

TECHBRIEF



The Long-Term Pavement Performance (LTPP) program is a large research project for the study of in-service pavements across North America. Its goal is to extend the life of highway pavements through various designs of new and rehabilitated pavement structures, using different materials and under different loads, environments, subgrade soil, and maintenance practices. LTPP was established under the Strategic Highway Research Program and is now managed by the Federal Highway Administration.



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Determination of In-Place Elastic Layer Modulus: LTPP Backcalculation Methodology and Procedures

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This document is a technical summary of the Federal Highway Administration report *Long-Term Pavement Performance Program Determination of In-Place Elastic Layer Modulus: Backcalculation Methodology and Procedures* (FHWA-HRT-15-036).

Objective

This TechBrief provides an overview of the methodology and procedures used to backcalculate the elastic layer modulus from deflection basins for all test sections included in the Long-Term Pavement Performance (LTPP) database.

Background

Deflection data have been measured at periodic intervals with the falling weight deflectometer (FWD) on all rigid, flexible, and composite pavement test sections included in the LTPP program. These data are used to determine the load-response properties of the pavement structure and subgrade. Currently, there are 16,364 FWD testing days and more than 2,400 test sections in the LTPP database.

A common use of deflection data is to backcalculate in-place layered elastic modulus values. These modulus values, and how the values change over time, are inputs for estimating remaining life and determining an appropriate rehabilitation and design strategy. In addition, many agencies have used the LTPP deflection data for calibrating mechanistic-empirical distress transfer functions, including those in the *Mechanistic-Empirical Pavement Design Guide* (MEPDG).⁽¹⁾

Several years ago, the Federal Highway Administration (FHWA) sponsored studies to backcalculate elastic layer modulus

values from deflection basins and included the computed values in the LTPP database. (See references 2 through 5.) Since then, the amount of deflection data in the LTPP database has increased substantially, especially for the Specific Pavement Studies (SPS) sites. Therefore, FHWA sponsored a follow-up project to revisit the methods used in the first round of backcalculation and to calculate the elastic layer modulus values for the deflection data that did not exist during the first round of backcalculation.

Project Goals

The major goal of the backcalculation project was to determine the in-place elastic layer moduli from deflection basin measurements for the LTPP test sections and execute those methods for all flexible, rigid, and composite pavement sections included in the LTPP program. Another key goal was to automate the process and make it less dependent on the user so that others not directly involved in the development of the tools and procedures can recreate the results.

Challenges with Backcalculation

One of the difficulties in backcalculation is that it does not determine a unique solution or set of elastic layer moduli for a specific set of measured deflection basins. More importantly, the quality of the results depends greatly on the expertise of the user in setting up the problem. In other words, different users can obtain different results for the same set of deflection basins. The non-uniqueness of these solutions has been a major deterrent for some agencies to take full advantage of backcalculation methods for routine rehabilitation design. In addition, many agencies limit use of the deflection data to only determine the subgrade elastic modulus.

This TechBrief provides a general overview of the backcalculation process and summarizes the

steps that were automated in calculating the elastic layer moduli from deflection basin data. It also describes the tools written to simplify the backcalculation process while taking full advantage of the entire deflection basin dataset for rehabilitation design in accordance with the MEPDG.⁽¹⁾ The automated process is specific to LTPP and the data tables included in the LTPP database. The activities presented here, however, can be used to improve the backcalculation of elastic layer moduli for any rehabilitation project.

Products from Backcalculation Project

The backcalculation project resulted in the development of two major products: (1) a set of computed parameter tables (CPT) stored in the LTPP database and (2) analytical tools for the pre-and post-processing of the deflection basin data. A user's guide is available for executing the automated backcalculation process, as well as for the utility and software tools for organizing the results included in the CPTs.

LTPP Computed Parameter Tables

The backcalculated elastic layer modulus values, simulated pavement structures for each LTPP test section, and other related parameters were integrated into the CPTs of the LTPP database and are now available for use. Six CPTs were designed to store the results from the backcalculation process and assist in interpreting the results. One set of tables stores the *EVERCALC* or *MODCOMP* results, and a second set of tables stores the *BEST FIT* results. A third set of tables stores the non-backcalculated data and values for each test section. The backcalculated modulus values from *EVERCALC* or *MODCOMP* and the *BEST FIT* method are organized by agency

in separate files. Table 1 includes a listing of the following CPTs:

- *Non-backcalculated values table (the third column in table 1):* This table includes general information on each test section analyzed through the backcalculation programs and compares the pavement structure included in the LTPP database to the structure simulated in the backcalculation process. It also includes the number of basins analyzed and the number of basins and stations with acceptable moduli, as well as whether a rigid layer is present.
- *Backcalculated values from individual deflection basins (the first column in table 1):* This table includes all results for individual deflection basins measured along a test section for all test dates. The calculated layer moduli, even those identified as errors, are included in this table. Test time and pavement temperatures are included in this table,

as well as other factors that can be used to determine how the results are influenced from the different factors included in the backcalculation process. This information can be used to evaluate the stress sensitivity, temperature sensitivity, and seasonal sensitivity of the results.

- *Summary of results or processed data (the second column in table 1):* This table includes the average and standard deviation of elastic layer moduli along the test section on a test day basis. These values are the representative values for each test section that are layer dependent, test lane dependent, drop height dependent, season dependent, temperature dependent, etc. The averages and standard deviations were determined using the individual deflection basins not identified as an error.

Backcalculation Software Packages

The following three software packages were used to calculate the elastic layer moduli from

Table 1. Computed parameter tables stored in the LTPP database.

