USER MANUAL FOR PAVEMENT M-E DEFLECTION DATA ANALYSIS AND BACKCALCULATION TOOL

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The information disseminated in this document is designed to provide helpful information on the use of the Association's AASHTOWare Backcalculation Tool (BcT) in support of the Pavement ME Design software package in the interest of information exchange. References are provided for informational purposes only and do not constitute endorsement of any websites or other sources.

The Association has used it best efforts in preparing this document to supplement the use of the AASHTOWare BcT software package. These efforts include reviewing and testing of the approach and methodology to determine selected inputs to the Pavement ME Design software package. All work to develop the AASHTOWare BcT software package was conducted in accordance with generally accepted pavement engineering practice. No other warranty, expressed or implied, is made.

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Chapter 1 Introduction

The Pavement ME Deflection Data Analysis and Backcalculation Tool (BcT) is a standalone software program that can be used to generate elastic layer modulus and layer thickness inputs to the AASHTO Pavement ME Design® software for rehabilitation design. The BcT is capable of analyzing raw deflection data files obtained from Falling Weight Deflectometer (FWD) testing devices, backcalculating in-place elastic layer moduli for flexible and rigid pavements and generating selected inputs for performing rehabilitation design using the Pavement ME Design software package. In addition, it can be used to perform loss of support analysis and load transfer efficiency (LTE) calculations.

Version 1.0 of the BcT was developed under the AASHTO FY 2017 program to supplement the rehabilitation design module of Pavement ME software. Version 1.1 includes new features and enhancements requested by users of the software and was released in FY 2021.

The backcalculation engine embedded in the BcT is EVERCALC®, which is embedded into the software program. The output from the backcalculation process is modified from that generated by EVERCALC and is processed into a format to generate input files to the Pavement ME Design software for rehabilitation design. The BcT contains an instructional **Guided Process** feature that describes the process flow on the selected module. **Figure 1** shows a flowchart of the ME Backcalculation Tool procedure. The functionality of the tool can be broadly grouped into three phases:

(1) Pre-processing deflection data (including project segmentation).
(2) Backcalculation of elastic layer moduli.
(3) Post-processing of results to generate inputs for Pavement ME rehabilitation design.

The BcT can import and pre-process raw deflection data file formats from three FWD testing devices: Dynatest, JILS and KUAB. Segmentation of the project into analysis segments is performed based on the cumulative area difference method as described in the 1993 AASHTO Design Guide [(1)]. The automatically-generated segments are compared using a t-test to check for statistically equal mean deflections. Adjacent segments that have statistically similar means are combined, and the final list of automatic segments is displayed to the user. The user can either accept the computed segments or define their own segments prior to entering the pavement layer structure simulation. Inputs for the pavement layer structure such as layer type, thickness, Poisson's ratio and moduli (seed, maximum and minimum values) are then entered by the user, which are used in the backcalculation process.

Subsequent chapters of the User Manual describe the individual modules or tabs of the BcT, including requirements, limitations and the background processes involved. The chapters are listed below:

- Chapter 2 describes the deflection and layer thickness data.
- Chapter 3 describes the individual pre-processing modules in detail, along with the required user inputs, module controls and information displays.
- Chapter 4 describes the backcalculation and post-processing modules.

There are multiple appendices to the User Manual, which are listed below:

- Appendix A provides a brief overview of the rehabilitation design procedures in the Pavement ME Design software, which are discussed in detail in the Mechanistic Empirical Pavement Design Guide (MEPDG) Manual of Practice.[2]
- Appendix B describes how the cumulative area difference method is used for automatic segmentation of deflections measured along a proposed rehabilitation project or roadway segment.
- Appendix C provides the default values used by the BcT for various pavement layer properties.
- Appendix D contains a list of layer types used to define the pavement structure within the BcT. The material type selection in the Pavement ME software corresponding to each of the backcalculation layer types, e.g. AASHTO soil classes corresponding to coarse-grained or fine-grained subgrades are also provided in Appendix D.
- Appendix E overviews and describes the procedure to load deflection and thickness data files, backcalculate the pavement layer moduli and generate a rehabilitation design file for Pavement ME.

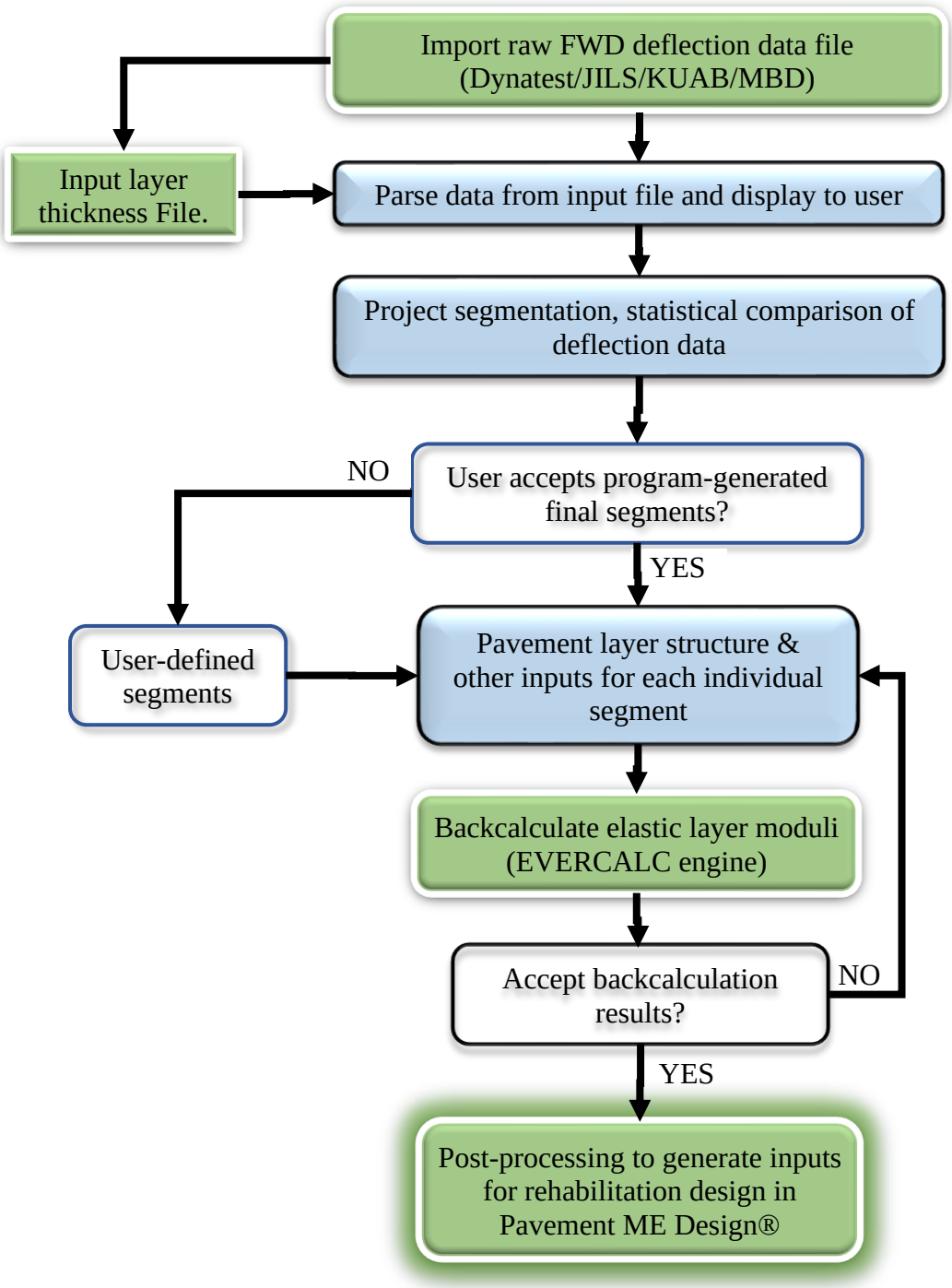


Figure 1 Pavement ME Backcalculation Tool (BcT) Process Flowchart

Chapter 2 Getting Started—Input FWD Data Module

Figure 2 shows the main user interface of the BcT. The functionality of the tool can be broadly divided into three phases: (1) pre-processing deflection data (including project segmentation); (2) backcalculation; and (3) post-processing of results to generate inputs for Pavement ME rehabilitation design (see figure 1). The interface is divided into several tabs or modules as shown on the left panel in **Figure 2**. The BcT also contains an instructional **Guided Process** feature that describes the process flow on the selected module.

The modules are executed sequentially, with some requiring user inputs or selections, while others just display information such as charts or results from internally performed calculations. Users can return to any of the previously completed modules to make changes, but can only proceed to the next incomplete module.

Completed modules for which all required information has been entered by the user are indicated by a green tick mark to the left of the module name. The module that is partially completed or being edited (Module-in-progress) is indicated by an orange circle. The module that is currently being viewed by the user is highlighted in blue, e.g. the Input FWD Data module in **Figure 2** is displayed in blue text. Incomplete or pending modules are indicated by encircled gray-colored minus signs as shown in **Figure 2**.

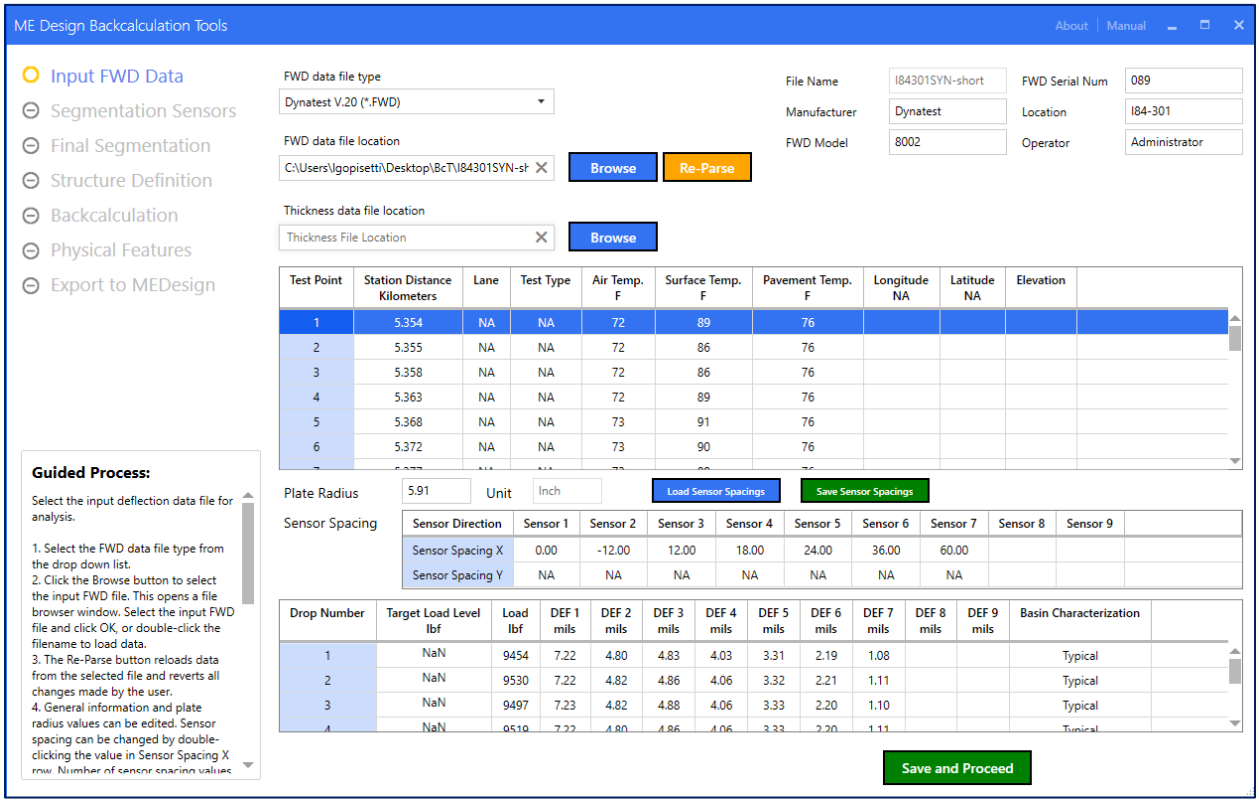


Figure 2 BcT User Interface after Opening the Software

The Input FWD Data module consists of several components as shown using labeled panels or blocks in **Figure 3**: (A) input FWD data file type and file selection and thickness data file selection; (B) general information; (C) station data; (D) sensor spacing; and (E) drop data – drop load, deflection readings and basin characterization. The following paragraphs explain the different panels or blocks included in the Input FWD data module.

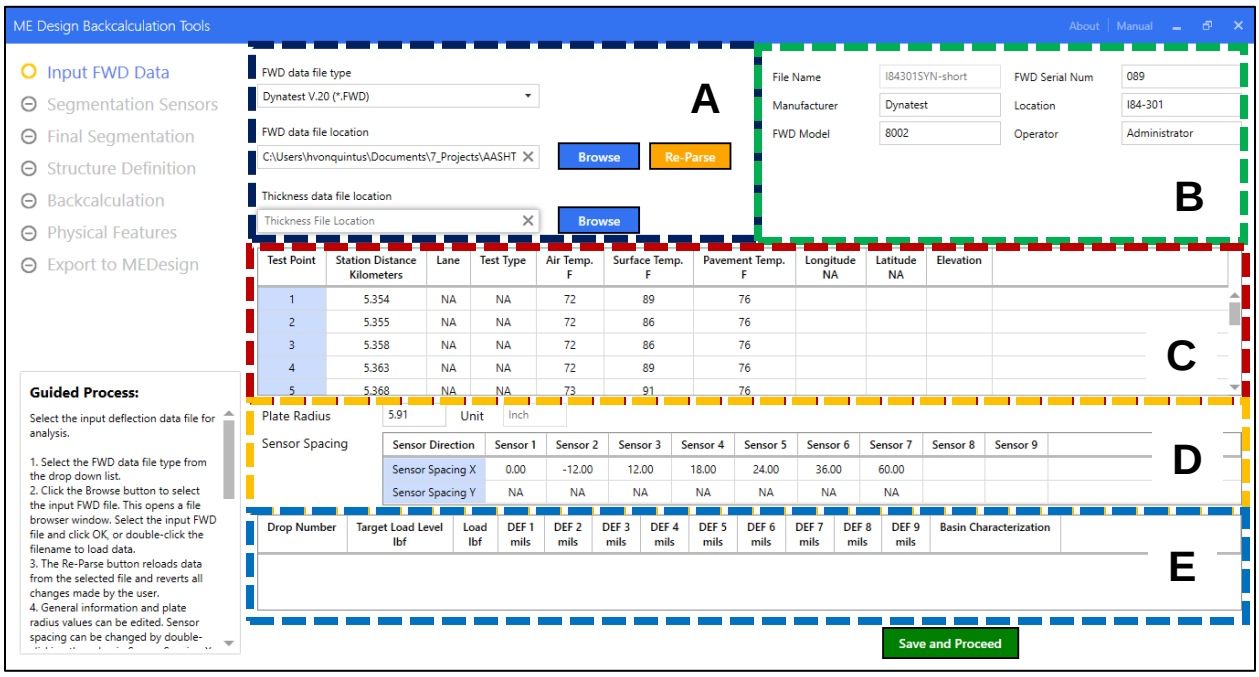


Figure 3 FWD Input Data Module Screen – Information Panels

FWD and Layer Thickness Data—Panel A

FWD Data File

The first step in using the BcT is to select a FWD data file in the requisite format. Selecting the FWD data file is a two-step process as shown below in **Figure 4** and discussed below.

1. First, the FWD data file type should be selected. The BcT allows six different file types from three FWD testing devices:
   - JILS - .DAT file format
   - KUAB - .FWD file format
   - Dynatest V20 - .FWD file format
   - Dynatest V20_SI - .F20 file format
   - Dynatest V25 - .F25 file format
   - Dynatest - .mbd file format

   The file type must be selected prior to browsing for the actual deflection data file, or the program displays an error message – "**Please select the source file type first**".

2. After selecting the file type, the **Browse** button is used to locate the project deflection data file. The file browser dialog displays only those files in the current folder whose extension is the same as the selected file type, e.g. FWD, DAT, F20 or F25.

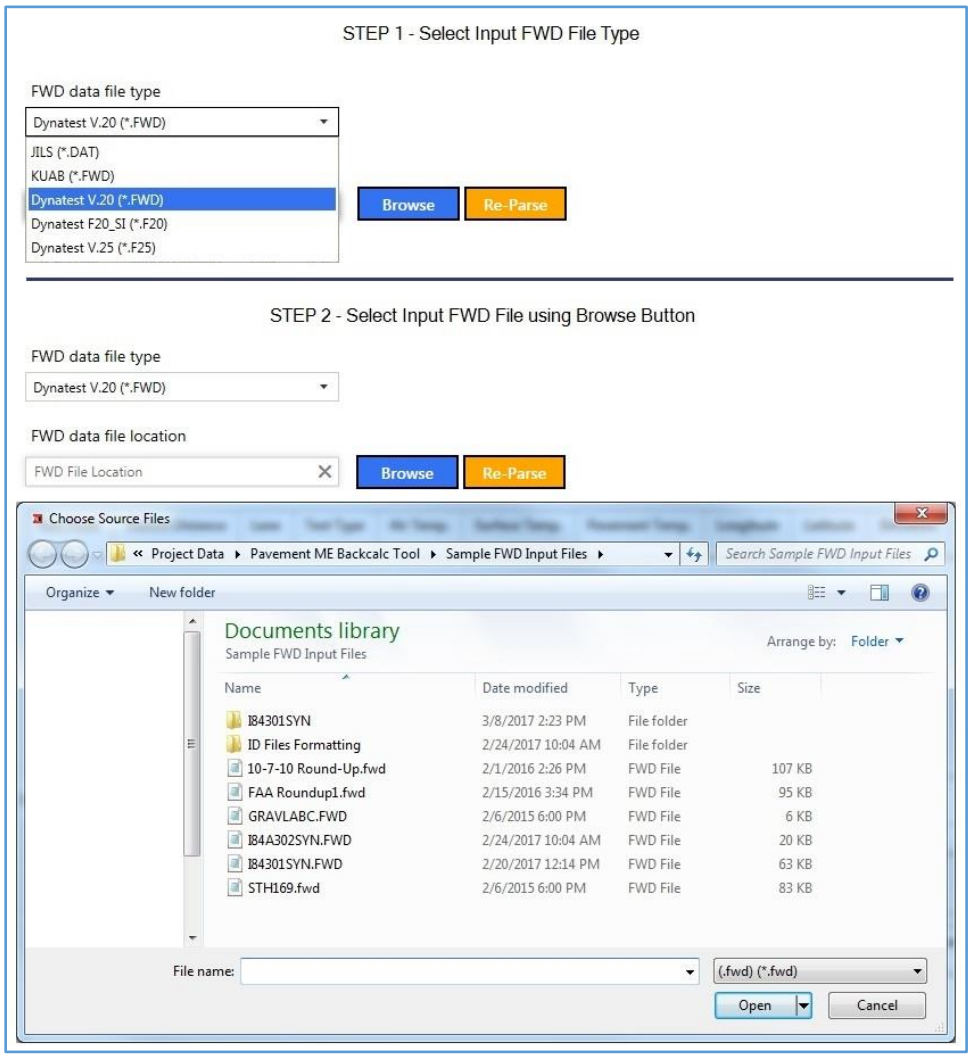


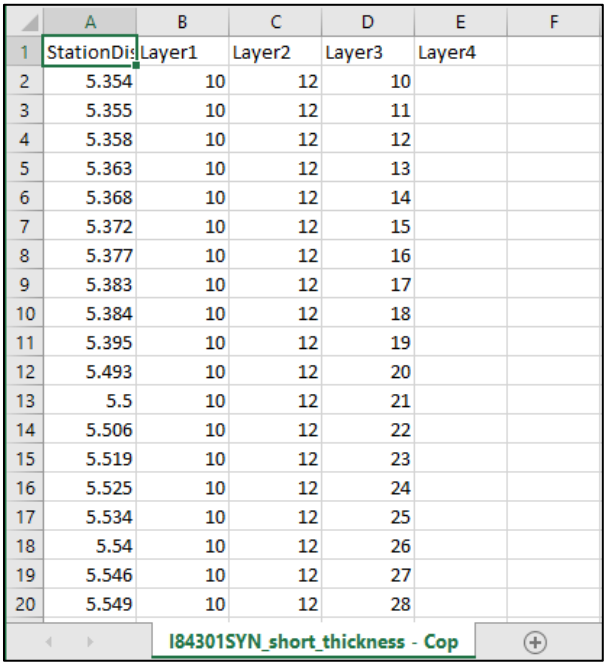
Figure 4 FWD Input Data File Selection

Users can click on the target file name and then click **Open**, or double-click the target file name to open the input file. The data from the input file is automatically parsed and is used to populate the appropriate fields and tables on the module screen. The **Re-Parse** button allows users to reload information from the FWD file and revert any changes made to the data. Since the re-parsing process replaces all information with that available in the original file, any additional information entered by the user (e.g. test type) will be lost.

Thickness Data File

The layout for the Input layer thickness data module is shown in **Figure 5**. The thickness data file simply consists of the thicknesses for each layer that is identified in the pavement structure for a total of 4 layers. A layer thickness data file is not mandatory for running the BcT, but is

suggested because the thickness dat is used to populate the layer structure simulation definition in the Structure Definition Module. The layer thickness file can be populated using results from borings and cores or ground penetrating radar (GPR). If GPR data are available, the GPR raw data must be processed externally to generate layer thicknesses; the BcT does not interpret GPR data to determine layer thickness.



	A	B	C	D	E	F
1	StationDis	Layer1	Layer2	Layer3	Layer4	
2	5.354	10	12	10		
3	5.355	10	12	11		
4	5.358	10	12	12		
5	5.363	10	12	13		
6	5.368	10	12	14		
7	5.372	10	12	15		
8	5.377	10	12	16		
9	5.383	10	12	17		
10	5.384	10	12	18		
11	5.395	10	12	19		
12	5.493	10	12	20		
13	5.5	10	12	21		
14	5.506	10	12	22		
15	5.519	10	12	23		
16	5.525	10	12	24		
17	5.534	10	12	25		
18	5.54	10	12	26		
19	5.546	10	12	27		
20	5.549	10	12	28		

Figure 5 Pavement Layer Thickness Data File

Units

The BcT is designed to analyze data in both US customary and SI units. The BcT selects the appropriate units for all variables in different modules based on the data in the input file. No user input is necessary to assign units for any of the variables. However, the units for the thickness data file must match the units for the FWD deflection file (US customary or SI units). The BcT follows one system of units throughout the execution process, so it is not possible to use an input file that has data with mixed units, e.g. sensor spacing in inches and deflection values in microns.

Station numbers are treated as numeric values but need not follow any system of units. However, the units and type of station numbering system used in the layer thickness file must match the units and numbering system used in the FWD deflection file. All other variables in the input file – temperatures, FWD plate radius, sensor spacing, load and deflections should follow the same unit system.

Station numbers should always be numeric values to allow segmentation.
Non-numeric station numbers should be corrected by user in the raw input FWD file.
Station number is the only variable that need not follow the unit system.

General Information—Panel B

The general information fields are displayed in the top right position of the module (Panel B) as shown in **Figure 3**. These values exist only to provide guidance to the user regarding the details of the file or FWD test and are not used in any computational procedures. **Figure 6** shows the general information loaded from the sample FWD input file.

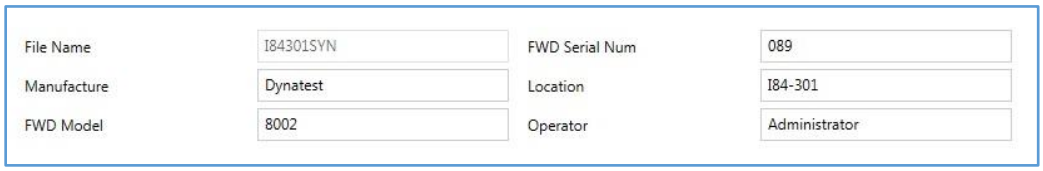


Figure 6 BcT General Information

The fields are automatically populated if the corresponding information is available in the deflection data file. Missing information can be entered and automatically-populated entries (except the File Name) can be changed by the user. The general information fields contain the following information:

- File Name
- FWD Manufacturer
- FWD Model
- FWD Serial Number
- Location
- Operator

Station Information Table—Panel C

The Station Information table displays the information pertaining to each station at which deflection data is available in the input file. **Figure 7** shows the station information table for a sample input file using US customary units.

Test Point	Station Distance Kilometers	Lane	Test Type	Air Temp. F	Surface Temp. F	Pavement Temp. F	Longitude NA	Latitude NA	Elevation
1	5.354	NA	NA	72	89	76			
2	5.355	NA	NA	72	86	76			
3	5.358	NA	NA	72	86	76			
4	5.363	NA	NA	72	89	76			
5	5.368	NA	NA	73	91	76			
6	5.372	NA	NA	73	90	76			
7	5.377	NA	NA	73	89	76			
8	5.383	NA	NA	73	91	76			

Figure 7 BcT Station Information

While parsing station information from the input file, the tool reads data for a fixed number of variables and populates the columns in the table. Temperature values are measured in ^{o}F for US customary and ^{o}C for SI units, and are automatically displayed to the user in the column headers.

- **Test point** – sequential test number as measured during the FWD test
- **Station distance** – also referred to as station number, no units required. The units for station distance, if available in the input file, are displayed in the column heading. Units for station distance may be different from those used for analysis variables such as sensor spacing, layer properties, loads and deflections.
- **Lane** – lane number in which the test was conducted
- **Test Type** – code for test type as assigned or specified by agency, e.g. wheel-path, mid-slab, slab corner or edge
- **Air temperature** – atmospheric or air temperature
- **Surface temperature** – temperature of the pavement surface
- **Pavement temperature** – manually entered pavement temperature, typically corresponding to a measurement within the pavement layer, such as AC mid-depth temperature
- **Latitude** – measured in degree-minutes
- **Longitude** – measured in degree-minutes
- **Elevation** – geographical elevation of the station location

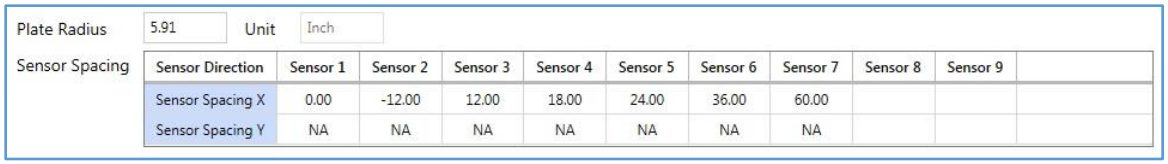
The units and display properties are defined by column and not by individual cells, hence all cells belonging to a column have the same properties. The variables Station Number, Latitude, Longitude and Elevation are attributes by which a station is identified and hence, cannot be edited by the user. Values in the other columns such as Lane, Test Type and Temperatures can be edited by the user.

Air, surface and pavement temperatures are either measured during the FWD test or can be entered by the user. Typical range of temperature values are from 20°F (-7°C) to 100°F (38°C) for the purpose of backcalculation. The range of air temperatures recorded in the Long Term Pavement Performance (LTPP) database [7] are -13°F (-25°C) to 140°F (60°C), while pavement temperatures measured at depths of 1 to 4 inches below the pavement surface are from -13°F (-25°C) to 200°F (93°C). Temperatures are not required, but provide valuable information for evaluating the elastic layer moduli and entering the Pavement ME Design software inputs. Air and surface temperatures are routinely included in the FWD deflection file, but pavement temperatures are generally not included. If pavement temperatures are unavailable, pavement temperature can be calculated using the Bells relationship.[3]

NOTE: The automatic calculation of pavement temperature within the BcT was not included in version 1.1, but is likely to be included in future versions.

Sensor Spacing and Plate Radius—Panel D

Plate radius is the radius of the FWD loading plate, which is automatically populated during parsing if available in the input file (see **Figure 8**). This is a ***required input*** and cannot be left blank, and can be changed by the user. The requirements for the units of plate radius is the same as described below for sensor spacing values.



Sensor Direction	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Sensor 5	Sensor 6	Sensor 7	Sensor 8	Sensor 9
Sensor Spacing X	0.00	-12.00	12.00	18.00	24.00	36.00	60.00		
Sensor Spacing Y	NA	NA	NA	NA	NA	NA	NA		

Figure 8 BcT Sensor Spacing and Plate Radius

Sensor spacing values are automatically populated in the table shown in **Figure 8**. The spacing information is a ***required input*** and must be entered by the user if not available in the input file. The sensor spacing values populated during parsing can be changed by the user.

Units for sensor spacing should follow the input data units system. If the data in the input file is in US customary units, sensor spacing should be in inches. Likewise, if the data in the input file is in SI units, sensor spacing should be in millimeters. The required units for sensor spacing are displayed in the read-only textbox immediately above the spacing table as shown in **Figure 8**.

The X sensor spacing represents the distance of sensors from the loading plate. A positive X-spacing indicates a leading sensor while a negative X-spacing indicates trailing sensor (on the opposite side of the load plate). Y sensor spacing indicates the distance of sensors from the loading plate in a direction perpendicular to the testing configuration. If the input FWD file has no sensors perpendicular to the test configuration, Y-spacing row is set by default to **NA** (information not available) or displays additional information about sensor placement in the X-direction (e.g. **Front**, **Center** or **Behind** as contained in a KUAB input file).

Drop Deflection Data Table—Panel E

The deflection values for individual drops are displayed in the table at the bottom of the screen. This table will be initially blank, as illustrated in **Figure 3**. This table is populated automatically as soon as the user clicks on any station or test point under **Panel C**. **Figure 9** shows the deflections for all sensors from the input file for a sample FWD test. The table displays the following information for each drop at a test point or station:

- **Drop Number** as recorded in the FWD data file
- **Target Load Level** – lbs. (US customary units) or N (SI units).
  The target load level is populated by the software as "NA," so the user needs to populate the target load. The target load is entered by the user for each drop in the test sequence, but only for one station or test point. The BcT automatically populates the remainder of the stations. As such, the same drop sequence must be used for all stations. Typical target load levels in US customary units are 6000, 9000, 12000 or 16000 lbs., which relate to the drop height of the FWD load during testing. Target load level values only assist the user to identify drops while selecting sensors for segmentation and are not used as input for calculations.
- **Drop Load** – lbs. (US customary units) or N (SI units).
- **Deflections** – number of columns with deflection readings is equal to the number of active sensors. The maximum number of sensors that can be accommodated is 9. If the input file contains deflection data at fewer number of sensors, the columns for the unused

sensors are displayed as empty cells. [NOTE: Recent versions of raw FWD deflection data allow for more than 9 sensors, but version 1.1 is limited to 9 sensors. It is likely that future versions of the BcT will increase the limit on the number of sensors. When more than 9 sensors are available, the user needs to decide which 9 sensors will be used for backcalculation and generate a FWD deflection file with 9 sensors.]

- **Basin Characterization** – displays the basin type as Typical, Type I, II or III based on the deflections. The different basin types and characterization procedure are described later in the filters section of the **Segmentation Sensors Module**.

Drop Number	Target Load Level lbf	Load lbf	DEF 1 mils	DEF 2 mils	DEF 3 mils	DEF 4 mils	DEF 5 mils	DEF 6 mils	DEF 7 mils	DEF 8 mils	DEF 9 mils	Basin Characterization
1	NaN	9454	7.22	4.80	4.83	4.03	3.31	2.19	1.08			Typical
2	NaN	9530	7.22	4.82	4.86	4.06	3.32	2.21	1.11			Typical
3	NaN	9497	7.23	4.82	4.88	4.06	3.33	2.20	1.10			Typical
4	NaN	9519	7.22	4.80	4.86	4.06	3.33	2.20	1.11			Typical

Figure 9 BcT FWD Drop Data

The Deflection Data table contains one or more rows of values, with each row corresponding to one FWD drop at a given station. The station for which deflection data is displayed is selected by clicking on the row corresponding to the desired station.

Values displayed in the deflection data table are read by the program from the input file and cannot be modified.

After loading data from the selected input file and providing the required inputs on the Input FWD Data tab, click **Save and Proceed** to navigate to the **Segmentation Sensors Module**.

Chapter 3 Pre-Processing and Structure Definition Modules

Pre-processing modules use raw deflection data to prepare inputs for backcalculation. The main activities performed during the pre-processing phase are reading and parsing deflection data from the user-supplied FWD data file and segmentation. The segmentation process is accomplished through two steps: statistical comparison and final segmentation. The segmentation can be completed using the deflection basin data or layer thickness data.

Segmentation Sensors Module

Deflection values measured at a specific sensor vary along the length of a pavement section. This variability may arise due to differences in the layer structure (change in pavement layer types, materials or properties), layer thickness or subgrade properties. The plot of deflections along the length of the pavement section can be used to identify the locations (individual stations or segments) and magnitude of deflection variability. This allows the user to define 'segments' into which the deflection data is divided and used for backcalculation. **Figure 10** shows the layout of the **Segmentation Sensors Module** screen for a sample FWD input file, but without a thickness file.

Figure 10 Segmentation Sensors Module – Screen Layout; without a Layer Thickness File

Segmentation Sensors

The BcT allows users to select up to three sensors whose deflections are used to compute segment intervals (see **Figure 10**). The module displays three charts of deflections along the length of the pavement section (deflections vs. stations), with each chart showing peak deflections measured using the selected sensor. Sensors can be selected using the drop-down boxes to the left of each chart. The X-axis on the charts shows the station numbers in units defined in the input file. The Y-axis shows deflection values in the input file unit system - mils for US customary and microns/μm for SI system.

The three sensors recommended for segmentation are the sensors at the load plate, the one further from the loading plate, and the one located at a distance from the loading plate that is slightly greater than the thickness of the bound layers. The user, however, should review the deflections measured at each sensor and make a selection based on how the deflections vary along the roadway relative to the deflections under the loading plate.

Deflection Charts Display Scaling – Zoom Feature

The deflection charts displayed on various module screens of the backcalculation tool are enabled with a horizontal scaling feature that allows users to zoom in and out of the charts using the mouse. The zoom feature is particularly useful to view deflection data from files with a large number of stations or closely spaced stations. To zoom-in on the charts, place the mouse over any one of the three charts and scroll the mouse button up to zoom-in or down to zoom-out. The zoom-in or zoom-out action is applied simultaneously to all the three charts on the screen. When zoomed-in on any of the charts, the user can scroll to stations to the left or right using the horizontal scrollbar at the bottom of the chart. **Figure 11** shows an example of the zoom feature, where the top chart shows the original deflection plot, and the bottom chart shows the zoomed-in deflection plot.

