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

Colton Baker, EIT Graduate Transportation Associate Tennessee Department of Transportation Charles Camp, Ph.D. Professor of Civil Engineering The University of Memphis 106B Engineering Science Building Memphis, TN 38152 cvcamp@memphis.edu

Farid Hosseinpour, EIT Graduate PhD Student University of Memphis

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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. 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.

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

Table 1: Material Properties of common roadway materials.

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

$$\rho_2 = \frac{A_2}{A_m}$$

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 Airlaunched 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)





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.

Route	Start		E	nd	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

Table 2: Optimized routes using ArcGIS routing function.

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).

📴 PCAS	SE 2.09.05										X
File P	references Add	-Ins Window Help									
🛛 🛸 Tra	affic 🙀 Design	Evaluation 🔛 DCP	🕲 Climate /	NDT Data	Core Reports	👃 Vehicle Edit	? Help / Utilities	GIS Reports	GIS/Tree Sel.	GIS Assignment Tool	
] Ti lnv	ventory 📰 List Sel	I. 🍓 Initialize PCASE G	IS								
C:\EMS	PROGRAM FILES	USER DATA\SAWEDF	PAVEMENT.MD	B							

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).

🔀 Traffic Module					• 🛛
Vehicles	Ľ		Show Mixed Tr	raffic / ACNPCN	
Create Pattern Delete Pattern M	odify Pattern Copy Pattern	Import Patte	erns	Standard Patterns	_
FWD	•			Edit Standard Patte	erns
Analysis Type Desi Mixed v Roa	n Type d ▼		English	Choose Standard Pa	attern
Add Vehicle	Delete Vehicle		Modify	Vehicle	
Vehicle	Weight (lb)	Passes	_		
AXLE, 18 KIP	18000	10	0		
			_		
, 					
				Ap	oply
				P	rint
				E	Exit

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).

NDT / Basin Data Reduction														
NDT	Τe	ests												
01 SR 361 4/24/2018														
	NDT Test Name 01 SR 361 4/24/2018													
	Software Version													
							11		,					
L							Uni	t or Measurement	• En	glish 🔿 M	etric			Sorted
		Tem	peratur	e (F)				Test						
Stati	on	Air	Surf	Pave	Lan	е	Code	Date (yymmdd)	Time (hhmm)	File Name		Lat		Reports
	1	72	80	0		1		170725	0732	SR361 Carte	er.FWD			Chart
L	3	75	83	0		1		170725	0740	SR361 Carte	er.FWD			
L	4	73	84	0		1		170725	0744	SR361 Carte	er.FWD			Import
	5	75	85	0		1		170725	0747	SR361 Cart	er.FWD		Ŧ	Export
1.0	_					111						•		
Sens	ors					Load	l Plates							bbA
		in(s)					in(s)						
XOf	fsel	t Y Of	fset Z	Offset		XO	ffset Y	Offset Radius						Edit
4	_	0	0	0	-		0	0 5.91						Save
	_					_					_	_	_	Cancel
Drop		(- (to	D 1		D D		(mil)			-11			
		1	8271	14.1	11	97	12	3 U4 723 466	201 L	124 0	22			Delete
		2	8676	14.7	73	10.2	21	1 7.56 4.91 3.2 1.26 0.52				Exit		

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.

Climat	e Dat	a En	try Fo	orm					•	- 0 8
Оре	Operational Climatic Data Summary							5 D	ay Mean Ir	nformation
Test	Date	Sele	ctor-				1	-		
•		Jul	v 20	17					High	Low
_			. ,	••				7/20/2017	93	64
Sun	Mon	Tue	Wed	Thu	Fri	Sat		7/21/2017	92	66
25	26	27	28	29	30	1		7/22/2017	96	68
2	3	4	5	6	4	8		7/23/2017	87	72
9	10	10	12	13	14	15		7/24/2017	89	67
23	24	25	26	20	28	22				5 Dau Mean
30	31	1	2	3	4	5		E D L D		
2) T od	ay: !	5/10	/201	8				e <u>L</u> anc	73.4
The 5 tempe then e	day n rature nter ti	nean . Clio ne pré	is use :k on eviou:	ed too the da s 5 da	deterr ate(s) avs of	nine in above tempe	as e th erat	phait modulus hat FWD data ure data in the	when it is ba was collected arid on the r	sed on d, and ? ight.

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).

