Determining Layer Thickness and Understanding Moisture Related Damage of State-Owned Roads Using GPR and Capturing Such in a GIS-Based Inventory

Final Report
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The Transportation Infrastructure Durability Center (TIDC) is the 2018 US DOT Region 1 (New England) University Transportation Center (UTC) located at the University of Maine Advanced Structures and Composites Center. TIDC's research focuses on efforts to improve the durability and extend the life of transportation infrastructure in New England and beyond through an integrated collaboration of universities, state DOTs, and industry. The TIDC comprises six New England universities, the University of Maine (lead), the University of Connecticut, the University of Massachusetts Lowell, the University of Rhode Island, the University of Vermont, and Western New England University.

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Abstract

The Rhode Island Department of Transportation (RIDOT) has a significant inventory of state-owned roads of which layer thickness and moisture related damage is uncertain. Discrete methods of assessment like coring and visual inspection provide limited data and are both time-consuming and costly in terms of traffic control and personnel. The objective of this study was to evaluate the efficient use of Ground Penetrating Radar (GPR) at traffic speeds to determine layer thickness- and moisture-related damage of rural state-owned roads in Rhode Island. This was accomplished through field studies of roads with both known and unknown compositions in close collaboration between University of Rhode Island (URI) and RIDOT researchers. The results are presented through Google Maps so that the information can be directly incorporated into RIDOT's GIS-based inventory of roads. This project provides a system for collecting and viewing pavement layer thickness and moisture related damage on a network level, which the RIDOT can use to better plan, prioritize and allocate funding for pavement related projects.

Chapter 1: Introduction and Background

Ground Penetrating Radar (GPR) has been used for many geotechnical and transportation applications. Specific to Rhode Island, the Rhode Island Department of Transportation (RIDOT) has used GPR for evaluating concrete bridge decks (Martino 2017; Asadi et al. 2019, 2020), identifying shallow bedrock, monitoring scour around bridges (Kanter 2017; Laurent et al. 2018), and void detection. GPR can also be used to estimate the thickness of pavement sections and the presence of a high groundwater table.

The thickness of pavement sections using GPR can be determined by measuring the velocity of an electromagnetic wave through a material with a known dielectric content (e.g. ASTM D4748; Holzschuher et al. 2007). If the dielectric constant varies throughout the pavement, base course, and subbase layers, additional information like moisture ingress and deterioration (in the forms of cracks, voids and delaminations) can be obtained. The dielectric constant of water is significantly higher than the dielectric constant of asphalt and soil, which makes its presence in cracks or defects easily identifiable by GPR.

GPR has been successfully used to determine pavement thickness for many years (e.g. ASTM D4748). Recent advancements include: automatic data analysis (Liu et al. 2016; Chen et al. 2016), integration with GPS/GIS to map thickness measurements (Lebens 2010; Maser and Vandre 2006), determination of density of new pavements (Cao et al. 2007), use on a network level with results validated through coring (Maser and Vandre 2006), correlation with falling weight deflectometer measurements, and moisture content measurements for pavement condition assessment (Chen and Zhang 2009).

1.1 Project Motivation

The RIDOT requested a proof of concept, using their GPR system and state-owned roads, to determine pavement thickness, and to incorporate the results into the GIS database for improved decision making. The same datasets were used in a separate analysis that identified locations of highly variable dielectric constants that pointed toward damaged pavement due to moisture ingress. Both studies were validated using coring and a visual analysis of the raw GPR data and surface conditions. This information is important for estimating the longevity of state-owned roads by identifying the onset of damage and helping to prioritize maintenance and replacement of road sections.

1.2 Research, Objectives, and Tasks

The overall objective of this study is to evaluate the efficient use of GPR at traffic speeds to determine layer thickness and moisture content of rural state-owned roads in the State. Specific objectives include the following:

1. Evaluate the capabilities of the existing GPR systems at RIDOT (e.g. GSSI RoadScan system) to distinguish between different pavement sections and subbase materials.
2. Identify state-owned roads applicable for field testing.
3. Perform field testing using RIDOT's multi-channel GPR at road speeds.

4. Assess pavement layer thickness using GPR and compare with existing RIDOT information from construction records, coring data, other non-destructive test results, etc.
5. Assess pavement layers in terms of damage due to moisture content, and determine if a connection exists between areas of dense cracking and higher dielectric content.
6. Investigate if locations of improper pavement construction, moisture content and cracking are easily detectable using GPR.
7. Incorporate the newly acquired data into RIDOT's GIS-based inventory of roads.
8. Evaluate methods for connecting information about the composition of road sections from GPR to planning and prioritizing future pavement related projects.

Chapter 2: Methodology

Candidate roadways were selected in coordination with the RIDOT and ultimately based on availability of ground truth (coring), surface condition, subbase type, and locations of suspected high groundwater table. The systems used to collect data were GSSI's Roadscan SIR 20 and Roadscan SIR 30 with one or three, 2.0 GHz air-launched antennae, respectively. These systems were selected because they are owned by the RIDOT, can perform surveys at traffic speeds, can collect data from a full lane's width, and can record the latitude/longitude coordinates of all data points collected. Thickness values and dielectric constants extracted from the post-processed datasets were analyzed to uncover locations of potential damage. These locations were then compared to the conditions of collected cores and a visual inspection of the roadway's surface to validate the findings. An important aspect of this study was the incorporation of these results into RIDOT's GIS-based inventory of roads. The results (thickness values and dielectric constants) were prepared and presented using Google Maps so that; 1) they can be easily transferred into the RIDOT's GIS system and 2) they can be used immediately in decision making associated with planning and prioritizing maintenance and replacement of damaged roads.

There will also be close collaboration on this study (through a sub-award) with Dr. Nicole Martino of Roger Williams University (RWU). Dr. Martino has worked for several years with RIDOT personnel on identification of damage to concrete bridge decks in Rhode Island using GPR and Infrared Thermography (Asadi et al. 2019; 2020).

