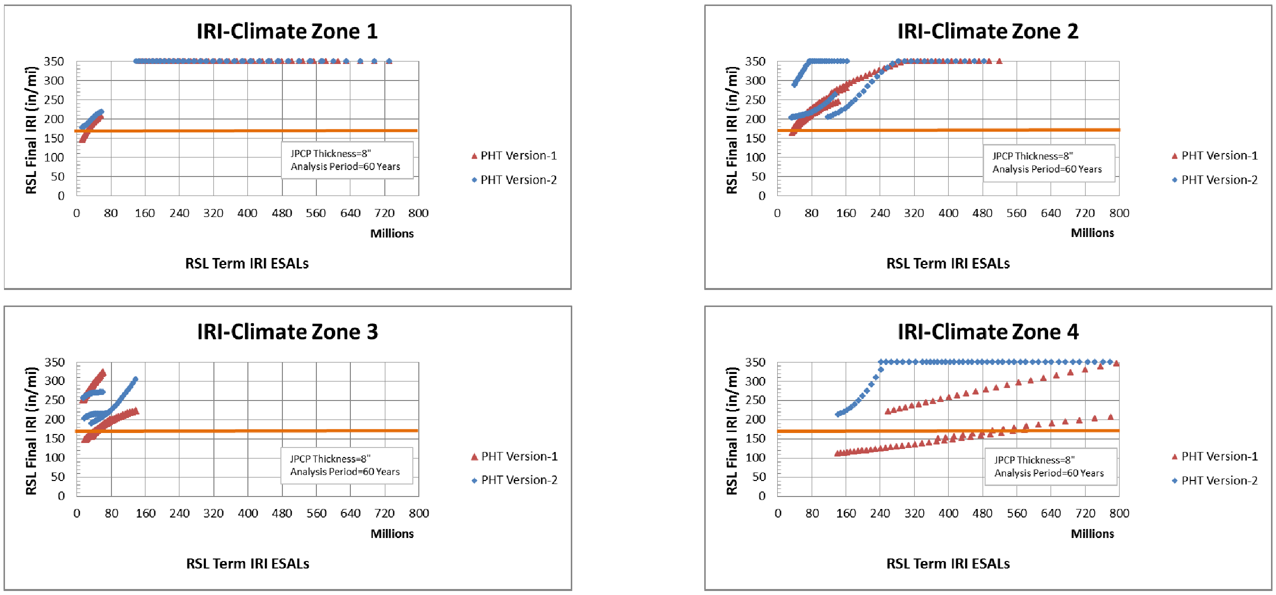

Figure 46. IRI by Climate Zone for JPCP Thickness of 8 inches

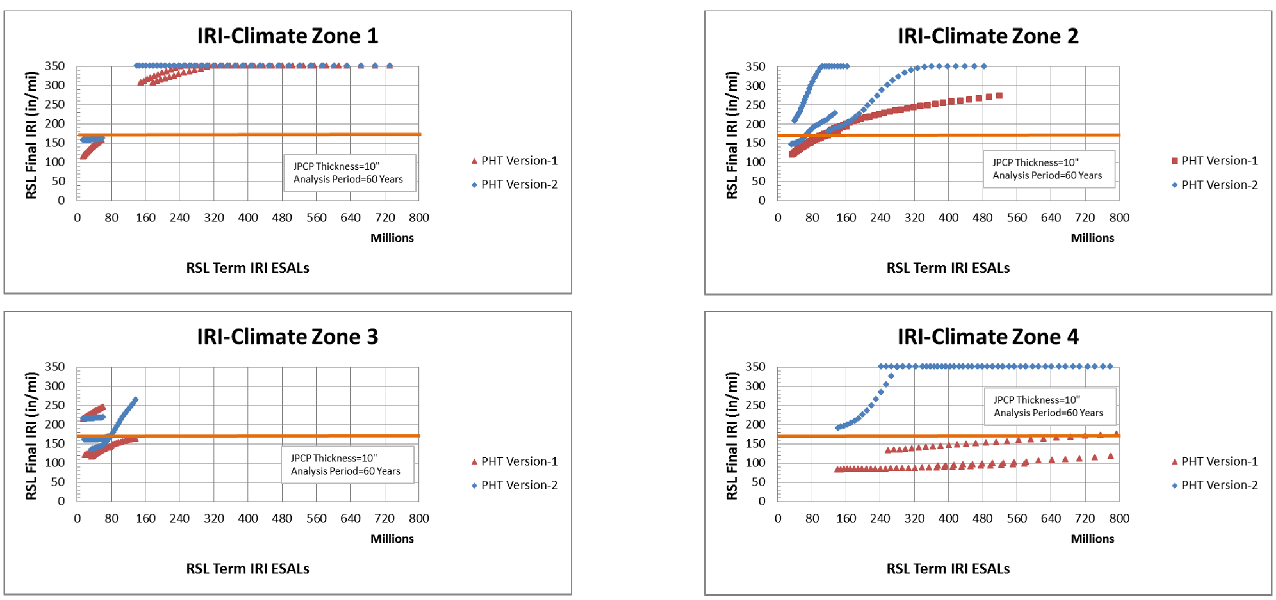

Figure 47. IRI by Climate Zone for JPCP Thickness of 10 inches

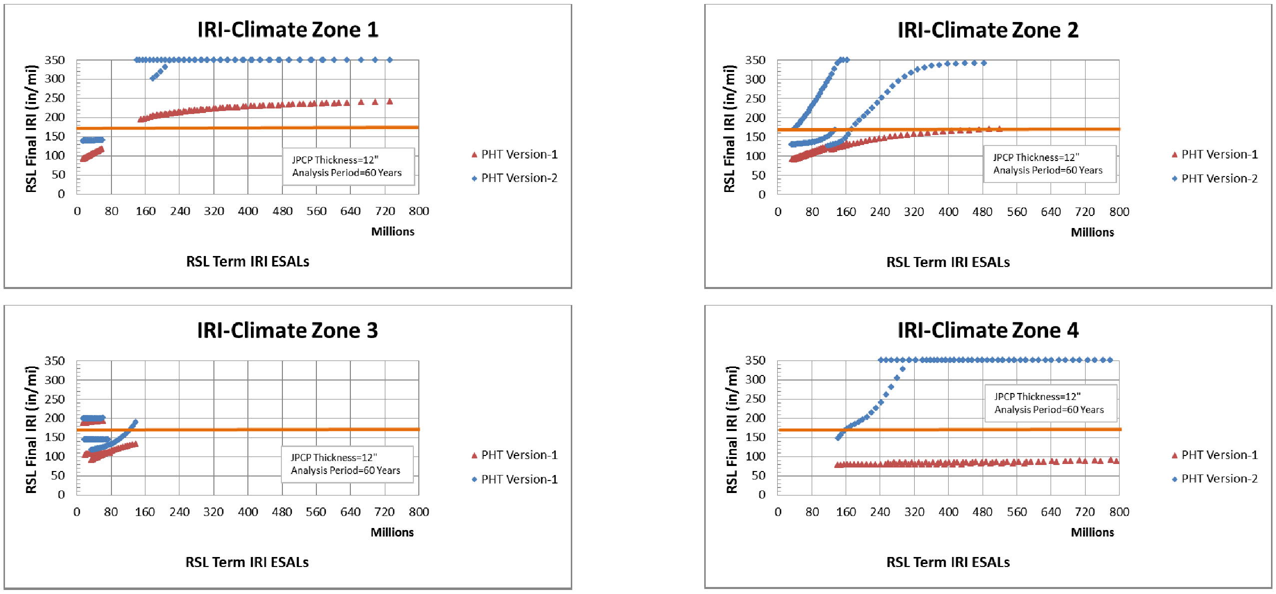

Figure 48. IRI by Climate Zone for JPCP Thickness of 12 inches

Faulting models are less sensitive to pavement thickness than the previous version. Since faulting is caused mainly due to difference in elevation across a joint or crack usually associated with un-doweled joint construction as well as base and sub-base strength, this is an improvement over previous version of PHT. The Faulting results by climate zone and JPCP thickness are illustrated in Figure 49 through Figure 51.

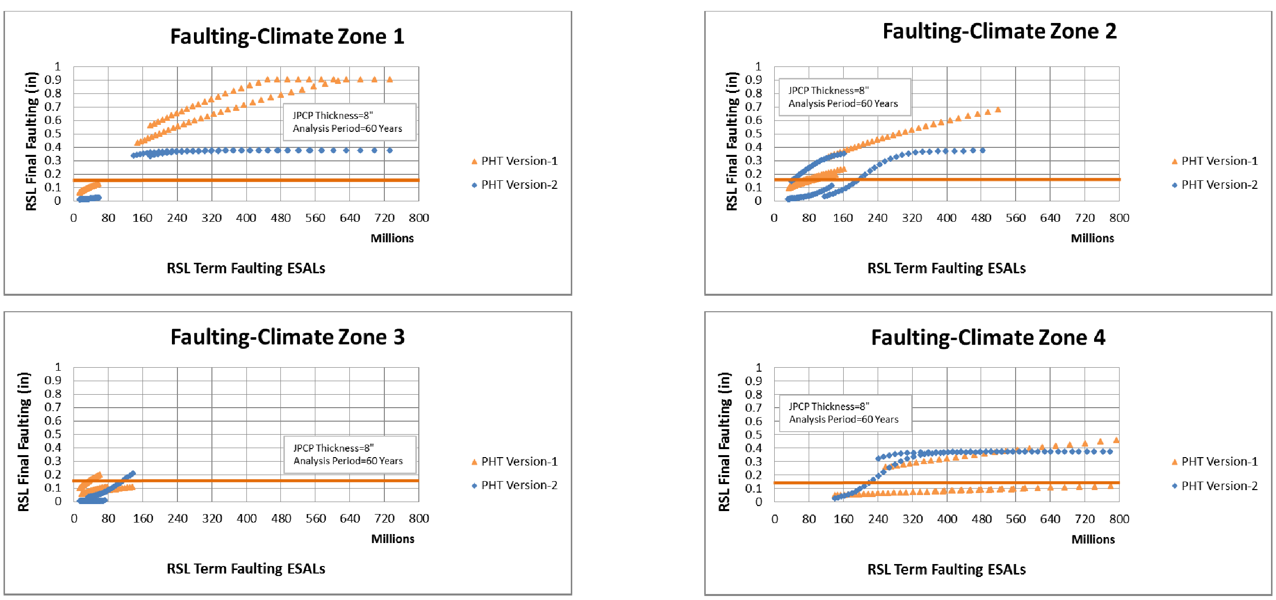

Figure 49. Faulting by Climate Zone for JPCP Thickness of 8 inches

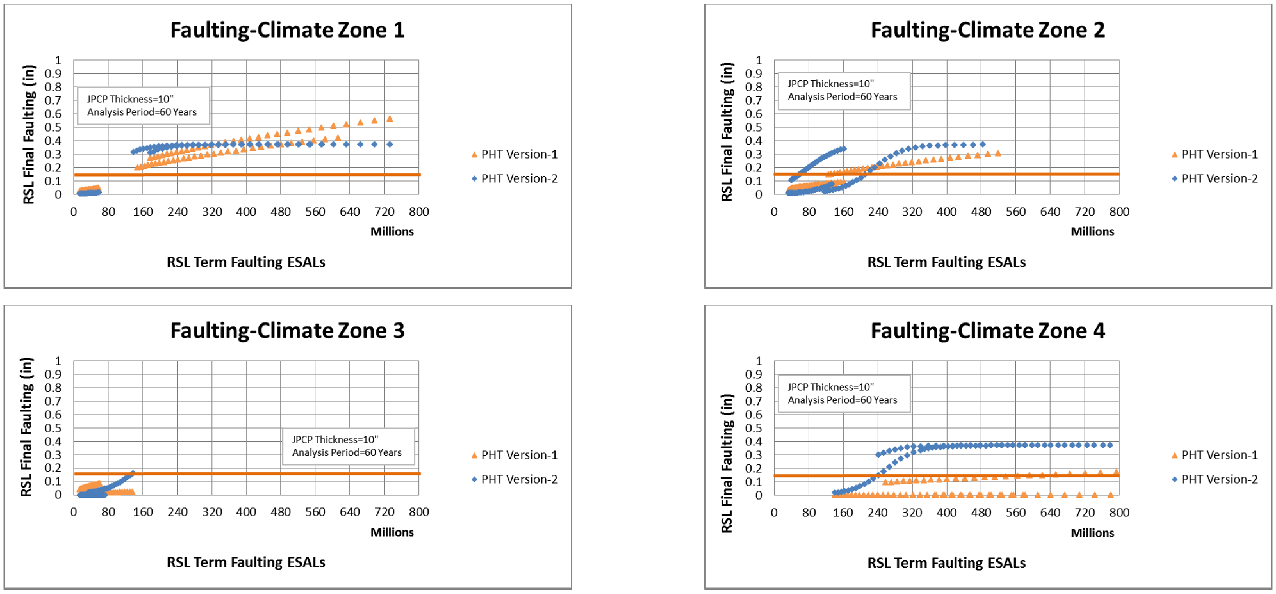

Figure 50. Faulting by Climate Zone for JPCP Thickness of 10 inches

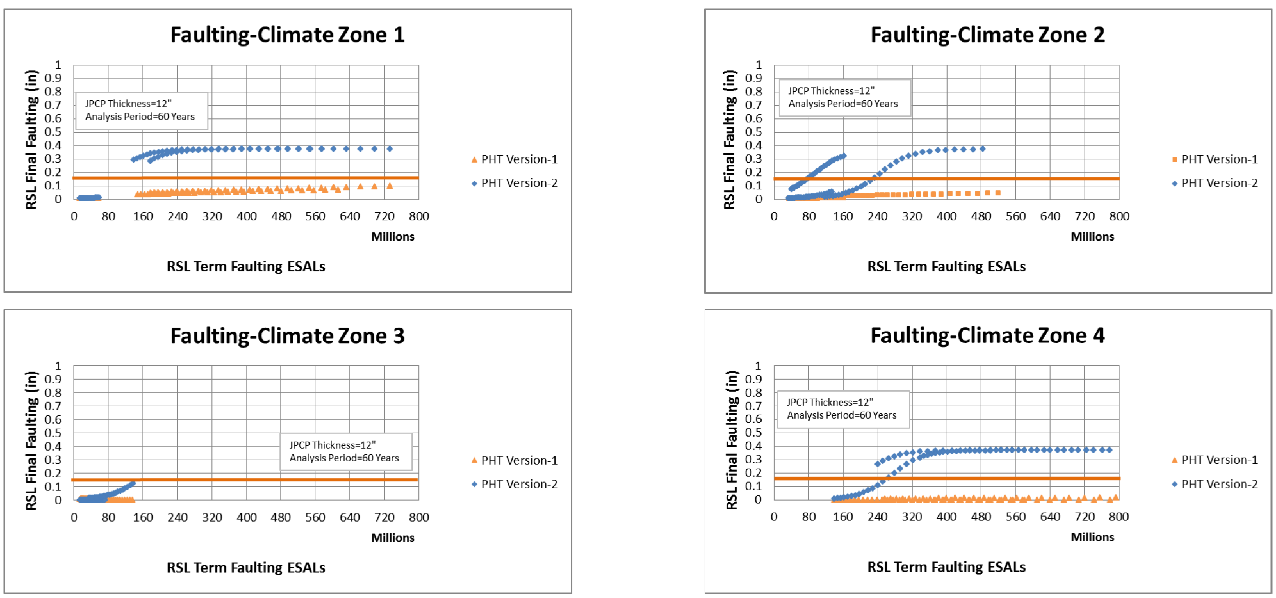

Figure 51. Faulting by Climate Zone for JPCP Thickness of 12 inches

The distress propagation of percent of slab cracking as reported by the new PHT tools shows lower responsive to traffic loading than previous version and reach beyond the critical distress value at the end of the analysis period. Except for pavement sections within climate zone 3, all others are experiencing higher slab cracking percentage. The increase of cracking percentage for climate zone 4 is extremely high. The sensitivity with respect to pavement thickness has also increased. The Cracking Percent results by climate zone and JPCP thickness are illustrated in Figure 52 through Figure 54.

