Changes to the Mechanistic Empirical Pavement Design Guide Software Through Version 0.900, July 2006

DETAILS

24 pages | | PAPERBACK
ISBN 978-0-309-42928-3 | DOI 10.17226/23218

AUTHORS

September 2006

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Subject Area: IIB Pavement Design, Management, and Performance

Responsible Senior Program Officer: Edward T. Harrigan

Research Results Digest 308

CHANGES TO THE *MECHANISTIC-EMPIRICAL PAVEMENT DESIGN GUIDE* SOFTWARE THROUGH VERSION 0.900, JULY 2006

This digest summarizes key findings from NCHRP Project 1-40D, "Technical Assistance to NCHRP and NCHRP Project 1-40A: Versions 0.900 and 1.0 of the M-E Pavement Design Software," conducted by Applied Research Associates, Inc., and Arizona State University. The digest was prepared by Michael I. Darter, Jag Mallela, Leslie Titus-Glover, Chetana Rao, Gregg Larson, Alex Gotlif, and Harold Von Quintus, Applied Research Associates, Inc.; Lev Khazanovich, University of Minnesota; and Matthew Witczak, Mohamed El-Basyouny, Sherif El-Badawy, Aleksander Zborowski, and Claudia Zapata, Arizona State University.

CONTENTS

INTRODUCTION

This digest summarizes numerous changes made under NCHRP Project 1-40D to the original Version 0.7 of the *Mechanistic-Empirical Pavement Design Guide* (MEPDG) software delivered under NCHRP Project 1-37A in July 2004. Specifically, the digest describes the corrections incorporated in Version 0.8 (released in November 2005) and the mainly technical improvements and enhancements included in Version 0.900 (released in July 2006).

Changes in Version 0.900 include software changes in general (including changes to traffic and other general topics), as well as changes in the integrated climatic model, in flexible pavement design and analysis, and in rigid pavement design and analysis. These changes reflect the recommendations of the NCHRP 1-40A independent review team, the NCHRP 1-40 panel, the general design community, various other researchers, and the Project 1-40D team itself. Most of these changes have been tracked and summarized in the "Bug Tracker" system at www.ara-tracker.com (the item number for each change is provided in parentheses). Some changes were more technical, including definition changes, and were not included in the Bug Tracker system.

Users of Version 0.900 should recognize the following:

- The climatic database used in the latest calibration and available for design is now substantially larger and enhanced. Old databases downloaded with Versions 0.7 and 0.8 should be eliminated.
- Design solutions and associated files generated with Versions 0.7 and 0.8 require some additional inputs and may experience some problems if simply reloaded and run. It is recommended that the user verify each input (by clicking "ok") before rerunning an old file. It is especially important to review the inputs for the unbound materials (i.e., base,

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

subbase, and subgrade) because several unbound materials require new inputs. If a run still experiences problems, it is recommended that the user re-enter the project inputs as a "new" file and then re-run. The research team recommends that problems of interest be run again with the new version for comparison with earlier solutions.

Version 0.900 of the *Mechanistic-Empirical Pavement Design Guide* software may be downloaded for evaluation at www.trb.org/mepdg/. A final Version 1.0, incorporating additional improvements and enhancements, is scheduled for release by the end of 2006. The AASHTO Joint Technical Committee on Pavements plan to use Versions 0.900 and 1.0 to advance the *Mechanistic-Empirical Pavement Design Guide* through the AASHTO balloting process.

SOFTWARE IN GENERAL (INCLUDING TRAFFIC)

The following general changes were made to the software, including the traffic module:

1. **(#430) Add CRCP and JPCP plots to ACC/PCC outputs.** Plots for LTE, Punchout, Crack Width, Cracking, and Cracking Damage were provided.
2. **(#427) Import/Export capability for unbound material grain size distribution, PI, LL.** Import/export capability for unbound materials so that a default grain size and LL/PI values for soils of interest can be created and used when needed.
3. **(#426) Calculate ESALs for flexible pavement.** The panel wanted ESALs calculated and available to the user, but given that the procedure is NOT based on ESALs, they would only appear in intermediate files and not on the official output for a project. Calculation of ESALs for JPCP has been included in an intermediate file. A similar calculation for flexible pavements was completed. Calculated ESALs are found in the intermediate files under the project folder.
4. **(#414) Include proper default values for grain size distribution and Atterberg limits for unbound materials.** Unbound materials data from several hundred LTPP sections were obtained for all available AASHTO soil classifications. Mean and standard deviations were computed for the range of grain size distribution and Atterberg limits and other properties and incorporated into the defaults of the Design Guide.
5. **(#259) When reducing the number of years, model traffic still calculated for a longer period, which affected run time negatively, perhaps by 20 to 30 seconds.** This problem was resolved.
6. **(#252) Change default design period start dates for all analyses.** September 2006 was used as the start date for all new analyses.
7. **(#244) Create traffic export/import capabilities.** The user is now allowed to import/export all of the data needed for the traffic files within the interface.
8. **(#232) Multiple file select for the batch mode.** Made it possible to use multiple file select to add files to batch mode.
9. **(#231) Increase the width of batch mode file entry screen.** The batch mode screen was widened.
10. **(#125) Double clicking on cone file (*.dgp) crashes.** Opening an MEPDG project file by clicking on the file did not work properly in earlier versions. This problem was fixed.
11. **(#116) Incorporate NCHRP 1-39 Traf-Load files into the MEPDG.** The code was modified to allow the direct use of the outputs of 1-39 software in the MEPDG.
12. **(#79) Batch Mode Option of Software.** Runs in batch mode are now allowed.
13. **(#78) Inadequate amount of climatic data for given file.** An improved warning message was provided for climatic files with less than 12 months of climatic data. Also, several procedures to estimate missing data were included in the software.
14. **(#77) Base type default values.** Work was completed to change the default values when the base type is changed.
15. **(#76) Problems with "Save-As" option.** On a few occasions, two input files containing the same data produced different outputs. This occurred when the file was changed and then saved using the Save-As command in the file menu of the software, and then re-run. The changed inputs might actually not be saved. This problem was corrected.
16. **(#70) Summation of Axle Load Distribution Factors.** In earlier versions, the Axle Load Distribution Factors in the traffic analy-

sis did not appear to count in the last load level in the summation column. This problem was fixed.

17. **(#66) Remove single tire configuration for traffic input.** In earlier versions, the General Traffic Input screen showed both dual and single tire pressure options. The single tire option was removed, given that the software only uses dual tire axles.
18. **(#65) Special axle configuration problems.** Several problems were uncovered with the Special Axle Configuration portion of Version 0.8:
    - Considerable information for the Special Vehicle Help option was added.
    - The asphalt.Td file was corrected to ensure that the correct wheel load coordinate locations are input into the file. In earlier versions, the program allowed the user to input wheel load coordinate locations. Unfortunately, the program read all coordinates at an x=0; y=0 location for each tire of the special vehicle.
    - When the Special Vehicle Option is selected the General Traffic Output summary information was replaced with the key input traffic wheel load properties of the special vehicle.
    - A repetitive error message was eliminated by correcting the code.
    - A problem with the frequency input associated with the use of the Special Vehicle in a Rehabilitation scenario was corrected.
19. **(#50) Changing pavement types after completed run.** Changing the type of pavement analysis once the run was completed caused the program to hang (e.g., changing CRCP to HMA Overlay of CRCP). The problem was fixed.

INTEGRATED CLIMATIC MODEL

Extensive changes were made to the integrated climatic model and the state climatic files to improve the predictive capabilities of the climatic model. These were as follows:

1. **Addition of more climatic data for each weather station.** A new set of weather station files with up to 9 years of hourly data for 851 stations has been provided. It is recommended that old weather stations be deleted and not used with the new version. The new weather stations should be downloaded and used with Version 0.900.
2. **(#360) Review and correct Hourly Climatic Database.** The Version 0.8 Hourly Climatic Database had some errors in the precipitation. This was reviewed and repaired in December 2005. Unfortunately, the fixed files were not widely disseminated.
3. **(#276) Failure in climatic model building.** When trying to build a climatic model from weather stations around Delaware, Iowa, every combination of the six weather stations near the site (42°28′ N 91°21′W, elev = 1053′) reported missing data for month 200101. This problem was fixed.
4. **(#253) Update ICM to allow use of the NCHRP 9-23 Models.** A grain-size distribution plot was created. A grain-size distribution to index property correlation and a base moisture model to the Thornthwaite Moisture Index (TMI) method were updated.
5. **Defaults provided for all unbound materials based on measured properties from several hundred LTPP sections across the United States.**
6. **(#229) Failed ICM stability check. After pressing Run Analysis, the Traffic module completes, then the Climatic module tries to load, but stops with the error "Failed ICM stability check."** The problem was fixed.
7. **(#122) ICM crashes with file and directory names of over 80 characters.** The problem was fixed.
8. **(#74) The Enhanced Integrated Climatic Model (EICM) has been modified and enhanced, based on the results of the NCHRP 9-23 project.** See the Flexible Pavements section.

FLEXIBLE PAVEMENTS

The following changes were made to the software to enhance the design of flexible pavements:

1. **(#413) Granular layer placed over stabilized base crashes for flexible pavement.** The modulus for the granular layer was not being output in _space.dat. The problem was fixed. This makes it possible to include, for example, a lime-stabilized layer below an unbound granular base/subbase layer.

2. **(#74) The EICM has been modified and enhanced, based on the results of the NCHRP 9-23 project.** Several models have been revised and incorporated into the MEPDG code. These models include the following:
   - New Suction Models;
   - New ASU—TMI Models;
   - New SWCC Models;
   - Moisture Content Models with p200-w%;
   - Revise Compaction Models;
   - Revised Specific Gravity Models; and
   - New Saturated Hydraulic Conductivity (ksat) Model.
3. **Version 0.900 will run in batch mode.**
4. **(#124) The analysis period (design life) is increased from 25 to 50 years.**
5. **The run time of the program is decreased.**
6. **The calibration models in the settings screens are updated.**
7. **The national calibration factors of the distress models are updated based on the enhancements done to the models.** In addition, these calibration factors are based on the most up-to-date database.