PCASE Evaluation Module									
	Current Section: 01 SR 361 4/24/201	8							
<u>R</u> un Properties	Layer Manager	<u>E</u> dit Settings							
Create/Retrieve Section]								
- Section Properties	-								
Evaluation Type Traffic Area	Analysis Type								
Road 🗸 🖌	Layered Elastic Criteria (Modulus Value	es) - LEEP 📃 💌							
PCI > 40 PCI									
Yes 🗸 Sa	et ?								
Traffic Pattern									
FWD	<u>-</u>								
FwD Special Options Multi-File Import									
Save Data Exit Help Repo	rts <u>D</u> efaults <u>S</u> ection List	🔲 Always Save							

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).

E PCASE Evalua	tion Module									
Current Section: 01 SR 361 4/24/2018										
<u>B</u> ur	Bun Properties Layer Manager Edit Settings									
Build Structure	es		-		<i>p</i> .					
Layer Typ	pe Frost	Thick (in)	Backcalc E	Analysis E	*	EWesdef EWespave				
Asphalt		6.75	Temp	Wesdef						
Base	FO	9.46	Wesdef	Wesdef	=					
Natural S	ubgrad FO	28.79	Wesdef	Wesdef						
Layer Set Co Edit Sav Pavement Ty Commands Run BackC Current Vehick AXLE, 18 KIP Results No Data	pe: Flexible	Add De	I Copy Both lysis Pro	gress Bar Label	grade Settings 240 - Above Bedrock	NDT Controls - 1 of 30 Use NDT Station: N/A Drop: N/A Available Basins: 30 Assigned Basins: 30 Certate Select Basins Get All Basins Graph E's Set this structure & basin as active for analysis and report ? Move to Active Not Active				
<u>Save Data</u>	<u>Exit</u> <u>H</u> elp	<u>R</u> epor	ts <u>D</u> efaults	Section List		🗖 Always Save				

Figure 18: Evaluation Module (Layer Managers)

Run Prope	erties	γ	Layer Mar	nager	\neg		Edit Settinas
ackcalculation	C Analusis			-			
ackcalculation Se Maximum Iteration effection Tolerance	Analysis ttings s: 10 V	Stay In Limi Cutoff Basir	ts Load	berature Calcula Frequency: ETemp: Ise Avg ETemp	ation Sett 20 for all ba	ings H: ps	z si
100uius i oleranci	e: /			Show /	AllETem	P	
Base Natural Subgrad		61000 40363	5000 35363	150000 45363	0.35 0.40	1	

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).

