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NCHRP 10-48

ASSESSING PAVEMENT LAYER CONDITION USING DEFLECTION DATA

APPENDIX F

A Program Guide to APLCAP

(Asphalt Pavement Layer Condition Assessment Program)

Prepared for
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INTRODUCTION

This appendix provides an overview of the computer program that implements the condition evaluation procedures described in the main text of NCHRP 10-48 final report. The prototype implementation of this software package, called APLCAP—Asphalt Pavement Layer Condition Assessment Program, embeds the primary procedures summarized in Chapter 3 of the final report. A copy of the appropriate section on "Pavement Layer Condition Evaluation Procedures" is included at the end of this appendix. The primary function of these procedures in APLCAP is to assess the asphalt pavement layer condition using Falling Weight Deflectometer (FWD) measurements.

The prototype is implemented using MS Visual Basic (6.0) for MS Windows-based computing platforms. It is styled and structured similar to typical Windows-based applications. The compiled version of the executable binary file is designed to run as a stand-alone program on computers running MS Windows, and does not require the use of any proprietary software packages.

APLCAP should be viewed as a functional *prototype* of a software package that represents the key functions and features. Although some debugging, validation, and testing have been performed, like typical prototypes, it has not been subjected to rigorous QA/QC that is required of commercial quality software packages. Similarly, some help utilities to guide a user are provided, but could be improved in commercial distribution versions.

The following sections describe briefly the major components of APLCAP.

APLCAP OVERALL STRUCTURE

The program is implemented such that the user could access all the components of APLCAP via a set of menu options. The main menu items include: *File Menu, Analysis Menu, Results Display Menu,* and *Help Menu.* Each of these menu items is described below.

File Menu

This menu item includes the following options: *New File, Open File, Convert FWD File,* and *Exit.*

New File

This option allows the user to create a new condition assessment scenario by inputting new FWD data. Upon invoking this menu option, a Pavement Specification input interface (Figure F-1) is displayed, via which the user will input the following set of information.

Title – a unique name to identify the specific scenario.

Number of Test Locations – the number of locations at which the FWD data to be analyzed.

Pavement Type – select one of: Aggregate Base, Full Depth, and AC/Fractured PCC (PCC and CTB will be included later).

Climate Zone – specify one of the standard regions (Wet-Freeze, Wet-No Freeze, Dry-Freeze, Dry-No Freeze). The corresponding values for the temperature correction constants a and *b* are assigned, and displayed in this interface.

Average Temperature One Day Before Test – the average (based on low and high) temperature on day of testing. (This value is used as the default value corresponding to each location, and could be modified later.)

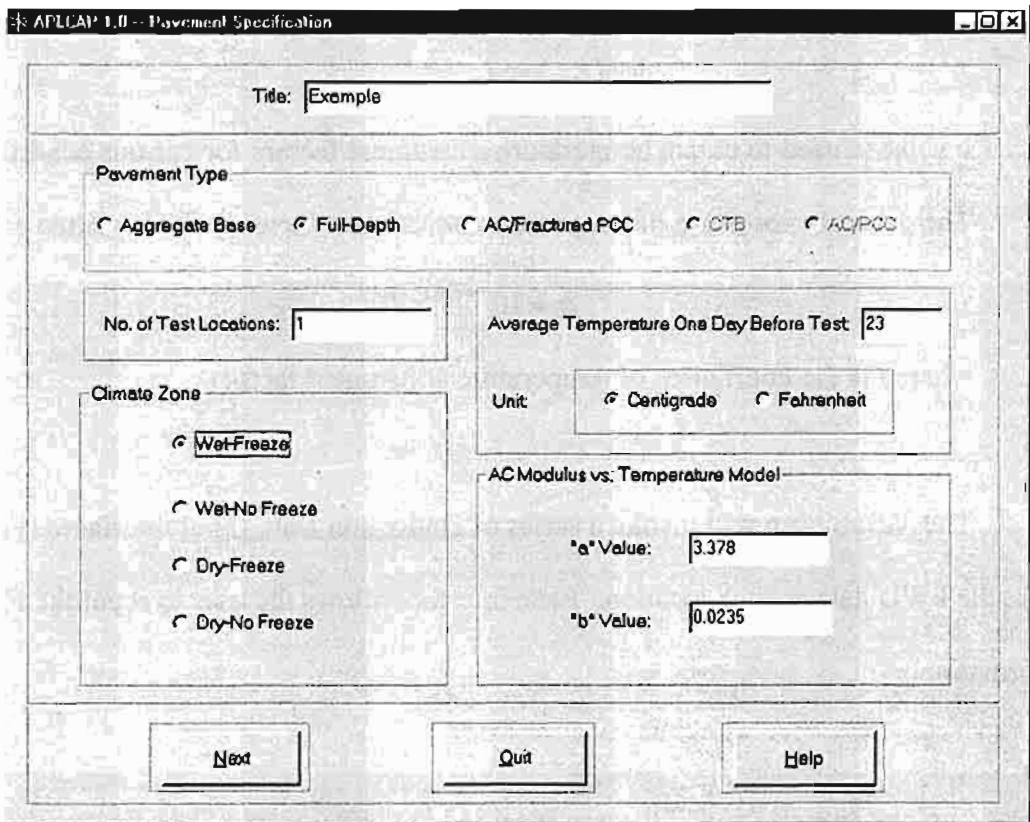


Figure F-1. Pavement Specification interface

AC Modulus vs. Temperature Model Constants - Default values for the temperature correction constants are assigned based on the region where the FWD testing was conducted.

AC modulus vs. temperature model is expressed as:

$$\log(E_{ac}) = a - b * T \tag{F-1}$$

b value is used to obtain temperature adjustment factors for various condition indicators. The general expression of temperature adjustment factors can be written as:

$$\alpha = 10^{-f*b*(T_m - T_r)} \tag{F-2}$$

where f is the coefficient of temperature adjustment factor.

The *Next* button will invoke a series of Deflection Data Input interfaces (Figure F-2) to input the FWD data at each location. Each interface allows the user to input the following information.

Title – a unique scenario specific name specified in the Pavement Specification input interface is displayed

Location Number – a unique number for each FWD test location. (An ascending series of numbers, starting with 1, is automatically assigned.)

Load Level – the weight used in the FWD testing. (This value is used as the default value corresponding to each location, and could be modified later.)

Thickness Information – the thickness information of pavement layer(s) corresponding to the test locations. (This is used as the default values corresponding to all other location, and could be modified later.)

Surface Temperature – the measured surface temperature at the test location.

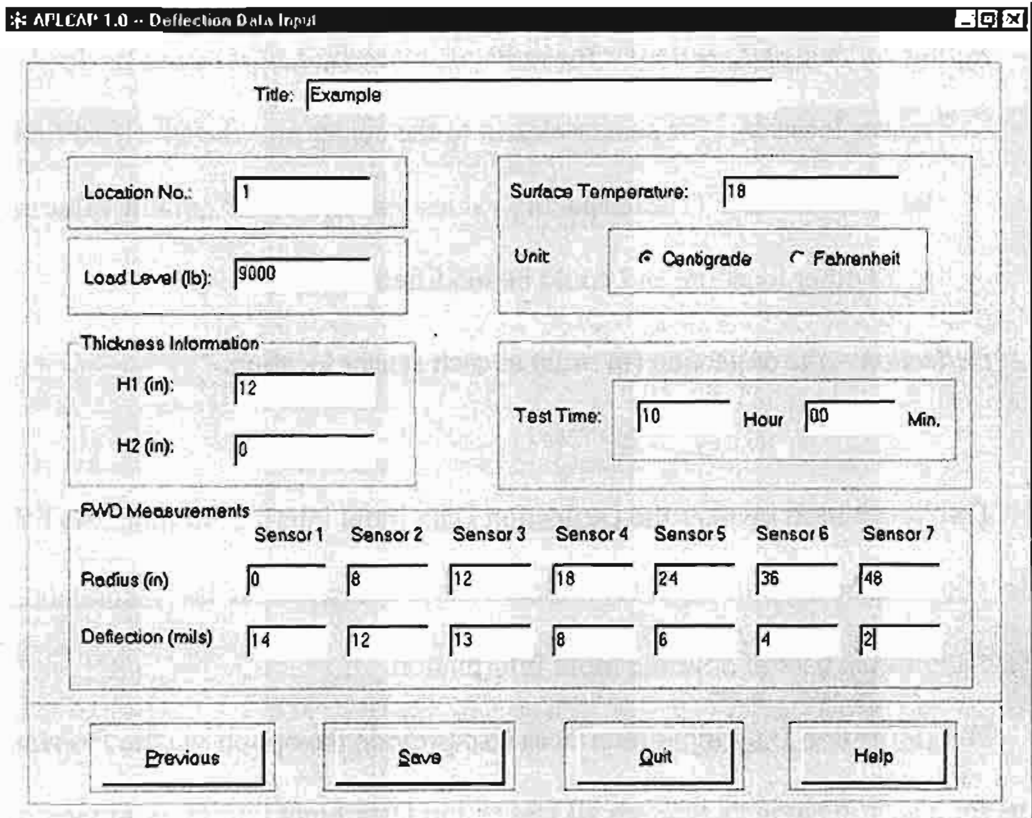


Figure F-2. Deflection Data Input interface

Test Time – the time of day when the test was conducted.