Tables for Backcalculated Modulus Values from Individual Basins	Tables for Summary of Results and Processed Data from a Test Day	Tables for Non-Backcalculated Values
Elastic layer moduli that are basin-specific from the <i>EVERCALC</i> or <i>MODCOMP</i> software packages for all test sections (rigid, flexible, and composite) included in the LTPP program.	Average and standard deviation of the elastic layer moduli for a test day (all rigid, flexible, and composite test sections), lane number, and drop height. This set of tables excludes the backcalculation results that were rejected from the acceptance criteria.	Backcalculation section information that identifies the number of basins used to calculate the elastic layer moduli and whether a rigid layer was included in the simulation.
Elastic layer moduli from the <i>BEST FIT</i> method for test sections with PCC surfaces for bonded and unbonded simulations that are basin-specific.	Average and standard deviation of the elastic layer moduli from the <i>BEST FIT</i> method for the bonded and unbonded simulations for a test day, lane number, and drop height for LTPP test sections with PCC surfaces.	Structure used in the backcalculation process using <i>EVERCALC</i> or <i>MODCOMP</i> for a specific test day (layer thickness and material type).
LTE for tests performed at transfer joints and crack locations that are basin-specific.	Average and standard deviation of the LTE for a test day, lane number, and drop height for LTPP test sections with PCC surfaces.	Structure used in the calculation process using the <i>BEST FIT</i> method for a specific test day (layer thickness and material type).

CPT = Computed parameter table.

LTE = Load transfer efficiency.

LTPP = Long-Term Pavement Performance.

PCC = Portland cement concrete.

deflection basins measured on flexible, rigid, and composite pavements:

- *EVERCALC 5.0* was the primary program used for the analyses and was used for all data and all pavement types. The pre- and post-processing utility tools for the *EVERCALC* analyses were fully automated. The automation process included generating the input files based on pavement simulation rules, executing *EVERCALC*, and post-processing the results.
- *MODCOMP 6.0* was used as the auxiliary program to backcalculate results for those LTPP sections that did not yield acceptable results with *EVERCALC*. The *MODCOMP* analyses were semi-automated as an iterative approach, and the simulated backcalculation structure was selected on a case-by-case basis until the results converged within the selected criteria. A few test sections or portions of test sections did not converge to produce satisfactory results even after multiple efforts using *EVERCALC* and *MODCOMP*.
- The *BEST FIT* procedure was used to analyze LTPP sections with a portland cement concrete (PCC) surface to obtain the subgrade *k*-value and the elastic moduli of the PCC and base layers. The PCC and base modulus values were determined for bonded and unbonded interface conditions.

All three programs were executed in a batch mode process on a State-by-State basis to handle the computational effort needed for the large volume of deflection basins in the LTPP database. The *BEST FIT* method provides unique solutions for PCC-surfaced pavements using a three-layered structure. The *EVERCALC* and *MODCOMP* analyses were performed in four

main analysis phases. Each phase progressively identified and filtered out those cases with poor quality results and made appropriate adjustments to the analysis parameters to improve the convergence in the subsequent phase. The first phase included all LTPP data, while the second phase used a subset from the first phase. The third and fourth analysis phases, if required, used a subset from the second phase. Phases 1 and 2 used *EVERCALC*, and phases 3 and 4 used *MODCOMP*.

Computational Tools

The backcalculation methods and procedures, including the pre- and post-processing tools, were automated to minimize manual errors and enable independent users (those not directly involved in the development of the tools and procedures) to recreate the results. In addition, the automation process was designed to enable users to generate results for additional data collected by LTPP in the future.

A user's manual and source code were prepared for all software packages and tools that were modified, revised, or developed as a part of the backcalculation project. In addition, source codes were prepared for each of the pre- and post-processing utility tools used in the backcalculation process. Source codes were not prepared for any unchanged program that was already available in the public domain.