Fite Text Num: SRLEPUP Version: 7 7 Version: 0	SR181	- Notepa	d				12				1.00						-		
Tet Norm: Split FVD Measurement: 0 Samerer: 7 Construction 0 0 0 0 0 0 0 Construction 0	File Ed	it Forma	t View	Help															
Version: Description: # Setter: 7 1 24 35 47 # Setter: 0	Test Nan	ne:		SR181.	FWD														
Meanure P Strature 7 X Ottar: 0	Version :			20															
# Standard T V COME: 0	Measure	ment :			E														
X Offset: 0	# Sensor	s :		7															
Y Offst: 0<	X Offset	: 0	8	12	18	24	35	47											
Z Offer: 0 0 0 0 0 0 X Offer: 0 0 0 0 0 0 X Offer: 0 0 0 0 0 0 0 0 0 0 0 X Offer: 0	Y Offset	: 0	0	0	0	0	0	0											
± Load: 1 X Other: 0 X Other: 0 <	Z Offest	: 0	0	0	0	0	0	0											
A Unit: 0 Dist Unit: 0 D2 D3 D4 D5 D6 D7 1 1 63 70 70 1 180131 1360 WESKRW%LGPINTSW 866 22.7 17.69 15.02 11.49 8.61 3.89 191 2 2 2 62 70 70 1 180131 130 WESKRW%LGPINTSW 886 22.7 17.69 15.02 11.49 8.61 3.86 197 24.45 15.7 14.81 11.86 WESKRW%LGPINTSW 887 24.13 10.29 11.39 9.31 7.6 4.57 1.88 3 1 3 64 73 7.2 1 180131 1319 WESKRW%LGPINTSW 897 2.44 11.86 1.44 11.46 6.67 2.47 4 2 3 63 71 72 1 180131 322 WESKRW%LGPINTSW 8912 2.37 12.31 1.	# Loads	:		1															
Line: Org Station Air Temp Sur Temp Prev Temp Lane Type Date Time Field L D1 D2 D3 D4 D5 D6 D7 1 2 1 63 70 70 1 180131 136 WESKRW34.GPINTSW. 9091 23.7 17.96 15.04 14.98 8.43 15.14 2 2 62 70 70 1 180131 131 WESKRW34.GPINTSW. 9991 2.61 1.32 9.42 7.69 1.62 1.45 1.83 1.64 7.7 1.81 18131 131 WESKRW34.GPINTSW. 9999 2.21 1.32 1.32 1.44 1.16 6.97 2.44 1.33 6.3 7.1 7.2 1 180131 1.33 WESKRW34.GPINTSW. 9999 2.21 1.32 1.44 11.66 6.37 2.29 1.33 1.44 11.46 6.81 2.29 1.33 1.44 1.44 1.45	X Offset	:0																	
Data Off Station Air Temp Sur Temp Pave Temp Pave Temp Lame Time Field 1 D1 D2 D3 D4 D5 D5 D5 1 1 1 63 0 0 1 11000 1100 1100 11	1 Uffset	5.01																	
1 1 <th1< th=""> 1 <th1< th=""> <th1< th=""></th1<></th1<></th1<>	Record#	Dron#	Station	Air	Temp Sur	Temp Pave	Temp	Lane	Type	Date	Time FileId I 1	DI	D2	D3	D4	D5	D6	D7	
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	1	1	1	63	70	70	1	Lunc	180131	1306	WESKRW%L-GPINT2SW	9059	23.17	17.96	15 16	11.63	8 69	3.89	1 91
2 1 2 2 62 70 70 1 180131 1317 WESKRW40-CPINT2SW 8870 1431 12.9 9.42 7.90 4.63 1.87 3 1 3 64 73 7.2 1 180131 1317 WESKRW40-CPINT2SW 8870 1431 12.95 16.22 13.7 14.58 11.68 6.7 2.44 3 63 711 7.2 1 180131 1319 WESKRW40-CPINT2SW 9942 2.45 16.22 15.7 16.22 15.7 16.25 2.5 1.5 3 63 711 7.2 1 180131 1320 WESKRW40-CPINT2SW 9942 2.48 2.07 18.15 14.06 11.96 7.14 2.86 2.87 1.87 14.14 16.86 1.96 7.14 2.86 2.79 6.37 1.72 1.40 11.31 11.31 13.33 WESKRW40-CPINT2SW 916 2.41 11.40 11.42 6.3 2.79 6.3 7.11 1.10 11.01 13.03 WESKRW40-CPINT2SW	1	2	i	63	70	70	i		180131	1306	WESKRW%L-GP1NT2\$W	8961	22.7	17.69	15.02	11.49	8.61	3.86	1.91
2 2 2 62 70 70 1 180131 1317 WESKRW44_CPINT2SW 9873 14.31 12.95 11.99 9.31 7.6 4.57 1.88 3 2 3 64 73 7.2 1 180131 1319 WESKRW44_CPINT2SW 9894 2.27 16.92 13.74 11.15 6.67 2.49 4 2 3 63 711 7.2 1 180131 1320 WESKRW44_CPINT2SW 9944 2.36 19.79 17.51 14.04 11.56 6.51 2.56 5 2 3 63 711 72 1 180131 1320 WESKRW44_CPINT2SW 9942 2.32 17.33 14.04 11.49 6.81 2.61 6 1 3 63 71 71 1 180131 1335 WESKRW44_CPINT2SW 910 2.34 19.21 17.34 14.34 11.94 7.62 2.79 7 2 3 63 72 72 1 180131 1349	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