2.1 Selection of Sites

URI and RIDOT collaborated to identify state-owned roads applicable for this study. All the roadways discussed are shown on a map of Rhode Island in Figure 1. Some of the identifying factors included the surface condition, road composition, presence of high-water table, recent construction, and the limits of the road. The surface condition of the candidates ranged from poor to excellent, composite and non-composite roadways (with and without a concrete subbase) were considered, and any recent changes to the roadways were discussed. Having a diverse selection of roads was necessary to understand the capability and limitations of the GPR system.

While the nine roads displayed in Figure 1 were surveyed, three of those roads were analyzed in detail for this project: Route 117, East Main Road, and South of Commons Road Since ground truth was available for Route 117 via road cores, this road was used to evaluate the accuracy of GPR in determining pavement depth. 6.5 miles of East Main Road was used to collect data. This roadway had varying surface conditions, making it a good candidate for a dielectric analysis. Lastly, the key aspect of South of Commons Road was the presence of a high water table, allowing the impact of a high water table on dielectric constant and pavement condition to be investigated.

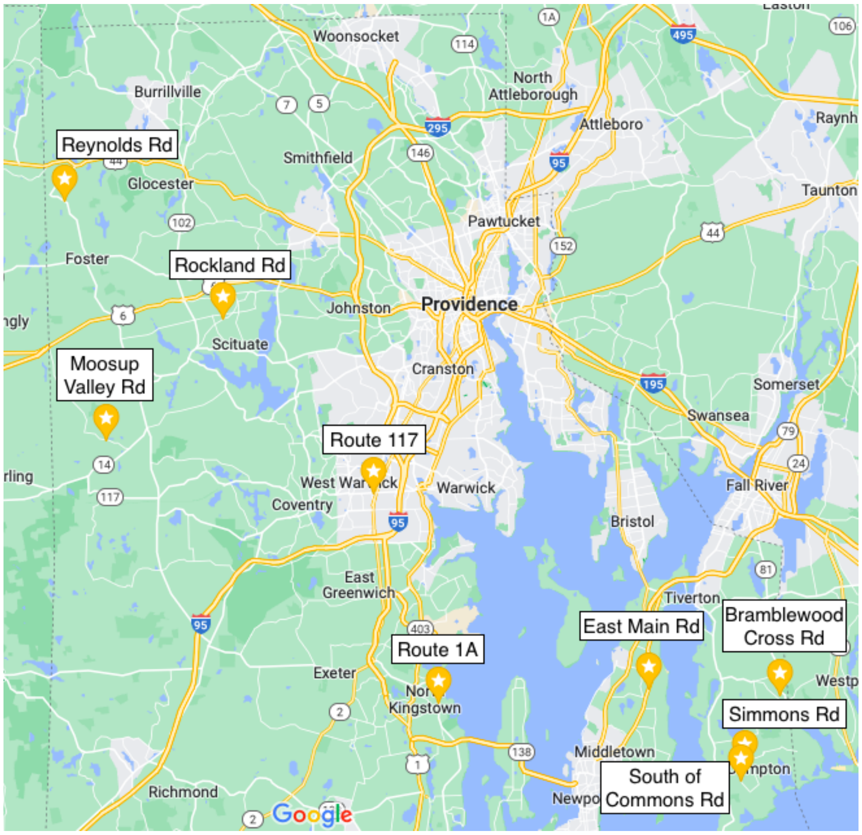

Figure 1: Map of surveyed state-owned roads

2.2 Instrumentation Set-up

The physical setup of the Roadscan system included mounting one (SIR 20) or three (SIR 30) 2 GHz antennas onto the front of a RIDOT owned van as shown in Figure 2. Availability drove the choice of which system would be used on a particular day. The Roadscan-devoted laptop (with the data collection software) and data acquisition units (SIR 20/SIR 30) were mounted in the interior of the RIDOT van and connected to the antenna control cables, power supply, and GPS. The GPS hardware was located on the top, back-center of the van. To ensure accurate coordinates would be collected, the coordinates of the GPS hardware in relation to each mounted antenna were inputted into the laptop. Additionally, filters were applied to each antenna to remove noise that would hinder the visibility of the data file.

Figure 2: Three, 2 GHz antennas installed on the front of the RIDOT van

2.3 Data Collection and Transfer

The first file collected using the Roadscan is null. The second is a metal plate file. This file is used to remove the bouncing effects in the data because of the van not traveling over an even surface, and to calibrate the data so that time 'zero' is at the roadway's surface. This file was collected by placing a metal plate under one of the antennas, and collecting data in time mode for a few seconds, while a person jumps up and down on the van's bumper. This is usually completed in a parking lot near the roadway of interest. An example of the raw metal plate file can be seen in Figure 3 below.