The following changes were made to improve or correct problems in the software for the design of new and rehabilitated flexible pavements:

1. **(#56) Reflective Cracking was not reported correctly to the output summary sheet.** The problem was corrected and reflective cracking is now reported correctly under the column "Reflective Cracking from the Existing Layers."
2. **The methodology used to report area cracking in the HMA rehabilitation design is based on Reflective Cracking reflected from the existing pavement through the overlay to the surface of the pavement in addition to the amount of fatigue cracking occurring in the new layer.** The results should be interpreted by looking at the time the cracking reached the surface, not by the amount of cracking at the end of the design life.
3. **(#57) In the distress summary output sheet, for the Rehab Analysis, the "Alligator Cracking" output column name is changed to "Alligator Cracking in New Overlay."**
4. **(#58) A new output column named "Total Cracking at Surface" is added to the output.** This column represents the sum of the "Alligator Cracking in New Overlay" and the "Reflective Cracking from the Existing Layers."
5. **(#99) In some cases of AC over AC Rehab Analysis, the software does not accept more than one AC layer.** The problem was corrected and the program now accepts up to three new AC layers over the existing flexible pavement.
6. **The software wrongly allows the user to input any material over the existing layers.** The problem was corrected and the software is now allowing the user to input either AC materials or base courses (unbound or CTB).
7. **(#54) In Level 1 Rehab Analysis, if the user did not input the FWD modulus, the software crashed.** The problem was corrected by incorporating a warning to the user to input the FWD modulus so that the software would not crash.
8. **(#64) In Level 1 and Level 2 Rehab Analyses, if the user did not input the actual rutting and cracking for the existing pavement, the software crashed or yielded unreasonable results.** The problem was corrected by incorporating a warning to the user to input the actual rutting and cracking for the existing pavement so that the software would not crash or yield unreasonable results.
9. **(#55) The damage function in Level 2 Rehab yields results incompatible with Level 3.** The problem was corrected.
10. **The input summary worksheet in the output file for the Rehab Analyses Levels 1, 2, and 3 is missing a lot of information.** The problem was corrected.
11. **Use of any new or overlay AC sublayers with thicknesses greater than 9 in. may lead to sublayering yielding AC thicknesses greater than the original input thickness of the layer.** The problem was corrected.
12. **(#158) The program crashed if the user has a limited access account.** The problem was corrected.

The following changes and corrections were made in the treatment of E* in the design of flexible pavements:

1. **(#67) An error message usually appears when using Level 1 E* characterization in HMA analysis.** The problem was corrected.
2. **Several Level 1 E* input data for AC mixtures cause program crashes.** The problem was corrected. The seed values for the optimization process used for developing the E* master curve coefficients (Time-Temperature Superposition Optimization) were reviewed and updated based on the historical database in order to prevent the program from crashing.
3. **(#72) In Level 1 input analysis for HMA, inputting E* values at a small range of temperatures may result in an incorrect master curve, which may cause the program to crash or yield very incorrect results.** The problem was corrected. The program restricted the E* input values to be at least at three temperatures in a wide range (Temperature > 125°F, Temperature between 60 and 90°F, and Temperature < 45°F).
4. **In Level 1 input analysis for HMA, limits were imposed on the temperature for the G* testing to provide a reasonable range of temperatures.** The G* temperature cannot be less than 40°F or more than 300°F.

The following errors that led to discontinuities in the calculation of rutting in the flexible pavement design were corrected:

1. **(#68) A discontinuity occurs in the AC rut depth with very small changes in AC layer thickness due to the sublayering scheme used in the software.** This discontinuity error was sometimes as high as 20 to 25 percent. The problem was corrected and the error was reduced to less than 10 percent.
2. **(#68) A discontinuity occurs in the subgrade rut depth with small changes in the AC layer thickness.** The problem was corrected and the error was totally eliminated.

The following improvements and corrections in the treatment of unbound materials were made:

1. **The typical default values and ranges for the unbound materials resilient modulus at optimum moisture condition have some wrong values.** The problem was corrected. Table 1 provides new guidelines for use with the program for flexible pavements.
2. **The software mistakenly uses the default values for the unbound materials resilient modulus at optimum moisture condition**

TABLE 1 Recommended resilient modulus input (at optimum density and moisture) for subgrades under flexible pavements and rehabilitation of flexible pavements

AASHTO Soil Classification	Mean Modulus (psi)*	Standard Deviation (psi)	Corrected Mean Modulus (psi)	Standard Deviation (psi)	Recommended Resilient Modulus at Optimum (psi)**
A-1-a	44,471	22,970	29,650	15,315	29,500
A-1-b	39,965	19,428	26,646	12,953	26,500
A-3	37,041	17,853	24,697	11,903	24,500
A-2-4	32,013	19,807	21,344	13,206	21,500
A-2-5	--	--	--	--	21,000
A-2-6	30,832	18,443	20,556	12,297	20,500
A-2-7	24,373	6,897	16,250	4,598	16,500
A-4	29,797	18,442	16,429	12,296	16,500
A-5	--	--	--	--	15,500
A-6	26,313	13,657	14,508	9,106	14,500
A-7-5	23,586	19,595	13,004	13,065	13,000
A-7-6	21,159	11,801	11,666	7,868	11,500

* Results are based on 594 back-calculated values extracted from the MON_FLX_BACKCAL_SECT table found in the Long-Term Pavement Performance (LTPP) database.

** Information obtained after correcting the NDT values to reflect laboratory results at optimum conditions.

when the user chooses Representative Value (Design Value). The problem was corrected and a new set of typical default values and ranges for the Representative Value (Design Value) for the unbound materials resilient modulus has been incorporated.

3. **(#157) The software crashes when running an analysis with unbound materials Level 2 seasonal modulus.** The problem was corrected.

The following improvements and corrections in the treatment of thermal fracture were made:

1. **(#71) In the Level 3 predictive system for thermal fracture, as Vb_{eff} (effective bitumen content) increases, prediction of thermal cracking increases.** The problem was corrected and the Level 3 models for the creep compliance and the tensile strength prediction were modified based on a larger database. Separate creep compliance predictive equations were developed for every test temperature (0, –10, –20°C) to replace a universal equation for all temperatures used in the old version of the Level 3 analysis. These new models provide thermal fracture predictions that meet the test of engineering reasonableness.

Details of the new models for thermal fracture are provided in Figures 1 and 2.

The following issues related to special axle configurations were resolved:

1. **(#65-2) Asphalt.td file does not read the wheel load coordinates input by the user. Instead, it sets all the coordinates to zeros.** The problem was corrected.
2. **(#65-3) The output summary for the special axle configuration shows the wrong data.** The problem was corrected.
3. **(#65-4) An error message appears when performing an analysis using the special axle configuration.** The problem was corrected.
4. **(#65-5) In Rehab Analysis, the software requires the user to input the frequency for the cases of AC, granular base and subgrade layers; however, the frequency should be a required input only for the AC layers.** The problem was corrected.
5. **(#65-5) The program does not save the frequency values input by the user.** In other words, once the user inputs the frequency and clicks "OK," then returns to the same screen, he/she will find that the previously input frequency values disappeared. The problem was corrected.

$$S_t = 4976.34 - 42.49 \cdot Va - 2.73 \cdot Va^2 - 80.61 \cdot VFA + 0.465 \cdot VFA^2 + 174.35 \cdot \log(Pen77) - 1{,}217.54 \cdot \log(A_{RTFO})$$

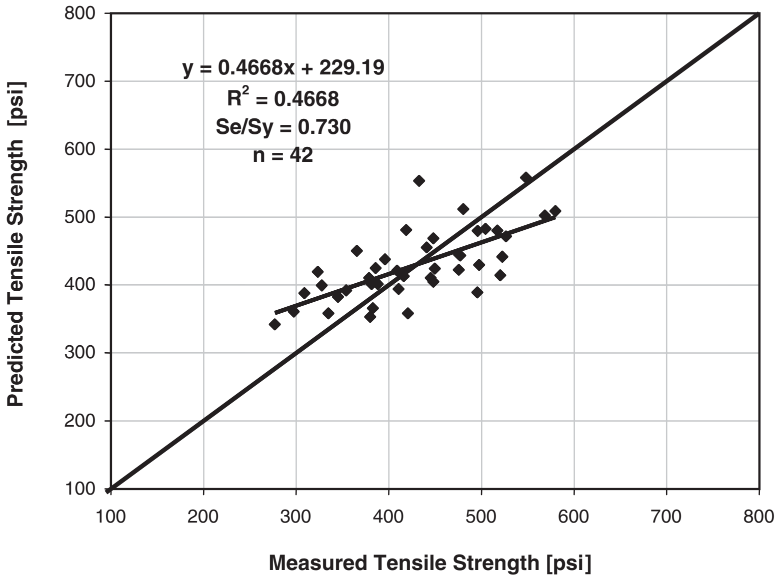
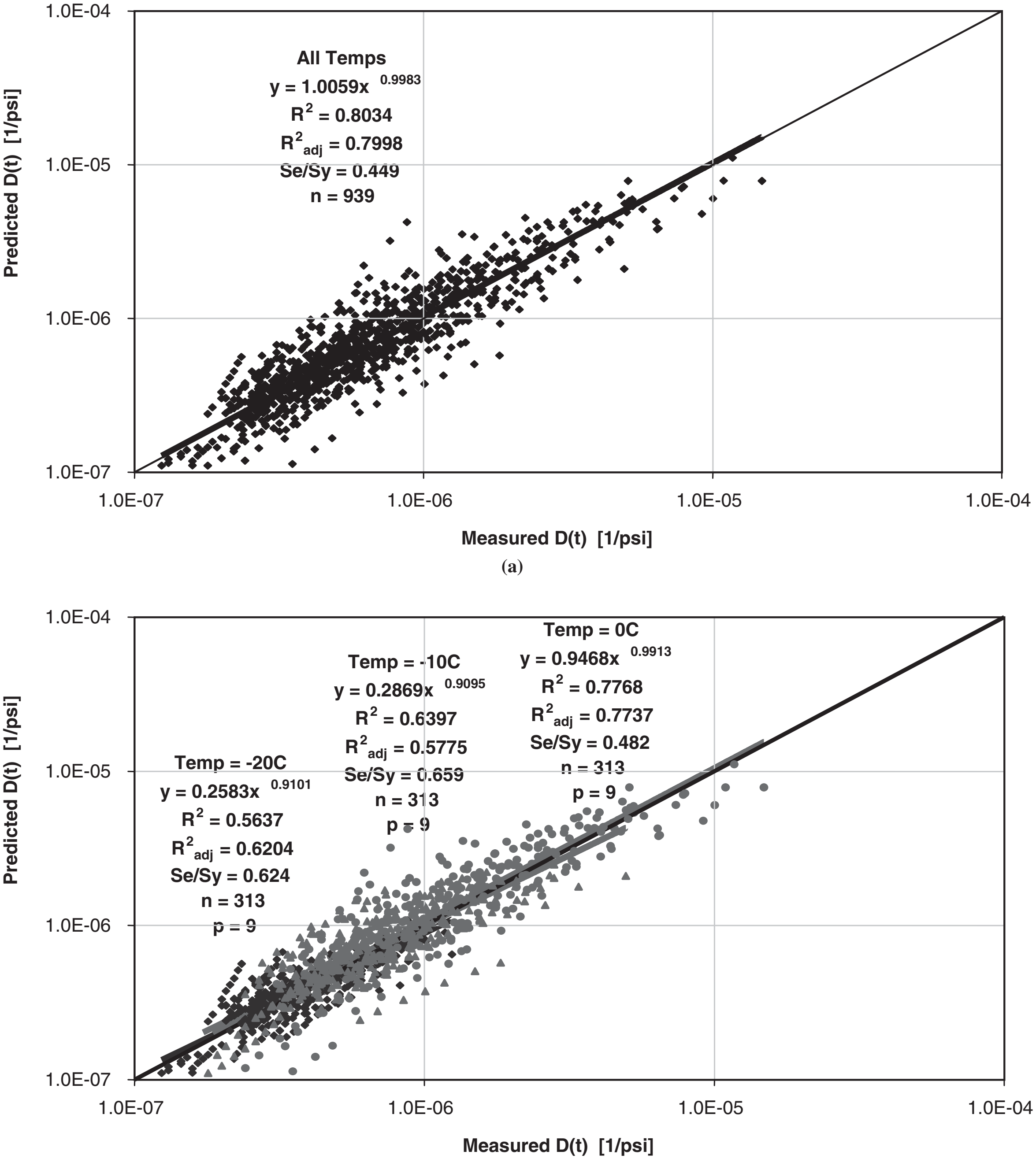