FWD Measurements –

Radius (of Sensor Location) – the radial distance (in inches) from the load center to each sensor location. The sensor closest to the center must be specified first, and the farthest one last. (These spacing values are used as the default value corresponding to all other location, and could be modified later.)

Deflection – the deflection (in mils) at each sensor location.

The *Next* button invokes the Deflection Data Input interface to input the FWD data at the next location. Once the data input for all locations is complete, the last Deflection Data Input interface allows the user to *Save* the input information.

The Deflection Data Input interfaces also provide the option via the *Previous* and *Next* buttons for a user to navigate through all Deflection Data Input interfaces to view and modify the data before saving the file.

Open File

This option allows the user to open an already saved file from a previous session. Selecting this menu option displays a Windows File Dialog box from which the user can specify the desired file. After the file is selected, the user can view and modify the data via the input interfaces Pavement Specification and Deflection Data Input as described above in *New File* menu option.

Convert FWD File

This option enables the user to import FWD information gathered using the DYNATEST and KUAB procedure. On selection of this option, the user is prompted to specify the file containing the FWD information. Upon loading this file, the user is prompted also to input additional information (e.g., temperature, climate zone) that is needed for the condition evaluation procedures. A use specifies this information via the Pavement Specification interface and the Deflection Data Input interface.

Exit

Selecting this will close all files and the program.

Analysis Menu

This menu item includes the following options: *Screen Deflection Data* and *Analyze Deflection Data.*

Screen Deflection Data

This option allows the user to view and screen the deflection input data, to identify potentially erroneous measurement information, and to correct the data using the SLIC method. When this menu option is selected, the Deflection Data Screening interface (Figure F-3) is displayed. This interface allows the user to select one test location at a time to view the deflection data. For each selected test location, three graphs showing the variation of deflection, surface modulus, and SLIC Method Information with sensor location are displayed. Also, an evaluation of the deflection data is provided on the top of the panel; this indicates any

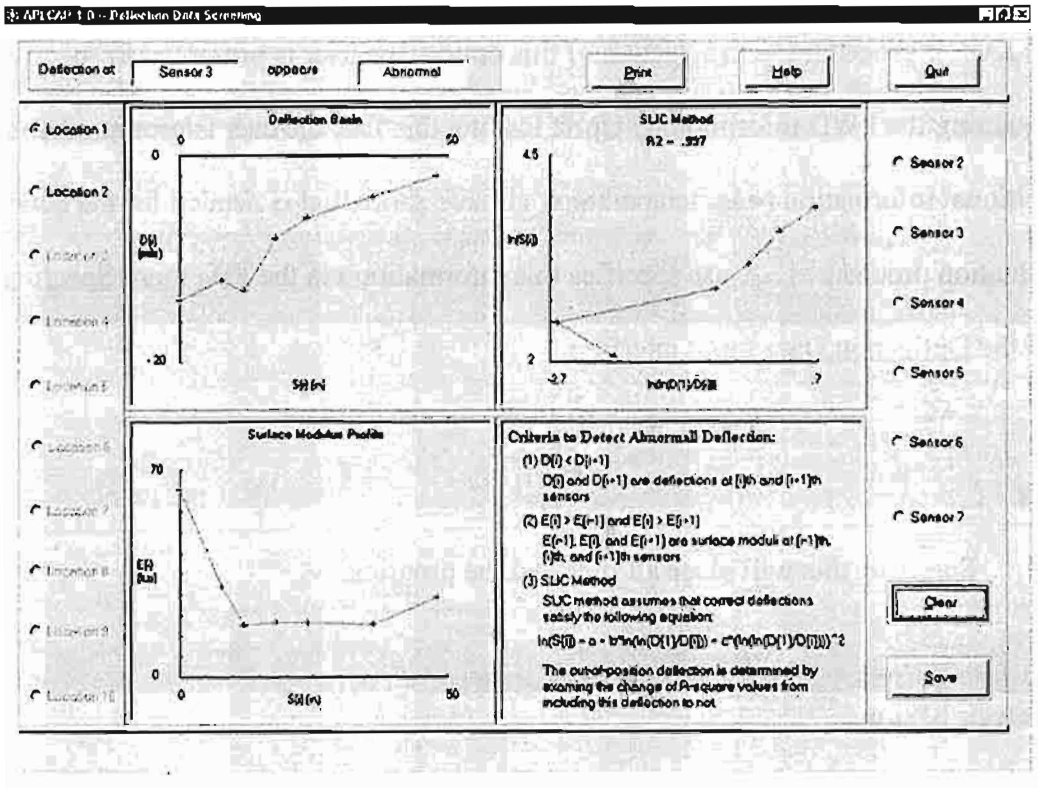


Figure F-3. Deflection Data Screening interface abnormality that may exist at any specific sensor location. The right hand side panel enables the user to select one sensor location where the deflection data may appear to be erroneous, and then apply the SLIC method. The modified deflection information is displayed before the user selects to accept or reject the modifications. If the modifications are accepted, then this modified deflection information is used in all subsequent analyses.

Analyze Deflection Data

Selecting this option invokes the condition assessment procedures presented later in the flowcharts (Figures F-8 and F-10). An interface (Figure F-4) displayed in response to its selection shows the default output file names and the path names where they will be stored. Using the *Browse* button, the user may override these defaults.

Results Display Menu

This menu item includes the following options: *Deflection Data, Output Figures, Output Tables,* and *Print Summary Output File.*

Deflection Data

This option allows the user to view the deflection data that was used in the condition assessment procedure. The Display Deflection Data interface (Figure F-5), similar to the Deflection Data Screening interface described above, is used to display the variation of deflection, surface modulus, and SLIC Method Information with sensor location. A *Print* option allows the user to print the graphs.