3 1 3 64 73 72 1 100131 1319 WESKRW%4_CPINT2SW 9999 24.13 20.19 17.73 14.38 11.68 6.67 2.49 4 1 3 63 71 72 1 180131 1319 WESKRW%4_CPINT2SW 9937 24.62 20.58 18.03 14.56 1.05 6.67 2.49 4 2 3 63 71 72 1 180131 1320 WESKRW%4_CPINT2SW 9932 24.8 20.77 18.15 14.66 1.6 6.85 2.56 5 2 3 63 71 71 1 180131 1332 WESKRW%4_CPINT2SW 9914 24.31 20.32 11.72 14.43 11.86 70.2 7.7 1 3 63 71 71 1 180131 1335 WESKRW44_CPINT2SW 9134 24.31 20.43 19.44 14.40 11.47 6.8 2.57 7 1 3 63 72 72 1 180131	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 2 3 64 73 72 1 180131 1319 WESKRW%L-QPINT2SW 9994 22.97 19.27 16.92 13.74 11.15 6.67 7.07 2.67 4 2 3 63 71 72 1 180131 1320 WESKRW%L-QPINT2SW 9943 23.67 19.79 17.36 14.04 11.56 6.70 2.67 5 2 3 63 71 72 1 180131 1332 WESKRW%L-QPINT2SW 9944 23.82 19.82 17.33 14.04 11.86 6.8 7.02 2.79 6 2 3 63 71 71 1 180131 1335 WESKRW%L-QPINT2SW 9015 23.46 19.92 17.46 14.22 11.64 6.89 2.59 7 2 3 63 72 72 1 180131 13.94 WESKRW%L-QPINT2SW 9015 23.46 19.92 17.46 14.22 11.44 6.89 2.59 2.5 6.3 71 70 1 <t< td=""><td>3</td><td>1</td><td>3</td><td>64</td><td>73</td><td>72</td><td>1</td><td></td><td>180131</td><td>1319</td><td>WESKRW%L-GP1NT2\$W</td><td>9399</td><td>24.13</td><td>20.19</td><td>17.73</td><td>14.38</td><td>11.68</td><td>6.97</td><td>2.64</td></t<>	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
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	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 2 3 63 71 72 1 180131 1320 WESKRW%LCPINT2SW 9048 23.67 19.79 17.36 1.404 11.56 6.85 2.65 5 2 3 63 71 72 1 180131 1332 WESKRW%LCPINT2SW 9942 23.82 19.82 17.33 14.44 11.49 6.81 2.61 6 2 3 63 71 71 1 180131 1335 WESKRW%LCPINT2SW 9917 23.09 19.69 17.31 14.45 11.47 6.9 2.22 7 2 3 63 72 72 1 180131 1339 WESKRW%LCPINT2SW 9105 23.46 19.92 17.46 14.22 11.64 6.88 2.59 8 1 4 63 73 72 1 180131 1344 WESKRW%LCPINT2SW 9005 20.71 14.65 12.07 8.06 6.94 4.01 2.27 8 1 4 63 73 72 1	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
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	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
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	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
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	2	2	3	63	71	72	1		180131	1322	WESKRW%L-GP1N12\$W_	8994	23.82	19.82	17.33	14.04	11.49	6.81	2.61
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	0	1	5	63	/1	/1	1		180131	1550	WESKRW%L-GPIN125W_	9130	24.51	20.25	17.72	14.45	11.80	7.02	2.79
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	7	1	2	62	71	71	1		180131	1220	WESKRW %L-GPINI23W	0160	23.09	20.2	17.51	14.05	11.47	7.00	2.52
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	1	2	3	63	72	72	1		180131	1339	WESKRW%L GPINT2SW	0015	24.22	10.07	17.62	14.01	11.51	6.08	2.09
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	8	1	4	63	73	72	i		180131	1344	WESKRW%LGPINT2SW	9180	21.13	14.96	12.3	9 11	7.09	4.05	2.27
9 1 5 63 71 70 1 180131 1346 WESKEW%3L_GPINT2SW 9224 1455 12.57 11.04 9 7.41 4.7 191 10 1 6 63 72 71 1 180131 1346 WESKEW%3L_GPINT2SW 9224 12.37 11.04 9 7.31 4.59 184 10 2 6 63 72 71 1 180131 1349 WESKEW%3L_GPINT2SW 921 12.32 9.81 8.52 6.96 5.65 3.46 1.61 11 2 7 62 71 71 1 180131 1351 WESKRW%3L-GPINT2SW 9912 2.42 7.63 6.72 5.78 3.68 1.64 11 2 7 63 70 69 1 180131 1353 WESKRW%3L-GPINT2SW 9912 2.34 19.43 15.48 11.2 5.78 3.68 1.64 2.06 <t< td=""><td>8</td><td>2</td><td>4</td><td>63</td><td>73</td><td>72</td><td>i</td><td></td><td>180131</td><td>1344</td><td>WESKRW%L-GP1NT2\$W</td><td>9005</td><td>20.72</td><td>14.65</td><td>12.07</td><td>8.96</td><td>6.94</td><td>4.01</td><td>2.2</td></t<>	8	2	4	63	73	72	i		180131	1344	WESKRW%L-GP1NT2\$W	9005	20.72	14.65	12.07	8.96	6.94	4.01	2.2
9 2 5 63 71 70 1 180131 1346 WESKRW%4LGPINT2SW 9294 14.09 12.25 10.78 8.79 7.23 4.59 1.84 10 2 6 63 72 71 1 180131 1349 WESKRW%4LGPINT2SW 9212 12.25 9.81 8.52 6.94 5.65 3.46 1.61 11 2 7 62 71 71 1 180131 1351 WESKRW%4LGPINT2SW 8912 12.2 9.81 8.52 6.94 5.98 3.81 1.72 12 7 63 70 69 1 180131 1353 WESKRW%4LGPINT2SW 9913 2.44 19.43 15.98 1.22 9.11 4.77 2.07 13 1 8 64 71 71 1 180131 1355 WESKRW%4LGPINT2SW 9267 13.89 9.51 7.38 6.45 3.66 1.83	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