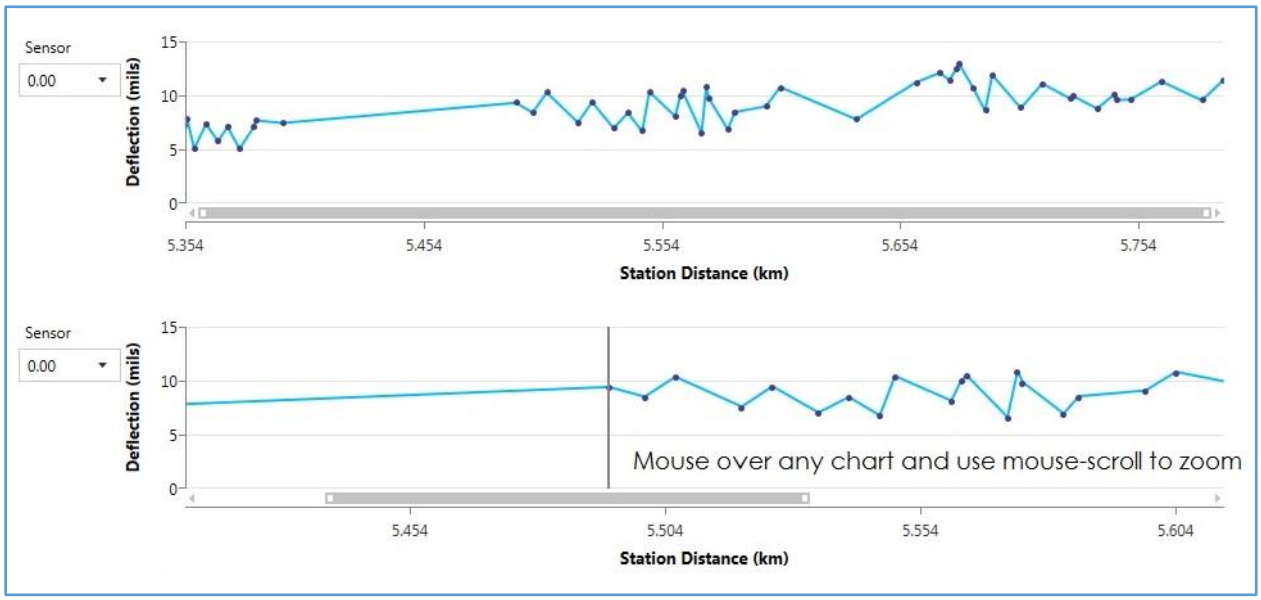


Figure 11 Segmentation Sensors – Zoom Feature in Deflection Charts

The module has multiple filters that can be selected to modify the data displayed on the charts. These filters are located at the top of the screen on this module as shown in **Figure 12**, and are applied simultaneously to all three charts. A brief description of the filters, along with options and functions is provided in the subsequent sections.

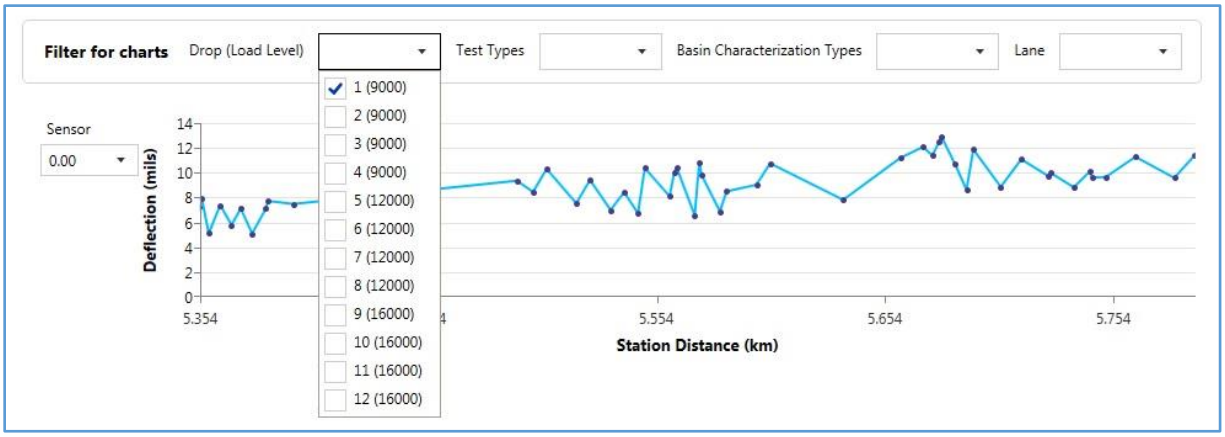


Figure 12 Segmentation Sensors Module - Filters

Drop Filter

The **Drop** filter can be used to select the individual FWD drops for which deflection data is displayed on the charts. The filter's drop-down menu contains drop numbers from the input file from which users can select multiple drops at the same time. The numbers in parentheses next to the drop number represent the target load level as entered by the user in the deflection data table on the **Input FWD Data** module. If the target load levels are not entered by the user, the value 'N/A' is displayed in parentheses.

The user should review the deflections at each target load to look for inconsistencies or large changes in deflections between the different drops or target loads throughout the project length. To proceed with segmentation, however, users must select only one drop only at the desired target load level. The user can select any of the sensors for segmentation, but it is suggested the drop selected by the user for segmentation be based on deflections measured for the middle to higher drops.

When the Segmentation Sensors screen is loaded initially, the first drop in the list is selected by default which can be changed by the user. Deflections corresponding to the selected drop number are used for segmentation in the subsequent modules. The drop number selection applies only to segmentation – the program performs backcalculation for all drops and stations irrespective of the selected drop number.

Test Types Filter

The **Test Types** filter allows users to select the drops to be used only for backcalculation. Input FWD files can contain deflection data collected from different locations on a pavement section. The information regarding the testing location is also recorded differently, which may or may not be available in the input FWD file. If test type information is not available in the input file, users

can manually enter the information in the station data table of the **Input FWD Data** module. The test types are automatically populated in the drop-down menu from the codes in the input FWD file.

Test locations within the pavement lane are assigned codes by agencies. The codes used by the LTPP program for both flexible and rigid pavements are shown below to illustrate this. Possible FWD test locations for a flexible pavement section along with their corresponding codes from the LTPP test program are as follows:

- Mid-lane (LTPP Code: F1)
- Outer wheelpath (LTPP Code: F3)
- Load transfer in outer wheelpath crack (LTPP Code: F4 and F5)

Possible FWD test locations for a JPC pavement section along with their corresponding codes from the LTPP test program are as follows:

- Outer wheel path (LTPP Code: J0)
- Mid-lane at middle panel (LTPP Code: J1)
- Pavement edge at corner (LTPP Code: J2)
- Pavement edge at mid-slab (LTPP Code: J3)
- Load transfer in outer wheel path at joint approach (LTPP Code: J4)
- Load transfer in outer wheel path at joint leave (LTPP Code: J5)

Backcalculation of in-place elastic layer modulus requires deflection data measured at either mid-lane (non-wheelpath) or wheelpath locations for flexible pavements, and mid-slab location for rigid pavements. If test type information is not available in the input FWD file, the BcT assumes all data is collected from wheelpath location for flexible pavements and mid-slab locations for rigid pavements. Care should be taken to ensure that the test type information, either available in the input FWD file or user-entered, corresponds to the pavement location at which deflections were measured during testing.

It is suggested that test points for measuring deflections adjacent to cracks or joints for calculating the load transfer efficiencies be identified and/or stored in a separate file. Backcalculating elastic layer moduli over a crack or joint should not be used to determine the average elastic layer modulus to be entered into the Pavement ME Design software.

Basin Characterization Types Filter

The **Basin Characterization Types** filter allows users to toggle different deflection basin types that are displayed on the chart. FWD deflection basins are separated into four types based on deflection values measured at different sensors (Typical, Type I, Type II, and Type III). The procedure and criterion for evaluating or separating the deflection basin into four types is the procedure recommended for use by Von Quintus et al. [4, 5]. The basin type is determined by normalizing the deflection values to the center-load deflections. Typical and Type II deflection basins are consistent or have the characteristics of deflections calculated with elastic layer theory. Conversely, Type I and III deflection basins are inconsistent with elastic layer theory. The following paragraphs describe and define each deflection basin types.

[NOTE: Type I and III deflection basins occur more frequently on PCC surfaced pavements, which may be characteristic of areas with voids, loss of support, severe thermal gradient causing curling of the PCC slab, and/or a combination of these conditions.]

Typical Deflection Basins
Typical deflection basins follow the elastic layer theory in that the deflection at any sensor (other than the center-load deflection) is lower than all sensors closer to the load. These basins generally have very low root mean squared errors (RMSE); less than 2 percent error. **Figure 13** shows an example of a typical deflection basin. [NOTE: RMSE is defined and calculated from the measured and calculated deflection basins and a product from the backcalculation process, which is explained in the next chapter of the User Manual for interpreting the results from the backcalculated moduli.]

Type II Deflection Basins
The deflections at adjacent sensors show a significant decrease in magnitude, which result in a drop or break in the deflection basin. Elastic theory is applicable to Type II deflection basins, but the error terms vary from a low value (about 2 percent) to a large value of 5 percent depending on the magnitude of the deflection drop. **Figure 14** shows an example of a Type II deflection basin.

Type I Deflection Basins
These basins are characterized by deflections at some sensors being greater than the center-load deflection. Among the different deflection basin types, Type I deflection basins generally have the highest error, and can exceed 10 percent. **Figure 15** shows an example of a Type I deflection basin.

Type III Deflection Basins
Deflections measured at a sensor further away from the load is equal to or greater than that measured at the adjacent sensor closer to the load, which is indicative of non-decreasing deflections at adjacent sensors. Similar to Type I deflection basins, elastic layer theory is not applicable to Type III deflection basins. The RMSE for these basin types range from values as low as 2 percent to greater than 10 percent, depending on where in the deflection basin the inconsistency with elastic layer theory occurs. **Figure 16** shows an example of a Type III deflection basin.

The BcT displays the deflection basin types for each individual drop in the **Drop Data** table on the **Input FWD Data** tab. However, only those drops which have Typical, or Type II deflection basins are used for segmentation and backcalculation. Type I and Type III deflection basins are excluded from backcalculation, because these are inconsistent with elastic layer theory.

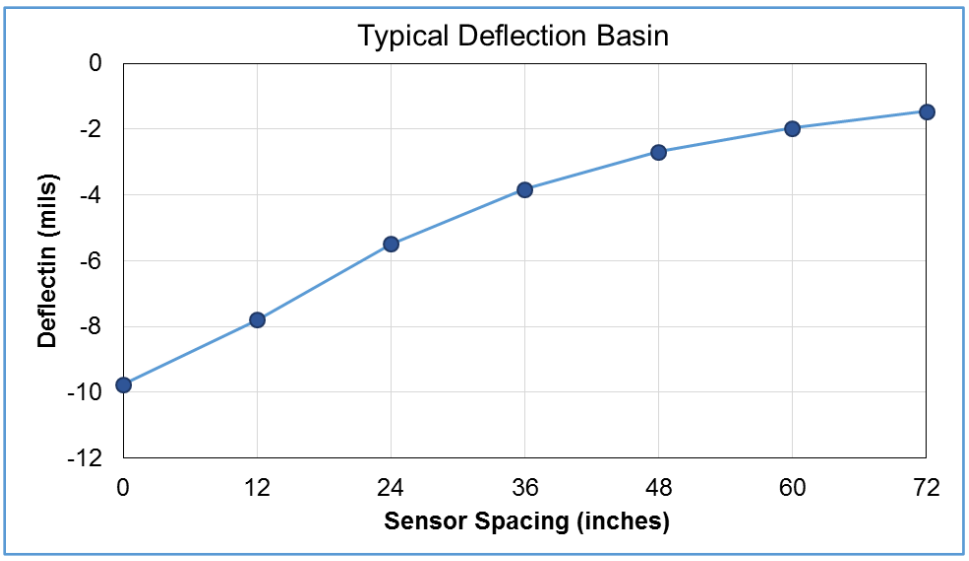


Figure 13 Typical Deflection Basin Example

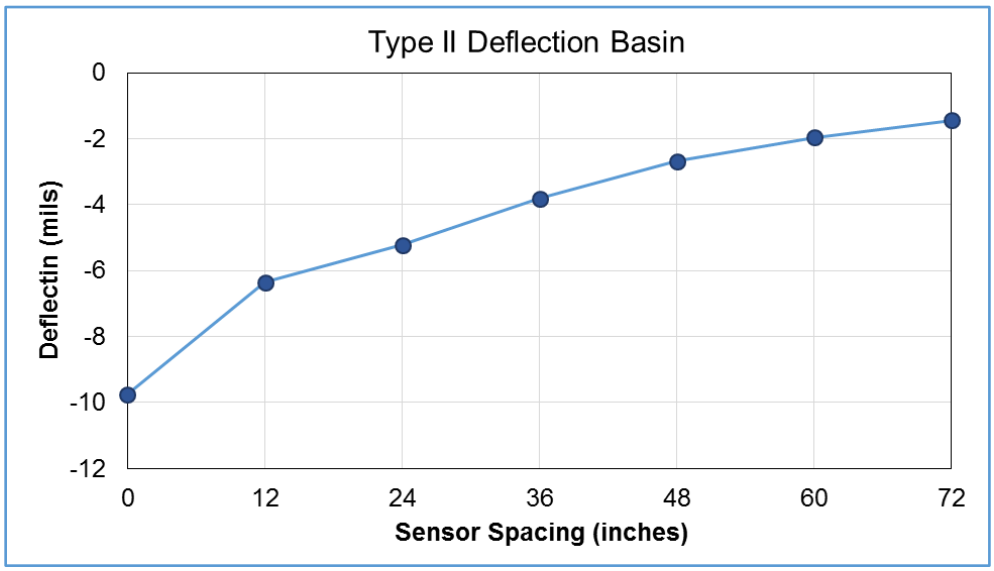


Figure 14 Type II Deflection Basin Example

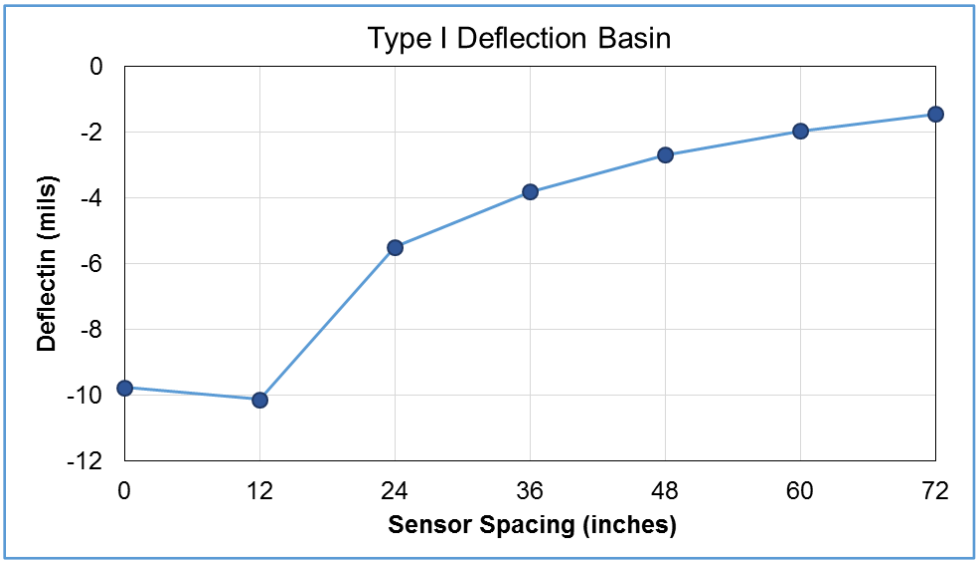


Figure 15 Type I Deflection Basin Example

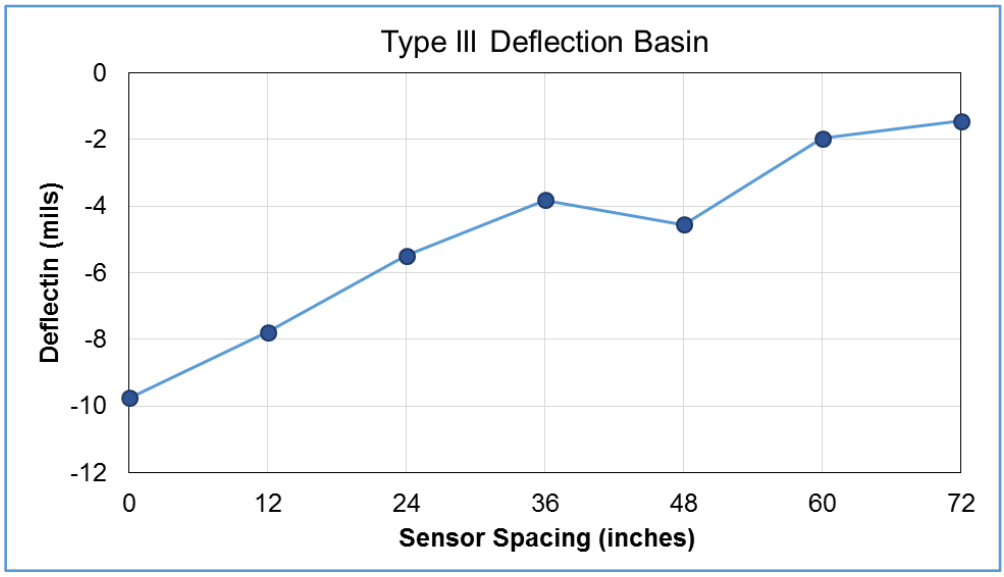


Figure 16 Type III Deflection Basin Example

Lane Filter

The **Lane** filter allows users to filter the deflection data from the input FWD file by lane number or position. If an input file contains deflection testing data from multiple lane positions such as mid-lane or wheel path, a partial set of deflection data corresponding to selected lane positions can be used in the backcalculation process. Unlike the test type filter, lane filter only populates the lane number or position value from the input file and cannot be entered by the user.

Layer Thickness Chart, if Available

If the user imported a layer thickness file (see **Figure 3** in Chapter 2), the BcT will display a chart of layer thickness along the length of the project at the bottom of the **Segmentation Sensors** Module, as shown in **Figure 17**.

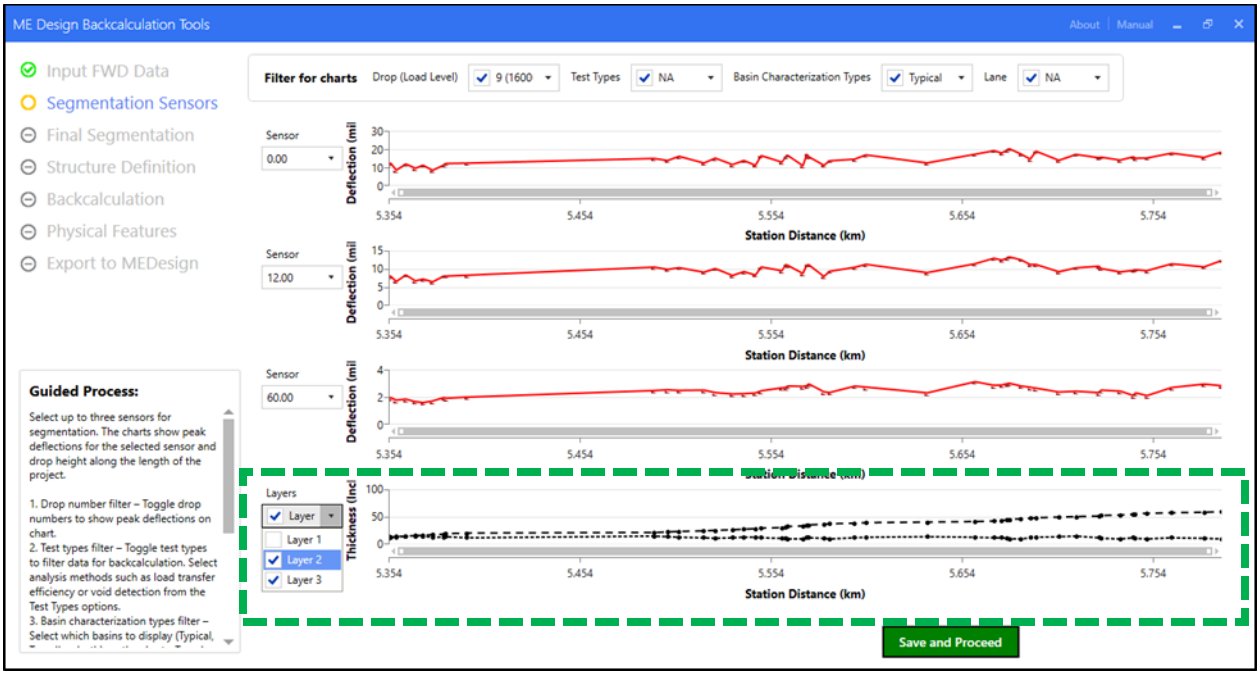


Figure 17 Segmentation Sensors Module – Screen Layout; with a Layer Thickness File

A user can review the layer thicknesses along the project by simply checking the individual layers in the drop box. One to all of the layers can be displayed in the chart. The layers that are checked by the user will be transferred to the next module or **Final Segmentation** module for use in segmenting the project.

Final Segmentation Module

Segmentation Based on Deflection Data, without Thickness Data

The segmentation of the project using deflection data uses two methods: the cumulative area method or preliminary segmentation and a statistical comparison method. Both can be considered by the user for segmenting the project and are defined in the following paragraphs.

Cumulative Area Method – Preliminary Segmentation Mode
The **Final Segmentation** module displays the segments calculated using deflection data for the three sensors selected by the user on the segmentation sensors tab. The purpose of this module is only to display information and does not require any input from the user. Calculation of segment intervals is based on cumulative area difference method as described in **Appendix B**.

The module consists of three charts with deflection data for the three selected sensors plotted along the length of the pavement section as shown in **Figure 18**. Locations of segments are shown using vertical lines on the chart between two adjacent stations. The station to the left of the vertical line represents the end location of the previous segment, and the station to the right of the vertical line represents the start location of the next segment. The vertical dashed lines correspond to the **Preliminary Segmentation Mode**, shown in **Figure 18**.

[NOTE: The charts on the **Final Segmentation** module screen also incorporate the zoom feature as described in the **Segmentation Sensors** module.]

The minimum segment length is defined as seven stations. The definition in terms of the number of stations as opposed to distance accounts for pavements sections with irregular station spacing. If the input FWD project file has a reasonably small number of stations (20 stations or fewer) where multiple segments having a minimum of seven stations is not possible, the tool does not perform segmentation for the file. In such cases, the entire pavement section is considered as one segment.

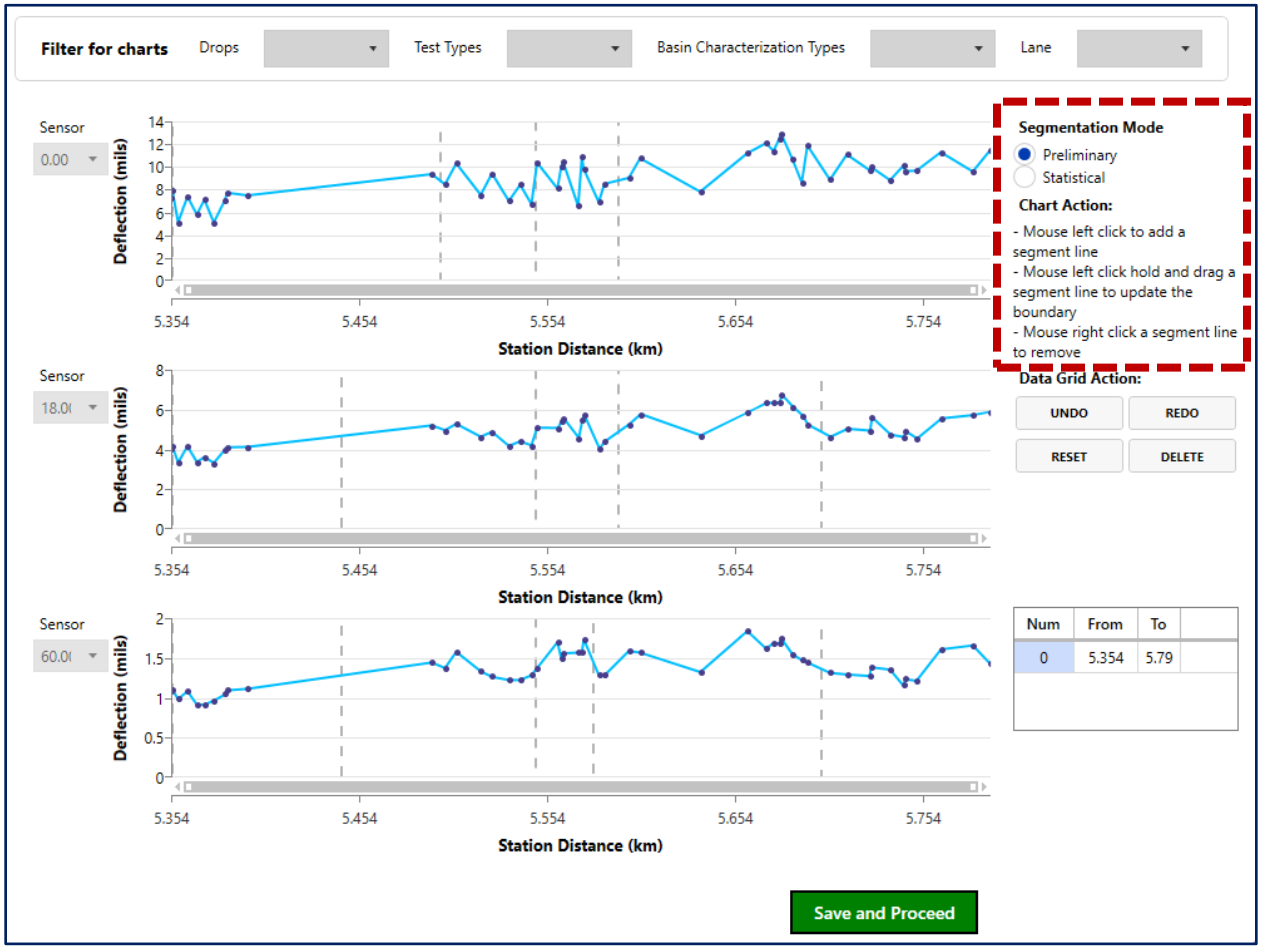


Figure 18 Deflection-Based Segmentation – Example without Thickness Data

Statistical Comparison Method – Statistical Segmentation Mode
In this module, adjacent segments are compared to determine and merge statistically similar segments. Each segment (except the final segment) is compared with the subsequent segment to check for equality of deflection mean value and standard deviation. The F-test is used to check for equal variances of the two sets of deflection data from adjacent segments, and the student's t-test is used for checking equality of the mean deflections. **Appendix B** provides details on how the BcT statically segments the project based on deflection data.

For a pavement section which is divided into N segments during preliminary segmentation, mean deflections for each i^{th} (i < N) segment is compared to the $(i + 1)^{th}$ segment, i.e. next adjacent segment. The two segments are then merged into a single segment if the mean deflections are statistically equal. Segments whose mean deflections are statistically equal but spatially separated (non-adjacent segments) are not merged. The procedure used for statistical comparison can be compared to the **Preliminary Segmentation Mode** by checking the circles in the designated area shown in **Figure 18**, and observing how the vertical lines change between the preliminary and statistical modes.

Segmentation using Thickness Data

When layer thickness data is available, the data are graphically presented, as shown in **Figure 19**. The layer thickness data are graphically presented for each layer included in the thickness file. In addition, a layer type table is included on the screen (see **Figure 19**).

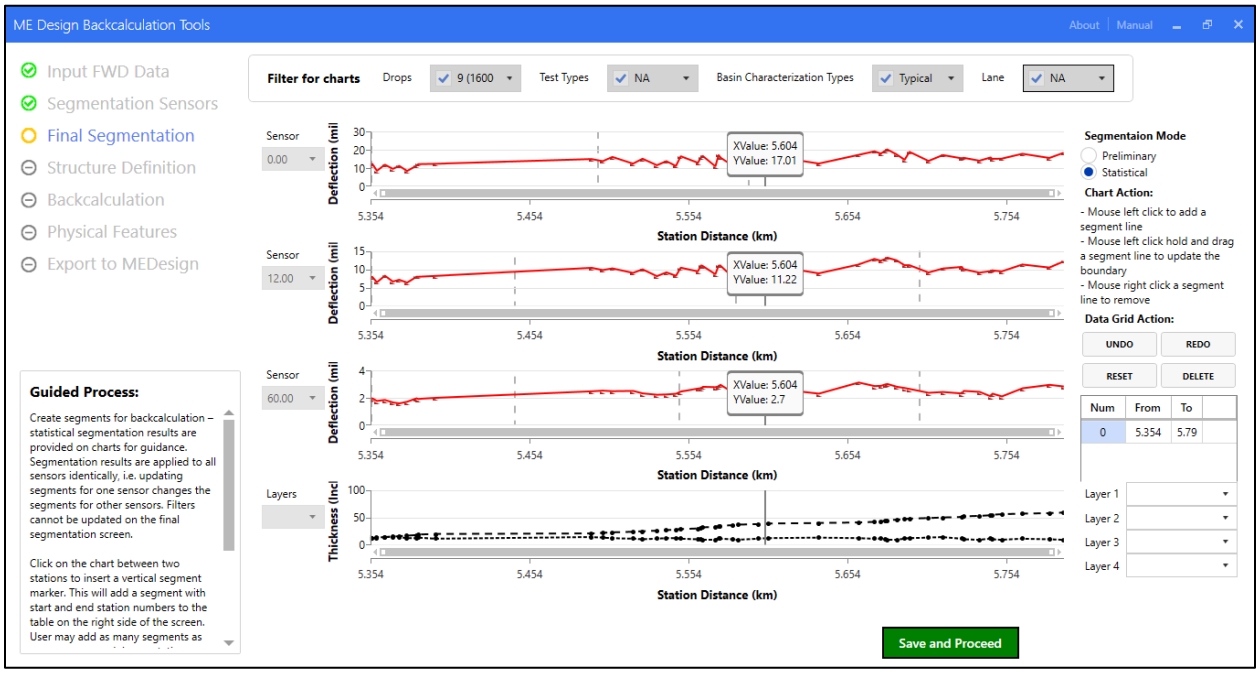


Figure 19 Statistical Mode, Final Segmentation – Example with Thickness Data

The BcT does not automatically define the segmentation for layer thickness. The thickness data is included so the user can consider the layer thickness and how it changes along the roadway in making a decision on the final segmentation to be used in the backcalculation process. As noted

in the previous section, only the drop down boxes checked in the **Segmentation Sensors** Module are displayed in the **Final Segmentation Module.**

Final Segmentation – User Defined

The Final Segmentation module sets the limits for the final list of segments into which the pavement section is divided for backcalculation. The two major features of this module are that there is no limit on the length of a segment (as compared to the minimum segment length for the automatic procedure) and the user can retain or override the results from the cumulative area difference and statistical methods. The layout of the final segmentation module is shown in **Figure 18** when layer thickness data is unavailable and **Figure 19** shows the segmentation when layer thickness data is available.

The charts show the peak deflections for the selected sensors along the length of the pavement section. Dashed vertical lines represent the locations of segments calculated from the preliminary and statistical segmentation methods. As opposed to the preliminary segmentation and statistical comparison modules, the cursor does not snap to station points but moves smoothly over the charts to allow users to select the segment locations to be used in the backcalculation process.

Segments are selected by clicking between two stations where the one on the left indicates the end of previous segment and the one on the right indicates the beginning of the next segment. Selections made on one of the three charts are automatically reflected on the other two charts. The user can select as many segments as the total number of stations along the section length. Segment locations selected by the user by clicking on the charts are shown by red dashed vertical lines as shown in **Figure 20**. The station numbers corresponding to the two segments are updated in the table to the right of the module screen. The reset button located above the table removes all segment markings, following which a new set of segments can be assigned.

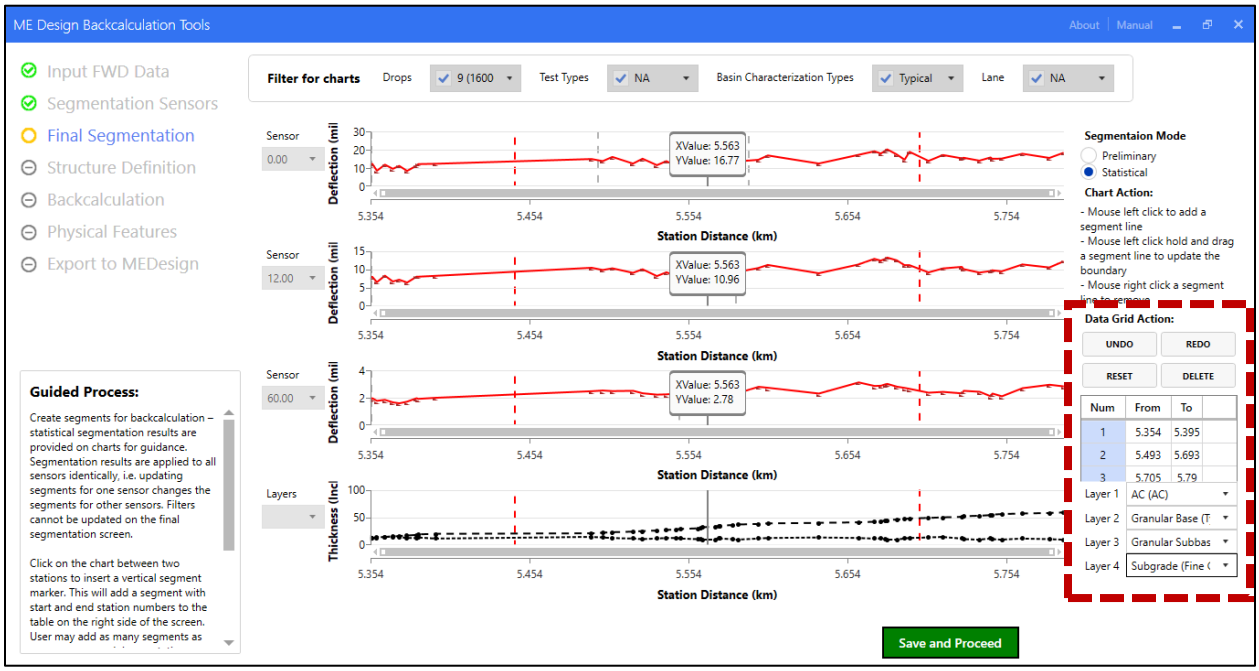


Figure 20 Segmentation Limits defined by User

After the user defines the final segmentation and a layer thickness file is included, the user must define a layer type for each layer along the project. The number of layers included are the total number of layers in the thickness file plus one for the last layer with an infinite thickness. The layer type is selected by the user from a drop down arrow on the layer type table with the standard layer types included in the BcT, as shown in **Figure 21**. The average thickness for each layer within a segment are automatically populated in the **Structure Definition Module**, see next section.

NOTE: The layer number assigned to a layer type must be the same for all segments within the project. If the layer structure simulation and layer types assigned to a layer number within the project limits differs, then the deflection and thickness files must be grouped into separate files.

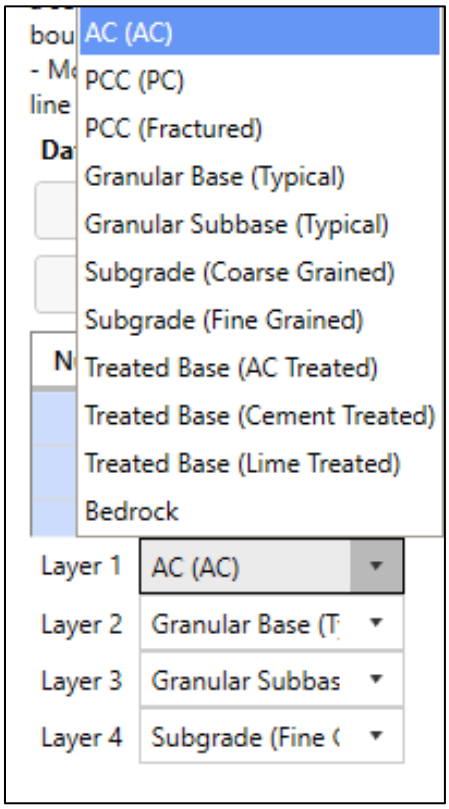


Figure 21 Selection of Layer Type from Standard List of Materials included in the BcT

Structure Definition Module

The pavement layer structure and inputs necessary for backcalculation are entered in the structure definition module, when a thickness file is unavailable. When a thickness file was imported by the user, the pavement structure will be populated with the average layer thicknesses for each segment.