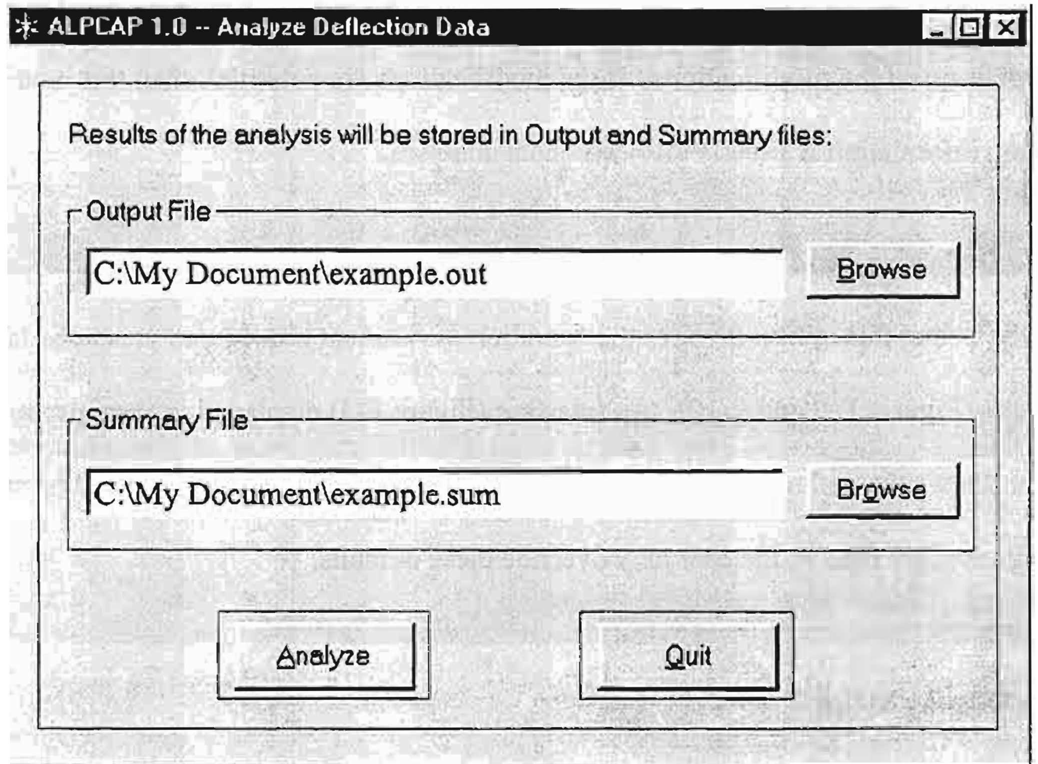


Figure F-4. Analyze Deflection Data interface

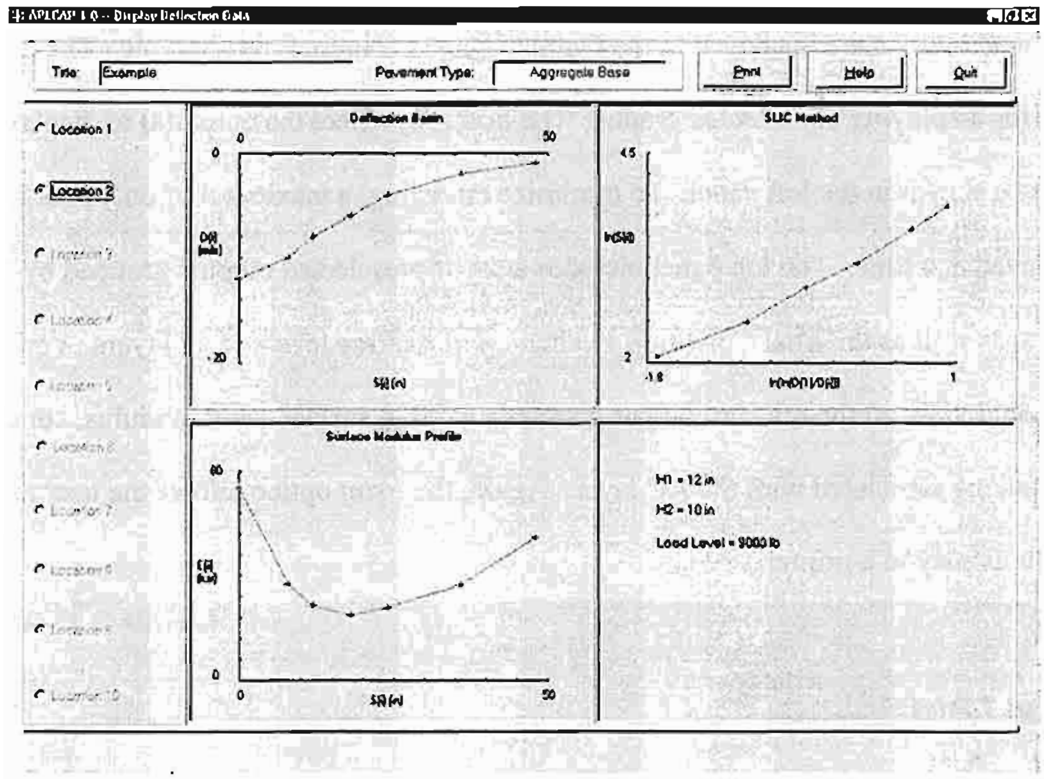


Figure F-5. Display Deflection Data interface

Output Figures

Selecting this option displays the outputs from the analyses in a set of graphs. The graphical outputs are displayed in the Output Figures (Figure F-6) interface. The center panel is used for displaying the selected graphs. The user may select the output(s) to display from the list of items shown in the left panel. To minimize crowding, a maximum of only four items could be displayed at a time. The top panel includes a set of preselected outputs grouped by the different layers, as well as the final Condition Evaluation of distress levels of all layers. For example, the use could view all the relevant output graphs (e.g., SCI, surface layer modulus, condition evaluation) associated with the AC layer. Again, the *Print* option allows the user to send the screen display to a printer.

Output Tables

Selecting this option displays a table that summarizes all the outputs from the analyses. Outputs for all locations and condition evaluation parameters are shown in a single table in the Output Tables (Figure F-7) interface. Again, the *Print* option allows the user to send the table to a printer.