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	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
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	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
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	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
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	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
$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	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
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	12	1	-	63	70	69	1		180131	1353	WESKRW%L-GPIN12\$W_	9191	24.24	19.83	15.98	12.2	9.11	4.77	2.07
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	12	2	6	03	70	09	1		180131	1303	WESKRW%L-GPINI25W_	8972	23.04	19.45	10.08	0.12	8.94	4.08	2.00
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	13	2	8	64	71	71	1		180131	1355	WESKRW%L-GPINT2\$W	9207 8072	13.44	10.80	0.51	7.88	6.45	3.66	1.71
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	14	ĩ	9	63	71	70	i		180131	1358	WESKRW%L-GP1NT2SW	9158	15.65	13.57	11.89	7.55	6.2	4	1.74
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	14	2	9	63	71	70	i		180131	1358	WESKRW%L-GP1NT2\$W	8884	15.21	13.26	11.65	7.35	5.99	3.89	1.6
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	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
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	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
$ \begin{array}{cccccccccccccccccccccccccccccccccccc$	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
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	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
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	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
18 1 13 65 74 74 1 180131 1407 WESKRW%4L_GPINT2SW_ 9103 14.89 13.05 11.5 9.4 7.46 4.03 1.78 19 1 14 65 76 75 1 180131 1407 WESKRW%4L_GPINT2SW_ 8785 14.44 12.65 10.88 8.35 6.74 4.02 1.79 19 1 14 65 76 75 1 180131 1409 WESKRW%4L-GPINT2SW_ 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%4L-GPINT2SW_ 9399 16.13 12.35 10.58 8.14 6.55 3.9 1.71 20 1 15 65 76 75 1 180131 1411 WESKRW%4L-GPINT2SW_ 9399 8.13 6.57 5.1 4.6 3.3 1.92 20 2 15 65 76 75 1 18013	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
$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$	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
19 1 40 0 70 72 1 180131 1409 WESKRW%3L-GPINI25W 924 16.09 12.05 10.88 8.35 6.74 4.02 1.79 19 2 14 65 76 75 1 180131 1409 WESKRW%3L-GPINI25W 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%3L-GPINI25W 9399 8.22 6.6 5.73 5.1 4.36 3.34 1.92 20 2 5 65 76 75 1 180131 1411 WESKRW%3L-GPINI25W 9399 8.22 6.6 5.73 5.1 4.36 3.34 1.92 20 2 5 5 76 75 1 180131 1411 WESKRW%3L-GPINI25W 8928 8.35 6.29 5.48 4.87 4.22 3.19 1.66 END A A A A	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 2 14 0.5 7.6 7.5 1 100151 1409 WESKKW%6L-GPIN125W 8999 10.15 12.35 10.38 8.14 0.55 3.9 1.71 20 1 15 65 76 75 1 180131 1411 WESKKW%6L-GPIN125W 9399 8.25 6.6 5.73 5.1 4.36 3.34 1.92 20 2 15 65 76 75 1 180131 1411 WESKRW%6L-GPIN125W 8928 8.35 6.29 5.48 4.87 4.22 3.19 1.66 END Image: state s	19	1	14	60	/6	/S	1		180131	1409	WESKRW%L-GPINI2SW	9224	16.09	12.00	10.88	8.50	0.74	4.02	1.79
20 2 15 65 76 75 1 180131 1411 WESKRW 96L-GP1N125W 8928 8.35 6.29 5.48 4.87 4.22 3.19 1.66 END	20	2	14	0.) 65	/0 76	75	1		180131	1409	WESKRW%L-GPINI2SW_	8939	10.15	12.55	10.38	8.14 5.1	0.33	3.9	1./1
END	20	2	15	65	76	75	1		180131	1411	WESKRW%I_GPINT2\$W_	8028	8.35	6.29	5.48	4.87	4.50	3.19	1.92
	END	-	1.5	00	/0	15			100101	1411	"Longer / Je-of 11(125W_	0720	0.35	0.23	0.40	4.07	4.22	5.15	1.00