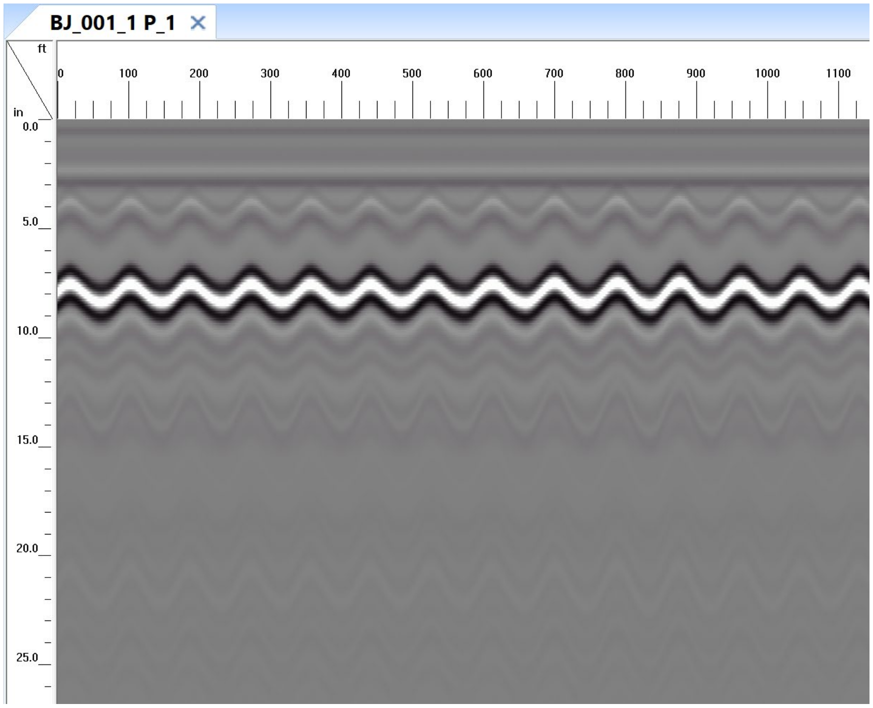

Figure 3: Raw Metal Plate File

Once the metal plate file was collected, data collection from the roadway of interest began using the Roadscan-devoted laptop with the preinstalled data collection software. Data was collected from an entire road (from start to finish) or a pre-established segment of road. If the Roadscan SIR 20 with one antenna was used, data would be collected from each antenna mounting location, from each lane. These locations equate to the right wheel path, left wheel path and the center of the roadway. If the Roadscan SIR 30 with three antennas was used, data would be collected from all three mounting locations at the same time (Figure 4), from each lane (Figure 5). Once data collection was complete, the data was transferred from the laptop to an external USB drive for further processing, analysis and visualization.

Figure 4: Snapshot of video from East Main Road data collection

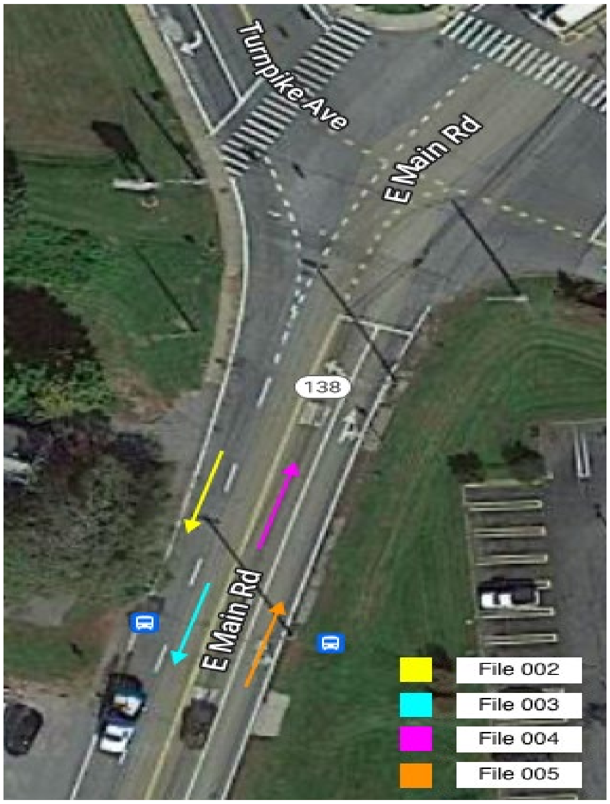

Figure 5: East Main Road snapshot of path for each file

2.4 Data Analysis and Interpretation

All the raw data was post-processed using GSSI's Radan software. Post-processing steps included removing gain and using the metal plate file to perform a calibration. At this stage of analysis, one can visually estimate the pavement thickness by observing the reflections of the B-scan. The points located at the estimated layer depth can be manually selected in Radan, as shown in Figure 6. These selected points were then exported to a .CSV file. The exported information associated with the selected points includes: file name, distance (from data collection starting point), amplitude of the return signal, depth, and dielectric. For some sites, the estimated pavement depths from Radan were compared with actual, measured pavement depths from cores that were collected from strategic locations along the roadway.

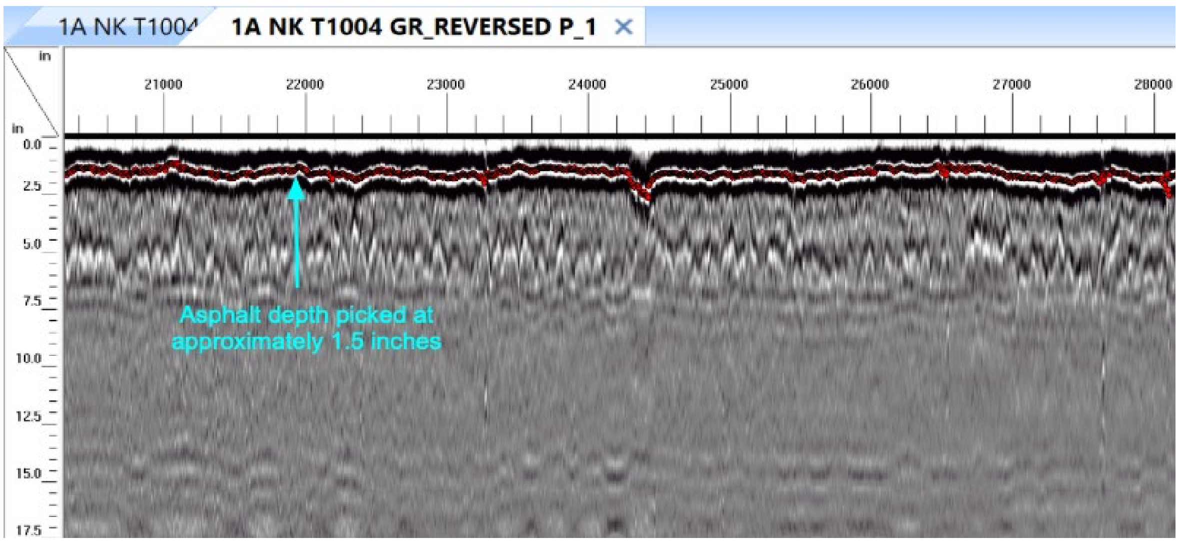

Figure 6: Calibrated B-Scan Collected from Route 1A

2.5 Incorporation into Google Maps

The utilization of Google Maps allows an owner to easily view their roadway's depth, dielectric constant, and specific points (like suggested locations to extract a core) in a similar manner to color-coded live traffic data. This platform was selected because the information can be easily transferred into the RIDOT's GIS platform and RIDOT's interest in using Google Maps. Specific points, like coring locations, can be incorporated by using the measuring tool in Google Maps. The user can then click on any core to see the core number, road direction, and GPS coordinates, as depicted in Figure 19. Asphalt thicknesses were categorized at 1-inch intervals, with each thickness interval being displayed as its own color. The user can toggle over any section within the data collection limits of the road and view the approximate asphalt thickness by observing the color of the highlighted section and matching it to a thickness displayed in the legend.