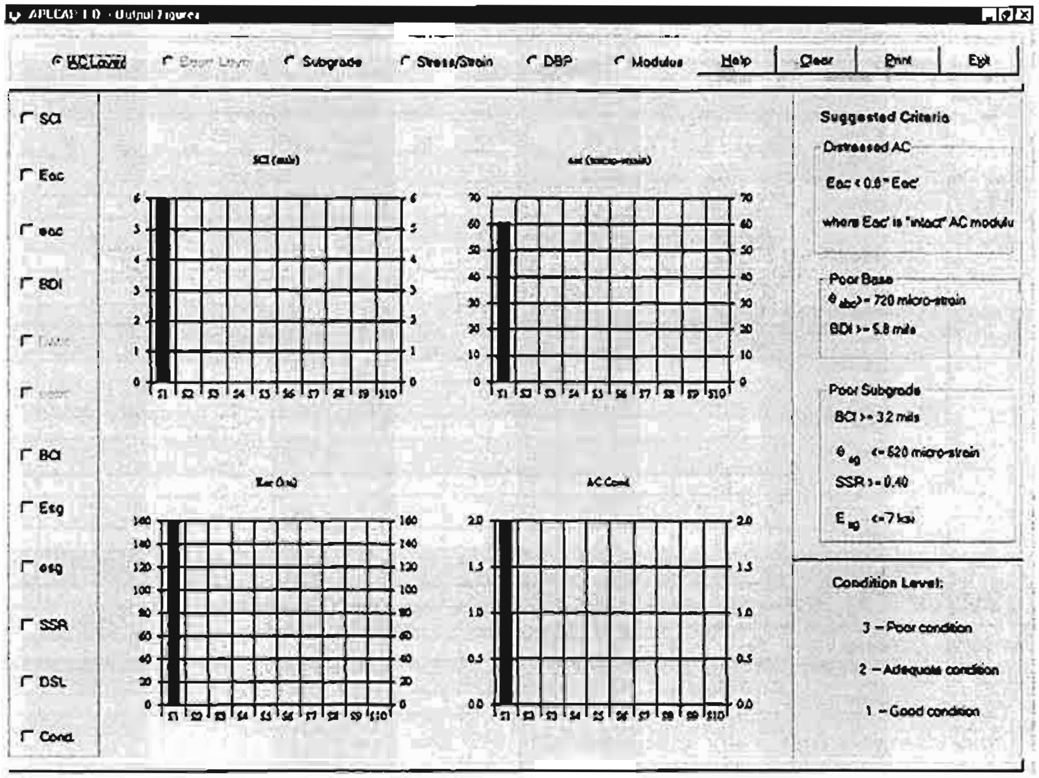


Figure F-6. Output Figures interface

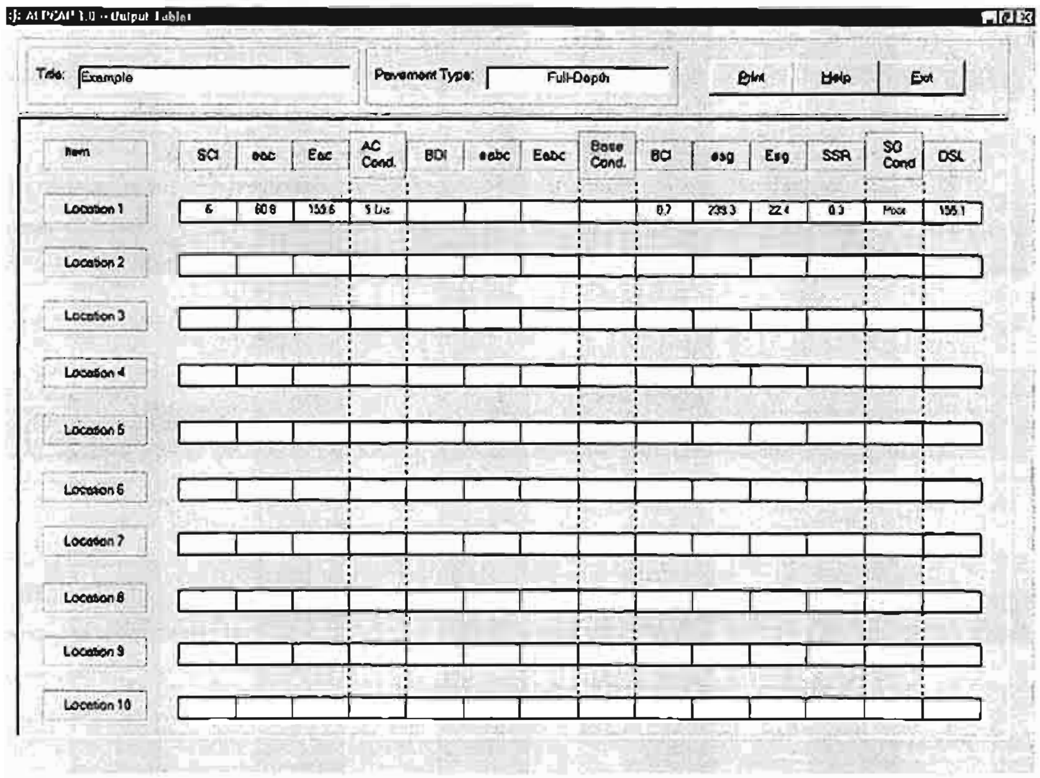


Figure F-7. Output Tables interface

Print Summary Output File

When the *Analyze FWD Data* menu option is invoked, all the outputs from the analyses are written to a summary file in ASCII format. By selecting this menu option, the user sends this file out to a printer.

Help Menu

This menu item provides a summary help screen. Information in here is limited to providing an overview. More detailed help instructions are provided in each screen via a Help button. In addition, information about items displayed on the different interfaces are provided through Windows-style pop-up notes when the cursor is placed over an item.

PAVEMENT LAYER CONDITION EVALUATION PROCEDURES

Applicable procedures for evaluating pavement layer conditions from the FWD raw deflection data, the corresponding list of symbols, and the definition of deflection basin parameters are presented here. Since irregular deflection basins, i.e., nonmonotonic changes in the deflections, cause errors in layer condition prediction, it is important to first check whether the deflection basin is irregular or not before performing deflection analysis. One way to detect irregular basin is to use two simple criteria proposed in this research. They are:

$$\text{Criterion 1:} \quad d_i < d_{i+1}, \qquad i = 1,2,\ldots,6 \tag{F-3}$$

$$\text{Criterion 2:} \quad E_i > E_{i+1} \quad and \quad E_i > E_{i-1}, \qquad i = 2,3,\ldots,6 \tag{F-4}$$

where d_i is the deflection at the i^{th} sensor, and E_i is the surface modulus at the i^{th} sensor, which is calculated from the following equations:

$$E_i = \frac{2(1-\mu^2)p}{ad_i} \qquad when \qquad i = 1 \tag{F-5}$$

$$E_i = \frac{(1-\mu^2)pa}{R_i d_i} \qquad when \qquad i = 2,3,\ldots,7 \tag{F-6}$$

where p is the load pressure, a is the radius of load area, R_i is the adjusted radial distance at the i^{th} sensor. The adjusted radial distances were suggested by Johnson and Baus (F-1) as 7.095, 11.414, 17.52, 23.41, 36, and 48 inches for sensors 2 to 7, respectively. When either of the above criteria is met, the pavement at the test location is considered irregular.

The SLIC method, developed by Stubstad et al. (F-2), can also be used to detect irregular deflection basins. In the SLIC method, S_i, radial distance of the i^{th} sensor, is first plotted against d_1/d_i, deflection ratio of the center deflection to the deflection at the i^{th} sensor, in a log-double log scale. A 2nd order polynomial function is then applied to fit the relationship between S_i and d_1/d_i, which is expressed as follows:

$$\ln(S_i) = a + b * \ln(\ln(\frac{d_1}{d_i})) + c * [\ln(\ln(\frac{d_1}{d_i}))]^2, \qquad i = 2,3,...,7 \qquad \text{(F-7)}$$

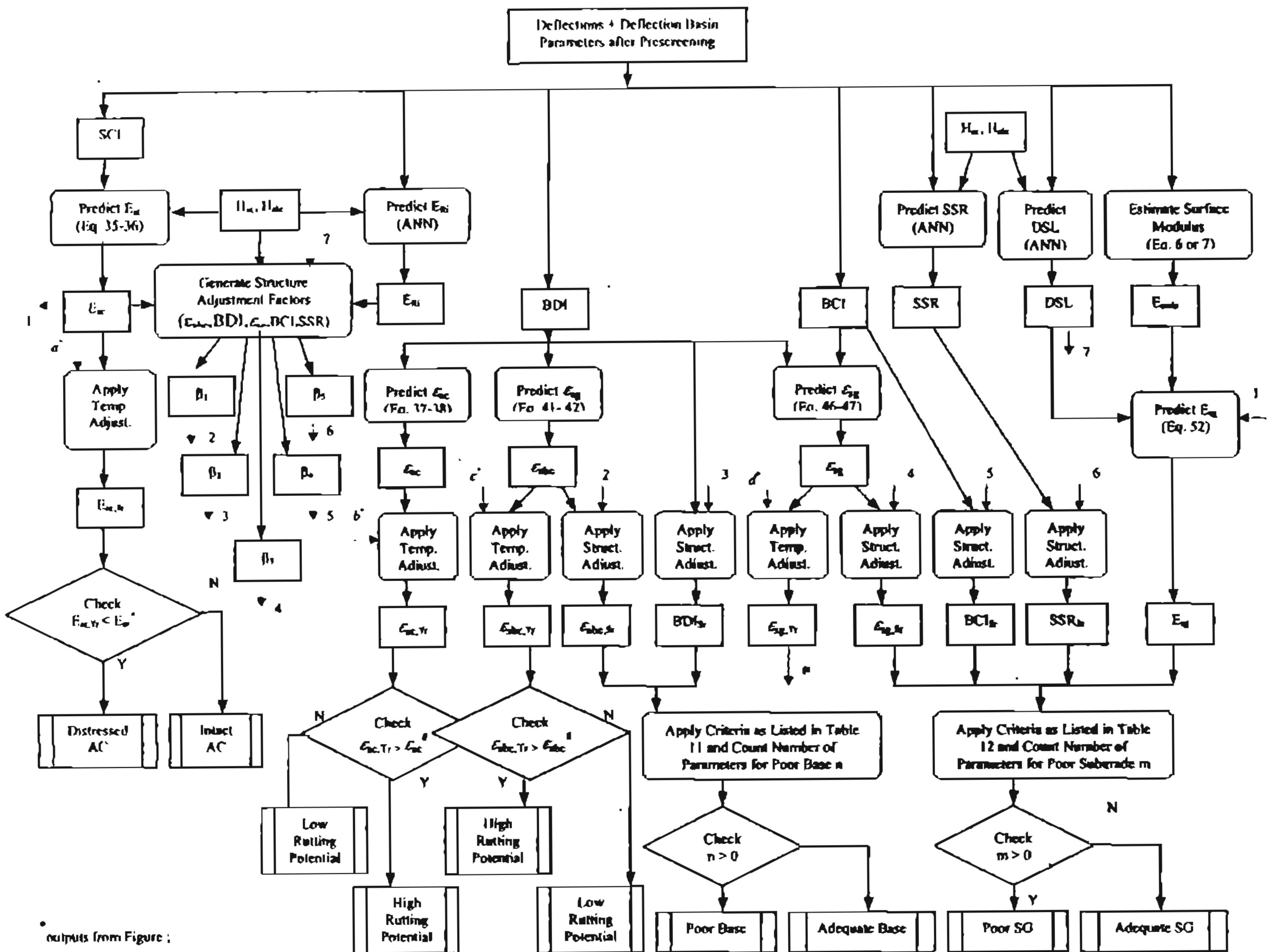
where a, b, and c are regression constants. A poor curve fitting indicates irregular deflection.