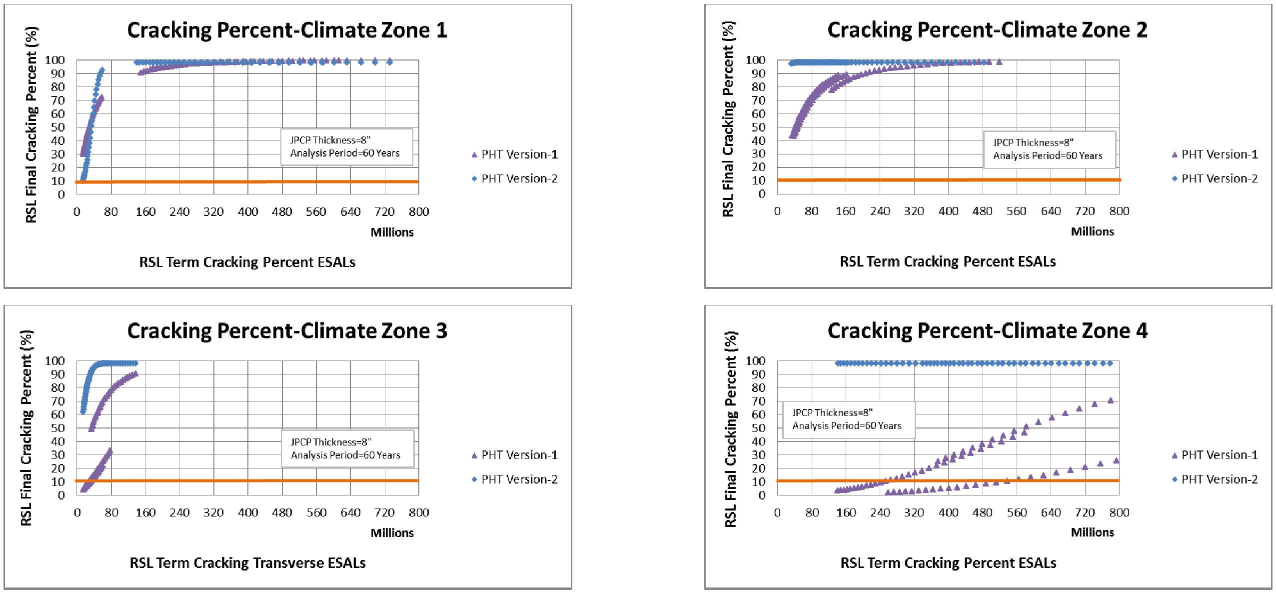

Figure 52. Cracking Percent by Climate Zone for JPCP Thickness of 8 inches

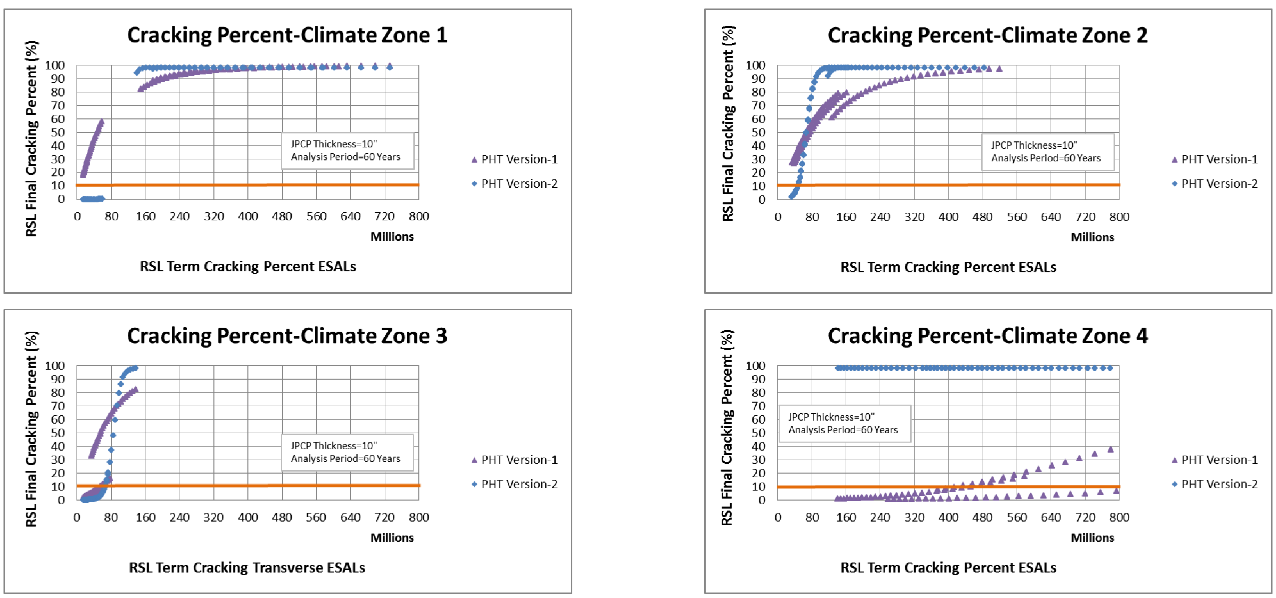

Figure 53. Cracking Percent by Climate Zone for JPCP Thickness of 10 inches

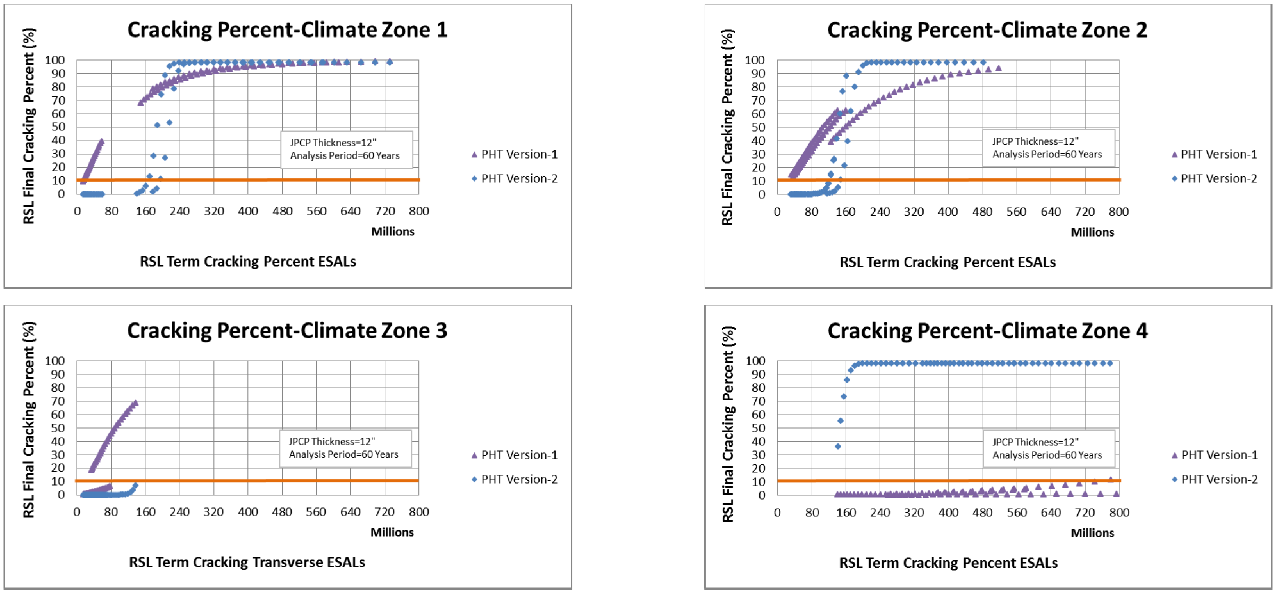

Figure 54. Cracking Percent by Climate Zone for JPCP Thickness of 12 inches

AC/AC Evaluation

The distress propagation as well as improvement reported by PHT 1.1 for A/C shows similar trend that of HMA pavements. The IRI results by climate zone and AC overlay thickness are illustrated in Figure 55 through Figure 57.

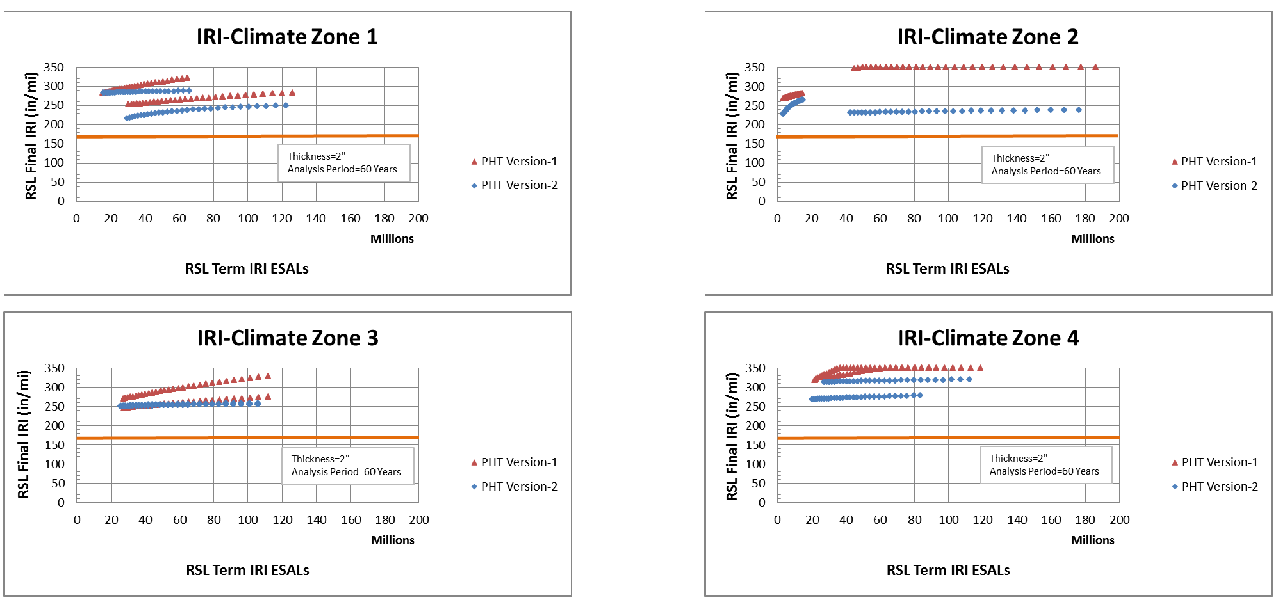

Figure 55. IRI by Climate Zone for AC Overlay Thickness of 2 inches

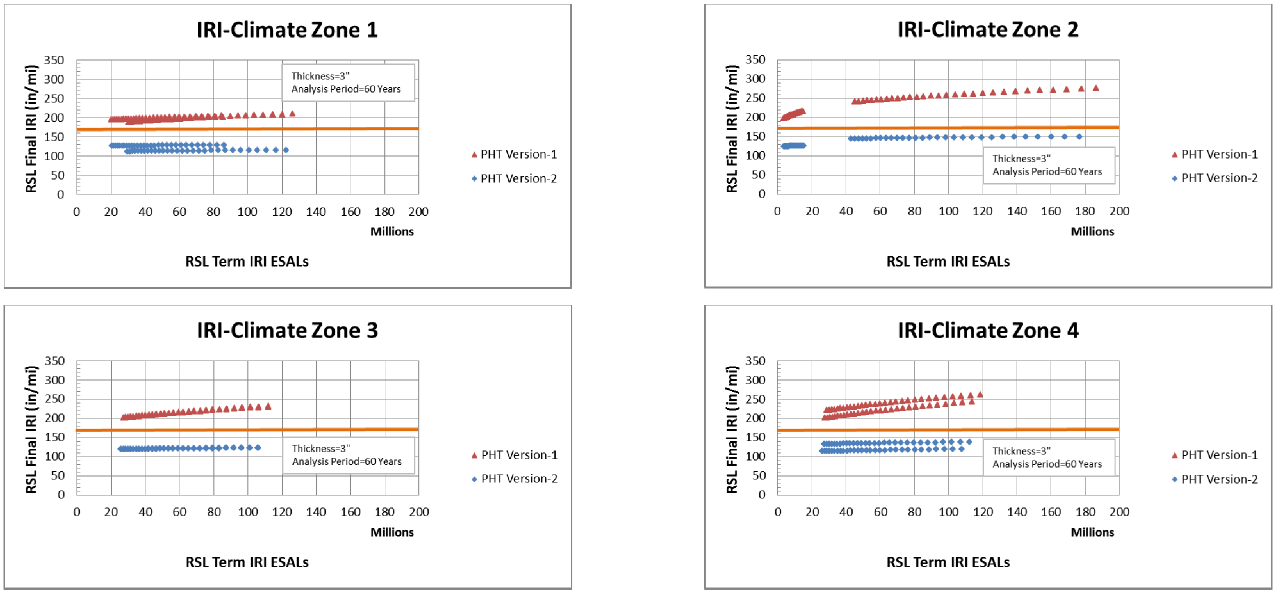

Figure 56. IRI by Climate Zone for AC Overlay Thickness of 3 inches

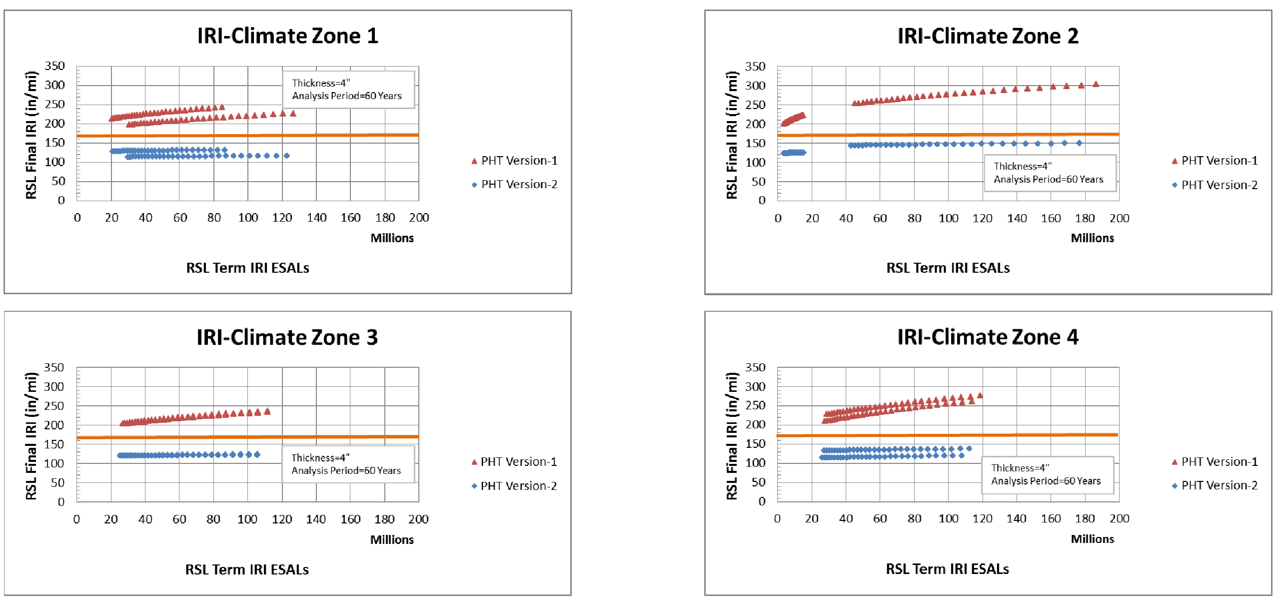

Figure 57. IRI by Climate Zone for AC Overlay Thickness of 4 inches

The Rutting distress estimates from the newer PHT version shows a slower rate of progressive rutting as a function of load and pavement thickness compare to the previous PHT version. This is an improvement over the previous version. The Rutting results by climate zone and AC overlay thickness are illustrated in Figure 58 through Figure 60.

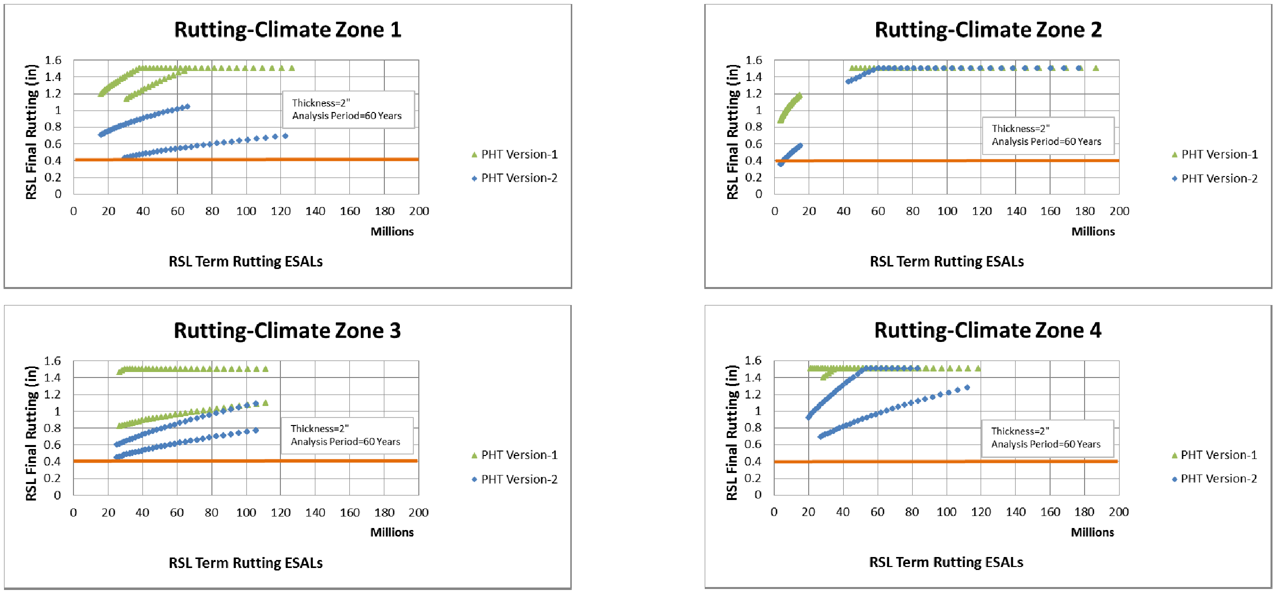

Figure 58. Rutting by Climate Zone for AC Overlay Thickness of 2 inches

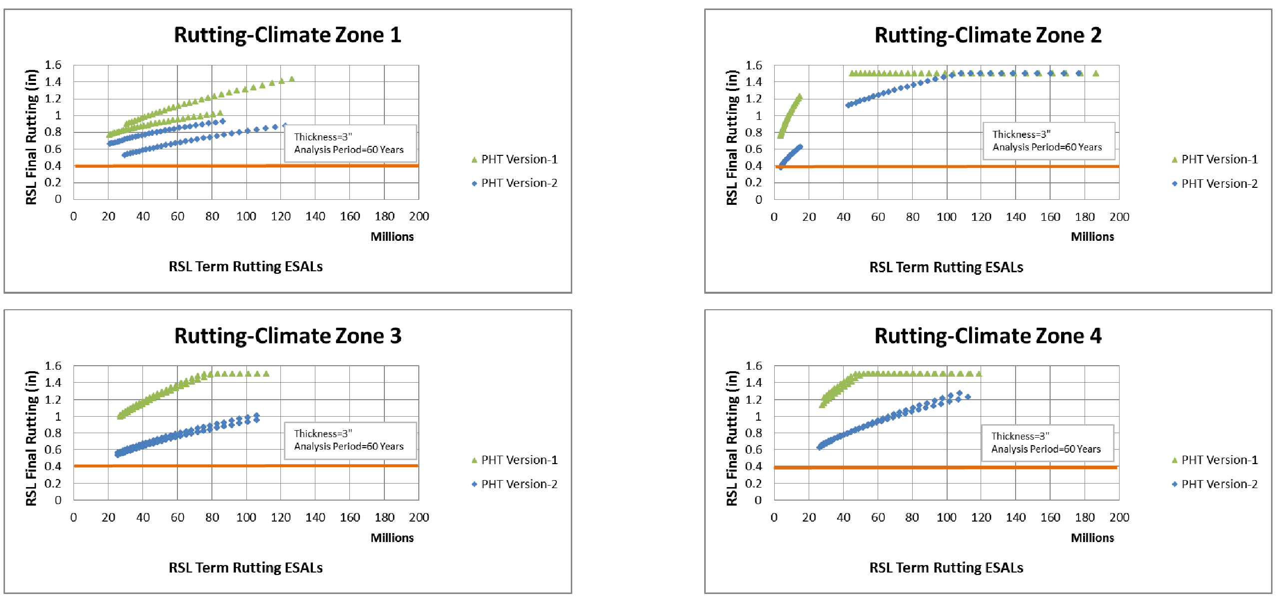

Figure 59. Rutting by Climate Zone for AC Overlay Thickness of 3 inches

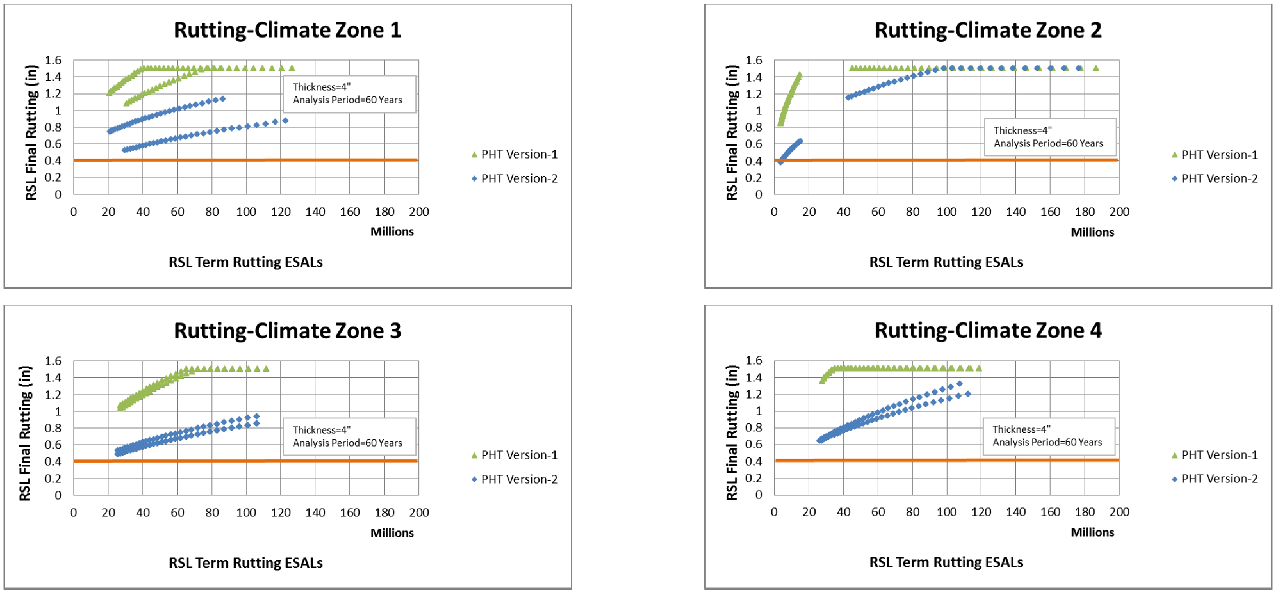

Figure 60. Rutting by Climate Zone for AC Overlay Thickness of 4 inches

The alligator cracking distress estimates from the newer PHT version show a similar trend as the new HMA pavements. The Cracking Percent results by climate zone and AC overlay thickness are illustrated in Figure 61 through Figure 63.