After the user clicks on the Structure Definition Module, the deflections measured by the sensor under the loading plate along the project and final segments are shown, but the pavement structure is not shown on the screen. The user must click on each individual segment for the pavement structure to be shown on the screen, as shown in **Figure 22**. The user can assign different structures for each of the segments defined in the final segmentation module. The segments are shown on the chart by solid vertical lines.

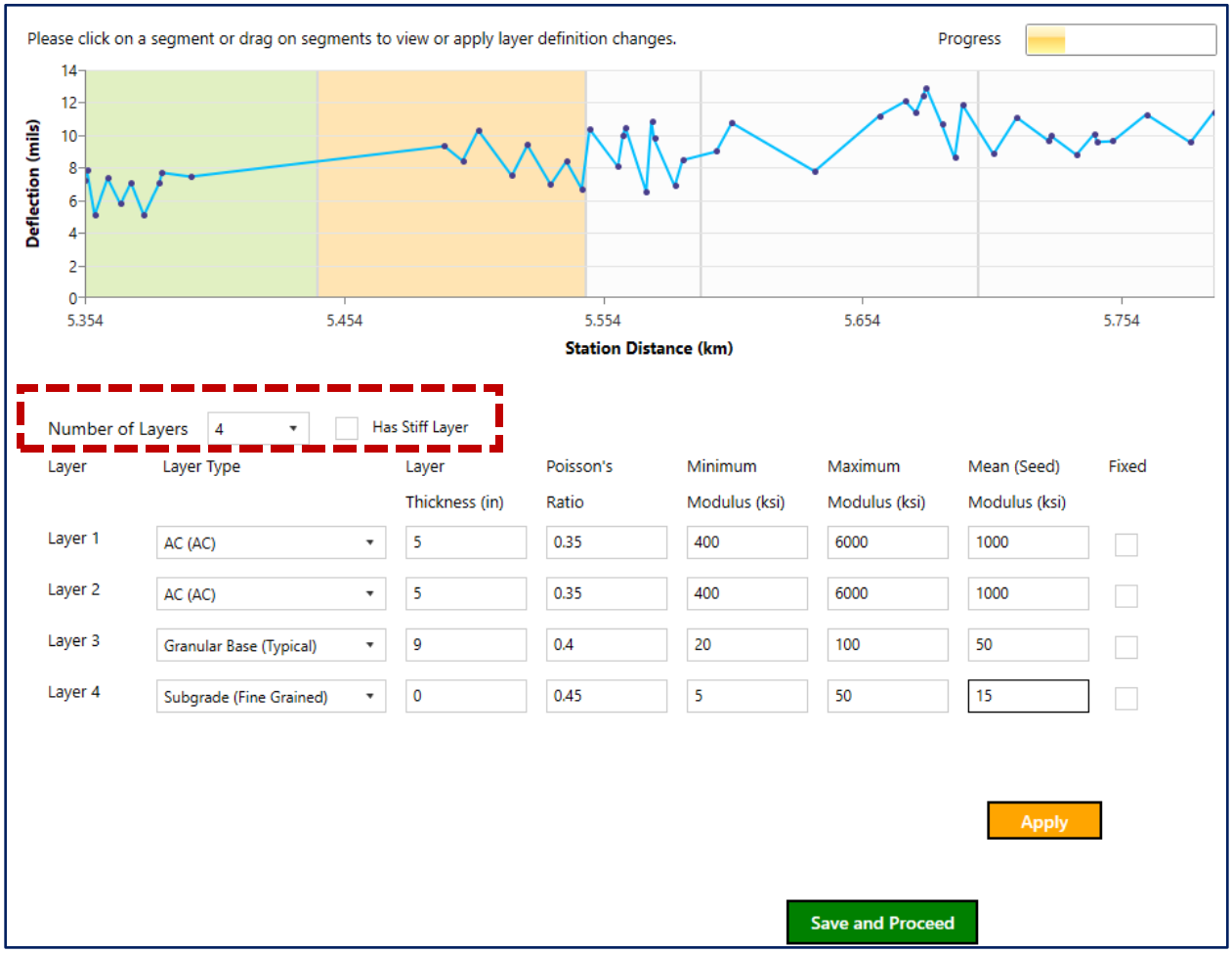


Figure 22 Structure Definition Module

Structure Definition without Thickness File

To assign a layer structure and enter backcalculation inputs, each segment must be made active by clicking on the segment on the chart. The area on the chart corresponding to the currently selected (active) segment is highlighted in orange. To assign layer structure and other inputs to the active segment, the number of layers should first be selected from the **Number of Layers** drop down list. The maximum number of layers is limited to five, including the last layer, in accordance with the limitation of the backcalculation program EVERCALC®. Once the number of layers for the segment is selected, the program generates rows for entering inputs for each

layer. If bedrock or a rigid/stiff layer is known to exist along the project, the box for the **Stiff Layer** should be checked. The BcT will calculate the depth to bedrock or the stiff layer.

Material type for each layer is selected using the options provided in the drop-down menu under **Layer Type** property (see **Figure 21**). The layer type options available to the user are as shown below:

- AC (AC) – Asphalt layer/mixture
- PCC (PC) – Portland cement concrete layer
- PCC (Fractured) – Fractured or rubblized PCC
- Granular Base (Typical) – Granular base course
- Granular Subbase (Typical) – Granular subbase course
- Subgrade (Coarse Grained) – Coarse-grained subgrade layer
- Subgrade (Fine Grained) – Fine-grained subgrade layer
- Treated Base – Asphalt-treated, cement-treated or stabilized base course
- Bedrock – Rigid bedrock layer below subgrade (always last layer)

Layer type selection contains generic options for different materials used in surface, base, subbase and subgrade layers which are different from the material types available in the Pavement ME software. The exact material type is not a critical input for backcalculation, but it is a necessary input for M-E design. Therefore, selection of the specific material type is done in the **Export to ME Design** module.

Unit system for the layer properties is consistent with that of the input FWD data file. The program automatically populates the layer properties with default values in the appropriate units when a layer type is selected. The default values are typical of the "undamaged" layer material and are listed in Appendix B. However, these range of typical modulus values may not be representative of "damaged" material or material defects. The following information should be entered for each layer; it is suggested that the range of typical default modulus values not be included but a wider range of modulus values should be included for each layer type.

- **Layer thickness** – represents the average layer thickness within the segment. The thickness of the pavement layers should typically increase with depth below the surface, and thin layers (generally less than 2 inches) should not be simulated.
- **Poisson's ratio** (no units) – suggested that the default value be used, because Poisson's ratio does not have a significant impact on the backcalculated elastic layer modulus.
- **Minimum modulus** – the modulus representing a damaged condition; as an example: stripping for asphalt mixtures, contamination of unbound base and subbase layers, saturated materials, etc.
- **Maximum modulus** – the modulus representing very strong materials; as an example: aged asphalt mixtures at cold temperatures, dry high plasticity clay soils, dry coarse aggregate layers, etc.
- **Seed modulus** (initial guess) – the seed modulus does not have a significant impact on the final backcalculated modulus results, so it is generally suggested that the default seed modulus values be used.

- **Fixed layer** (bedrock layer modulus is fixed by default) – fixed layers or layers with a fixed modulus values close to the surface should not be used for backcalculation. The only layer with a fixed modulus is typically bedrock.

The progress bar on the top-right corner of the module screen displays the progress of data entry completion for the various segments. When all necessary information for an active segment has been correctly entered and the **Apply** button is pressed, the color of the segment on the chart turns to green, indicating that the information for that segment has been successfully entered and saved. The progress bar becomes full when all segments has been completed. Users can modify the information for a completed segment any time before proceeding to the backcalculation module.

Thin layers – layers having a thickness less than 3 inches (7.5 cm) should be avoided, if possible. There should be at least one layer with variable modulus, i.e. all layers cannot be fixed simultaneously.

Structure Definition with Thickness File

When the user imports a thickness file, the simulated structure is automatically populated with the average layer thicknesses for each segment that is defined by the user. The user still needs to click on each segment for the structure simulation to appear on the screen and then hit the **Apply** button to accept the structure for each segment. The layer thickness within each segment should be verified by the user. It is also important to note that the BcT will populate the structure with the default values for each layer. The minimum and maximum layer modulus values should be revised or expanded, as discussed in the above section.

NOTE: When the thickness file for the project contains layers that are included in only some areas of the projects, the segmentation should be assigned by the user to ensure a consistent layer structure relative to the layer types within the same segment. This is to ensure the average thickness for a layer that is not present throughout the project length is not biased or altered by missing layer thicknesses. The user should remember that layer thickness is an important variable in backcalculating elastic layer modulus.

The **Save and Proceed** button generates input files for the backcalculation process that is based on the EVERCALC engine. Separate input files are generated for each segment, where the files only contain the set of deflection data for stations within the individual segments. File formats for the input files are the same as required for the EVERCALC program – general information (except layer thickness) entered in the structure definition module is used to create a .GEN file and deflection data along with station number, layer thicknesses and temperatures (air and pavement) is used to create a .DEF file. The GEN and DEF files for each segment are used as input to EVERCALC to backcalculate the elastic layer moduli of layers.

Chapter 4 Backcalculation and Post-Processing Modules

Backcalculation Module

The Backcalculation module incorporates the EVERCALC engine to backcalculate elastic layer moduli. A detailed description of the backcalculation program EVERCALC is provided in the EVERSERIES user manual by Washington State Department of Transportation [6]. **Figure 23** shows the backcalculation module screen.

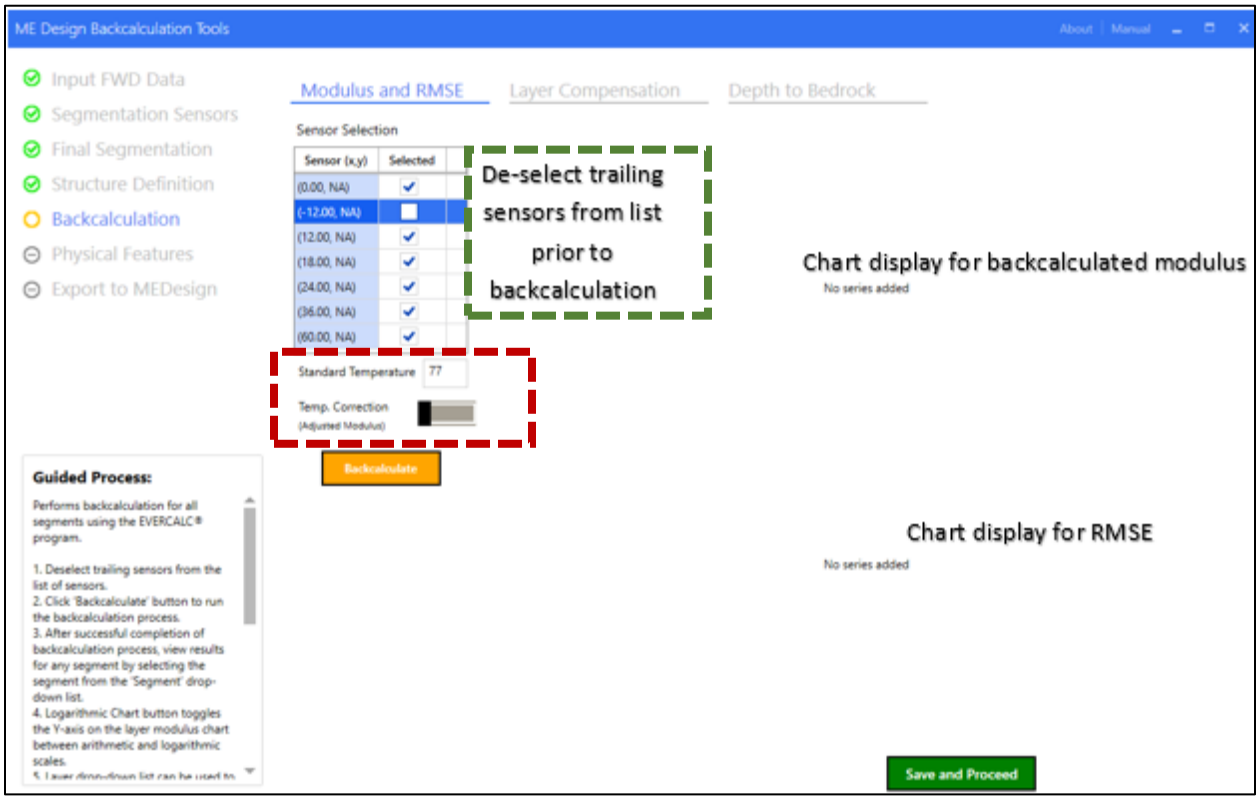


Figure 23 Backcalculation Module – Initial Load Screen

The user input required in this module is the sensors whose deflection data is used for backcalculation, and if the backcalculated elastic layer moduli are to be adjusted to a reference temperature, both of which are discussed below.

- **Sensors to be excluded from the Backcalculation Process**. Sensors located behind the loading plate (trailing sensors) should be excluded by unchecking them from the list of sensors shown in the **Sensor Selection** table. In addition, any sensor that the user does not want to include in the backcalculation process should be unchecked.
- **Backcalculated Elastic Modulus Adjusted to Reference Temperature**. The user can activate the temperature correction or adjustment procedure for adjusting the elastic layer moduli to a standard reference temperature. Clicking on the Temperature Correction bar activates the procedure (changing from "No" to "Yes"). When activated all of the asphalt layer moduli are adjusted to a standard temperature, but only when the temperatures are available in the deflection file. If temperatures are unavailable, this procedure should not

be activated. However, it is suggested that the backcalculation process be completed at the temperatures measured along the roadway and no adjustments be made to a reference temperature.

The backcalculation process is executed by pressing the **Backcalculate** button. The BcT generates GEN-DEF file combinations for each segment, which are used as input to the EVERCALC program. While the backcalculation process is in progress, the screen is temporarily locked by displaying the progress message "Backcalculating, Please Wait …" as shown in **Figure 24**. Most of the runs or problems take less than a minute to run.

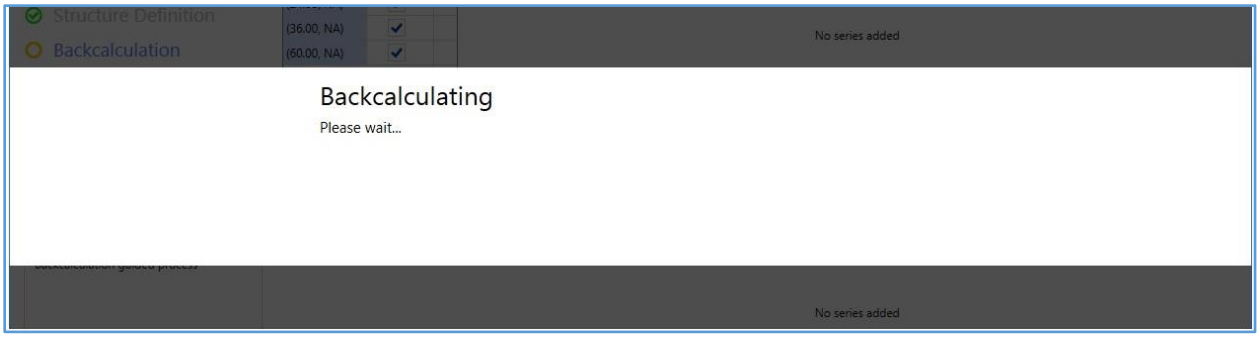


Figure 24 Backcalculation Module – EVERCALC Runtime Status Message

The BcT displays the message "*Success! Backcalculation run complete. All segments run successfully*" after the backcalculation process is completed as shown in **Figure 25**. Output files are created for each segment in the same folder that contains the input files. The SUM output file contains a summary of backcalculated moduli for all individual drops, as well as normalized moduli for each station. The OUT file contains stress, strain and optimization details for each drop and LOG file contains the moduli and RMSE values at each iteration. The input and output files cannot be accessed from within the BcT's interface but are stored in the project folder. The backcalculation results for the segments can be viewed from the charts of backcalculated moduli and RMSE.

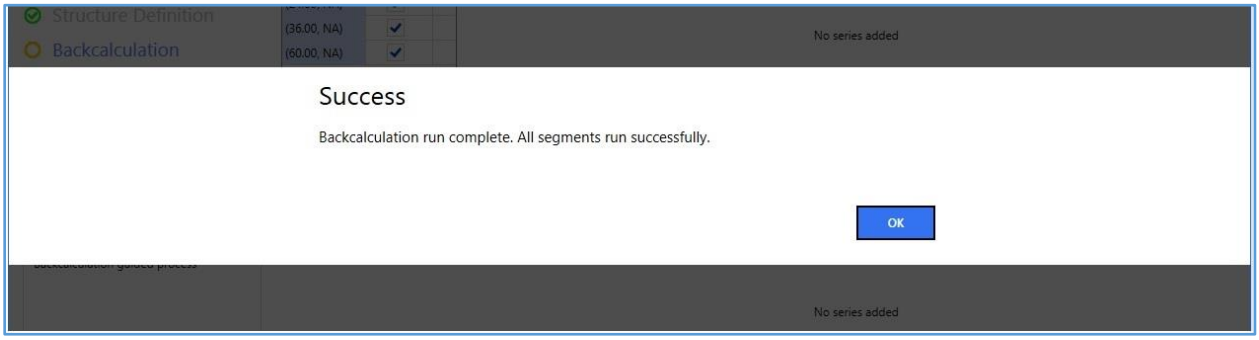


Figure 25 Backcalculation Module – EVERCALC Runtime Status Message

The limitations of the EVERCALC program on GEN and DEF files restrict the total length of the filenames to a maximum of 255 characters. If the total length of the GEN or DEF file path (e.g. C:\Users\LocalUser\Documents\...\BackcalculationFile_S1.GEN) exceeds 255 characters, the

execution of EVERCALC is terminated and an error message is displayed, even if all backcalculation inputs, deflection data, segments and layer properties have been defined correctly.

Backcalculation Results – Modulus and RMSE Charts Screen

After the backcalculation is completed, the user has various button controls in reviewing the results, which are explained in the following paragraphs.

- **Segment Selection**. The segment for which results are to be displayed is selected from the Segment drop-down list as shown in **Figure 26**. When a segment is selected, the charts display backcalculation results – backcalculated moduli and RMSE for the specific segment as shown in **Figure 26**. The chart on the top shows the average backcalculated modulus for each station and the chart on the bottom shows the average RMSE of all drops at the stations within the segment. When a segment is selected, the charts initially show the average backcalculated modulus and RMSE at all drops versus station distance for all pavement layers. The default position for the drops used in the backcalculation process is all drops are checked in the box in the lower left corner of **Figure 26.**
- **Logarithmic Scale.** The Y-axis of the backcalculated modulus plot can be changed to a logarithmic scale using the **Logarithmic Chart** switch. The switch is triggered by clicking anywhere within the rectangular area of the logarithmic chart button. The switch status is set to 'Yes' (blue-colored button) when the Y-axis is in logarithmic scale (see **Figure 26)** and 'No' (grey-colored button) when the Y-axis is in the arithmetic scale.
- **Layer Selection**. Modulus plots for individual layers can be turned on or off using the checkboxes in the **Layer** drop down list on the top-right corner of the module screen, as shown in **Figure 27**.
- **Drop Selection**. When a segment is selected, the charts display backcalculation results – backcalculated moduli and RMSE for the specific segment as shown in **Figure 26**. Additionally, individual drops may be deselected to remove them from the average modulus calculation by unchecking boxes in the list at the bottom-left corner of the screen, as shown in **Figure 27**. For instance, selecting drops 5 through 8 (12,000 lb. target load) by checking the boxes corresponding to the four drops and unchecking the boxes for all other drops will recalculate the average modulus at only the four selected drops. The target load levels checked by the user are displayed for each drop number to assist with the drop selection process. For the condition when highly stress sensitive soils and aggregate base layers are included in the pavement structure, the backcalculated modulus values can be dependent on the drop height. Under this case, it is suggested that the backcalculated results for one target load level or drop height be used in exporting the results to a Pavement ME Design file for rehabilitation design.

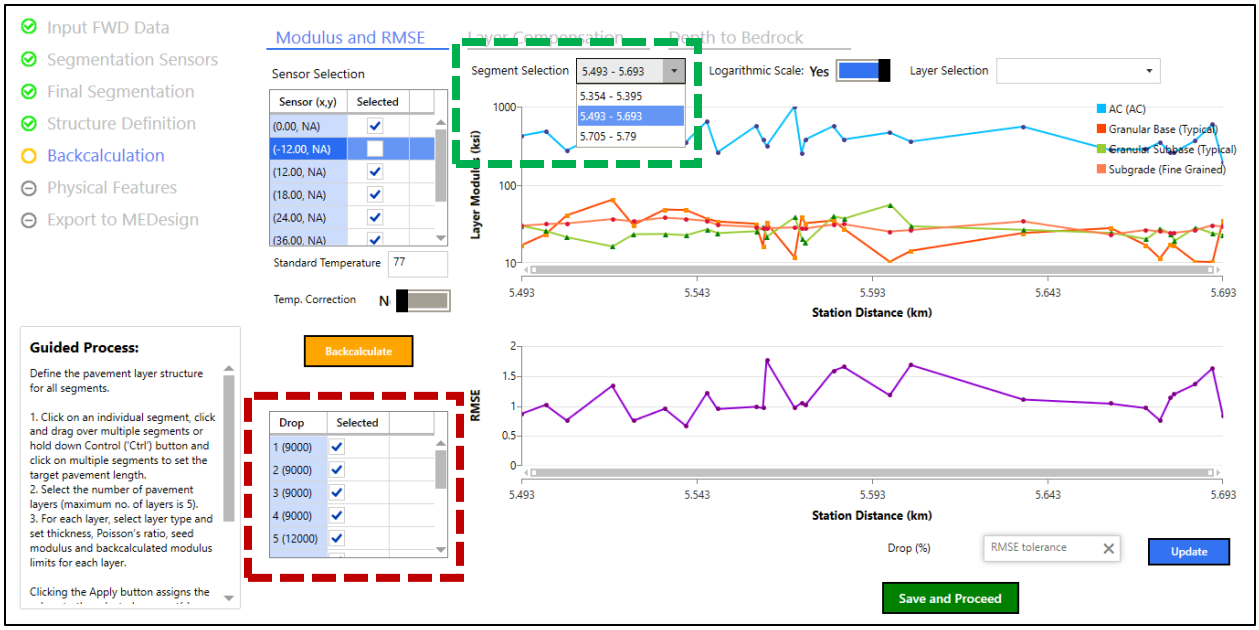


Figure 26 Backcalculation Module – Segment Selection to Display Results; Segment 2

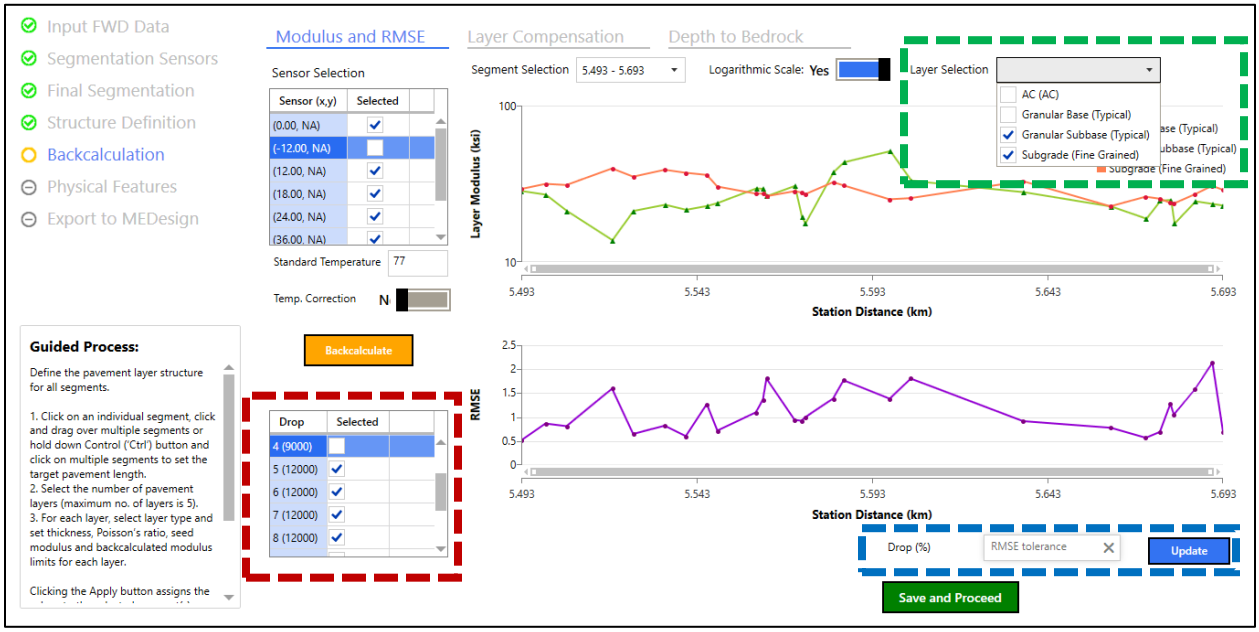


Figure 27 Backcalculation Module – Layer Selection to Display Results; Segment 2

The backcalculation process starts with a set of initial (seed) modulus values for each pavement layer that are adjusted until the error between the measured and predicted deflections is lower than a specified tolerance limit. The tolerance criterion is expressed in terms of RMSE, which is defined as the square root of the average of sum of squared differences between measured and predicted deflections at all sensors. The RMSE is calculated for each FWD drop in the deflection data. If *n* sensors are used in FWD testing where the measured deflection at any sensor *i* is

denoted by $d_{i-Measured}$ and predicted deflection is denoted by $d_{i-Predicted}$, RMSE is calculated using equation 1.

$$RMSE(\%) = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(d_{i-Measured} - d_{d-Predicted})^2} \qquad \textbf{Equation 1}$$

The BcT also allows users to filter backcalculation results by removing drops having an RMSE greater than a specific tolerance from the average modulus calculation. The RMSE tolerance level is specified using the **RMSE Tolerance** field at the bottom of the screen, as shown in **Figure 27.** Numeric values between 1 percent and 100 percent (no filtering) can be entered. It is suggested that the results for RMSEs greater than 5 percent not be used, because the fit between the measured and calculated deflection basins is considered poor. After entering the tolerance value, pressing the **Update** button removes individual drops whose RMSE is greater than the tolerance value and re-calculates the average layer moduli at all stations. The charts display the updated average moduli and average RMSE values after applying the filter, which are exported to the Pavement M-E Design software.

Backcalculation is often an iterative procedure where adjustments are made to the pavement layer properties – layer structure, initial seed modulus and modulus limits, in order to achieve better convergence of deflection basins and lower RMSE. If the average RMSE for the current backcalculation run is not acceptable, the user may click on the **Structure Definition** button on the modules menu on the left of the screen, re-define the pavement structure for the segment and save it, and re-run the backcalculation module. This process can be repeated as many times as necessary until the desired error tolerance is achieved.

Layer Compensation Screen

Layer compensating errors may arise from the iterative procedure used in backcalculation of pavement layer moduli. The AASHTO Pavement ME Manual of Practice[(2)] defines compensating error as a continuous increase in the modulus of one pavement layer and a simultaneous decrease in the modulus of an adjacent layer (inversely proportional) while trying to minimize the RMSE. Compensating errors can be identified from the presence of clearly discernible trends (inversely proportional) in the plot of backcalculated modulus of adjacent unbound layers; compensating errors do not apply to adjacent bound and unbound layers.

The BcT displays plots of backcalculated modulus of adjacent unbound layers (base, subbase or subgrade layers), which can be viewed by clicking on the Layer Compensation Error at the top of the screen. No charts are shown if the pavement has only one unbound layer, while users can switch between charts for more than two unbound layers using the arrow button as shown in **Figure 28**.

The layer compensating error chart in **Figure 28** shows the backcalculated modulus for the granular base layer in logarithmic scale on the X-axis versus the backcalculated modulus of the subbase layer on the Y-axis. Statistics for linear regression between the two moduli (log. E_{BASE} versus $E_{SUBGRADE}$) are also shown below the plot. In the example shown, there is a strong linear relationship between the two moduli (R^2 = 0.89) with a negative slope of -1.10, indicating the presence of compensating error effect. A positive slope would suggest no compensating error.

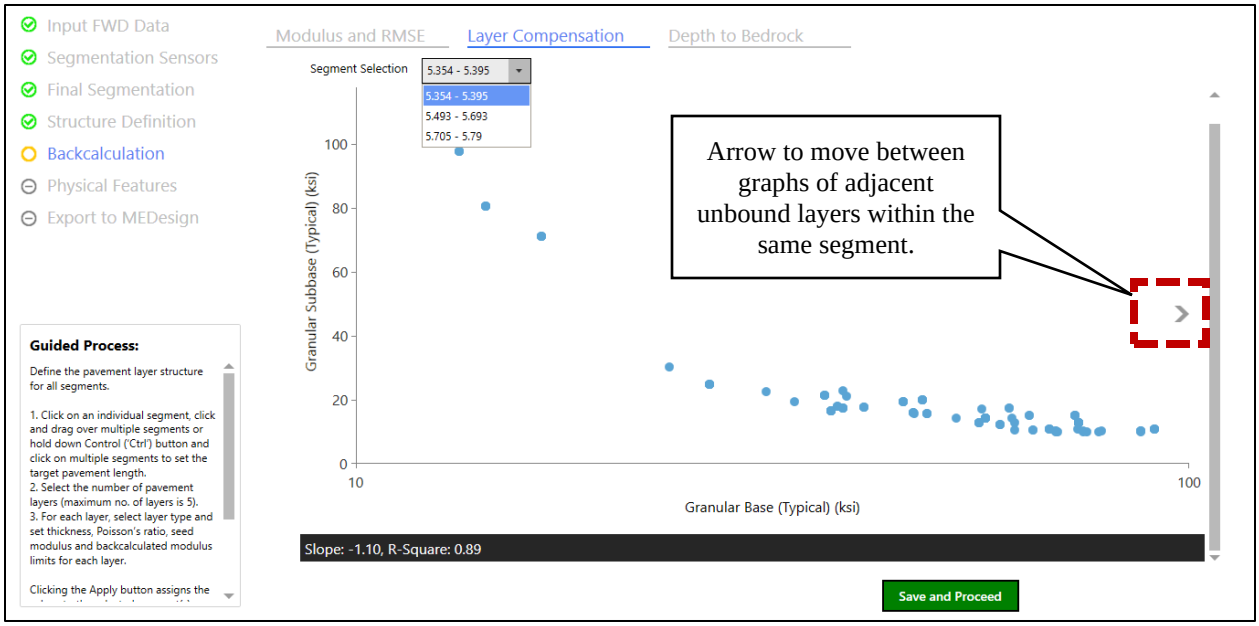


Figure 28 Layer Compensation Error Charts for Segment 1 – Granular Base versus Granular Subbase; Compensating Error Highly Probable

Figure 29 shows the backcalculated modulus for the granular subbase in logarithmic scale on the x-axis versus the backcalculated modulus of the subgrade on the Y-axis. Statistics for linear regression between the two moduli (log. E_{BASE} versus $E_{SUBGRADE}$) are also shown below the plot. In the example shown, there is a poor linear relationship between the two moduli ($R^2 = 0.04$) with a negative slope of -0.10, indicating compensating errors probably do not exist.

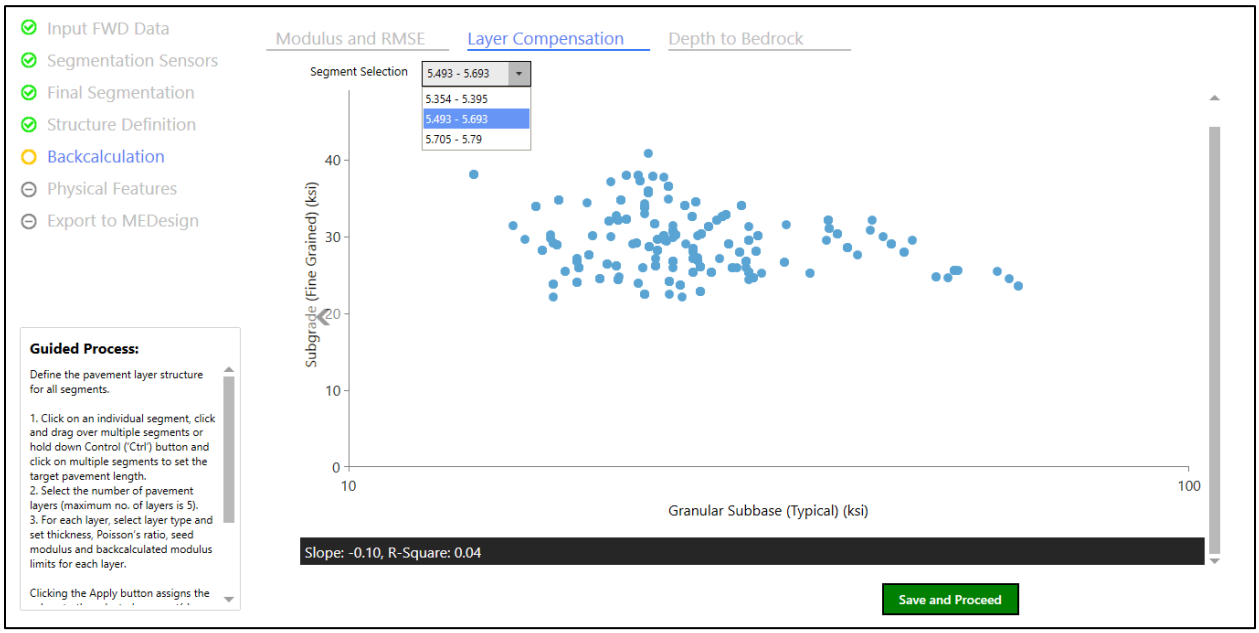


Figure 29 Layer Compensation Error Charts for Segment 2 – Granular Subbase versus Subgrade; Compensating Error Not Probable

The user should try to eliminate any compensating errors because the results do not typically represent reality, even when the RMSE is much less than 5 percent. The following lists a general guideline for judging whether compensating errors are an outcome of the backcalculation process.

- The R-square is greater than 0.4 with a negative slope exceeding a negative value of -0.20.