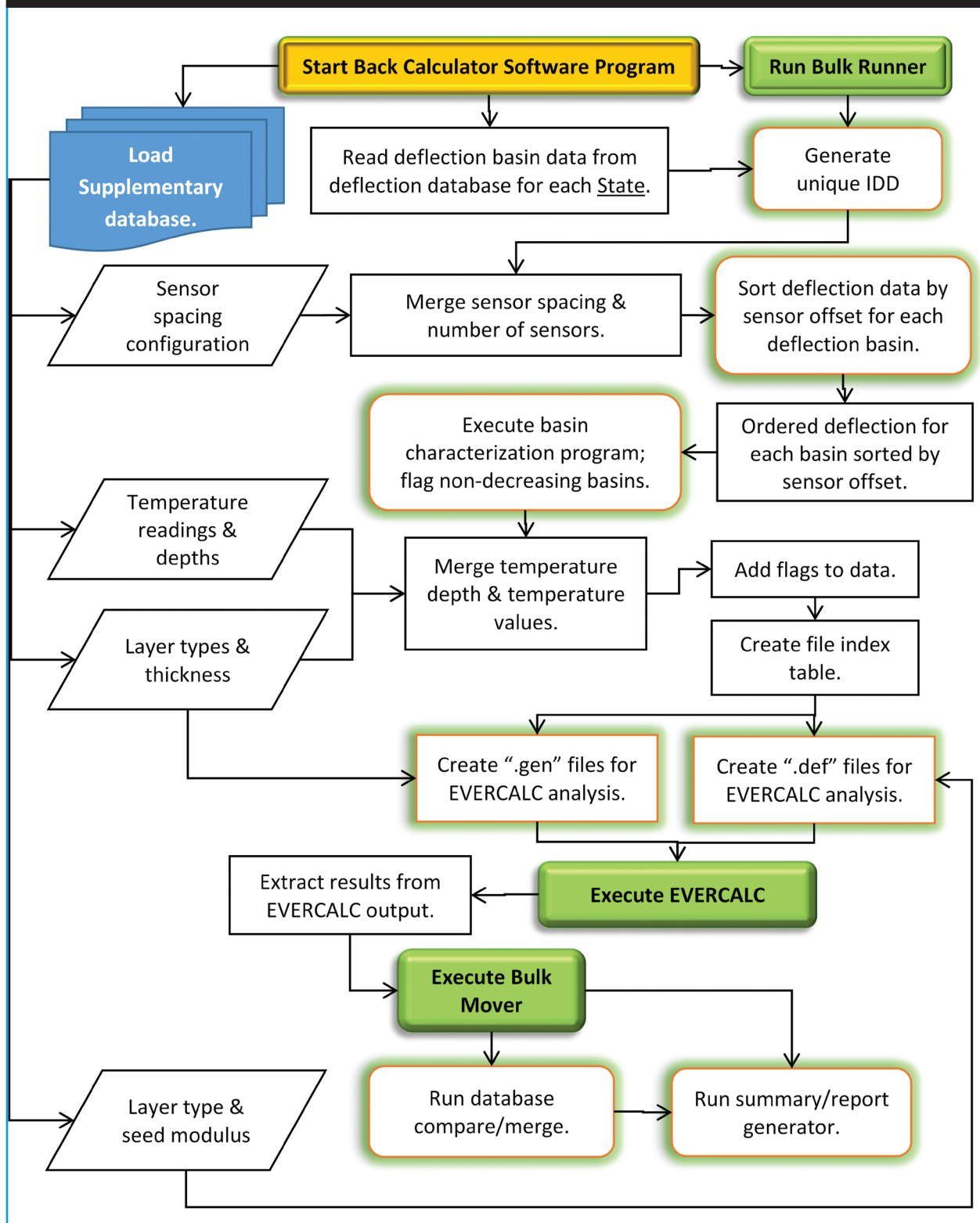
The computational tools utilize raw data in Microsoft® Access format from the LTPP database as the starting point to generate the backcalculation results. The results are merged back into Microsoft® Access tables with common reference fields with the original deflection tables. Therefore, Microsoft® Access-based macros, Microsoft® Windows-based utilities, and necessary graphical user interfaces were developed to do the following:

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- Perform general data validity checks.
 - Use the original LTPP tables to merge deflection, sensor spacing, and temperature data.
 - Establish data flags to filter out problem basins (i.e., those with non-decreasing deflections, missing deflection data, or missing sensor spacing data). Missing temperature data were flagged but not discarded for backcalculation.
 - Process pavement layer information from raw data in LTPP tables to develop backcalculation structure suitable for use in the *EVERCALC* program. This process involved combining pavement layers to reduce the pavement structure to an equivalent backcalculation layer structure meeting *EVERCALC* requirements.
 - Assign reasonable seed modulus values and a range of modulus values for use in the backcalculation process.
 - Generate the input files in the format necessary for use in the *EVERCALC* program.
 - Generate input files in the format necessary for use in the *MODCOMP* analyses. Because the *MODCOMP* analyses followed *EVERCALC*, the input files for *MODCOMP* were created by modifying the *EVERCALC* input files.
 - Generate the input files in the format necessary for the *BEST FIT* analyses program. These files were created directly from the Microsoft® Access data tables and were independent of the *EVERCALC* or *MODCOMP* analyses.
 - Execute the *EVERCALC* analyses in a batch mode.
 - Execute the *MODCOMP* analyses in a batch mode.
 - Execute the *BEST FIT* analyses in a batch mode.
 - Calculate the load transfer efficiency across the transverse and longitudinal joints in jointed plain concrete pavement sections and across transverse cracks in continuously reinforced concrete pavement sections.
 - Read output data files, merge results, and compute summary tables for inclusion in the LTPP results database.
- The macros were developed in Microsoft® Access primarily because the raw data resided in Microsoft® Access tables. The macros were used to perform the preliminary data checks and create supplementary data tables. Supplementary data include all data other than the raw FWD deflection data that are necessary to perform the backcalculation analyses, including sensor spacing; temperature data; backcalculation layer structure and layer thicknesses; layer material information, including specified ranges for *EVERCALC* analysis; and beta factors for the *BEST FIT* analysis methods.

Backcalculation Tool

A standalone software program, *Back Calculator*, was developed for bulk processing and filtering the deflection data, executing *EVERCALC* and *BEST FIT* programs, and processing the backcalculation results. Figure 1 shows a simplified flowchart of the *Back Calculator* program using the *EVERCALC* software package. *MODCOMP* analyses were not included in this program because only a limited number of sections were analyzed using *MODCOMP*. *MODCOMP* analyses were performed in a batch mode by executing the application file from an MS-DOS® prompt.

Figure 1. Simplified flowchart for the *Back Calculator* program using *EVERCALC* as the backcalculation software package.



Decision Criteria for Defining Acceptable Results

Two criteria were used to establish a quantitative measurement for categorizing the validity of the backcalculated modulus values: the root mean squared error (RMSE) and a range of the elastic modulus values. The RMSE criterion was set at 3 percent (i.e., for the results to be valid, the RMSE needed to be at or below 3 percent). The range of backcalculated modulus values for each layer had to fall within an acceptable or atypical range for each layer type and layer category based on the default range of values included in the MEPDG.⁽¹⁾

Another factor included in the automated process for evaluating the acceptability of the results was to determine whether the calculated elastic layer moduli are characteristic of a normal distribution. Nearly all volumetric and structural properties exhibit a normal distribution unless some type of bias was created during construction or a boundary condition. Thus, results from a single test day were evaluated to determine whether those results exhibited a normal distribution. The verification for normal distribution was performed using the Jarque-Bera test statistic, which asymptotically has a chi-squared distribution with 2 degrees of freedom.