Knowing the pavement depth aids the RIDOT with reconstruction and/or rehabilitation preparation. This same process was carried out for the depiction of dielectric constant, presenting the RIDOT with locations of potential damage via high dielectric constant. Examples are presented in the following chapter.

Chapter 3: Results and Discussion

This chapter focuses on the results from the three roads studied: Route 117, East Main Road, and South of Commons Road. Each road is presented as a subsection of this chapter and includes: a map of the location within the state of Rhode Island, a second map highlighting the exact location of data collection from the roadway, output required per the RIDOT (pavement depth, dielectric constant) visual observations of the GPR data files and a summary of the interpreted data. Specific details about each roadway (i.e. the comparison of the pavement depth measured from cores collected from Route 117 vs the interpreted depth using the GPR data) can be found in the attached appendices.

3.1 Route 117

Route 117 is located in Warwick, RI, as displayed in Figure 7. The approximate limits of data collection are highlighted in Figure 8 and are between I95 and Quaker Lane. The majority of Route 117 consisted of one westbound lane and one eastbound lane. Data was collected in the approximate center of both lanes using a single antenna and the SIR-20 unit. .

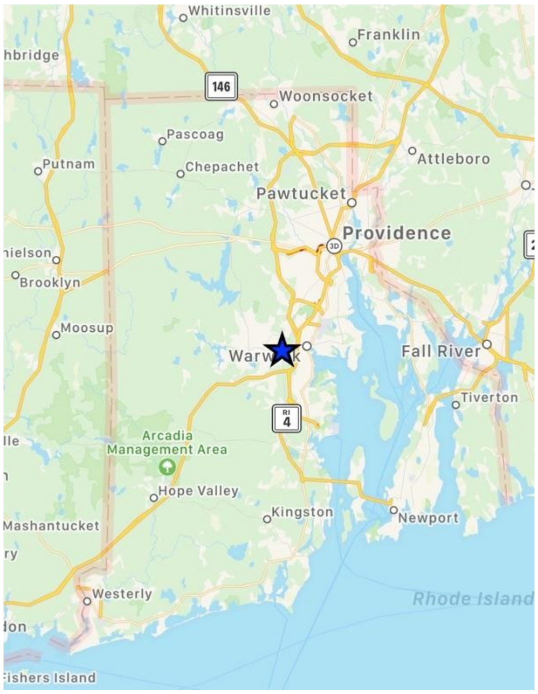

Figure 7: Route 117 location in Warwick, RI

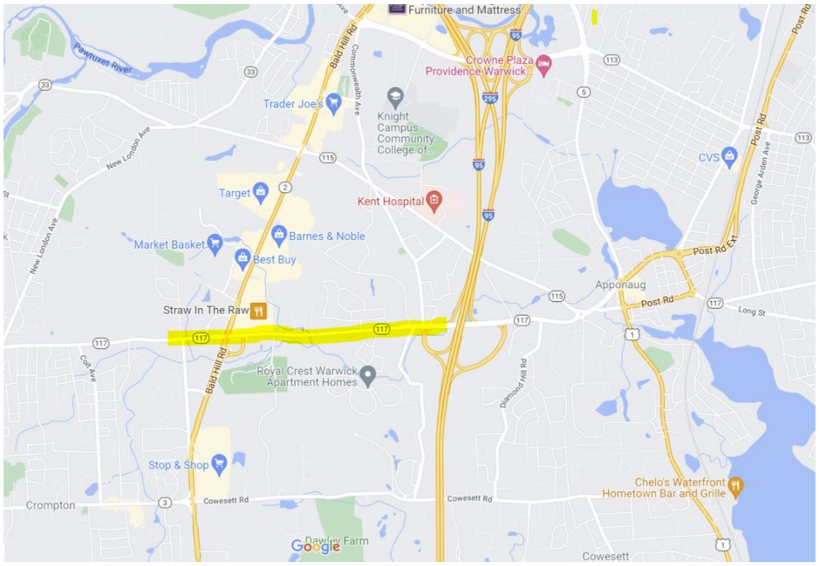

Figure 8: Limits encompassing approximately 1.3 miles of Route 117

After the files were calibrated in Radan, the roadway's surface and the bottom of the asphalt were manually 'picked' as layers in Radan. For this site, the RIDOT was interested in the pavement depth and the identification of any composite sections. The surface layer is picked in yellow and the bottom of the asphalt layer is picked in red, as shown in Figure 9. A CSV file was outputted from Radan to include the depth and dielectric constant of each 'pick' in each layer. When picking the bottom layer, it was discovered that the road consists of both a composite and non-composite base. In Figure 9, the composite section of the road is shown as the red layer with the bright reflection from approximately 71,000 inches to 77,400 inches. A section of the road with a non-composite base is shown as the red layer with a duller reflection after 77,400 inches.