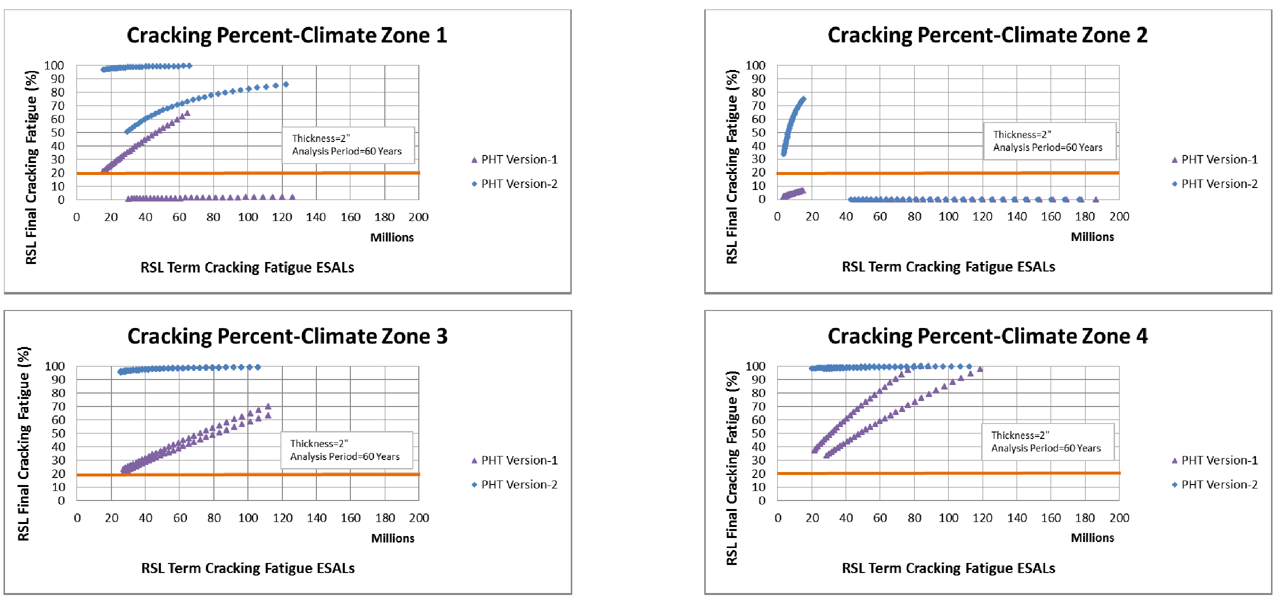

Figure 61. Cracking Percent by Climate Zone for AC Overlay Thickness of 2 inches

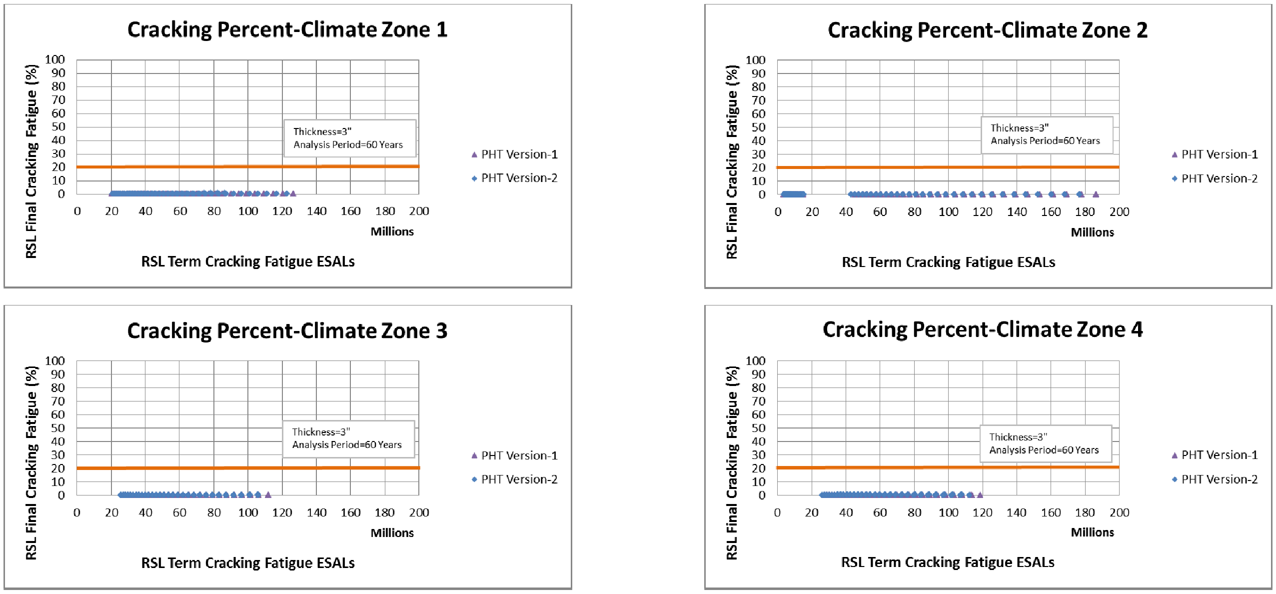

Figure 62. Cracking Percent by Climate Zone for AC Overlay Thickness of 3 inches

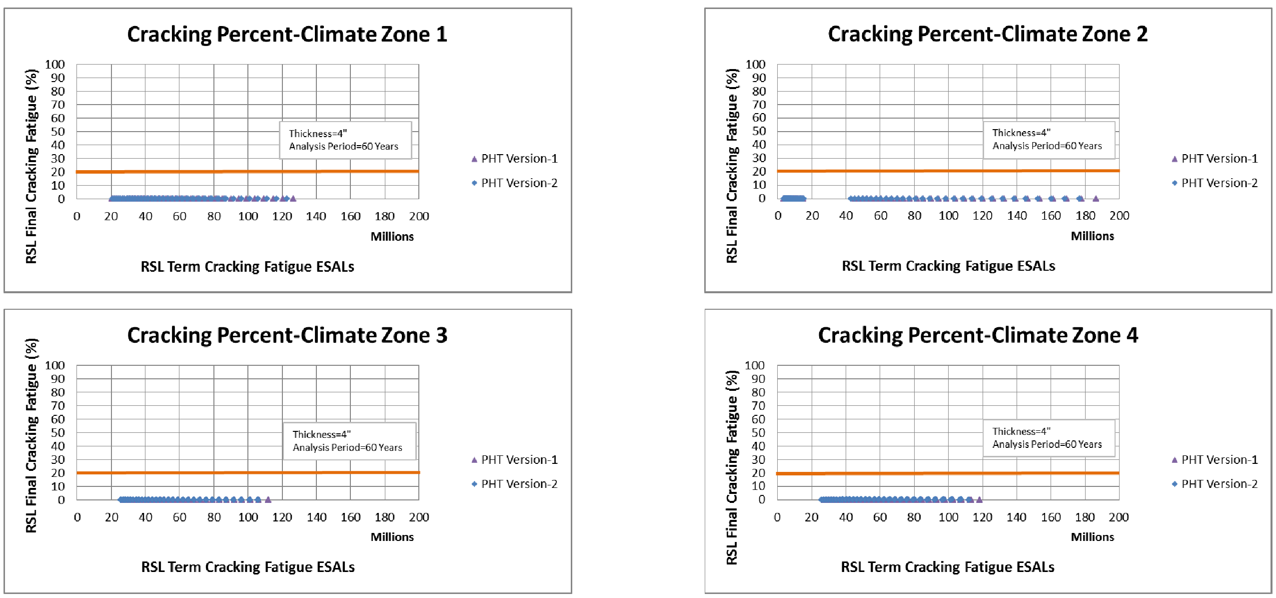

Figure 63. Cracking Percent by Climate Zone for AC Overlay Thickness of 4 inches

The transverse cracking distress estimates from the newer PHT version show a similar trend as the new HMA pavements. The Cracking Length results by climate zone and AC overlay thickness are illustrated in Figure 64 through Figure 66.

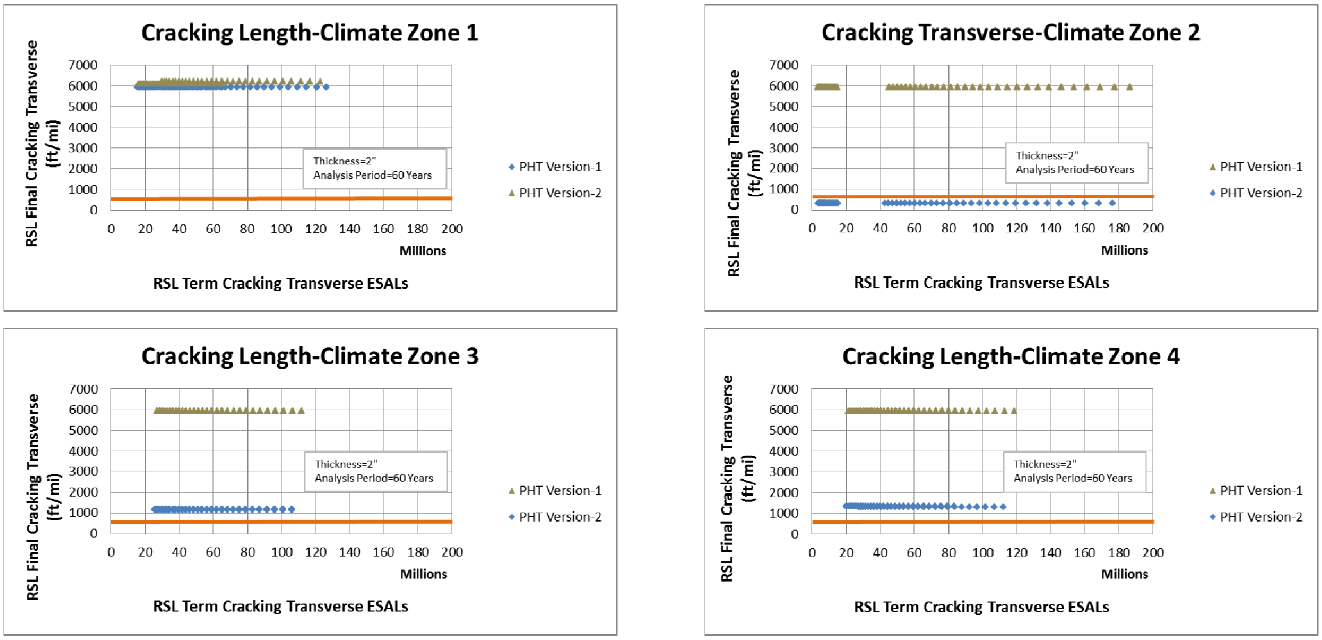

Figure 64. Cracking Length by Climate Zone for AC Overlay Thickness of 2 inches

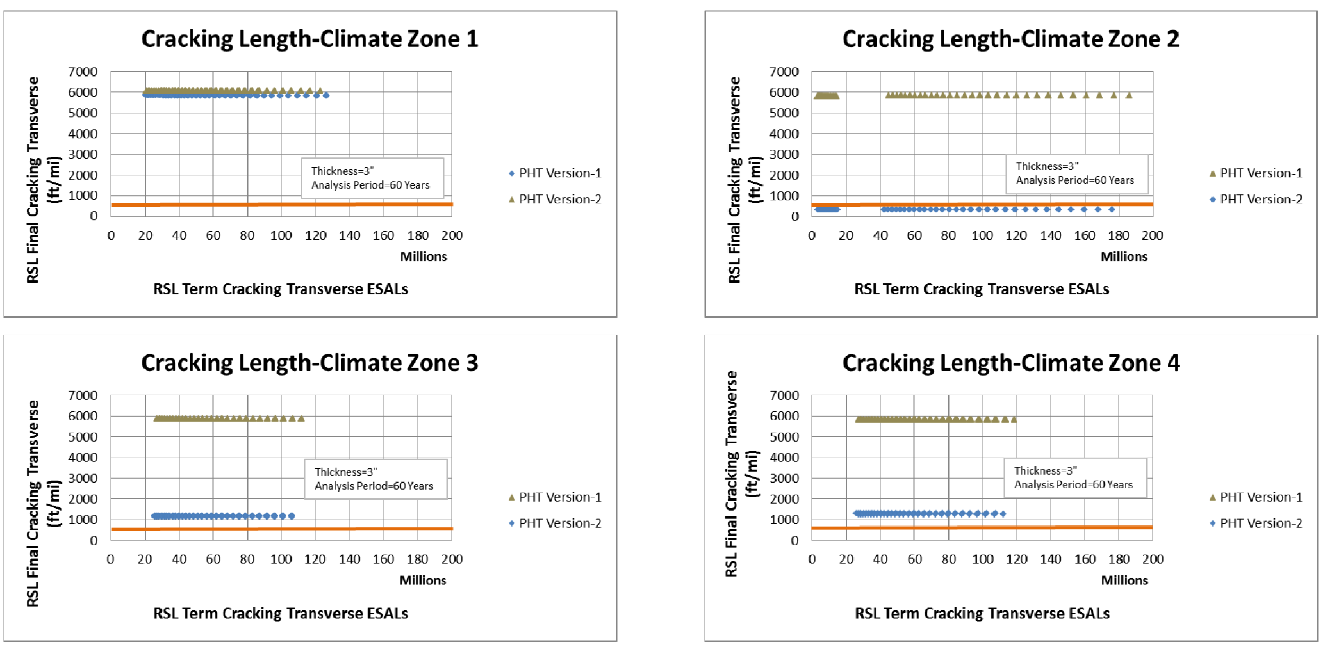

Figure 65. Cracking Length by Climate Zone for AC Overlay Thickness of 3 inches

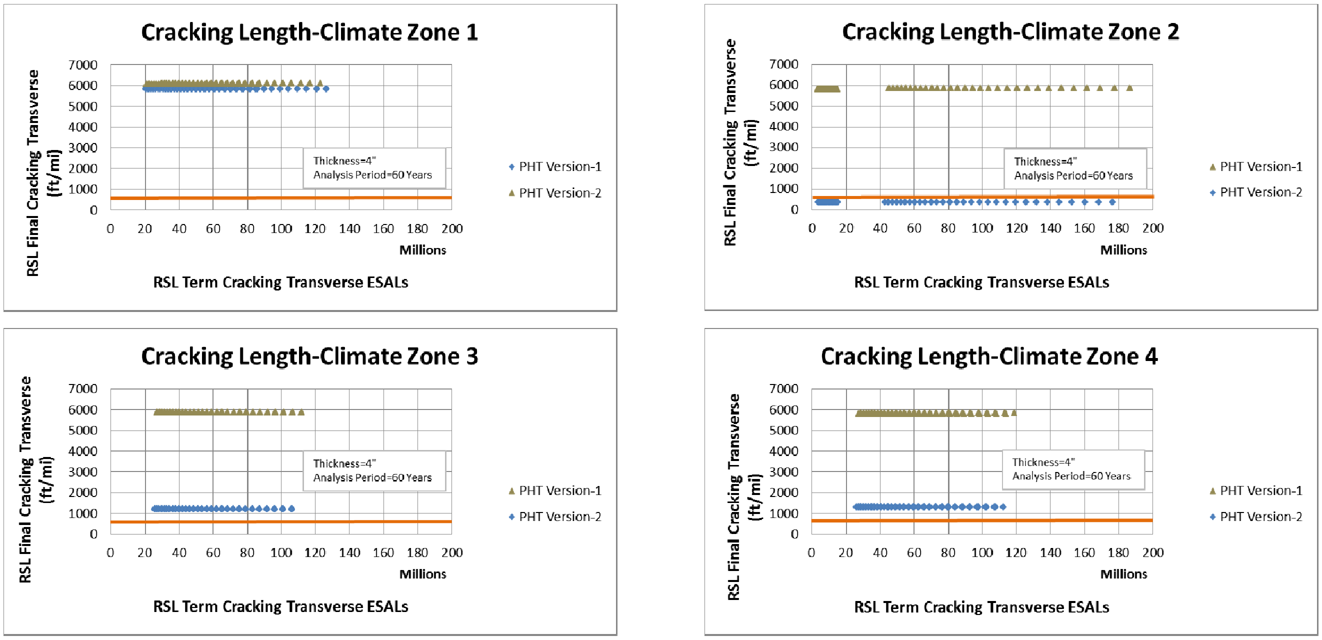

Figure 66. Cracking Length by Climate Zone for AC Overlay Thickness of 4 inches

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PHT Analysis Log System

Introduction

A comprehensive log system is useful to explain and document the analysis process to aid in understanding of the results and the inputs and conditions that affected it. The objective of this task was to develop a log system for the PHT Analysis Tool to create a process history log that records errors, warnings, and key actions that occur during the analysis.

The log system for PHT analysis engine collects and records key information for each PHT step during the run-time analysis, and provides a sequential log file for the whole analysis procedure. The information in the log file contains

- Information Messages about input data, process steps, and key processing results
- Warning messages about unusual input data and processed results
- Error Messages about invalid input data, recoverable and critical analysis errors

The log information provided by the log system is beneficial to both PHT users and developers. As a PHT user, the information can be used to trace each key analysis step, understand the engineering process, verify analysis result during each step, and identify potential issues caused by input data. To PHT developers, the information can be used to assist the program debug, identify programs bugs, and improve the code maintenance efficiency.

Implementation

Data communication between PHT user interface and PHT analysis engine is through an in-memory dataset. However, the log information size can be very big and it is not efficient to pass the log information by dataset or through computer memory. Rather, the log system generates a log file and PHT user interface reads and interprets the log file for log information. There are three types of log message:

- Info: Information, function start/end, input data, output result
- Warning: Warning information, uncommon input data or analysis result
- Error: Error information, invalid data range/format, invalid analysis result

The PHT log system records the following information.

- PHT analysis start
- Total projects number
- Current project Analysis start
- Input data verification for current project (data range, and data format)
- Default data selection for current project
- EASLs and distress calculation for each year
- Distress correction with historical data
- Terminal value, age, and ESALs for each distress
- Overall RSL, distress, and ESALs
- Current project analysis end
- PHT analysis end

The log files generated by the PHT analysis are stored on the systems hard drive and are referenced by the PHT analysis results stored in the PHT database. By default, all the analysis log files are stored in the following directory:

```
C:\Users\Public\Documents\Battelle\BMFATv4\Plugins\PHTv2
```

The following excerpt of the PHT log for the analysis of a highway section illustrates some of the types of messages that may appear in the log system.

```
<info>  Record Index: 1
<Info>  ID = 1
<Info>  YearRecod = 2011
<Info>  StateCode = 4
<Info>  data check passed
<Info>  The maximum service life=15
<Info>  ACType = 4
<Info>  Precipitation = 11.3
<Info>  FI = 53.9
<Info>  FTCYC = 51.7
<Info>  GMT = 40
<Info>  AverageTemperature = 65.24166
<Info>  AirVoid = 5.14
<Info>  EffectBinder = 9.86
<Info>  base modulus = 1500000
<Info>  Clay_Percents = 6.1
<Info>  Sand_Percent = 42.4
<Info>  Silt_Percent = 14.2
<Info>  Overall RSL Age =5, Accumulated ESALs=1.062762E+07
<Info>  DistressType=2, Terminal Value=20, MaxServiceLife=46
<Info>  DistressType=2, Terminal Age=46, TotalESALs=97774080
<Info>  DistressType=0, Terminal Value=170, MaxServiceLife=46
<Info>  DistressType=0, Terminal Age=46, TotalESALs=97774080
<Info>  anaylsis succeeded for this project
```

The use of the log system has a negative impact on the overall runtime of the PHT analysis and is therefore disabled by default. When fully enabled for all logging, the overall analysis runtime increases on average of about two fold as shown in Figure 67.

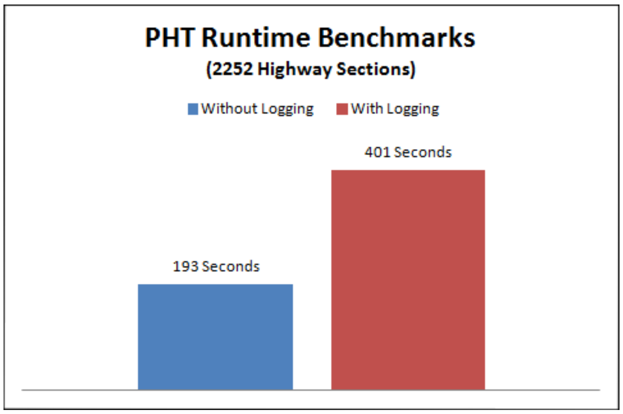

Figure 67. PHT Runtime Benchmarks with/without Logging

Graphical User Interface

The PHT log system is controlled from Logging tab of the PHT Properties dialog window as shown in Figure 68. This window is used to enable the PHT analysis logging capability and to specify the level of logging to be captured. When logging is enabled, the level of logging indicated will be captured; however, logging can significantly increase the analysis runtime and should be disabled when the log is not of interest.

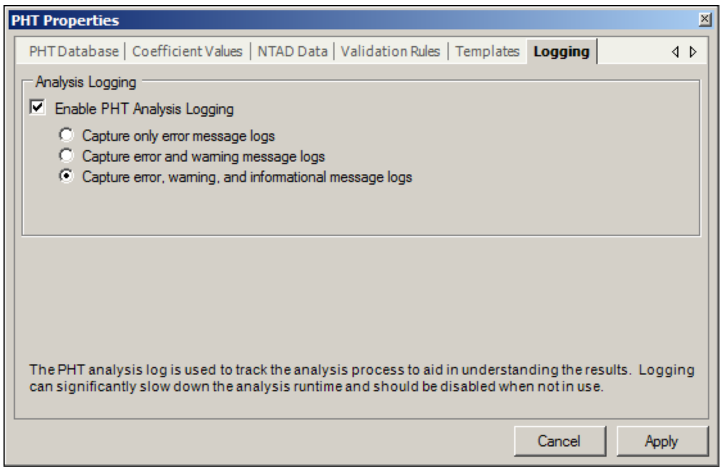

Figure 68. PHT Properties - Logging

When an analysis log has been captured, the logging for the analysis for each individual highway section is available on the Log tab of the PHT results window. The **Log** tab in the vertical panel of the Result Viewer is only available if a log file has been captured during the analysis and is available for display as shown in Figure 69.