Figure 1 Revised Level 3 prediction model for tensile strength at –10°C.

$$\log(D_1)_{-20C} = -11.92540+1.52206*\log(Va)+4.49876*\log(VFA)-3.81320*\log(A_{RTFO})$$
$$\log(D_1)_{-10C} = -10.76560+1.51960*\log(Va)+3.49983*\log(VFA)-2.99870*\log(A_{RTFO})$$
$$\log(D_1)_{0C} = -\ 9.80627+1.50845*\log(Va)+2.99000*\log(VFA)-2.90157*\log(A_{RTFO})$$

$$m_{-20C} = -1.75987+1.78187*Va^{0.02030} +0.00089*Pen77^{0.96870}$$
$$m_{-10C} = -1.82690+1.94218*Va^{0.01600} +0.00098*Pen77^{0.96857}$$
$$m_{0C} = -2.41043+2.59093*Va^{0.01547} +0.00199*Pen77^{0.97247}$$

$$D(t) = D_1*t^m$$



(a)

(b)

Figure 2 Prediction models for IDT creep compliance D(t) at 0, −10, and −20°C.

The following traffic-related issues in flexible pavement design were addressed:

1. **(#60) Potentially significant problem may occur with the use of the current "Representative Load Analysis Procedure," especially when evaluating overloaded vehicular traffic scenarios.** The problem was corrected and a fixed tire load of 4,500 lb is used as a representative load instead of the variable 95th percentile. This new procedure eliminated the potential problems in the distress prediction that might occur with the use of the old procedure.
2. **(#70) Axle load distribution factors in traffic analysis do not count in the last load level in summation (Total) column.** The problem was corrected.
3. **(#66) General traffic input screen shows "Dual and Single" tire pressure options; however, it should only show the Dual tire pressure option.** The problem was corrected.

The following items summarize the major recalibration of the flexible pavement distress models carried out:

1. A major effort was expended to recalibrate all of the flexible pavement models, including bottom-up fatigue cracking, top-down fatigue cracking, permanent deformation, transverse cracking, and IRI. The final newly calibrated models had a lower model error, reasonable sensitivity to changes in inputs, and better reliability than those originally developed under NCHRP 1-37A. Major steps in this effort included the following:
   - Improving the database
     - Updating all existing sections with 4 to 5 additional years of performance data, traffic data, materials data, climatic data, and rehabilitation data.
     - Incorporating the weather stations that included 9 years of historic hourly data.
     - Establishing the proper input subgrade resilient modulus through an iterative process that included back-calculation of in situ moduli for the sections.
   - Re-establishing the model coefficients for all of the models using the expanded database. Model coefficients were selected that minimized the residual error of prediction.
   - Re-establishing the reliability model coefficients for all of the models using the expanded database.
   - Conducting limited sensitivity analyses to validate the software and changes to the software.
   - Documenting work accomplished (to be published).
2. Revised calibration curves, relevant statistics, and revised models are shown in Figures 3 through 9.
3. Recalibration of the thermal fracture models.

Modification of the thermal fracture predictive equations was followed by the necessary recalibration of the Level 3 thermal cracking model. Given that no new sections were available, the 32 sections from the original calibration developed under NCHRP Project 1-37A were used for the recalibration. The final newly calibrated Level 3 model had, overall, much lower residual error of prediction compared with the old model, and, more important, led to thermal fracture predictions that meet the test of engineering reasonableness.

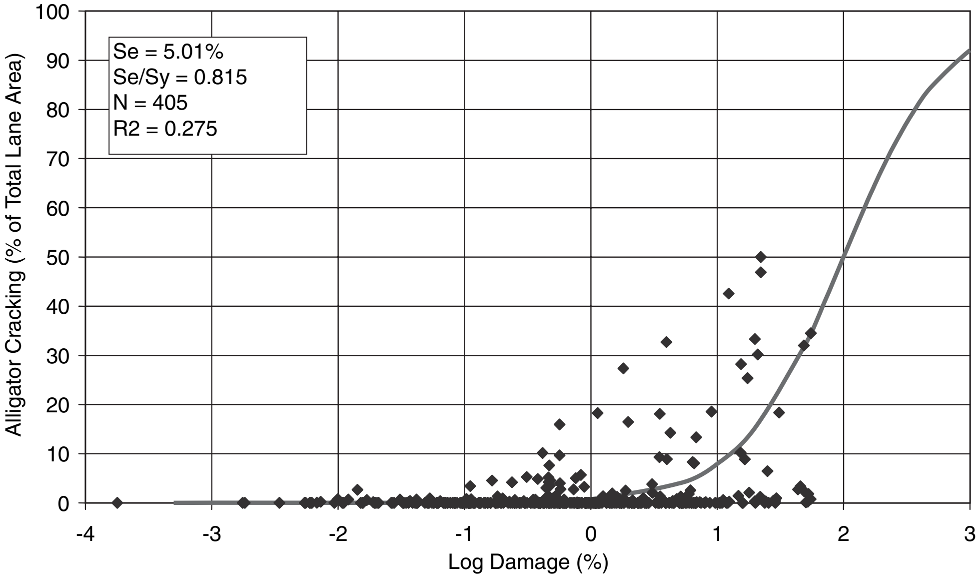
A comparison of predicted versus observed thermal cracking for newly calibrated Level 3 models and a comparison of standard deviation for new and old models are presented in Figures 10 and 11.

The new thermal fracture Level 3 calibration factor and the corresponding standard deviation are

$$Bt3 = 6.0$$
$$\text{Std.Dev (Thermal)} = 0.0869 * \text{Thermal} + 453.98$$

Given that no new sections were available when compared with the original calibration of the thermal fracture models for Level 1 and Level 2 analyses, the main objective of the new process was to calibrate the thermal cracking models with an expanded (9 years of hourly data) EICM climatic database.

The original calibration of the thermal fracture models developed under NCHRP Project 1-37A was done using the real climatic data corresponding to the time in service of the test sections (in some cases, 20 years). However, this calibration was done without the use of EICM and its database (because of the limited amount of data) that is the integral part of the MEPDG software. Level 1 and 2 factors from the original calibration task should be used in the forensic studies when "true" climatic data are available. However, it was more reasonable to calibrate the models using the same climatic database that will be further used in the performance prediction. Whenever



$$Se_{FCBottom} = 1.13+13/(1+e^{7.57-15.5*\log D})$$

New fatigue cracking calibration factors are
Bf1 = 0.00432 / 0.571 = 0.007566
Bf2 and Bf3 stay the same.

Figure 3 Bottom-up fatigue (alligator) cracking calibration and model.

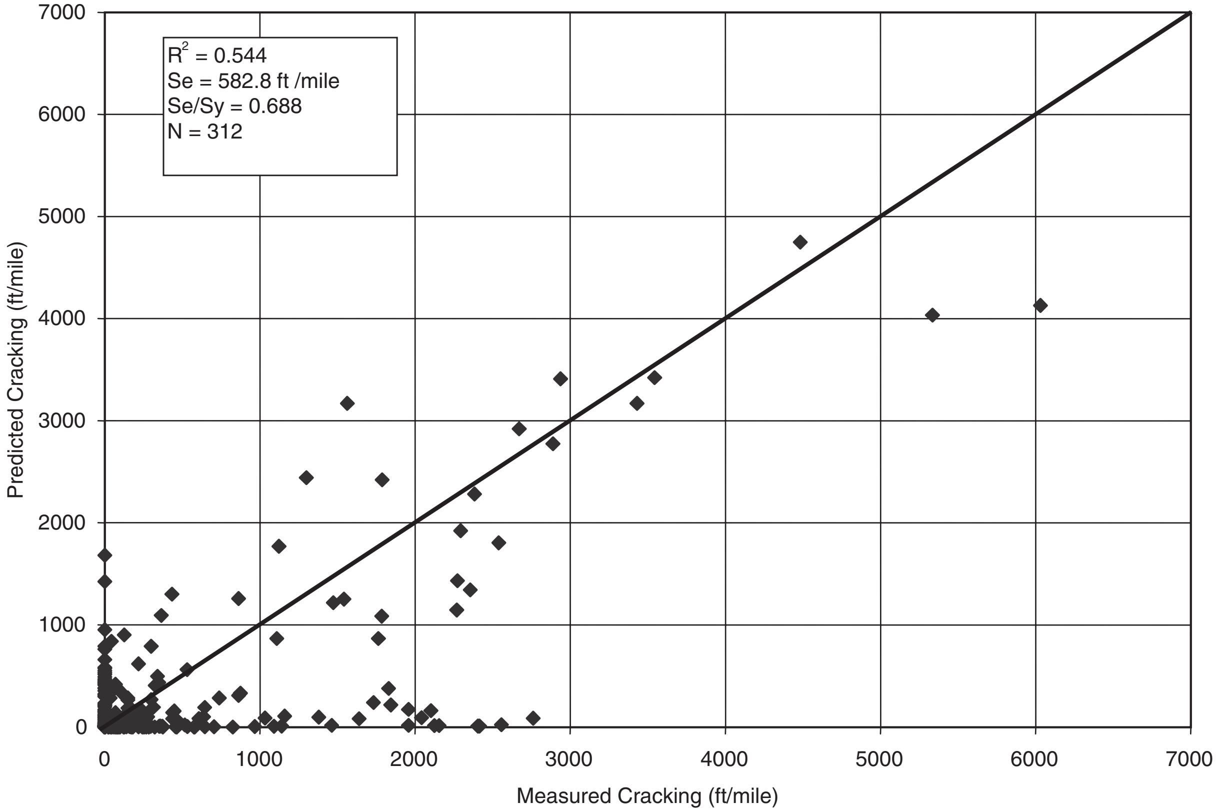
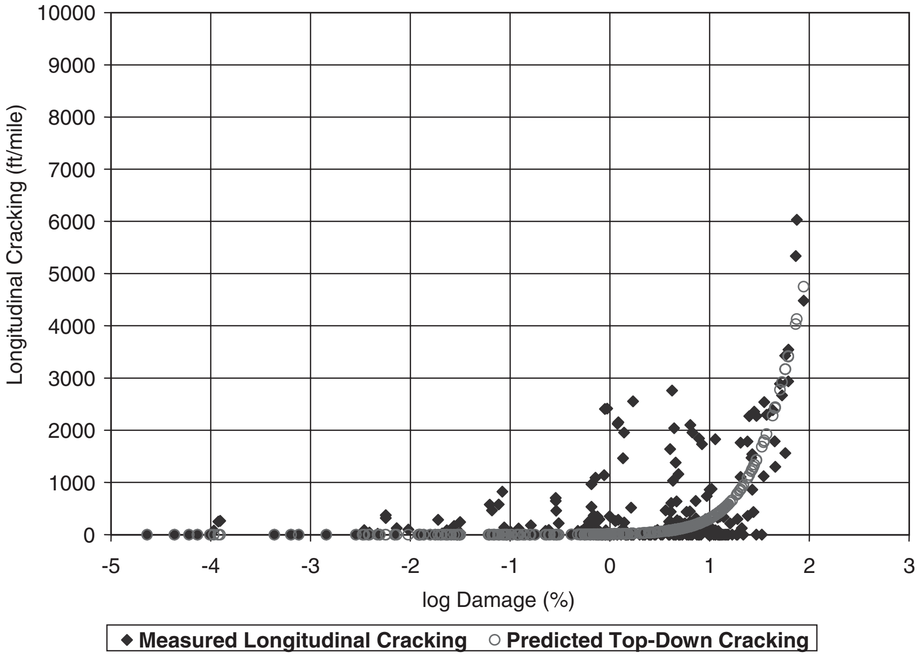