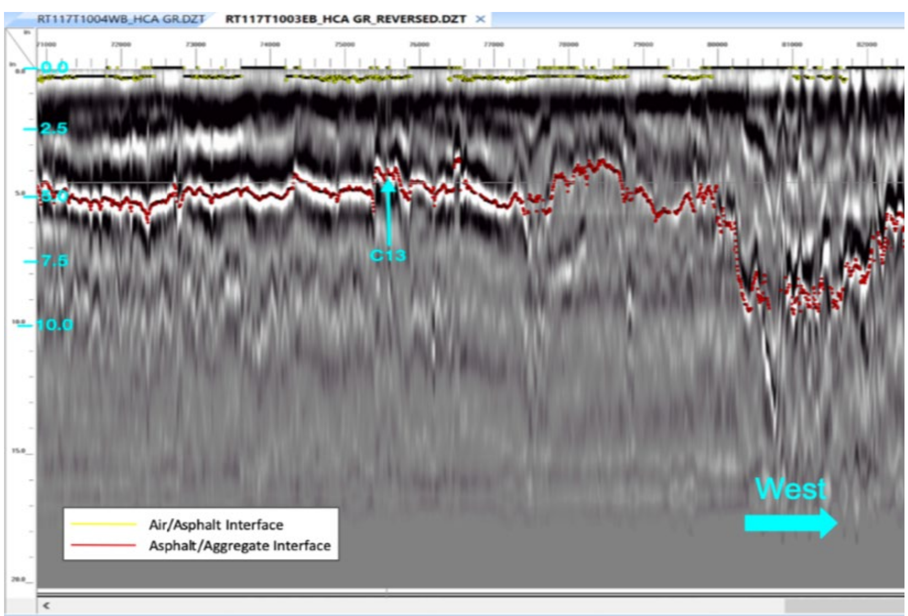

Figure 9: Example of picked Radan file consisting of a road section with areas of composite and non-composite base

Once the radar data was preliminarily analyzed, strategic locations with varying reflection depth and brightness were selected for coring, as well as locations of consistent depth and brightness. Coring was performed by the RIDOT as shown in Figure 10. The core locations were marked with road paint along Route 117 for the coring crew. Cores 1 through 15 were collected from the eastbound lane and cores 16 through 23 from the westbound lane.

As an example, the GPR image corresponding to core 5 (C5) is shown in Figure 11. The surface of the road corresponding to the same core location, shown in Figure 12, exhibits both longitudinal and transverse cracking. The estimated (per GPR) asphalt thickness of 4.5 inches at this location was confirmed by measuring the actual core thickness, which was about 4.6 inches. The actual core is displayed in Figures 13 and 14. As a second example, the GPR image corresponding to core 4 (C4) is shown in Figure 15. The surface of the road corresponding to the same location, shown in Figure 16, appears to be in good condition, having a smooth surface with no cracking. The estimated asphalt thickness of 5 inches at this location was confirmed by measuring the actual core thickness, equal to 5 inches. This measurement is displayed in Figure 17.