Basic Facts and Data About the Backcalculation Process

The deflection data were extracted from LTPP *Standard Data Release 270* and included specific data from all LTPP test sections for all days of deflection basin testing. The data needed for the backcalculation of layer modulus values were grouped into two categories: direct and indirect. The direct data were from those tables needed to establish the inputs for the backcalculation

and forward calculation of layer moduli, and the indirect data included were from tables needed to evaluate the results from the backcalculation process. The direct data elements were extracted from the LTPP database for all test sections on an experimental basis. The indirect data elements were extracted for those test sections that had an appreciable number of results that were considered unacceptable to identify potential reasons for the unacceptable or poor results.

The number of sections by each LTPP experiment included 1,744 sections with an asphalt concrete (AC) surface and 1,008 sections with a PCC surface. There were a total of 7,771 test days, of which 4,534 sections had an AC surface and 2,237 sections had a PCC surface. The surface type changed in 381 of the test sections. For example, a jointed plain concrete pavement that was eventually overlaid with AC is counted in two categories or experiments. Therefore, there were a total of 3,133 unique sections in all States combined. The number of deflection basins considered acceptable and unacceptable for the backcalculation process is as follows:

- *Deflection basins considered acceptable for backcalculation: 5,847,770.*
- *Deflection basins considered unacceptable for backcalculation: 195,709.*
- *Total deflection basins with backcalculated elastic layer moduli: 5,662,494.*

Nearly 97 percent of all deflection basins were considered acceptable for backcalculation. This high percentage is a testament to the LTPP quality control procedures. Slightly fewer of the data were reported with backcalculated moduli because of a lack of convergence in the backcalculation analysis and missing critical data elements. In addition some of the acceptable basins were borderline.

Of the deflection basins included in the backcalculation process, 4,311,814 resulted in elastic layer moduli that met the acceptance criteria, for a slightly more than 76 percent success rate. More importantly, some 75 to 90 percent of the deflection basins measured along most of the LTPP test sections exceeded the acceptance criteria.

Application of Results

The following sections provide some examples of how the results can be used related to pavement design and rehabilitation, as well as research topics that can be tackled with this data.

Confirm In-Place Damage Concept for Rehabilitation Design

Figure 2 and figure 3 illustrate the change in the AC modulus over time for two LTPP test sections in Minnesota. These data can be used to determine the in-place damage for rehabilitation designs and forensic investigations, as defined by the MEPDG.⁽¹⁾ Figure 2 shows no damage for test section 27-1018, while figure 3 shows damage in the later years of testing for test section 27-6251. The backcalculated elastic moduli can be used to confirm or reject the concept included in the MEPDG for rehabilitation designs in determining the in-place damage of bound layers. In addition, the backcalculation results can be used to determine the temperature-modulus relationship of various hot mix asphalt (HMA) mixtures.

Evaluate the In-Place Modulus of Fractured PCC Slabs

The backcalculated elastic modulus data can be used to determine the in-place layer modulus for different PCC repair techniques. Table 2 lists the average PCC elastic layer modulus values calculated from the deflection basins measured

on two test sections from the Oklahoma SPS-6 project before and after using the two fractured slab concepts (crack and seat and rubblization). Significantly different modulus values were obtained above and below the reinforcing steel for the rubblization test sections. These data can be used to confirm or revise the default values included in the MEPDG.⁽¹⁾

Figure 4 shows the elastic modulus of the fractured PCC slabs from the crack and seat and rubblization methods used in rigid pavement rehabilitation in comparison with the intact PCC slabs for the Michigan SPS-6 test sections. The backcalculation data can be used to determine the default modulus values at the time of rehabilitation and define how those values change over time.

More importantly, the current version of the MEPDG assumes that these modulus values remain constant over time. The backcalculation data can be used to confirm or recommend changes to that hypothesis.

Seasonal Variation of Pavement Response and Its Effect on Pavement Performance

Figure 5 shows the change in elastic modulus over time from the Idaho Seasonal Monitoring Program (SMP) test section. The backcalculation data can be used to estimate the effect of seasonal factors on the response of different unbound aggregate base layers, as well as for the subgrade soils and embankments.

Another important application of the backcalculation data is to define characteristics of the deflection basin that can be used to identify subsurface features that could have a significant impact on the rehabilitation or reconstruction project.

Figure 2. Minnesota section 27-1018.