Figure 4 Top-down fatigue cracking calibration, measured vs. predicted.



Se_{FCtop} = 165.68*Log D + 542.53

Damage in % and limit Se to 700 ft/mile

Figure 5 Top-down fatigue cracking calibration and model.

EICM is used to predict the thermal fracture performance of the pavement, the new calibration factors should be used. It was observed that recalibration resulted in higher standard deviations when compared with the original calibration; these higher standard deviations are due to the fact that EICM data were not as precise as the "true" climatic data used in the original calibration.

A comparison of predicted versus observed thermal cracking for recalibrated Level 1 and 2 models and a comparison of standard deviation for new and old models are presented in Figures 12 through 15.

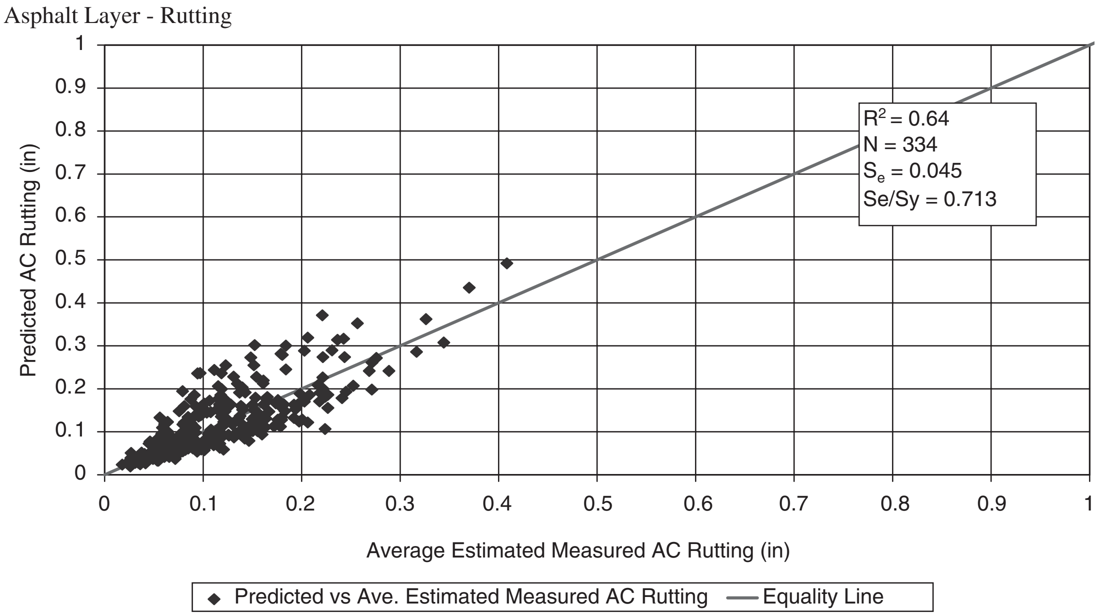


Figure 6 Permanent deformation calibration—rutting in the asphalt layer.

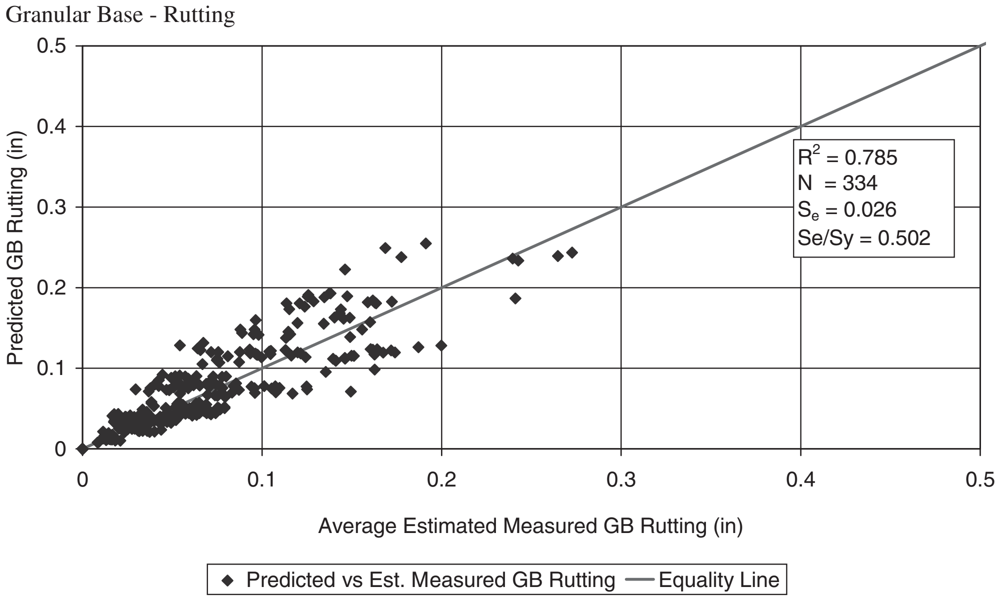


Figure 7 Permanent deformation calibration—rutting in the granular base.

The new thermal fracture Level 1 and Level 2 calibration factors and corresponding standard deviations are

$$Bt1 = 1.0$$
$$\text{Std.Dev (Thermal)} = -0.0899 * \text{Thermal} + 636.97$$
$$Bt2 = 0.5$$
$$\text{Std.Dev (Thermal)} = -0.0169 * \text{Thermal} + 654.86$$

Recalibration permitted the following updating of the flexible pavement IRI models:

1. Considerable additional flexible pavement distress and IRI data have become available since the original model was developed in 1999. Such data were extracted from LTPP and used in the analysis.
2. Two models were developed:
   - New flexible pavements and overlaid flexible pavements combined.
   - HMA overlays of jointed concrete pavements.

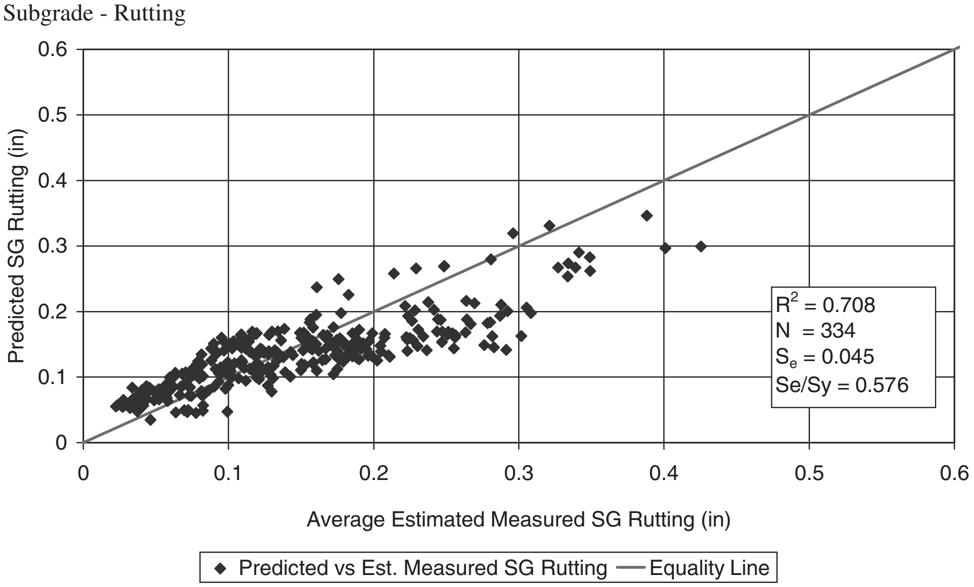
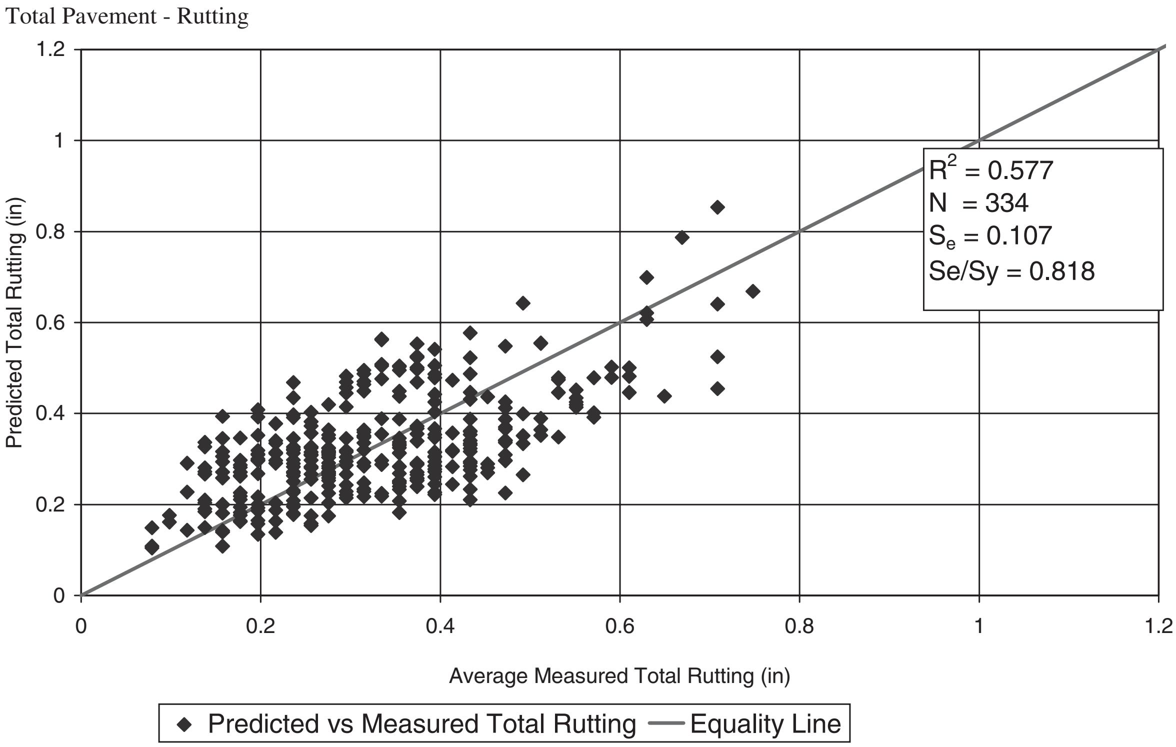


Figure 8 Permanent deformation calibration—rutting in the subgrade.