Figure 10: RIDOT taking core of Route 117

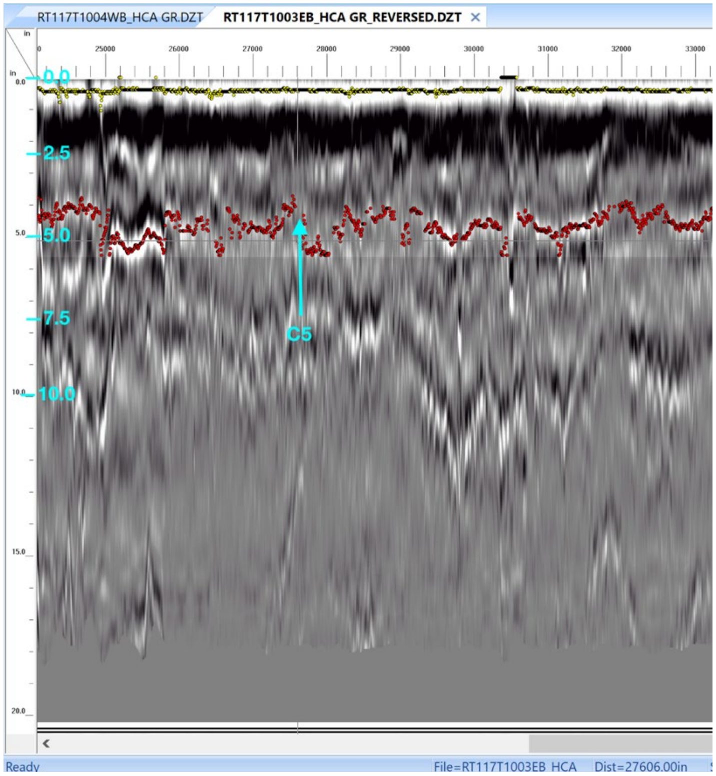

Figure 11: Core 5 approximate location shown in Radan


Figure 12: Core 5 location shown on the road

Figure 13: Picture of core immediately after being exhumed

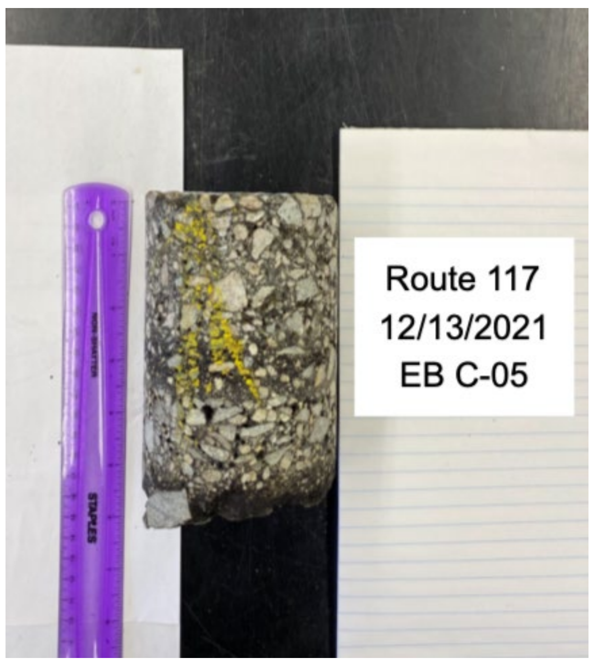

Figure 14: Comparing the estimated and measured depth of Core 5

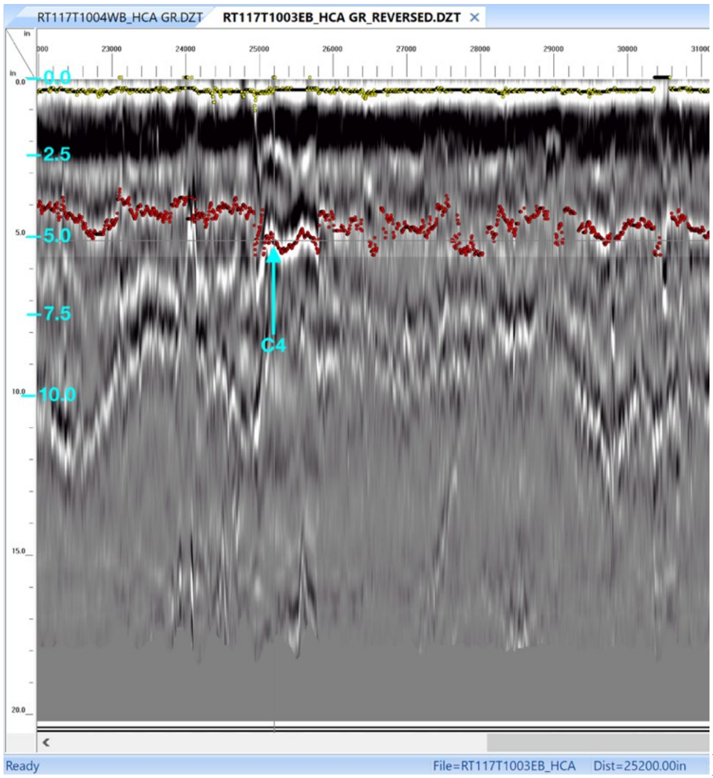

Figure 15: Core 4 location shown in Radan


Figure 16: Core 4 location shown on the road

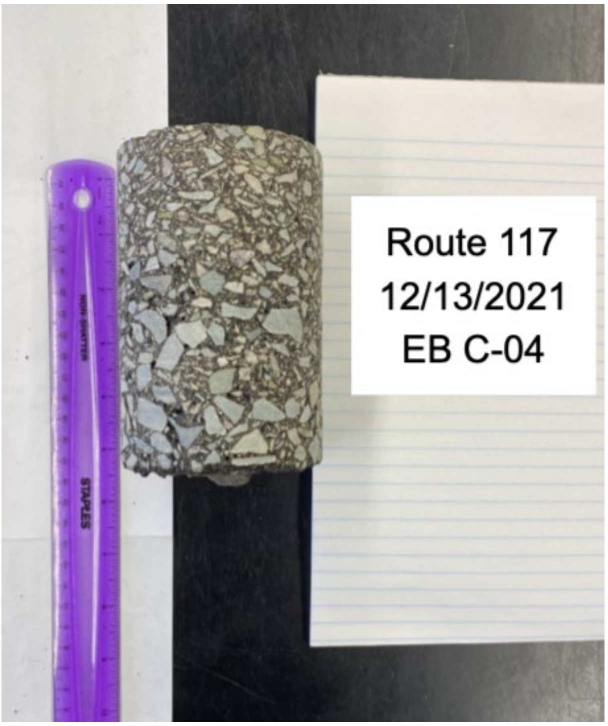

Figure 17: Comparing the estimated and measured depth of Core 4

A comparison of the estimated asphalt thicknesses (via GPR data) versus the actual thickness measured from the collected cores is displayed in Figure 18. The estimated and measured data had a percent error of 4.8%. The outlier, represented with an "X", was not included in the percent error calculation.

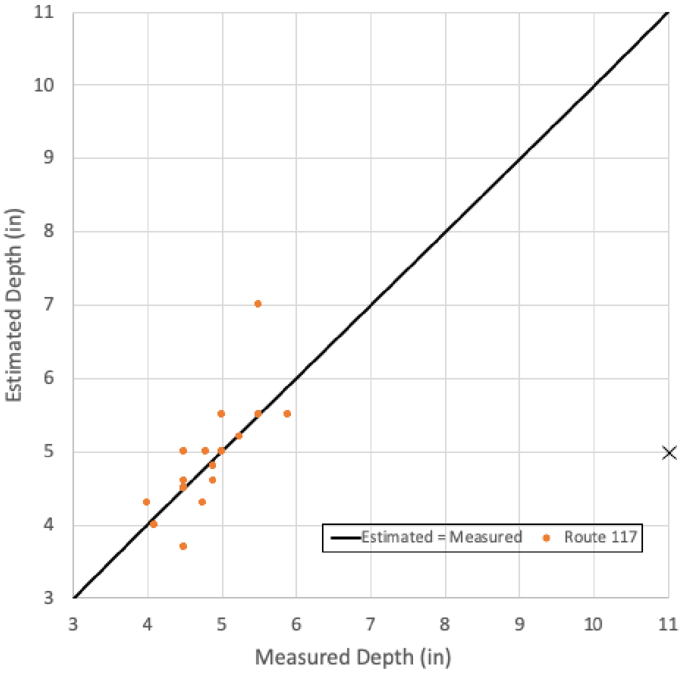

Figure 18: Comparing the estimated and measured depth of Route 117 cores

Google Maps was used for a visual display of core locations, asphalt thickness, areas potentially underlain by concrete, and dielectric constant of the roadway's surface. This is illustrated in Figures 19-21. In terms of asphalt thickness, green represented a section of asphalt with a thickness between 4.5" and 5.5", as shown in Figure 20. Also, the color black represents a section potentially underlain by concrete, and the bridge deck. In terms of the dielectric constant, there was significantly more variability in comparison to the thickness. Therefore, only sections of high dielectric and varying dielectric were displayed. The areas of high dielectric, being above 12, are shown in red, while the areas of inconsistent dielectric are shown in yellow. The sections with no color have consistent dielectric values close to the normalized value of 1 (normalized to the roadway's average dielectric constant). This is depicted in Figure 21. It can also be noted that the sections with the yellow or red color represent areas of old pavement, while the sections with no color represent new pavement. This coincides with the concept that newer pavement will have more consistent dielectric constants, while older or damaged pavement will likely have high or variable dielectric constants.

