Structural Evaluation of Low Volume Roads Using Ground Penetrating Radar (GPR)

Final Report

To:

Tennessee Department of Transportation

Research Development and Technology Program

BY

Adel Abdelnaby, Ph.D., P.E., S.E.
Assistant Professor of Civil Engineering
The University of Memphis
106C Engineering Science Building
Memphis, TN 38152
bdelnaby@memphis.edu

Charles Camp, Ph.D.
Professor of Civil Engineering
The University of Memphis
106B Engineering Science Building
Memphis, TN 38152
cvcamp@memphis.edu

Colton Baker, EIT
Graduate Transportation Associate
Tennessee Department of Transportation

Farid Hosseinpour, EIT
Graduate PhD Student
University of Memphis

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16. Abstract

Since 1983, TDOT has absorbed approximately 3,500 miles of former county roads into its system. The composition and structural capacity of a large portion of these road ways is unknown, except for new overlays that have been constructed since that time. The objective of this study is to utilize ground penetrating radar (GPR) technology to determine the pavement composition and structural capacity of these roads. In this study, GPR is used to obtain pavement layer thickness and identify layer structure for 264 TN state routes. The GPR data was validated using core test results at selected points on the roadway segments. Information from GPR data is then augmented by deflection data obtained from falling weight deflectometer (FWD) tests to determine structural capacity and overall pavement conditions of these roadways.

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1. Executive Summary

Ground penetrating radar (GPR) is a non-destructive, data collection tool that utilizes radar waves in order to map subsurface properties. This type of testing is of special interest to the field of Civil Engineering since it allows the engineer a glimpse inside of structures without damage while also providing data for the complete structure, instead of a single point like a core would provide. GPR is of special interest to highway engineers since it can supply pavement layer depth for a full length of road, a critical component in determining the service life left in a pavement.

The Tennessee Department of Transportation (TDOT) has requested this information on existing state routes as they continue updating the state's highways. Aided with information from GPR, TDOT can take a better approach to updating the state's highways, determining which routes are the most structurally unsound and may need to be repaired first. The purpose of this project is to collect over three thousand miles of GPR data for 264 routes in all four TDOT denoted regions and create an inventory that shows the layer thickness data for each route. For 25 of the scanned routes, Falling Weight Deflectometer (FWD) and core test data were collected and then using GPR and FWD data along with core test results an estimate of the service life left in those specific roads is provided.

Furthermore, the data collection/analysis process was augmented with integrated video and GPS. This allowed surface features related to varying conditions, construction changes, flaws, etc., to be correlated to subsurface characteristics in the GPR data that are much more easily interpreted than when GPR data is interpreted by itself. In fact, integration of GPR data with video and GPS sped up the data analysis because it reduced time of the ambiguity in data analysis process.

2. Introduction

2.1. GPR

Ground Penetrating Radar is a nondestructive test (NDT) that can be performed on pavements to determine several characteristics. While originally designed to search for tunnels in the Vietnam War (Loken, 2007) it has been utilized for several other purposes such as grave detection, location of rebar within concrete, foundation analysis on buildings, checking pavements for voids, and for gathering layer thickness information on existing pavement layers amongst other uses.

Radar is a system for detecting the presence, direction, distance and speed of objects by sending out pulses of high-frequency electromagnetic waves that are reflected off the object and back to the source. GPR is a type of radar that sends these pulses into the ground either directly from a ground coupled antenna or through the air in an air-launched horn antenna. The amplitude and arrival time of waves are then measured and recorded. The electrical properties of materials that the wave permeates influences the amplitudes and arrival times, so that using these properties can denote different pavement layers (Willet and Rister, 2013).

The electrical property of materials relevant to GPR is the dielectric constant. Dielectric constant is the permittivity of a material and is a direct measure of the ability of a material to resist an electric field. Using the one-dimensional electromagnetic wave propagation theory, which states that when an electromagnetic wave travels through a vacuum it travels at its fastest possible velocity, but when the wave travels through any medium its energy is absorbed by the individual atoms of the material. The absorbed energy causes the electrons to vibrate, which then creates a new electromagnetic wave at the same frequency as the first, and this new wave passes to the next atom. With the regeneration of the wave through each atom of the material, it slows down the velocity of the wave by an amount proportional to the dielectric constant of the material. The amplitude and speed of these waves that returned to the antenna is measured, and through that the material thickness can be determined. Table 1 lists the dielectric constants for common pavement materials.

Table 1: Material Properties of common roadway materials.

Material	Dielectric constant (-)	Propagation Velocity (m/s)
Air	1	0.30
Ice (Frozen soil)	4	0.15
Granite	9	0.10
Limestone	6	0.12
Sandstone	4	0.15
Dry Sand	4 to 6	0.12 to 0.15
Wet Sand	30	0.055
Dry Clay	8	0.11
Wet Clay	33	0.052
Asphalt	3 to 6	0.12 to 0.17
Concrete	9 to 12	0.087 to 0.10
Water	81	0.033
Metal	8	0

Figure 1 shows the measured wave from an actual GPR test for TN State Route (SR) 305. Where there are spikes in the amplitude is where there is a material change, since wave propagation theory states that the velocity changes when the wave goes through different materials. In practice the positive peak is set as the interchange between materials.

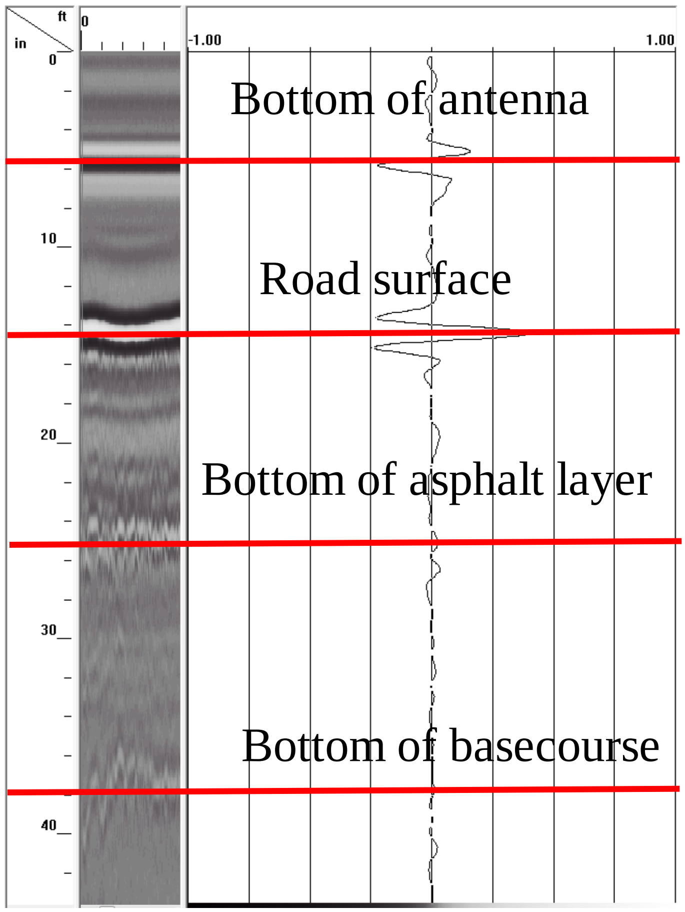


Figure 1: GPR wave schematic through SR pavement layers.

In Figure 1 the left pane of the image window shows the amplitude of the image converted into depths, the following equations show the process that the GSSI processor RADAN7 does to convert the amplitude into depths. First, an amplitude variable must be calculated.

$$\rho_1 = {}^{A_1}/_{A_m} \tag{1}$$

where: ρ_1 = amplitude variable

A_1 = the amplitude of the wave from the first layer of material

A_m = the amplitude of the wave from the metal calibration plate

In order to calibrate the antenna each day, the antenna is first placed over a metal calibration plate. This is done because metal reflects all of the electromagnetic wave to the antenna, as can be seen in Table 1 by the propagation velocity being zero, so the amplitude matches the amplitude of the wave that the antenna is sending out. Once the amplitude variable of the first layer is calculated, the dielectric constant for that layer can be calculated.

$$\sqrt{\varepsilon_1} = \frac{1 + \rho_1}{1 - \rho_1} \tag{2}$$

where: ε_1 = the dielectric constant for layer 1

The dielectric constant for other layers also must be calculated in order to obtain the depth of those layers.

$$\sqrt{\varepsilon_2} = \sqrt{\varepsilon_1} \times \frac{1 - {\rho_1}^2 + \rho_2}{1 - {\rho_1}^2 - \rho_2} \tag{3}$$

where: ε_2 = the dielectric constant for the second layer

$\rho_2 = {}^{A_2}/_{A_m}$

A_2 = the amplitude of the wave from the second layer of material

Using the now calculated dielectric constant of the layer, the propagation velocity can be calculated. Propagation velocity is the ratio of the speed that a wave travels through a medium to the speed of the wave in a vacuum, which is equal to the speed of light.

$$v_i = \frac{11.8\ {}^{in}/_{ns}}{\sqrt{\varepsilon_i}} \tag{4}$$

where: v_i = the propagation velocity of the layer of interest

ε_i = the dielectric constant of the layer of interest

The height of the layer can be calculated using the propagation velocity and the amount of time that it took the wave to pass through the layer, t_i. The system records the two-way travel time, or the amount of time that it takes the signal to pass through and return through the layer so the recorded time must be divided by two.

$$h_i = \frac{v_i \times\ t_i}{2} \tag{5}$$

where: h_i = the thickness of the layer of interest

t_i = the two-way travel time through the layer of interest

2.2. Objectives

The objective of this study is to estimate the pavement structure including hot-mix asphalt (HMA), base, and subbase layer thickness, on former county roads that were absorbed by TDOT in 1983. To meet this objective a network-level scanning of these roads is performed using 2 GHz antenna (center of lane) while collecting data on posted roadway speed. The GPR data was then processed using

RADAN7 software. In addition, video and GPS data were collected with the scanning process. The processed data (and software) were validated with seventy selected core tests taken at specific points on the roadway segments. The structural capacity of these selected roadway segments was determined by performing FWD tests at 0.1- mile interval and integrating FWD and GPR data. A graphical user interface GIS-based application was used to allow sage the collected GPR, core, video, GPS, and FWD data for easy dissemination.

3. Literature Review

David A. Willet and Brad Rister (Willet and Rister, 2013) in association with the Kentucky Transportation Center at the University of Kentucky and in cooperation with the Kentucky Research Cabinet performed a study that covers whether or not GPR would be a useful tool for evaluating Kentucky roads. The main focus of the report is the total accuracy of the system on the common Kentucky pavements, asphalt and non-reinforced concrete, and how many ground truth cores would be required for accurate data interpretation. A ground truth core is where known layer depth can be inserted into the data, and the RADAN software recalculates the layers thickness for the entire depth based upon the inputted core data. An interesting subtest of the report was whether or not surface water has any influence on the data. The report was selected to be included since Kentucky has similar geography and climate to Tennessee.

The researchers used a GSSI SIR10 receiving unit along with a 1.0 GHz air horn antenna for data collection and RADAN for processing the collected data. This is an older equipment than what is used for the project, but it the same style except for the horn antenna. A 1.0 GHz antenna gives better resolutions for road scanning but was banned by the Federal Communications Commission (FCC) after the report was published so for the TDOT project a 2.0 GHz antenna was used.

To determine if ground water had any effect on the layer depth, a University of Kentucky parking lot was scanned dry, then half sprayed down with water for 20 minutes and rescanned. The parking lot was left for a day and the whole surface was sprayed for 20 minutes and scanned. After processing, it was determined that the presence of surface water changed the difference from the core value by 5% when the surface was half wetted and half dry as compared to a fully dry surface, while when the surface was totally wetted it was 0.3% different than the dry surface. This change did not create enough of a change to be deemed of consequence, though it should be noted this study does not cover the effect of a fully saturated layer or standing water on the surface. This is of importance to the project since afternoon showers are frequent during the summer and does not have to cancel a day worth of scanning.

The report found that GPR is more reliable for Kentucky pavements if ground truth cores are taken. The accuracy of the data gets exponentially better based upon the number of cores as seen in Figure 2. This is of major importance for project level testing, where the GPR data is analyzed in-depth for a specific route and more time and resources are allocated to the data, compared to network level testing where data is collected for all the routes in a network and does not undergo in-depth analysis. It should also be noted that the processing of GPR data also has a significant effect on layer depth so that can explain some of the inaccuracies of not using the ground truth data.