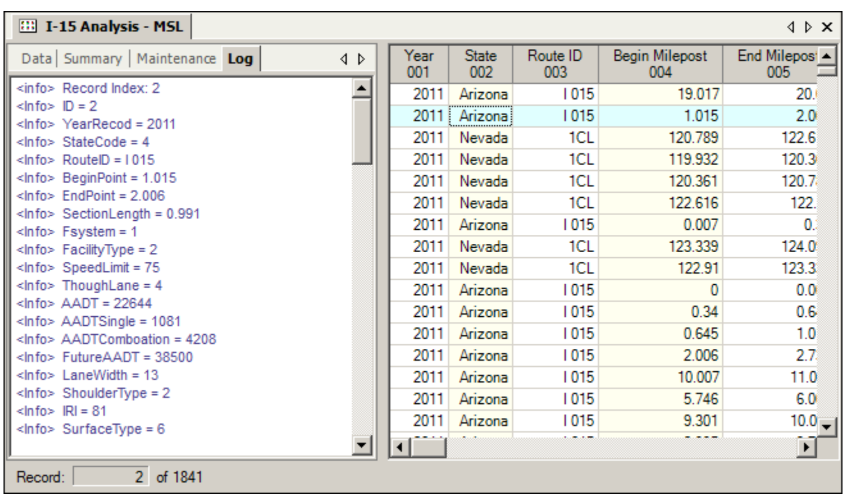

Figure 69. PHT Logging User Interface

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HPMS2010 Validation Rules

Introduction

The results of the PHT analysis are only as reliable and accurate as the source data on which the analysis is being performed. The objective of this task was to implement a set of validation rules for the HPMS2010 source data to help ensure that the data being analyzed by the tool are valid, thus improving the quality of the analysis results.

The HPMS2010 data format is still relatively new and the data validation rules are being defined by the FHWA. Assembling a working set of validation rules for the HPMS2010 data fields used by PHT analysis tool was done using the following sources:

- HPMS2010 Field Manual
- HPMS2010 Validation rules provided by the FHWA
- Existing HPMS2000 validation rules that are still applicable to the HPMS2010 data
- Engineering analysis by the Battelle team members

A detailed listing of the HPMS validation rules that were implemented into the PHT analysis tool is provided in Appendix B of this document.

Graphical User Interface

The HPMS2010 validation rules are implemented into the PHT graphical user interface in a way that allows the user to selectively enable individual highway data validation rules that are applied to the input PHT database. The list of validation rules is available in **Validation Rules** tab of the **PHT Properties** window as shown in Figure 70. Each validation rule is displayed along with a checkbox to enable or disable it. If a rule is checked, it is enabled and will be enforced.

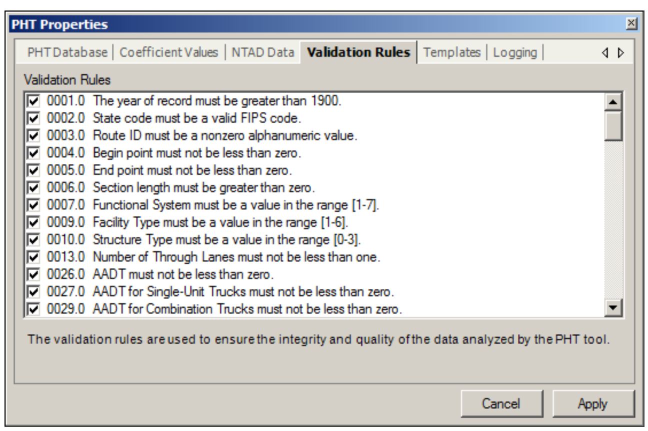

Figure 70. HPMS2010 Validation Rules User Interface

In all cases, the validation rules implemented in the graphical user interface are informational in nature and do not preclude the use of any individual record in the PHT analysis. If a highway section record fails one or more validation rules, it is flag in the Highway Data Viewer user interface for review by the user. The user may choose to correct the violation, ignore it and proceed with the analysis or skip the record entirely.

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State PMS Data Reader and Converter

Introduction

Many states maintain their own pavement condition data in local pavement management systems (PMS) that are customized to each state's needs and priorities. The objective of this task was to provide an enhanced mechanism to read pavement condition information required for the PHT analysis directly from existing State pavement management systems when the data is not available in the standard HPMS2010 format.

Graphical User Interface

The State PMS Data Reader and Converter is implemented into the PHT graphical user interface in the form of an import wizard dialog window. The wizard proceeds through three logical steps in select and external data source, map and convert existing State PMS data to the PHT database fields, and optionally filter the source data to select a subset of records for analysis.

This first tab allows you to select the data source to read the highway data as shown in Figure 71.

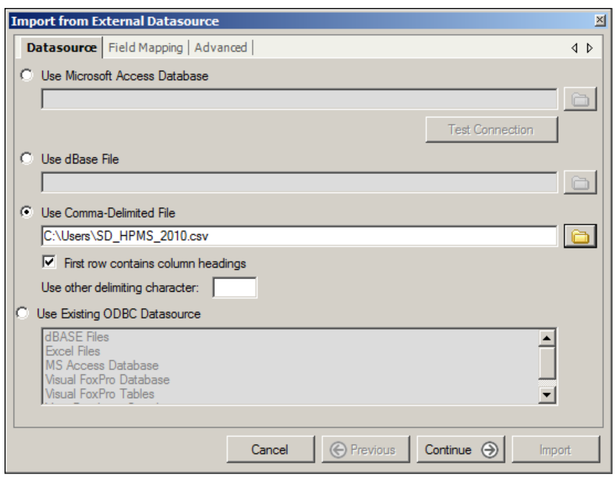

Figure 71. State PMS Reader/Converter – Data Sources

There are four options to select from when importing a State PMS data source:

- The first option is to import data stored in a Microsoft® Access database. Using this option will also require you to select a source table within the Access database. Data cannot be read from multiple tables; therefore if the data reside in multiple tables, it will be necessary to design a query to combine all the data into a single table prior to importing it into the PHT analysis tool.
- The second option is to import data from a dBase file.
- The third option is to import data from a comma-delimited text file. When using this option, you will need to indicate if the first line of the source file contains field names. It is easier to create the field map if descriptive field names are provided.
- The fourth option is to import data from any defined ODBC data source such as Oracle, FoxPro, Paradox, or even spreadsheets such as Excel.

The next tab, shown in Figure 72, allows the user to select the source table (if applicable) and define a field map between the data fields in the source data and those of the PHT data table. For each PHT field, a matching field that provides the data must be selected. Hard-coded value can be directly entered also or a field can be left blank if the source table has no matching item. The mapped field must have a compatible data type with the PHT field.

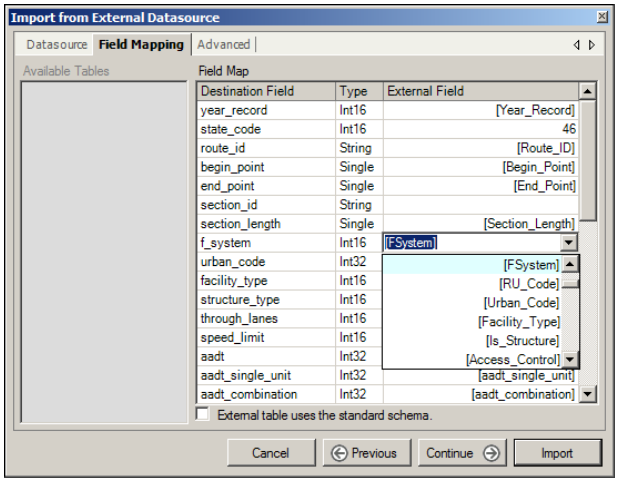

Figure 72. State PMS Reader/Converter – Field Map

In addition to one-to-one field mapping, the import wizard also provides formulas to calculate a required value when it is not directly available in the source data. The formula builder provides a list of all of the data fields in the source data. The expression can use simple math, functions, and the values of the other fields in the record to calculate the new value as shown in Figure 73. The supported math and string functions are described in Table 12.

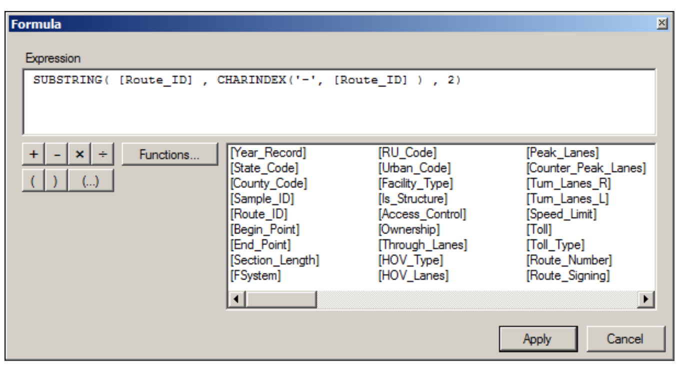

Figure 73. State PMS Reader/Converter – Formula Builder

Table 12. Supported Math and String Functions

Function	Prototype	Description
SIN	SIN(<cell>)	Returns the sine of the specified angle
COS	COS(<cell>)	Returns the cosine of the specified angle
TAN	TAN(<cell>)	Returns the tangent of the specified angle
ASIN	ASIN(<cell>)	Returns the angle whose sine is the specified number
ACOS	ACOS(<cell>)	Returns the angle whose cosine is the specified number
ATAN	ATAN(<cell>)	Returns the angle whose tangent is the specified number
SINH	SINH(<cell>)	Returns the hyperbolic sine of the specified angle
COSH	COSH(<cell>)	Returns the hyperbolic cosine of the specified angle
TANH	TANH(<cell>)	Returns the hyperbolic tangent of the specified angle
ABS	ABS(<cell>)	Returns the absolute value of a specified number
EXP	EXP(<cell>)	Returns e raised to the specified power
LOG	LOG(<cell>)	Returns the logarithm of a specified number
LOG10	LOG10(<cell>)	Returns the base 10 logarithm of a specified number
CEILING	CEILING(<cell>)	Returns the smallest integer greater than or equal to the specified number
RAND	RAND(<cell>)	Returns a random number
ROUND	ROUND(<cell>)	Rounds a value to the nearest integer
SIGN	SIGN(<cell>)	Returns a value indicating the sign of a number
SQRT	SQRT(<cell>)	Returns the square root of a specified number
LEFT	LEFT(<cell>, <length>)	Returns a substring from a string starting from the left-most character
RIGHT	RIGHT(<cell>, <length>)	Returns a substring from a string starting from the right-most character
LEN	LEN(<cell>)	Returns the length of the string
SUBSTRING	SUBSTRING(<cell>, <index>, <length>)	Returns a substring from a string, starting at any position using a 1-based index
CHARINDEX	CHARINDEX(<string>, <cell>)	Returns the index of the first occurrence of the specified case-sensitive character string
CASE	CASE <cell> WHEN <cell> THEN <cell> ELSE <cell> END	Compares an expression to a set of simple expressions to determine the result

The final tab, shown in Figure 74, provides an advanced option to filter the records in the source table prior to importing the data to the PHT table. This is useful to read a sub-set of the records that are in the source table. The filter wizard used to create the SQL clause to filter the data, or use a SQL Text window is available to enter the filter clause directly.

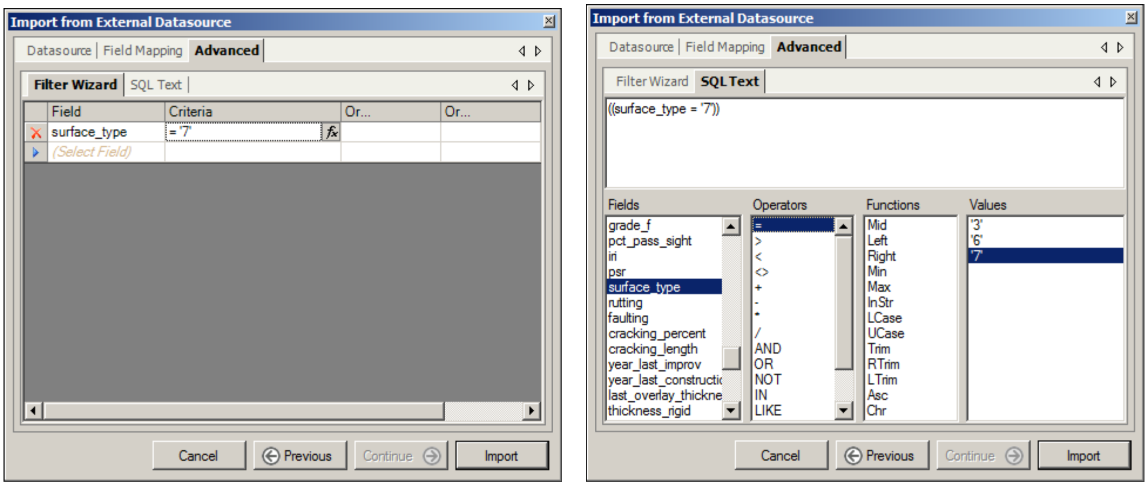

Figure 74. State PMS Reader/Converter – Advanced Filtering

Maintenance Cost Model

Introduction

With aging of highway pavements in the nation and increasingly limited funding for maintenance activities, state highway agencies, metropolitan transportation organizations, and other local transportation agencies are increasingly looking to using available funding available for highway construction and maintenance as efficiently as possible. Efficiency in this context implies getting the most in terms of pavement health for every investment made on their highway pavement corridors or networks. One way of increasing efficiency is the adoption of pavement preventive maintenance improvements in addition to the more intensive rehabilitation and reconstruction improvements as part of pavement management.

Preventive maintenance (PM) has been described as a planned strategy of cost-effective maintenance activities applied to an existing highway pavement that preserves the pavement health, retards the rate of future deterioration, and improves pavement functional condition without significantly increasing structural capacity.

PM improvements are significantly cheaper options for agencies with limited budgets. Research has demonstrated that PM improvements, when applied in a timely manner do prevent or delay onset of significant deterioration thereby prolonging pavement service life. Although more expensive rehabilitation and reconstruction improvements must be performed eventually on all pavements, costly rehabilitation or reconstruction can be delayed with timely PM improvements. Delaying PM improvements increases the extent of pavement deterioration leading to higher future rehabilitation and reconstruction costs.

The PHT analysis tool does not consider the effect of maintenance or rehabilitation treatments when forecasting future pavement distress and smoothness, and thus it uses the *do-nothing* approach to estimate RSL. The objective of this task was to develop a model to account for the effect of maintenance activities in characterizing pavement health and on the RSL predictions and the associated budgetary needs. Another equally important objective was to incorporate into the PHT Tool the ability to identify deficient pavement sections, identify feasible/preferred treatment options, and prioritize needed improvements according to predetermined budgetary or performance constraints.

Maintenance Model

The PHT maintenance model estimates benefits of each pavement section improvement quantified in terms of the value added to the pavement infrastructure. Benefits are calculated based on the following assumptions:

- Straight-line depreciation is used to depreciate individual pavement assets over their service life.
- The post-treatment rate of depreciation remains the same.
- The initial service life of the pavement is the sum of the current pavement age and the RSL where the current pavement age is the difference between the current year of record and the original year of construction for new pavements; or the year of last improvement for rehabilitated pavements.

Straight-line depreciation, along with the effect of the application of a maintenance treatment on increasing the service life and asset value, is shown in Figure 75.

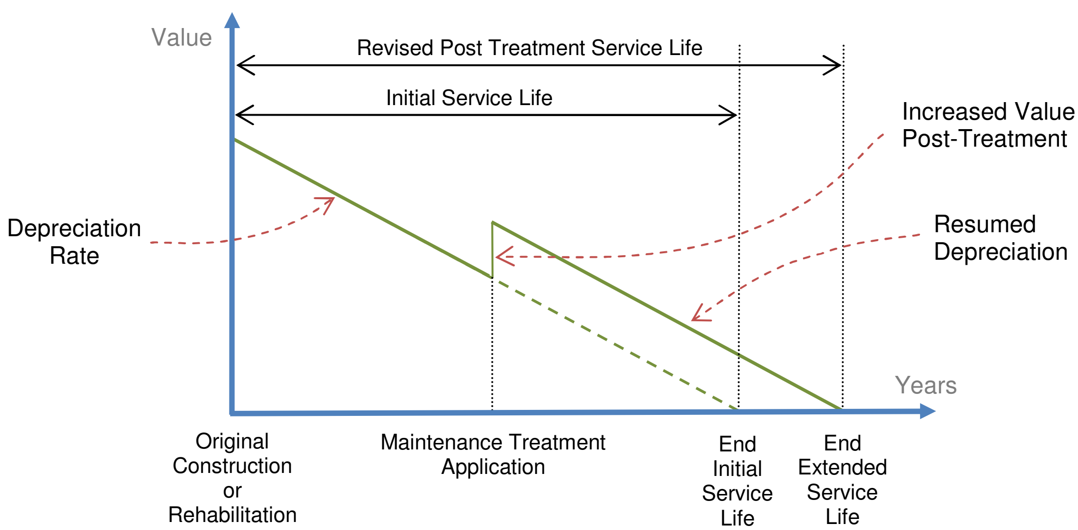

Figure 75. Straight-Line Depreciation with Maintenance Treatment

The following equations described how the PHT maintenance model determines the overall cost and benefits of the application of a maintenance treatment.

Determine the initial service life of the pavement.

$$ISL = (CYR - OCYR) + RSL \quad \text{(New Pavement)} \tag{1}$$
$$ISL = (CYR - LIYR) + RSL \quad \text{(Rehabilitated Pavement)}$$

Where:

ISL	=	Initial Service Life, years
CYR	=	Current Year, (field: `year_record`)
OCYR	=	Original Year of Construction, (field: `year_last_construction`)
LIYR	=	Year of Last Improvement, (field: `year_last_improv`)
RSL	=	Estimated Remaining Service Life, (field `f_Overall_RSL_Years`).

Estimate monetary benefit of the maintenance action for the highway section.

$$BENEFIT = SLE \times \left(\left(\frac{NPAC \times \beta}{ISL} \right) + ((NPAC - COST) \times DR) \right) \times (LN \times LEN) \tag{2}$$

Where:

BENEFIT	=	Estimated Monetary Benefit
SLE	=	Service Life Extension, (see Table 18)
NPAC	=	New Pavement Asset Cost, (see Table 17)
ISL	=	Initial Service Life, (see Equation 1)
COST	=	Maintenance Cost, (see Table 17)
DR	=	Discount Rate
LEN	=	Length of the Highway Section, miles, (field: `section_length`)
LN	=	Number of Lanes, (field: `through_lanes`)
β	=	Adjustment Factor, (see Table 15).

Calculate the total cost of the maintenance action for the highway section.

$$COST = UCOST \times (LEN \times LN) \tag{3}$$

Where:

COST	=	Estimated Cost of Improvements
UCOST	=	Unit Cost of Improvement per Lane-Mile, (see Table 17)
LEN	=	Length of the Highway Section, miles, (field: `section_length`)
LN	=	Number of Lanes, (field: `through_lanes`).

Calculate the Benefit-to-Cost Ratio.

$$BCR = \left(\frac{BENEFIT}{COST} \right) \tag{4}$$

Where:

BCR	=	Benefit to Cost Ratio
BENEFIT	=	Estimated Monetary Benefit, (see Equation 2)
COST	=	Estimated Cost of Improvements (see Equation 3).

Feasible maintenance treatments are established by pavement type and highway functional class and are described in Table 13 and Table 14.