SeRDAC = 0 .24 ACrut^0.8026 limit to a max value of 0.1
SeRDGB = 0.1477 GBrut^0.6711 limit to a max value of 0.055
SeRDSG = 0.1235 SGrut^0.5012 limit to a max value of 0.065

New Rutting calibration factors are
Br1 = -3.35412, Br2 and Br3 stay the same.

BrGB = 2.03, BrSG = 1.67

Figure 9 Permanent deformation calibration—total pavement rutting.

3. The updated model included the key M-E predicted distress types as follows:
   - Fatigue cracking: bottom up and top down, all severities.
   - Permanent deformation, mean values.
   - Transverse cracking (all severities).
4. The updated models also included the following site factors: mean annual air temperature; freezing index; annual precipitation; percentages of silt, clay, and sand in the subgrade soil; and age of the section.
5. The re-calibrated IRI models were an improvement on the existing models because
   - The functional form is more similar to IRI for rigid pavements.
   - Problematic non-predicted distress models were removed.
   - They are based on a large number of additional LTPP sections.
   - They are based on sections with additional distress and IRI development over time (1998–2005).
   - They directly consider the effect of each M-E-predicted distress on IRI:
     - Permanent deformation
     - Wheelpath cracking: Alligator and Longitudinal fatigue
     - Transverse cracking
   - They consider the effect of site conditions:
     - Subgrade: percent fine sand, silt, clay, and PI
     - Climate: freezing index, precipitation
     - Age: represents cycles of hot/cold, wet/dry, freeze/thaw

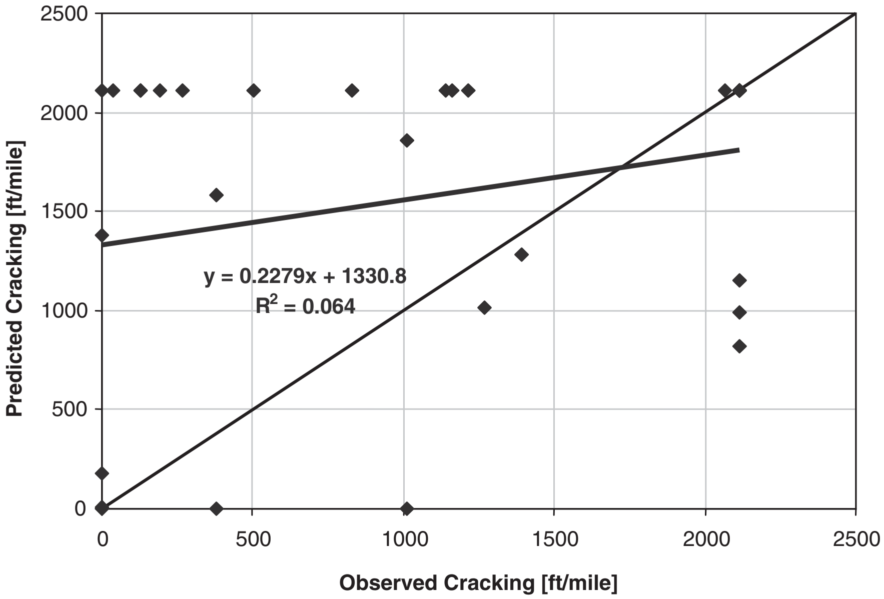


Figure 10 Thermal cracking model calibration DG2002 Level 3—calibration factor = 6.0.

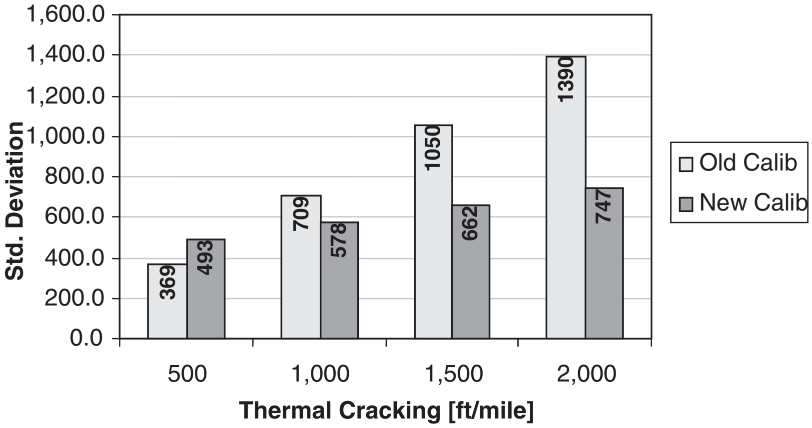


Figure 11 Level 3 thermal cracking model—old vs. new calibration.

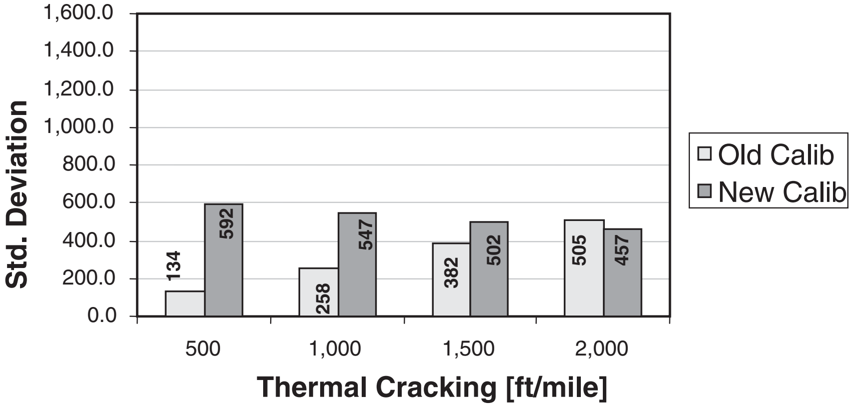


Figure 12 Thermal cracking Level 1 model—old vs. new calibration.

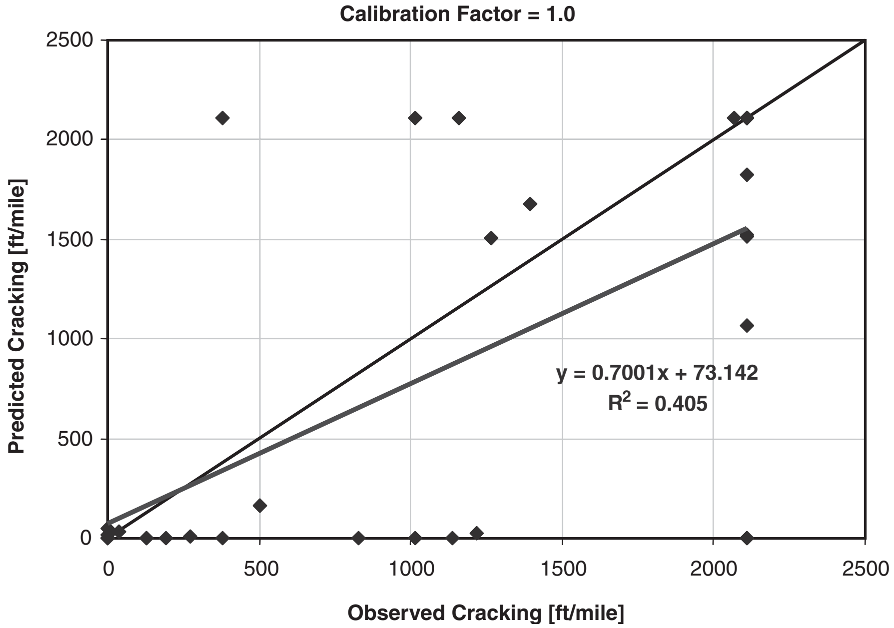


Figure 13 Thermal cracking Level 1 model calibration, observed vs. predicted.

- Sensitivity shows the reasonableness of effects of distress on IRI.
- There is a far larger database of sections:
  - Flexible pavement IRI: 1950 vs. 1978
  - Five years of additional distress development (to better determine the effect on IRI)
  - Standard error of prediction slightly lower
  - 18.9 vs. 24.5 in/mi

6. Variance models were developed for use in reliability design with IRI. They produce realistic results and are similar to those developed for IRI of rigid pavements.

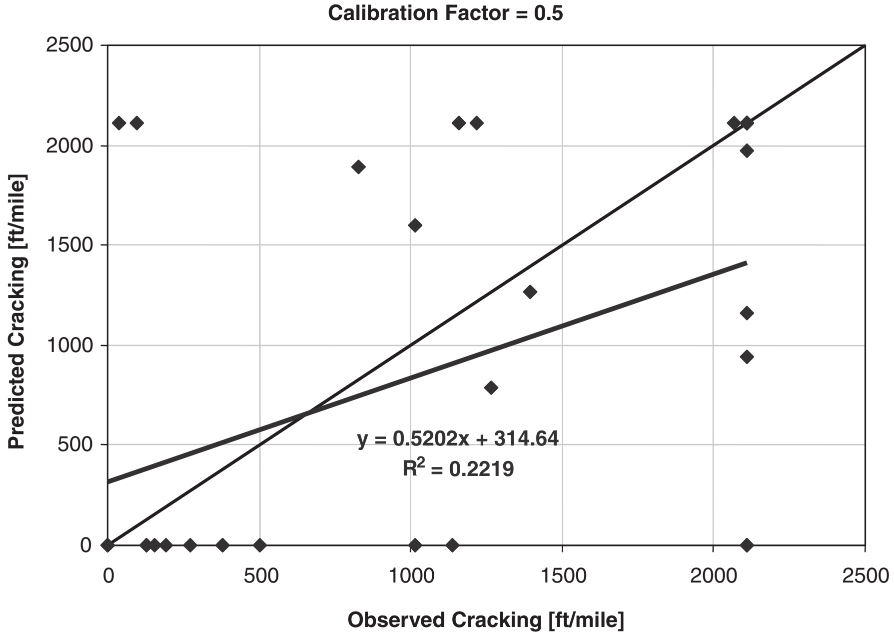


Figure 14 Thermal cracking Level 2 model calibration, observed vs. predicted.