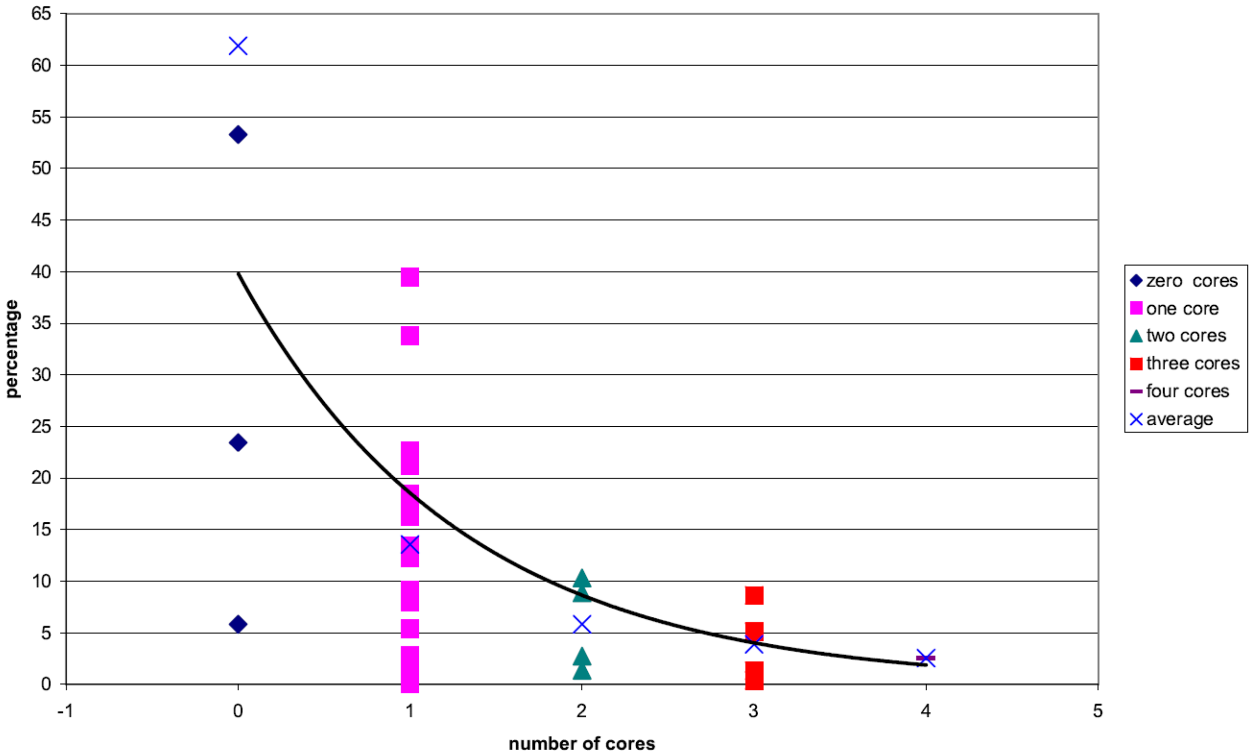


Figure 2: Percentage difference between core values and GPR depths per Kentucky report.

4. Methodology/Data Analysis

The methodology of using GPR equipment, processing the data and integrating it with video and GPS data are presented herein this section. In addition, the FWD data collection procedures as well as core test location selection are illustrated.

4.1. GPR

This section of the report covers the TDOT Tennessee Highways project specifically. It includes what specific equipment was used, how GPR data is integrated with video and GPS data and what all is entailed in the process of collecting and processing the data.

Equipment

The system used by the University of Memphis is the GSSI SIR 30 computer using 2.0 GHz Air-launched horn antennas. The system is mounted to a Ford F-150 that was procured for the project. A schematic of the system is shown in Figure 3.

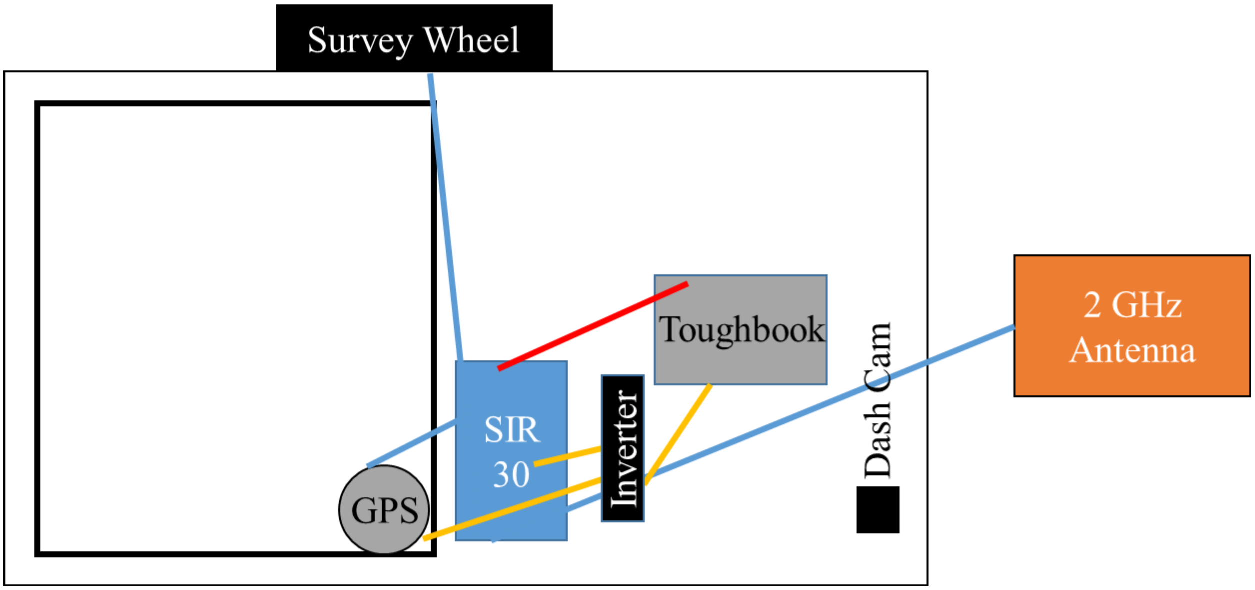


Figure 3: Schematic of the GPR system setup at the University of Memphis.

In the schematic, the blue lines feed information into the SIR 30, the red line transfers information from the SIR 30 into the Toughbook and the yellow lines are instruments that receive power from the inverter.

An additional bumper was installed on the truck in order to have a place for the antennas to be attached. This mount needed to be bolted/welded to the chassis of the truck to reduce as much vibration as possible. Two arms are mounted on this bumper where the GPR antennas are attached to. The arms contain dampers to also reduce vibration effects during driving on high speed. With this mount, there is the option to set up two antennas in the wheel path of the truck or a single antenna in the centerline of the truck. While we have utilized the wheel path options in the past with double antennas, it was decided to start using the centerline placement instead in order to reduce by half the amount of processing that must be done for each road. Doing so fell within the scope of work set out by TDOT since it is still obtaining accurate layer information. It should also give better results as it will not include any added thicknesses for crowns in the roads that could exist in the driver's wheel path.

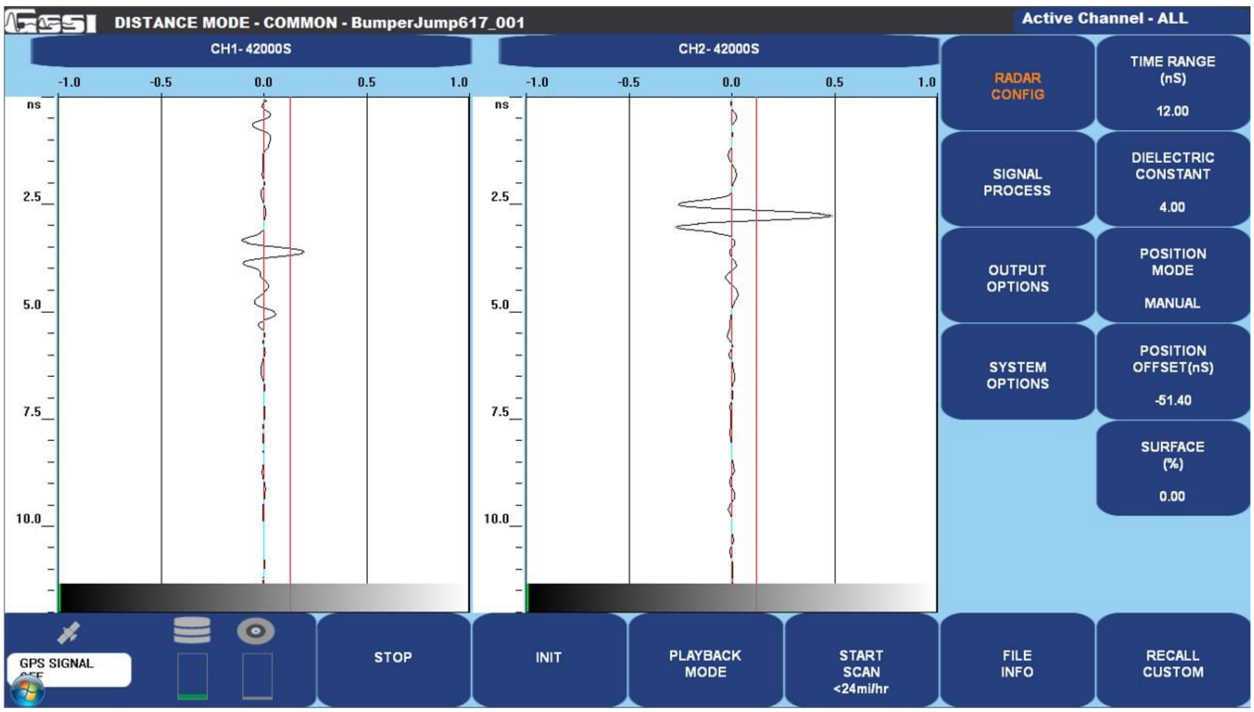
As mentioned earlier, connected to the bumpers is a 2.0 GHz Air-launched horn antenna provided by GSSI. This antenna is considered a smart id antenna meaning that when it synchronizes to the SIR 30 computer it uploads its preset values for model number, dielectric constant and radio frequencies. These antennas are also equipped with a noise reduction filter that allows better data to be taken in urban environments; it filters out miscellaneous signals from cell phones and radio frequencies. Even equipped with this filter though, the data still can become washed out if it rides beside power lines or in a close proximity to a power line. Figure 4 is a picture of the antennas set up in the wheel path configuration.

Figure 4: Picture of the antennas setup in the wheel path configuration.

The antenna is directly connected into the SIR 30 multi-channel radar control unit furnished by GSSI. This computer runs on a windows-based operating system and can control up to four antennas at the same time. The survey wheel and GPS also transmit data into the system which displays distance traveled and GPS coordinates from these respectively. The SIR 30 saves all the scanned data into a form that the processing software RADAN7 can read. While scanning, the SIR 30 is linked to the Toughbook via Ethernet that acts as a monitor and keyboard for the computer. Figure 5 (a) and (b) are pictures of the front and back of the system while set up; Figure 5 (c) is what the main screen looks like while the system is operating.

(a)

(b)



(c)

Figure 5: SIR-30 front (a); SIR-30 back (b); Screenshot of Toughbook during operation (c).

Measuring distance for the system is done by a survey wheel. It attaches to the rear driver side wheel and counts distance in tick marks. Each day of scanning the wheel must be calibrated to ensure the best data possible. Figure 6 is a picture of the survey wheel attached to the truck.

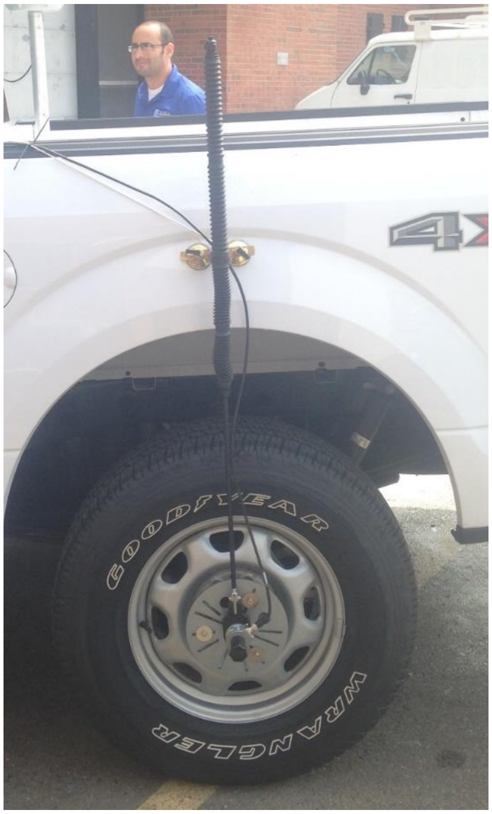


Figure 6: Survey wheel attached to the truck.

GPS data is collected using a CHC X20, and an agricultural GPS that can create GPS coordinates for every half foot of data. This particular GPS is accurate to the foot. Accuracy is something that was taken into consideration for this project since all the data created would need to be stored in a GIS system. The foot accuracy was an acceptable amount of error since the standard lane width for a rural collector road is 10-12 feet wide and we would still be within the correct lane at 1 foot off center.