When irregularity is detected in FWD deflection basins, correction must be made before processing the deflection information for condition evaluation. The steps to correct the irregular surface deflection are: (1) to obtain the best fitting curve by applying the SLIC method to all the regular deflections; (2) to estimate the correct deflection by inputting the radial distance into the fitting curve.

After prescreening FWD raw data, the developed procedures are then applied. The following sections present the proposed procedures to predict pavement layer condition from the prescreened FWD deflections. These procedures are grouped by pavement type and presented in a flow chart with a stepwise description.

Aggregate Base Pavements

Figures F-8 and F-9 give the flow chart of the overall procedures in determining layer conditions of aggregate base pavements. The stepwise description of the procedure is presented below.



* outputs from Figure ;
[a] critical ε_{ac} and ε_{abc};
[**] follows the similar procedure as ε_{abc}

Figure F-8. Layer condition assessment procedure for aggregate base pavement

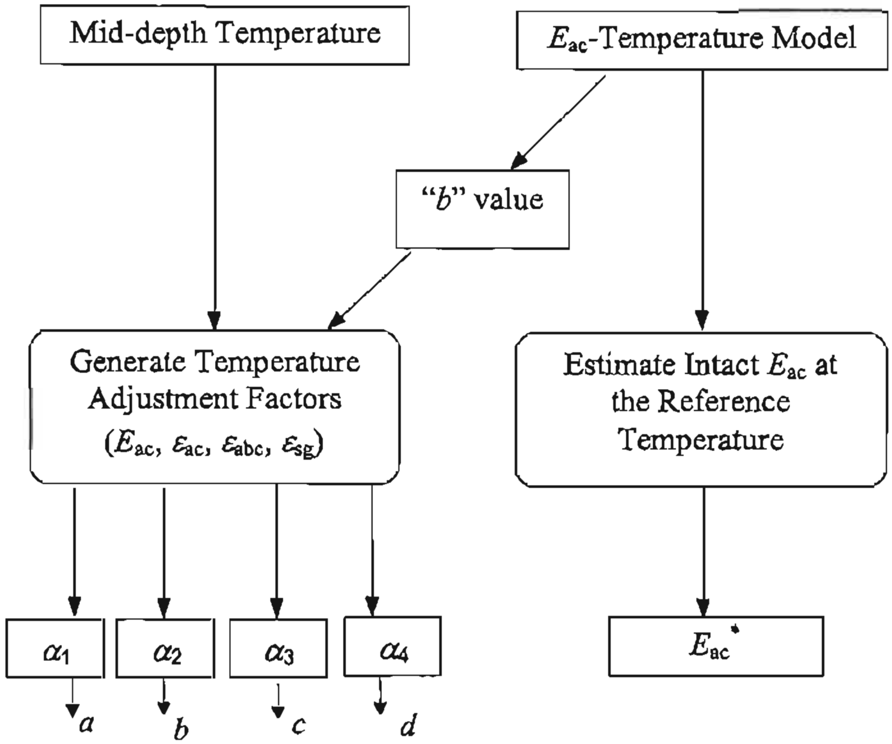


Figure F-9. Procedure for generating temperature adjustment factors for aggregate base pavements

Step 1: *FWD data collection and prescreening*

a) Perform FWD test. If possible, the FWD test should be performed at both wheel path and center of lanes;

b) Collect surface deflections, thicknesses, and temperature information;

c) Input AC modulus-temperature model suitable for the pavement in question;

d) Calculate surface modulus profile using Eqs. F-5 and F-6;

e) Screen deflections using the SLIC method and the two proposed criteria (Eqs. F-3, F-4, and F-7);

f) Normalize deflections to 9000 lb;

g) Adjust deflections to the standard sensor spacings of 0, 8, 12, 18, 24, 36, 48 inches using the SLIC method.

Step 2: *Assessing AC layer condition*

a) Calculate *SCI* and *BDI* values;

b) Predict mid-depth temperature using the *BELL3* method, which can be expressed as:

$$\begin{aligned} T_d &= 0.95 + 0.892 * IR + 0.042 * IR * \sin(hr_{18} - 13.5) \\ &+ \{\log(d) - 1.25\}\{-0.448 * IR + 0.621 * (1 - day) + 1.83 * \sin(hr_{18} - 15.5)\} \end{aligned} \tag{F-8}$$

where

T_d	=	AC temperature at depth d, °C,
IR	=	infrared surface temperature, °C,
d	=	depth at which temperature is to be predicted, mm,
1-day	=	average air temperature the day before testing,
log	=	base 10 logarithm,
sin	=	sine function in 18-hour clock system, with 2π radians equal to one 18-hour cycle,

hr_{18} = time of day, in 24-hour system, but calculated using an 18 hour AC temperature rise and fall time cycle, as indicated below:

When using the sin(hr_{18}-15.5) function, only use times from 11:00 to 05:00 hrs. If the actual time is not within this time range, consider 11:00 hrs as the actual time. If the actual time is between 0:00 and 5:00 hrs, add 24 to the actual time. The calculate as follows: If the time is 13:15, then in decimal form, 13.25-15.50=-2.25; -2.25/18=-0.125; -0.125 x 2π=-0.785 radians; sin(-0.785)=0.707.

When using the sin(hr_{18}-13.5) function, only use times from 09:00 to 03:00 hrs. If the actual time is not within this time range, consider 09:00 hrs as the actual time. If the actual time is between 0:00 and 3:00 hrs, add 24 to the actual time.

c) Evaluate the "intact" AC modulus value at 25°C based on intact modulus vs. temperature model;

d) Predict the actual AC modulus, E_{ac}, using the trained ANN or the following regression equations:

For $H_{ac} \geq 6$ inches,

$$\log(E_{ac}) = -1.1435 * \log(SCI) - 2.5435 * \log(H_{ac}) + 0.0498 * H_{ac} + 5.2005 \qquad \text{(F-9)}$$

$$R^2 = 0.988 \qquad SEE = 0.039$$

For $H_{ac} < 6$ inches,

$$\begin{aligned}\log(E_{ac}) = &-2.4527 * \log(SCI) + 1.4116 * \log(BDI) - 2.1621 * \log(H_{ac}) \\ &+ 0.0013 * H_{abc} + 5.1230\end{aligned} \qquad \text{(F-10)}$$

$$R^2 = 0.965 \qquad SEE = 0.099$$

Apply the temperature correction factor as the following equation to estimate the actual AC modulus at the reference temperature of 25°C:

$$\alpha = \frac{E_{ac,T_m}}{E_{ac,T_r}} = 10^{-b*(T_m - T_r)} \tag{F-11}$$

e) Compare the AC modulus values from Steps c) and d). If the actual AC modulus value is 30% less than the "intact" AC modulus value, the AC layer is considered distressed. Otherwise, the AC layer is considered intact;

f) If the AC layer is predicted to be intact from Step e), then predict ε_{ac} values from the following equations:

For $H_{ac} \geq 6$ inches,

$$\log(\varepsilon_{ac}) = 1.0230 * \log(BDI) + 1.7227 \tag{F-12}$$

$$R^2 = 0.981 \qquad SEE = 0.052$$

For H_{ac} <6 inches,

$$\begin{aligned} \log(\varepsilon_{ac}) &= 0.7798 * \log(SCI) + 0.2279 * \log(BDI) + 0.5736 * \log(H_{ac}) \\ &+ 0.0410 * \log(H_{abc}) + 1.1604 \end{aligned} \tag{F-13}$$

$$R^2 = 0.969 \qquad SEE = 0.041$$

Then, apply the temperature correction factor α_1 to determine the adjusted ε_{ac} value. α_1 is defined as:

$$\alpha_1 = \frac{\varepsilon_{ac,T_m}}{\varepsilon_{ac,T_r}} = 10^{-0.6411*\left[\log(E_{ac,T_m}) - \log(E_{ac,T_r})\right]} \tag{F-14}$$