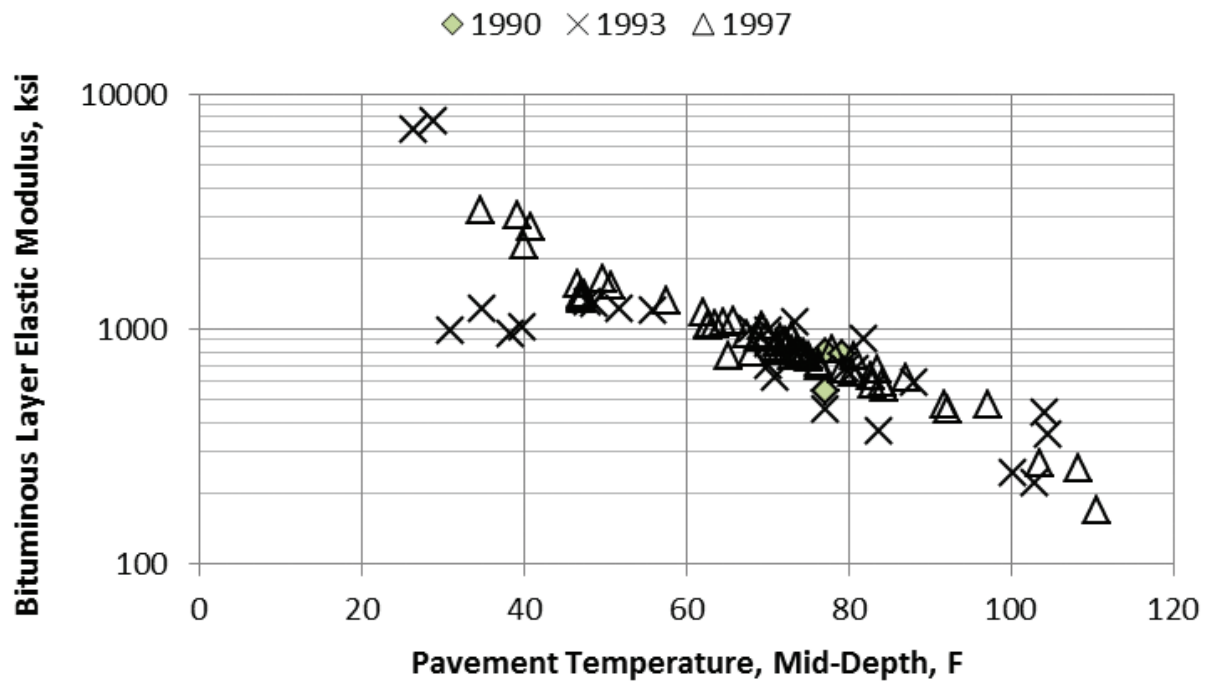


Figure 3. Minnesota section 27-6251.

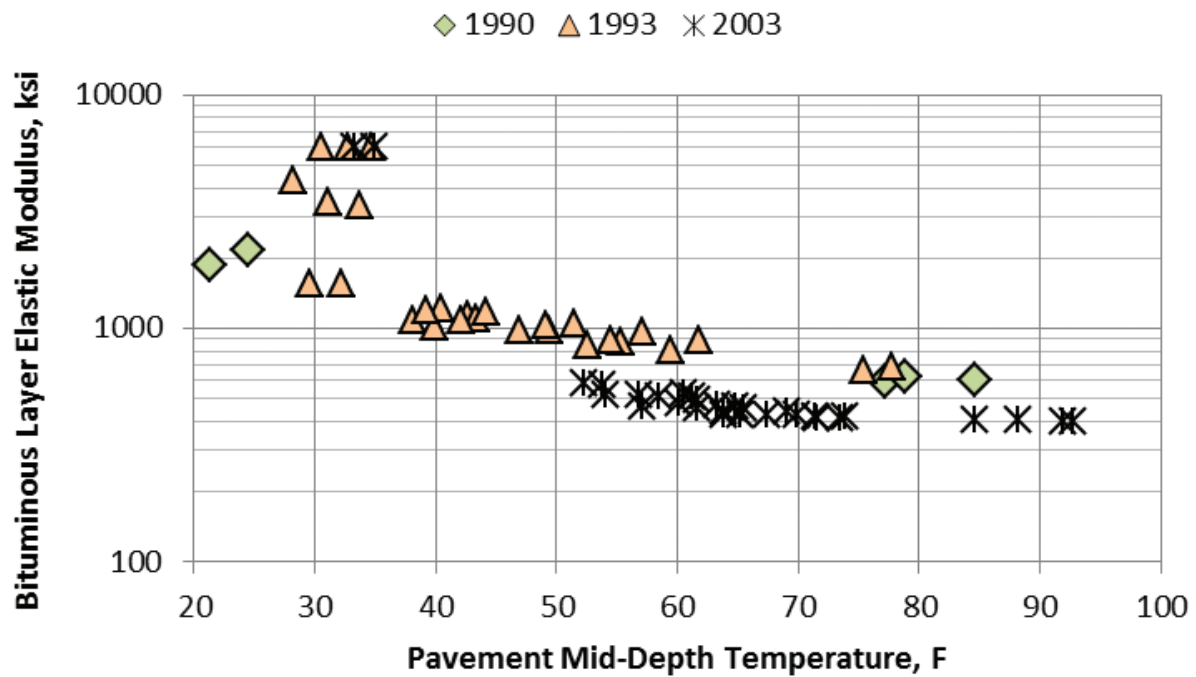


Table 2. Average PCC elastic layer moduli before and after fracturing, Oklahoma SPS-6 project.

Section	Fracture Method	Prior to Fracturing; Intact Slabs	After Fracturing Slabs
40-0606	Crack and seat method	4,799 ksi	3,615 ksi
40-0608	Rubblization method	5,082 ksi	284 ksi
			2,013 ksi

Figure 4. Michigan SPS-6 project.