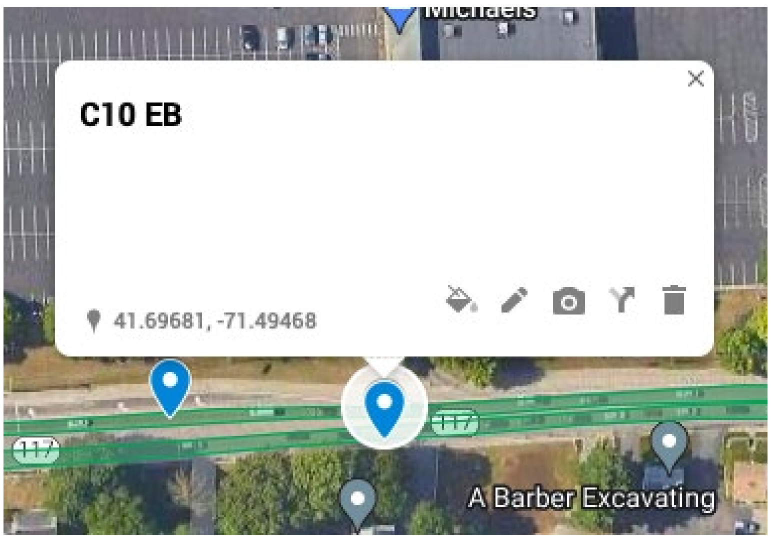

Figure 19: Example of the Google Map showing the core number, road direction, and GPS coordinates

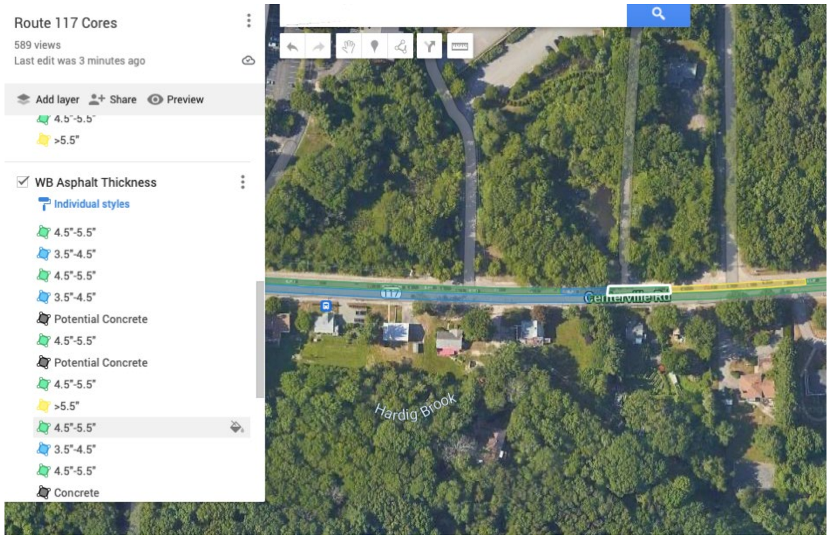

Figure 20: Example of the Google Map showing a section of the road with a depth of 4.5" – 5.5"

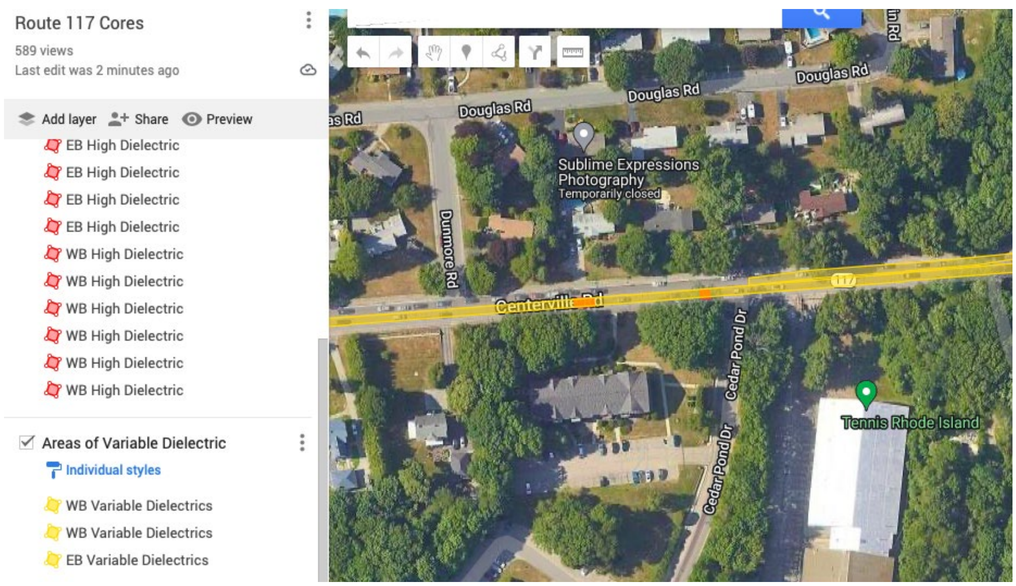

Figure 21: Example of the Google Map showing areas of high dielectric and variable dielectric

A further analysis comparing the dielectric values of the roadway's surface and bottom of the asphalt layer (as directly outputted from Radan) was performed. Figure 22 displays the dielectrics of the eastbound lane. The surface dielectric values are shown in blue, and the bottom of the asphalt layer in orange, which appear to be the same values. Additionally, the red lines represent suggested limits that may be considered when determining locations of damage via dielectric values. These limits were determined by normalizing the dielectric values to the average for the entire roadway and then calculating +/- 15% from 1.0. As a result, the graph shows how far each value of surface dielectric constant strays from the average dielectric constant of the roadway. This analysis was more-so used for the next roadway discussed because it is obvious that the beginning portion of the eastbound lane is old, damaged pavement which transitions to new pavement at about 40,250 ft. This is indicated by the portion of the graph before 40,250 ft being much more variable than the latter, more consistent, portion of the graph. The same analysis for the westbound lane was performed and are displayed in Figure 23.