Depth to Bedrock Screen

The depth to bedrock is calculated by the BcT for each segment identified with a Stiff Layer or designated by the user by checking the Stiff Layer box (see **Figure 22**). The results are displayed in the Depth to Bedrock screen, as shown in **Figure 30.**

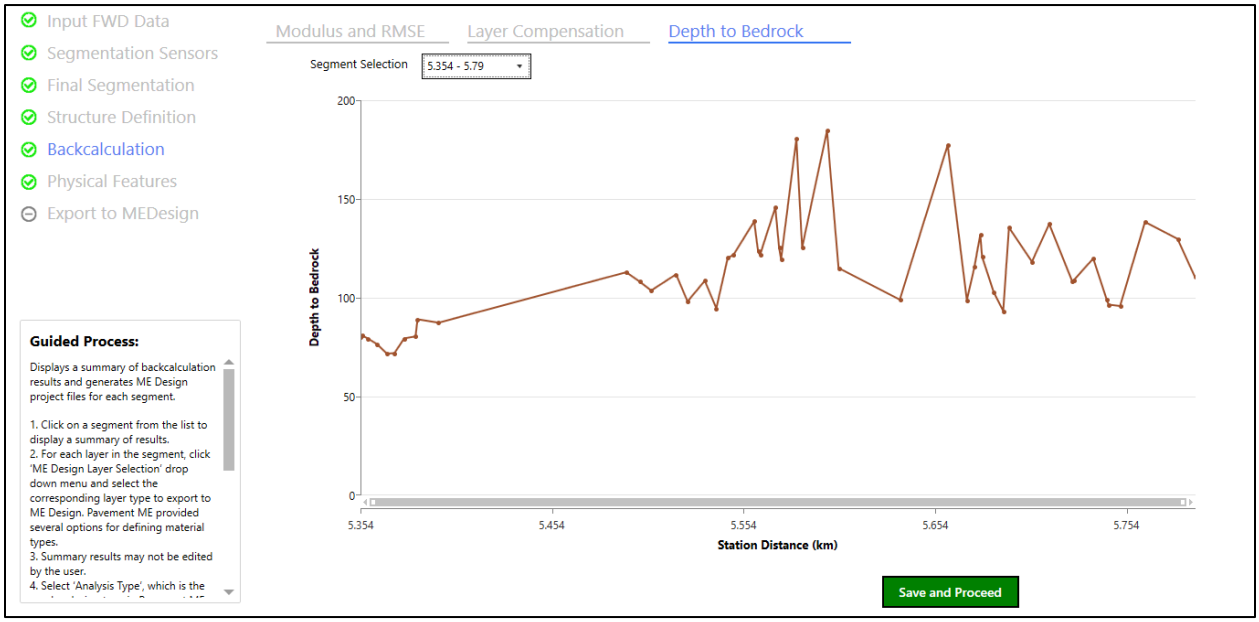


Figure 30 Depth to Bedrock Screen

Physical Features Module

The Physical Features module displays the results of load transfer efficiency (LTE) calculation and loss of support analysis.

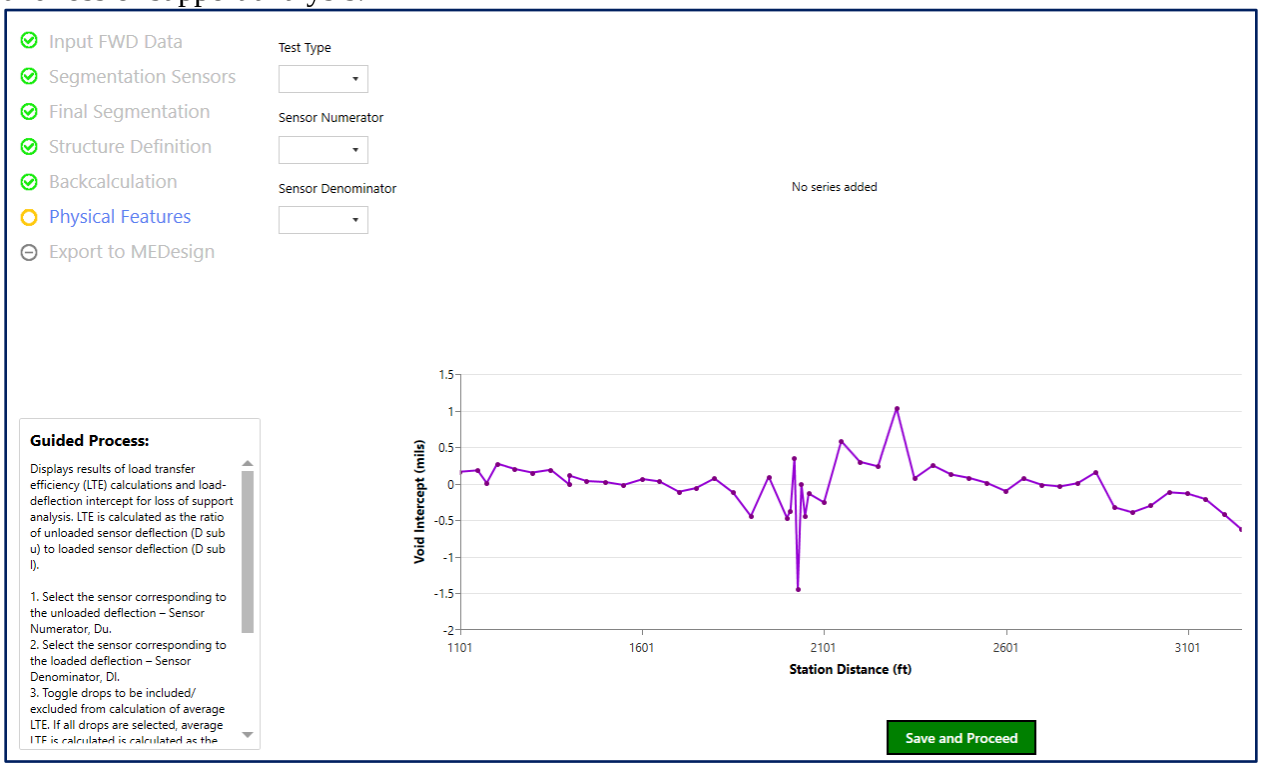


Figure 31 shows a screenshot of the physical features module screen. The screen shows two charts – the first chart (top) shows average LTE for all drops, and the second chart (bottom) shows the average intercept of the deflection-load relationship at stations along the length of the entire pavement section. LTE and void detection features are subject to the input FWD file containing the following information:

- **LTE** – The input FWD file should contain deflections measured at a trailing sensor, e.g. deflections measured at a sensor located 8 inches or 12 inches behind the FWD loading plate. It is possible, though not recommended, to use deflections at any two leading sensors to calculate LTE. The data displayed on the chart is computed based on the two sensors selected by the user from the **Sensor Numerator** and **Sensor Denominator** drop-down boxes on the screen.

- **Loss of Support** – The input FWD file should contain at least one drop at multiple (two or more) target load levels to develop a deflection-load relationship. The intercept from this linear relationship is displayed to the user on the chart, which can be used to identify the presence of voids in the pavement at the test location. The loss of support might also identify some anomaly or defect (i.e.; stripping) in asphalt mixtures/layers.

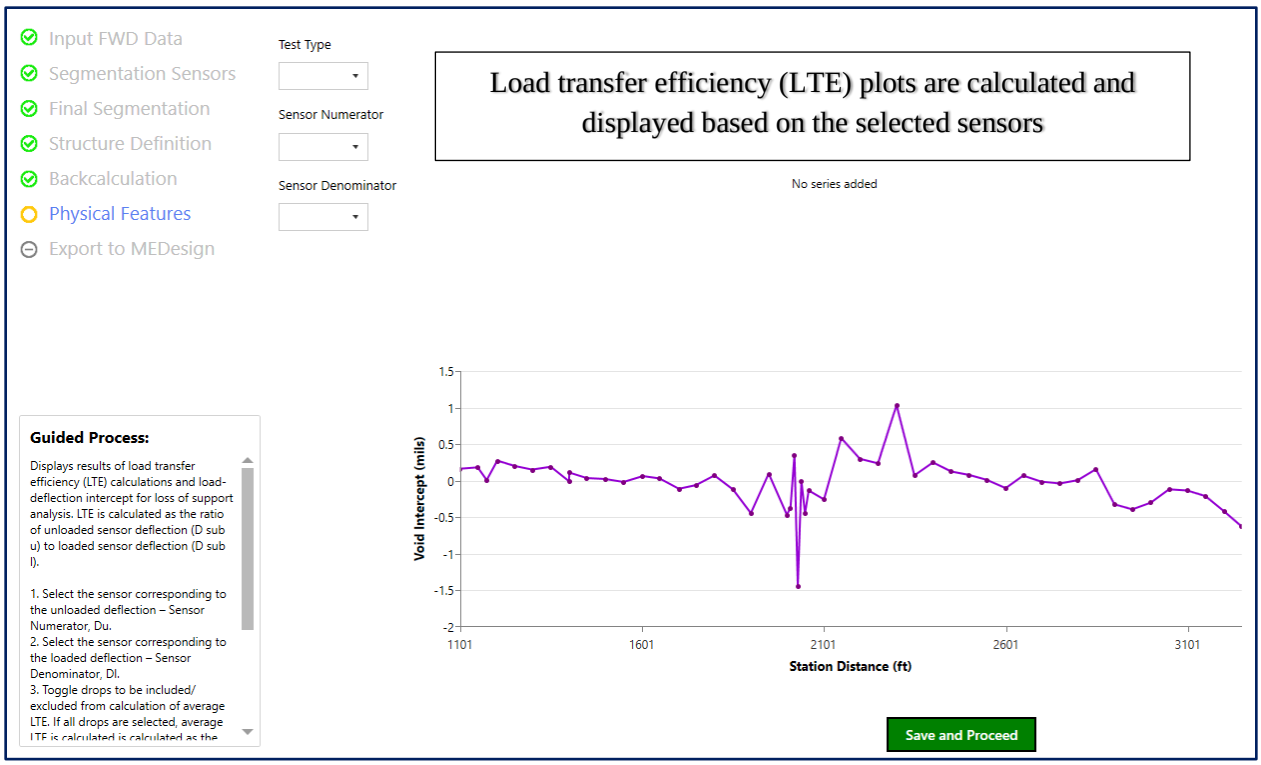


Figure 31 Charts Showing Physical Features – LTE and Loss of Support

Load Transfer Efficiency Calculation

The numerator and denominator sensors correspond to the sensors at the unloaded (d_u) and loaded (d_l) locations on the pavement as described in the LTE calculation within this section.

In a jointed concrete pavement, traffic loading causes both the approach and leave slabs to deflect due to load transfer from one slab to the other. The magnitude of stresses and deflections in a slab are typically much lower in the presence of a joint, as compared to a slab with a free edge. Load transfer efficiency is defined as a ratio of the maximum deflection of the loaded slab to the maximum deflection of the unloaded slab, as shown in equation 2.

$$LTE(\%) = \frac{d_u}{d_l} \times 100 \qquad \textbf{Equation 2}$$

Where:

LTE is the load transfer efficiency
d_u is the deflection measured at the unloaded (leave) slab
d_l is the deflection measured at the loaded (approach) slab

Figure 32 shows the sensor configuration for an FWD test to calculate load transfer efficiency. The unloaded deflection is measured by using a trailing sensor located on the unloaded (leave) slab.

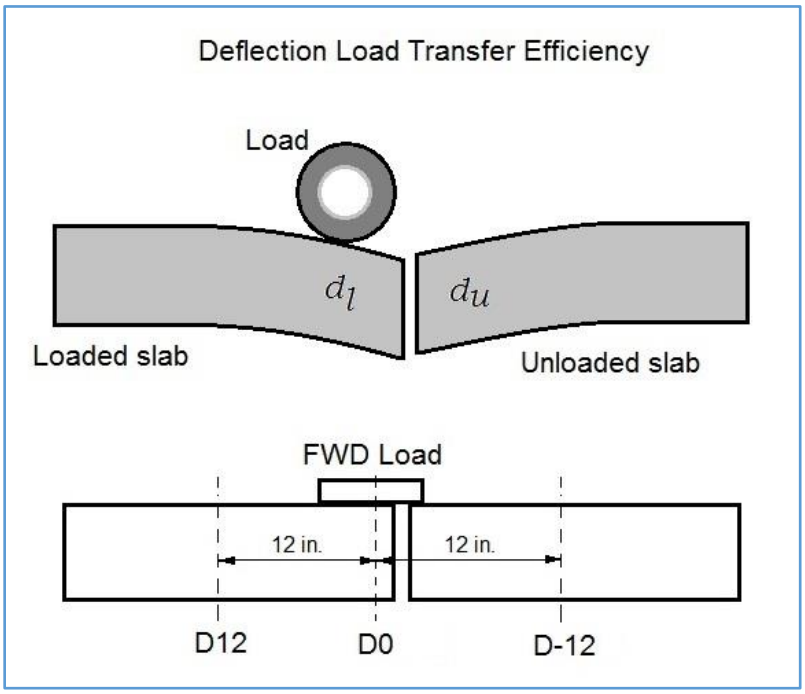


Figure 32 LTE Testing Configuration and Deflection Measurement

Depending on the location of the FWD load, the loaded deflection D_0 is the center-load deflection and the unloaded deflection is either D_{12} or D_{-12}. Equation 2 can therefore be written in terms of the measured deflections D_0 and D_{-12} as shown below in equation 3.

$$LTE(\%) = \frac{d_{-12}}{d_0} \times 100 \qquad \textbf{Equation 3}$$

The sensor configuration varies from one project to another, thereby requiring the user to define the sensors at which loaded and unloaded deflections are measured. The LTE calculations are always performed using equation 3, for which the user selects the unloaded and loaded deflections from the drop-down menus. For the example shown in **Figure 32**, the unloaded deflection (d_u) is measured at the -12 inches sensor while the loaded deflections (d_l) are measured under the FWD load or 0-inch sensor.

The charts initially display the calculated LTE and deflection-load intercepts for all drops at each station (see **Figure 33**). The **Drop** list on the top left of the module screen can be used to change which drops are displayed on the charts. It is also important to note that while the **Drop** list allows control of the charts, the selected drops are also used to calculate the average LTE and intercept at a station. If the selection of drops is changed by selecting the first four drops while unchecking all the other drops, the average LTE is calculated using only the data for drops 1, 2, 3 and 4.

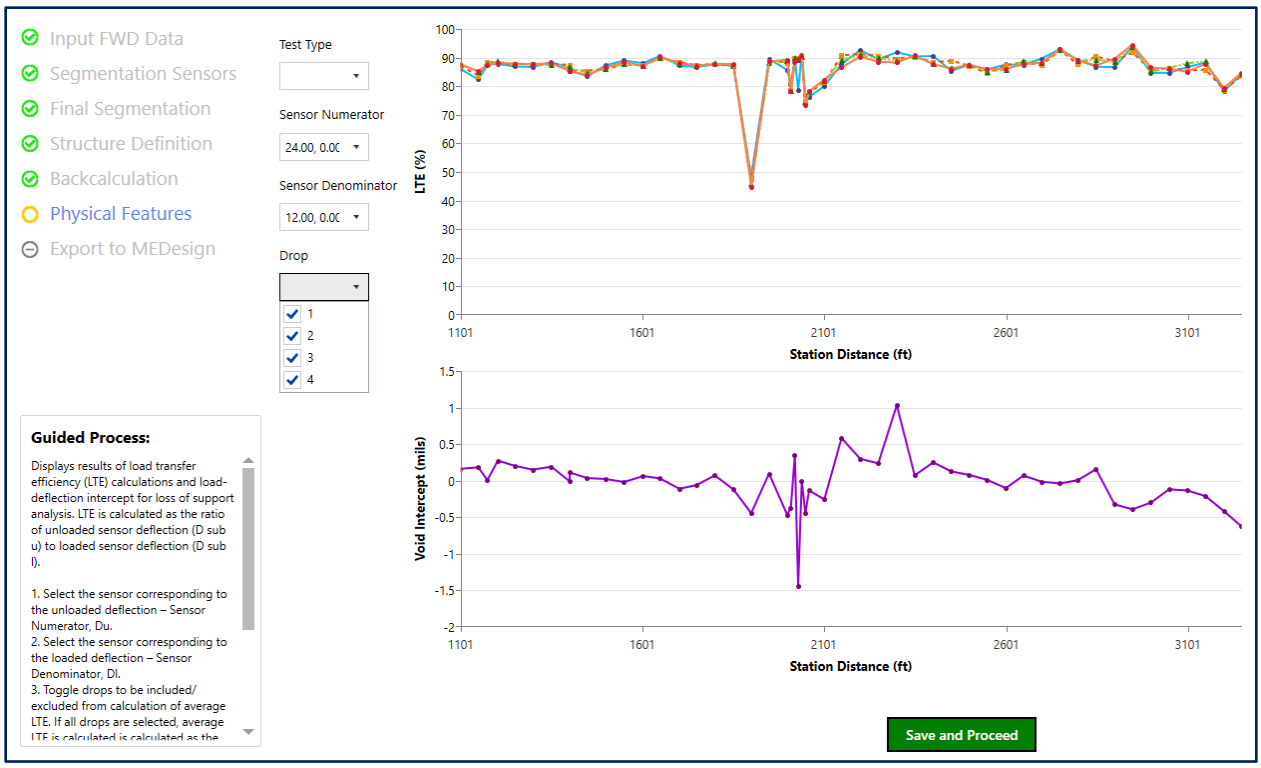


Figure 33 Charts Showing Physical Features – Drop Selection for Average LTE

Loss of Support Calculation Procedure

FWD testing to evaluate loss of support under rigid or flexible pavements is conducted by measuring deflections at different target load levels – typically 9000, 12000 and 16000 lbs. The measured deflections are plotted against the load using a linear relationship. The intercept of linear regression fit between the load and deflections is used to estimate the presence of a void. The load-deflection intercept represents the deflection under zero load. Depending on the magnitude of the intercept, the potential for voids is estimated by comparing the intercept to a tolerance limit such as 2 mils or 3 mils, indicating the possibility of voids when intercept > tolerance limit. The BcT calculates the void intercept for each station and plots the results as shown in the bottom plot in **Figure 33**.

Table 1 shows an example set of deflection data measured at a slab corner of a JPC pavement. The data shows deflections measured at three different load levels – 9,000 lbs., 12,000 lbs. and 15,000 lbs. Intercept of the deflection-load curve is obtained through linear regression, which is equal to 2.08 mils for the data shown in **Table 1**. Comparing the calculated intercept with a tolerance of 2 mils for the intercept, it is estimated that there is a potential for a void at the JPCP test location.

Figure 34 shows the results of linear regression between FWD drop loads on the X-axis and the center-load deflections on the Y-axis.

Table 1 Void Detection Example – Deflection Data

Drop No.	Load (lb.)	D0 (mil)	D1 (mil)	D2 (mil)	D3 (mil)	D4 (mil)	D5 (mil)	D6 (mil)	D7 (mil)	D8 (mil)
1	8810	10.3	9.01	8.34	7.36	6.43	5.05	3.87	2.97	8.4
2	12160	13.19	11.54	10.66	9.54	8.32	6.46	5	3.79	10.98
3	14720	15.79	13.8	12.82	11.38	9.98	7.75	5.97	4.53	13.29

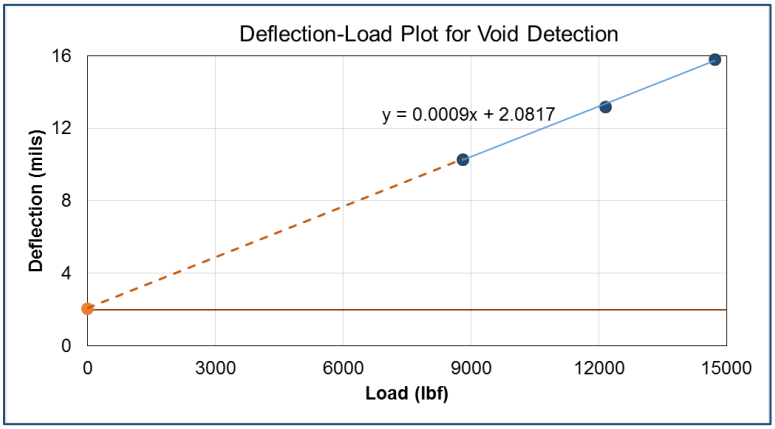


Figure 34 Void Detection – Deflection-Load Plot for Example Dataset

Export to ME Design Module

The **Export to ME Design** module displays a summary of the backcalculation results for exporting to an ME rehabilitation design file. A separate ME design file is generated for each segment with the pavement layer structure as defined in the structure definition module. **Figure 35** shows the export module screen, where users can select a segment from the list to view a summary of backcalculation results.

Selecting the first segment displays the summary for that segment as shown in **Figure 36**. The average LTE and pavement temperature are also displayed for the selected segment in the fields visible in **Figure 36**, while the loading frequency is required as an input from the user for estimating the damaged modulus of the existing asphalt concrete layer. A default value of 30 Hz is assumed, which can be changed depending on agency practice or specification. The summary table on the export screen displays the following information for the selected segment:

- **Layer Type** as defined in the structure definition module. This corresponds to the backcalculation layer type which is used to populate the corresponding layer materials available in the ME design guide software.

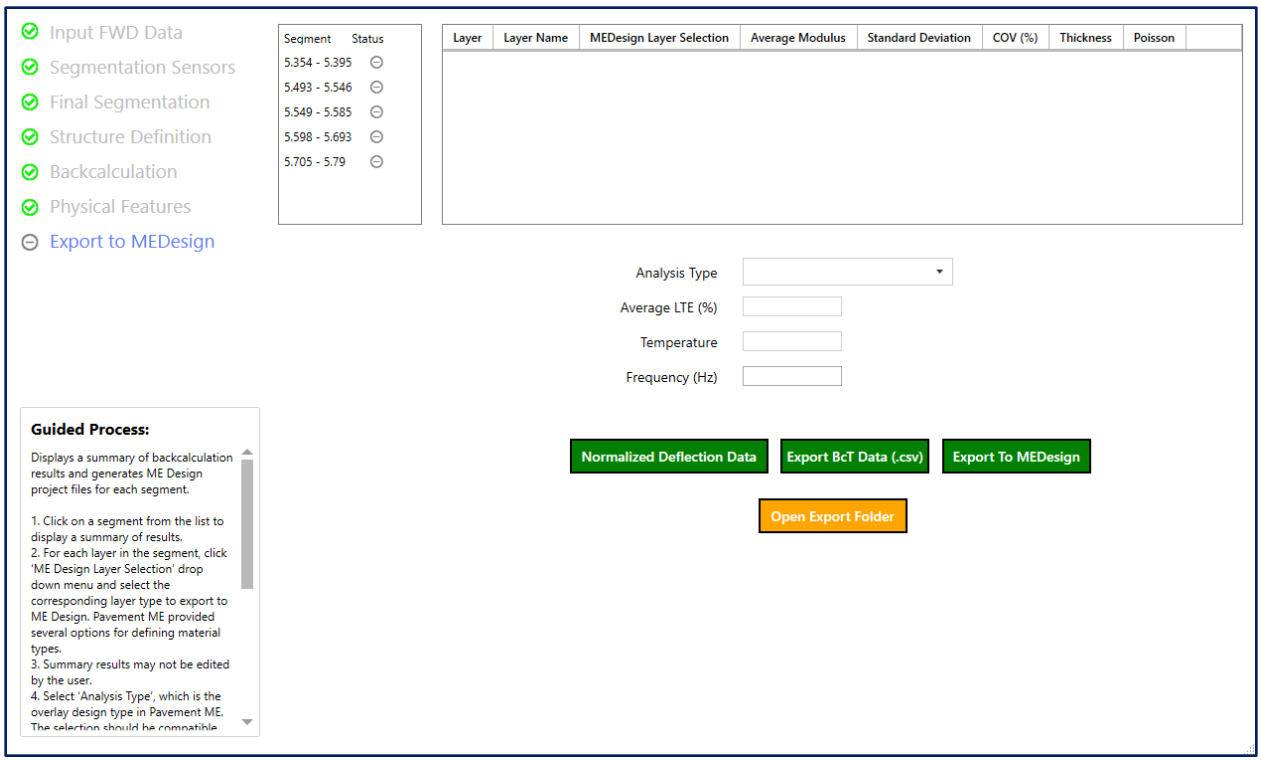


Figure 35 Export to ME Design Module Screen – Default Layout

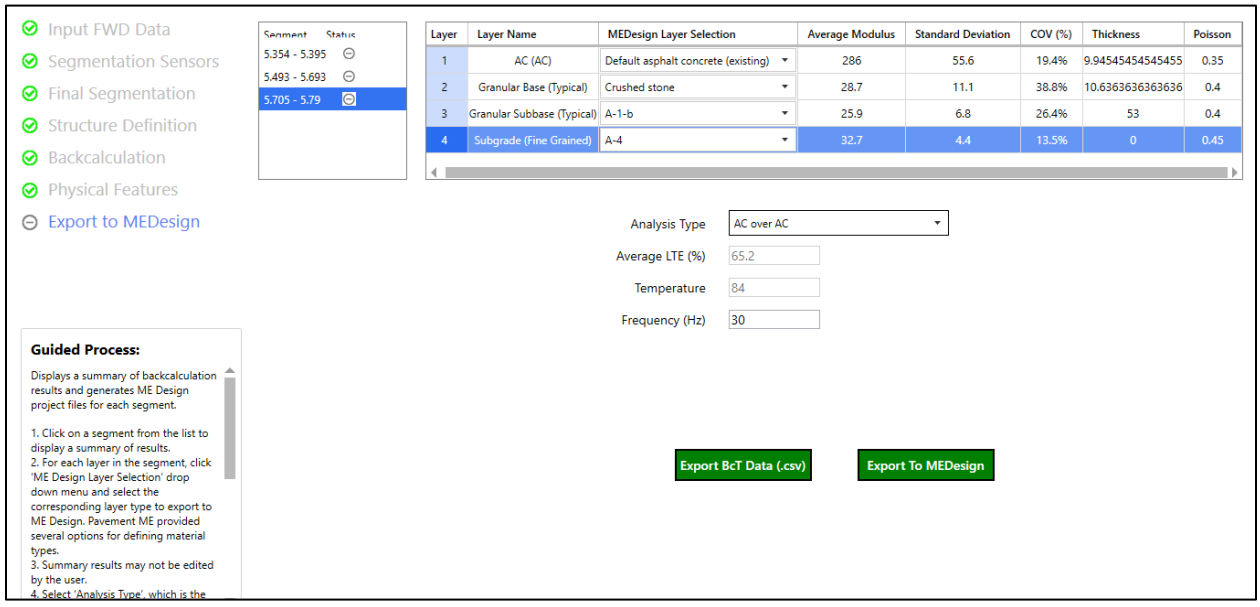


Figure 36 Export to ME Design Module Screen – Segment 3 Summary

- **ME Design Name**, which is a drop-down list of layers corresponding to the backcalculation layer type. This is the actual material type which is exported to the ME design file. The ME design layer type is a user input, which should be selected by the user prior to exporting.

- **Average Modulus**, which is the average backcalculated modulus across all stations for the pavement layer over the entire length of the segment. This field contains a single representative modulus for the existing layer as obtained from backcalculation. The average backcalculated modulus is exported to the ME design file as the layer modulus.
- **Standard Deviation**, which is calculated as the average value over the entire segment length. This is an information variable which is not exported to the ME design file.
- **COV** (%) is the average coefficient of variation, calculated as the ratio of the standard deviation to the average modulus. A high coefficient of variation indicates a high degree of variability of the backcalculated layer modulus along the length of the segment. The user should consider making revisions to the final segmentation and/or structure when the COV gets significantly greater than 50 percent. This is also an information variable which is not exported to the ME design file.
- **Thickness** is the pavement layer thickness as entered by the user in the structure definition module for the selected segment. The backcalculation tool displays a thickness value of zero for the last subgrade or bedrock layer, which is assumed to be a semi-infinite layer in the ME design file.
- **Poisson's ratio**, as entered by the user in the structure definition module for the selected segment. The Poisson's ratio is a read-only field whose value is exported to the ME design file.

For an overlay design (AC or PCC overlay) of a flexible pavement, the design may include milling of a specified thickness of the existing asphalt layer resulting in a reduced layer thickness when setting up the ME rehabilitation design file. The backcalculation tool does not provide this functionality, therefore, milled thickness should be entered as a regular input in each individual ME Design file.

An important requirement for setting up the ME design file is the selection of the rehabilitation strategy for the existing pavement. Depending on the existing pavement type – flexible, semi-rigid or rigid, different design alternatives exist in Pavement ME. **Table 2** shows the rehabilitation design types for both flexible (semi-rigid is included in the flexible column) and rigid pavements available in Pavement ME design guide software. The overlay design type is selected from the **Rehabilitation Design Type** drop-down list. The options allowed for each segment depend on the layer structure for the segment. For example, for a segment whose layer structure is defined as a flexible pavement (layer 1 = AC), the tool allows users to only select the options in the column labeled *Overlays of AC Pavements* shown in **Table 2**.

Creating and Running Pavement ME Design Files

After all the necessary inputs – analysis type, ME Design layer types and frequency (for overlay of existing flexible pavement) are entered for all segments, clicking the **Export to MEDesign** button will generate separate ME Design files for each segment. The files are saved to a folder titled MEDesign Project Files within the backcalculation project folder. E.g.: If the input FWD file selected is I84301.FWD, the tool creates a folder with the same name as the filename to save the backcalculation files. The MEDesign Project Files folder is created within the project folder, where the ME Design files are saved. The tool displays a message to the user with the directory name when the ME Design files are successfully generated and saved as shown in **Figure 37**.

Table 2 ME Design Rehabilitation Design Types

Overlays of AC Pavements	Overlays of PCC Pavements
AC over AC	Bonded PCC/JPCP
AC over AC with Seal Coat	Bonded PCC/CRCP
AC over AC with Interlayer	JPCP over CRCP (unbonded)
AC over Semi-Rigid	JPCP over JPCP (unbonded)
JPCP over AC	CRCP over CRCP (unbonded)
CRCP over AC	CRCP over JPCP (unbonded)
SJPCP over AC	AC over JPCP
	AC over CRCP
	AC over JPCP (fractured)

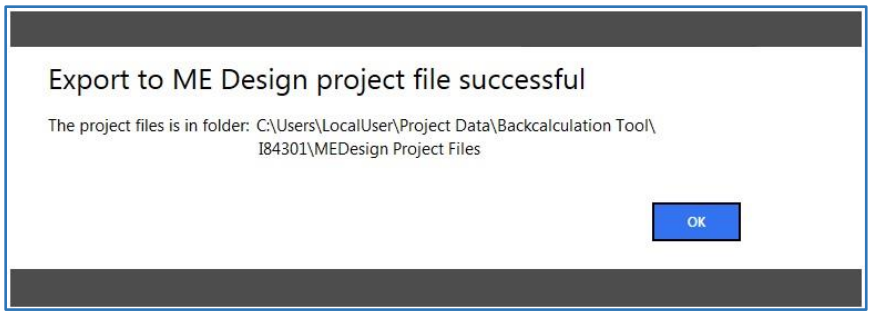


Figure 37 Export to ME Design Module – ME Design Files Save Location

Normalize Deflection Data to User Defined Target Load Level

In the Export step, an input is available to allow the user to specify the target load level to normalize the deflection values to. After specifying the target load level, the user can click the Normalize Deflection Data button to calculate and export the normalized deflection data to the export folder which is highlighted in blue in **Figure 38**. User can then click the Open Export Folder to locate all the exported data which is highlighted in orange in **Figure 38**.

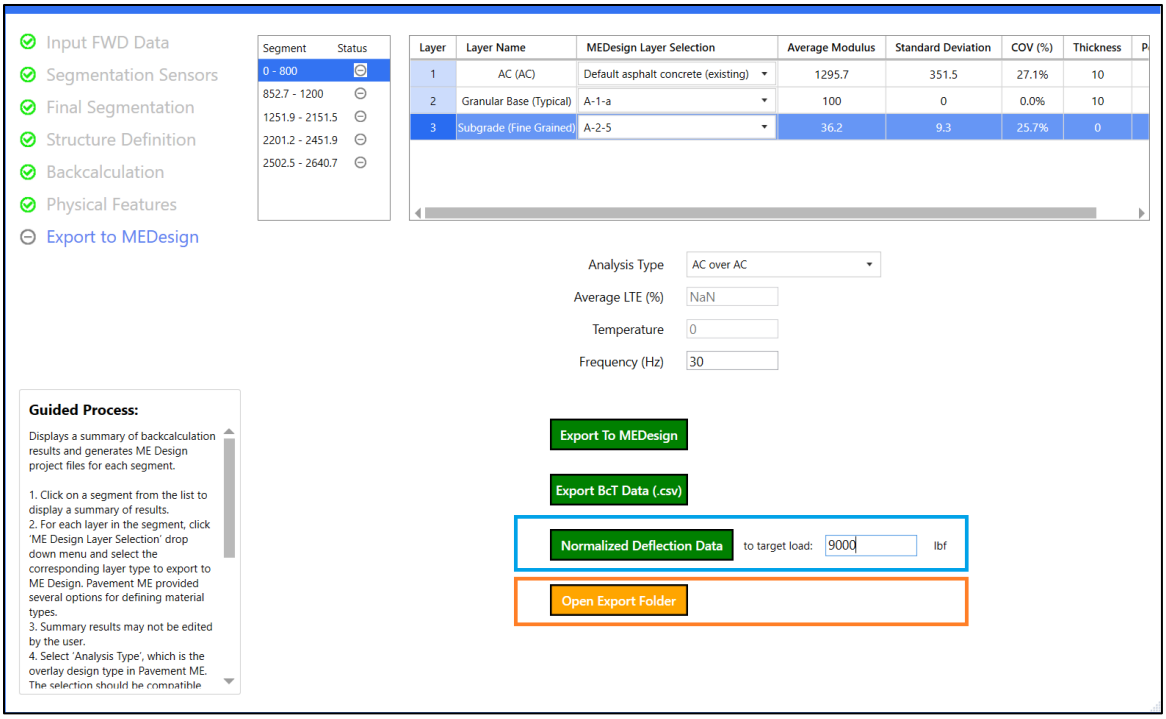


Figure 38 Normalize deflection data to a user defined target load level and open the export folder.

The normalized deflection data file is in a .csv format that contains all stations from the FWD import file. A sample export file is presented in **Figure 39** below.

	A	B	C	D	E	F	G	H	I	J	K	L
1	Station	Load	Deflection	Deflection	Deflection	Deflection	Deflection	Deflection	Deflection	Deflection	Deflection9	
2	0	9000	4.075272	2.902045	2.449132	2.017164	1.622833	1.219684	1.034409	0.846771	0.688188	
3	50.6	9000	3.739994	2.843824	2.479624	2.076985	1.712339	1.260593	1.1355	0.827285	0.709962	
4	0	9000	3.98151	2.878746	2.435777	1.985075	1.619611	1.218228	1.063445	0.835486	0.727527	
5	52.3	9000	4.946427	2.902142	2.423213	2.124428	1.805249	1.156321	1.057643	0.827785	0.678071	
6	101.2	9000	4.658716	3.62933	3.255321	2.77097	2.356448	1.79535	1.439629	1.16408	0.997504	
7	151.5	9000	4.246947	3.197124	2.842796	2.489136	2.033807	1.499646	1.24315	1.036653	0.918822	
8	202.1	9000	4.350977	3.460785	3.085956	2.582197	2.188973	1.656641	1.371455	1.095021	0.917518	
9	253.1	9000	3.74723	2.838368	2.534029	2.099872	1.764802	1.31101	1.135575	0.927401	0.799409	
10	302.1	9000	4.588627	3.451689	3.016878	2.633498	2.389403	1.845308	1.710855	1.302286	1.105328	
11	352.3	9000	5.122494	3.931668	3.515941	2.990466	2.683733	2.068886	1.901902	1.614793	1.30605	
12	402.1	9000	5.097944	4.06499	3.519174	3.173027	2.815999	2.281064	1.962165	1.666238	1.39822	
13	450.2	9000	4.804333	3.805963	3.372584	2.958488	2.573498	2.021729	1.71656	1.480139	1.20157	
14	501.7	9000	5.806966	4.609283	4.023775	3.660006	3.154498	2.531598	2.197829	1.810148	1.563481	
15	551.5	9000	4.937192	4.244462	3.878028	3.552692	3.176807	2.47339	2.098191	1.781483	1.535186	
16	601.7	9000	5.301269	4.221974	3.777615	3.243402	2.79832	2.146131	1.740327	1.423943	1.227125	
17	651.5	9000	6.158266	4.839949	4.325392	3.711897	3.167473	2.415173	1.980351	1.614334	1.336989	
18	701.3	9000	5.569506	4.389848	3.764593	3.338852	2.933841	2.228829	1.952479	1.565278	1.298198	
19	751.5	9000	4.720612	3.659549	3.19341	2.886499	2.549037	2.003671	1.835767	1.547312	1.339739	
20	800	9000	5.000768	3.675048	3.25658	2.898271	2.66012	2.051705	1.883079	1.55403	1.345086	
21	852.7	9000	5.904897	4.53468	4.079005	3.533021	3.086625	2.441465	2.074451	1.747231	1.508776	
22	901.2	9000	4.92429	3.712258	3.345603	2.808948	2.412293	1.925736	1.699376	1.349867	1.19095	
23	950.2	9000	5.738537	4.834545	4.317795	3.90203	3.455772	2.700697	2.29375	1.906212	1.618182	

NormalizedDeflection

Figure 39 Example of a exported normalized deflection data file.