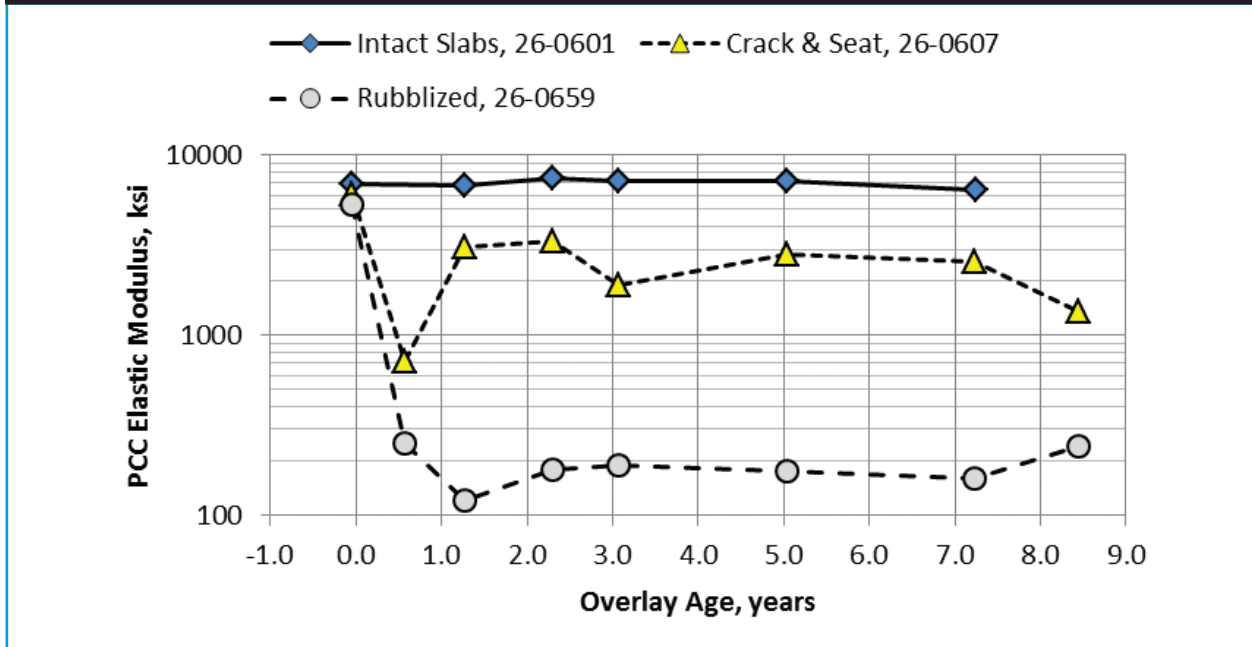
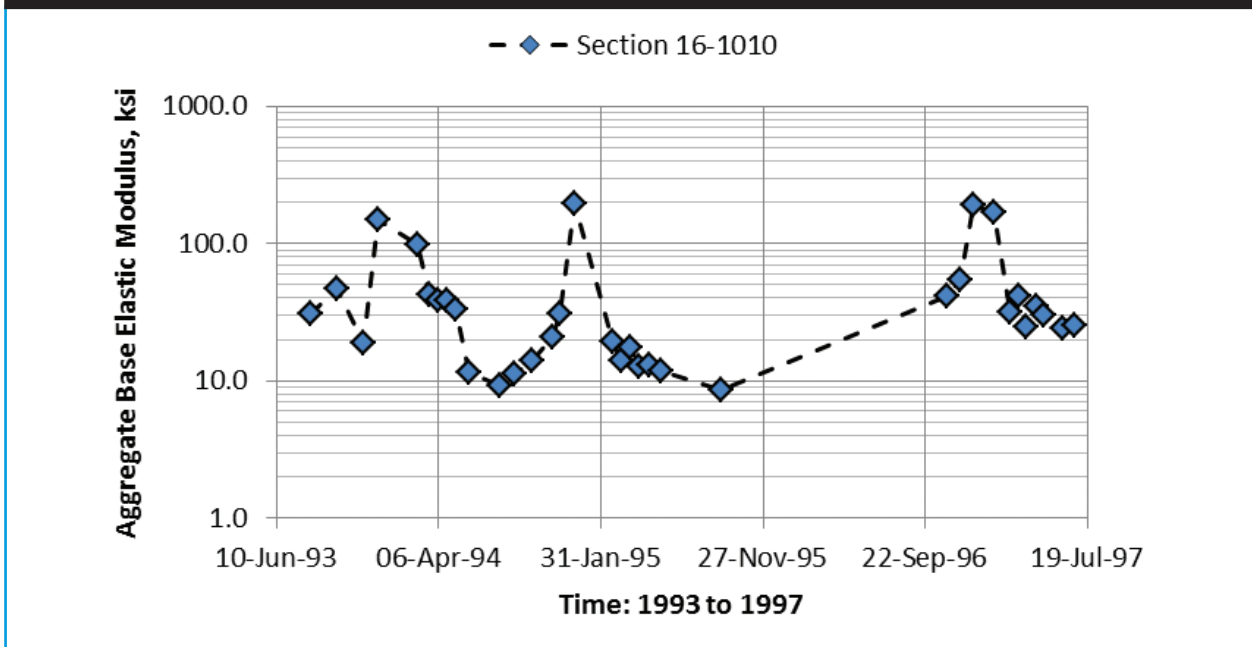


Figure 5. Idaho SMP project.



Evaluate Differences of the In-Place Mixture Responses

Figure 6 compares the elastic modulus of different HMA mixtures (with and without reclaimed asphalt pavement (RAP)) in the Minnesota SPS-5 project for flexible pavement rehabilitation. The backcalculation data can be used to compare the load-response characteristics between different mixtures, which can be compared with laboratory-measured dynamic values in determining whether there will be any significant difference in performance. Most of the SPS-5 projects exhibit no significant difference between the in-place elastic modulus values for mixtures with and without RAP.

Determination of Coefficients for the MEPDG Fatigue Cracking Transfer Function

Figure 7 shows a relationship between the in-place damage and the amount of fatigue cracking for the Georgia LTPP test sections and other roadway segments that were used in their

local calibration project.⁽⁶⁾ The in-place damage is defined as the ratio of the backcalculated elastic modulus values and laboratory-measured dynamic modulus values in accordance with the MEPDG.⁽¹⁾

The backcalculated elastic layer moduli and fatigue cracking data were used to determine the coefficients of the fatigue cracking transfer function independent of executing the MEPDG software. The coefficients from this relationship were found to result in no bias between the predicted and measured fatigue cracking. Confirmation of this concept and determination of the coefficients independent of the software reduces the amount of field work and materials testing required for local calibration. More importantly, confirmation of this damage concept permits agencies to make more use of their deflection basin data for rehabilitation design in day-to-day practice, as well as in selecting and planning preventive maintenance type projects.