Video is collected using a Garmin Dash Cam 20, which stamps the video with GPS and time stamps. GPR technology is not capable of determining pavement cracking well, so videos of the road surfaces are taken to provide a way to measure surface cracking. Figure 7 is an example of a frame from the video file.

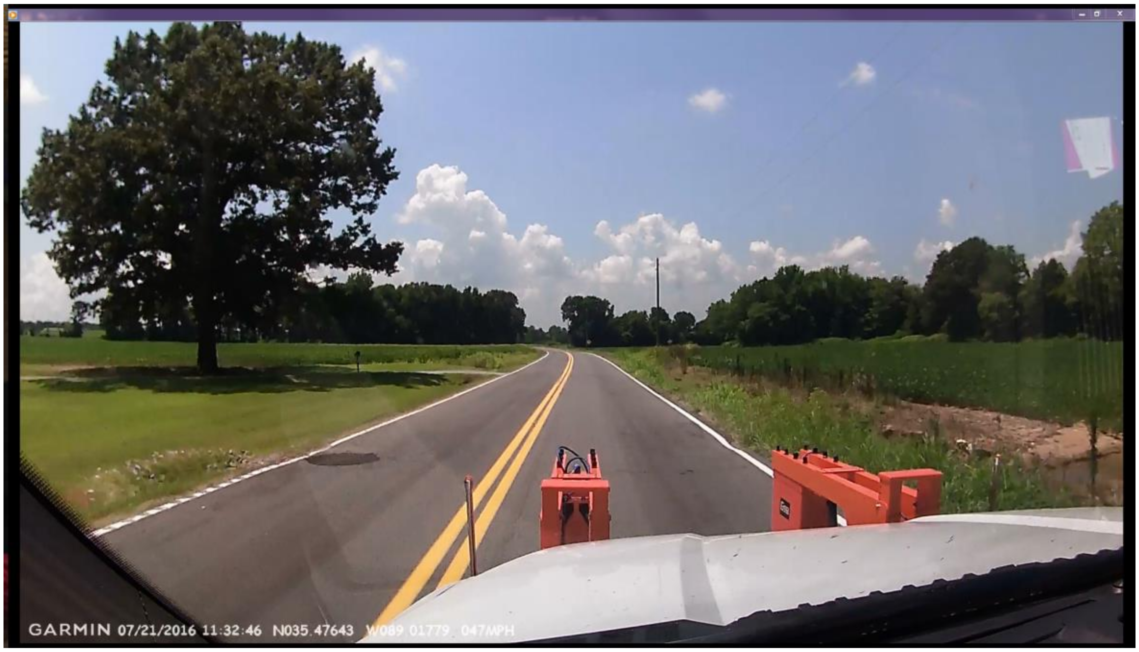


Figure 7: Screenshot of video collected using Dash cam.

Power is supplied to the system using an ExelTech 600 XP power inverter that is wired directly to the vehicles battery along with an uninterrupted power supply (UPS). The power inverter makes up to 120V available to the system. When testing the inverters supplied voltage it was found that it was dropping voltage to 70V at times so it was deemed necessary to add in the UPS to act as a buffer and keep a constant voltage available to the system.

It was suggested by GSSI that the team uses an agricultural type GPS since it would be accurate and directly compatible with the SIR 30. GSSI mounted their GPS unit to the vehicle using a magnet to the top of the van. Since the truck used in data collection was a 2015 Ford F150 with Aluminum alloy body, it was not possible to attach the GPS to the truck using a magnet. Therefore, a mount was made for the bed of the truck by the Herff College of Engineering technicians that the GPS unit can screw into. The mount and GPS is shown in Figure 8.

Figure 8: GPS mounted on the back of the truck.

GPR Data Collection and Processing Training

A crucial part of setting this project was traveling to Nashua, New Hampshire at GSSI headquarters location in order to receive further instruction and training in how the system operates. On March 20-24 of 2016, Dr. Abdelnaby and Mr. Colton Baker drove the truck with all the equipment in it to GSSI for the training.

The GSSI personnel assisted the team to setup the GPR system and have it working in Nashua, NH at GSSI location. After setting up the system, the first scan was done in a parking lot next the GSSI building. This was done to demonstrate how the system would look while running and allowed us to get familiar with the user marks that could be entered while collecting data. User marks allow the user to set markers in the data for anything that the user deems important or would create irregular data points. For the practice run, it included manhole covers and speed bumps. In practice bridges, railroads, rough patches of pavement, pavement patches and a change of material are all tracked using user marks. All of this concluded the first day at the GSSI facility.

Part of the training included collecting some real data and then going over how to process it with the GSSI staff. RADAN7 and its capabilities were introduced by GSSI and the team got practice in processing the data collected earlier that morning along with some actual state route data from a previous project that GSSI had access to. No major problems occurred during processing the data files and by the end of the training workshop at GSSI, the team was certified in using RADAN7 for data processing and for GPR data collection.

4.2. Road Scanning Process

After configuring the GPR system, the equipment was ready for scanning by May of 2016. The first thing that had to be done for the project was to start setting up routes to be scanned and to set up a process to best use the time spent in the truck. Setting up a program that would route based off the distance between GPS coordinates was considered for this, but it was ultimately decided that this would not necessarily give the best results. The program would have no way of knowing where roads were and this would prove to be problematic for the majority of the state since it is rural. The rural setting along with numerous protected wildlife areas caused there to be no road where the program assumed there to be; hence, the program would not be able to select the optimal route. The routing function within ArcGIS was also considered for routing purposes.

In the ArcGIS function, GPS coordinate points are entered in and then it can optimize the routes based on roads and certain functions entered in, much the way a car GPS system works. This function would be ideal, except for the fact that it operates on single points and not routes, with no way of specifying the order that points were to be reached. Using this feature of ArcGIS created routes that missed scanning the state routes that needed to be collected but collected the start and end points.

It was decided that the best way to optimize routes was to do so visually, without the aid of a program. Using ArcGIS, state routes were entered into the map and the best route was selected based on roads that connected them in the basemap, usually traveling north to south or south to north while minimizing back tracking. Once an optimal route was selected, typically covering between 100-150 miles of scannable state routes, the points would be entered into Google Maps. If it seemed that this route took too much time, ArcGIS would be reentered to select a new route that would take less time. Figure 9 is what an optimized route looks like in ArcGIS for TDOT region 1.

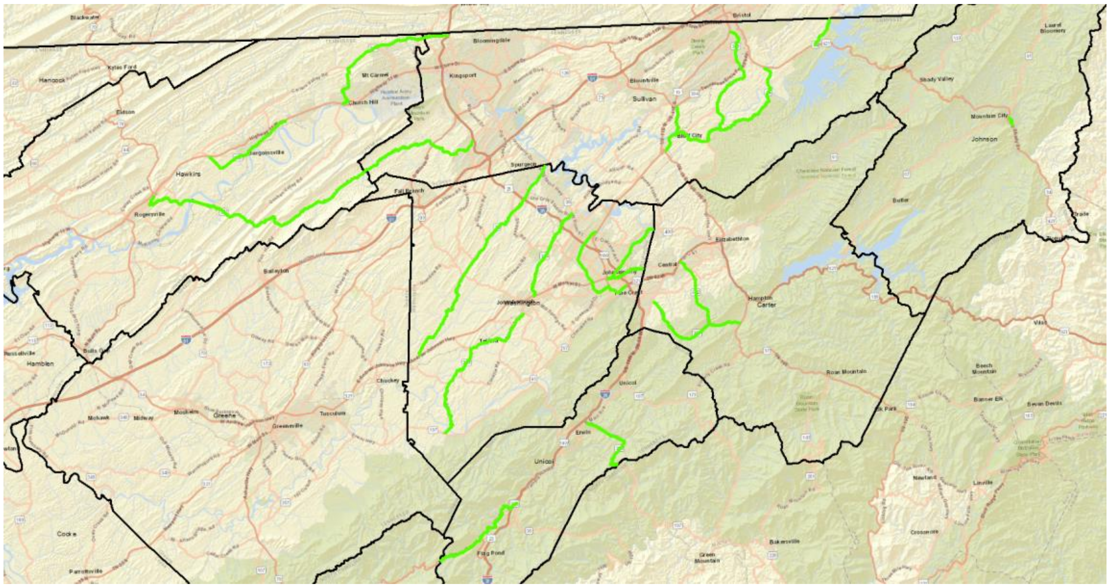


Figure 9: Optimized routes using ArcGIS.

The route pictured is Route 1.1 and was scheduled to take nine hours to scan 143 miles. An atypical problem with this route is the isolated half-mile state route located in the northeast of the map that added an extra hour to the route.

The only issue with using ArcGIS is that it is a not a readily available software. To combat this all of the GIS routes were exported into a .kml Google Earth file in order to be more accessible while on the road. In order for easier input while scanning all routes were also entered into a spreadsheet with the starting and ending point in the order that they would be scanned. Table 2 is an example of the above route in table form.

Table 2: Optimized routes using ArcGIS routing function.

Route	Start		End		Miles	Time
SR-418	36.468017	-81.80417	36.475949	-81.809145	0.76	
SR-44a	36.565167	-82.07060	36.595617	-82.045720	2.6	
SR-390	36.503917	-82.26260	36.480593	-82.266600	2.45	
SR-358	36.475900	-82.20397	36.583800	-82.185730	9.45	
SR-44b	36.542617	-82.14053	36.450783	-82.288700	12.02	2h 4min
SR-400	36.346950	-82.22080	36.317100	-82.361920	5.28	
SR-400a	36.310217	-82.36577	36.334483	-82.343930	1.63	
SR-91b	36.326361	-82.31528	36.316534	-82.367560	1.35	
SR-91a	36.316717	-82.36688	36.319800	-82.344500	1.32	
SR-362	36.328517	-82.26928	36.261833	-82.228950	5.95	1h 15min
SR-361	36.261383	-82.18632	36.288533	-82.305730	8.87	
SR-395	36.158250	-82.40230	36.106867	-82.352770	6.16	
SR-352	36.016167	-82.59658	36.123017	-82.444750	9.06	
SR-381	36.300670	-82.35217	36.368217	-82.378430	7.63	2h 19min
SR-354	36.389783	-82.41098	36.29965	-82.468570	7.48	
SR-353	36.281617	-82.48400	36.151167	-82.59640	13.3	
SR-75	36.237983	-82.62713	36.444000	-82.445920	18.5	
SR-347	36.474617	-82.54348	36.426367	-82.983500	10.62	
SR-346a	36.466167	-82.90542	36.503283	-82.799550	7.5	2h 48min
SR-346b	36.519483	-82.72067	36.591700	-82.571980	11.9	26min
				sum	143.83	8h 52min

When all information is gathered, trips are put together consisting of the routes. TDOT regions 1, 2 and 3 are all put into trips while region 4 is scanned on day outings for each route. As a side effect of this region 4 takes many more routes to scan the full region than any of the other regions simply due to not starting the day next to the starting point.

To start scanning the system must be set up. This process involves mounting antennas and arms to the truck, attaching the survey wheel to its plate and calibrating, connecting the GPS and creating the bumper jump file. The bumper jump file is completed by placing a metal plate underneath the antenna and then scanning while jumping up and down on the front bumper of the truck. One of the reasons that this is done is that it ensures the pavement surface is measured accurately and does not reflect the movement in the antenna arms caused by the truck's suspension. Doing this helps to smooth out the data having the road surface go from appearing to have waves in it, into more constant elevations.

Once the system is set up, data can begin to be collected. Data collection requires two people to complete, one to drive the truck and another to operate the equipment. The equipment operator has several tasks to complete while collecting data. The first task is to be the navigator making sure that all the routes get covered in the specified order by entering in the coordinates into the GPS and making sure that the actual state route is followed, not the quickest GPS generated route. The equipment operator also operates the dash cam, turning it on a half mile before a route starts. The main thing that the operator does is run the GPR equipment. It is his responsibility to make sure that system is operating correctly, that it is reading reasonable values and picking up the GPS signal. While scanning, he must also add user marks for any changes in the road.

4.3. FWD

The team also provided suggested routes to be tested under FWD. The routes that were selected represent the majority of the 3,306-mile state routes. The falling weight deflectometer (FWD) is a non-destructive testing (NDT) and non-intrusive device. It is used to determine the elastic modulus of separate pavement layers. The FWD plays a crucial role in selecting optimum pavement maintenance and rehabilitation strategies. It is a system that mimics heavy wheel loads by dropping a variable weight from differing heights and measures the deflections in the pavement using sensors placed at user specified distance from the weight (Figure 10). Knowing asphalt thickness is necessary for subsequent data processing. In this study, the asphalt thickness was estimated by using GPR data. This data was also verified by core test results.