Appendix A MEPDG Rehabilitation Design Procedure and Inputs

The AASHTO Pavement ME Design software is capable of performing rehabilitation designs for flexible, rigid and composite pavements, which requires information on the overall condition of the existing pavement. Structural condition of the pavement can be assessed through the use of non-destructive testing (NDT) devices such as the Falling Weight Deflectometer (FWD), Ground Penetrating Radar (GPR) and profile testing, or estimated from distress surveys. NDT using the FWD allows in place structural characterization of the existing pavement condition in the form of layer modulus backcalculation, load transfer efficiencies and detection of voids beneath PCC pavements. Cores extracted from the existing pavement (destructive testing) can also be used to measure layer thicknesses and strength.

NDT is recommended for evaluating pavement structural condition and selecting test locations for destructive testing. Deflection basin data measured at various intervals along the length of a project can be used for backcalculating layer moduli, and selecting design sections and rehabilitation strategies. In-place layer moduli backcalculated from deflection data should be adjusted to laboratory conditions, in accordance with the Pavement ME Design procedure.

The AASHTO Pavement ME Design Manual of Practice [(2)] provides guidance on the use of deflection data and backcalculated layer moduli as ME design inputs, as shown below in **Table 3**.

Table 3 Use of Deflection Data and Backcalculation Results as ME Design Inputs

Layer Type (Existing)	Measured/Calculated Data from Deflection Testing	ME Design Input
All existing pavement types	Deflections or deflection-based indices along project length	Used for selection of design segments and rehabilitation strategies
Asphalt	Backcalculated asphalt layer modulus	Dynamic modulus, E_{HMA}
PCC	Backcalculated PCC-layer modulus	Elastic modulus, E_{PCC}
	Joint load transfer efficiency (LTE)	Determining need for dowel bar retro-fit and potential for reflection cracking
	Los of support under slab corner (e.g. void detection)	Selection of rehabilitation and repair strategies
Stabilized base/subbase	Backcalculated elastic modulus of stabilized layer	Elastic modulus, E_{CTB}
Unbound materials – base/subbase/subgrade	Backcalculated elastic modulus of unbound layer	Resilient modulus, M_R

Pavement ME provides several options for overlay design of both flexible and rigid pavements as shown below in **Figure 37**. The first step to performing an overlay design in Pavement ME is to select an overlay design strategy that is applicable to the existing pavement. **Figure 40** shows a list of overlay design types in Pavement ME software.

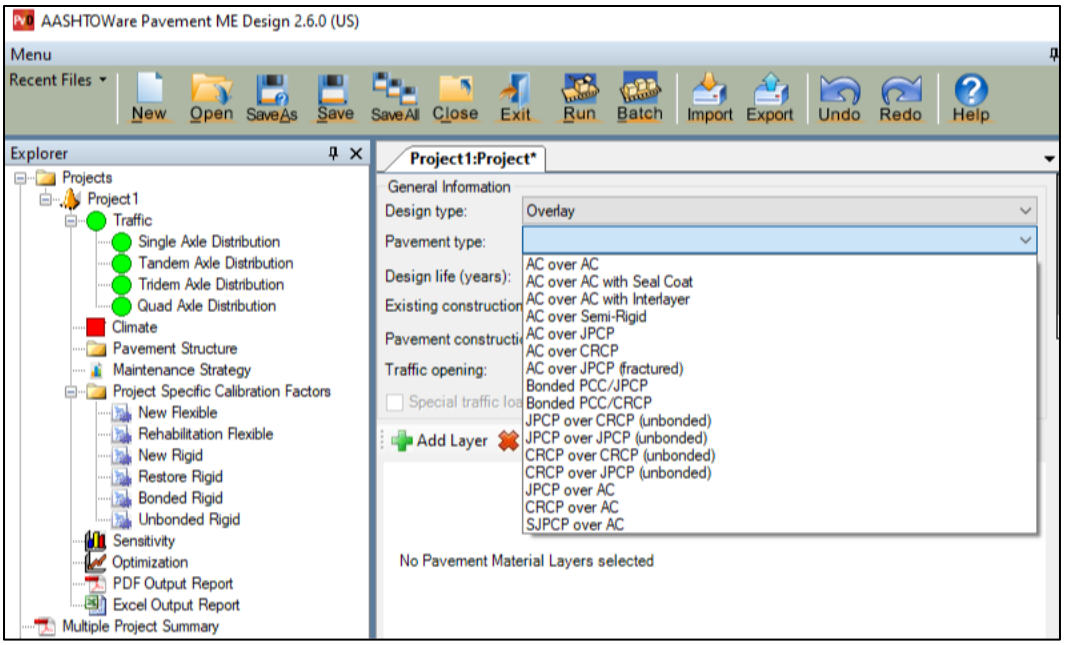


Figure 40 List of overlay design types in Pavement ME Design software

The Pavement ME Backcalculation Tool is designed to analyze deflection data obtained from FWD testing, select design segments, backcalculate layer moduli and generate the necessary inputs required to perform an overlay design using Pavement ME Design software. The type of overlay design is selected within the backcalculation tool and is used as the initial input to generate a Pavement ME Design input (.DGPX) file.

Overlay Design of Existing Asphalt and Semi-Rigid Pavements

Pavement ME Design provides the following overlay types for existing asphalt and semi-rigid pavements:

- AC over AC
- AC over AC with Seal Coat
- AC over AC with Interlayer
- AC over Semi-Rigid
- JPCP over AC
- CRCP over AC
- SJPCP over AC

[NOTE: The Pavement ME software uses abbreviations for the different design scenarios, as shown in **Figure 40**. AC refers to asphalt concrete as the existing surface or an overlay. The

term asphalt concrete, however, is no longer being used by industry. Asphalt pavements, asphalt layers, and/or asphalt overlays are terms now being used. As such, AC refers to the software term and asphalt layers or pavements is the term used in the text within this manual.]

The input requirements for underlying layers – base, subbase, subgrade and bedrock layers are consistent for all overlays. The input level for existing asphalt surface layer is determined by the designer from available information. Rehabilitation level 1 inputs can be selected when the existing asphalt layer is characterized using deflection basins and backcalculated layer modulus through FWD testing and thickness from field cores and GPR surveys. The input requirements for Level 1 rehabilitation design of existing asphalt or semi-rigid pavements are shown in **Figure 41**.

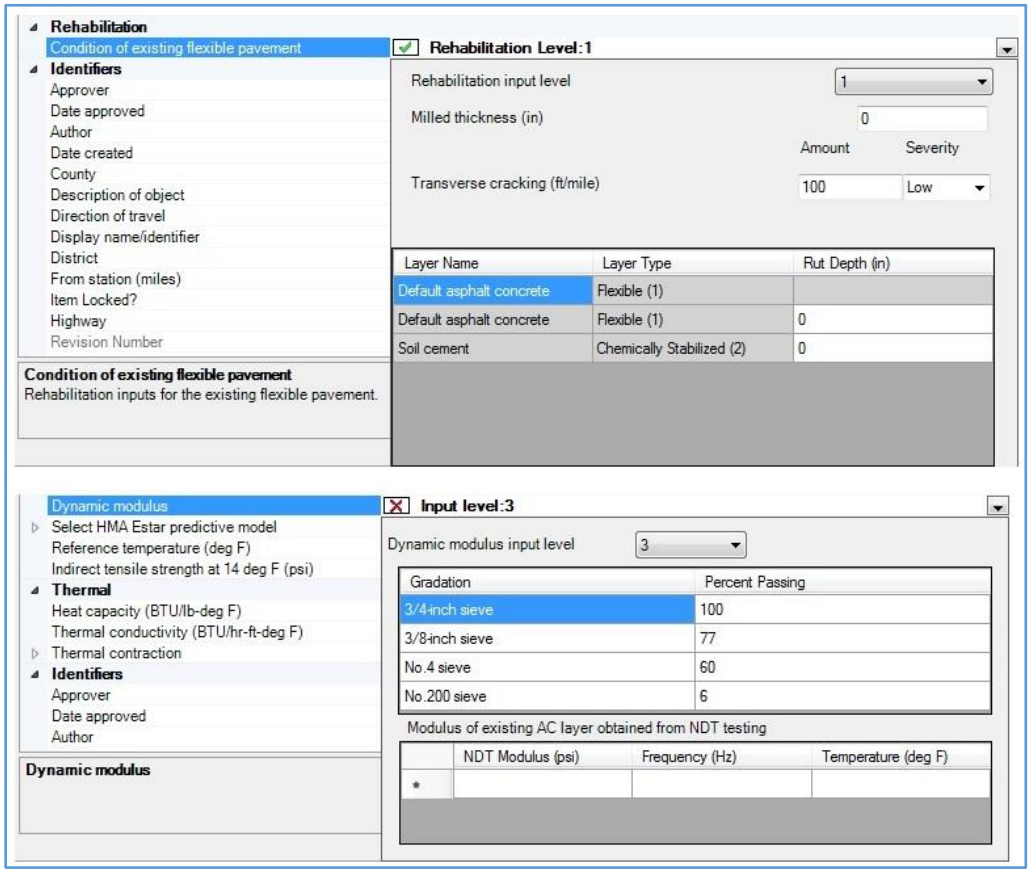


Figure 41 AASHTO Pavement ME Asphalt Rehabilitation Level 1 Inputs

Rehabilitation level 2 inputs require a detailed condition survey to measure the percentage of total pavement area exhibiting fatigue cracking. Input requirements for Level 2 rehabilitation design are shown in **Figure 42**. The Pavements for which only an initial condition assessment is available are characterized using Rehabilitation level 3 inputs. **Figure 43** shows the Pavement ME input requirements for Level 3 rehabilitation design.

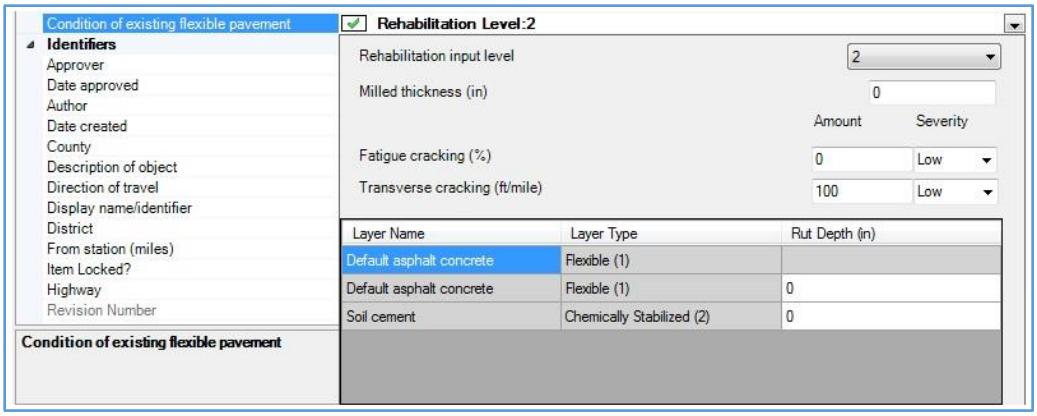


Figure 42 AASHTO Pavement ME Asphalt Rehabilitation Level 2 Inputs

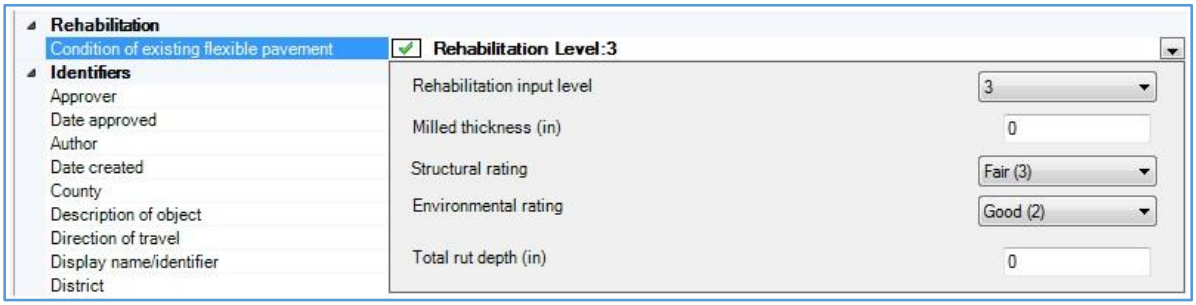


Figure 43 AASHTO Pavement ME – Asphalt Rehabilitation Level 3 Inputs

The backcalculation tool provides inputs for performing a Level 1 rehabilitation design of asphalt pavements. The results from the tool's backcalculation module are used to populate NDT modulus, temperature and frequency values shown in **Figure 41**. These inputs are used in Pavement ME to calculate a damaged modulus value for the existing asphalt layer by adjusting the undamaged dynamic modulus master curve as shown below in **Figure 44**.

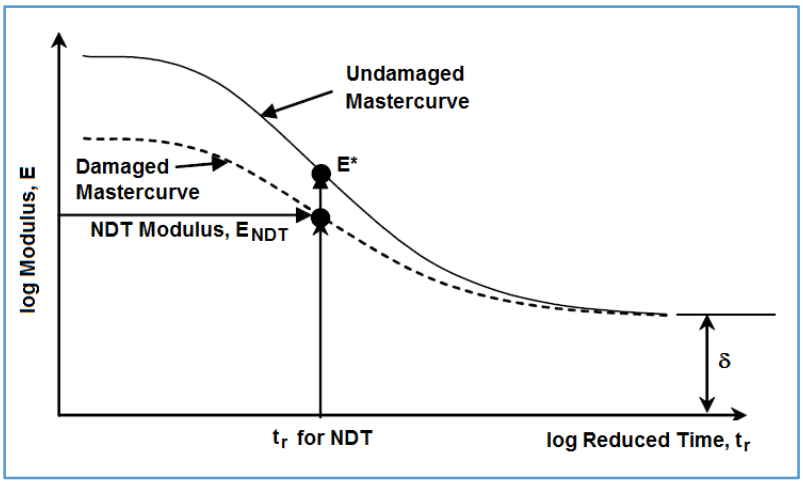


Figure 44 AASHTO Pavement ME – Calculation of Damaged Asphalt Layer Modulus

Dynamic modulus of the existing asphalt layer always requires Level 3 inputs, irrespective of the rehabilitation input level as shown in **Figure 41**. Other asphalt layer properties such as Poisson's ratio and thickness within the ME design file are obtained from backcalculation inputs. Pavement ME also allows users to specify a milled thickness, which is used to calculate a reduced thickness of the existing asphalt layer in the overlay design process.

Overlay Design of Existing PCC (JPC/ Fractured JPC/CRC) Pavements

Design of flexible or rigid overlays of existing JPC or CRC pavements requires existing layer properties of the PCC layer and other rehabilitation inputs such as transverse joint load transfer efficiency (LTE). Inputs for characterizing the PCC layer are similar to those necessary for a new rigid pavement design as shown for a JPC layer in **Figure 45**. Strength input in Pavement ME is identical for both JPC and CRC layers. Output from the backcalculation tool generates Level 3 inputs for PCC strength, i.e. in-place elastic modulus of the PCC layer. The backcalculated layer modulus is used to define the 28-day PCC elastic modulus, while the modulus of rupture is assigned a default value of 690 psi (US customary units) which can be changed by the user in the design (.DGPX) file.

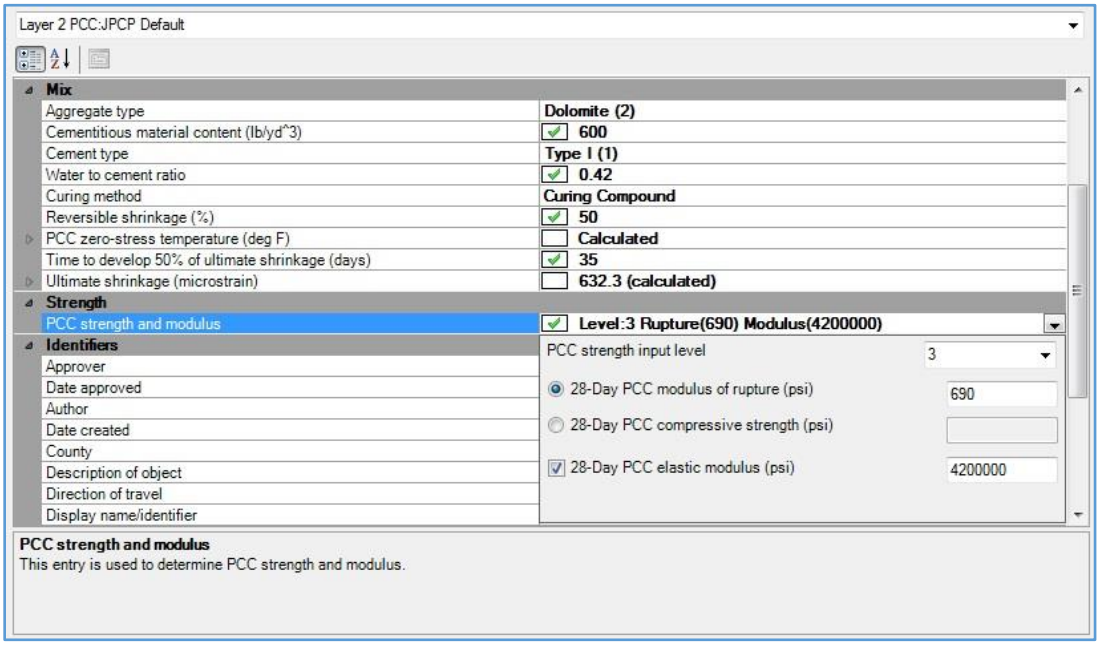


Figure 45 AASHTO Pavement ME – Level 3 JPCP Compressive Strength

Rehabilitation inputs for overlay of existing JPCP requires percentage of slabs distressed, replaced or repaired before restoration and LTE, whereas overlay design of CRCP requires the number of punchouts in the existing pavement. **Figure 46** shows the rehabilitation inputs required for overlay design of JPCP and CRCP. The transverse joint LTE can be computed using the backcalculation tool if the input FWD file contains test data pertaining to LTE measurements. A default value of 50 percent is used when LTE is not calculated from the tool. Punchouts in existing CRCP are not part of the backcalculation tool output and should be entered by the user. The default value of punchouts is set to zero in the ME design file.

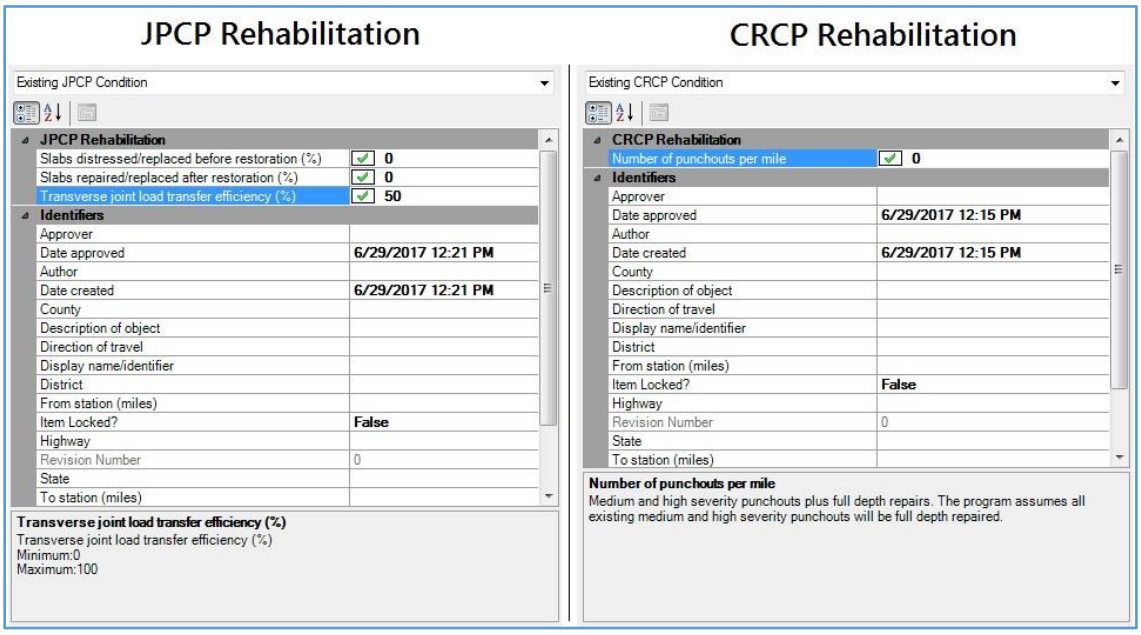


Figure 46 AASHTO Pavement ME – JPCP and CRCP Rehabilitation Inputs

Appendix B Segmentation Procedure

As noted in Chapter 3, two methods are used for the segmentation of the project based on deflection data: the cumulative area difference method and the statistical comparison method. Both are discussed in this appendix.

Cumulative Area Difference Method

The cumulative area difference method is an area-based procedure used to divide a pavement section into statistically homogeneous segments. The cumulative difference approach is recommended by the 1993 AASHTO Pavement Design Guide, Appendix J [(1)]. Other variables such as the backcalculated modulus can also be used as the response in the cumulative difference approach.

The response variable (deflection) is plotted along the station distance over the entire length of the pavement section, and the cumulative area under the deflection-distance curve is calculated at each station. An average response or deflection is also calculated and the cumulative area from the average deflection is plotted on the same curve. The difference between the two cumulative area curves – measured deflection and average deflection curves is calculated and plotted against the station distance on a separate curve. Segmentation locations are identified as stations at which the algebraic sign of the cumulative area difference curve changes. The overall procedure is explained using an example in this section. Input data for this example is the same as used in the example in Appendix E.

Step 1

Select the response variable, *r*. The backcalculation tool uses deflections at the selected drop number and sensor as the response. E.g.: If the sensors at the load center, 18 inches and 60 inches and drop #1 corresponding to a 9000 lb. target load level are selected, the tool performs segmentation using three response variables – D_0, D_{18} and D_{60} at drop #1.

This section provides a detailed explanation of the procedure using the center-load sensor – D_0 at drop #1 as the response variable. **Table 4** shows a truncated set of deflection data used in the segmentation example.

Table 4 Deflection Data (Truncated) for Segmentation Example

Station No.	Distance (km)	Drop No.	Load (lbf)	D_0 (mils)	D_{60} (mils)
1	5.354	1	9454	7.22	1.08
2	5.355	1	9366	7.85	1.1
3	5.358	1	9322	5.07	0.98
4	5.363	1	9322	7.34	1.08
5	5.368	1	9289	5.75	0.91
6	5.372	1	9180	7.07	0.91
…	…	…	…	…	…
44	5.744	1	8939	10.05	1.15

45	5.745	1	8972	9.57	1.23
46	5.751	1	9015	9.61	1.21
47	5.764	1	8983	11.24	1.6
48	5.781	1	8972	9.54	1.65
49	5.79	1	8906	11.37	1.43

Step 2

Calculate the average response $\bar{r}$ at each station. The value of $\bar{r}$ at station *i* is calculated as the average of the deflections at station *i* and station *i* – 1. The station interval between two consecutive stations is also calculated as $\Delta x_i = x_i - x_{i-1}$, where *x* is the station distance.

E.g.: $\bar{r}$ at Station 4 = ($\overline{D}_0$ (Station 4) + $\overline{D}_0$ (Station 3)) / 2 = (7.34 + 5.07) / 2 = 6.205
Δx At Station 4, $\Delta x_4 = x_4 - x_3 = 5.363 - 5.358 = 0.005$

Average deflection at the first station (*i* = 1) is assumed to be equal to the deflection measured at station *i*. Similarly, the station interval for the first station is also assumed to be equal to zero.

Table 5 shows the calculated $\bar{r}$ or $\overline{D}_0$ for the example deflection dataset.

Table 5 Calculation of Average Deflection and Station Interval Distance

Station No.	Distance (km)	Load (lbf)	D0 (mils)	$\overline{D}_0$	Δx
1	5.354	9454	7.22	7.22	0
2	5.355	9366	7.85	7.535	0.001
3	5.358	9322	5.07	6.46	0.003
4	5.363	9322	7.34	6.205	0.005
5	5.368	9289	5.75	6.545	0.005
6	5.372	9180	7.07	6.41	0.004
…	…	…	…	…	…
44	5.744	8939	10.05	9.415	0.007
45	5.745	8972	9.57	9.81	0.001
46	5.751	9015	9.61	9.59	0.006
47	5.764	8983	11.24	10.425	0.013
48	5.781	8972	9.54	10.39	0.017
49	5.79	8906	11.37	10.455	0.009

Step 3

Calculate the area under the deflection curve at each station – this area is equal to the actual interval area. The area at each station *i* is calculated as $a_i = \overline{D}_{0(i)} \times \Delta x_i$, i.e. multiplying the average deflection and station interval as calculated in Step 2. The cumulative area at each

station, Σa_i is also calculated as the sum of all interval areas from station 1 to station *i*. **Table 6** shows the interval areas and cumulative areas for the truncated dataset.

E.g.: Interval area at Station 4, $a_4 = \overline{D}_{0(4)} \times \Delta x_4 = 6.205 \times 0.005 = 0.031025$

Cumulative area at Station 4, $\Sigma a_4 = \sum_{i=1}^{4} a_i = a_1 + a_2 + a_3 + a_4$

$= 0 + 0.007535 + 0.01938 + 0.031025 = 0.05794$

Table 6 Calculation of Interval Area and Cumulative Area

Station No.	D_0 (mils)	$\overline{D}_0$	Δx	a_i	Σa_i
1	7.22	7.22	0	0	0
2	7.85	7.535	0.001	0.007535	0.007535
3	5.07	6.46	0.003	0.01938	0.026915
4	7.34	6.205	0.005	0.031025	0.05794
5	5.75	6.545	0.005	0.032725	0.090665
6	7.07	6.41	0.004	0.02564	0.116305
…	…	…	…	…	…
44	10.05	9.415	0.007	0.065905	3.453905
45	9.57	9.81	0.001	0.00981	3.463715
46	9.61	9.59	0.006	0.05754	3.521255
47	11.24	10.425	0.013	0.135525	3.65678
48	9.54	10.39	0.017	0.17663	3.83341
49	11.37	10.455	0.009	0.094095	3.927505

Step 4

Calculate the average project response, D* using the cumulative area Σa_i calculated for the final station in the project. Assuming that D* represents an average response over the entire length of the project L, the area under the D*-station curve should be equal to the overall cumulative area $\Sigma a_{x=L}$ or Σa_{49}. The concept of the average cumulative area curve is shown schematically in **Figure 47**.

The average response, D* is calculated as the ratio of the overall cumulative area $\Sigma a_{x=L}$ to the length of the project L.

$$D^* = \frac{\sum a_{x=L}}{L} \qquad \textbf{Equation 4}$$

E.g.: The overall project length, $L = x_{i=49} - x_{i=1} = 5.790 - 5.354 = 0.436$

The value of D* for the example dataset is equal to D* = $\Sigma a_{x=L}$ / L = 3.9275/0.436 = 9.008

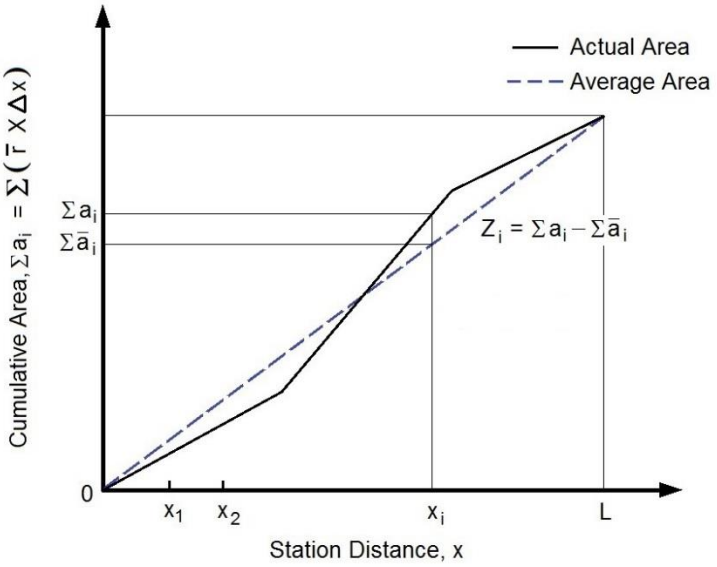


Figure 47 Illustration – Average Cumulative Area

Step 5

Calculate the difference Z_i between the actual cumulative area Σa_i and the average cumulative area, $\Sigma \overline{a}_i$ at each station i. The actual cumulative area Σa_i is calculated as explained in Step 3.

The average cumulative area $\Sigma \overline{a}_i$ is calculated as the product of the station interval Δx with the average response or deflection D*.

$$\Sigma \overline{a}_i = \Delta x \times D^* \qquad \textbf{Equation 5}$$

Table 7 shows the cumulative area difference for the truncated dataset.

Figure 48 shows the plot of cumulative area difference along the length of the pavement section. From this plot, stations at which the curve changes direction are identified as shown by orange circles on the plot. The selection of stations is also subjected to the constraint for minimum segment length – there should be a minimum of seven stations within a segment. If a direction change occurs at a station that is less than 7 stations from the beginning of the segment, the change is ignored, and the process continues to evaluate the next station at which the curve changes sign. In mathematical terms, the station at which the slope of the cumulative area difference curve changes sign (negative to positive) is identified as the end of the previous segment and the subsequent station is identified as the beginning of a new segment.

Table 7 Calculation of Cumulative Area Difference

St. No.	D_0 (mils)	$\overline{D}_0$	Δx	a_i	Σa_i	$\Sigma \overline{a}_i$	Z_i
1	1.08	7.22	0	0	0	0	0
2	1.1	7.535	0.001	0.007535	0.007535	0.001371	-0.00028
3	0.98	6.46	0.003	0.01938	0.026915	0.005485	-0.00128
4	1.08	6.205	0.005	0.031025	0.05794	0.012341	-0.00298
5	0.91	6.545	0.005	0.032725	0.090665	0.019198	-0.00486
6	0.91	6.41	0.004	0.02564	0.116305	0.024683	-0.00671
…	…	…	…	…	…	…	…
44	1.15	9.415	0.007	0.065905	3.453905	0.534796	-0.00518
45	1.23	9.81	0.001	0.00981	3.463715	0.536168	-0.00536
46	1.21	9.59	0.006	0.05754	3.521255	0.544395	-0.00627
47	1.6	10.425	0.013	0.135525	3.65678	0.562222	-0.00583
48	1.65	10.39	0.017	0.17663	3.83341	0.585534	-0.00152
49	1.43	10.455	0.009	0.094095	3.927505	0.597875	0

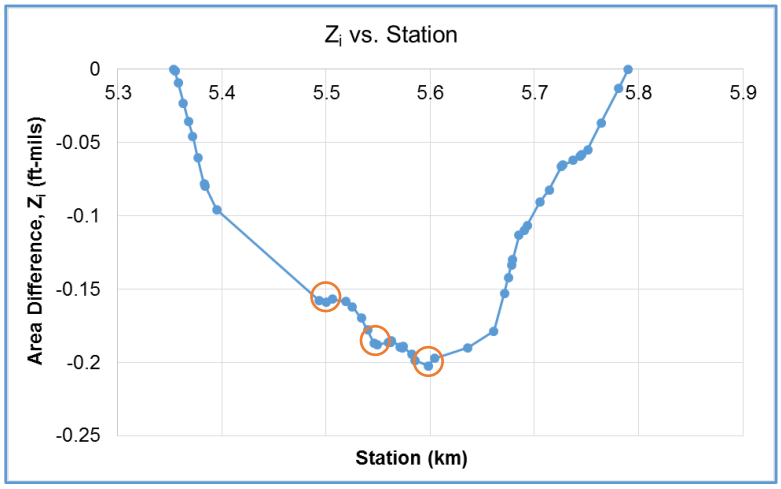


Figure 48 Plot of Cumulative Area Difference

Four segments are identified from the cumulative area difference approach for the example dataset as shown below in **Table 8**. The length of the segment as shown in **Table 8** is the number of stations within the segment, subject to a minimum of 7 stations.

Table 8 Segments Calculated from Cumulative Area Difference Approach

Segment	Start Station #	End Station #	Length	Start Station	End Station
1	1	11	11	5.354	5.493
2	12	18	7	5.5	5.546
3	19	27	9	5.549	5.585

4	28	49	22	5.598	5.79

Step 6
The segments defined by the cumulative area method are compared sequentially to identify segments that have statistically similar mean and standard deviations. The first step in the statistical comparison process is to calculate the mean and standard deviation of deflections at the selected sensor (D_0 in this example). The calculated mean and standard deviation of center-load deflection D0 for the example dataset is shown below in **Table 9**.

Table 9 Mean Deflection and Standard Deviation for Segments

Segment	Start	End	Size	Mean	Std. Dev	Variance
1	5.354	5.493	11	6.985455	1.262326	1.593467
2	5.5	5.546	7	8.218571	1.297053	1.682348
3	5.549	5.585	9	9.013333	1.599633	2.558825
4	5.598	5.79	22	10.36273	1.361977	1.854983

The segment variances are compared to each other using an F-test to test for equality of variance. The procedure is explained in detail in Statistical Comparison Module section of this manual. Results of the F-test for the example dataset are shown below in **Table 10**. Segment variances are statistically not different if the calculated F-value is less than the critical F-value. From the results shown in **Table 10**, the variances of all segment combinations are found to be statistically not different.

Table 10 F-test Results for Example Dataset Segments

Segment *i*	Segment *j*	F-value	F-critical	p-value	Variances
1	2	1.055778	3.01233	0.893423	Equal
1	3	1.605822	2.896223	0.47479	Equal
1	4	1.164117	2.626127	0.83561	Equal
2	3	1.520985	3.676675	0.627092	Equal
2	4	1.102616	3.426042	0.982471	Equal
3	4	1.379433	2.341937	0.52348	Equal

After comparing equality of variances for all segment combinations, a t-test is performed to check for equality of mean deflections. The procedure for calculating the pooled degrees of freedom, student's t-test value and critical t-value is explained in the Statistical Comparison Module section. **Table 11** shows the results of the t-test for comparing segment means of the example datasets.

Table 11 F-test Results for Example Dataset Segments

Seg. *I*	Seg. *j*	Equal Variance	Pooled DOF	Mean $D_{0,i}$	Mean $D_{0,j}$	$\|D_i - D_j\|$	t-value	t-critical
1	2	Equal	16	6.9855	8.2186	1.2331	1.9996	2.1199
1	3	Equal	18	6.9855	9.0133	2.0279	3.1725	2.1009
1	4	Equal	31	6.9855	10.3627	3.3773	6.8731	2.0395
2	3	Equal	14	8.2186	9.0133	0.7948	1.0673	2.1448
2	4	Equal	27	8.2186	10.3627	2.1442	3.666	2.0518
3	4	Equal	29	9.0133	10.3627	1.3494	2.382	2.0452

Segment means are tested for equality in a sequential manner, i.e., Segment 1 is compared to Segment 2, Segment 2 is compared to Segment 3, and so on. This is shown using shaded rows in **Table 11**. The mean deflections of any *i* – *j* segment combination is considered to be statistically different if the t-value is greater than t-critical. The statistical comparison results can be explained as follows:

- Segment 1 is equal to Segment 2 (t = 1.9996 < t-critical = 2.1199)
- Segment 2 is equal to Segment 3 (t = 1.0673 < t-critical = 2.0395)
- Segment 3 is not equal to Segment 4 (t = 2.382 > t-critical = 2.0452)

The statistical comparison procedure merges segments whose mean deflections are statistically equal into one segment. For the example dataset, Segments 1, 2 and 3 are combined into a single segment, whereas Segment 4 is considered as a separate segment. The combined segments and their start and end locations are shown below in **Table 12**.