Step 3: *Assessing base layer condition*

a) Calculate *SCI* and *BDI* values from surface deflections;

b) Predict E_{ac} from either the regression-based approach (Eq. F-9 or F-10) or a trained ANN;

c) Predict E_{Ri} from the ANN-based approach;

d) Predict value of ε_{abc} from either *BDI* or *SCI* and *BDI* using the following equations depending on AC thickness:

For $H_{ac} \geq 6$ inches,

$$\log(\varepsilon_{abc}) = 0.9958 * \log(BDI) + 2.1955 \tag{F-15}$$

$$R^2 = 0.976 \qquad SEE = 0.052$$

For $H_{ac} < 6$ inches,

$$\begin{aligned}\log(\varepsilon_{abc}) &= 0.7357 * \log(SCI) + 0.1043 * \log(BDI) \\ &+ 0.1240 * \log(H_{ac}) + 0.0648 * \log(H_{abc}) + 2.073\end{aligned} \tag{F-16}$$

$$R^2 = 0.963 \qquad SEE = 0.054$$

e) Apply structural correction factor β to estimate adjusted values for *BDI* and ε_{abc}. β is determined using the following steps:

1) condition indicator parameter was first described in terms of these structure specific properties based on the synthetic database. The following relationships were established:

$$\begin{aligned}\log(BDI) &= -0.5169 * \log(E_{ac}) - 0.9696 * \log(H_{ac}) - 0.0252 * H_{ac} \\ &- 0.1576 * \log(H_{abc}) - 0.0531 * \log(E_{Ri}) + 3.1552\end{aligned} \tag{F-17}$$

$$R^2 = 0.983 \qquad SEE = 0.087$$

$$\begin{aligned}\log(\varepsilon_{abc}) &= -0.5700 * \log(E_{ac}) - 0.8404 * \log(H_{ac}) - 0.0322 * H_{ac} \\ &- 0.0170 * \log(H_{abc}) - 0.0045 * \log(E_{Ri}) + 5.2106\end{aligned} \tag{F-18}$$

2) Using these equations, the indicators *BDI* and ε_{abc} are estimated for the pavement structure in question and for a standard structure. The following standard structure was used: $H_{ac} = 6$ inch, $E_{ac} = 500$ ksi, $H_{abc} = 10$ inch, $E_{Ri} = 7$ ksi, and H_{sg} = infinite. The ratio of these values is then defined as a structural correction factor.

f) Apply temperature correction α_2 to estimate adjusted ε_{abc} values. α_2 is defined as:

$$\alpha_2 = \frac{\varepsilon_{abc,T_m}}{\varepsilon_{abc,T_r}} = 10^{-0.57*\left[\log(E_{ac,T_m})-\log(E_{ac,T_r})\right]} \tag{F-19}$$

g) If either adjusted *BDI* value or ε_{abc} value is less than its pre-determined critical value shown in Table F-1, base layer is considered distressed;

h) Predict E_{abc} from the ANN-based approach.

Step 4: *Assessing subgrade condition*

a) Calculate values of *BDI*, *BCI*, F_3, F_2, and AI_4;

b) Predict E_{ac} value using the ANN-based procedure or regression approach (Eq. F-9 or F-10);

c) Predict E_{abc} value using the ANN-based procedure;

d) Predict *DSL* value using the ANN-based procedure;

e) Predict *SSR* and E_{Ri} values using the ANN-based procedures;

f) Calculate ε_{sg} value based on the *BDI* and *BCI* values using the following equations:

For $H_{ac} \geq 6$ inches,

$$\begin{aligned}\log(\varepsilon_{sg}) = 0.2811*\log(BDI) + 0.6788*\log(BCI) - 0.0135*\log(H_{ac}) \\ - 0.0123*H_{abc} + 2.2083\end{aligned} \tag{F-20}$$

$$R^2 = 0.988 \qquad SEE = 0.016$$

For $H_{ac} < 6$ inches,

Table F-1. Suggested criteria for poor base in aggregate base pavements

Base condition indicators	Criterion for poor base condition
Adjusted ε_{abc}	$\geq$ 720 microstrain
Adjusted *BDI*	$\geq$ 5.8 mils

$$\log(\varepsilon_{sg}) = 0.8835*\log(BDI) + 0.1526*\log(BCI) - 0.0995*\log(H_{ac}) - 0.0185*H_{abc} + 2.2461 \tag{F-21}$$

$$R^2 = 0.976 \qquad SEE = 0.010$$

g) Similar to *BDI* and ε_{abc}, apply structural correction to estimate adjusted *BCI*, ε_{sg}, and *SSR* values;

h) Similar to ε_{ac} and ε_{abc}, apply temperature correction to estimate temperature adjusted ε_{sg};

i) Calculate E_{sg} from the surface modulus method:

1) Determine E_{smin} from surface modulus profile;

2) Calculate F_{ac} from H_{ac}, H_{abc}, and predicted E_{ac} using the following equation:

$$F_{ac} = \frac{H_{ac}\sqrt[3]{E_{ac}} + cH_{abc}}{100} \tag{F-22}$$

where c is a constant, which is assigned a value of 3, 4, and 5 for poor, marginal, and sstrong base, respectively.

3) Calculate E_{sg} using E_{smin}, F_{ac}, and *DSL* using the following equations:

For $H_{sg} \geq 160$ inches,

$$E_{sg} = \frac{E_{s\min} - 0.2860*F_{ac}^{\ 2} - 6.1389*F_{ac} + 1.7244}{0.0861*F_{ac}^{\ 2} - 0.3233*F_{ac} + 1.1059} \tag{F-23}$$

$$R^2 = 0.978 \qquad SEE = 1.021$$

For $H_{sg} < 160$ inches,

$$E_{sg} = \frac{E_{s\min} - 0.0145*F_{ac}^{\ 2} - 5.6922*F_{ac} + 0.2353}{0.045*F_{ac}^{\ 2} - 0.115*F_{ac} + 23.2748*\dfrac{F_{ac}}{D_{sg}^{\ 3}} + 1.0091} \tag{F-24}$$

$$R^2 = 0.901 \qquad SEE = 1.545$$

j) Compare E_{sg} and adjusted *BCI*, ε_{sg}, and *SSR* values with their critical values shown in Table F-2. If any one of these values are in the critical range, subgrade condition is considered to be poor.

Full-depth pavements

The flow chart of the overall procedure of the determination of pavement layer conditions is shown in Figures F-10 and F-11. The stepwise description of the procedure is presented below.

Step1: *FWD data collection and prescreening*

a) Perform FWD test. If possible, FWD test should be performed at both wheel path and the center of lanes;
b) Measure surface deflections and collect thickness and temperature information;
c) Calculate surface modulus profile (Eqs. F-5 and F-6);
d) Screen deflections using the two proposed criteria (Eqs. 3 and 4) and the SLIC method;
e) Normalize deflection to 9000 lb;
f) Adjust deflections to the reference sensor spacings of 0, 8, 12, 18, 24, 36, 48 inches using the SLIC method.