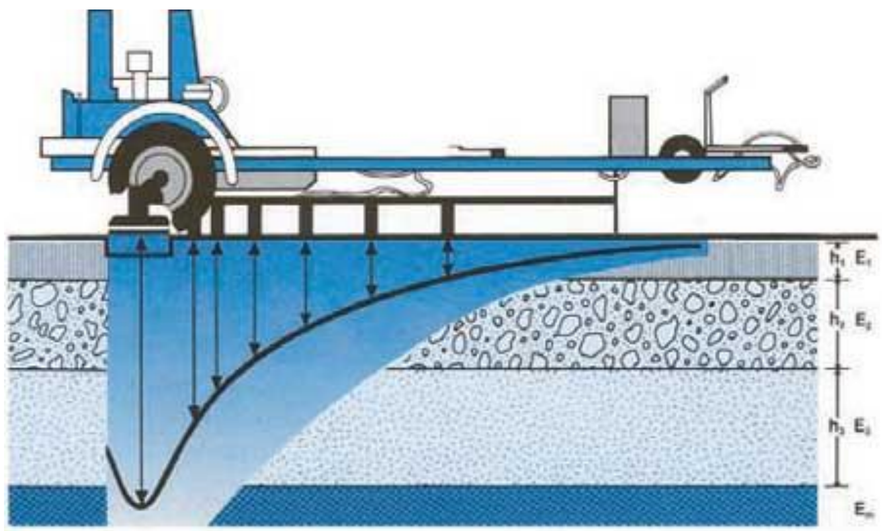


Figure 10: FWD test.

The FWD system used included processor Processor Control System, Power Source, Computer Display, Hydraulically operated loading weights, Rubber Loading Plate and Geophone sensors as shown in Figure 11.

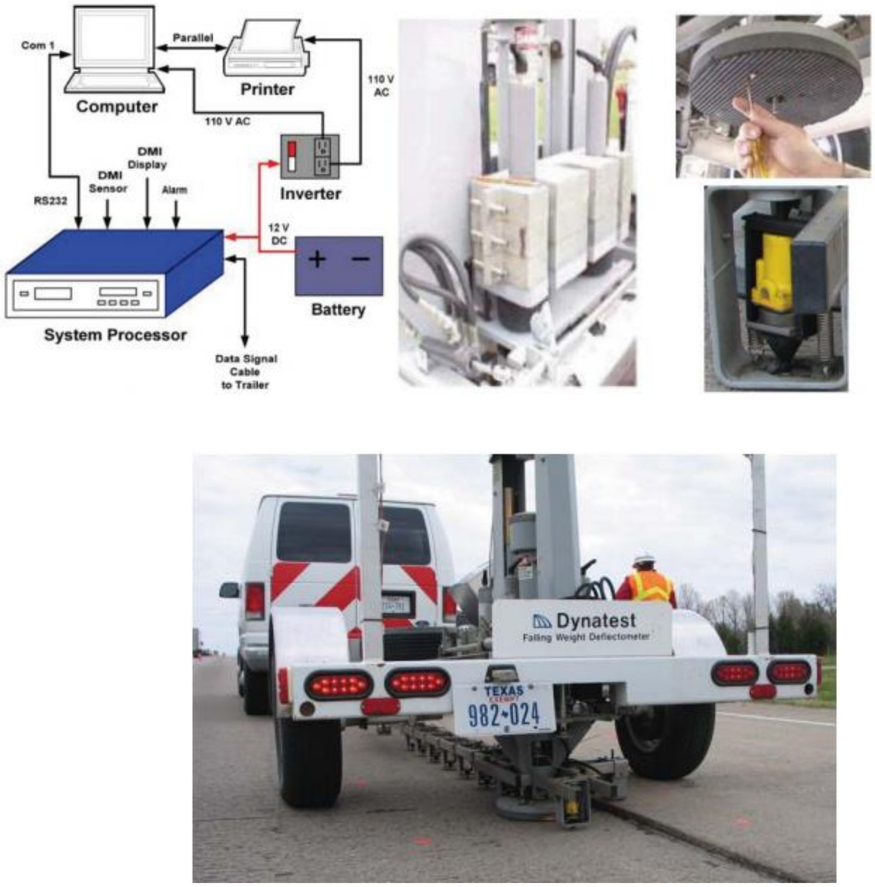


Figure 11: Typical FWD system.

Routes Selection Criteria

The team was tasked with selecting 25 testing sites in the state that would give a general SN for existing state routes. These 25 routes were selected to represent the entire 264 routes in the four regions. The selection criteria were based on the following:

- Accessibility of routes for TDOT crews
- The 25 routes represented various layer thicknesses
- Sites with good GPR data
- Bedrock at least 20 feet below pavement surface

TDOT FWD Training

- Main emphasis of training was an introduction to and troubleshooting for TDOT's existing FWD machine
- First meeting consisted of PowerPoint presentations on the FWD machine; the history of Dynatest, the mechanical workings of the machine and then trouble shooting for common problems

- Second day esting consisted of running the machine in TDOT garage, familiarizing TDOT personnel with the computer system and knowing what to look for.

Testing Procedures

- Based upon ASTM D4695-03(Calculating Elastic Modulus) and D4694-09 (Falling Weight Deflectometer)
- Need to collect data in the wheel path, with any loose debris cleared from underneath the load plate
- Must perform a seating drop to ensure that plate is seated flatly on the ground
- Perform two drops that will simulate a 9000 lb wheel load that do not differ more than 3% in maximum deflection
- Record at least the air and surface temp at site location (subsurface temperature can be empirically calculated from these)
- Must know depth to bedrock and layer thicknesses
- For project level testing, collect 15 points of data along a continuous stretch of pavement per ASTM D4695-03

PCASE 2.09.05

To get elasticity modulus and allowable number of passes based on a certain load, PCASE 2.09.05 was employed (Figure 12). Pavement-Transportation Computer Assisted Structural Engineering (PCASE) develops software tools to aid in the design and evaluation of transportation systems (PCASE User Manual).

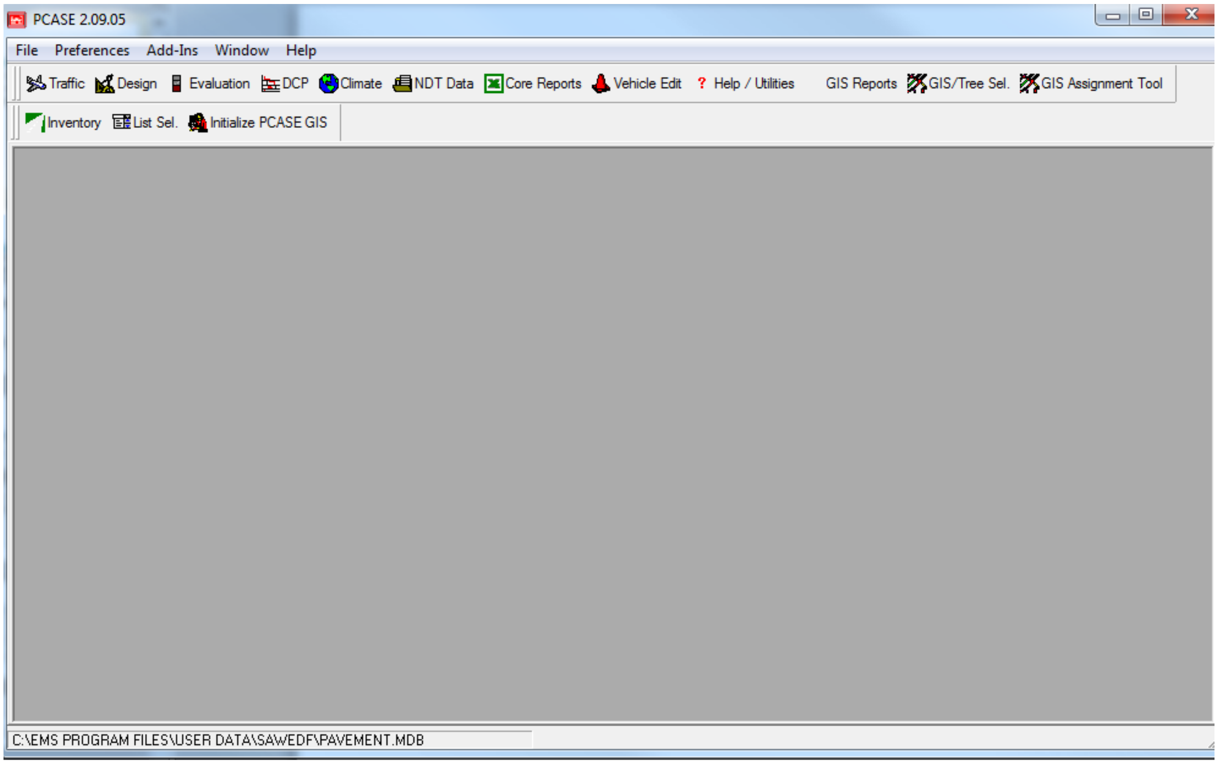


Figure 12: PCASE 2.09.05

We used four modulus in this software to evaluate the selected sections:

1. Traffic
2. NDT Data
3. Climate
4. Evaluation

Traffic: Traffic module is capable of building traffic models to be used in the design or evaluation modules using vehicles provided in the database. The AXLE, 18 KIP vehicle was selected for the road design to evaluate the pavement condition (Figure 13).

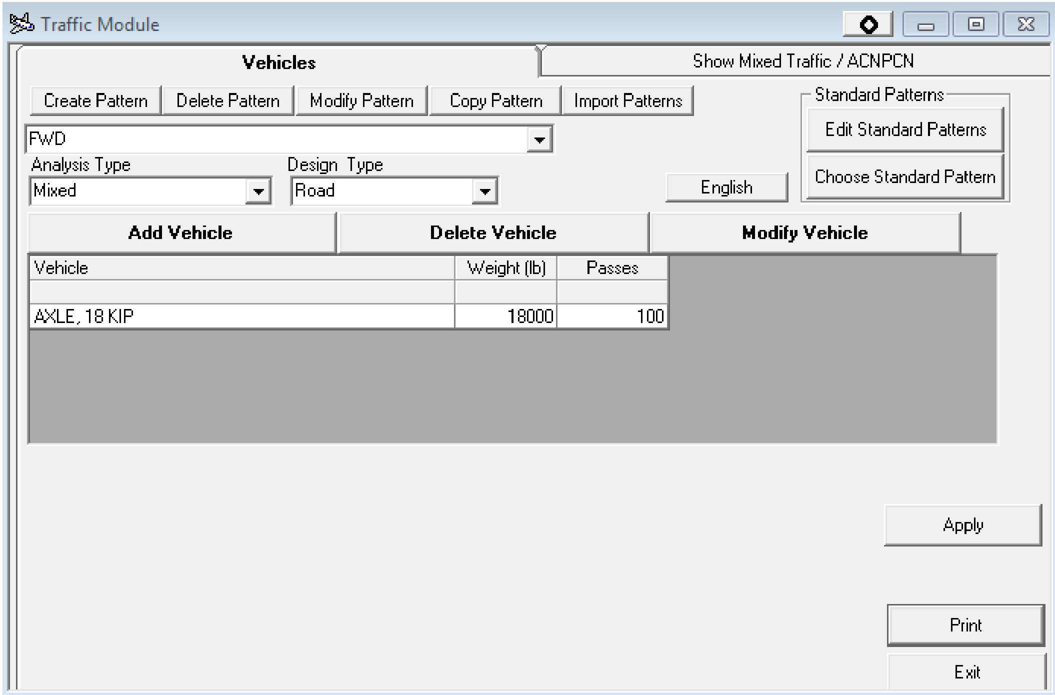


Figure 13: Traffic Module

NDT Data: NDT module (Figure 14) is capable of importing and viewing falling weight deflectometer data (FWD), defining section boundaries and assigning data for backcalculation. We used stiffness plots (Stiffness, Load/ Displacement versus Station ID) and divided the routes to different sections (based on stiffness values). All the stations in the assigned sections had close stiffness. This was determined based on Statistics button in "Charts" window (Figure 15).