Table 12 Combined Segments from Statistical Comparison

Preliminary Segments				Combined Segments			
No.	Start	End	Size	No.	Start	End	Size
1	5.354	5.493	11	1	5.354	5.585	27
2	5.5	5.546	7				
3	5.549	5.585	9				
4	5.598	5.79	22	2	5.598	5.790	22

Figure 49 shows the charts displayed on the preliminary segmentation and statistical comparison module screens for the sensor under the FWD load (D_0). Results are displayed to the users in graphical form as shown in **Figure 49**.

Statistical Comparison Method

In this module, adjacent segments are compared to determine and merge statistically similar segments. Each segment (except the final segment) is compared with the subsequent segment to check for equality of deflection mean value and standard deviation. The F-test is used to check for equal variances of the two sets of deflection data from adjacent segments, and the student's t-test is used for checking equality of the mean deflections.

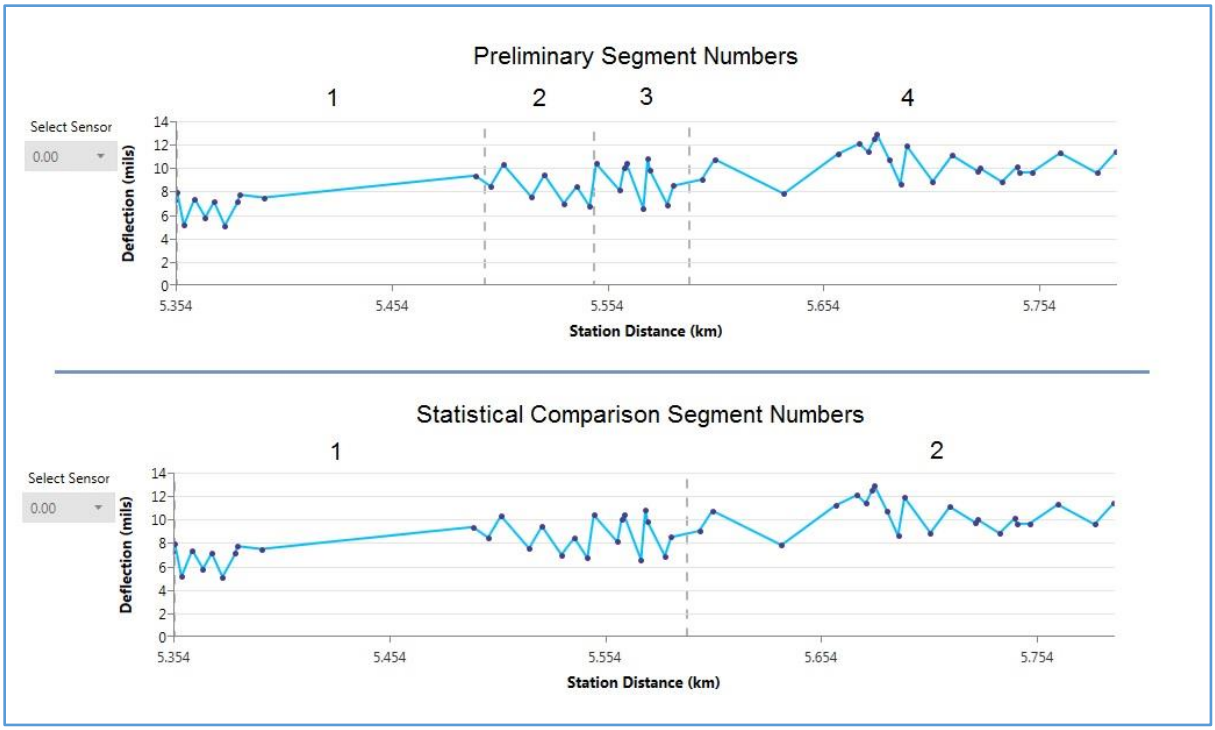


Figure 49 BcT Segmentation Results for Center-Load Sensor

For a pavement section which is divided into N segments from the cumulative area method or preliminary segmentation, mean deflections for each i^{th} (i < N) segment is compared to the (i + 1)th segment, i.e. next adjacent segment. The two segments are then merged into a single segment if the mean deflections are statistically equal. Segments whose mean deflections are statistically equal but spatially separated (non-adjacent segments) are not merged. The procedure used for statistical comparison, which occurs after the preliminary segments have been identified in the previous module, is described below.

Step 1

Calculate the mean deflection and variance for each of the N segments using **equation 6**. Consider the i^{th} segment, which consists of n_i stations. The deflections at each of the stations is denoted by d_{ik}, where the subscript i refers to the segment number and subscript k refers to the station of the segment.

$$\bar{d}_i = \frac{1}{n_i}\sum_{k=1}^{n_i} d_{ik} \qquad \textbf{Equation 6}$$

Where:

$\bar{d}_i$ is the mean deflection for segment i, which has a length of n_i stations

n_i is the number of stations in segment i

d_{ik} is the deflection at the k^{th} station of the i^{th} segment

The variance of deflection values S_i^2 for the i^{th} segment is calculated as shown in **equation** 7.

$$S_i^2 = \frac{1}{n_i - 1}\sum_{k=1}^{n_i}(d_{ik} - \bar{d}_i)^2 \qquad \textbf{Equation 7}$$

Step 2

Conduct an F-test for equal variance for each $i - j$ combination of the N segment variances. The module first calculates the variances for all segments identified from preliminary segmentation. An F-test is conducted to check for equal variances of each $i - j$ segment pair, where the test statistic is calculated using **equation 8**.

$$F = \frac{S_i^2}{S_j^2} \text{ or } \frac{S_j^2}{S_i^2} \text{ such that } F > 1 \qquad \textbf{Equation 8}$$

Where S_i^2 is the variance of the i^{th} segment and S_j^2 is the variance of the j^{th} segment ($i \neq j$). The ratio of variances is calculated such that the value of the F-test statistic is always greater than 1. The critical F-value is calculated from F-test tables at a 95% ($\alpha = 0.05$) confidence level as:

- $F_{critical} = F(\alpha, n_i, n_j)$ when $S_i^2 > S_j^2$
- $F_{critical} = F(\alpha, n_j, n_i)$ when $S_j^2 > S_i^2$

The program internally computes the critical F-value and compares it with the calculated F-value to check for equality of variance. The variances of the two segments are treated as equal if F is less than the $F_{critical}$, and different if F is greater than $F_{critical}$.

- $F < F_{critical} \rightarrow$ Variances of segment i and j are equal
- $F \geq F_{critical} \rightarrow$ Variances of segment i and j are not equal

The results of the F-test can be best visualized as shown in **Table 13**. Since each segment is compared to other segments, the cells from only the diagonal and upper triangle, shown in grey represent whether the variances are equal or unequal. The example in **Table 13** shows the variances of each segment in comparison to all other segments. The information presented in **Table 13** is only for illustrating the comparison process and is based on hypothetical data.

Table 13 F-Test Results – Illustrative Example

Segment #	j = 2	j = 3	…		j = N – 1	j = N
i = 1	✓	×	×	×	✓	✓
i = 2		✓	✓	×	✓	✓
3			×	✓	✓	✓
…				✓	×	✓
					✓	✓
i = N – 1						×

✓ - Variances are equal, × - Variances are not equal

Step 3

Conduct a student's t-test to check for equality of deflection means for each $i - j$ combination of N segments. The pooled degrees of freedom (DOF) and pooled variance for the t-test are calculated based on results from the F-test for equal variances.

Equal Variance: When the two segments i and j have equal variances, the pooled DOF is calculated as shown in **equation 9**.

$$DOF_{Pooled} = n_i + n_j - 2 \qquad \textbf{Equation 9}$$

The pooled variance for two samples having variances S_i and S_j, where the variances are equal (as determined from the F-test) is given by **equation 10**.

$$S_p^2(i,j) = \frac{S_i^2(n_i - 1) + S_j^2(n_j - 1)}{DOF_{Pooled}} \qquad \textbf{Equation 10}$$

The pooled standard deviation $S_p(i,j)$ is calculated as the square-root of the variance, i.e. $S_p(i,j) = \sqrt{S_p^2}$.

The t-statistic for two samples i and j of size n_i and n_j, having mean deflections of d_i and d_j, respectively, and a pooled standard deviation of $S_p(i,j)$ is calculated using **equation 11**.

$$t = \frac{\left|\bar{d}_i - \bar{d}_j\right|}{S_p(i,j)\sqrt{\frac{1}{n_i} + \frac{1}{n_j}}} \qquad \textbf{Equation 11}$$

Unequal Variance: When the two segments, i.e. segment i and segment j have unequal variances, the pooled DOF is calculated as shown in **equation 12**.

$$DOF_{Pooled} = \frac{(S_i^2/n_i + S_j^2/n_j)^2}{\left[\frac{(S_i^2/n_i)^2}{n_i - 1} + \frac{(S_j^2/n_j)^2}{n_j - 1}\right]} \qquad \textbf{Equation 12}$$

The value of the student's t-statistic is calculated using **equation 13**.

$$t = \frac{\left|\bar{d}_i - \bar{d}_j\right|}{\sqrt{\frac{S_i^2}{n_i} + \frac{S_j^2}{n_j}}} \qquad \textbf{Equation 13}$$

The critical *t*-value is calculated as a two-sided *t*-test value at a 95% ($\alpha = 0.05$) confidence level as:

- $t_{critical} = t(1 - \alpha/2, DOF_{Pooled})$
- $t_{critical} = t(1 - \alpha/2, DOF_{Pooled})$

Similar to the F-test, the t-statistics are calculated for all $i - j$ segment pairs. Comparison of segments is performed in a sequential manner, i.e. hypothesis testing for equality of segment means uses the t-statistics computed for the $i - (i + 1)$ segment pairs. The means of the two segments are treated as equal if the calculated value of t is less than the $t_{critical}$, and different if t is greater than $t_{critical}$.

- $t < t_{critical} \rightarrow$ Means of segment i and j are equal
- $t \geq t_{critical} \rightarrow$ Means of segment i and j are not equal

The results of the *t*-test can be best visualized as shown in **Table 14**. Since each segment is compared to only the next adjacent segment, the cells in grey represent the *t* values used for combining the segments. The information presented in **Table 14** is only for illustrating the comparison process and is based on hypothetical data.

Table 14 *t*-Test Results – Illustrative Example

Segment #	$j = 2$	$j = 3$	$j = 4$		$j = N - 1$	$j = N$
$i = 1$	✓					
$i = 2$		✓				
3			×			
…				✓		
					✓	
$i = N - 1$						×

✓ - Means are equal, × - Means are not equal

In the example above, the equality of mean deflections of the first four segments can be described as follows:

- Segment 1 is equal to Segment 2
- Segment 2 is equal to Segment 3
- Segment 3 is not equal to Segment 4

Segments 1, 2 and 3 are combined into a single segment as the mean deflections are statistically equal. It should be noted that the process of combining segments follows a sequential procedure where equality of means for Segments 1 and 3 is not considered, as it is not possible to combine spatially separated segments. The process is extended to all segments and the final segments are calculated and displayed to the user on the **Final Segmentation** screen.

Appendix C Pavement Layer Default Property Values

Table 15 Default Pavement Layer Properties – US Customary Units

Layer Type	Poisson's Ratio	Minimum Modulus (ksi)	Maximum Modulus (ksi)	Seed Modulus (ksi)
AC (AC)	0.35	400	6000	1000
PCC (PC)	0.2	1000	10000	4000
PCC (fractured)	0.3	500	10000	1500
Granular base (typical)	0.4	20	100	50
Granular subbase (typical)	0.4	15	100	25
Subgrade (coarse-grained)	0.35	10	80	25
Subgrade (fine-grained)	0.35	5	50	15
Treated base (AC treated)	0.35	400	6000	1000
Treated base (cement-treated)	0.45	20	500	100
Treated base (other)	0.45	15	1000	50
Bedrock*	0.2			500

Table 16 Default Pavement Layer Properties – SI Units

Layer Type	Poisson's Ratio	Minimum Modulus (MPa)	Maximum Modulus (MPa)	Seed Modulus (MPa)
AC (AC)	0.35	2750	42000	7000
PCC (PC)	0.2	7000	70000	28000
PCC (fractured)	0.3	3500	70000	10000
Granular base (typical)	0.4	135	700	350
Granular subbase (typical)	0.4	100	700	175
Subgrade (coarse-grained)	0.35	65	600	175
Subgrade (fine-grained)	0.35	35	350	100
Treated base (AC treated)	0.35	2750	1000	150
Treated base (cement-treated)	0.45	135	3500	700
Treated base (other)	0.45	100	7000	350
Bedrock*	0.2			3500

* Bedrock is always considered a fixed layer in the backcalculation process, which has a fixed modulus. The default modulus of 500 ksi or 3500 MPa can be changed by the user in the **Structure Definition** module of the backcalculation tool.

Appendix D Backcalculation and ME Design Layer Type Correspondence

Table 17 Layer Type Correspondence from BcT and Pavement ME

Backcalculation Material	Pavement ME Materials
AC (AC)	Default asphalt concrete (existing)
PC (PCC)	Bonded PCC default
	CRCP default
	Default PCC mix 1
	Default PCC mix 2
	Default PCC mix 3
	Default JPCP 1
	Default JPCP 2
	Default JPCP 3
	Default PCC
	JPCP default
	SJPCP default
PCC (Fractured)	Fractured JPCP
Granular Base (Typical) or Granular Subbase (Typical)	A-1-a
	A-1-b
	A-2-4
	A-2-5
	A-2-6
	A-2-7
	A-3
	Cold recycled asphalt – RAP (includes millings)
	Cold recycled asphalt – RAP pulverized in place
	Crushed gravel
	Crushed stone
	Permeable aggregate
	River-run gravel
Subgrade (coarse grained)	A-1-a
	A-1-b
	A-2-4
Subgrade (fine grained)	A-2-5
	A-2-6
	A-2-7
	A-3
	A-4
	A-5
	A-6
	A-7-5
	A-7-6

Table 17 continued

Backcalculation Material	Pavement ME Materials
Treated base (AC treated)	Default asphalt concrete (existing)
Treated base (cement treated)	Cement stabilized
	Lime cement fly ash
	Soil cement
Treated base (other)	Lime cement fly ash
	Lime fly ash
Bedrock	Highly fractured and weathered
	Massive continuous

Appendix E Example – Use of BcT to Establish Inputs to the Rehabilitation Design

This section provides a detailed walkthrough of the process of using the BcT to develop rehabilitation design files for the AASHTO Pavement ME software. The input FWD file used in this example is obtained from testing conducted on a flexible pavement section on Interstate 84 west of Boise, Idaho. The input FWD file is a Dynatest V20 file in US customary units. An excerpt of the example input file is provided below in **Figure 50** to illustrate the layout of a typical Dynatest FWD file. The layout differs for files from different FWD providers (Dynatest, JILS and KUAB) and also between different versions of the FWD device from the same manufacturer (Dynatest FWD and F20/F25 formats).

```
R80    67    990609X84301036F20
711021008002-08952339.7902111  8
 150   0-305 305 457 610 9141524  5.91 0.00 -12.00 12.00 18.00 24.00 36.00 60.00
C:\Program Files (x86)\Dynat.FWD
I84-301
S
S
402063  86231-50   5.354  15.751
10.418.0 3.510.0 3.020.0 3.010.0
Ld   982 0.989  63.9           .
D1  1251 1.023 1.023           .
D2  3310 1.016 0.965           .
D3  1253 1.027 1.005           .
D4  1256 1.013 1.007           .
D5  3611 1.014 1.017           .
D6  1258 1.018 1.021           .
D7  1257 1.017 1.012           .
D* N0    1.000 1.000           .
D* N0    1.000 1.000           .
D* N0    1.000 1.000           .
Administrator
11020300.......................
0   0   0   0    ..............
*0000 +00.0
DtCty PxNnnnS
  Cty P Nnnn
*0000 +00.0
..............................
 11060  -11060      0   0Peak...32  0   ......
12345.....................................................................................
B12341111111111111111111111111111111111111111111111111111111144444444444444444
.....................................................................................
.************************************************************************************
.....................................................................................
.....................................................................................
Testing,
*3
S  5.354      24.7   31 22 71039  76  89  72
 595 183 122 123 102  84  56  27  9454  7.22  4.80  4.83  4.03  3.31  2.19  1.08
 600 183 122 123 103  84  56  28  9530  7.22  4.82  4.86  4.06  3.32  2.21  1.11
 598 184 122 124 103  85  56  28  9497  7.23  4.82  4.88  4.06  3.33  2.20  1.10
 599 183 122 123 103  85  56  28  9519  7.22  4.80  4.86  4.06  3.33  2.20  1.11
```

Figure 50 I-84 Flexible Pavement Dynatest F20 (.FWD) Example File Contents

The flexible pavement section used in this example is a three-layered structure consisting of 10 inches of asphalt concrete, 9 inches of unbound (granular) base course on top of a fine-grained subgrade. The procedure is demonstrated using two approaches: (1) backcalculation of layer moduli of a three-layered pavement structure with a 10 in. AC layer and default property inputs, and (2) backcalculation of layer inputs for a four-layered pavement structure with two 5 in. AC layers and modified values of seed moduli to achieve a lower RMSE.

The individual steps performed to load the input file, verify inputs, develop segments, assign the pavement layer structure and their properties, backcalculation, reviewing results and exporting to ME design (.DGPX) files are described in detail using screenshots.

Step 1: Start an instance of the Backcalculation Tool software

The default screen of the Backcalculation Tool is loaded as shown in **Figure 51**.

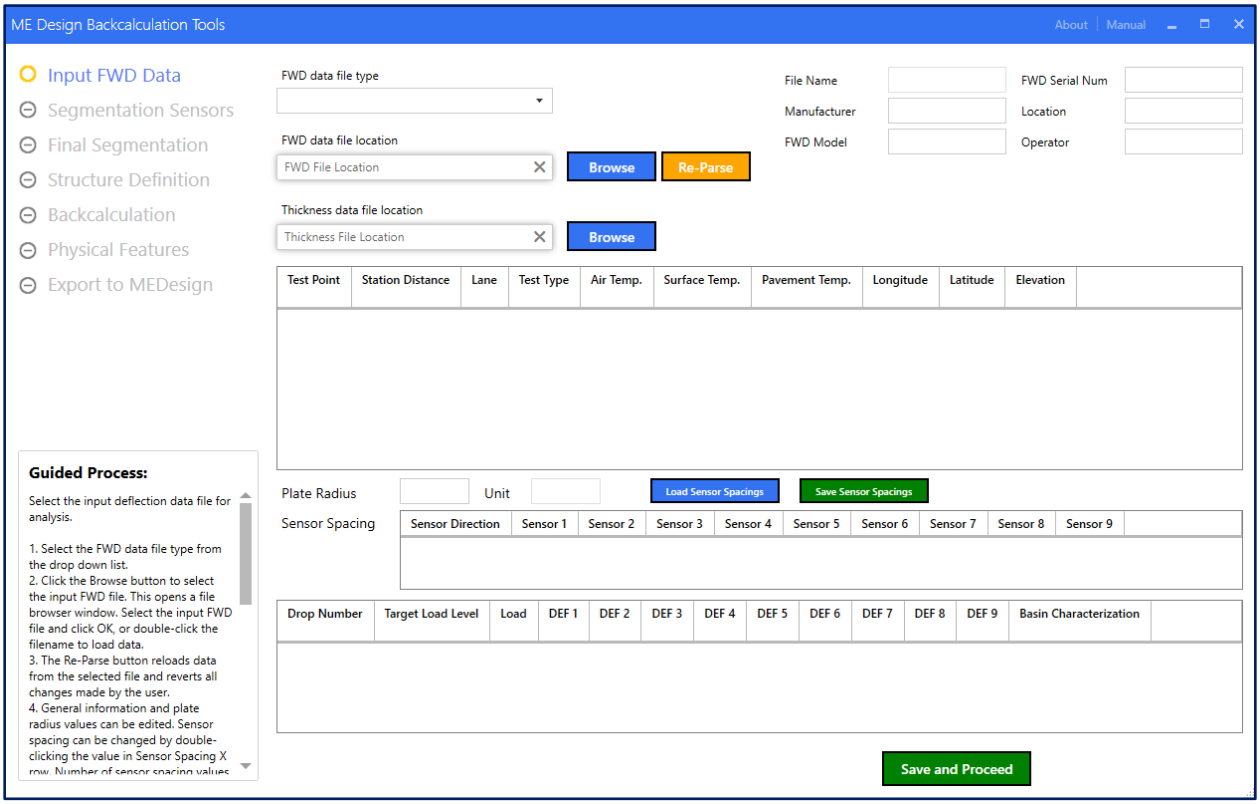


Figure 51 Backcalculation Tool – Default Load Screen

Step 2: Select the FWD data file type

The input FWD file type is selected using the FWD data file type drop-down menu. The example uses a Dynatest V20 file in .FWD format, so the option 'Dynatest V.20 (*.FWD)' option is selected from the list as shown in **Figure 52**.

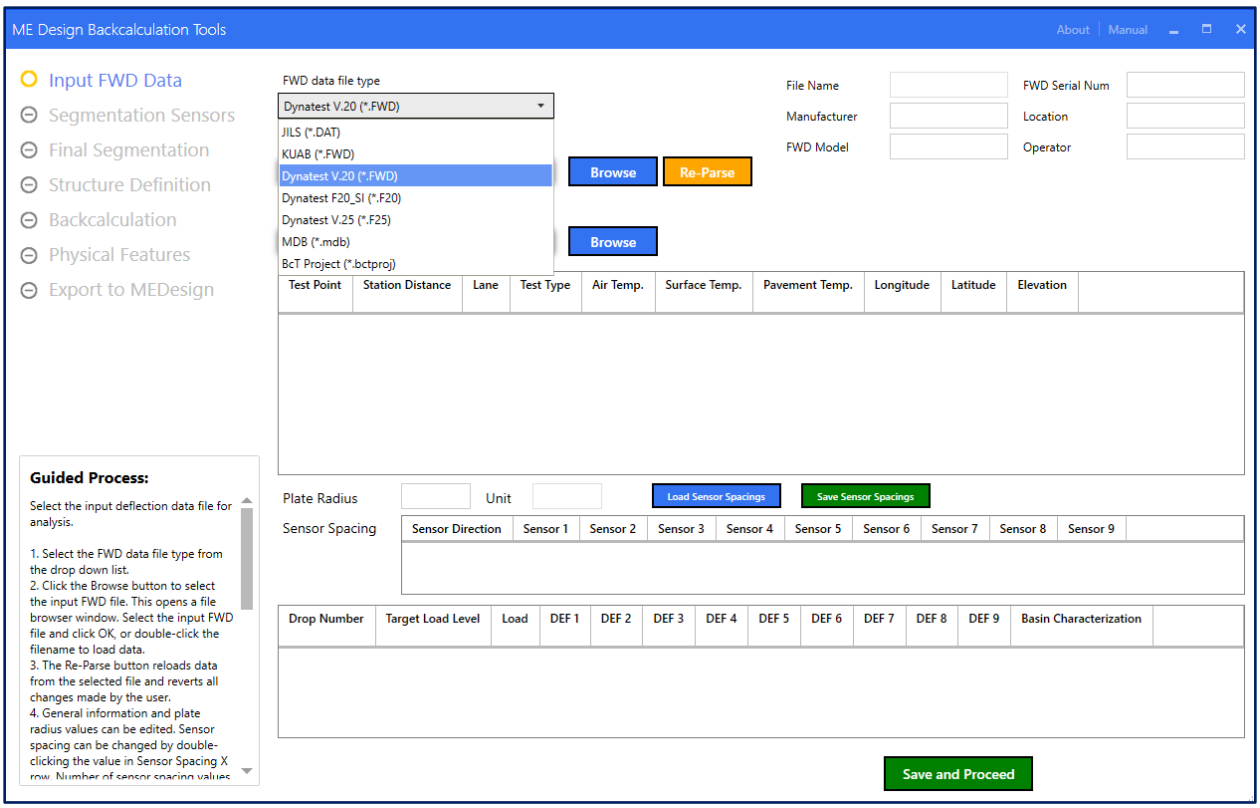


Figure 52 Backcalculation Tool – Select FWD Data File Type

Step 3: Select the input FWD data file using Browse button

Click the Browse button to select the input FWD data file. The data file used in this example is 'I84301Reduced.FWD'. Selecting the input file as described in the **Input FWD Data Module** section of the user manual will automatically load the contents of the file into the respective fields on the Input FWD Data screen as shown in **Figure 53**.

The contents of the file are displayed in the appropriate fields as shown in **Figure 53**. The general information data displayed on the screen is available in the input file. The values may be changed by the user if necessary. Plate radius and sensor spacing values are also populated automatically. These values should be verified by the user to ensure their accuracy and may be changed if any errors are observed. The sensor spacing values show that there are a total of 7 sensors, with Sensor 2 located 12 inches behind the loading plate (trailing sensor) as shown by the -12.00 value.

The input file is in US customary units, which is used to set the units for all variables except station numbers. Units for station numbers are populated as recorded during the FWD test, which is in units of kilometers for the selected file. Temperatures (^{o}F), plate radius (inches), sensor spacing (inches) and deflections (mils or milli-inches) are assigned US customary units.

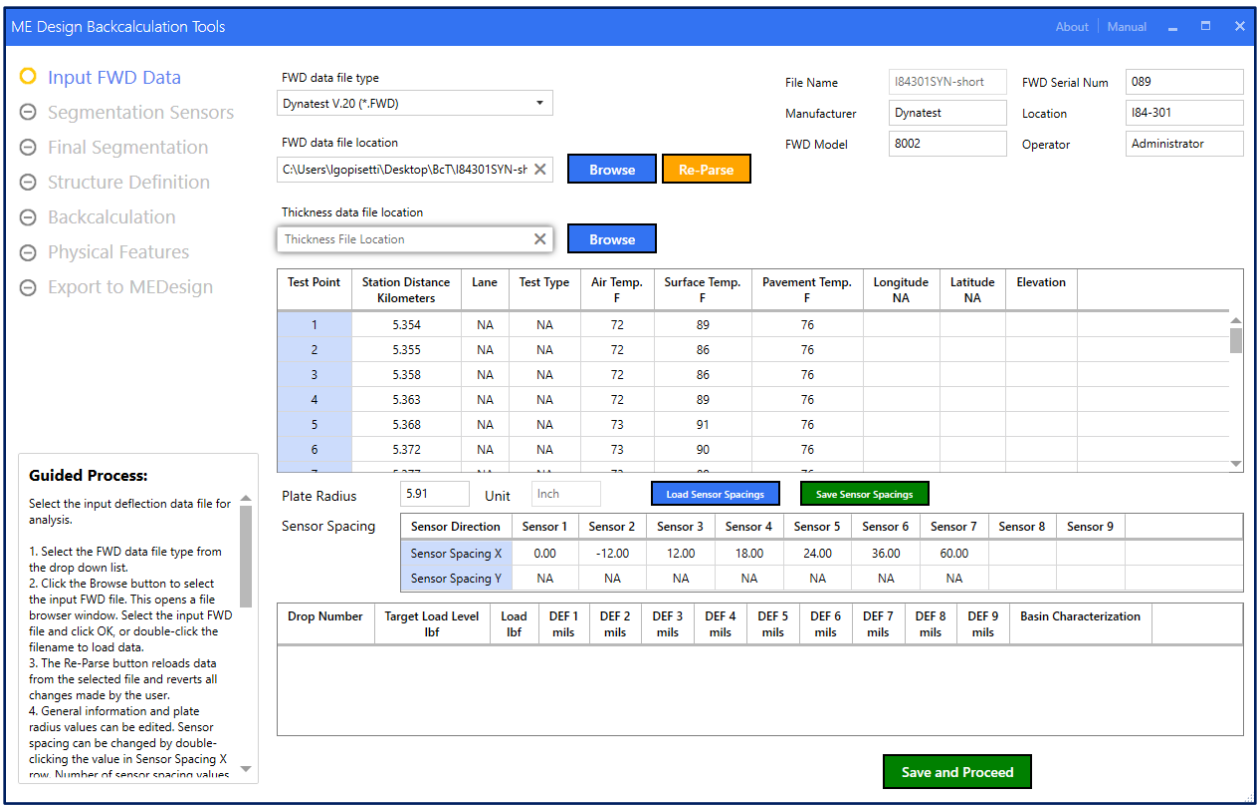


Figure 53 Display of Input FWD Data File Contents on Main Screen

Step 4: Click on a station row to view deflection data measured at that station

Click on the row corresponding to the first station, i.e. Test Point 1 or Station Distance 5.354. This populates the deflections measured at Station 5.354 in the drop data table at the bottom of the screen, as shown in **Figure 54**.

The drop data table contains a total of 12 rows, equal to the number of FWD drops at the selected station. Each row contains the measured FWD load and deflections for the drop, as well as the basin characterization (Typical, Type I, Type II or Type III).

Step 5 (OPTIONAL): Assign target FWD drop load values to drops

The user may choose to assign target FWD drop load values to each of the 12 individual drops. The values need to be entered for each drop at only one station as shown in **Figure 55**, which are automatically applied to corresponding drop numbers at all other stations.

a) Click on the Target Load Level cell for Drop 1 and enter a value of 9000. The target load level is selected by the user, and is typically based on the actual load value. In this example, Drop 1 has a measured FWD load of 9454 lbs. which corresponds to a 9000 lbs. target load level.
b) Repeat the process (enter a value of 9000) for Drops 2, 3 and 4.
c) Enter a target load level of 12,000 lbs. for Drops 5 to 8, and 16,000 lbs. for Drops 9 to 12.

d) Clicking on any other stations shows that the target values are applied to drops at all stations. For instance, click on Station 36 as shown in **Figure 56**. The drop data table shows that the target load values are assigned to all the 12 drops as entered by the user for Station 1.

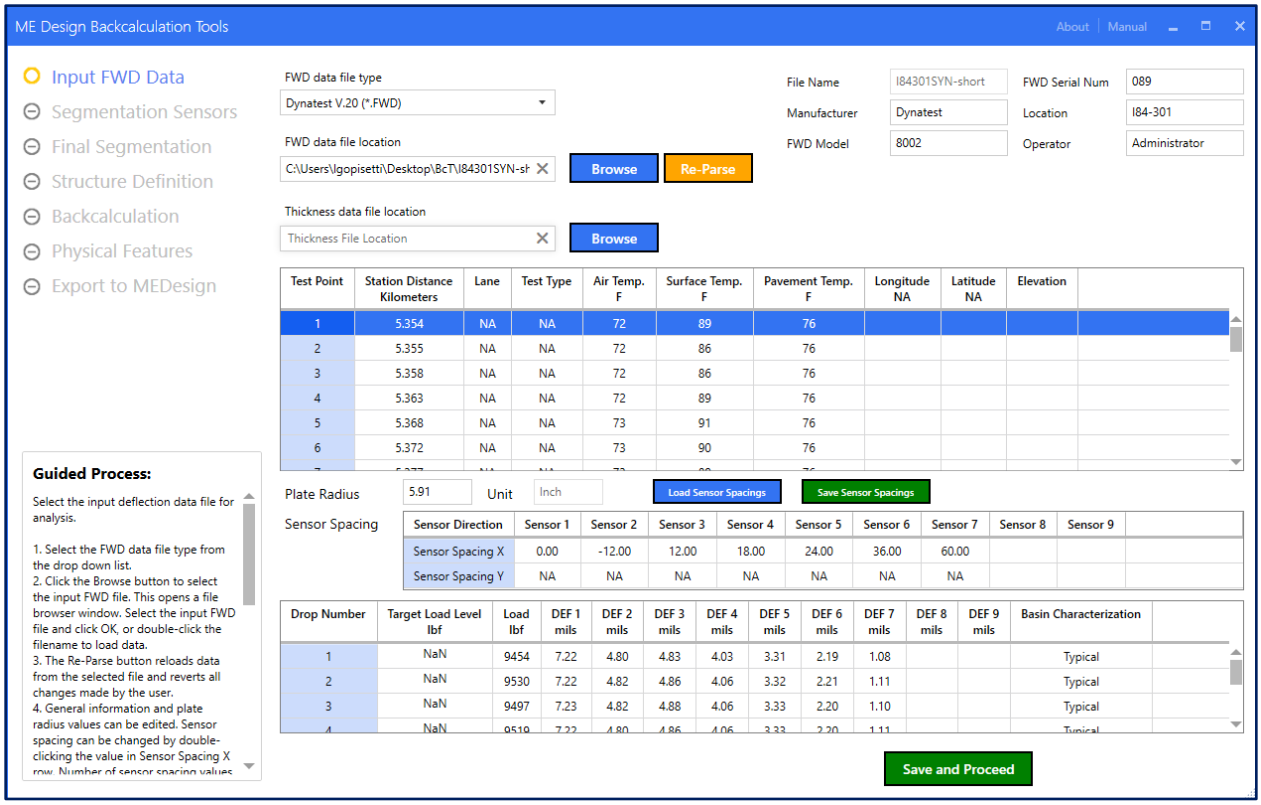


Figure 54 Display of Input FWD Data File Contents for Specific Test point Main Screen

This step is completely optional if the user is unsure of the target load levels for the drops. Target load levels are not used for calculation and are purely informational. The information entered is useful to identify drops based on the target load level on the segmentation, backcalculation and physical feature screens.

Step 6: Click Save and Proceed to progress to Segmentation Sensors screen

Verify that all the inputs on the Input FWD Data screen are valid and accurate. Click on the Save and Proceed button to proceed to the Segmentation Sensors screen.

Step 7: Select sensors on the Segmentation Sensors screen

The default view of the Segmentation Sensors screen shows three pre-selected sensors: first, middle and last sensors in the sensor spacing table on the Input FWD Data screen. **Figure 57** shows the default Segmentation Sensors screen for the example, with sensors at 0.00 inches (first), 18.00 (middle) and 60.00 (last) sensors selected in the three options.