Table 13. Description of Feasible AC Surfaced Pavement Treatments

PM Group	General Description	Applicable PM Actions	Extent of Application	Functional Class	
				Principal & Major	Minor
1	Surface sealing	• Chip seals & surface treatment (single & double) • Slurry seal • Microsurfacing • Hot in place recycling • Microsurfacing	100% of lane area		✓
2	Full depth patching with OR without grinding	• Full depth AC patching (including base replacement) • Grinding & grooving	Patching as needed with 100% lane area sealing	✓	✓
3	Full depth patching with AC OL OR surface recycling*	• Hot-in-place recycling • Microsurfacing • Ultra-thin HMA overlays (e.g., novachip) • Thin AC overlay • Mill & thin AC overlay	100% lane area	✓	
4	Major Rehabilitation	• Placement of thick 2- to 8-in AC overlay	100% lane area	✓	✓
5	Reconstruction	• Reconstruct entire AC layer thickness only	100% lane area	✓	✓

Table 14. Description of Feasible JPCP Pavement Treatments

PM Group	General Description	Applicable PM Actions	Extent of Application	Functional Class	
				Principal & Major	Minor
1	Functional repair	• Full-depth concrete repair or slab replacement including slab jacking • Joint load transfer restoration (dowel bar retrofit & joint patching) • Diamond grinding & grooving	Up to 5% of lane area	✓	
2	Surface seals & thin overlay*	• Seals (surface sealing, slurry seal, & microsurfacing) • Thin HMA overlay	100% of lane area	✓	✓
3	Major rehabilitation	• Placement of thick 2- to 8-in AC overlay OR unbonded PCC overlay	100% lane area	✓	✓
4	Reconstruction	• Reconstruct entire AC/PCC layer thickness only	100% lane area	✓	✓

Each highway section is evaluated by the maintenance model to determine if it is a candidate for a feasible maintenance treatment. A flowchart of the PHT maintenance model algorithm is illustrated in Figure 76.

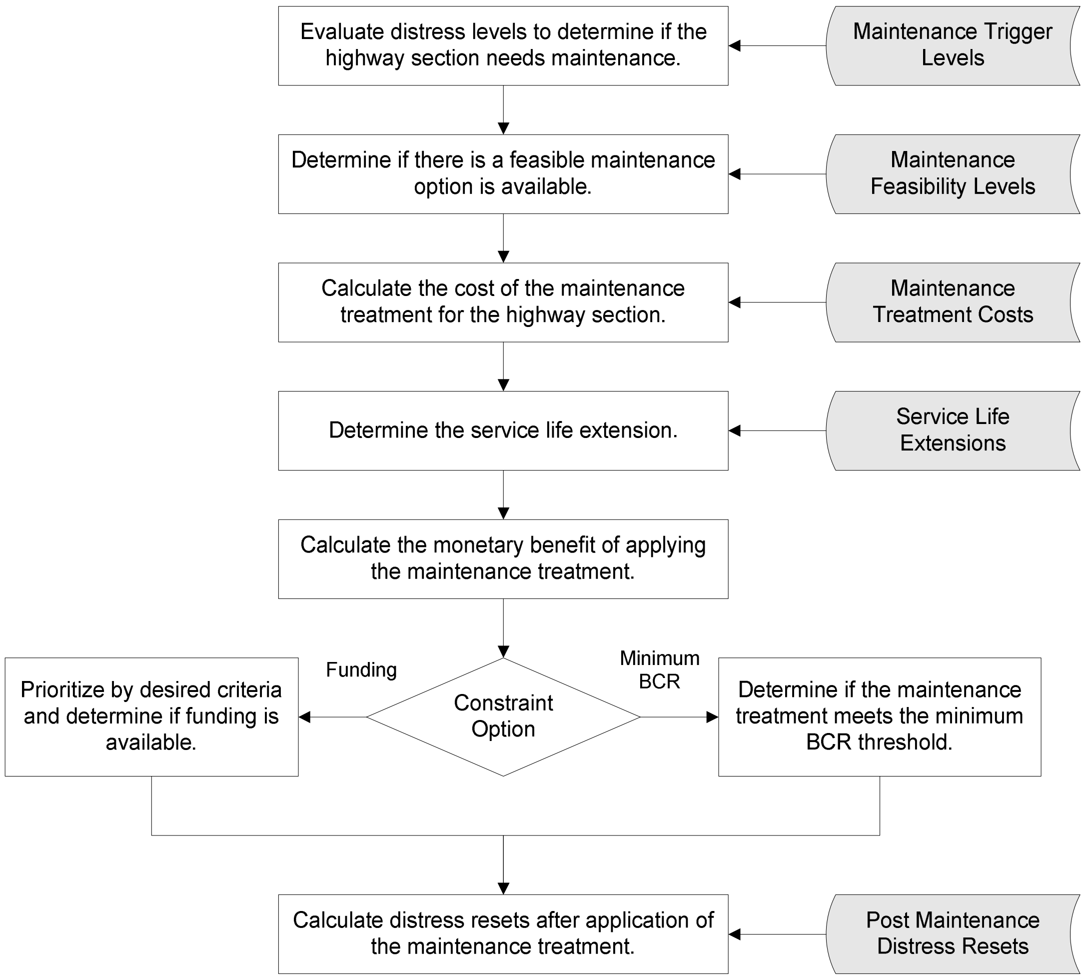

Figure 76. PHT Maintenance Model Flowchart

Adjustment Factors

The initial value of the pavement at original construction or rehabilitation is determined by the new construction costs multiplied by the adjustment factors shown in Table 15.

Table 15. Initial Pavement Value Adjustment Factors

Pavement Type	HPMS Surface Type	Adjustment Factor
New Pavement	2, 3, 4, 5	1.00
Rehabilitated Pavement, thin overlay	6, 7, 8, 9, 10, 11	0.60
Rehabilitated Pavement, thick overlay		0.60

Lookup Tables

The maintenance model uses five lookup tables as shown in Table 16 through Table 20. These tables describe the default values used by the PHT maintenance as described below.

- **Trigger Levels.** The trigger-level table provides the deficiency thresholds for each distress type that defines at what point a maintenance treatment is warranted. Any distress exceeding its threshold triggers the need for a maintenance action.
- **Feasibility Thresholds.** The feasibility thresholds provide the decision criteria for selecting the improvement option based on the pavement distress and RSL. The preferred improvement will be the lowest feasible improvement group that will address the pavement's conditions.
- **Post-Maintenance Resets.** The post-maintenance reset table provides the percentage of improvement for each distress type as a result of a maintenance treatment. The extent of the improvement is determined based on the existing distress level and the type of treatment applied. A value of 0% means no change to the distress while a value of 100% implies that the distress is reset to a like-new condition.
- **Service Life Extensions.** The service life extension table provides the post-improvement extension to the RSL (years) as a result of the application of a maintenance treatment. Additional extensions to the service life are provided to take into account the effect of climate and traffic conditions and pavement construction.
- **Treatment Costs.** The treatment cost table provides the estimated cost of applying a maintenance treatment as measured in current dollars per lane-mile.

The model will select a preferred treatment strategy from the list in Table 19 and Table 20 based on each option's selection criteria. The model will select the lowest feasible improvement group by order of severity that will address the distress/IRI and RSL conditions.

Table 16. Default Maintenance Trigger Levels

Surface Type	Class	IRI	Cracking		Rutting	Faulting
			Percent	Length		
Flexible, Composite	Interstate	80	0 %	250 ft/mi	0.25 in.	
	Primary	100	0 %	1000 ft/mi	0.25 in.	
	Secondary	125	5 %	1000 ft/mi	0.25 in.	
Rigid	Interstate	100	0 %			0.10 in.
	Primary	100	0 %			0.10 in.
	Secondary	125	0 %			0.15 in.

Table 17. Default Post-Maintenance Resets (%) and Treatment Costs

Surface Type	Treatment	IRI	Cracking		Rutting	Faulting	Cost per Lane-Mile
			Percent	Length			
Flexible, Composite	Surface Sealing	0 %	40 %	15 %	10 %		$ 12,250
	Full-Depth Patching	0 %	40 %	15 %	25 %		$ 32,500
	Patching and Overlay	30 %	100 %	90 %	50 %		$ 42,000
	Rehabilitation	100 %	100 %	100 %	100 %		$ 92,000
	New / Reconstruction	100 %	100 %	100 %	100 %		$ 290,000
Rigid	Functional Repair	50 %	7 %			70 %	$ 27,750
	Seal and Overlay	0 %	0 %			0 %	$ 22,000
	Rehabilitation	0 %	0 %			0 %	$ 132,750
	New / Reconstruction	100 %	100 %			100 %	$ 450,000

Note: A value of 0% means no change while a value of 100% implies reset to like-new conditions.

Table 18. Default Service Life Extensions (Years)

Surface Type	Treatment	RSL Extension	Additive (+)				
			Climate (non-freeze)	Climate (dry)	Class (non-principal)	Pavement (composite)	Sub-Grade (fine)
Flexible, Composite	Surface Sealing	1.5					
	Full-Depth Patching	0.5	1		2	0	0
	Patching and Overlay	5.5	0		0	0	0
	Rehabilitation	10	2.5		2	5	3
	Reconstruction	20					
Rigid	Functional Repair	6	1	2	0		0
	Seal and Overlay	5.5					
	Rehabilitation	15					
	Reconstruction	30					

Table 19. Feasible Improvements for Flexible and Composite (AC) Pavements

	Interstate	Primary	Secondary
Surface sealing	N/A	N/A	RSL > 5 years Rutting < 0.35 in Cracking Length < 2500 Cracking Percent < 5 % IRI < 150 in/mi
Full depth patching with OR without grinding	RSL > 10 years Rutting < 0.25 in Cracking Length < 250 Cracking Percent < 5 % IRI < 125 in/mi	RSL > 5 years Rutting < 0.25 in Cracking Length < 1000 Cracking Percent < 5 % IRI < 150 in/mi	RSL > 5 years Rutting < 0.35 in Cracking Length < 1000 Cracking Percent < 5 % IRI < 125 in/mi
Full depth patching with thin AC overlay OR surface recycling	RSL > 10 years Rutting < 0.35 in Cracking Length < 1000 Cracking Percent < 10 % IRI < 125 in/mi	RSL > 5 years Rutting < 0. 5 in Cracking Length < 2000 Cracking Percent < 10 % IRI < 150 in/mi	N/A
Major rehabilitation	RSL > 3 years Rutting < 0.35 in Cracking Length < 2000 Cracking Percent < 15 % IRI < 150 in/mi	RSL > 3 years Rutting < 0.5 in Cracking Length < 2000 Cracking Percent < 15 % IRI < 150 in/mi	RSL > 3 years Rutting < 0.75 in Cracking Length < 2500 Cracking Percent < 15 % IRI < 175 in/mi
New or reconstruction	RSL < 3 years Rutting > 0.35 in Cracking Length > 2000 Cracking Percent > 15 % IRI > 150 in/mi	RSL < 3 years Rutting > 0.5 in Cracking Length > 2000 Cracking Percent > 15 % IRI > 150 in/mi	RSL < 3 years Rutting > 0.75 in Cracking Length > 2500 Cracking Percent > 15 % IRI > 175 in/mi

Table 20. Feasible Improvements for Rigid Pavements

	Interstate	Primary	Secondary
Functional repair	RSL > 10 yrs Cracking Percent < 10% Faulting < 0.15 in IRI < 125 in/mi	RSL > 10 yrs Cracking Percent < 10% Faulting < 0.15 in IRI < 125 in/mi	N/A
Surface seals & thin overlay	RSL > 10 yrs Cracking Percent < 1% Faulting < 0.1 in IRI < 150 in/mi	RSL > 10 yrs Cracking Percent < 1% Faulting < 0.1 in IRI < 150 in/mi	RSL > 10 yrs Cracking Percent < 1% Faulting < 0.1 in IRI < 150 in/mi
Major rehabilitation	RSL > 5 yrs Cracking Percent < 15% Faulting < 0.2 in IRI < 175 in/mi	RSL > 5 yrs Cracking Percent < 15% Faulting < 0.2 in IRI < 175 in/mi	RSL > 5 yrs Cracking Percent < 20% Faulting < 0.2 in IRI < 175 in/mi
Reconstruction	RSL < 5 yrs Cracking Percent > 15% Faulting > 0.2 in IRI > 175 in/mi	RSL < 5 yrs Cracking Percent > 15% Faulting > 0.2 in IRI > 175 in/mi	RSL < 5 yrs Cracking Percent > 20% Faulting > 0.2 in IRI > 175 in/mi

Graphical User Interface

The PHT maintenance model is implemented into the PHT graphical user interface as an integrated feature of the PHT results viewer window. The **Maintenance** tab in the vertical panel provides access to the PHT maintenance model as shown in Figure 77.

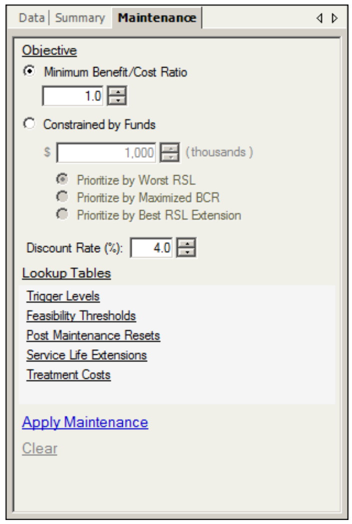

Figure 77. PHT Maintenance Model User Interface

There are two objectives for the maintenance model:

- Minimum Benefit/Cost Ratio (BCR). This objective will identify all highway sections that have a feasible maintenance treatment option available that will produce a benefit/cost ratio greater than some specified level regardless of cost.
- Constrained by Funds. This objective will identify all highway sections that have a feasible maintenance treatment option available and prioritize each until some specified level of funding has been exhausted. Prioritization is performed using one of three selection methods:
    - Worst RSL. This method selects as the first to be treated those highway sections that have the lowest RSL as forecasted by the PHT analysis.
    - Maximized BCR. This method selects as the first to be treated highway sections that have a maintenance treatment option that will produce the highest BCR.
    - Best RSL Extension. This method selects as the first to be treated those highway sections that have a maintenance treatment option that will produce the highest service life extension.

The discount rate percentage is used by the maintenance analysis for estimating the benefits associated with postponing reconstruction costs by performing a less expensive maintenance treatment to prolong the life of the existing pavement.

The results of the PHT maintenance model analysis provide the following information:

- Maintenance Option. Recommended maintenance treatment for the highway section.
- Service Life Extension. The extension in service life of the pavement as a result of applying the recommended maintenance treatment.
- Maintenance Cost. Overall total cost of applying the recommended maintenance treatment taking into account the length of the highway section and the number of lanes treated.
- Overall Benefit. Benefit, quantified in terms of the value added to the pavement infrastructure due to the application of a given maintenance treatment.
- Benefit/Cost Ratio. Ratio of the overall benefit and total maintenance cost.
- Revised Distresses. The revised post-maintenance distress values for IRI, rutting, cracking, and faulting as a result of applying the recommended maintenance treatment.

Profile Map Viewer

Introduction

The objective of this task was to implement a custom viewer window that will display a selected route corridor on a geographic information system (GIS) map along with profile information about the corridor. The previous version of the PHT Analysis tool allowed the user to view profile information about a pre defined corridor route and a GIS window to define a corridor route, but not an interface that displays both sets of information collectively. An interface that displays both the source corridor and its profile information together provides better aid for decision makers in understanding the roadways to which the RSL forecasts apply.

A profile viewer window has been implemented to display a selected route corridor on a GIS map along with up to four profile information attributes about the corridor. A corridor is defined as a set of arcs representing a transportation infrastructure such as highways that have the following properties.

- It will consist of unbroken continuous sets of arcs
- The arcs will be connected at their ends only
- No more than two arcs will meet in any intersections (no forks).

Before a profile map can be generated, it is necessary for the user to define a corridor using the GIS selection utility. A GIS selection is based on a GIS shape file and is used to define a set of highway sections that make up the corridor.

A set of data fields are used to link the PHT database with the GIS shape file as follows:

- **State FIPS**. This item identifies the field that contains the state FIPS code.
- **Route ID**. This item identifies the field that contains the route identifier.
- **Beginning Milepost**. This item identifies the field that contains the beginning milepost along the route where the highway section begins.
- **Section ID**. This item identifies the field that contains a state-wide unique highway section identifier. A section identifier is an alphanumeric value. The section identifier field is optional, but if provided it will be used in lieu of the route identifier and beginning milepost fields.
- **Section Length**. This item identifies the field that contains section length information.

The viewer supports auto-arranging the layout of the window based on the orientation of the selected corridor. For example, if the general direction of the corridor is from east-west, the viewer will show the GIS map on the top or bottom portion of the window, while a north-south orientation will be shown on the left or right of the window. Manual arrangement of the window layout is also supported. The viewer also provides zooming controls such that when zooming into a profile chart, the data displayed in the other profile charts and the GIS map will change to match the selected range.

Graphical User Interface

The PHT profile map viewer is implemented into the PHT graphical user interface as an integrated feature of the PHT analysis window. The **Corridor Analysis** tab provides access to the PHT profile map viewer as shown in Figure 78.

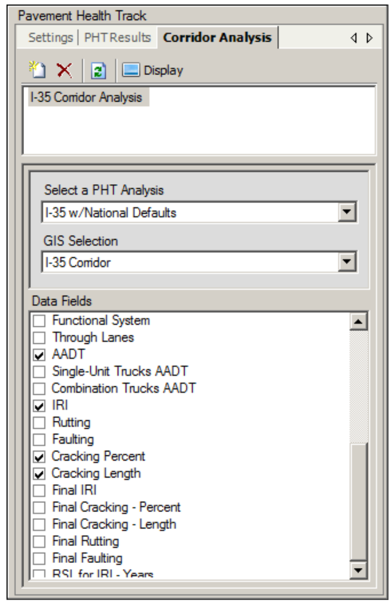

Figure 78. PHT Corridor Analysis User Interface

The top pane in the window displays a list of existing corridor profiles for you to select from, while the bottom pane displays the options for the selected corridor profile. You must select a set of PHT analysis results, a GIS selection that represents the continuous corridor, and up to four data items to profile.

Once you have selected the profile options, click the *Display* button in the toolbar to view the corridor profile. If you make any changes to the options for the profile, you must then click the *Display* button again to refresh the display window.

The toolbar at the top of the window provides for the following functions:

 **Create New.** Create a new profile analysis.

 **Delete.** Delete the currently selected profile analysis.

 **Refresh.** Refresh the display.

Display. Display the results of the currently selected profile. After making any changes, click this button to refresh the display of the corridor profile.

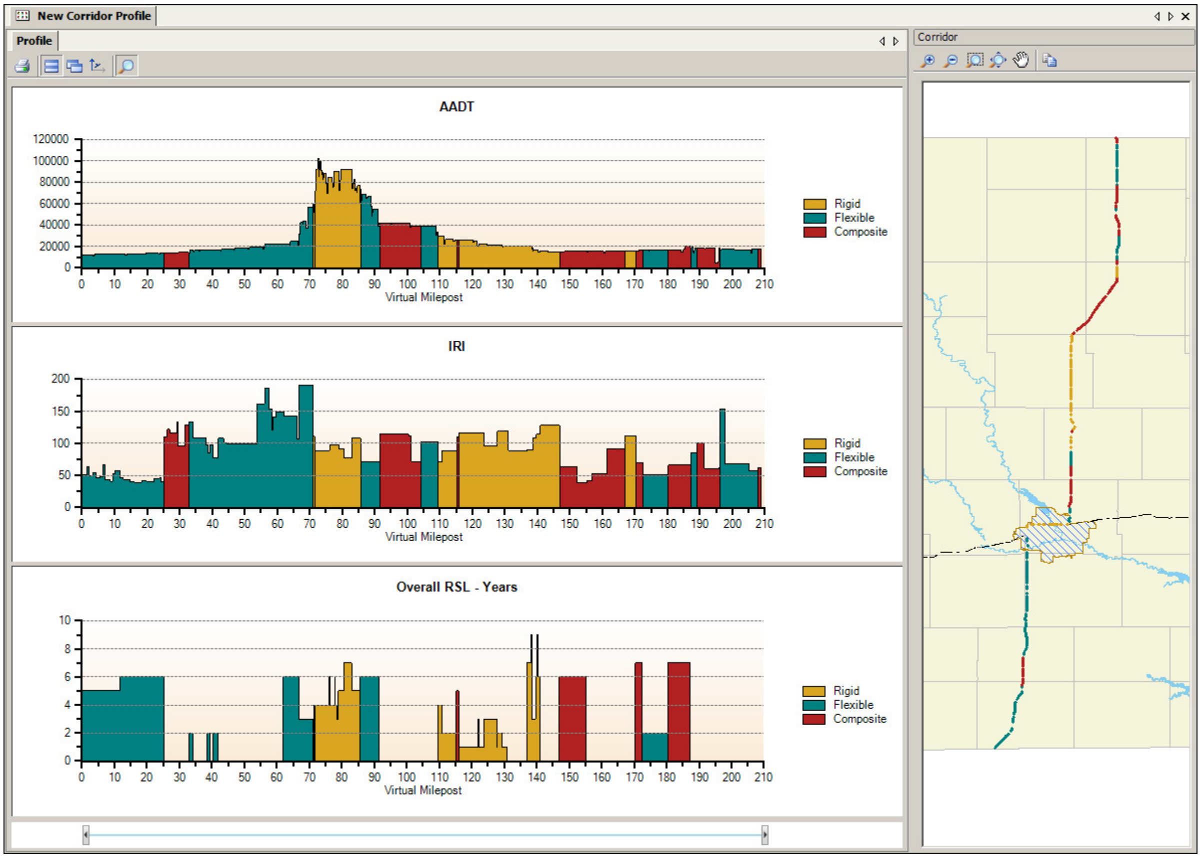

Figure 79. PHT Corridor Profile

The corridor profile identifies the pavement type of each highway section as a color code depicting rigid, flexible, and composite pavements for those regions of the corridor that have sample PHT data as shown in Figure 79. Regions without sample data appear gray. Corridors are characterized by virtual mileposts beginning at zero and incrementing based on the lengths of the highway sections that make up the corridor.