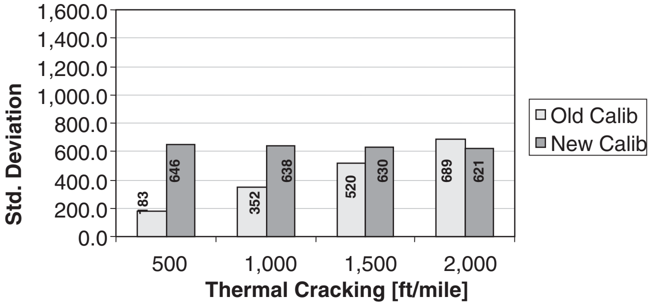


Figure 15 Thermal cracking Level 2 model, old vs. new calibration.

7. Sensitivity analyses were run to verify the reasonableness of the IRI models.
8. Figures 16 and 17 show the predicted versus measured IRI for new flexible pavements, HMA over flexible pavements, and HMA over rigid pavements.

RIGID PAVEMENTS

The following modifications were made in response to items identified in the Bug Tracker database (www.ara-tracker.com):

1. **(#434) CPR model for slab cracking.** The CPR algorithm for damage and slab cracking (after CPR) was found deficient because it uses percent cracked/replaced slabs to obtain an estimate of overall accumulated fatigue damage. This damage was neither top nor bottom fatigue but a composite of both that was not very accurate. Top-down and bottom-up damage needs to be directly correlated with measured cracking and an improved methodology installed. This upgrade was completed and verified. The CPR cracking model is now more theoretically correct and provides a better projection of future cracking after diamond grinding and other repairs.
2. **(#433) Widened slab computation deficiency.** A deficiency in the fatigue damage algorithm was identified for JPCP. The program does not provide for proper damage calculation for widening less than 24 inches. The problem was fixed so that user may enter 3, 6, 12, etc., up to 24 inches and the program will calculate fatigue damage properly. After approximately 15 inches, the critical fatigue location shifts from the outer slab edge of the widened portion to the inner slab edge near the lane-to-lane longitudinal joint. The algorithm makes this switch properly.
3. **(#428) HMA overlay of JPCP and CRCP includes several major deficiencies that require updating.** The modeling of HMA over JPCP and CRCP in the existing version has serious deficiencies in how the overlay and concrete slab and base course are transformed into an equivalent section for stress calculation purposes. Major modifications are required for both HMA over JPCP and HMA over CRCP to make this a more effective overlay design procedure. [Note: these modifications have not been completed in Version 0.900 yet. It is recommended that this overlay design procedure not be used until this is completed in late July 2006.]
4. **(#425) Level 1 inputs for PCC incorrect for HMA over JPCP and HMA over CRCP.** The program is using the xx year (e.g., 30 year) flexural strength instead of the input (long term) existing strength. The problem was corrected.
5. **(#393) CRCP shoulder load transfer factor (Js) reporting incorrectly.** The problem was corrected.
6. **(#386) When designing the AC overlay of JPCP, the design screen displays the AC overlay instead of the PCC thickness.** The problem was corrected.
7. **(#385) CRCP crashes on exit for analysis of more than 500 months.** The problem was corrected.

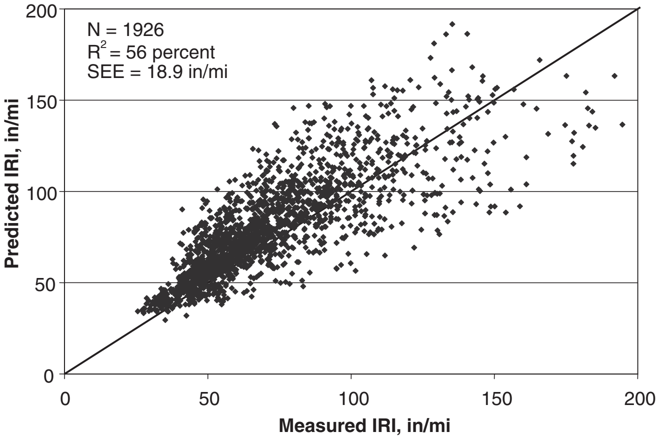


Figure 16 IRI for new HMA and HMA over HMA flexible pavements.

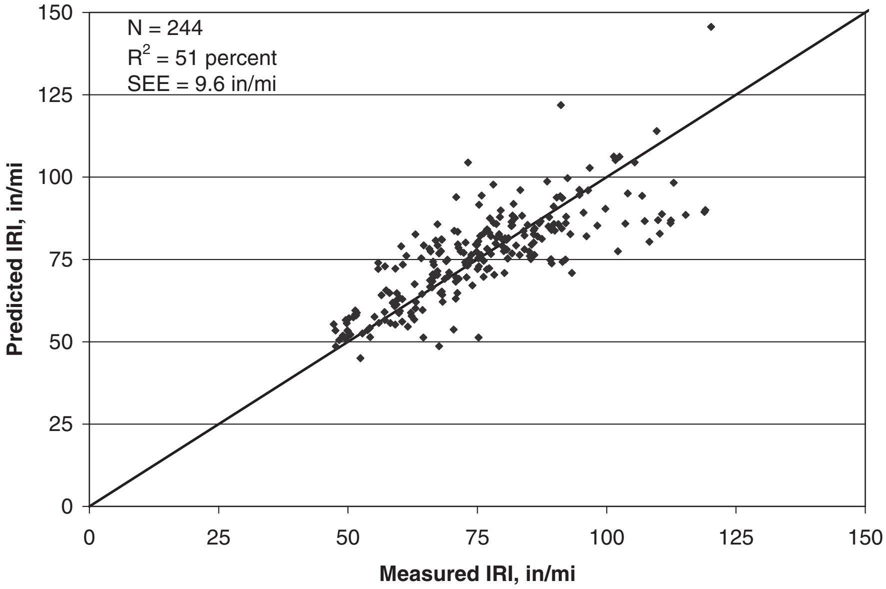


Figure 17 IRI for HMA overlaid PCC pavements.

8. **(#382) Open to traffic date and construction dates that differ by more than 11 months cause crashes for JPCP.** The problem was corrected.
9. **(#364) Remove drainage inputs from interface.** Use of the TMI model makes entry of drainage path and infiltration unnecessary.
10. **(#362) Erosion models for CRCP were revised to show more effect on performance per review comments.** Major revisions were made to the models and incorporated into the program. Tests indicated further bugs that were fixed.
11. **(#359) JPCP Cracking model stopped at 40 Years.** The problem was corrected. Design life can be over 80 years.
12. **(#345) Addition of algorithm to compute equivalent temperature gradient for "bonded" slab/base conditions.** "Bonded" herein means full-contact friction with no slippage between layers at the interface. The existing JPCP model includes a procedure for computing the equivalent linear temperature gradient through the concrete slab given a non-linear gradient. The procedure assumes that the slab and base are unbonded. A similar procedure is needed to compute an equivalent linear temperature gradient through the concrete slab for bonded (no slippage, full-contact friction) conditions. The significance of the bonding condition has been determined to be very high. This change required a change to the linearization and damage calculation algorithms of the MEPDG cracking model. Note: It was discovered that an error existed in the 2004 Version 0.7 of the Design Guide wherein bonding of slab and base only lasted for 12 months, regardless of the input by the user. This was fixed under #343 and contact friction or bonding now works properly.
13. **(#344) Modification of JPCP computational algorithm that includes "design periods" due to various problems.** JPCP computational algorithm includes periods over which fatigue damage is being computed throughout the design analysis period. These were introduced to reduce the run time. An error was identified in conjunction with the "bonding" slab/base algorithm and extrapolation procedures over the design periods that are not easily solved. The design period procedure may not have as much effect on computer run time as previously thought and it was modified so that the damage accumulation will be done month by month and year by year using exact strength, modulus, contact friction, k-values, and so forth. This approach will also help the implementation of other features into the JPCP design procedure. CRCP already works in this way.

14. **(#343) Contact friction between concrete slab and base course (commonly called "bonding") has an error in computational algorithm.** The user can select the number of months over which the slab and base will remain "bonded" (this is really contact friction). Some sensitivity analysis indicated this input to have small effect. Investigation showed that an error in the coding is causing this result. Subsequent runs and the calibration process indicated that most slabs and base courses show more full-contract friction over their lives than previously believed. Design input recommendations were revised.
15. **(#241) Difference in CRCP results between estimated crack spacing and user input crack spacing.** There was a difference in CRCP output results when the program uses the internal model to predict crack spacing and when the user inputs the exact same crack spacing. For example, if the program model predicts 31.7 in, and this is input and the program re-run, a different output may result. The problem was fixed.
16. **(#240) Permanent curl/warp input needs further examination to determine improved estimation procedures.** Currently, a −10°F is recommended for design. This is inadequate as the permanent curl/warp is known to depend on several key factors. Develop procedures to estimate the permanent curl/warp input for JPCP and CRCP separately. Through the calibration process, attempt to identify values or relationships that will minimize error of prediction for all JPCP and CRCP distress models. Time and resources were insufficient to solve this problem at this time. It is recommended that it be addressed in the next program version.
17. **(#239) Base erosion index does not appear to have adequate sensitivity to performance.** Evaluated the effect of the base erosion index on performance of CRCP and JPCP and determined that it needed improvement. New erosion models were derived for each type of base course and subgrade type so that the loss of support along the edge is computed automatically, not dependent on user input of erosion factor.
18. **(#238) Add CRCP design criteria (Crack Width, Crack LTE, Crack Spacing) to Output Reliability Screen.** CRCP design criteria include crack width, crack spacing, and crack LTE in addition to punchouts. These were added to the Reliability output screen to emphasize that they are just as important as punchouts and IRI (even though there is no reliability level associated with them).
    - Crack Width < 0.02 in
    - Crack LTE > 95 percent
    - Crack spacing 3 to 6 ft

The following modifications were completed, but were not included in the Bug Tracker database:

1. The definition of a CRCP punchout was revised, based on review comments, to include only medium- and high-severity punchouts and y-cracks. Distress maps for all CRCP sections were reviewed and the correct number of punchouts (including y-cracks) was included for each time frame. This change is reflected in the design input recommendations for critical levels for design.
2. The AC/JPCP or AC/CRCP overlay design procedure was found to contain various technical deficiencies. One problem was that the 2004 version did not fully consider the width of transverse cracking (after many years of aging), the load transfer efficiency (which may have deteriorated), and the extent of erosion along the slab edge that exists in the field at the time of placement of a new overlay. In addition, procedures to calculate the equivalent slab thickness (where the overlay is combined with the CRCP slab) with proper full-friction included errors. These deficiencies are being fixed in the software and this type of overlay is being tested to ensure reasonableness. This fix is not in Version 0.900 but will be in the next version.
3. A major effort was expended to recalibrate all of the JPCP, CRCP, and rehabilitation distress models, including joint faulting (new and rehab), slab top-down and bottom-up cracking (new and rehab), punchout (new and rehab), and crack spacing. The final newly calibrated models had a lower model error even with an expanded data set, reasonable sensitivity to changes in inputs, greater robustness because of an expanded data set, and better reliability than those originally developed under NCHRP