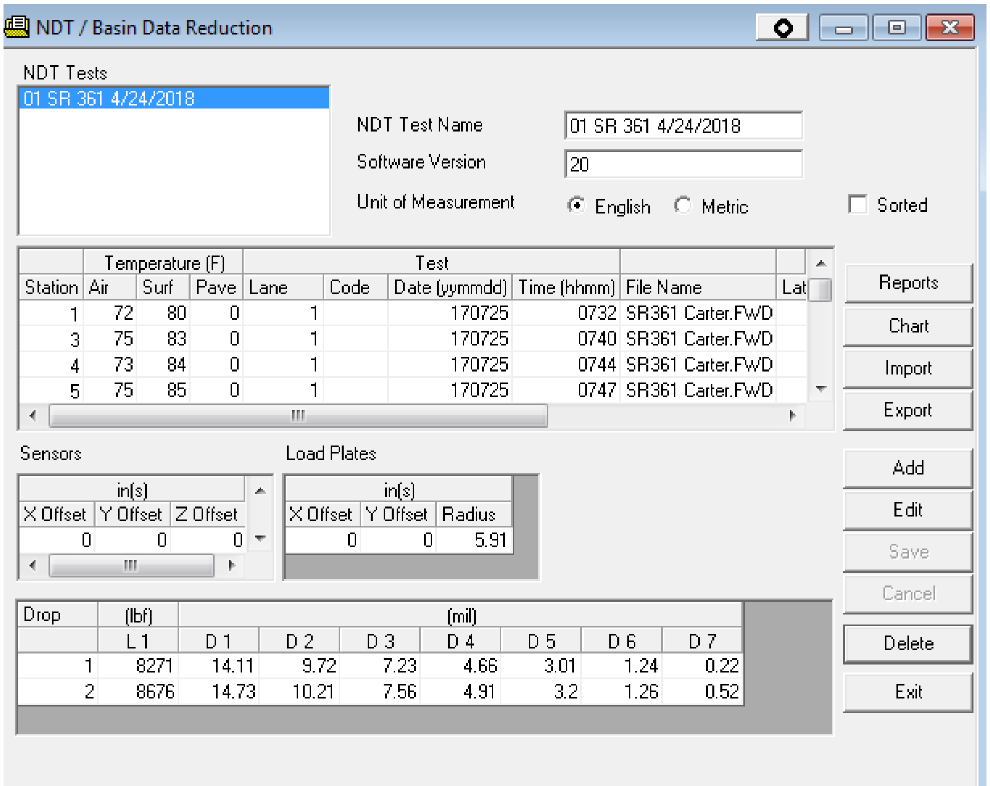


Figure 14: NDT Module

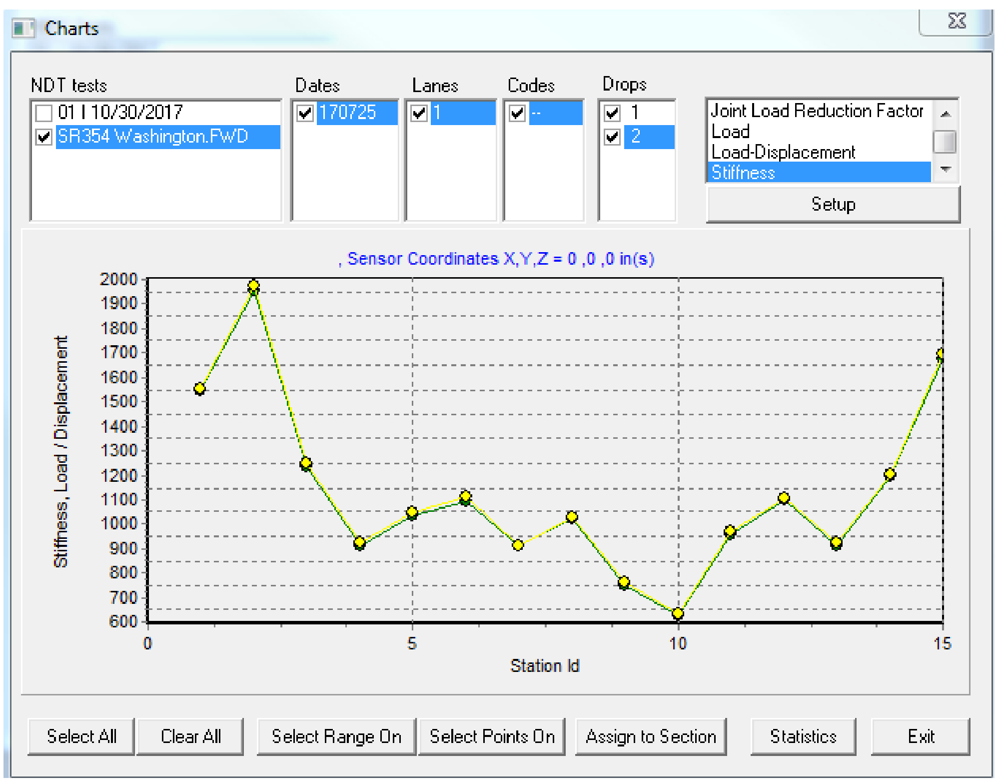


Figure 15: Stiffness Chart

Climate: Climate module is capable of calculating temperature data used in the evaluation module. We used the Temp option for asphalt. In the Backcalc E option, the Temp refers to the temperature at time of NDT testing and sets asphalt modulus based on previous 5 day mean temperature for backcalulating other layers (Figure 16). The temp option should be considered in the Backcalculate E option if the asphalt thickness is less than 4.0 inches or the backcalculated values are outside the acceptable range of asphalt modulus. In the Analysis E option, the temp refers to the design pavement temperature and sets the design modulus for the asphalt layer.

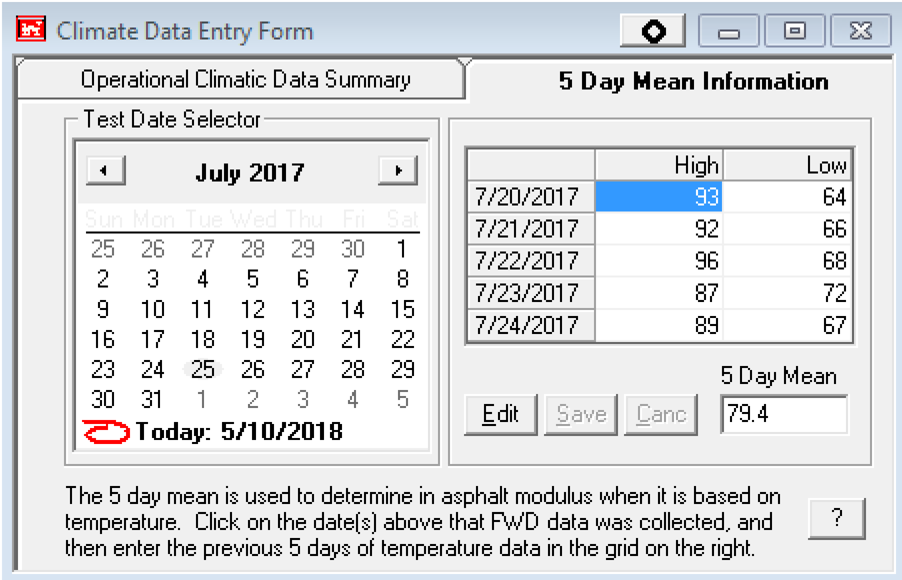


Figure 16: Climate Module

Evaluation: Evaluation module is capable of analyzing flexible, rigid, and aggregate roadway and airfield pavement and producing resultant allowable loads, passes, Aircraft Classification Numbers (ACN), Pavement Classification Numbers (PCN), and overlay requirements. There are three TABs in evaluation module. In the first tab, evaluation type (Road), analysis type (Layered Elastic Criteria (Modulus Values) – LEEP), pavement condition (PCI>40), and traffic pattern are introduced (Figure 17).

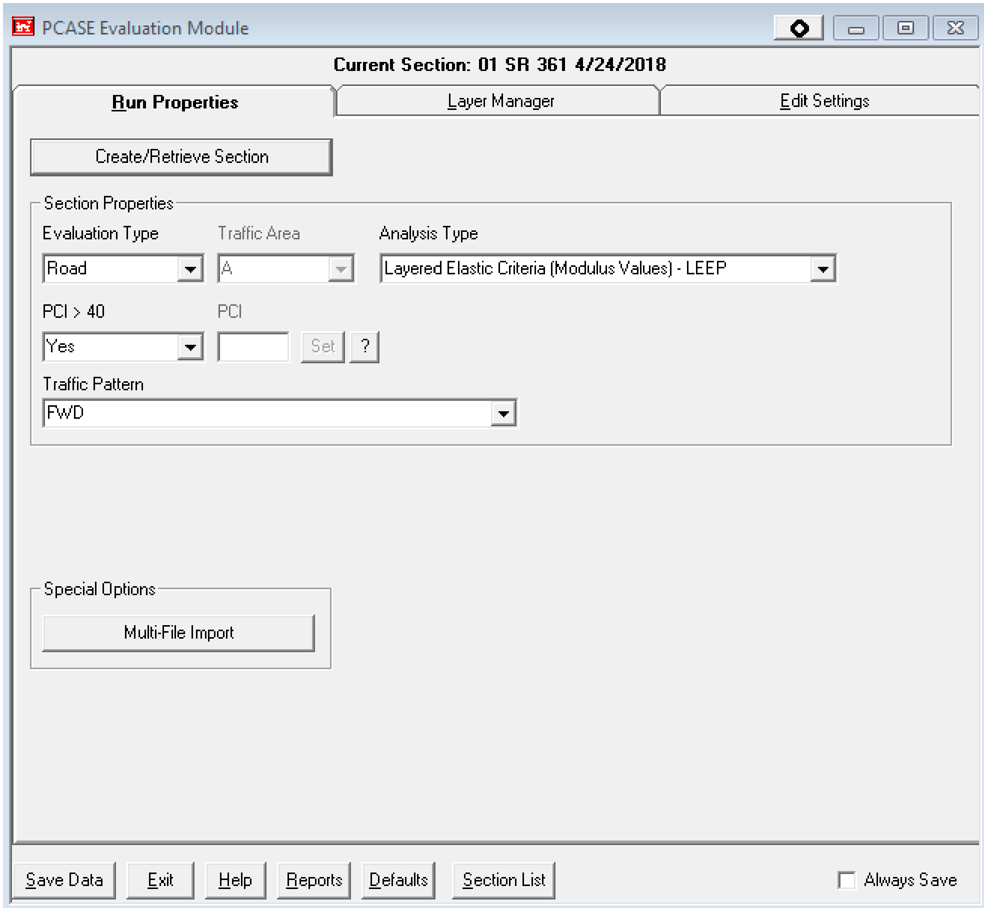


Figure 17: Evaluation Module (Run Properties)

In the second tab, the layer structure is created. This includes the thickness for different layers including Asphalt, Base, and Natural Subgrade. These data were obtained from GPR testing (Figure 18).

The third tab also includes settings for Backcalculation and analysis. In this tab, minimum and maximum limits for the strength of different layers are introduced along with tolerances and number of iterations (Figure 19).

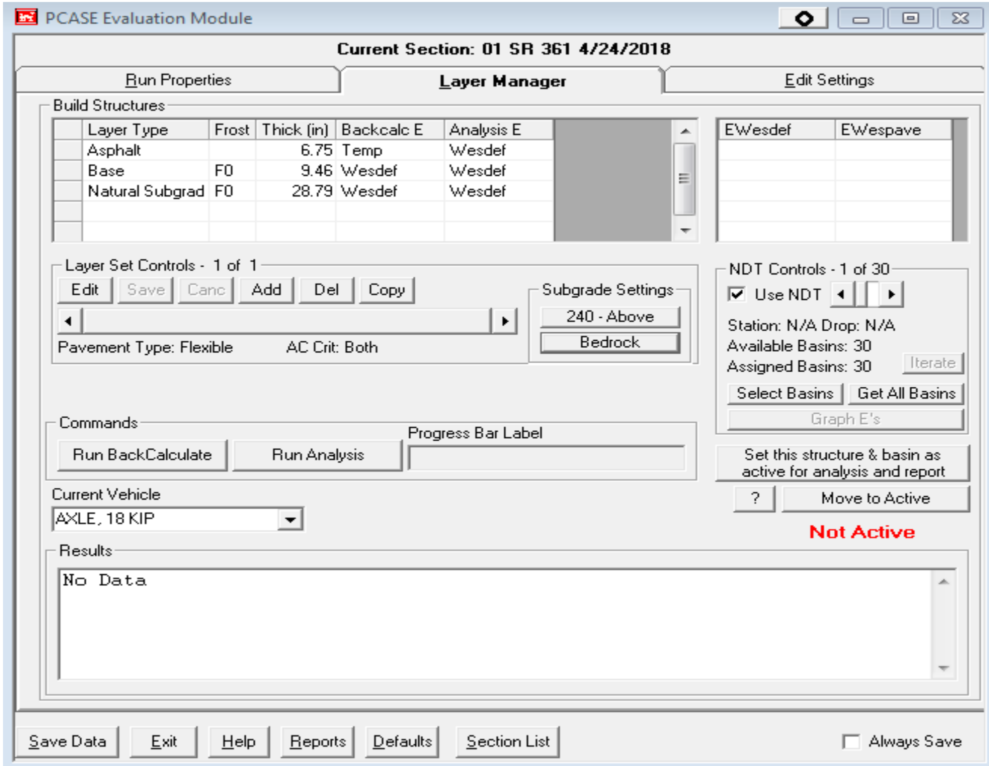


Figure 18: Evaluation Module (Layer Managers)