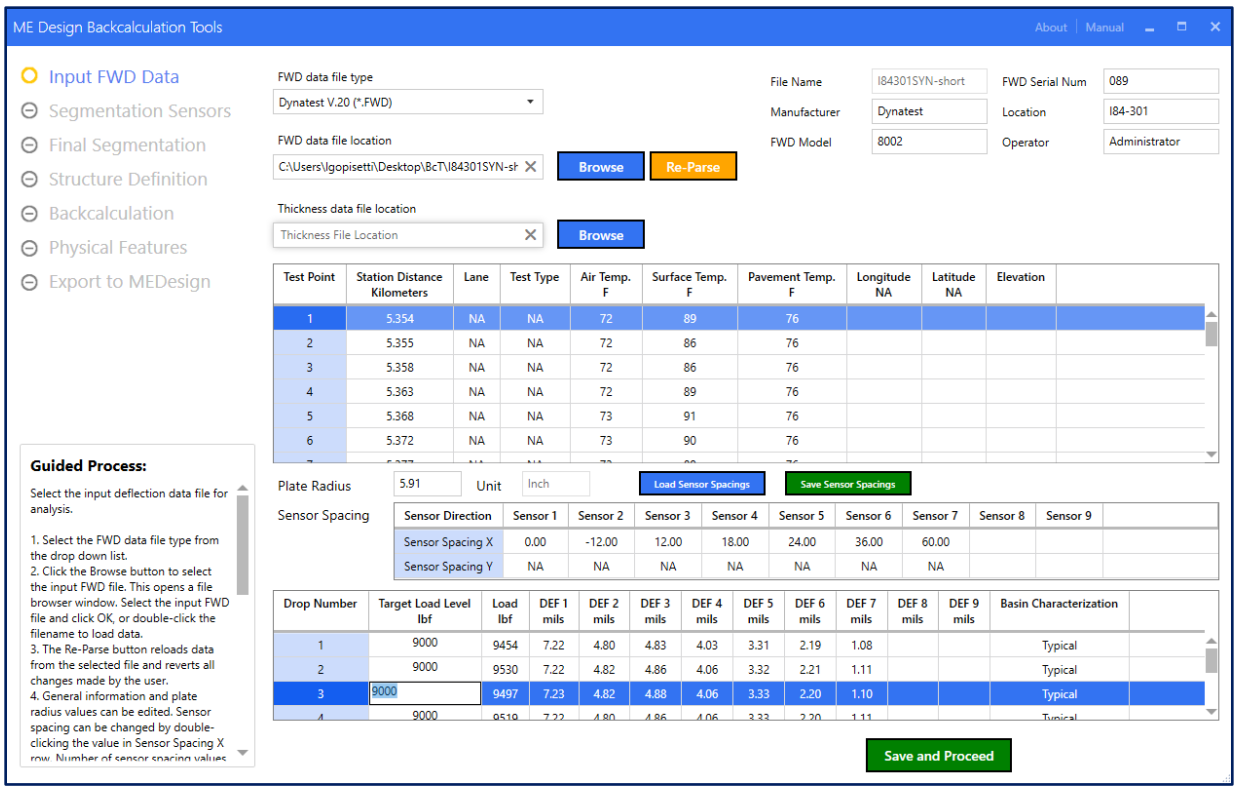


Figure 55 Assigning Target Load Level Values

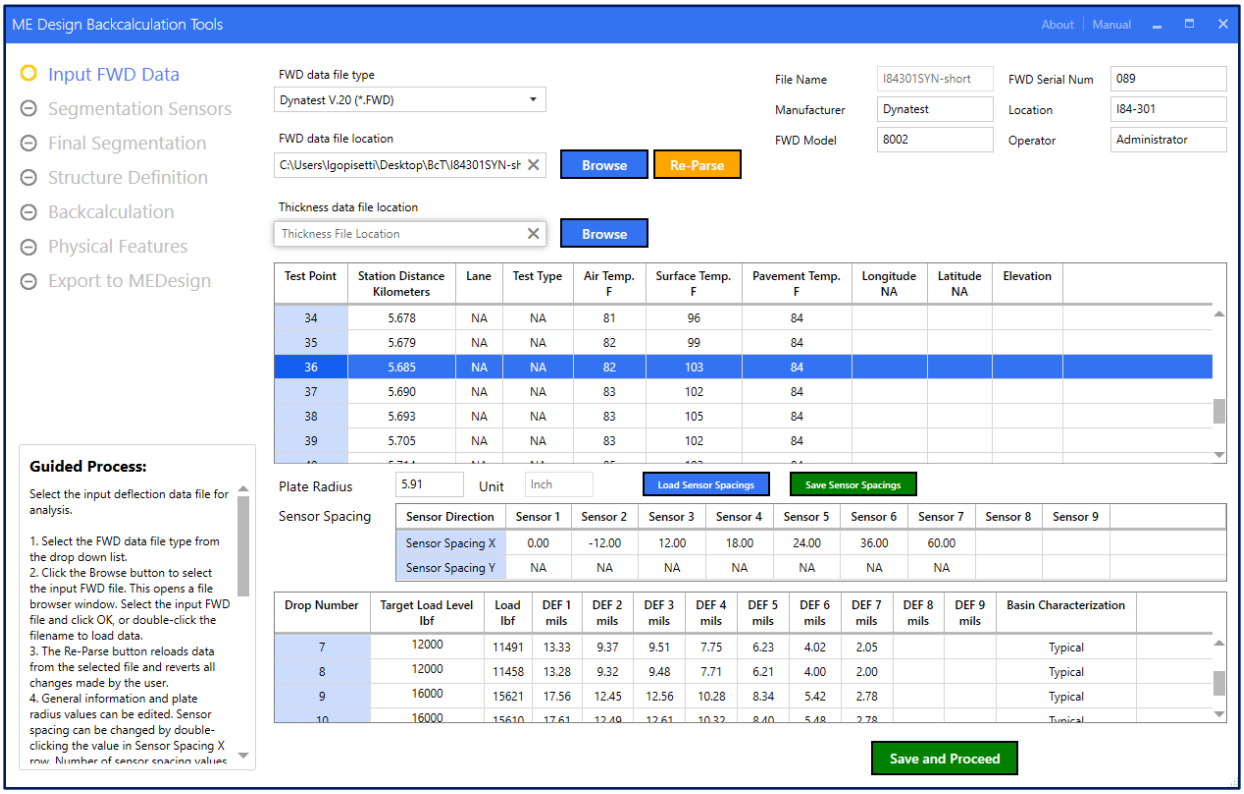


Figure 56 Assigning Target Load Level Values

Figure 57 Segmentation Sensors Default Screen – Selected Sensors

Step 8: Select 0, 12 and 60 inch sensors for segmentation

Users may change the sensors whose deflection data along the length of the pavement section is used to perform automatic segmentation. For the example FWD file, change sensor 2 using the drop-down to the left of the second (middle) chart from 18.00 to 12.00 inches. The chart is updated to display the deflections measured at the 12 inch sensor along the length of the pavement section as shown in **Figure 58**.

Step 9: Drop (Load Level) Filter – View deflections at multiple drops on chart

The default view of the charts displays the deflections measured at the first drop at each station. The Drop filter can be used to view the deflections at multiple drops. The selection is applied simultaneously to all charts, where the deflections at selected drops are displayed for the three sensors as shown in **Figure 59**.

a) Click on the Drop (Load Level) drop down list.
b) Check the boxes corresponding to Drops 1 (already checked), 2, 3 and 4.
c) All three charts are updated to show four line-plots for each of the selected drop numbers.

Figure 58 Segmentation Sensors – Selecting 12-inch Sensor for Segmentation

Figure 59 shows deflections at drops 1, 2, 3 and 4, which have the same target load level. The deflections at the center-load and 12-inch sensors are similar in magnitude, whereas those measured at 60 inches show some variability. **Figure 60** shows deflections at drops 1, 5 and 9, which have target load levels of 9,000 lbs., 12,000 lbs., and 16,000 lbs., respectively. This selection can be used to evaluate the variability of measured deflections at drops having different target load levels.

Selecting different drops using the drop-down list is for the purpose of display only. The user should finally select ***exactly one drop*** to proceed with segmentation.

Step 10: Basin Characterization Types Filter

The Basin Characterization Types filter allows users to toggle points on the chart to display drops that have the selected basin types. The entries in the drop-down list are populated from the basin types identified for all drops in the input FWD file. If the input file contains only Typical and Type II basins, the drop-down list only shows two options – Typical and Type II. **Figure 61** shows the deflection charts for drop number 1 with typical basins only. It is observed that a majority of the drops have typical basins, indicating good data. A large number of Type I or Type III basins in the input file is an indicator of bad quality data.

Backcalculation can be performed using only Typical or Type II deflection basins. Type I and Type III deflection basins should be deselected from the filter options.

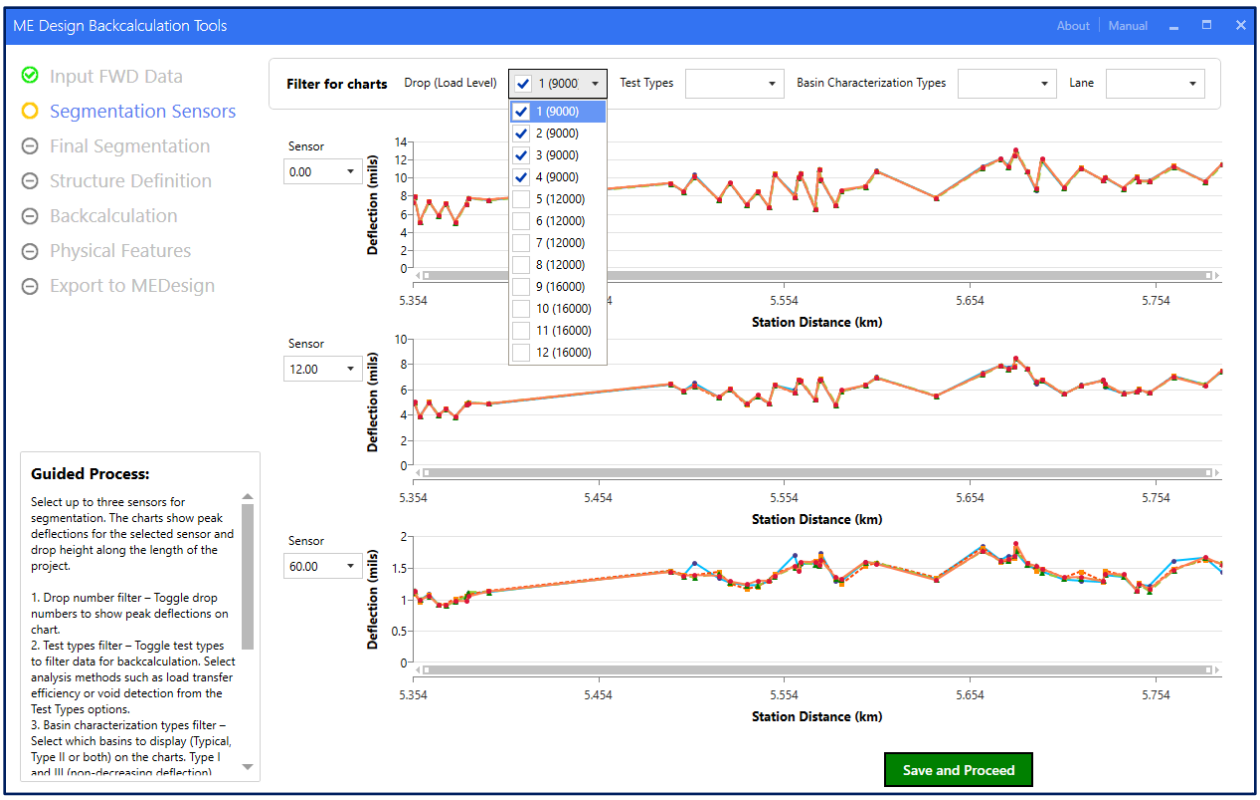


Figure 59 Segmentation Sensors – Deflections at Same Target Load Level Drops

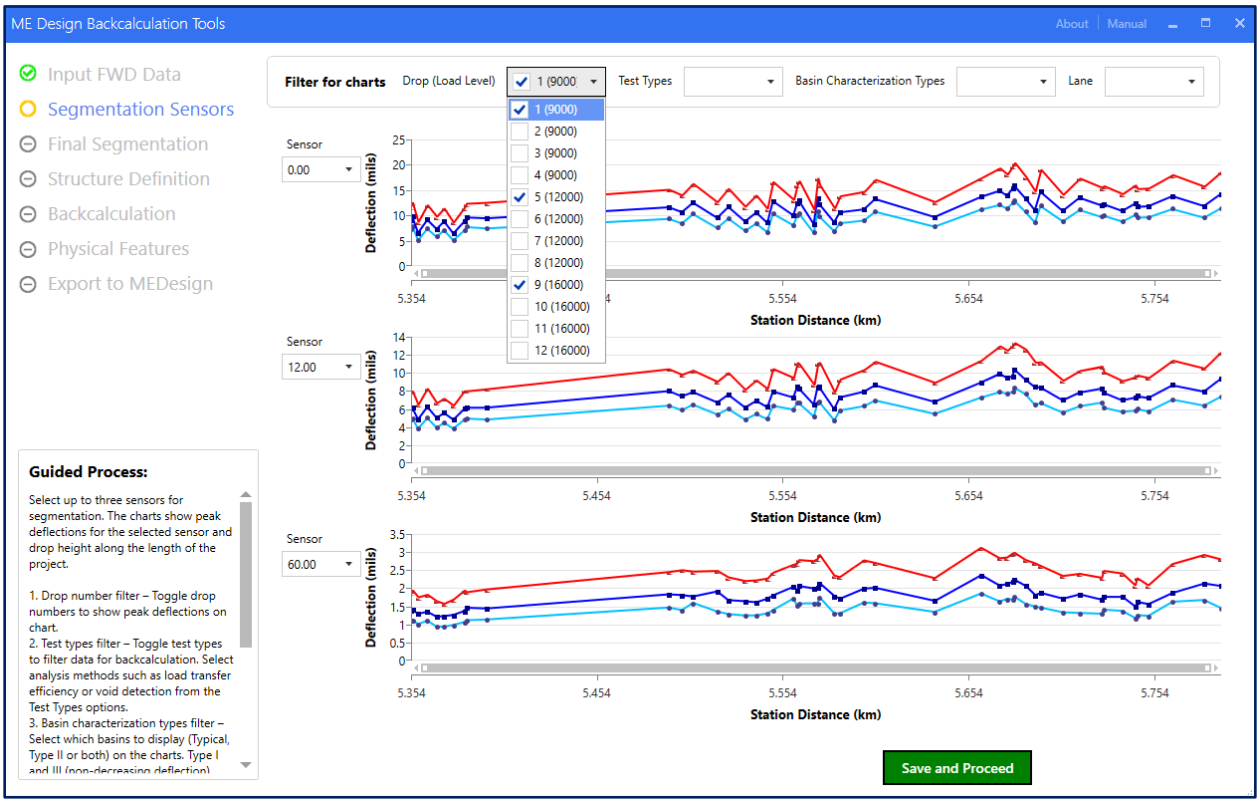


Figure 60 Segmentation Sensors – Deflections at Different Target Load Level Drops

Figure 61 Charts with Typical Deflection Basins Only

Step 11: Test Type and Lane filters

The selected input file does not have any test type and lane information associated with the stations. The drop-down options for the two filters therefore do not contain any entries. If the input file contains deflection data at multiple test locations (test types) or lane positions, the filters can be used to select data to be used in backcalculation.

Select Drop 1 and both basin types and click on Save and Proceed to continue with Preliminary Segmentation.

Step 12: Preliminary Segmentation

Results of preliminary segmentation are displayed on the Preliminary Segmentation screen. This is a view-only module and does not require any user inputs. Segments are calculated using deflection data at each of the three sensors and the segment locations are displayed using gray, dashed vertical lines on all three charts as shown in **Figure 62**.

From the charts shown in **Figure 62**, the cumulative area difference method results in four segments using deflection data at Sensor 0.00 (center-load sensor), five segments using deflection data at Sensor 12.00 (12-inch sensor) and five segments using deflection data at Sensor 60.00 (last sensor).

Figure 62 Preliminary Segmentation Results

Step 13: Statistical comparison of preliminary segments

The segments calculated during preliminary segmentation are compared for statistical equality of mean deflections. Adjacent segments which have statistically similar means are merged into a single segment as described in the **Statistical Comparison** section of the manual. **Figure 63** shows the results of statistical comparison.

The chart for center-load sensor in **Figure 63** shows two segments. The first segment is a combination of the first two segments in **Figure 62**, while the second segment is a combination of the latter two segments shown in **Figure 62**.

Figure 63 Statistical Comparison Results

Step 14: Final segmentation

Final segmentation screen displays the results of statistical comparison, which can be used as guidance to select final segments for the pavement section. To create a new segment, click on any one of the three charts between two stations. A red, dashed line is added to all three charts at the click location, denoting the creation of a segment. The starting and ending stations of the two segments are shown in the table to the right of the charts. **Figure 64** shows four segments added by clicking at three locations on different charts – first gray dashed line on Chart 2 (Sensor 12.00), only gray dashed line on Chart 1 (Sensor 0.00) and third gray dashed line on Chart 3 (Sensor 60.00). The solid gray line on all three charts in **Figure 64** indicates the location of the cursor.

Users may use statistical comparison results as guidance to determine final segments or select segments independently. Since the flexible pavement in this example has a uniform layer structure throughout the length of the section, the entire section is treated as a single segment. Click the Reset button to remove the segment markings created in the previous step and revert to a single segment as shown in **Figure 65**. Click on Save and Proceed to define the pavement layer structure, layer properties and backcalculation inputs.

Figure 64 Final Segments – Dividing Pavement Section into Four Segments

Figure 65 Final Segments – Entire Section as Single Segment

Step 15: Pavement layer structure definition

The pavement layer structure, layer properties and backcalculation inputs are entered on the Structure Definition screen. The individual steps to be taken on this screen for the current example are as follows:

a) Click on the deflection chart. Since there is only segment, the structure and other inputs are assigned to the selected segment. The selected segment is highlighted in orange.
b) Click on the Number of Layers drop-down list to select the number of layers in the pavement structure. Select the number of layers as 3 from the list.
c) Three rows are added to the screen where the layer type and properties can be entered.
d) Click on the drop-down box to the right of Layer 1. A list of various pavement layer types are shown as shown in **Figure 66**. Select AC (AC) for Layer 1.
e) Select Granular Base (Typical) as the material type for Layer 2 and Subgrade (Fine-Grained) for Layer 3.
f) The default thickness of each layer is set to zero inches. Change the thickness of AC layer (Layer 1) to 10 inches and base layer to 9 inches (Layer 2). The thickness of the last layer (subgrade) is fixed at 0 inches, which denotes the last layer as semi-infinite. Use the default values of Poisson's ratio and seed moduli for the initial backcalculation trial. The final screen with the layer types, thickness and other inputs are shown in **Figure 67**.

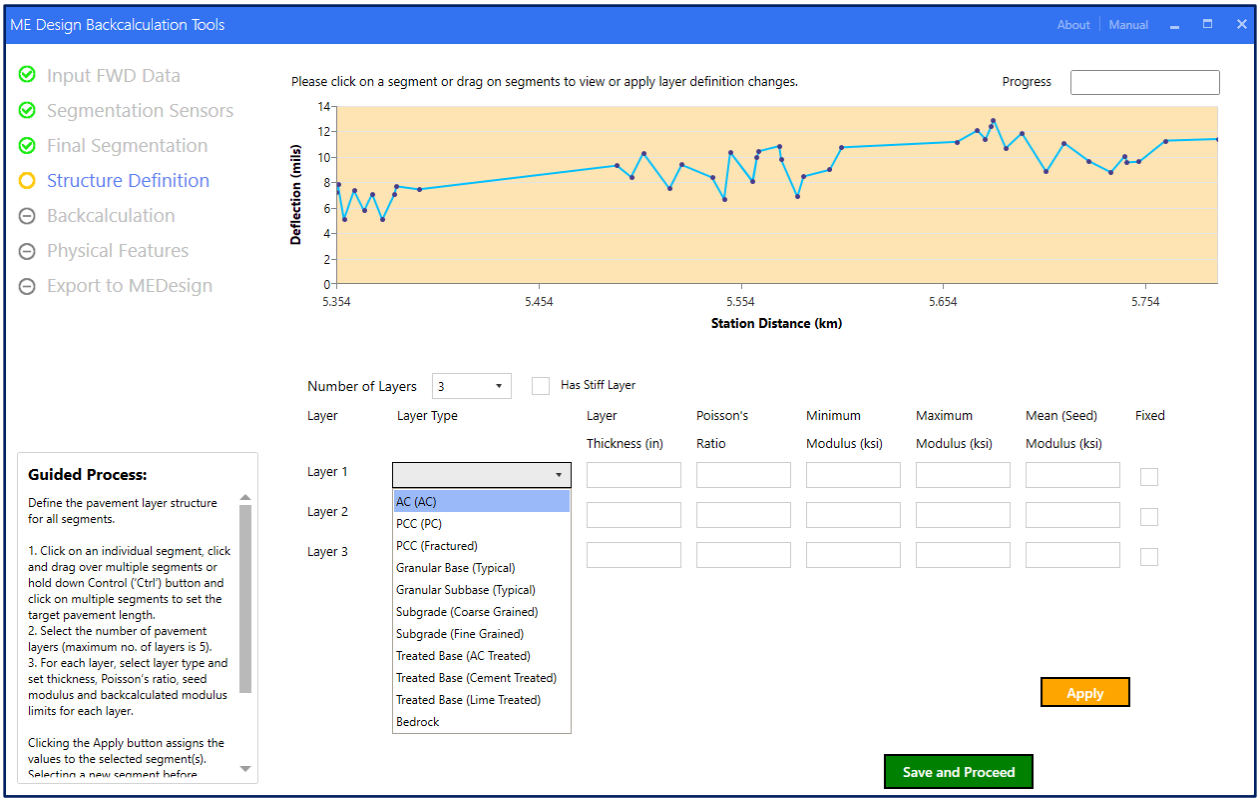


Figure 66 Structure Definition – Selecting Layer Type for Layer 1

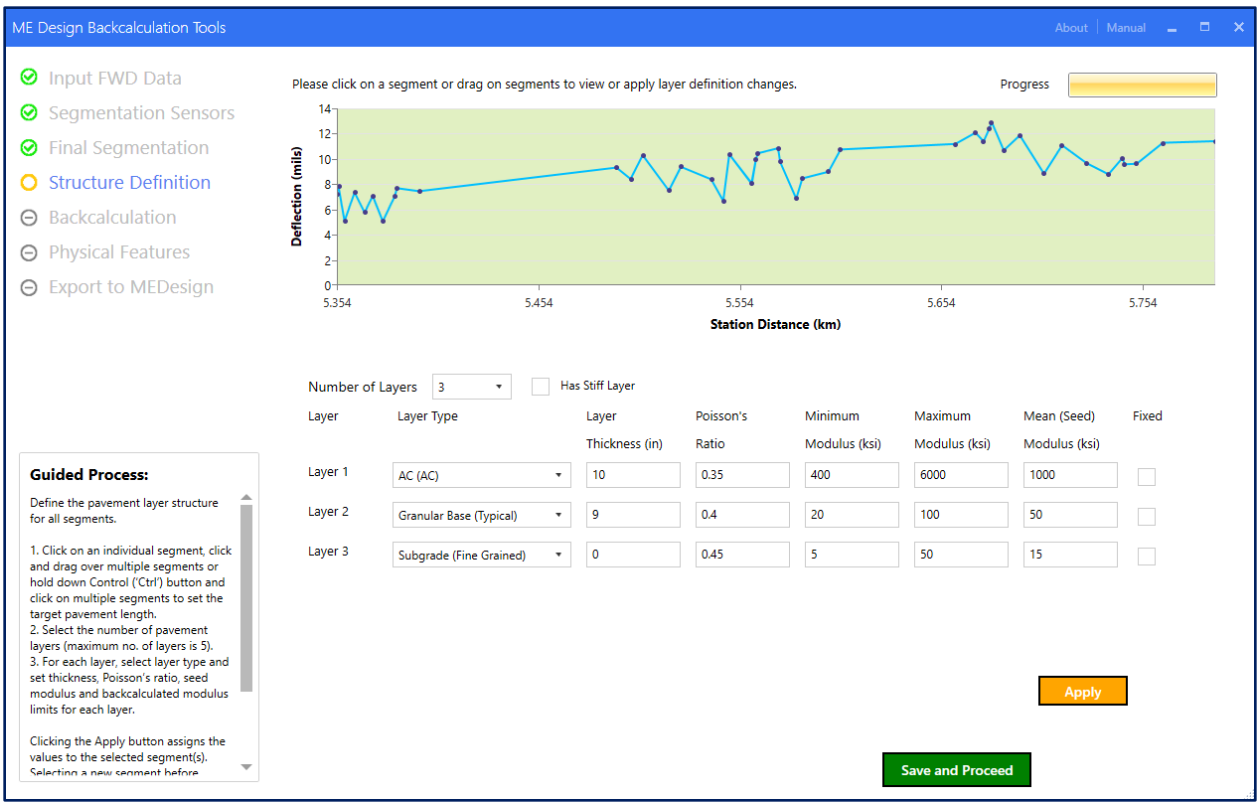


Figure 67 Structure Definition and Backcalculation Inputs

Click the Apply button to assign the layer structure to the selected segment. Segments for which inputs have been entered and applied are highlighted in green. The progress bar at the top right corner of the screen is filled completely when the inputs for all segments are entered. If the section is divided into multiple segments, the layer structure and inputs should be entered and applied for each segment individually.

Click on Save and Proceed to continue with the backcalculation process.

Step 16: Running the backcalculation program

The default screen of the Backcalculation module shows a list of all sensors in the input FWD file. Backcalculation is performed using deflection data at only the center-load and leading sensors, hence trailing sensors should be de-selected from the list by the user manually. Click on the option corresponding to the -12-inch sensor to deselect it as shown in **Figure 68**.

Click the Backcalculate button located below the sensor list table to run backcalculation. The tool displays an error message if the trailing sensor is not deselected prior to running backcalculation.

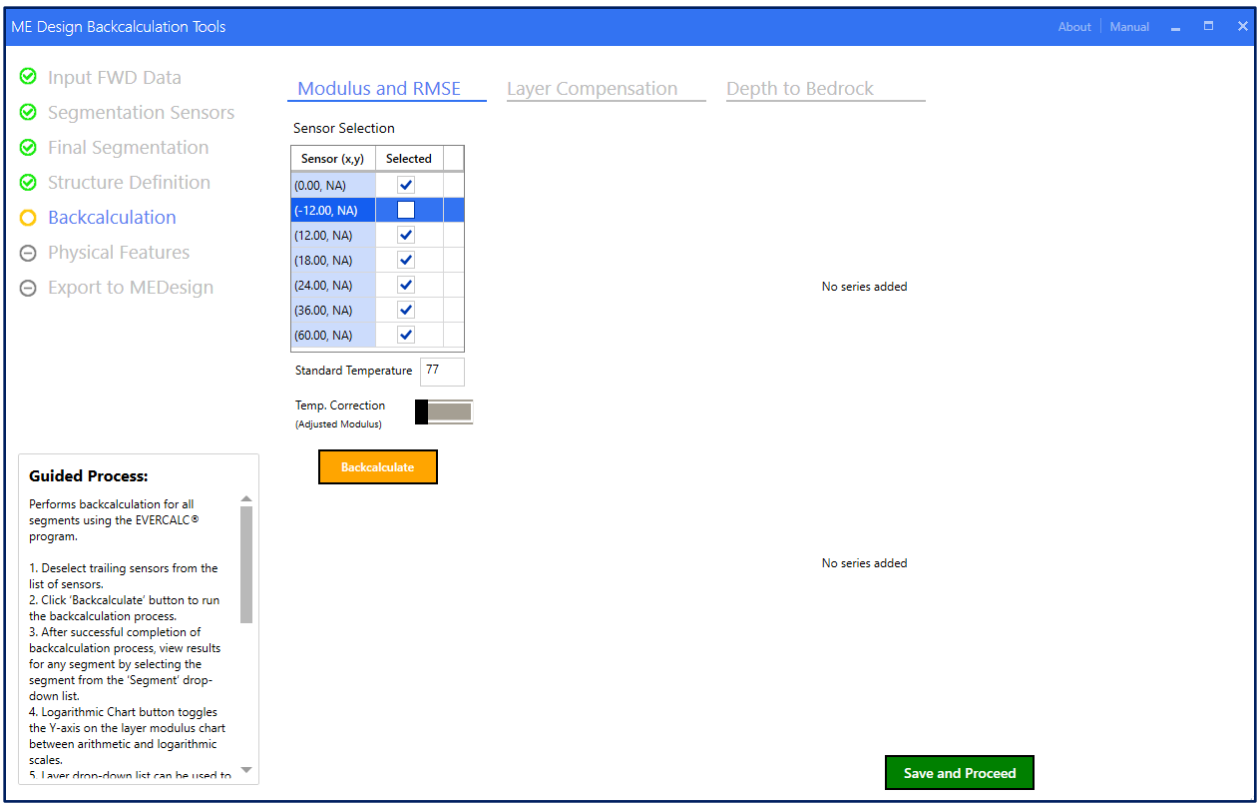


Figure 68 Backcalculation – Deselecting Trailing Sensor

Step 17: Review backcalculation results

The backcalculation results for each segment are displayed on two charts on the module screen. The first chart (top) shows the average backcalculated modulus and second chart (bottom) shows the average RMSE of all drops at the stations in the selected segment. Since the pavement section in the example contains only one segment, select the segment from the Segment drop-down list.

a) Click on the Segment drop-down list to select the only segment. If the pavement is divided into multiple segments, results for each segment can be viewed by selecting individual segments from the drop-down list.
b) The average backcalculated modulus for all drops at each station is shown for the three layers as shown in **Figure 69**. The average RMSE is also shown in the bottom chart. The legend for the layers is shown in the right corner on the top chart.
c) Toggle the Logarithmic Scale button on the top of the screen to convert the Y-axis of the top chart to a logarithmic scale. This allows the user to better view the backcalculated moduli on the chart. The logarithmic chart is shown in **Figure 70**.
d) To view results for individual layers, the layers can be toggled on or off using the Layer drop-down menu. The backcalculated subgrade modulus is displayed on the chart by unchecking AC and base layers from the list as shown in **Figure 71**.

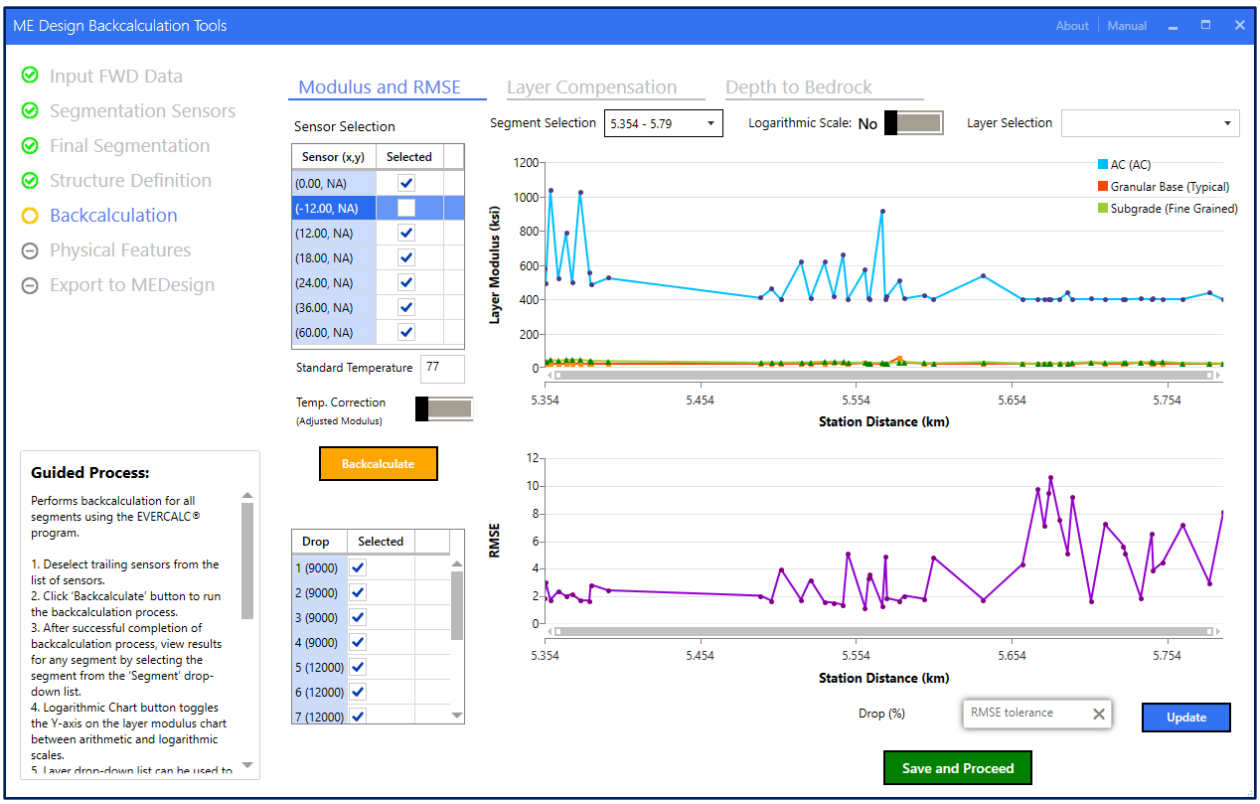


Figure 69 Backcalculation Results for Segment 1

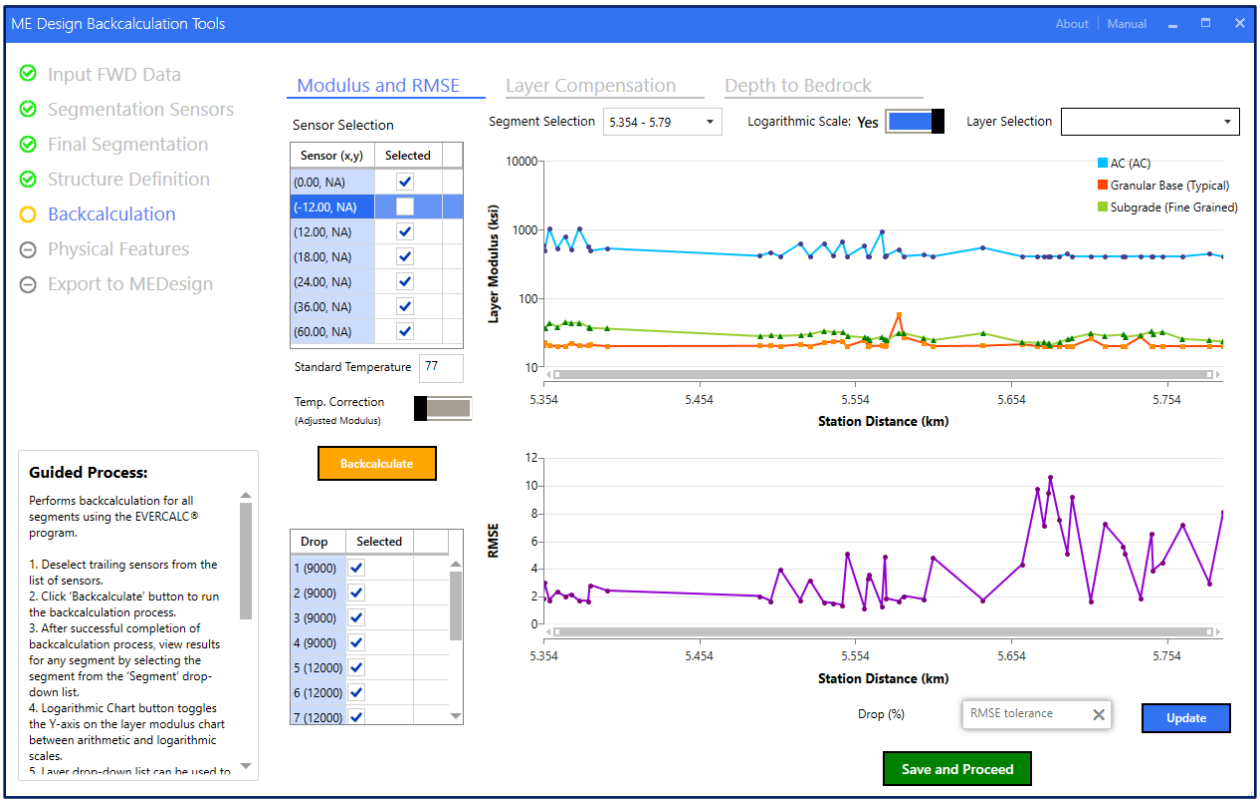


Figure 70 Backcalculation Results – Backcalculation Modulus in Log Scale

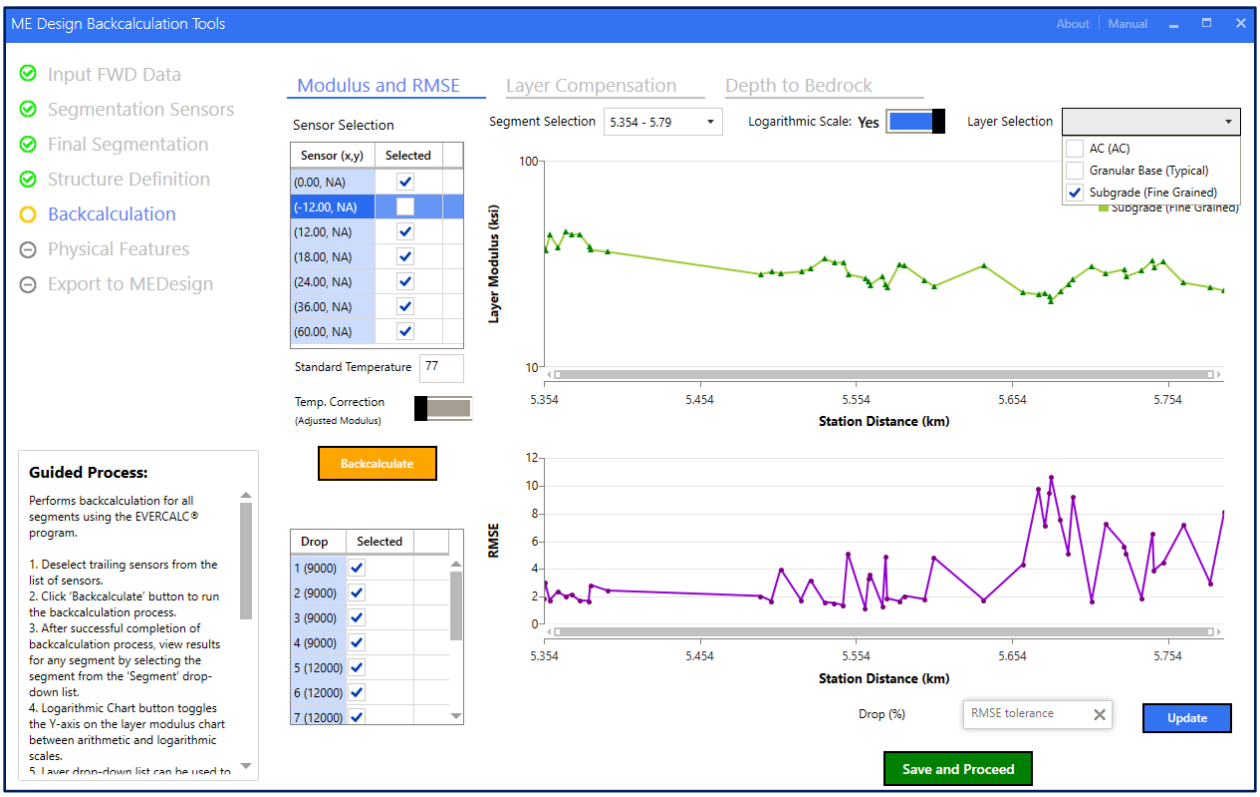


Figure 71 Backcalculated Layer Modulus Chart for Subgrade Layer

e) Since the pavement consists of two unbound layers (granular base and subgrade), the moduli of the two layers plotted against each other can be used to identify the presence of a compensating error effect. Click on the Show button next to Layer Compensating Error to view the plot. The chart for layer compensating error is as shown in **Figure 72**.