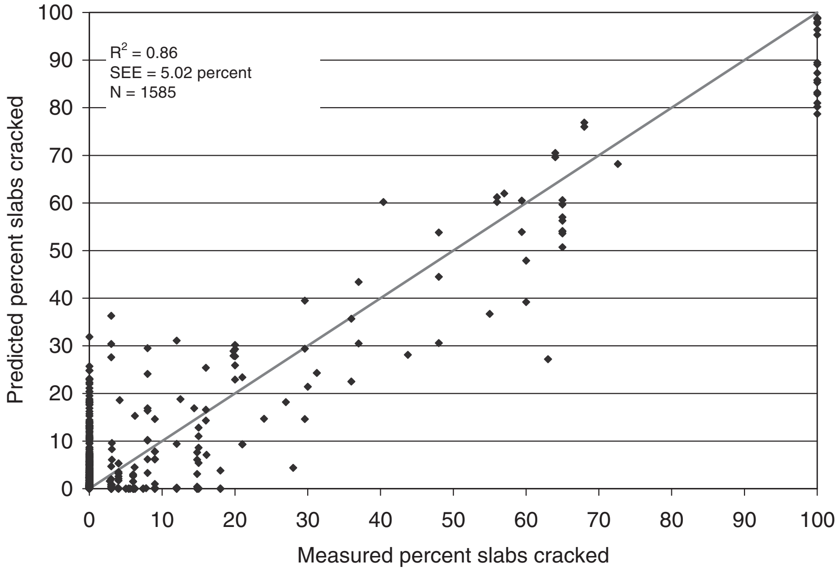


Figure 18 Transverse cracking for new JPCP calibration.

1-37A. Major steps in this effort included the following:

- Improving the database.
  - Updating all existing sections with 4 to 5 additional years of performance data, traffic data, materials data, climatic data, and rehabilitation data.
  - Identifying additional LTPP and other sections for inclusion in the calibration.
  - Incorporating the weather stations that included 9 years of historic hourly data.
  - Establishing the proper input subgrade resilient modulus through an iterative process that included back-calculation of in situ moduli for the sections.
- Re-establishing the model coefficients for all the models using the expanded database.
- Re-establishing the reliability model coefficients for all the models using the expanded database.
- Conducting limited sensitivity analyses to validate the software and changes to the software.
- Documenting work accomplished (not yet completed).

Figures 18 through 20 show measured and predicted JPCP cracking distress for new JPCP, unbonded JPCP overlays, and JPCP subjected to restoration.

Figures 21 through 23 show the measured and predicted JPCP faulting distress for new JPCP, unbonded JPCP overlays, and JPCP subjected to restoration.

Figure 24 shows the measured and predicted CRCP punchout distress for new CRCP.

The following improvements were made to the input guidelines:

1. **Input resilient modulus, Mr, for subgrade.** Calibration required a complete re-establishment of the proper input subgrade Mr at optimum moisture content that would ultimately provide an in situ modulus that matched the FWD back-calculated value at each test section site. The modification of the ICM and subdrainage models resulted in a change of in situ Mr resulting in this required work. As a result of this, the JPCP and CRCP

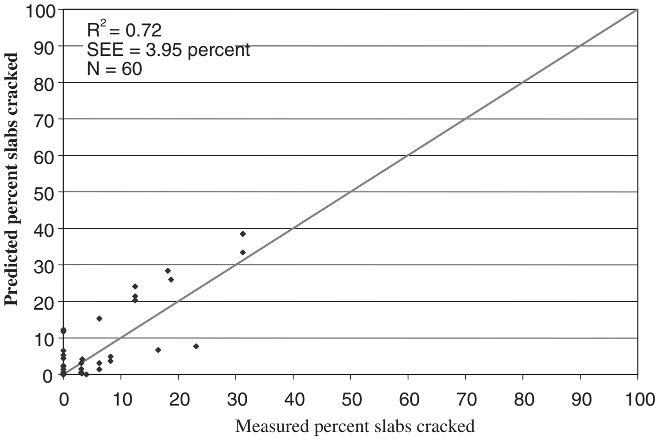


Figure 19 Transverse cracking for unbonded JPCP overlay calibration.

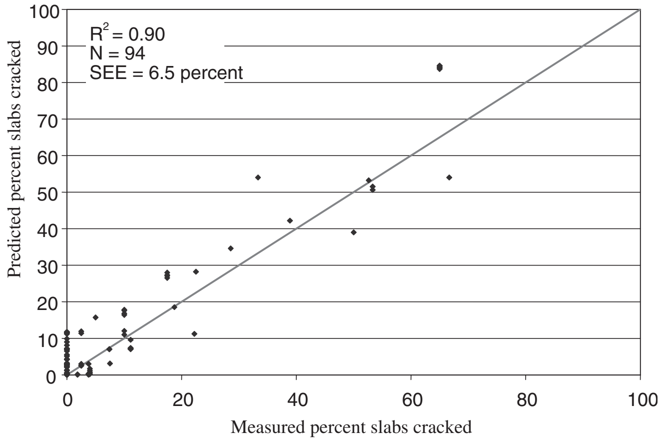


Figure 20 Transverse cracking for restored JPCP (CPR) calibration.

sections provide a large database from which to obtain typical values for Mr for each AASHTO soil class. It was discovered that the in situ Mr varied greatly for any given LTPP classification of subgrade soils and, thus, the selection of typical values for use as defaults or recommended values for Level 3 was difficult. The values obtained were averages from all of the data and represent the best Level 3 source of information available. Separate recommendations for rigid pavements made based on these results are presented in Table 2.

2. **Input resilient modulus, Mr, for base/subbase.** The values recommended in the 2004 version of the Design Guide are recommended for the base and subbase.
3. Grain size distribution, Atterberg limits, and other soil properties were updated based on extensive data from LTPP test sites across the United States.
4. **Contact friction between slab and base (formerly called bonding).** This value was found to be far more significant than before because of an error in the software. Guidelines on how many months of full friction to select for different base courses were based on best fit to match cracking in the field. Results are as follows which are recommended for input:
    - Asphalt stabilized base: 60 to 360 months with an average of 229 months.
    - Cement stabilized or lean concrete base: 0 to 360 months with an average of 136 months.
    - Unbound material base: 0 to 360 months with an average of 245 months.
    - Lime stabilized base: 0 to 360 months with an average of 176 months.
    - Unbonded overlay (with HMA separation layer): 0 months of full-friction (bond) to match cracking.
    - These values were used in the calibration and are recommended for design.
5. Recommendations for the modulus of existing PCC slabs for use in unbonded overlay design were updated.

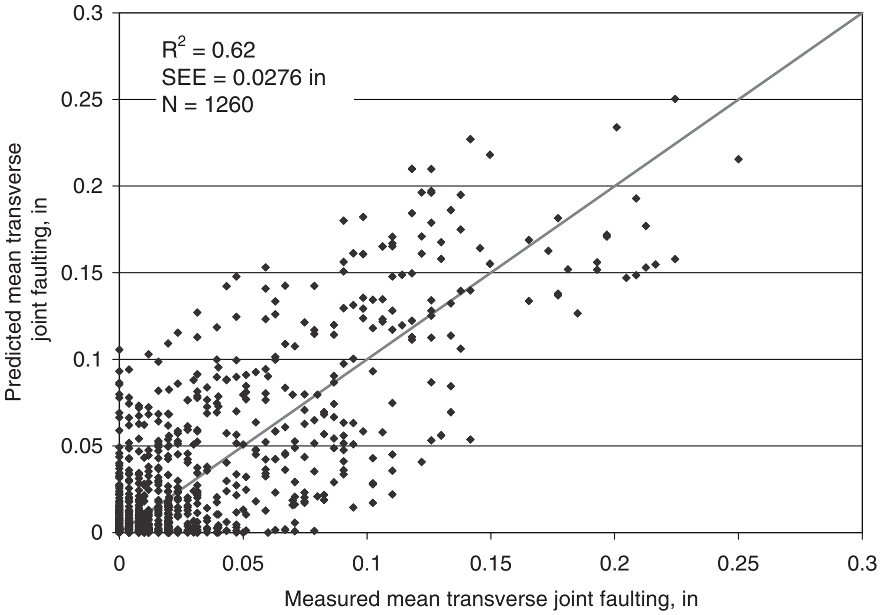


Figure 21 Transverse joint faulting for new JPCP calibration.

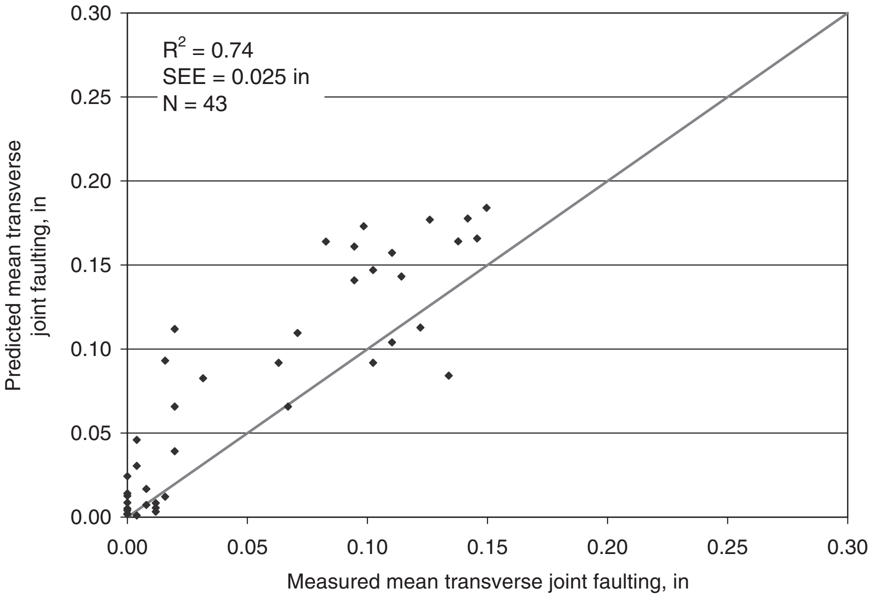


Figure 22 Transverse joint faulting for unbonded JPCP overlays calibration.