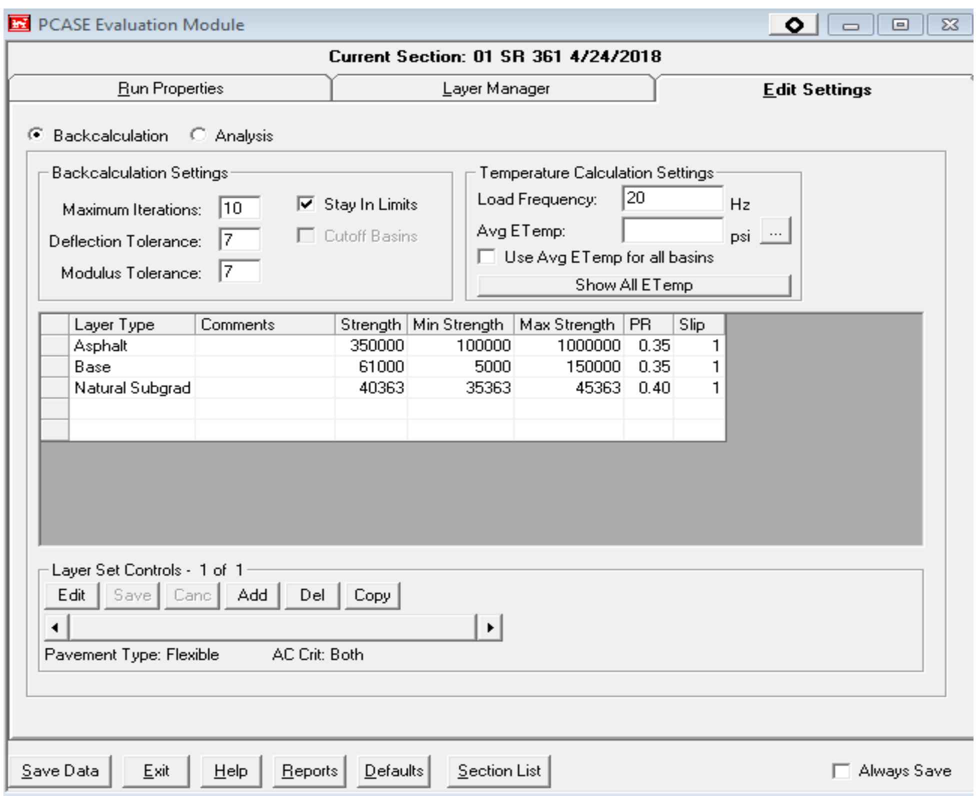


Figure 19: Evaluation Module (Edit Settings)

Routes

We did analyses on FWD test results using PCASE 2.09.05 software. The Considered routes included:

- SR181
- SR182
- SR185
- SR187
- SR190
- SR192
- SR399
- SR284
- SR44
- SR340
- SR345
- SR351
- SR354
- SR361

Analysis procedure

The results from FWD tests in .FWD format were employed and uploaded through NDT tab in PCASE software to plot stiffness charts (Figure 20).

SR181 - Notepad

File Edit Format View Help

Test Name : SR181.FWD
Version : 20
Measurement : E
Sensors : 7
X Offset : 0 8 12 18 24 35 47
Y Offset : 0 0 0 0 0 0 0
Z Offest : 0 0 0 0 0 0 0
Loads : 1
X Offset : 0
Y Offset : 0
Radius : 5.91

Record#	Drop#	Station	Air Temp	Sur Temp	Pave Temp	Lane	Type	Date	Time FileId L1	D1	D2	D3	D4	D5	D6	D7	
1	1	1	63	70	70	1	180131	1306	WESKRW%L-GP1NT2$W_	9059	23.17	17.96	15.16	11.63	8.69	3.89	1.91
1	2	1	63	70	70	1	180131	1306	WESKRW%L-GP1NT2$W_	8961	22.7	17.69	15.02	11.49	8.61	3.86	1.91
2	1	2	62	70	70	1	180131	1317	WESKRW%L-GP1NT2$W_	8950	14.51	13.09	11.52	9.42	7.69	4.63	1.87
2	2	2	62	70	70	1	180131	1317	WESKRW%L-GP1NT2$W_	8873	14.31	12.95	11.39	9.31	7.6	4.57	1.88
3	1	3	64	73	72	1	180131	1319	WESKRW%L-GP1NT2$W_	9399	24.13	20.19	17.73	14.38	11.68	6.97	2.64
3	2	3	64	73	72	1	180131	1319	WESKRW%L-GP1NT2$W_	8994	22.97	19.27	16.92	13.74	11.15	6.67	2.49
4	1	3	63	71	72	1	180131	1320	WESKRW%L-GP1NT2$W_	9377	24.62	20.58	18.03	14.56	11.96	7.07	2.67
4	2	3	63	71	72	1	180131	1320	WESKRW%L-GP1NT2$W_	9048	23.67	19.79	17.36	14.04	11.56	6.85	2.56
5	1	3	63	71	72	1	180131	1322	WESKRW%L-GP1NT2$W_	9322	24.8	20.7	18.15	14.65	11.96	7.14	2.68
5	2	3	63	71	72	1	180131	1322	WESKRW%L-GP1NT2$W_	8994	23.82	19.82	17.33	14.04	11.49	6.81	2.61
6	1	3	63	71	71	1	180131	1335	WESKRW%L-GP1NT2$W_	9136	24.31	20.23	17.72	14.43	11.86	7.02	2.79
6	2	3	63	71	71	1	180131	1335	WESKRW%L-GP1NT2$W_	8917	23.09	19.69	17.31	14.05	11.47	6.9	2.52
7	1	3	63	72	72	1	180131	1339	WESKRW%L-GP1NT2$W_	9169	24.22	20.3	17.82	14.51	11.91	7.09	2.69
7	2	3	63	72	72	1	180131	1339	WESKRW%L-GP1NT2$W_	9015	23.46	19.92	17.46	14.22	11.64	6.98	2.59
8	1	4	63	73	72	1	180131	1344	WESKRW%L-GP1NT2$W_	9180	21.13	14.96	12.3	9.11	7.09	4.05	2.27
8	2	4	63	73	72	1	180131	1344	WESKRW%L-GP1NT2$W_	9005	20.72	14.65	12.07	8.96	6.94	4.01	2.2
9	1	5	63	71	70	1	180131	1346	WESKRW%L-GP1NT2$W_	9224	14.55	12.57	11.04	9	7.41	4.7	1.91
9	2	5	63	71	70	1	180131	1346	WESKRW%L-GP1NT2$W_	8994	14.09	12.25	10.78	8.79	7.23	4.59	1.84
10	1	6	63	72	71	1	180131	1349	WESKRW%L-GP1NT2$W_	9224	12.7	10.09	8.75	7.16	5.8	3.57	1.63
10	2	6	63	72	71	1	180131	1349	WESKRW%L-GP1NT2$W_	8972	12.32	9.81	8.52	6.96	5.65	3.46	1.61
11	1	7	62	71	71	1	180131	1351	WESKRW%L-GP1NT2$W_	9213	10.76	8.53	7.91	6.94	5.98	3.81	1.72
11	2	7	62	71	71	1	180131	1351	WESKRW%L-GP1NT2$W_	8895	10.29	8.24	7.63	6.72	5.78	3.68	1.64
12	1	7	63	70	69	1	180131	1353	WESKRW%L-GP1NT2$W_	9191	24.24	19.83	15.98	12.2	9.11	4.77	2.07
12	2	7	63	70	69	1	180131	1353	WESKRW%L-GP1NT2$W_	8972	23.64	19.43	15.68	11.94	8.94	4.68	2.06
13	1	8	64	71	71	1	180131	1355	WESKRW%L-GP1NT2$W_	9267	13.89	11.28	9.84	8.13	6.65	3.76	1.91
13	2	8	64	71	71	1	180131	1355	WESKRW%L-GP1NT2$W_	8972	13.44	10.89	9.51	7.88	6.45	3.66	1.83
14	1	9	63	71	70	1	180131	1358	WESKRW%L-GP1NT2$W_	9158	15.65	13.57	11.89	7.55	6.2	4	1.74
14	2	9	63	71	70	1	180131	1358	WESKRW%L-GP1NT2$W_	8884	15.21	13.26	11.65	7.35	5.99	3.89	1.6
15	1	10	62	72	71	1	180131	1400	WESKRW%L-GP1NT2$W_	9081	23.73	20.59	17.91	14.52	11.85	5.04	2.44
15	2	10	62	72	71	1	180131	1400	WESKRW%L-GP1NT2$W_	8928	23.23	20.16	17.57	14.26	11.63	4.93	2.4
16	1	11	65	73	73	1	180131	1402	WESKRW%L-GP1NT2$W_	9147	20.36	16.76	13.65	10.7	8.21	5.11	2
16	2	11	65	73	73	1	180131	1402	WESKRW%L-GP1NT2$W_	8851	19.83	16.22	13.33	10.4	8.02	4.96	1.96
17	1	12	66	74	73	1	180131	1404	WESKRW%L-GP1NT2$W_	9213	16.84	11.78	9.96	7.47	5.76	3.39	1.54
17	2	12	66	74	73	1	180131	1404	WESKRW%L-GP1NT2$W_	8917	15.94	11.35	9.46	7.21	5.58	3.28	1.49
18	1	13	65	74	74	1	180131	1407	WESKRW%L-GP1NT2$W_	9103	14.89	13.05	11.5	9.4	7.46	4.03	1.78
18	2	13	65	74	74	1	180131	1407	WESKRW%L-GP1NT2$W_	8785	14.44	12.69	11.17	9.11	7.2	3.92	1.69
19	1	14	65	76	75	1	180131	1409	WESKRW%L-GP1NT2$W_	9224	16.69	12.65	10.88	8.35	6.74	4.02	1.79
19	2	14	65	76	75	1	180131	1409	WESKRW%L-GP1NT2$W_	8939	16.13	12.35	10.58	8.14	6.55	3.9	1.71
20	1	15	65	76	75	1	180131	1411	WESKRW%L-GP1NT2$W_	9399	8.82	6.6	5.73	5.1	4.36	3.34	1.92
20	2	15	65	76	75	1	180131	1411	WESKRW%L-GP1NT2$W_	8928	8.35	6.29	5.48	4.87	4.22	3.19	1.66

END

Figure 20: Data from FWD test

The stiffness charts for the regions were assigned to different sections based on network, branch, section, and inception date (Figure 21).

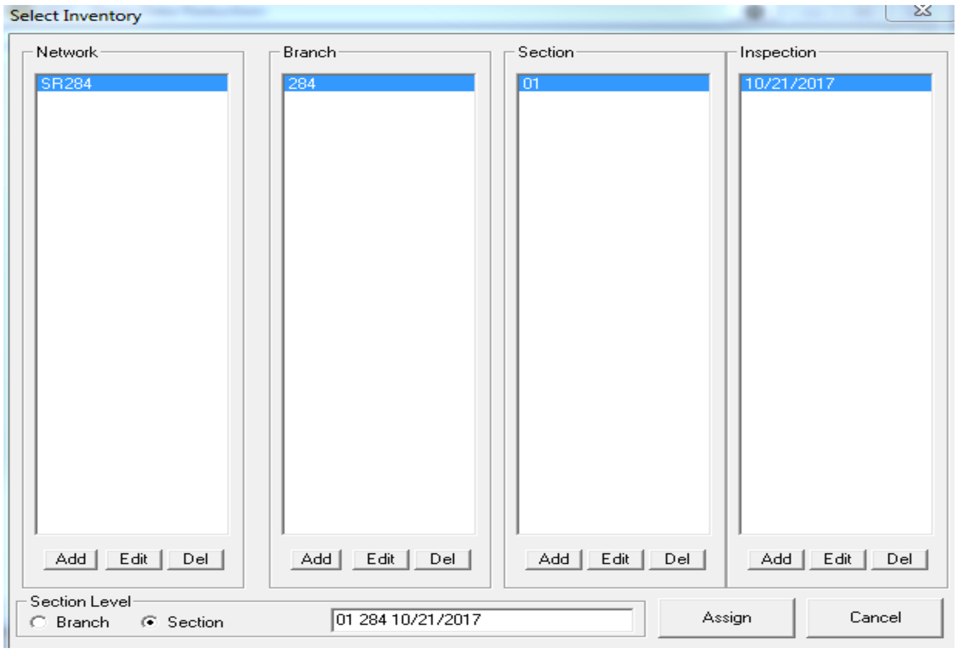


Figure 21: Assigning the stiffness charts to sections.

The average five day mean temperature was defined through climate tab and using the data provided by https://www.usclimatedata.com (Figure 22).