Figure 6. Minnesota SPS-5 project.

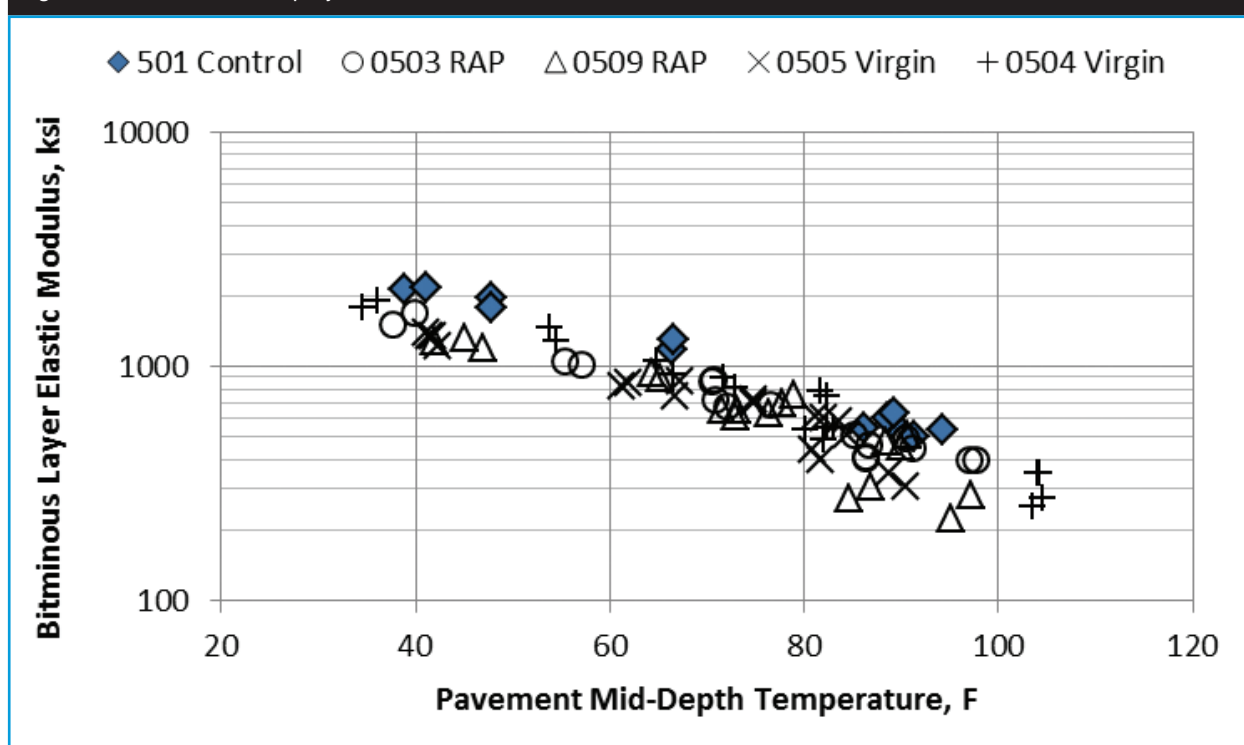
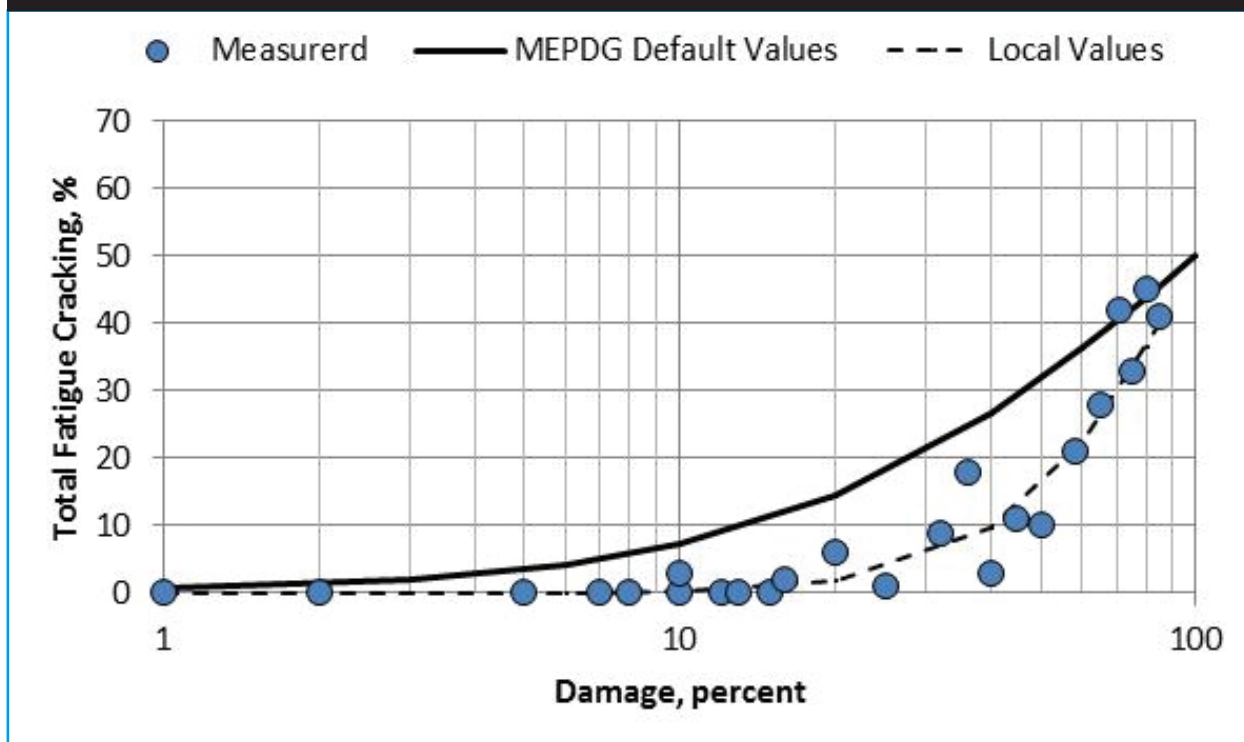


Figure 7. Georgia LTPP test sections used in local calibration.