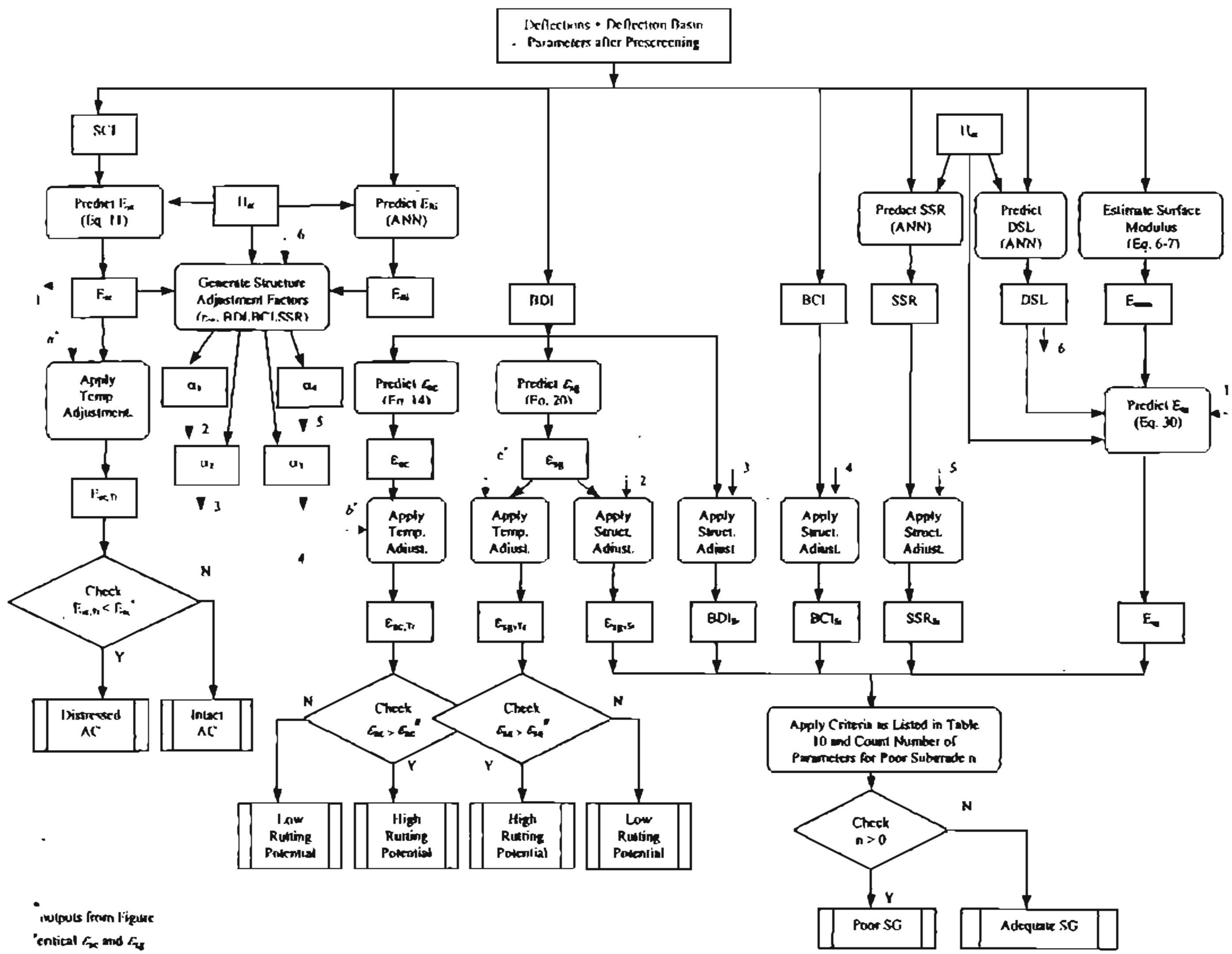


Figure F-10. Layer condition assessment procedure for full-depth pavement

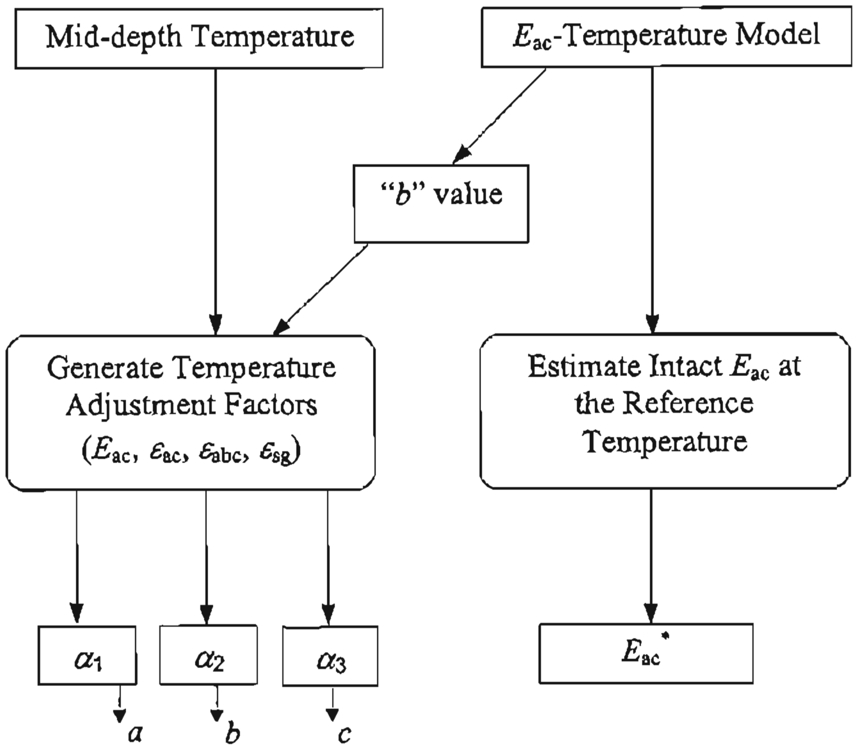


Figure F-11. Procedure for generating temperature adjustment factors for full-depth pavements

Step 2: *Assessing AC layer condition*

a) Calculate SCI values, and predict mid-depth temperature using *BELL3* method (Eq. F-8);

b) Calculate "intact" AC modulus value at 25°C using pre-determined modulus vs. temperature equation;

c) Predict actual AC modulus E_{ac} using the following equation:

$$\log(E_{ac}) = -1.0831 * \log(SCI) - 2.6210 * \log(H_{ac}) + 0.0482 * H_{ac} + 5.2961 \qquad \text{(F-25)}$$

$$R^2 = 0.994 \qquad SEE = 0.028$$

Then, apply temperature correction to estimate actual AC modulus at 25°C;

d) Compare the AC modulus values from Steps b) and c). If the actual AC modulus value is 30% less than the "intact" AC modulus value, the AC layer is considered distressed. Otherwise, the AC layer is considered intact;

e) If the AC layer is predicted to be intact from Step d), then predict ε_{ac} values using the following equation:

$$\log(\varepsilon_{ac}) = 0.9977 * \log(BDI) + 1.7142 \qquad \text{(F-26)}$$

$$R^2 = 0.987 \qquad SEE = 0.049$$

Then, apply temperature correction to get the adjusted ε_{ac} value.

Step 3: *Assessing subgrade condition*

a) Calculate values of *BDI*, *BCI*, F_3, F_2, and AI_4;

b) Predict E_{ac} value using the ANN-based procedure or regression approach (Eq. F-25);

c) Predict *DSL* value using the ANN-based procedure;

d) Predict *SSR* and E_{Ri} values using the ANN-based procedures;

e) Calculate ε_{sg} value based on the *BDI* and *BCI* values using the following equation:

$$\log(\varepsilon_{sg}) = 0.9823 * \log(BDI) + 2.1460 \quad \text{(F-27)}$$

$$R^2 = 0.978 \qquad SEE = 0.063$$

f) Apply structural correction to estimate adjusted *BCI*, ε_{sg}, and *SSR* values;

g) Apply temperature correction to estimate temperature adjusted ε_{sg};

h) Calculate E_{sg} from the surface modulus method:

1) Determine E_{smin} from surface modulus profile;

2) Calculate F_{ac} from H_{ac}, and predicted E_{ac};

3) Calculate E_{sg} using E_{smin}, F_{ac} and *DSL* using the following equations:

For $H_{sg} \geq 160$ inches,

$$E_{sg} = \frac{E_{s\min} - 0.1406 * F_{ac}^{\ 2} - 7.2188 * F_{ac} + 2.2688}{0.1139 * F_{ac}^{\ 2} - 0.4112 * F_{ac} + 1.1551} \quad \text{(F-28)}$$

$$R^2 = 0.999 \qquad SEE = 0.34$$

For $H_{sg} < 160$ inches,

$$E_{sg} = \frac{E_{s\min} - 0.0186 * F_{ac}^{\ 2} - 5.4088 * F_{ac} + 1.0637}{0.108 * F_{ac}^{\ 2} - 0.1944 * F_{ac} + 39.5426 * \dfrac{F_{ac}}{D_{sg}^{\ 3}} + 1.033} \quad \text{(F-29)}$$

i) Compare E_{sg} and adjusted *BDI*, *BCI*, ε_{sg}, and *SSR* values with their critical values shown in Table F-3. If any of these values is in the critical range, subgrade condition is considered to be poor.