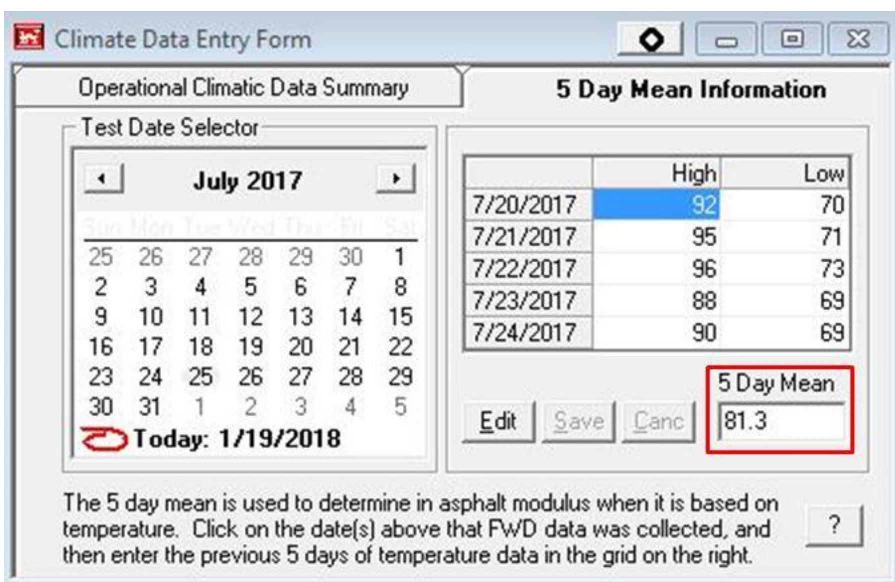


Figure 22: Climate data.

Finally, the data was analyzed using evaluation tab based on evaluation type, analysis type, PCI, and traffic pattern as follows:

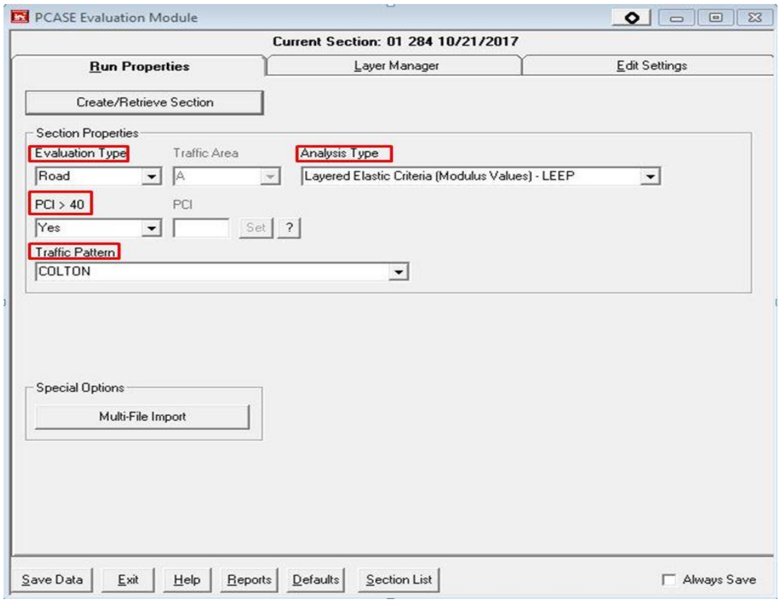


Figure 23: Evaluation tab.

We defined 3 layers including asphalt, base, and subgrade as it was defined in the previous section (Figure 24). The thicknesses of the asphalt and base layers were provided by the results of GPR test.

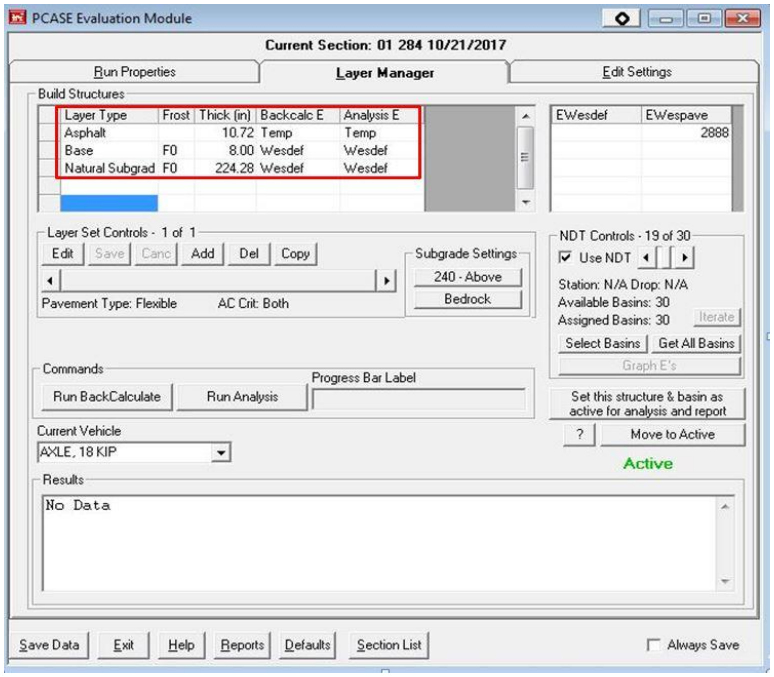


Figure 24: Pavement layers.

5. Results and Findings

5.1. GPR

To process the GPR data, the GSSI program RADAN7s RoadScan functionality is used. This program converts the measurements taken during data collection and turns it into a graph of the frequencies. In figure 14, the green returns are positive wave lengths and the blue represent negative. At the interface of two materials the return of the two wavelengths become more prominent shown highlighted in the box within Figure 25. Pavement layers are manually selected based upon these wavelengths.

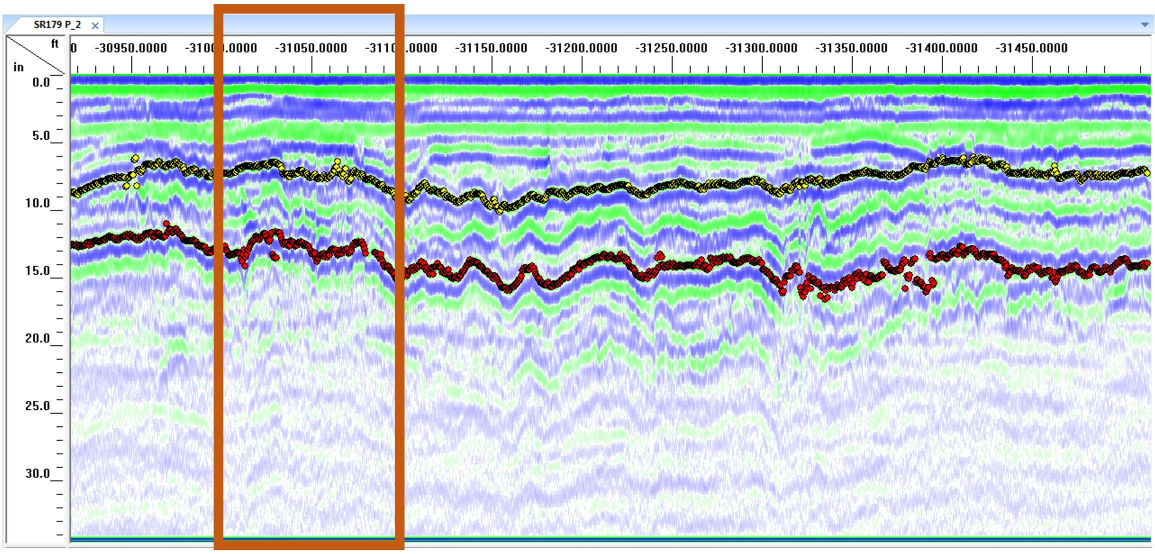
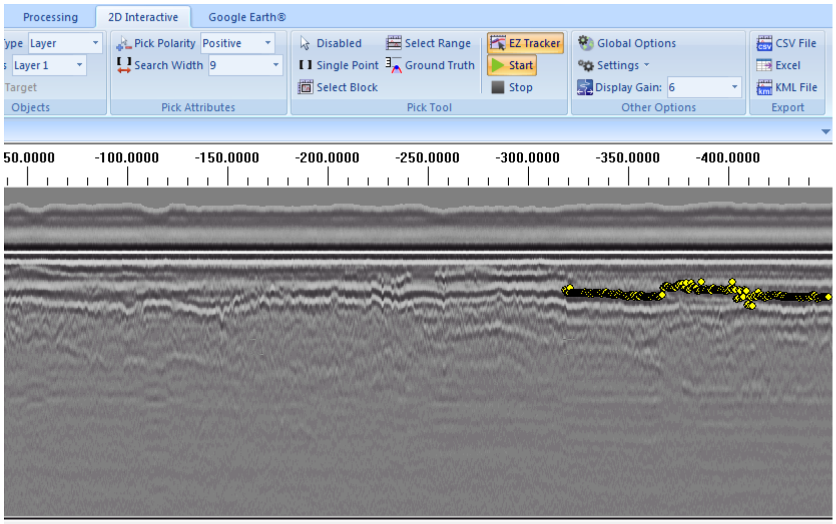


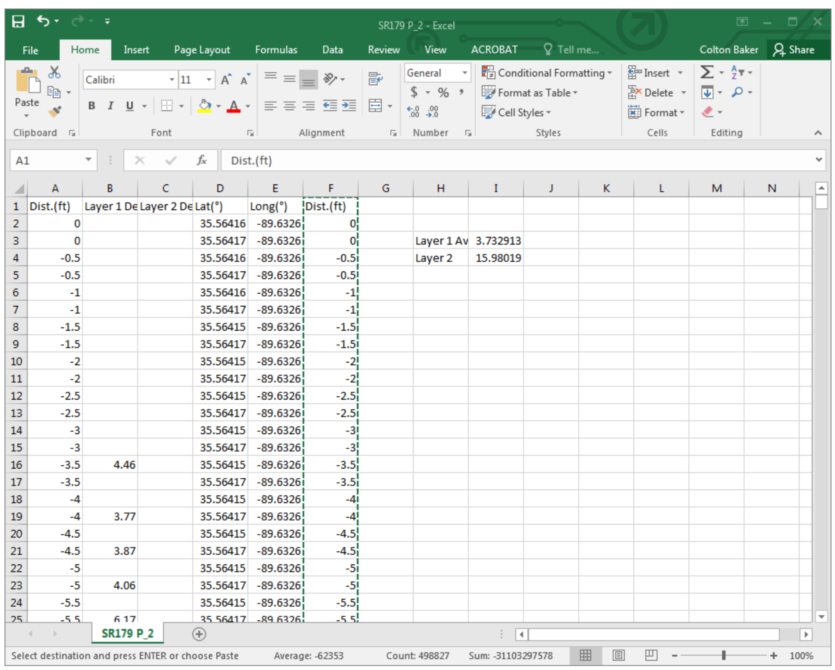
Figure 25: Layer thickness selection based on wave reflection.

RADAN7 has built in layer picking programs, but it is not accurate and assumes that there are more layers than are actually present. It has no way of filtering out erroneous wavelengths that are reflections of the actual data. Instead of using this function of the program all layers are picked by hand using the 2D Interactive toolbox. Within this toolbox up to 7 layers can be selected, using a tool called the EZ Tracker. The EZ tracker enables the user to select a depth frequency and will then assign depths for the data until another frequency is selected by the user. This fills in depths at half-foot intervals and allows for faster processing than having to select each depth point individually.