Conclusions

Backcalculation of elastic properties is not an exact science and requires user interaction in some cases. To reduce the impact of user interaction, bias, and/or inexperience, the process was automated through a series of utility functions and tools. Results from this automated procedure provide elastic layer load response properties that are consistent with previous experience and laboratory material studies related to the effect of temperature, stress state, and seasonal effects on the material load-response behavior. The following lists some of the important findings from this study:

- Over 76 percent of the deflection basins analyzed with *EVERCALC* and *MODCOMP* resulted in layer moduli with an RMSE less than or equal to 3 percent and layer moduli within an expanded typical range of modulus values.

- There is no consensus on the “best” backcalculation package that provides the most reliable and accurate results. Nonetheless, the findings from the backcalculation project were similar to the findings documented in a previous study.⁽⁷⁾ Specifically, *EVERCALC* consistently resulted in lower error terms and a higher number of successful modulus determinations when considering all deflection basins. When only considering those deflection basins that ran successfully, however, the *MODCOMP* program resulted in lower RMSE values. It should also be noted that the *MODCOMP* program was used only for sections that were resulting in poor RMSE values from the *EVERCALC* analysis.
- The use of four layers generally resulted in lower RMSEs than the use of three layers. In many cases, separating the subgrade

into at least two layers improved the match between the measured and calculated deflection basins.

- In an earlier study, Von Quintus and Killingsworth recommended one software package to be used because of large differences between multiple programs.⁽⁸⁾ The current backcalculation project used three programs: *EVERCALC*, *MODCOMP*, and *BEST FIT*, all of which are available in the public domain. *EVERCALC* and *MODCOMP* were used to calculate the elastic layer moduli of all pavement sections in the LTPP database, while the *BEST FIT* method was used for all PCC-surfaced test sections. *EVERCALC* and *MODCOMP* provide non-unique solutions (i.e., the results are dependent on the user inputs of layer structure and the range of modulus values for iterations). In contrast, the *BEST FIT* method provides unique solutions for subgrade modulus and effective modulus; however, user decision on the layers representing the base and the condition of the PCC-base interface bond are needed for selecting slab and base modulus values. The following list summarizes some of the findings as related to the results and their interpretation between different software programs:
 - *EVERCALC* and *MODCOMP* resulted in statistically indifferent results for deflection basins classified as typical or in conformance with elastic layer theory as defined by Von Quintus and Simpson and Von Quintus and Killingsworth.^(5,8) For type 2 deflection basins, the *EVERCALC* and *MODCOMP* programs resulted in statistically different elastic moduli for the intermediate layers (the weathered soil layer and thinner aggregate base layers, which accounted for about 25 percent of the deflection basins analyzed). The pavements exhibiting deflection-softening behavior with type 2 deflection basins were the most difficult to analyze and were generally found to have higher RMSEs. Some of these deflection basin analyses resulted in no reasonable solution, or the solution provided unrealistic layer moduli for the type of material defined in the LTPP database. *Unrealistic* is defined as the resulting moduli values being outside the expanded typical range for at least one of the layers within a test section.
 - The PCC elastic moduli calculated with *EVERCALC* resulted in significantly greater values than the moduli calculated with the *BEST FIT* unbonded method. Thus, results from the two methods should not be combined, or a factor needs to be used to adjust the *EVERCALC*-generated PCC moduli to the *BEST FIT* unbonded condition method or laboratory-measured elastic moduli.
 - Historically, a constant modulus for the PCC rubblized slabs has been used for rehabilitation design projects. However, the elastic modulus of the rubblized PCC slabs was found to steadily increase over time for some of the LTPP SPS-6 test sections.
- No consistent difference was found in the load-response properties (stiffness) between the RAP and virgin mixtures of the SPS-5 experiment.

- Similar c -factor values were found in this project to the values included in the MEPDG.⁽¹⁾ More importantly, no significant difference or bias was found between the laboratory-derived dynamic modulus and the field-derived values for the AC layers.
- The use of drop heights one through four in the LTPP deflection testing program did not result in significantly different elastic moduli for the unbound layers. As such, it was difficult to determine the coefficients of a constitutive equation to estimate the stress sensitivity of an unbound layer because of the variation in moduli over time and along a specific test section. The stress levels resulting from the four drop heights used in the LTPP deflection testing program are simply too narrow.
- Damage was determined in accordance with the MEPDG procedure for multiple LTPP test sections to demonstrate its use in rehabilitation design.⁽¹⁾ The results were positive and were used to support the MEPDG procedure. The damage concept as applied to interpreting the backcalculated moduli can be useful in explaining low moduli. The Florida Department of Transportation was one of the first agencies to monitor changes in the deflection basin (similar to this damage concept) over time in planning rehabilitation projects from a pavement management standpoint. From the case study sites and examples of data use, the damage concept can be used to evaluate the condition of the existing pavement and plan future rehabilitation projects.

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