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).

Select Inventory			23
Select Inventory	Branch 284	O1	Inspection 10/21/2017
Add Edit Del	Add Edit Del	Add Edit Del	Add Edit Del

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).

Test	Date	Sele	ctor						lauon
•		.lul	lu 20	17				High	Low
		· · ·	.y 20				7/20/2017	92	70
5110	Mon	Toe	V/ed	Thu	En	S.81.	7/21/2017	95	71
25	26	27	28	29	30	1	7/22/2017	96	73
2	3	4	5	6	7	8	7/23/2017	88	69
9	10	11	12	13	14	15	7/24/2017	90	69
16	17	18	19	20	21	22			
23	24	25	26	27	28	29		5 D a	ay Mean
30	31	1	2	3	4	5	Edit Save	Canc 81	3
\sim	Tod	lay: `	1/19	/201	8				

Figure 22: Climate data.

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

	Current Section: 01 284 10/21/2017	
<u>R</u> un Properties	Layer Manager	<u>E</u> dit Settings
Create/Retrieve Section		
Section Properties		
valuation Type Traffic Area	Analysis Type	
Road 🗾 🗚 💆	Layered Elastic Criteria (Modulus Values)	LEEP
PCI > 40 PCI		
Yes 💽 Set	?	
raffic Pattern		
CULTUN	-	
Special Options		
Multi-File Import		

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.

			Current Se	ection: 01 284 10/21/	2017		
<u>B</u> un	Properties)	Layer Manager		Ec	lit Settings
Build Structure	s		-		-	125	
Layer Typ Asphalt Base Natural St	e Frost F0 Ibgrad F0	Thick (in) 10.72 8.00 224.28	Backcalc E Temp Wesdef Wesdef	Analysis E Temp Wesdef Wesdef	* III	EWesdef	EWespave 288
Layer Set Co Edit Save	ntrols • 1 of	1 Add De	I Copy	Subgrade 9	Settings	NDT Cont	rols - 19 of 30 DT
Pavement Typ Commands Run BackC	e: Flexible	AC Crit Run Ana	Both Pro	gress Bar Label		Available E Assigned E Select Ba Set this active fo	Basins: 30 Basins: 30 Itera Basins Get All Basin Graph E's structure & basin as r analysis and report
Pavement Typ Commands Run BackC Current Vehicle	e: Flexible	AC Crit Run Ana	Both	gress Bar Label		Available E Assigned E Select Ba Set this active fo ?	Basins: 30 Basins: 30 <u>Itera</u> asins <u>Get All Basin</u> Graph E's structure & basin as r analysis and report Move to Active
Pavement Typ Commands Run BackCo Current Vehicle AXLE, 18 KIP	e: Flexible	AC Crit Run Ana	Both	gress Bar Label		Available E Assigned E Select Ba Set this active fo	Basins: 30 Basins: 30 Itera Sins: Get All Basin Graph E's structure & basin as r analysis and report Move to Active
Pavement Typ Commands Run BackC Current Vehicle AXLE, 18 KIP Results	e: Flexible	AC Crit Run Ana	: Both	gress Bar Label		Available E Assigned E Select Ba Set this active fo	Basins: 30 Basins: 30 Itera sisins Get All Basin Graph E's structure & basin as r analysis and report Move to Active Active

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)