The toolbars provide for the following functions:

 **Print.** Display the print dialog to print the charts to a file, printer, or clipboard.

 **Stack Charts.** Display the chart windows stacked vertically.

 **Tab Charts.** Display each chart as an individual tabbed window.

 **Synchronize Y Axis.** Synchronize the Y Axis of all the charts to a single scale.

 **Zoom.** Activate chart zooming.

 **Copy.** Copy the GIS map image to the clipboard.

 **Zoom and Pan.** Zoom in or out, and pan through the GIS map.

When zooming into an area of the profile, the zoom control will appear at the bottom of the window. Drag the beginning and ending markers left or right to adjust the zoom region. The GIS map will automatically track with the zoom region of the corridor and will highlight only those highway sections that appear in the profile charts. Toggle the zoom mode on/off by clicking the Zoom button o the toolbar.

The synchronize Y-axis button will cause all of the charts in the display to use the same scale for their vertical axis. This can be useful when comparing similar data on multiple charts.

The data fields for the maintenance analysis can be profiled also. Before the maintenance analysis results can be profiled you must first open the PHT analysis result window and apply a maintenance analysis to the PHT result data. The maintenance analysis results are not persisted or saved when the PHT result window is closed, so this window must remain open with a maintenance analysis applied for the maintenance analysis results to be available to be profiled.

When you select a set of PHT analysis results that has had a maintenance analysis, the additional results fields for the maintenance analysis will be appended to the list of data fields available for profiling. Simply select the maintenance data field(s) of interest as you would any other data field and click the *Display* button to refresh the profile chart.

Highway Data Viewer

Introduction

The objective of this task was to implement a custom data viewer window for the PHT Analysis tool user interface that provides rich features for editing HPMS2010 formatted data, specifically the PHT required data subset.

HPMS is the official source of data on the extent, condition, performance, use, and operating characteristics of the nation‘s highways. In 2010 the FHWA completed its reassessment of the HPMS data and produced a specification that significantly changes its format, content, and nature from the previous 2000 format specification. The 2010 specification designates the HPMS data to be stored in an active relational database, but still provides a flat file export format. The previous version of the PHT analysis tool used the flat file format and displays it using a simple table viewer with no HPMS-specific capabilities. An HPMS customized viewer window as developed to provide both the HPMS data and the PHT analysis results, with features designed specifically to augment the user experience.

The following features are provided.

- Custom drop-down lists for enumerated data items
- Color-coded display to enhance viewing source data, analysis results, and records that identify data validation errors
- Validation error report window that links detected validation errors to individual records and fields
- Customizable layout that allows the user to arrange and hide data columns
- Vertical record display that provides a more usable and readable view
- Improved user interface for selecting highway sections.
- Quick summary window that provides summation of the current conditions of the highway sections prior to running the analysis.
- PHT results interpreter so that the user can quickly

Graphical User Interface

The PHT database is the source data for the RSL analysis. It contains the data fields that describe the condition of each highway section. Each record in the database represents a highway section and can be individually selected for analysis. The PHT database window is shown in Figure 80.

The table interprets enumerated values and translates them into human readable text. It also provides for a customizable layout that allows the columns to be arranged and hidden in any why desired by the user. The table is normally in read-only mode to prevent unintentional changes to the highway data, but can be placed in an edit mode if needed.

A vertical oriented panel is available that displays the data items of the selected highway section in a convent format that allows all of the data items to be seen at once. The vertical panel is located on the left of the window and can be expanded by dragging the slider bar to the right.

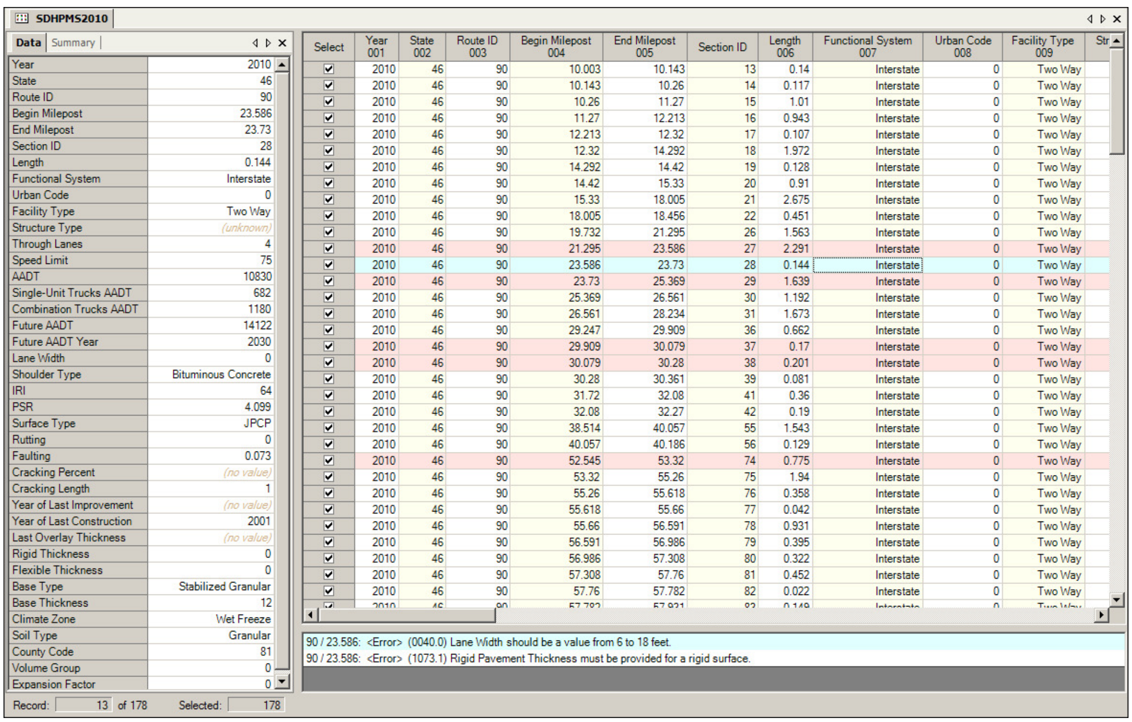

Figure 80. PHT Database Window

The PHT database window provides layout formatting, editing, and validation testing through popup menus. The menus are activated by RIGHT-clicking on individual records or on the column headers. Each menu is described in the following paragraphs.

When validation testing has been performed, individual highway sections that have violated one or more validation tests are highlighted with a red shaded background. When one of these errant records is selected, a list of its validation errors is displayed in the panel at the bottom of the window. DOUBLE-clicking on an error message entry will cause the application to jump focus to the specific record and data item that has caused the error. Individual validation rules can be enabled or disabled from the PHT properties window.

The error message panel for the validation rules normally displays the validation errors for the selected highway section; however it can also show all the validation errors of the entire dataset or a list of each unique error message in that dataset. To change how the validation errors are displayed, RIGHT-click on the panel to display its popup menu and select an option under the *View* menu item.

Selecting Highway Sections

The first column in the table determines if a highway section will be included in the PHT analysis. If this field is checked, the record will be analyzed by the PHT tool when the analysis is run; otherwise the record will be ignored. To select or unselect a highway section, you can manually click on its checkbox or use the selection commands available from the menu that is activated by RIGHT-clicking on the *Select* column header. This menu provides the following options for selecting records.

- **Select All**. Select all highway sections.
- **Select Range**. Select the highway sections in the highlighted range, unselect others.
- **Clear Selection**. Unselect all highway sections.
- **Toggle Selection**. Toggle the selection state of all highway sections.
- **Select Valid Records**. Select only highway sections without validation errors.
- **Select Errant Records**. Select only highway sections with validation errors.
- **Select by Query**. Display a query wizard to select highway.

When selecting highway sections by Query, the query builder shown in Figure 81 is used.

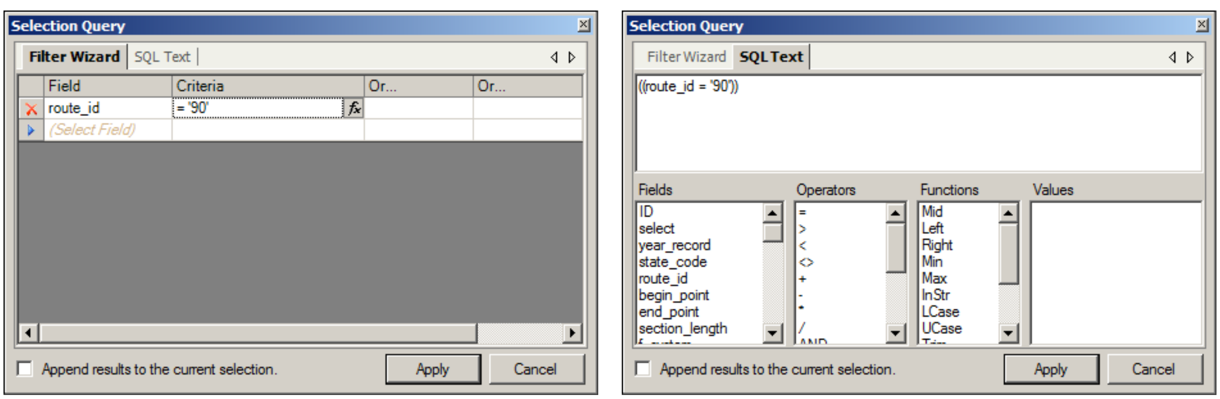

Figure 81. Selection Query Builder

The *Filter Wizard* tab provides an interface to select the data fields and enter the selection criteria to select the records that meet the criteria. The selection can either add to the current selection or replace it entirely.

Users that are comfortable working directly with the SQL language may also enter the SQL text using the SQL text window. The SQL text represents the WHERE clause of a SQL statement and must comply with all SQL syntax rules. This window provides a list of available data fields, operators, built-in functions, and a list of unique values for the selected field.

Editing the Highway Data

Normally the Highway Data Viewer window is in a read-only mode with the only edit that are allowed are the setting of the selection column. However, when the need arises to modify the highway data to address validation issues, the highway data viewer can be placed into edit mode which will allow the use r to make any necessary changes.

Placing the Highway Data Viewer window into edit mode is done using the popup menu which appears when you RIGHT click on any record in the table. The items in the *Record* menu apply to the selected record, while the items in the *Table* sub-menu apply to the entire table.

These menu items are provided in the Record menu:

Menu Item	Function
Select	Select the record for analysis
Unselect	Unselect the record so it will not be included in the PHT analysis
Validate	Perform validation testing on the selected record
Table	Displays the Table sub-menu
Copy Row(s)	Copy the selected row(s) to the clipboard
Copy with Headers	Copy the row(s) along with the column headers to the clipboard
Paste	Paste the contents of the clipboard to the table

These menu items are provided in the Table menu:

Menu Item	Function
Begin Editing	Place the PHT database window in edit mode to allow user editing of the highway data table. If already in edit mode, this item will labeled End Editing and will terminate the PHT database window edit mode
Save	Save all changes to the highway data table
Validate All	Validate all records in the highway data table
Save Layout	Save the current layout of the table
Restore Layout	Restore the default layout of the table

Each data item provides a popup menu that appears when by RIGHT-clicking on the column header. Items in this menu apply only to the column that was clicked.

Menu Item	Function
Fill Data	Display a dialog window that allows you to fill the selected column with a new value, overwriting all previously existing values in the column
Search and Replace	Display a dialog window that allows search the selected column for a particular value and replace it with a new value
Sort	Sort the selected column in ascending or descending order
Hide	Hide the selected column
Show	List hidden columns so that individual columns can be re-shown
Show All	Show all hidden columns

The *Search and Replace* window allows you to search a column of data for a particular value and replace it with a new value. The search operation can apply to a selected range or to the entire column. The *Fill* Data window allows you to fill a column of data with a new value overwriting all previously existing values in the column. The fill operation can apply to a selected range, from the current record to the end of the table, or the entire column.

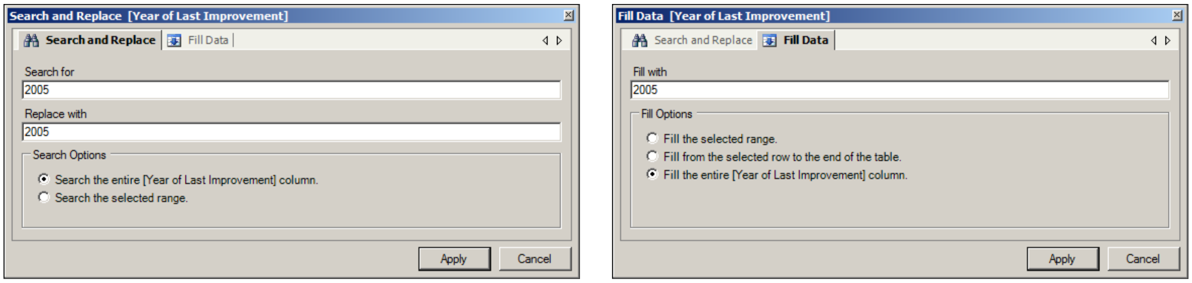

Figure 82. Search/Replace and Fill Dialog Window

Highway Data Summary

The Highway Data Viewer window provides a summary of the highway records in the data set to summarize the percentage of highway sections that already have a failing measured distress or have exceed their maximum service life as well as the minimum, maximum, and average distress values and surface age for the rigid, flexible, and composite pavement types. This summary is useful to help assess the highway data set prior to running the analysis.

The distress thresholds and maximum service life durations are defined as part of the PHT analysis parameters. To perform a summary analysis, first select the PHT parameters metrics from the drop-down list at the top of the window and click the *Refresh* button.

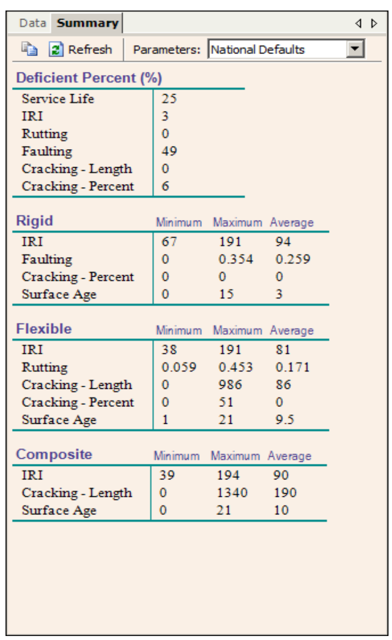

Figure 83. Highway Data Summary

Only the highway sections that are selected in the data set are used when performing the summary analysis. This allows summaries of different subsets of highway sections, by first selecting only the sections of interest and then clicking the Refresh button.

The *Copy* button on the toolbar will copy the summary analysis results to the Windows clipboard in a format that is compatible with Microsoft® Word or Excel.

Result Viewer Window

After the PHT analysis is complete, the results are displayed in a viewer similar to the highway data viewer window as shown in Figure 84.

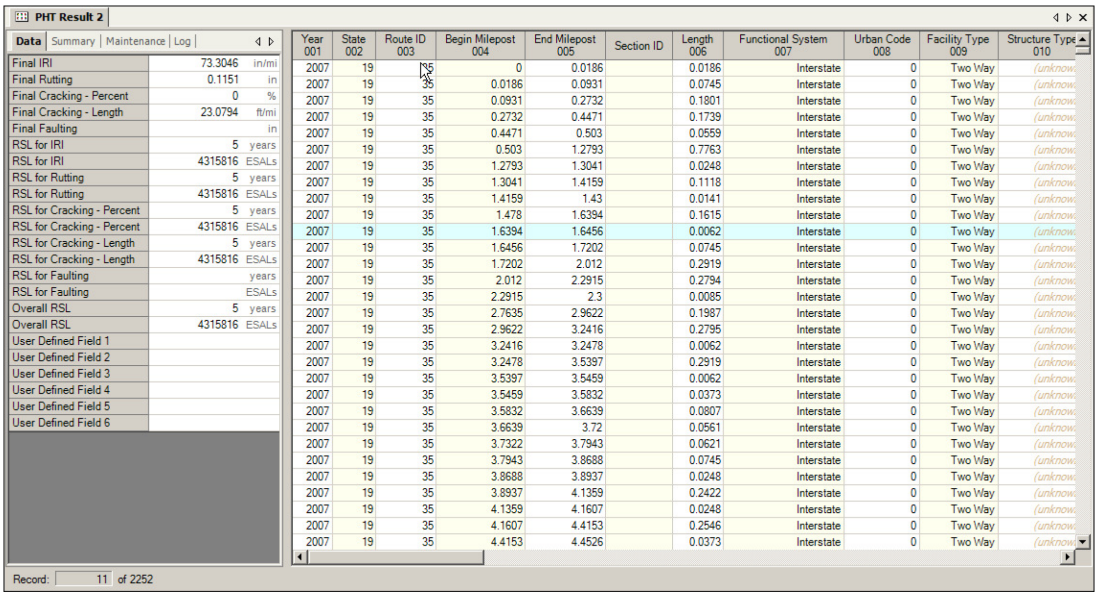

Figure 84. PHT Result Viewer

The Result Viewer window displays the original highway data that was analyzed by the PHT tool using the same interface as the PHT Database window. The vertical oriented panel on the left of the window provides information about the analysis for the highway data record selected in the table including the RSL estimates, a summary report, and an analysis log. All data items in this window are read-only and cannot be modified.

The *Data* tab in the vertical panel provides a view of the PHT analysis results for the highway data record selected in the table. All the RSL data items can be displayed, or you can filter the display into categories using a popup menu that appears when you RIGHT-click anywhere on the data list. The filtering options include RSL by years, by ESALs, and user-defined fields

The *Log* tab is only available if a log file has been captured during the analysis and the file is available for display. The content of the log file is determined by the logging properties that are set as part of the PHT properties. It displays the log entries created in the log file for the highway data record selected in the table. The log entries are useful to track the analysis process to aid in understanding the results. Each log entry is identified as an error, warning, or informational message.

Result Summary

The *Summary* tab provides a user-friendly readable summary of the analysis results for the highway data record selected in the table as shown in Figure 85. The summary highlights the estimated RSL for the pavement surface and illustrates the distresses and service life limits that contributed to the RSL estimate. It also annotates the analysis with notes that describe the pavement construction and any unusual conditions in the data.

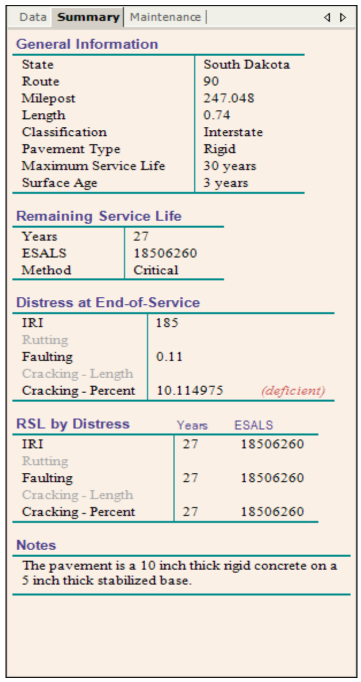

Figure 85. Result Summary Window

The result summary can provide the following annotations.

- A description of the highway sections construction including its surface and base type, and its pavement, base, and overlay thickness.
- An indication if the pavement has already exceeded its maximum service life.
- An indication if the pavement will exceed its maximum service life prior to any distress exceeds it terminal threshold.
- An indication if any distress has already exceeded its terminal thresholds prior to beginning of the PHT analysis period.
- An indication of which distress(s) have exceeded it terminal threshold.
- Maintenance options available if the maintenance model is applied.

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Chart Template Feature

Introduction

The objective of this task was to provide the ability to create open customizable chart templates that define the type of data to be displayed along with the chart layout and appearance. An open template provides complete freedom to select and query HPMS and/or RSL data from any PHT analysis result dataset, choose how the data are displayed in the chart, and adjust the chart appearance properties. User-defined chart templates are then stored in a library for subsequent reuse with other analysis results.