The plot of subgrade modulus versus base modulus does not show any discernible trend, which does not support the presence of compensating errors. Click the Close button on the chart window to close it and return to the backcalculation screen.

f) The backcalculated modulus and RMSE charts show the average of all drops at a station, as shown in the drop selection checklist on the left of the screen. Drops can be unchecked to remove them from the average modulus and RMSE calculation. The average backcalculated modulus and RMSE for drops at the 9,000 lb. load level only is displayed when drops 5 through 12 are unchecked, as shown in **Figure 73**.

The RMSE chart shows higher errors for a majority of the stations, as observed from comparison of the charts on **Figure 69** and **Figure 73**.

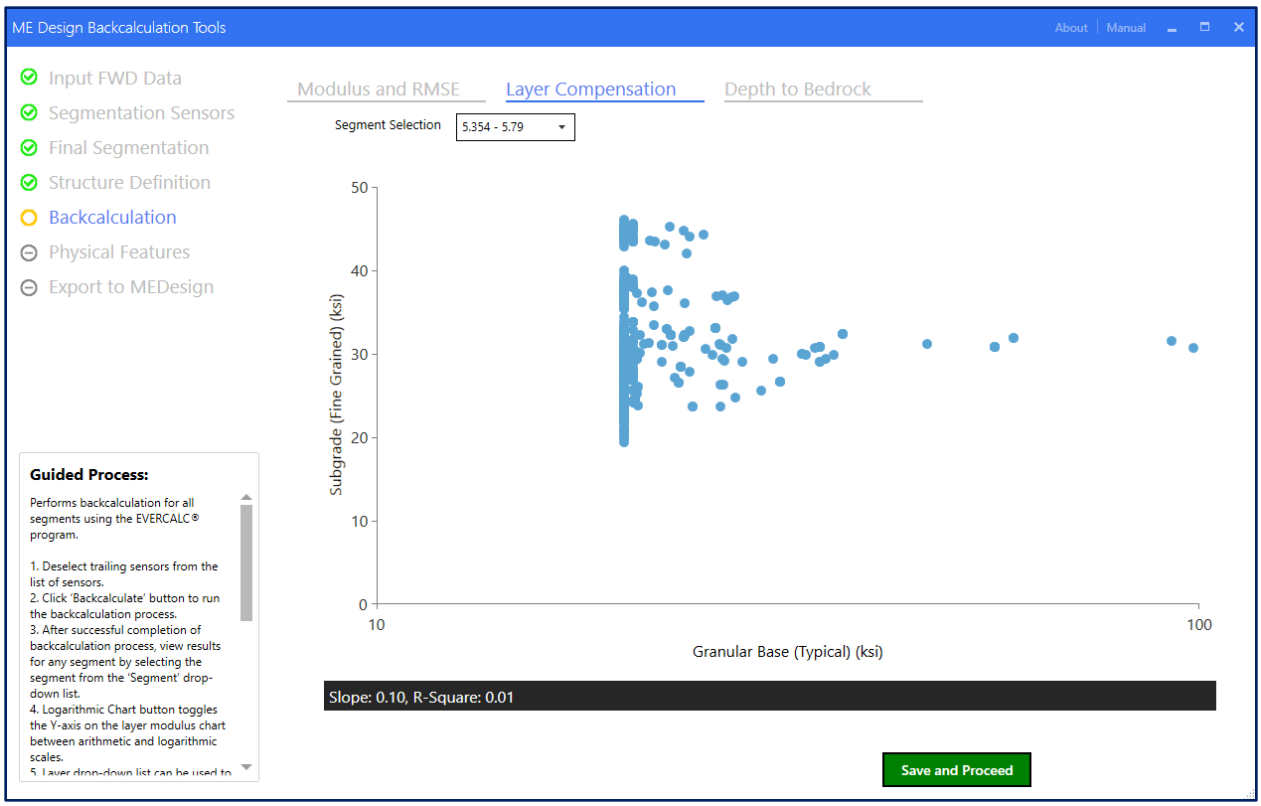


Figure 72 Chart for Layer Compensating Error Effect

Figure 73 Average Backcalculated Moduli and RMSE for 9,000 lb. Load Level Drops

g) Drop tolerance value (range 0 to 100) can be entered by the user to remove individual drops whose RMSE is greater than the tolerance from the average. Drops whose RMSE is greater than the tolerance are removed from average backcalculated modulus and RMSE calculation. Enter a value of 5 in the RMSE Tolerance box and click Update, which recalculates the chart data as shown in **Figure 74**.

h) The RMSE chart in **Figure 69** shows high errors (greater than 5 percent) for the second half of the segment. It is recommended in such cases to make adjustments to the pavement layer structure such as dividing the AC layer into two separate layers, adding a weathered subgrade layer on top of the natural subgrade or introducing a rigid layer below the subgrade to reduce backcalculation error.

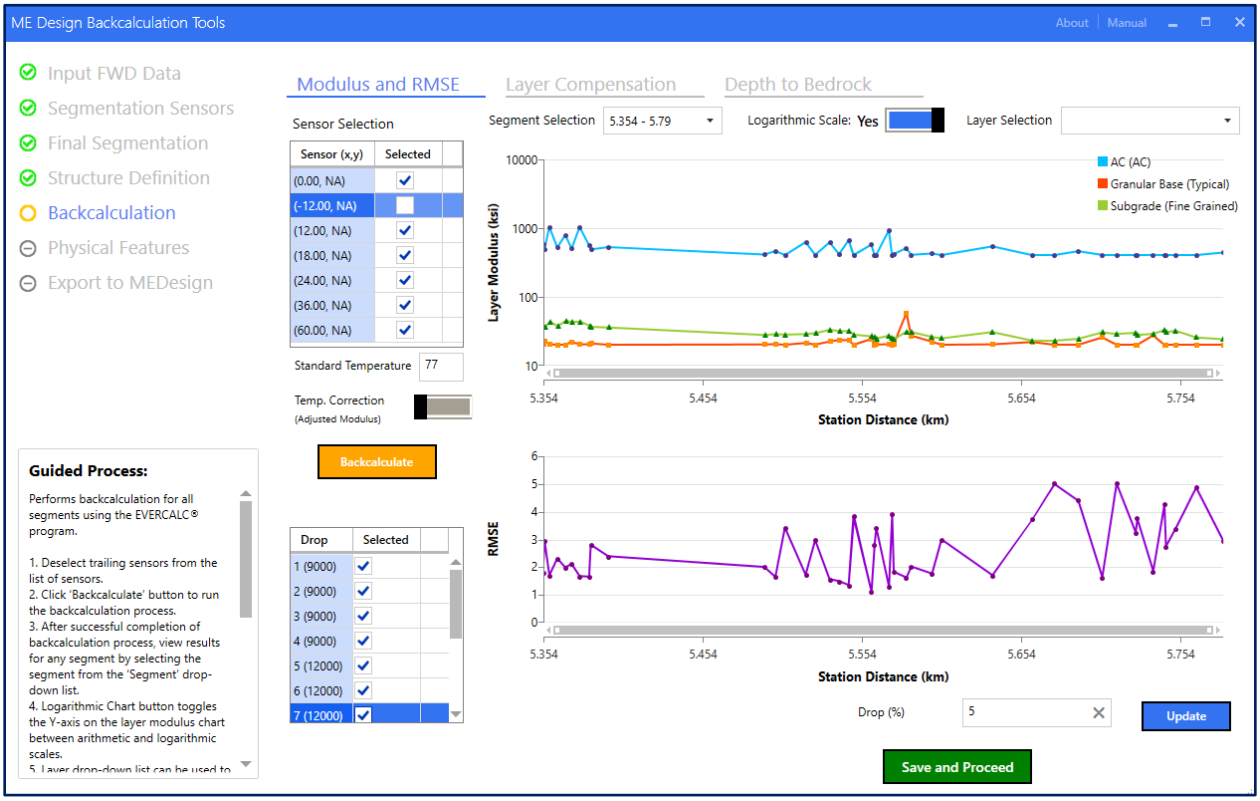


Figure 74 Average Backcalculated Moduli and RMSE with Drop Tolerance of 5 Percent

Step 18: Modify structure definition and re-run backcalculation

Navigate to the Structure Definition module by clicking on the option in the list of program tabs.

a) Select the segment by clicking on the chart and change the number of layers to 4.
b) Set the layer type for layers 1 and 2 to AC each having a thickness of 5 inches.
c) Select layer 3 as granular base (typical) having a thickness of 9 inches and layer 4 as subgrade (fine-grained).
d) Change minimum modulus for the AC layers to 100 ksi, base and subgrade layers to 1 ksi.
e) Click on the Apply button to save the entered values.

The modified structure definition is as shown in **Figure 75**.

Re-run the backcalculation procedure and review backcalculation results as described in Steps 16 and 17.

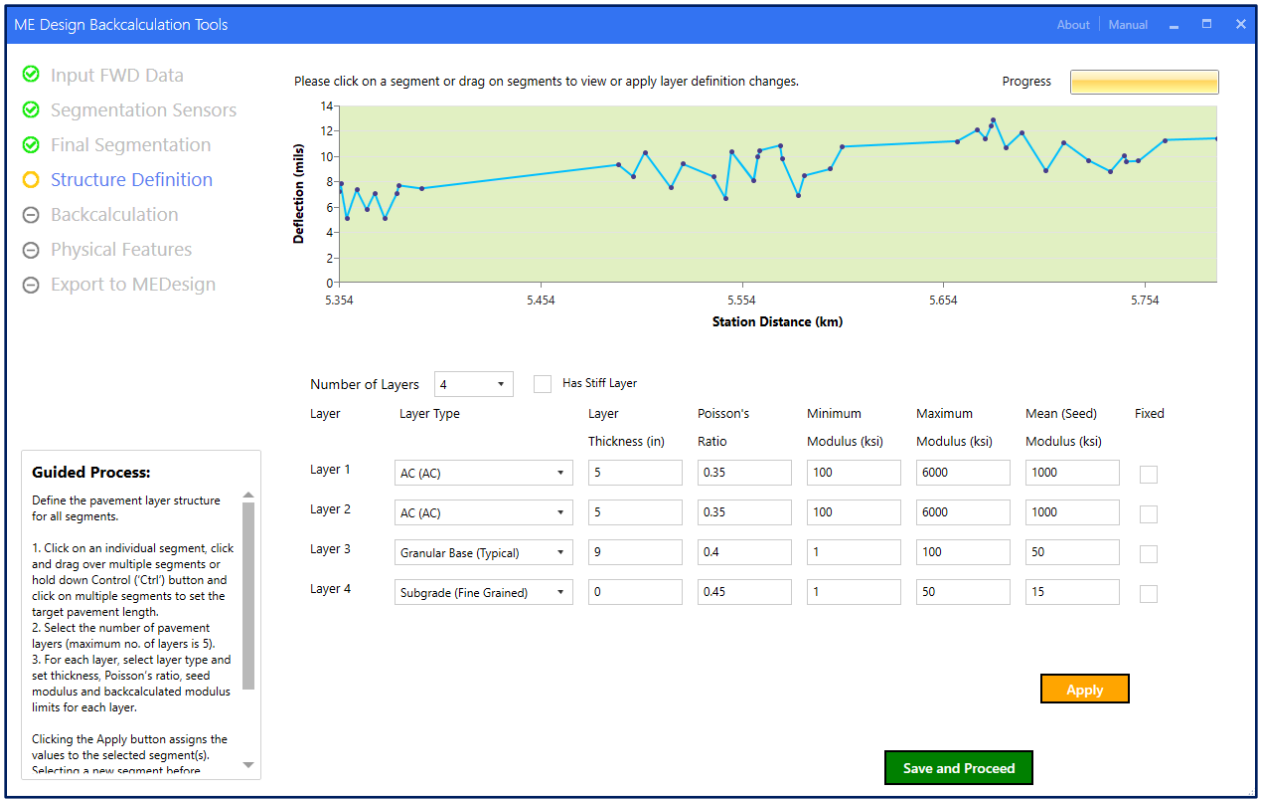


Figure 75 Modified Structure Definition – Four-Layered Pavement Structure

The backcalculated moduli and RMSE charts for the four-layered pavement structure are shown in **Figure 76**. The average RMSE as shown on the chart in **Figure 76** is much lower (less than 3 percent at all stations) than that for the three-layered structure. The RMSE should be acceptable to the user to consider the backcalculation process as complete.

Click on Save and Proceed to navigate to the Physical Features screen.

Step 19: LTE calculation and view loss of support analysis results

The Physical Features screen displays results of LTE calculation and loss of support analysis. Results are displayed on this screen only for input files whose data satisfies the requirements as described in the **Physical Features** section of the manual. The data used in this example satisfied both the criteria:

a) Deflections should be measured at a trailing sensor (-12 inch sensor)
b) Deflections should be measured at least at two different load levels – the deflection data contains drops at three different load levels.

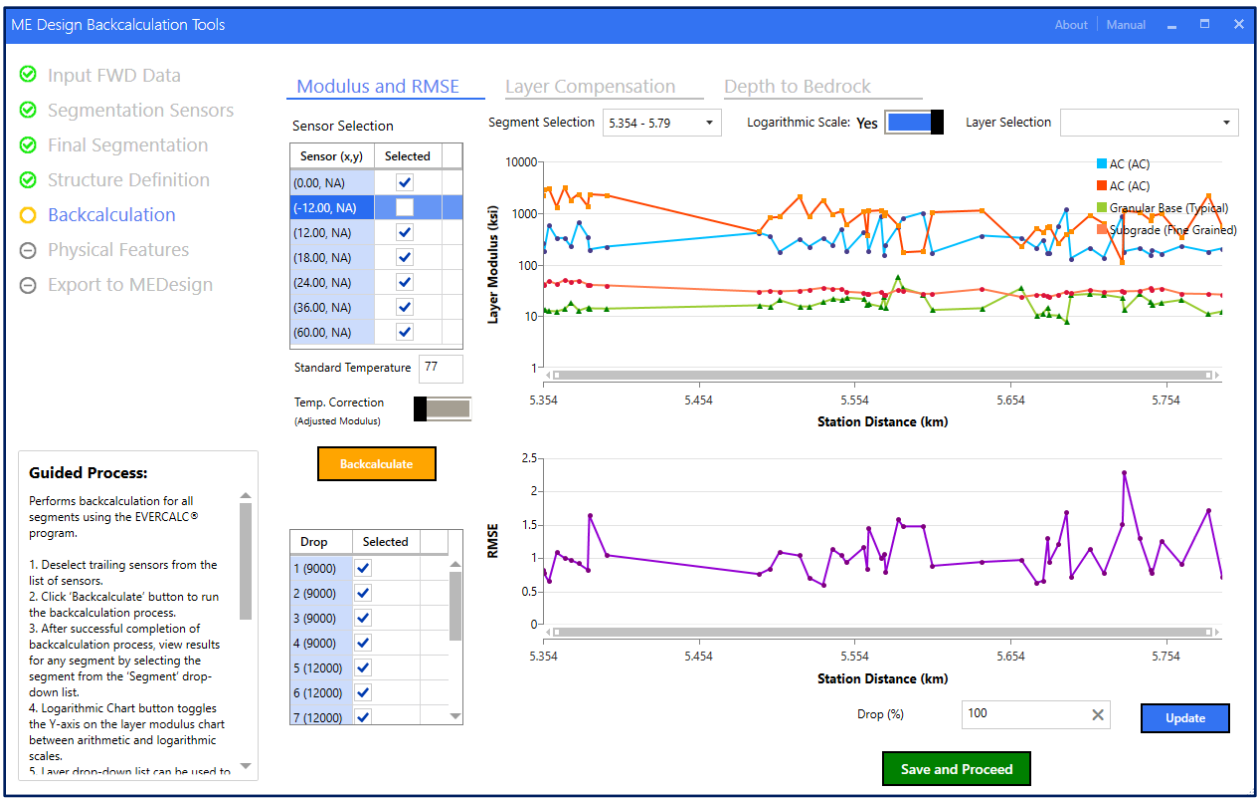


Figure 76 Backcalculation Results for Four-Layered Structure

Select -12 inches as the numerator sensor and 0 inches as the denominator sensor using the drop-down menus. The LTE and load-deflection curve intercepts for void detection are displayed in the charts as shown in **Figure 77**.

The average LTE for all drops at the stations in the segment varies between 60 and 80 percent. The load-deflection intercept exceeds 2 mils at the end of the segment, indicating loss of support.

Step 20: View backcalculation results summary

The Export to ME Design screen displays a summary of backcalculation results for each segment. Click on the segment name in the Segment box to view a summary of results for that segment. The backcalculation results summary for the selected segment is shown in **Figure 78**.

The average backcalculated moduli for the pavement layers are:
Layer 1 (AC) = 335.8 ksi
Layer 2 (AC) = 752.8 ksi
Layer 3 (Granular base) = 18.2 ksi
Layer 4 (Subgrade) = 31.2 ksi

The moduli exhibit a high coefficient of variation, i.e., variability of the individual station moduli as compared to the mean value.

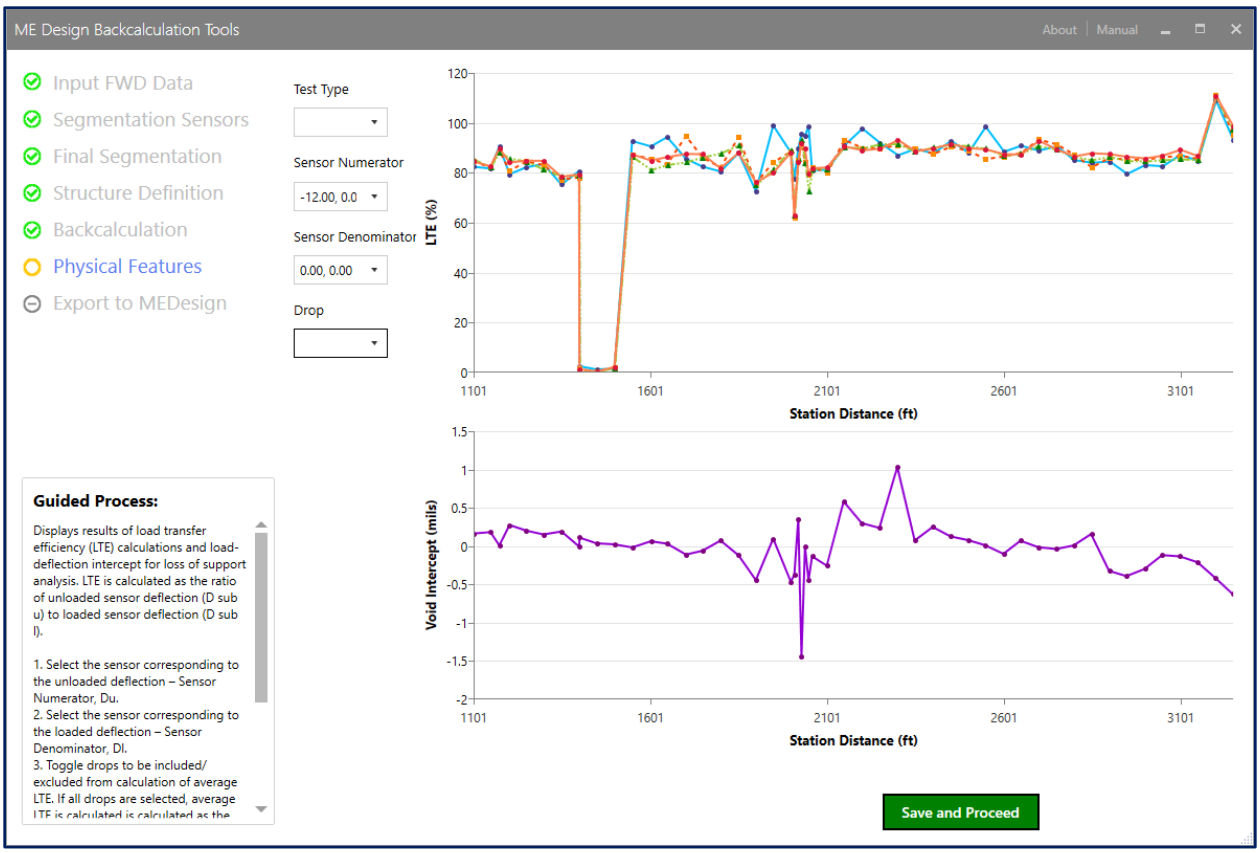


Figure 77 Physical Features Results

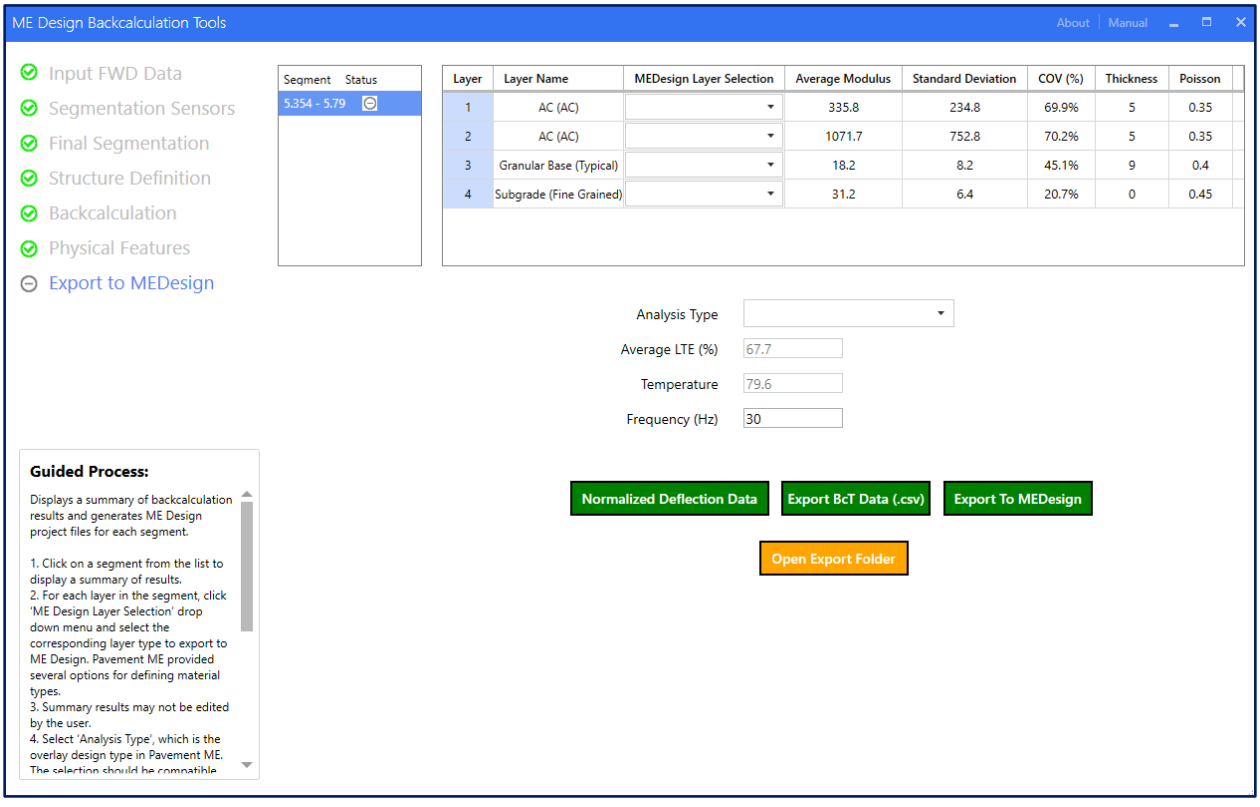


Figure 78 Backcalculation Results Summary for Selected Segment

Step 21: Export to ME Design file options and generating DGPX files

The user inputs required on this screen are the ME Design layer types for all layers in the pavement structure, analysis (rehabilitation design) type and FWD loading frequency.

a) Select the analysis type as AC over AC. This will generate an ME Design input (.DGPX) file with a design type of AC overlay of an existing flexible pavement.
b) Using the ME Design Layer Selection drop-down menus, select default asphalt concrete as the material type for both AC layers.
c) Select crushed stone as the material type for the base layer and A-4 as the material type for subgrade.
d) Use the default value of 30 Hz for FWD loading frequency.

The selected options on the Export to ME Design screen are shown in **Figure 79**. Click on the Export to ME Design button to generate the ME Design input (.DGPX) files. If the pavement section is divided into multiple segments, the tool creates a separate DGPX file for each segment. Users can also vary the analysis type for different segments.

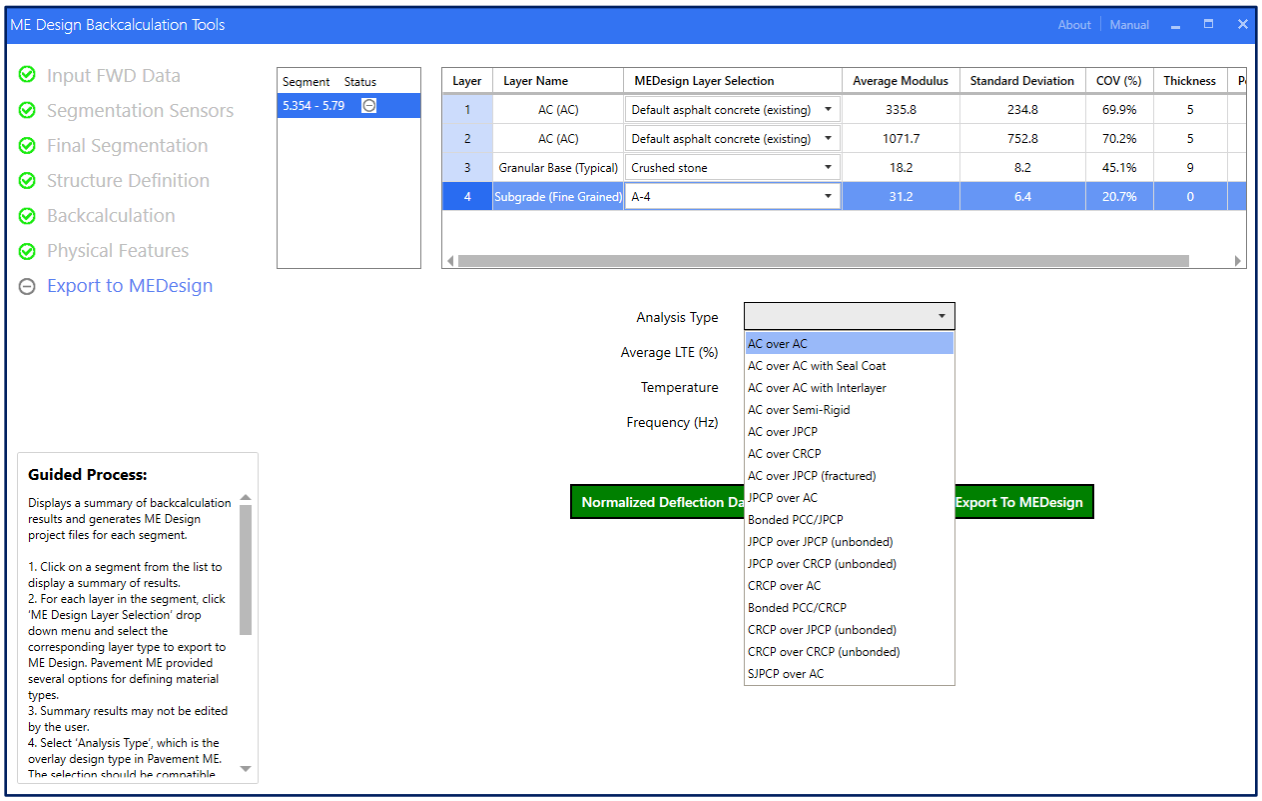


Figure 79 Selection of Export to ME Design Options

Figure 80 shows the setup of the generated ME Design project file for AC overlay design. The layer structure in the ME Design file consists of an AC overlay on top of the existing pavement structure. Backcalculated modulus of the AC layer is also shown in **Figure 80**, with the NDT

modulus equal to 335,800 psi. The backcalculated moduli are assigned to resilient modulus of base and subgrade layers.

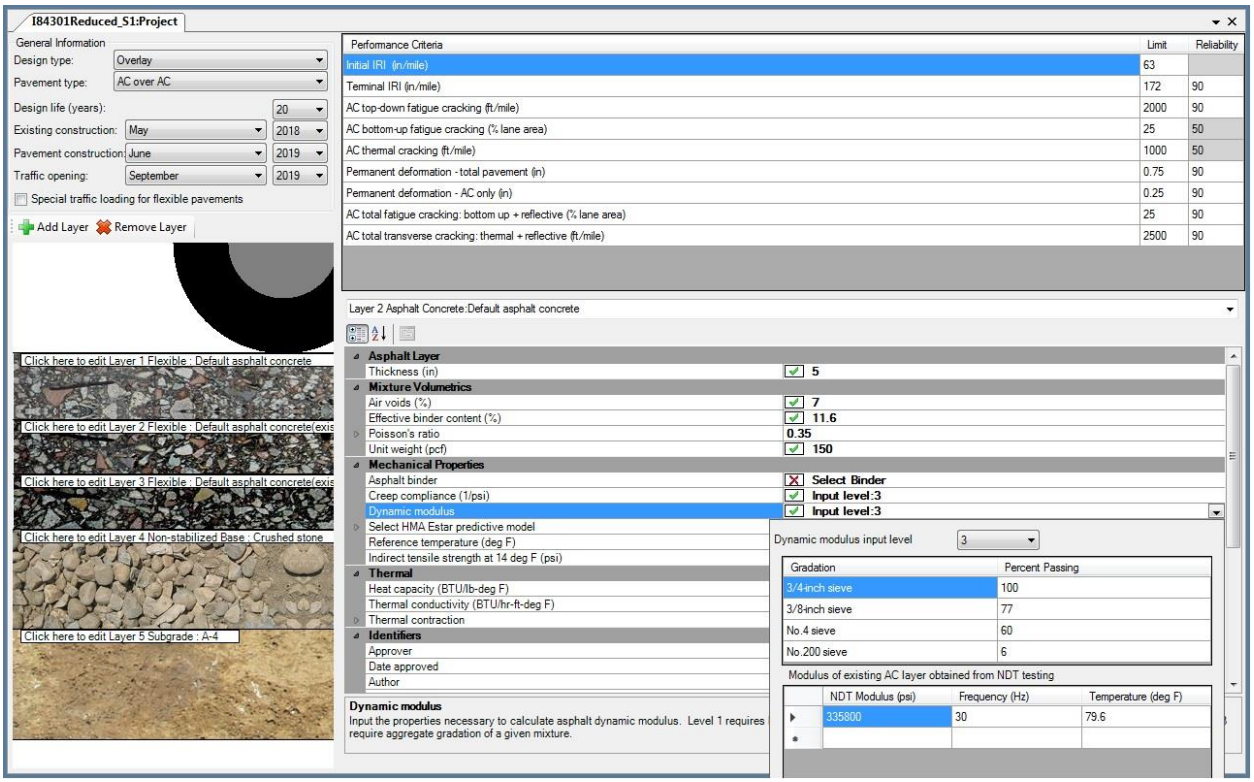


Figure 80 Pavement ME Design File for AC Overlay Design

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2. AASHTO. *Mechanistic-Empirical Pavement Design Guide – A Manual of Practice*, Interim Edition, Publication Code MEPDG-1, American Association of State and Highway Transportation Officials, Washington, DC, July 2008.
3. FHWA, *LTPP Guide to Asphalt Temperature Prediction and Correction*, Publication Number FHWA-RD-98-085, Federal Highway Administration, McLean, VA, 1998.
4. Von Quintus, H.L. and Killingsworth, B. *Design Pamphlet for the Backcalculation of Pavement Layer Moduli in Support of the 1993 AASHTO Guide for the Design of Pavement* Structures, Final Report FHWA-RD-97-076, Washington D.C., September 1997.
5. Von Quintus, H.L. and A.L. Simpson, *Back-Calculation of Layer Parameters for LTPP Test Sections, Volume II: Layered Elastic Analysis for Flexible and Rigid Pavements, LTPP DATS*, Report No. FHWA-RD-01-0113, Federal Highway Administration, McLean, VA, December 2001.
6. Washington State Department of Transportation. *Everseries User's Guide – Pavement Analysis Computer Software and Case Studies*, Washington DOT, August 2005.
7. Federal Highway Administration. "LTPP InfoPave™", FHWA, Washington, D.C. Website: https://infopave.fhwa.dot.gov/Data/StandardDataRelease/, Accessed June 1, 2017.