Table F-3. Suggested criteria for poor subgrade in full-depth pavements

Subgrade condition indicators	Criteria for poor subgrade
Adjusted *BDI*	≥3.4 mils
Adjusted *BCI*	≥3 mils
Adjusted ε_{sg}	≥470 microstrain
Adjusted *SSR*	≥0.38
E_{sg}	≤7 ksi

DEFINITIONS OF DEFLECTION BASIN PARAMETERS

Table F-4. Available deflection basin parameters

Deflection Parameter	Formula	Measuring Device	Reference
Area	$AREA = \frac{6(D_0 + 2D_{12} + 2D_{24} + D_{36})}{D_0}$	FWD	Hoffman 1981
Add. Areas	$AREA_2 = \frac{6(D_{12} + 2D_{18} + D_{24})}{D_0}$ $AREA_3 = \frac{6(D_{24} + 2D_{36} + D_{48})}{D_0}$	FWD	
Area Indexes	$AI_1 = \frac{D_0 + D_{12}}{2D_0}$ $AI_2 = \frac{D_{12} + D_{24}}{2D_0}$ $AI_3 = \frac{D_{24} + D_{36}}{2D_0}$ $AI_4 = \frac{D_{36} + D_{48}}{D_0}$	FWD	
Area Under Pavement Profile	$AUPP = \frac{5D_0 - 2D_{12} - 2D_{24} - D_{36}}{2}$	FWD	Hill & Thompson
Base Curvature Index	$BCI = D_{60} - D_{48}$ or $BCI = D_{24} - D_{36}$	Dynaflect FWD	Peterson 1972
Base Damage Index	$BDI = D_{12} - D_{24}$	RR & FWD	
Bending Index	$BI = D_0 / a$	BB	Hveem 1954
Deflection Ratio	$DR = D_r / D_0$	FWD	Classen 1976
Load Spreadability Index	$LSI = (D_{48} / D_{24})xF$	FWD	Wimsatt 1995
Maximum Deflection	D_0	BB Dynaflect	Shrivner 1968
Radius of Curvature	$R = \frac{r^{2}*}{(2D_0(D_0 / D_r - 1))}$	CM & BB	Dehlen 1962
Radius of Influence	$RI = x / D_0$	BB	Ford 1962
Shape Factors	$F_1 = (D_0 - D_{24}) / D_{12}$ $F_2 = (D_{12} - D_{36}) / D_{24}$	FWD	Hoffman 1981
Add. Shape Factor	$F_3 = (D_{24} - D_{48}) / D_{36}$	FWD	
Slope of Deflection	$SD = \tan^{-1}[(D_0 - D_r)/r]$	BB	Kung 1967
Spreadability	$S = \frac{25(D_0 + D_{12} + D_{24} + D_{36})}{D_0}$	Dynaflect RR FWD	Vaswani 1971
Structural Strength Index	$SSI = A_x / (X_{min} xE_{min})$	FWD	Jung 1992
Structural Integrity Index	$SII = A_x / (X_s xE_m)$	FWD	Jung 1992
Surface Curvature Index	$SCI = D_0 - D_{12}$	BB RR Dynaflect FWD	Shrivner 1968
Tangent Slope	$TS = (D_0 - d'_x) / x$	FWD	Stock 1984

Table 2. (Cont'd)

D_r	Surface deflection	BB	Benkelman Beam
r	Distance from the load center (inch)	RR	Road Rater
a	¼ of deflection basin length	FWD	Falling Weight Deflectometer
x	Distance from point of maximum deflection to tangent point	CM	Curvaturemeter
		*	r=127 mm
d	Deflection at the tangent point		
F	Minimum of D_{12}/D_0, D_{24}/D_{12}, ..., or D_{72}/D_{60}		
A_x	Area under the surface modulus profile to X_s or to the minimum value (E_{min}) at $X = X_{min}$		
E_m	Estimated subgrade modulus		
X_s	Radial distance from the test load		

LIST OF SYMBOLS

H_{ac} = thickness of AC layer in inch,

H_{abc} = thickness of base layer in inch,

H_{pcc} = thickness of PCC layer in inch,

H_{ctb} = thickness of cement treated base layer in inch,

D_i = deflections where i is the distance in inches from the load center;

E_i = surface modulus where i is the distance in inches from the load center;

p = load pressure;

a = radius of load plate;

μ = Poisson's Ratio;

R_i = the adjusted radial distance at the i^{th} sensor;

E_{ac} = the AC modulus;

T = the AC mid-depth temperature;

ε_{ac} = the tensile strain at bottom of AC layer in microstrain;

E_{Ri} = the subgrade modulus in ksi at 6 psi deviator stress;

α_1 = temperature correction factor for ε_{ac} for full-depth pavements;

ε_{ac,T_m} = AC tensile strain in microstrain at measured temperature T_m;

ε_{ac,T_r} = AC tensile strain in microstrain at reference temperature T_r of 25°C;

E_{ac,T_m} = AC modulus in ksi at measured temperature T_m;

E_{ac,T_r} = AC modulus in ksi at reference temperature T_r of 25°C;

T_m = measured temperature in °C;

T_r = reference temperature of 25°C;

ε_{sg} = the compressive strain on top of subgrade in microstrain;

D_{sg} = the thickness of subgrade in feet;

E_{smin} = the smallest value of surface moduli;

F_{ac} = the effect of AC layer on the surface modulus;

ε_{sg,T_m} = subgrade compressive strain in microstrain at measured temperature T_m;

ε_{sg,T_r} = compressive strain in microstrain at reference temperature T_r of 25°C;

ε_{ac,T_m} = AC tensile strain in microstrain at measured temperature;

ε_{ac,T_r} = AC tensile strain in microstrain at reference temperature of 25°C;

ε_{abc} = compressive strain at the top of the aggregate base layer, in microstrain;

ε_{abc,T_m} = compressive strain on top of base layer in microstrain at measured temperature T_m;

ε_{abc,T_r} = compressive strain on top of base layer in microstrain at reference temperature of 25°C;

ε_{sg,T_m} = the subgrade compressive strain in microstrain at measured temperature T_m;

ε_{sg,T_r} = compressive strain in microstrain at reference temperature of 25°C;

α = temperature adjustment factor;

T_d = AC temperature at depth d, °C;

IR = infrared surface temperature, °C;

d = depth at which temperature is to be predicted, mm;

1-day = average air temperature the day before testing;

sin = sin function in 18 hour clock system, with 2π radians equal to one 18-hour cycle,

hr_{18} = time of day, in 24-hour system, but calculated using an 18 hour AC temperature rise and fall time cycle, as indicated below:

When using the $\sin(hr_{18}$-15.5) function, only use times from 11:00 to 05:00 hrs. If the actual time is not within this time range, consider 11:00 hrs as the actual time. If the actual time is between 0:00 and 5:00 hrs, add 24 to the actual time. The calculate as follows: If the time is 13:15, then in decimal form, 13.25-15.50=-2.25; -2.25/18=-0.125; -0.125 x 2π=-0.785 radians; sin(-0.785)=0.707.

REFERENCES

F-1 A.M. Johnson and R. L. Baus, "Simplified Direct Calculation of Subgrade Modulus from Nondestructive Pavement Deflection Testing," In Transportation Research Record 1406, TRB, National Research Council, Washington, D., C., 1993, pp. 133-141.

F-2 Stubstad, R. N., Irwin, L.H., Lukanen, E. O., and Clevenson, M.L., "It's IO o'clock - Do You Know Where Your Sensors Are?," Transportation Research Board, 79'h Annual Meeting, Washington, D., C., Jan., 2000.