Chart template definitions are stored in the chart library as well formatted XML files with defined and documented schema tags. Individual chart templates can be exported/imported allowing template definitions to be freely shared among PHT users.

Template Design

Chart templates begin by defining SQL queries to retrieve information from the database. The SQL query extracts data from a table that contains the results of a PHT analysis. When encoded into a template, the name of the table is replaced in the SQL query with a place holder. This process is then reversed when the template is reconstituted into a new chart by replacing the place-holder with the table name that contains the new PHT analysis results. In this manner, the SQL queries that retrieve the data for the chart become independent of any specific set of PHT analysis results.

The place holder character for the table name is the ASCII character 149 (Bullet). This character was selected because it has no meaning in the SQL syntax of a query statement and will not be confused with any other valid use.

The chart template is stored in XML format. Tags are included in the XML file to store the chart template SQL query statements for each data column in the charts spread sheet. In addition to the queries, it is also necessary for the chart template to store information about the schema of the data table that the queries are designed to operate with.

An example of the encoding for a chart template is shown in the following XML listing.

Chart templates are specific to a table schema and expect the data table to provide a prescribed set of field names and data types. In the case of the PHT analysis tool, this schema is that of the PHT result table that is produced for every analysis run. The table schema is identified by a schema signature which is a decimal number, calculated through an algorithm using the ASCII character values of the field name and data type for each data field in the table. In the case of the PHT result table, the signature has the following value.

```
49688.8028
```

Tags are included in the template XML file to store the table schema signature. An example of a chart template file is shown in the following XML listing.

```
<?xml version="1.0" encoding="utf-8"?>
<bco.chart>
   ...
   <column index="2">
      ...
      <bco.bmfat>
         <query>
          (SQL syntax for the selection query: i.e. "SELECT [abc] FROM [•]")
         </query>
      </bco.bmfat>
   </column>
   ...
   <bco.bmfat>
      <template>
         <schema>49688.8028</schema>
      </template>
   </bco.bmfat>
</bco.chart>
```

Graphical User Interface

The template library tab shown in Figure 86 provides management of the template library. The templates provide the format for predefined charts used to generate reports. Once a template is selected from the list, it can be deleted or exported to an XML file. In XML form, the template file can be shared with other PHT users who can import it into their own template library.

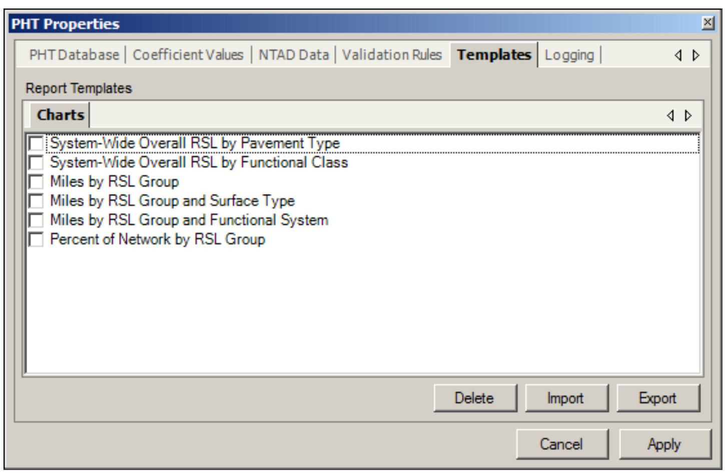

Figure 86. Chart Template Library

Chart templates can easily be created by first using the Report Wizard to produce a chart report, and then modifying the report to meet any unique needs. The report can then be saved as a template to the library.

There are four controls in the chart toolbar are exclusively for working with chart templates and the template library, and are only active immediately after the report wizard has generated the statistical chart. Once the chart window has been closed, the template controls will not be available the next time the chart window is opened from the document library.

The template controls are as follows:

- **PHT Analysis Results.** Identify the analysis results displayed in the chart
- **Refresh.** Refresh the chart after a different set of results are selected
- **Load.** Load a chart from the chart template library
- **Save.** Save the chart to the chart template library

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Improve PHT Runtime Performance

Introduction

The objective of this task was to optimize the PHT analysis engine performance to improve the overall analysis runtime when analyzing a large number of sections. Analyzing the complex algorithms of the PHT Analysis Tool may take a longer than ideal time to be completed. Advances in hardware design in modern computers such as multiple-core CPUs and 64-bit architecture can greatly improve the overall runtime of the analysis. It is essential to optimize the operation of the PHT analysis to the greatest extent possible while still ensuring its operational ability on older computers that are still commonly in use.

Implementation

Improvements to PHT Tool runtime were implemented at two levels; by increasing efficiency and optimization of computation algorithms and procedures and taking advantage of modern computer hardware features such as 64-bit architecture, multiple core CPUs, and large memory sizes and caches.

The primary contributor to the runtime improvements was incorporating multi-threading into PHT computational algorithms that allow for parallel computations and analysis. Multi-threaded programming has significantly improved the PHT computation performance on computer systems that have multiple CPUs, because the threads of the program permit concurrent execution of multiple PHT computations.

The improvement in runtime is a function of the number of core processors and the amount of memory available in the computer. The runtime benchmarks shown in Figure 87 were produced using a duel core 2.2GHz processor with 6Gbytes of memory.

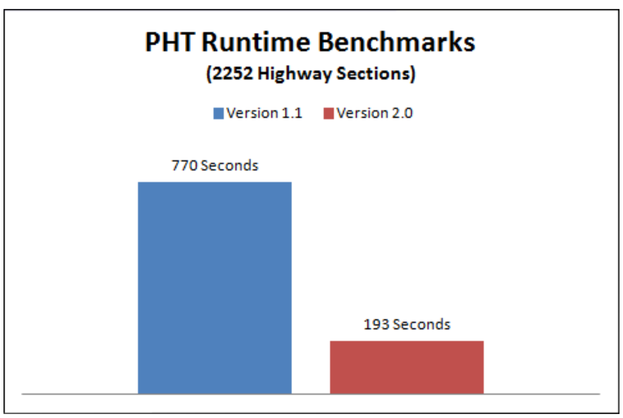

Figure 87. PHT Runtime Benchmarks, Version 1.1 and Version 2.0

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Expanded Reporting Module

Introduction

The objective of this task was to expand the current report wizard interface in include a wider variety or reporting options and take advantage of the extended Chart template features implemented in Task 10. The HPMS and RSL data produced is tabular in nature. The statistical data produced by the analysis is often better represented in a more graphical format such as a graph or chart, and geographical information is better visualized in a GIS map.

Graphical User Interface

The expanded Report Wizard provides an automated process to generate statistical charts and thematic maps useful to visualize the results of the analysis. The graphical user interface for the Report Wizard window is shown in Figure 88.

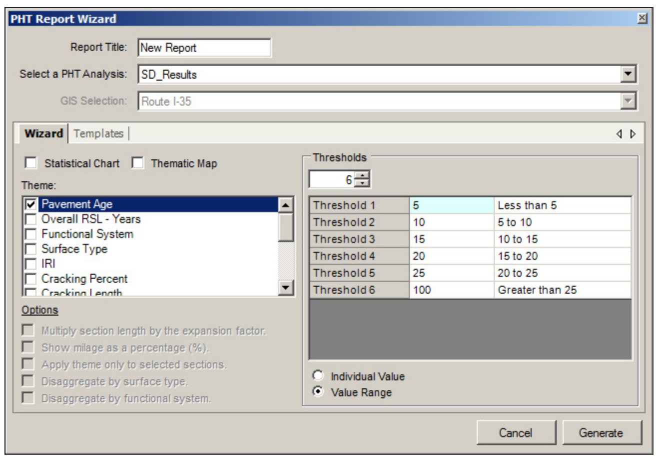


Figure 88. Expanded Reporting Wizard

A title must be provided for the report. To avoid confusion later, the report title should be both descriptive and unique. A set of PHT analysis results must also be selected to provide the basis for the report content.

A list of theme options is provided that determines the purpose of the report. When a theme option is selected, a suggested list of threshold values is automatically provided that defines groupings for the reports information. This is only a suggested list and can be edited by the user as necessary. Each threshold must specify a limit value for its range, followed by a textual description of the data group that the threshold is defining. The limit values can have two meanings as follows:

- **Individual Value.** The data in this grouping must equal the limit value. This setting is useful when the theme is based on an enumerated value, such as the function system.
- **Value Range.** The data in this grouping must lie within the range defined by the upper limit value inclusively and the previous threshold's upper limit value exclusively; for the first threshold, the range is defined as less-than limit value inclusively. When using this setting, the limit values for each subsequent threshold must always increment in value.

The Report Wizard can generate a statistical chart, a thematic map, or both together using the same settings. When the report is generated, it is automatically added to the document library and the current Study.

Statistical Charts

Statistical charts are used to create complex graphs that illustrate quantitative information generated by the PHT analysis. Extensive formatting features are available to create many types and styles of charts that can be saved to a template library for reuse. Check the *Statistical Chart* checkbox to instruct the wizard to generate a chart report. An example of a statistical chart is shown in Figure 89.

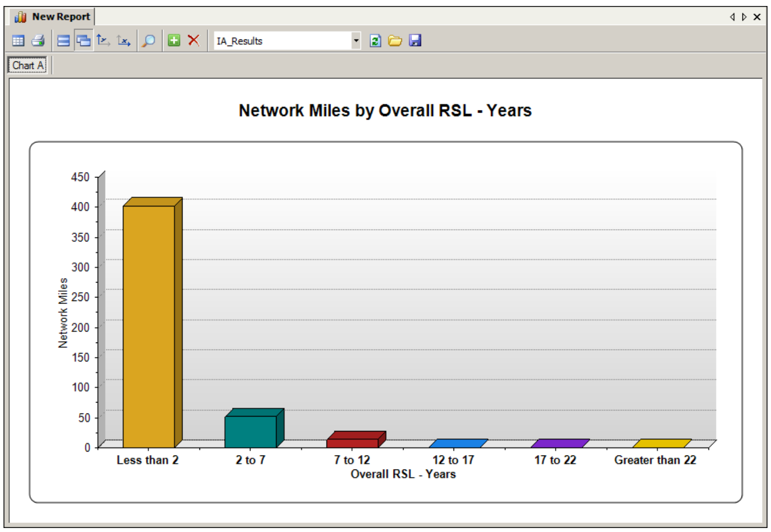


Figure 89. Statistical Chart Example

A number of options are available when generating a statistical chart report:

- Multiply section length by the expansion factor. This option will instruct the wizard to multiply the length of the highway section by its expansion factor when determining its overall total length. If no expansion factor is provided in the data, then the unmodified section length will be used. This option is useful when you have a small number of samples that represent a large number of miles and you want the report to more accurately represent the actual highway miles in the theme group.
- Show mileage as a percent. This option will instruct the wizard to determine the total number of miles in the data set and calculate the overall percent of miles included in the theme group to be used in the chart rather than actual miles.
- Disaggregate by surface type. This option will instruct the wizard to disaggregate the data for each theme group into sub-groups by the pavement surface type. This option in not available for thematic maps.
- Disaggregate by function system. This option will instruct the wizard to disaggregate the data for each theme group into sub-groups by the function system. This option in not available for thematic maps.

When displaying multiple charts you have the option to display them arranged as wither as *Tabbed* or *Stacked*. The tabbed feature has the advantage of maximizing the amount of screen space available to display each chart, but only displays one chart at a time, while the stacked feature allows you to view all the charts at once, but limits the amount of space available to display each chart.

The chart appearance can be customized using the chart properties window; simply RIGHT-click anywhere in the chart area window to activate the properties dialog for the chart. Settings include color and shading, 3D effects, chart types, legend appearance, plot types, grids, axis scales and annotations, and chart labels.

A common Y-axis scale can be applied for all the charts. This is useful feature to visualize the relative values among multiple charts that show similar information with a common unit of measurement. Synchronizing the X-axis will visually align the axis positions of several charts together. This is required when using the Zoom feature and the stacked page layout.

A zooming feature is available for the X-axis. When the zooming is active, a zoom bar appears at the bottom of the chart window. You can adjust the amount of zoom and pan by dragging the beginning and ending markers to the left or right as desired. When zooming is deactivated, all zooming will be removed from the charts.

When printing the chart, the print destination can be a printer, Windows clipboard, or a bitmap file. Options are available to set the position and scaling of the chart image as desired. A preview of the printed chart is also provided.

Thematic Maps

Thematic maps are used to create complex geographical information system (GIS) maps. A GIS defined selection must be chosen from the drop-down list for the wizard to use as the source for the map. The GIS selection provides the information about the GIS shape file and how to join the PHT analysis results to the shapes defined in the file. An example of a thematic map is shown in Figure 90.

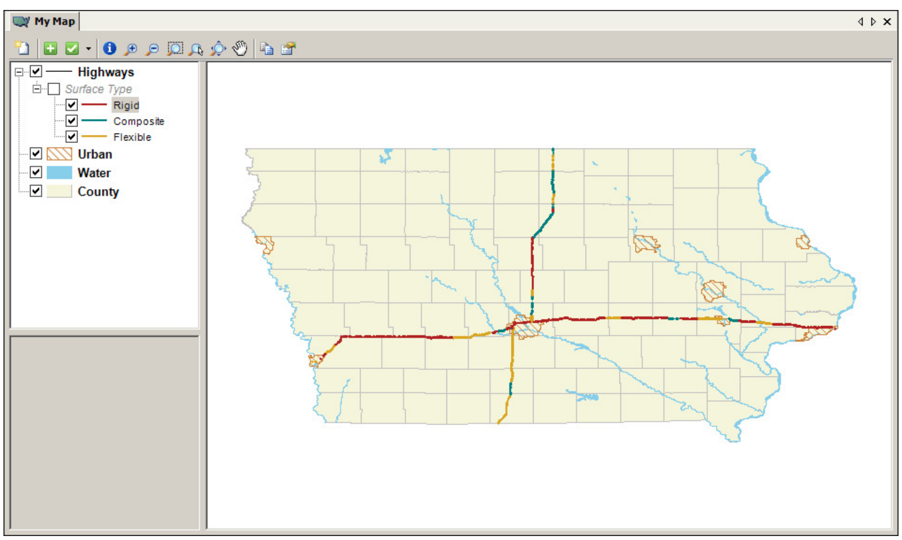


Figure 90. Thematic Map Example

Check the *Thematic Map* checkbox to instruct the wizard to generate a chart report. There is one option available when generating a thematic map report.

- Apply theme only to selected sections. This option will instruct the wizard to apply the map theme only to the highway sections that are selected in the GIS selection. This option is useful when you want the map theme to be highlighted only on a sub-section of the map such as a corridor, type of functional class, or a geographical region such as a county or urban area.

The map layer is the basic component of a map. A map can have multiple layers with each layer displaying the contents of a different shape file. The order in which the layers are displayed is shown in the legend with the layer at the top appearing above all layers beneath it.

To create a selection of items from the map, click the *Selection* button on the toolbar and a new selection is added to the currently selected layer and displayed in the legend. The selection is highlighted with a user-defined color, line thickness and style. The drop-down menu provides three methods available to add items to the selection.

- Select by Attributes. This option will display the query dialog where you can build a SQL query statement to select items based on their attributes. The query wizard allows you to define selection criteria to add items to the selection.
- Manual Selection. This option allows you to manually add items to the selection by clicking on them in the GIS map. Only items that are in the currently selected map layer can be added.
- Select by Shortest Path. This option applies to line-layers only and allows you to automatically select a map corridor between two points. If no unbroken path between the two points can be found, then no items will be added to the selection.

To view the attributes of any item in the map, click the *Identify* button on the toolbar and then click the item on the map. Items on any layer of the GIS map may have many attributes that describe them. These attributes are useful to create map selections and themes. The attributes for the item appear in a table under the legend.

Templates

The PHT report wizard can also automatically generated statistical charts based on a predefined template that resides in the template library. The template library is displayed by clicking on the Template tab as shown in Figure 91. The chart templates are created and formatted in accordance with design of the chart template feature discussed under Task 10.

Several predefined templates are provided with the PHT analysis tool. The following paragraphs discuss the purpose of these templates and provide an example of the chart produced by each template file.

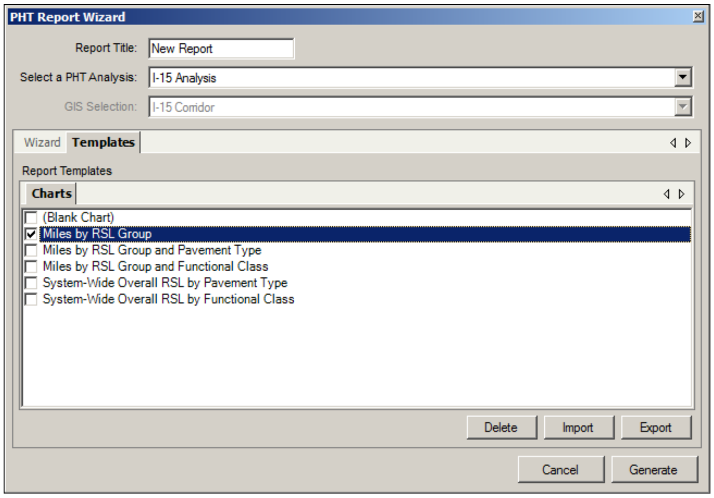
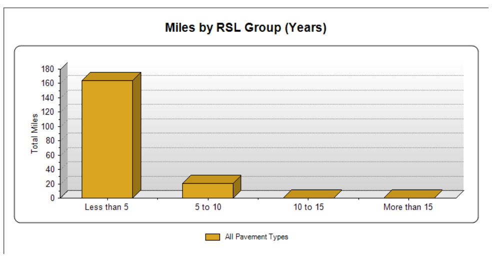
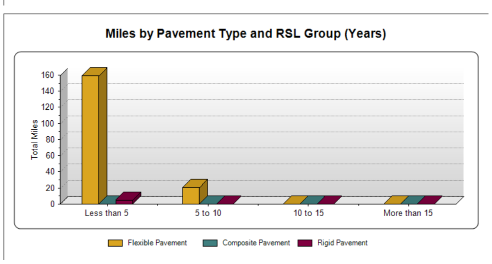


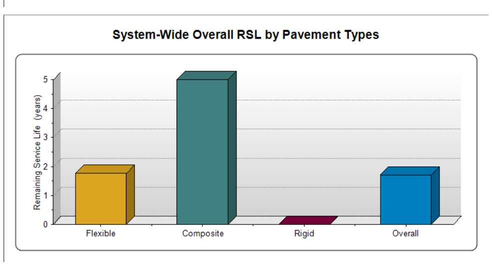
Figure 91. Chart Template Example



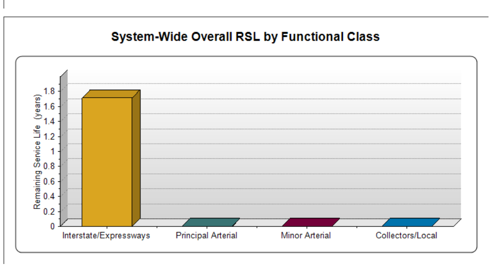
The miles by RSL group chart provides an accounting of the highway miles that have an RSL forecast in four ranges.



The miles by pavement type and RSL group is similar to the first chart except that it further disaggregates the highways by their pavement types. There is also a chart template that will disaggregate by functional class.



The system-wide RSL by pavement type provides the RSL estimates for all highway sections, disaggregated by their pavement type as well as an overall average RSL.



The system-wide RSL by functional class chart provides the RSL estimates for all highway sections disaggregated by their functional classes.