$\begin{tabular}{ c c c c c c c c c c c c c c c c c c c$	
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Clipboard Font Font Font Alignment Number Styles Cells Editing A1 <	
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A B C D E F G H I J K L M N 2 0 35.56416 -89.6326 0 1 J K L M N 3 0 35.56416 -89.6326 0 Layer 1 Av 3.732913 1 1 J K L M N 4 -0.5 35.56416 -89.6326 0 Layer 1 Av 3.732913 1	
1 Dist.(H) Layer 1 De Layer 2 De Lat(*) Long(*) 2 0 35.56416 88.6326 3 0 35.56416 88.6326 4 -0.5 35.56416 -89.6326 5 -0.5 35.56416 -89.6326 6 -1 35.56417 -89.6326 7 -1 35.56417 -89.6326 8 -1.5 35.56415 -89.6326 9 -1.5 35.56417 -89.6326 0 -2 35.56417 -89.6326	
2 0 35.56417 98.6326 0 4 -0.5 35.56417 98.6326 -0.5 5 -0.5 35.56417 98.6326 -0.5 6 -1 35.56417 98.6326 -1 7 -1 35.56417 98.6326 -1 8 -1.5 35.56415 -89.6326 -1 9 -1.5 35.56417 -89.6326 -1.5 9 -1.5 35.56417 -89.6326 -1.5 9 -1.5 35.56417 -89.6326 -1.5 9 -1.5 35.56417 -89.6326 -1.5 9 -1.5 35.56417 -89.6326 -1.5 10 -2 35.56417 -89.6326 -2.5	
3 0 35.0641 / -\$30.620 0.5 Layer 1 AV 3.74213 5 -0.5 35.5641 6 88.626 -0.5 Layer 2 15.39019 5 -0.5 35.5641 6 -88.626 -0.5 Layer 2 15.39019 6 -1 35.5641 6 -88.626 -1 -1 -1 -1 7 -1.5 35.56415 -88.626 -1 -1 -1 -1 8 -1.5 35.56415 -88.626 -1.5 -1 -1 -1 9 -1.5 35.56417 - 89.6326 -1.5 -1 -1 -1 9 -1.5 35.56417 - 89.6326 -1.5 -1 -1 -1 9 -1.5 35.56417 - 89.6326 -1.5 -1 -1 -1 10 -2 35.56417 - 89.6326 -2 -2 -2 -2	
4 -0.3 33.50410 -29.624 -1.03 Layer 2 15.36013 6 -1.1 35.56417 -89.6326 -1.1 <td>_</td>	_
5 -0.5 35.3941/-83.6320 -0.5 6 -1 35.56416 89.6326 -1 7 -1 35.56416 89.6326 -1 8 -1.5 35.56415 89.6326 -1 9 -1.5 35.56415 89.6326 -1.5 10 -2 35.56415 89.6326 -2	_
0 -1 33.50410 -53.6320 -1 7 -1 33.55417 -88.6326 -1 8 -1.5 35.56417 -88.6326 -1.5 9 -1.5 35.56417 -89.6326 -1.5 10 -2 35.56417 -89.6326 -2	_
7 -1 35.3647 -5.352 -1 8 -1.5 35.56415 -89.6326 -1.5 9 -1.5 35.56417 -89.6326 -1.5 10 -2 35.56417 -89.6326 -2	
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13 -2.5 35.56417 -89.6326 -2.5	
14 -3 35.56415 -89.6326 -3	
15 -3 35.56417 -89.6326 -3	
16 -3.5 4.46 35.56415 -89.6326 -3.5	
17 -3.5 35.56417 -89.6326 -3.5	
18 -4 35.56415 -89.6326 -4	
19 -4 3.77 35.56417 -89.6326 -4	
20 -4.5 35.56415 -89.6326 -4.5	
21 -4.5 3.87 35.56417 -89.6326 -4.5	
22 -5 35.56415 -89.6326 -5	
23 -5 4.06 35.56417 -89.6326 -5	
24 -5.5 35.56415 -89.6326 -5.5	
25 -55 617 3556417 -89.6326! -55!	•
SR1/9 M-2 (+) : 1	

(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)

<u>B</u> un Properties Build Structures		r	Lawor Manager		1 PT 40	
Build Structures			Layer Manager	1.1	<u>E</u> a	t Settings
Layer Type Fro	st Thick (in)	Backcalc E	Analysis E	*	EW/esdef	EWespave
Asphalt	10.72	Temp	Temp		1353	309 2888
Base F0	12.00	Wesdef	Wesdef	E	50	000 5000
Natural Subgrad F0	224.28	Wesdef	Wesdef		290	709 29709
Layer Set Controls - 1 of Edit Save Canc Pavement Type: Flexible Commands Run BackCalculate	f 1 Add De AC Crit Run Ana	Copy Both	Subgrade 240-A Bedr	Settings hbove ock	NDT Contr Vise ND Station: 15 Available B Assigned B Select Ba Set this s active for	ols - 30 of 30 T () () () () () () () () () () () () ()
AXLE 18 KIP	-				?	Move to Active
Results						Active
Desig Time Passe Jan-Dec 10	gn es 10		Allowable(K Load Pas 139.8 99000	(ips) ses 1000		^

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).