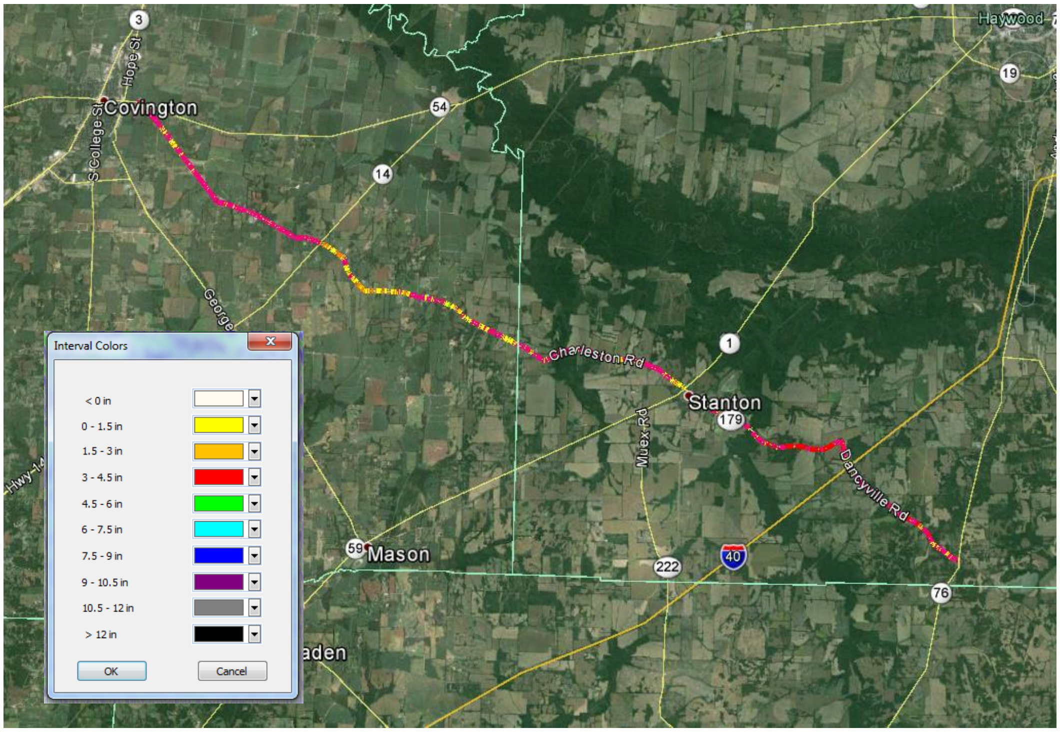
Once all the visible layers are selected, typically two or three, the data can be exported in three ways. The first way that the data can be exported is as an image file. Doing so does not give any of the layer information in tabular form but is useful if the data needs further interpreting later on. This is the largest file size since each page can only hold about 200 feet worth of data. The next way to export is to export any parameters selected into an Excel readable .csv file. This allows the information to be separated into rows and columns to make easy sense of the data. This method of exporting is good if any statistical analysis should ever need to be done on the files. The last method of exporting the data is to a .kml Google Earth file directly that will display layer depths, ground truths and user marks directly to the coordinates associated with the information. ArcGIS can then convert the .kml file into a layer. This method is useful if a quick visual of the road needs to be shown. Figure 26 below shows all three exporting options.



(a)



(b)



(c)

Figure 26: Exported image file (a); .csv file (b); .kml example (c).

All 264 routes have been scanned and processed. The team will send TDOT all data in one (1) hard drives. The hard drive contains GPR raw and processed images, excel files with pavement properties, GIS files, road surface photos and videos, and FWD data.

5.2. FWD

Elasticity modulus of the layers

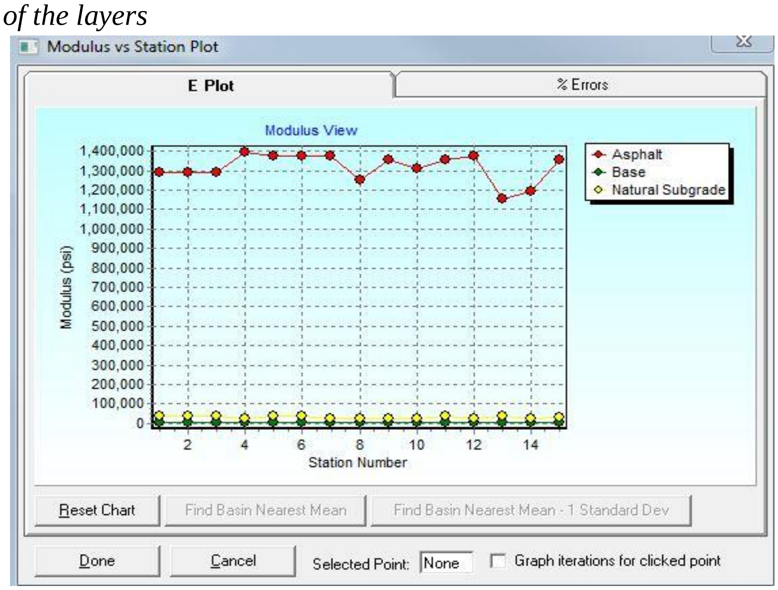


Figure 27: Elasticity modulus of the layers.

Allowable passes for full load (18Kips)

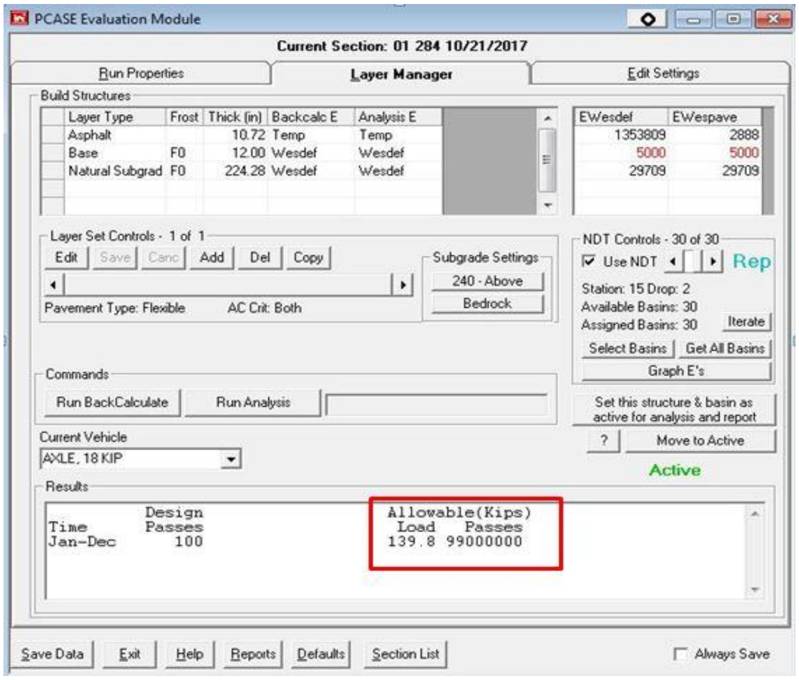


Figure 28: Allowable passes based on the load.

Required overlay to guarantee the minimum thickness requirements for surface and base layers are met (if needed).

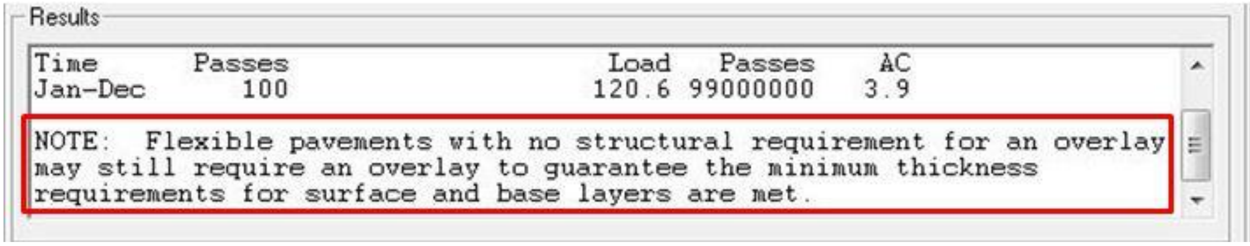


Figure 29: Overlay requirement.

Results

The results are summarized in the below table:

Station	Thickness			Elasticity Modulus			Allowable (Kips)		Overlay (in)
	Asphalt	Base	Natural Subgrade	Asphalt	Base	Natural Subgrade	Load	Passes	
SR44	9.50	11.88	32.62	472632	89021	13575	240.4	99000000	-
SR340	8.75	5.00	39.25	66042	163196	11877	88.0	99000000	-
SR345	11.25	3.26	24.50	76403	664956	12560	138.6	99000000	-
SR351	10.50	5.00	42.50	100694	131103	8459	93.1	99000000	-
SR354	8.75	5.00	41.25	224767	498139	11460	173.9	99000000	-
SR361	6.75	9.46	28.79	154621	95159	12379	114.9	99000000	-
SR181	4.83	7.42	44.75	671162	59984	7109	69.5	10255512	-
SR182	5.58	6.27	41.15	73373	43734	3178	27.0	1887	-
SR185	4.21	4.04	49.75	150205	1394193	7400	93.6	99000000	0.7
SR187	3.44	3.62	74.94	344164	1554191	8803	103.3	99000000	1.4
SR190	5.15	5.94	42.91	359286	52565	8372	58.0	4328803	-
SR192	3.29	3.73	75.98	277044	5543541	11126	179.3	99000000	1.6
SR399	6.03	4.74	39.23	278575	1930745	15222	233.5	99000000	-
SR284	10.53	5.00	26.47	826854	3162	12903	323.2	99000000	-

Challenge*s*

There are some challenges using PCASE software:

1- Since the manual does not clearly explain the options in some tabs, many default values provided by program were employed for the analyses.
2- Some options were not clearly defined in the manual such as EWesdef and EWespave (Figure 30).

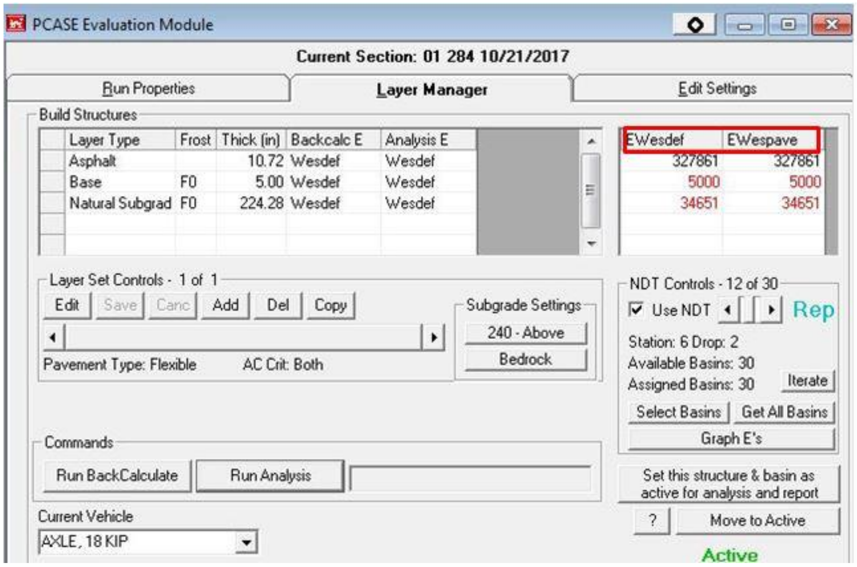


Figure 30: EWesdef and EWespave

3- Results might not be valid in some cases since some layers hit the limit and therefore invalid E values were generated (Figure 31).

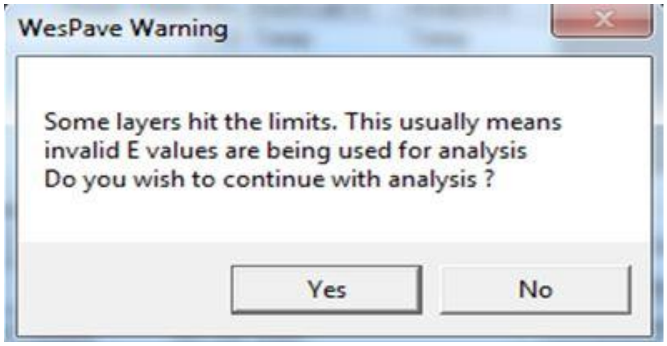


Figure 31: WesPave Warning.

6. Conclusion and Recommendations

At this stage we completed the work on schedule. We will send out one external hard drive that contains all the data we collected and processed. The data includes GPR Truck scans in (image format, excel files, GPS coordinates, GIS files, videos and photos collected by GPR Truck camera). The data also includes FWD test results that our team processed.

This study benefits TDOT in the following aspects:

1) Information on pavement composition and structural capacity of former county roads provided here by this research is of great value to TDOT, specifically the Pavement Design Office and the Division of Materials and Tests.
2) Identification of pavement layer structure and thickness, nondestructively and rapidly using GPR, provides for an inventory of the surveyed roadway system, which currently does not exist and provides data for a pavement management system (PMS).
3) This work provides TDOT with a network-level survey that identifies pavement composition of the 3,500 miles of roadway network and estimate the structural capacity of key points in the network using falling weight deflectometer (FWD).
4) Validation of GPR data (thickness of pavement layers) collected using core data provides a better understanding of the appropriate scan density for data collection for the entire 3,500 miles.
5) In this work, a geographic information system (GIS) can be integrated in the PMS. The GIS database provides a user-friendly tool to store, manage, and display pavement information along the scanned roadway segments.

This project deliverables include:

1) Data interpretation/output: distance along roadway, layer identification, thickness, and to the extent possible – pavement condition, identified/output for each roadway. Data is provided, as indicated, in a format compatible with TDOT's PMS database, in GIS format, and in spreadsheet-format.
2) A comparison between GPR and core data.
3) FWD data that provide structural capacity of roadway pavement at certain locations of the network miles scanned pavement.
4) Pavement layer profiles (distance vs. depth) are generated so that layer structure can be visualized.

5) A portable hard drive containing GPR data, video (in a compatible format with TDOT system), and all linked project files. From this drive, TDOT personnel can view GPR data interpretation coincident with linked video and GPS data.

7. References

1- Loken 2007, “Use of Ground Penetrating Radar to Evaluate Minnesota Roads” https://www.lrrb.org/pdf/200701.pdf

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