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APPENDIX A

SUMMARY OF SELECTED LTPP PROJECTS FOR SENSITIVITY ANALYSIS

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Selected Projects – Identification and Location

ID	State	Functional System	Route	Begin Milepost	End Milepost	Length
101051	Alabama	Principal Arterial	280	0	0.1	0.1
106042	Alabama	Interstate	59	0	0.1	0.1
141261	Alabama	Interstate	65	308.89	308.99	0.1
402201	Arizona	Interstate	10	109	109.1	0.1
405052	Arizona	Interstate	8	159.01	159.11	0.1
501161	Arkansas	Principal Arterial	63	0	0.1	0.1
602081	California	Principal Arterial	99	32.42	32.52	0.1
605632	California	Interstate	40	23.78	23.88	0.1
630421	California	Interstate	5	48.6	48.7	0.1
802201	Colorado	Interstate	76	18.46	18.56	0.1
810531	Colorado	Principal Arterial	50	75.3	75.4	0.1
1002021	Delaware	Principal Arterial	113	24.11	24.21	0.1
1201061	Florida	Principal Arterial	27	12.03	12.13	0.1
1205052	Florida	Principal Arterial	1	1.75	1.85	0.1
1238041	Florida	Interstate	75	262.4	262.5	0.1
1902151	Iowa	Freeway/Expressway	65	80.1	80.2	0.1
2001041	Kansas	Principal Arterial	54	114.94	115.04	0.1
2405092	Maryland	Principal Arterial	15	4	4.1	0.1
2510021	Massachusetts	Interstate	391	1.95	2.05	0.1
2805052	Mississippi	Interstate	55	136	136.1	0.1
3001181	Montana	Interstate	15	266.5	266.6	0.1
3005042	Montana	Interstate	90	366	366.1	0.1
3005082	Montana	Interstate	90	366	366.1	0.1
3405022	New Jersey	Interstate	195	11.4	11.5	0.1
3501051	New Mexico	Interstate	25	36.5	36.6	0.1
3510221	New Mexico	Principal Arterial	44	125.1	125.2	0.1
3802241	North Dakota	Interstate	94	331.7	331.8	0.1
3830061	North Dakota	Principal Arterial	2	207.73	207.83	0.1
4530121	South Carolina	Interstate	77	35.6	35.7	0.1
4810761	Texas	Principal Arterial	62	21.12	21.22	0.1
4835891	Texas	Principal Arterial	287	20	20.1	0.1
5330141	Washington	Principal Arterial	395	26.11	26.21	0.1
606042	California	Interstate	5	14.58	14.68	0.1
674562	California	Interstate	5	9.65	9.75	0.1
870352	Colorado	Interstate	70	286.25	286.35	0.1
401171	Arizona	Principal Arterial	93	52.62	52.72	0.1
1806032	Indiana	Principal Arterial	31	213.05	213.15	0.1
2906622	Missouri	Interstate	35	88	88.1	0.1
406042	Arizona	Interstate	40	202.16	202.26	0.1
5338132	Washington	Principal Arterial	14	11.03	11.13	0.1

Selected Projects – Surface Type and Construction

ID	Surface Type	Base Type	Rigid Thickness (inches)	Flexible Thickness (inches)	Base Thickness (inches)	Overlay Thickness (inches)	Year of Overlay	Year of Construction
101051	AC	Stabilized		4.1	4.1			2011
106042	AC/JCP	Aggregate	10.3		6.3	4	2011	1966
141261	AC	Aggregate		13.1	18.4			2011
402201	JPCP	Concrete	11.2		6.1			2011
405052	AC/AC	Aggregate		4.1	12.8	2.8	2011	1968
501161	AC	Stabilized		4.1	11.8			2011
602081	JPCP	Concrete	10.7		6			2011
605632	AC/AC	Aggregate		2.7	26.7	4.3	2011	1966
630421	JPCP	Aggregate	8.8		10.3			2011
802201	JPCP	Concrete	11.2		6.2			2011
810531	AC	Aggregate		4.6	28.9			2011
1002021	JPCP	Aggregate	8.8		28.5			2011
1201061	AC	Stabilized		7.7	8.3			2011
1205052	AC/AC	Aggregate		2.1	26.8	2.6	2011	1971
1238041	JPCP	Aggregate	12		6.7			2011
1902151	JPCP	Aggregate	11.4		29.8			2011
2001041	AC	Stabilized		6.6	12.1			2011
2405092	AC/AC	Aggregate		3.4	17.4	3.6	2011	1971
2510021	AC	Aggregate		7.8	12.4			2011
2805052	AC/AC	Stabilized		4.4	7.8	2	2011	1973
3001181	AC	Stabilized		4.6	8.5			2011
3005042	AC/AC	Aggregate		4.4	19.1	5.6	2011	1982
3005082	AC/AC	Aggregate		2.2	19.2	6.9	2011	1982
3405022	AC/AC	Aggregate		8.7	10	1.7	2011	1968
3501051	AC	Stabilized		5.8	4.1			2011
3510221	AC	Aggregate		6.3	10.6			2011
3802241	JPCP	Stabilized	11		4.1			2011
3830061	JPCP	Aggregate	8.4		4			2011
4530121	JPCP	Concrete	10		5.5			2011
4810761	AC	Aggregate		5.4	8.4			2011
4835891	JPCP	Aggregate	9.9		6.2			2011
5330141	JPCP	Aggregate	10.4		5.4			2011
606042	AC/JCP	Concrete	8.5		4.5	4.6	2011	1977
674562	AC/JCP	Aggregate	12		4.8	4.7	2011	1971
870352	AC/JCP	Aggregate	8.4		3.3	5	2011	1965
401171	AC	Stabilized		7.4	4			2011
1806032	AC/JCP	Stabilized	10.3		3.4	3.7	2011	1972
2906622	AC/JCP	Aggregate	9.4		4.5	8	2011	1975
406042	AC/JCP	Concrete	8.2		4.9	4	2011	1966
5338132	AC/JCP	Aggregate	8		8.9	5.2	2011	1966

Selected Projects – Traffic Loading and Climate and Soil Type

ID	AADT	AADT (Single Unit)	AADT (Combination)	Future AADT	Future AADT Year	Climate	Soil Type
101051	1500	325	1175	2805	2040	WNF	Fine
106042	9000	798	8202	16833	2040	WNF	Course
141261	3990	2206	3204	6378	2040	WNF	Course
402201	8544	1147	7397	19718	2040	DNF	Course
405052	1381	170	1213	2364	2040	DNF	Course
501161	9850	2127	7723	18417	2040	WF	Course
602081	4860	1128	3732	8170	2040	DNF	Course
605632	2478	240	2240	2478	2040	DNF	Fine
630421	7884	1372	6497	14116	2040	DNF	Fine
802201	741	190	551	1106	2040	DF	Fine
810531	6000	3971	2029	9122	2040	DF	Fine
1002021	371	173	198	999	2040	WF	Course
1201061	6000	919	5081	11222	2040	WNF	Course
1205052	338	271	68	563	2040	WNF	Course
1238041	2163	694	1471	3198	2040	WNF	Course
1902151	500	151	349	11056	2040	WF	Fine
2001041	7000	1485	5515	24344	2040	WF	Fine
2405092	1230	632	599	2173	2040	WF	Fine
2510021	2000	1173	827	2058	2040	WF	Course
2805052	2236	208	2028	3811	2040	WNF	Fine
3001181	5000	1164	3836	8022	2040	DF	Course
3005042	1366	210	1156	2372	2040	DF	Course
3005082	1366	210	1156	2372	2040	DF	Course
3405022	2125	1103	1020	3533	2040	WF	Course
3501051	1000	299	701	2376	2040	DNF	Fine
3510221	2000	599	1401	4447	2040	DF	Course
3802241	5000	1621	3379	9138	2040	WF	Course
3830061	500	172	327	940	2040	DF	Fine
4530121	3879	628	3254	6815	2040	WNF	Fine
4810761	2000	740	1260	2375	2040	DNF	Course
4835891	1429	217	1210	2153	2040	WNF	Course
5330141	2000	490	1510	2000	2040	DF	Course
606042	9000	1362	7638	22050	2040	DNF	Course
674562	9500	1205	8295	32599	2040	DNF	Course
870352	9500	3444	6056	32599	2040	DF	Fine
401171	9999	3530	6469	32599	2040	DNF	Course
1806032	9500	2147	7353	32599	2040	WF	Fine
2906622	8000	830	7170	32599	2040	WF	Fine
406042	9500	1021	8479	32599	2040	DNF	Course
5338132	9500	5719	3781	32599	2040	DF	Course

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APPENDIX B

PHT DATA VALIDATION CHECKS

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Range Validations

Number	Description
0001.0	The year of record must be greater than 1900. Condition: The **year_record** (1) field is less than 1900.
0002.0	State code must be a valid FIPS code. Condition: The **state_code** (2) field is not a valid state code.
0003.0	Route ID must be a nonzero alphanumeric value. Condition: The **route_id** (3) field blank or equal to 0.
0004.0	Begin point must not be less than zero. Condition: The **begin_point** (4) field is less than 0.
0005.0	End point must not be less than zero. Condition: The **end_point** (5) field is less than 0.
0006.0	Section length must be greater than zero. Condition: The **section_length** (6) field is not greater than 0.
0007.0	Functional System must be a value in the range [1-7]. Condition: The **f_system** (7) field is less than 1 or greater than 7.
0009.0	Facility Type must be a value in the range [1-6]. Condition: The **facility_type** (9) field is less than 1 or greater than 6.
0010.0	Structure Type must be a value in the range [0-3]. Condition: The **structure_type** (10) field is less than 0 or greater than 3.
0013.0	Number of Through Lanes must not be less than one. Condition: The **through_lanes** (13) field is less than 1.
0020.0	Speed Limit must be greater than zero and should be divisible by 5. Condition: The **speed_limit** (20) field is not greater than 0 and divisible by 5.
0026.0	AADT must not be less than zero. Condition: The **aadt** (26) field is less than 0.
0027.0	AADT for Single-Unit Trucks must not be less than zero. Condition: The **aadt_single_unit** (27) field is less than 0.
0029.0	AADT for Combination Trucks must not be less than zero. Condition: The **aadt_combination** (29) field is less than 0.

Number	Description
0033.0	Future AADT must be greater than zero. Condition: The **future_aadt** (33) field is not greater than 0.
0040.0	Lane Width should be a value from 6 to 18 feet. Condition: The **lane_width** (40) field is less than 6 or greater than 18.
0043.0	Shoulder Type must be a value in the range [1-7]. Condition: The **shoulder_type** (43) field is less than 1 or greater than 7.
0063.0	IRI must contain a value from 0 to 955. Condition: The **iri** (63) field is less than 0 or greater than 955.
0064.0	PSR must contain a value from 0.0 to 5.0. Condition: The **psr** (64) field is less than 0.0 or greater than 5.0.
0065.0	Surface Type must be a value in the range [1-11]. Condition: The **surface_type** (65) field is less than 1 or greater than 11.
0066.0	Rutting must not be less than zero. Condition: The **rutting** (66) field is less than 0.
0067.0	Faulting must not be less than zero. Condition: The **faulting** (67) field is less than 0.
0068.0	Cracking Percent must not be less than 0 or greater than 100. Condition: The **cracking_percent** (68) field is less than 0 or greater than 100.
0069.0	Cracking Length must not be less than zero. Condition: The **cracking_length** (69) field is less than 0.
0071.0	The year of construction must be greater than 1900. Condition: The **year_last_construction** (71) field is less than 1900.
0072.0	Last Overlay Thickness must not be less than zero. Condition: The **last_overlay_thickness** (72) field is less than 0.
0073.0	Rigid Pavement Thickness must not be less than zero. Condition: The **thickness_rigid** (73) field is less than 0.
0074.0	Flexible Pavement Thickness must not be less than zero. Condition: The **thickness_flexible** (74) field is less than 0.

Number	Description
0075.0	Base Type must be a value in the range [1-8]. Condition: The **base_type** (75) field is less than 1 or greater than 8.
0076.0	Base Pavement Thickness must not be less than zero. Condition: The **base_thickness** (76) field is less than 0.
0077.0	Climate Zone must be a value in the range [1-4]. Condition: The **climate_zone** (77) field is less than 1 or greater than 4.
0078.0	Soil Type must be a value in the range [1-2]. Condition: The **soil_type** (78) field is less than 1 or greater than 2.
0079.0	County code must be a valid FIPS code. Condition: The **county_code** (79) field is not a valid county code.
0089.0	Volume Group must be a value in the range [1-12]. Condition: The **volume_group** (89) field is less than 1 or greater than 12.
0090.0	Expansion Factor must not be less than one. Condition: The **expansion_factor** (90) field is less than 1.

Cross Field Validations

Number	Description
1005.0	End point must be greater than the Begin point. Condition: The **end_point** (5) field is not greater than the **begin_point** (4) field.
1006.0	The Section Length must equal the distance between the begin and end points within 0.1 miles. Condition: The **end_point** (5) field minus the **begin_point** (4) field does not equal the **section_length** (6) filed plus or minus 0.1 miles.
1009.0	Interstate should not be a one-way facility. Condition: The **facility_type** (9) field equals 1 (one-way) AND The **f_system** (7) field equals 1 (interstate).
1013.0	Number of Through Lanes must not be zero when the functional system is less than [6]. Condition: The **through_lanes** (13) field equals 0 AND The **f_system** (7) field does NOT equal 6 (minor collector) or 7 (local).
1013.1	Number of Through Lanes should be two or more for a paved two-way facility. Condition: The **through_lanes** (13) field is less than 2 AND The **facility_type** (9) field equals 2 (two-way) AND The **surface_type** (65) field does NOT equal 1 (unpaved)
1020.1	Low Speed Limit of less than 50 MPH on an interstate. Condition: The **speed_limit** (20) field is less than 50 AND The **f_system** (7) field equals 1 (interstate).
1026.0	AADT must not be less than the sum of the single-unit and combination truck AADT. Condition: The **aadt** (26) is less than the sum of **aadt_single_unit** (27) and **aadt_combination** (29).
1026.1	AADT must not be zero when the facility is an interstate, freeway or principal arterial. Condition: The **aadt** (26) field equals to zero AND The **f_system** (7) field equals 1 or 2 (interstate or freeway) or 3 (principal arterial).
1026.2	Low AADT on interstate of less than 1000. Condition: The **aadt** (26) field is less than 1000 AND The **f_system** (7) field equals 1 (interstate).
1026.3	Low AADT of less than 500 per lane with more than 4 through lanes. Condition: The **aadt** (26) field divided by **through_lanes** (13) is less than 500 AND The **through_lanes** (13) is greater than 4.

Number	Description
1027.0	The sum of the single-unit and combination truck AADT must not be zero on an interstate. Condition: The sum of **aadt_single_unit** (27) and **aadt_combination** (29) equals zero AND The **f_system** (7) field equals 1 (interstate).
1033.0	Future AADT growth is more than 4 times or less than 0.4 times the AADT. Condition: The **future_aadt** (33) field is greater than **aadt** (26) times 4 or less than **aadt** (26) times 0.4.
1033.1	Future AADT has the same value as the AADT. Condition: The **future_aadt** (33) field equals the **aadt** (26) field.
1034.0	Future AADT year should be between 18 and 25 years beyond the Year-of-Record. Condition: The **future_aadt_year** (34) is less than the **year_record** (1) plus 18 OR The **future_aadt_year** (34) is greater than **year_record** (1) plus 25.
1043.0	Shoulder Type is none or earth on Interstate. Condition: The **shoulder_type** (43) field equals 1 (none) or 6 (earth) AND The **f_system** (7) equals 1 (interstate).
1063.0	IRI should not be zero when the facility is paved. Condition: The **iri** (63) equals zero AND The **surface_type** (65) is greater than 1 (paved).
1063.1	IRI should be zero when the facility is unpaved. Condition: The **iri** (63) is NOT zero AND The **surface_type** (65) field equals 1 (unpaved).
1063.2	Facility has an extremely low IRI of less than 30. Condition: The **iri** (63) field is less than 30 and NOT equal to zero.
1063.3	Facility has an extremely high IRI of greater than 400. Condition: The **iri** (63) field is greater than 400.
1064.0	PSR should not be zero when the facility is paved and IRI is zero. Condition: The **psr** (64) is zero AND The **surface_type** (65) is greater than 1 (paved) AND The **iri** (63) field is zero.
1064.1	PSR should be zero when the facility is unpaved. Condition: The **psr** (64) is does NOT equal zero AND The **surface_type** (65) field equals 1 (unpaved).

Number	Description
1065.0	Unpaved facility on an interstate, freeway or principal arterial. Condition: The **surface_type** (65) field equals 1 (unpaved) AND The **f_system** (7) field equals 1 or 2 (interstate or freeway) or 3 (principal arterial).
1066.0	Rutting is not a distress for a rigid surface. Condition: The **rutting** (66) field data is provided AND The **surface_type** (65) field equals 3, 4, 5, 9 or 10 (rigid).
1066.1	Rutting must be provided for a flexible or composite surface. Condition: The **rutting** (66) field data is NOT provided AND The **surface_type** (65) field equals 2, 6, 7 or 8 (flexible or composite).
1067.0	Faulting is not a distress for a flexible or composite surface. Condition: The **faulting** (67) field data is provided AND The **surface_type** (65) field equals 2, 6, 7 or 8 (flexible or composite).
1067.1	Faulting must be provided for a rigid surface. Condition: The **faulting** (67) field data is NOT provided AND The **surface_type** (65) field equals 3, 4, 5, 9 or 10 (rigid).
1068.0	Cracking percent must be provided for a rigid, flexible or composite surface. Condition: The **cracking_percent** (68) field data is NOT provided AND The **surface_type** (65) field equals 2, 3, 4, 5, 6, 7, 8, 9 or 10 (rigid, flexible and composite).
1069.0	Cracking length is not a distress for a rigid surface. Condition: The **cracking_length** (69) field data is provided AND The **surface_type** (65) field equals 3, 4, 5, 9 or 10 (rigid).
1069.1	Cracking length must be provided for a flexible or composite surface. Condition: The **cracking_length** (69) field data is NOT provided AND The **surface_type** (65) field equals 2, 6, 7 or 8 (flexible or composite).
1070.0	The year of last improvement must not be less than the year of last construction. Condition: The **year_last_improv** (70) field is greater than 0 AND The **year_last_improv** (70) field is less than the **year_last_construction** (71) field.
1070.1	The year of last improvement must not be greater than the year of record. Condition: The **year_last_improv** (70) field is greater than the **year_record** (1) field.

Number	Description
1070.2	The year of last improvement must be provided when an overlay exists. Condition: The **year_last_improv** (70) field is NOT greater than zero AND The **surface_type** (65) field equals 6, 7 or 8 (overlay).
1070.3	The year of last improvement must equal the year of construction when no overlay exists. Condition: The **year_last_improv** (70) field is greater than zero AND The **year_last_improv** (70) field does NOT equal the **year_last_construction** (71) field AND The **surface_type** (65) field 1, 2, 3, 4, 5, 9, 10 or 11 (no overlay).
1071.0	The year of last construction must not be greater than the year of record. Condition: The **year_last_construction** (71) field is greater than the **year_record** (1) field.
1072.0	The last overlay thickness must be greater than zero if an overlay has been applied. Condition: The **last_overlay_thickness** (72) field is NOT greater than 0 AND The **surface_type** (65) field equals 6, 7 or 8 (overlay).
1072.1	The last overlay thickness must be zero when no overlay has been applied. Condition: The **last_overlay_thickness** (72) field is greater than 0 AND The **surface_type** (65) field equals 1, 2, 3, 4, 5, 9, 10 or 11 (no overlay).
1072.2	Unusual last overlay thickness of less than 1 or greater than 8 inches. Condition: The **last_overlay_thickness** (72) field is less than 1 OR greater than 8 AND The **surface_type** (65) field equals 6, 7 or 8 (overlay).
1073.0	Rigid Pavement Thickness should not be provided for a flexible surface. Condition: The **thickness_rigid** (73) is greater than 0 AND The **surface_type** (65) field is 2 or 6 (flexible).
1073.1	Rigid Pavement Thickness must be provided for a rigid or composite surface. Condition: The **thickness_rigid** (73) is NOT greater than 0 AND The **surface_type** (65) field is 3, 4, 5, 7, 8, 9, or 10 (rigid or composite).
1073.2	Rigid Pavement Thickness should be between 6 and 16 inches for a rigid surface. Condition: The **thickness_rigid** (73) is less than 6 OR greater than 16 AND. The **surface_type** (65) field is 3, 4, 5, 9, or 10 (rigid).
1074.0	Flexible Pavement Thickness should not be specified for a rigid or composite surface. Condition: The **thickness_flexible** (74) is greater than 0 AND The **surface_type** (65) field is 3, 4, 5, 7, 8, 9, or 10 (rigid or composite).

Number	Description
1074.1	Flexible Pavement Thickness must be provided for a flexible surface. Condition: The **thickness_flexible** (74) is NOT greater than 0 AND The **surface_type** (65) field is 2 or 6 (flexible).
1074.2	Flexible Pavement Thickness should be between 2 and 24 inches for a flexible surface. Condition: The **thickness_flexible** (74) is less than 2 OR greater than 24 AND The **surface_type** (65) field is 2 or 6 (flexible).
1076.0	Base Thickness must not be specified when the base type is none. Condition: The **base_thickness** (76) field is greater than 0 AND The **base_type** (75) field equals 1 (none).
1076.1	Base Thickness must be specified when the when a pavement base is present. Condition: The **base_thickness** (76) field is NOT greater than 0 AND The **base_type** (75) field is greater than 1 (has base).