Time	Passes	Load	Passes	AC	
Jan-Dec	100	120.6	99000000	3.9	
NOTE E	lemible ermenent	- with no staught	unal magnit		
NOTE: F.	lexible pavement	s with no struct	ural requi	rement for a	n overlay
NOTE: F. may stil.	lexible pavement l require an ove	s with no structuriants of the second structure structure structure structure structures and structures structures structures and structures structures and structures structures and structures structures structures and structures structures and structures structures and structures structures and structures structures structures and structures structures structures and structures structu	ural requi: s the minim	rement for a mum thicknes	n overlay s

Figure 29: Overlay requirement.

Results

		Thickne	SS	Ela	sticity Mo	dulus	Allowa	able (Kips)	
Station	Asphalt	Base	Natural Subgrade	Asphalt	Base	Natural Subgrade	Load	Passes	Overlay (in)
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	_

The results are summarized in the below table:

Challenges

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).

			Current Se	ection: 01 284 10	/21/2017		
<u>R</u> un Proper	ties		r	Layer Manager		<u>E</u> dit	Settings
Build Structures			50			71.2	
Layer Type	Frost	Thick (in)	Backcalc E	Analysis E	*	EWesdef	EWespave
Asphalt		10.72	Wesdef	Wesdef		3278	61 327861
Base	FO	5.00	Wesdef	Wesdef	=	500	0 5000
Natural Subgrad	FO	224.28	Wesdef	Wesdef		3465	51 34651
Edit Save Ca	1 of 1 nc / 7	Add De	I Copy	_ Subg	rade Settings	NDT Control	s - 12 of 30 「 ∢ [[
Edit Save Ca Image: Controls Ca Image: Contres Ca </td <td>1 of 1 nc</td> <td>Add De</td> <td>Copy</td> <td>Subg</td> <td>rade Settings 10 - Above Bedrock</td> <td>NDT Control</td> <td>Is - 12 of 30 </td>	1 of 1 nc	Add De	Copy	Subg	rade Settings 10 - Above Bedrock	NDT Control	Is - 12 of 30
Edit Save Controls - Edit Save Ca	1 of 1	Add De	Copy	Subg	ade Settings 10 - Above Bedrock	NDT Control	s - 12 of 30 • • • • • Re op: 2 sins: 30 sins: 30 Iterations: 1
Edit Save Controls - Edit Save Ca	1 of 1 nc	Add De	Copy	Subg	rade Settings 10 - Above Bedrock	NDT Control Use ND1 Station: 6 Dr Available Ba Assigned Ba Select Basi	s - 12 of 30 () () () () () () () () () () () () () (
Edit Save Controls - Edit Save Ca	1 of 1 nc	Add De	I Copy	Subg	rade Settings 10 - Above Bedrock	NDT Control Use NDT Station: 6 Dr Available Ba Assigned Ba Select Basi	is 12 of 30 op: 2 sins: 30 isins: 30 Iteratu ns Get All Basin àraph E's
Edit Save Ca edit Save Ca Pavement Type: Flex Commands Run BackCalculate	1 of 1 nc	Add De	I Copy Both	Subg	rade Settings	NDT Control Vise NDT Station: 6 Dr Available Ba Assigned Ba Select Basi Co Set this str active for a	Is 12 of 30 I I Re op: 2 sins: 30 Iteratu ins Get All Basin itaph E's ucture & basin as analysis and report
Edit Save Ca Edit Save Ca Pavement Type: Flex Commands Run BackCalculate	1 of 1	Add De	I Copy : Both	Subg	rade Settings 10 - Above Bedrock	NDT Control	Is - 12 of 30 op: 2 sins: 30 sins: 30 Ins Get All B àraph E's ucture & basir analysis and re

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
- 2- Willt and Rister 2013, "Ground Penetrating Radar Pavement Layer Thickness Evaluation" https://uknowledge.uky.edu/cgi/viewcontent.cgi?article=1249&context=ktc_researchreports
- 3- PCASE User Manual: <u>http://www.erdc.usace.army.mil/Media/Fact-Sheets/Fact-Sheet-Article-</u> View/Article/476785/the-pcase-program/