6. **Permanent curl/warp gradient through slab.** A value of −10°F was found in the original calibration in 2002–2004 to provide the lowest error in slab cracking prediction. This value was used for nearly all projects of JPCP and CRCP in the 2006 calibration. However, those projects cured with water or constructed at night required a lower value (−3°F) and those built under harsh curing conditions (e.g., morning paving, sunshine, wind) often required greater than −10°F, even up to −25°F. Additional research is needed to quantify this important input.
7. CTE recommendations were upgraded to the latest LTPP data analysis of this parameter as shown in Table 3.
8. Improved estimates of wheel base percentages were obtained from two states. They were somewhat different than the 33, 33, and 34 percent assumed for short, medium, and

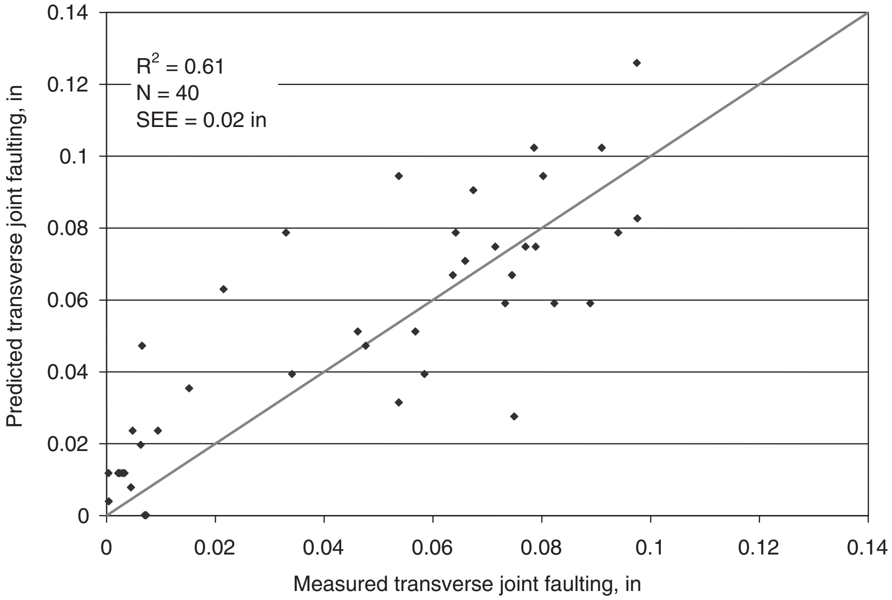


Figure 23 Transverse joint faulting for restored JPCP (CPR) calibration.

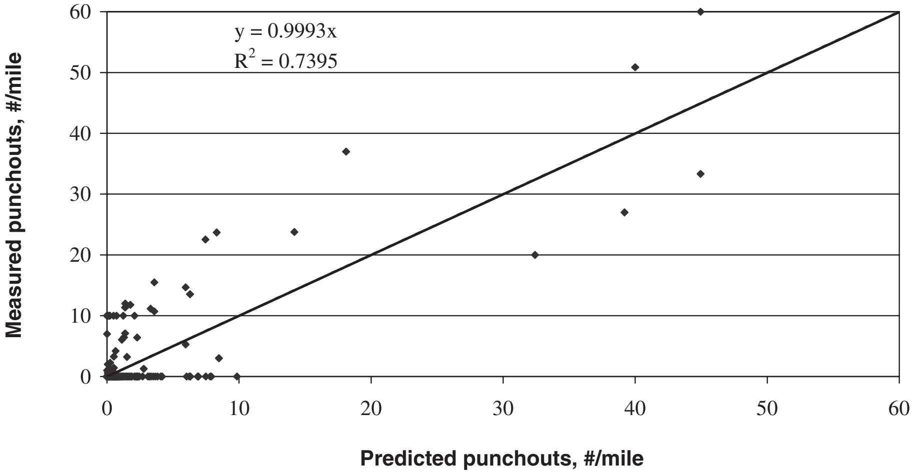


Figure 24 Plot of predicted versus measured punchouts for new CRCP calibration.

TABLE 2 Recommended subgrade/embankment resilient modulus input (at optimum density and moisture) for rigid pavements and rehabilitation of rigid pavements[1,2,3]

Subgrade AASHTO Soil Class	Optimum Dry Density (mean, std. dev.)*	Optimum Moisture Content (mean)* %	Design Guide Input Resilient Modulus at Optimum Density/Moist. (mean, std. dev.)**	Design Guide Back-calculated Output Dynamic k-value (mean, std. dev.)**	Recommended Input Subgrade Resilient Modulus (Opt. Density/Moisture Content)
A-1-a	128 pcf, 17 pcf	11	13,228 psi, 3,083 psi	322 psi/in, 68 psi/in	18,000 psi
A-1-b	122, 9	11	14,760, 8,817	335, 92	18,000
A-3	NA	NA	NA	NA	16,500
A-2-4	119, 7	11	14,002, 5,730	256, 79	16,000
A-2-5	NA	NA	NA	NA	16,000
A-2-6	120, 6	12	16,610, 6,620	289, 51	16,000
A-2-7	NA	NA	NA	NA	16,000
A-4	119, 7	12	17,763, 8,889	270, 88	15,000
A-5	NA	NA	NA	NA	8,000
A-6	114, 5	14	14,109, 5,935	211, 54	14,000
A-7-5	103, 19	19	7,984, 3,132	148, 32	10,000
A-7-6	102, 8	20	13,218, 322	203, 53	13,000

*Information provided in these columns was obtained from the LTPP database (optimum density and moisture).
**Information was obtained from Design Guide back-calculation and from use of the Design Guide (input subgrade resilient modulus, Mr, at optimum density and moisture).

[1] These results are based on about 250 JPCP and CRCP pavements located across the U.S. and used in the calibration of the Design Guide rigid pavements.
[2] Use of resilient modulus input (at optimum density and moisture) for a project that is significantly different than these test results and recommendations may result in erroneous model prediction. Specifically, input of higher resilient modulus that results in significantly higher output dynamic k-values may result in erroneous model prediction as very few LTPP sections across the country showed higher values. Note that bedrock close to the surface would be an exception to this guideline.
[3] Do not use these resilient modulus values for compacted base or subbase course. Use appropriate table for base/subbase course resilient modulus.

TABLE 3 PCC CTE results sorted by aggregate origin and classification

Primary Origin	Primary Aggregate Class	Average CTE[2]	Standard Deviation (s)	Sample Count (n)
Igneous (Extrusive)	Andesite	5.3	0.5	23
Igneous (Extrusive)	Basalt	5.2	0.7	47
Igneous (Extrusive)[1]	*Diabase*	*4.6*	*0.5*	*4*
Igneous (Plutonic)	Diabase	5.2	0.5	17
Igneous (Plutonic)[1]	*Gabbro*	*5.3*	*0.6*	*4*
Igneous (Plutonic)	Granite	5.8	0.6	83
Metamorphic	Schist	5.6	0.5	17
Sedimentary	Chert	6.6	0.8	28
Sedimentary	Dolomite	5.8	0.8	124
Sedimentary	Limestone	5.4	0.7	236
Sedimentary	Quartzite	6.2	0.7	69
Sedimentary	Sandstone	6.1	0.8	18
Lightweight[1]	*Expanded shale*	*5.7*	*0.5*	*3*

LTPP test section results.
Testing conducted by FHWA at the Turner-Fairbank Highway Research Center.
Mallela, J., et al. (2005) Measurement and Significance of the Coefficient of Thermal Expansion of Concrete in Rigid Pavement Design" *Transportation Research Record 1919*, Transportation Research Board, Washington, DC.

[1] Results based on very limited testing.
[2] units are in in/in per °F x10-6.

long wheel bases used in the original design guide calibration. Further study is needed to more firmly establish the wheel base percentages and then they will be used in a JPCP calibration.

Major technical improvements in Version 0.900 for rigid pavements are summarized as follows:

1. Addition of algorithm to compute equivalent temperature gradient for "bonded" slab/base conditions (unbonded only was available). This was used in calibration whenever full-contact friction was specified.
2. Modification of JPCP computational algorithm so that it now includes month-by-month damage accumulation, rather than accumulating over a multiyear period.
3. Fixed a bug in the algorithm for contact friction between concrete slab and base ("time to de-bond"). The term "bond or bonding" was changed to "contact friction" to better describe the amount of slippage between the PCC slab and the base course. Recommendations were provided.
4. Erosion prediction for CRCP was improved.
    - Program calculates loss of support along edge over time as a function of
        - Base type and quality
        - HMA: asphalt content
        - CTB: Ec
        - Granular: fines content
        - Annual precipitation
        - Type and quality of subbase/subgrade (strength, fines)
    - Erosion calculated for 10 years, but uniformly accumulated year by year with practical cap.
5. Re-calibrations of all JPCP and CRCP models were successful. Partial sensitivity indicates the calibrated models are reasonable. Further sensitivity analyses are needed.
6. Re-calibration of all rehabilitation models for JPCP and CRCP were successful.
7. Results confirm that original 2004 models were valid over a much wider range of design parameters and a larger number of additional sections throughout the United States.
8. Joint spacing for skewed joints was increased by the amount of skew in a 12-ft-wide slab (normally 2-ft) to account for increased curl/warp stresses over that of a perpendicular joint.
9. Improved recommendations for subgrade resilient modulus inputs are provided.
10. Slab widening algorithm for JPCP was improved to allow smaller widening values (e.g., 3 to 24 inches) with proper calculation of fatigue damage at each edge of slab.
11. Concrete pavement restoration algorithm for cracking was upgraded to predict top-down and bottom-up damage and cracking more accurately.

These digests are issued in order to increase awareness of research results emanating from projects in the Cooperative Research Programs (CRP). Persons wanting to pursue the project subject matter in greater depth should contact the CRP Staff, Transportation Research Board of the National Academies, 500 Fifth Street, NW, Washington, DC 20001.

COPYRIGHT PERMISSION

Authors herein are responsible for the authenticity of their materials and for obtaining written permissions from publishers or persons who own the copyright to any previously published or copyrighted material used herein.

Cooperative Research Programs (CRP) grants permission to reproduce material in this publication for classroom and not-for-profit purposes. Permission is given with the understanding that none of the material will be used to imply TRB, AASHTO, FAA, FHWA, FMCSA, FTA, or Transit Development Corporation endorsement of a particular product, method, or practice. It is expected that those reproducing the material in this document for educational and not-for-profit uses will give appropriate acknowledgment of the source of any reprinted or reproduced material. For other uses of the material, request permission from CRP.

THE NATIONAL ACADEMIES™
Advisers to the Nation on Science, Engineering, and Medicine

The nation turns to the National Academies—National Academy of Sciences, National Academy of Engineering, Institute of Medicine, and National Research Council—for independent, objective advice on issues that affect people's lives worldwide.
www.national-academies.org

TRB
Transportation Research Board
500 Fifth Street, NW
Washington, DC 20001

Copyright National Academy of Sciences. All rights reserved.