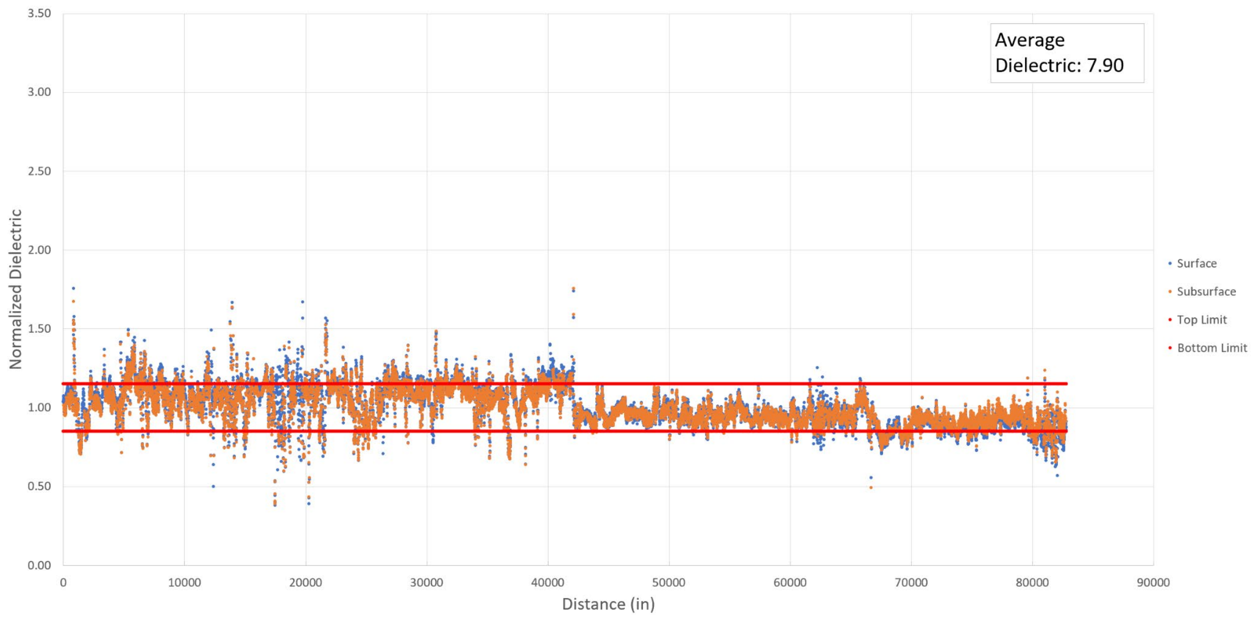

Figure 22: Route 117 Eastbound Dielectric Constants

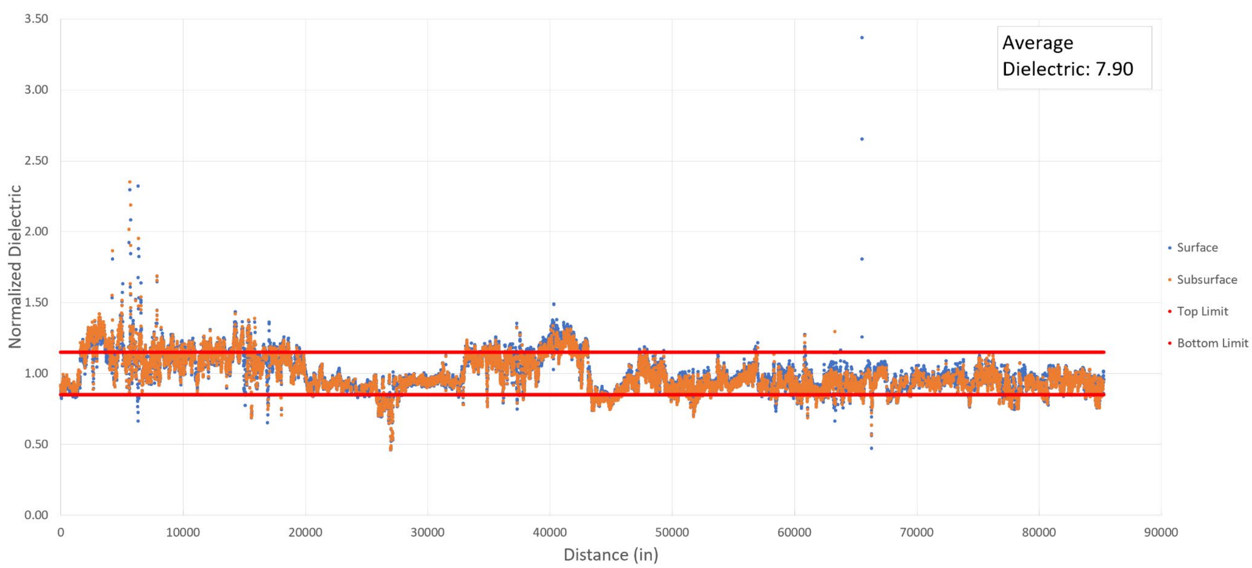

Figure 23: Route 117 Westbound Dielectric Constants

3.2 East Main Road, Middletown/Portsmouth

East Main Road is located in Middletown and Portsmouth, RI, as indicated with a star in Figure 24. The approximate limits of the data collection were between Aquidneck Avenue and Turnpike Avenue, as highlighted in Figure 25. The road consisted of two northbound and southbound lanes. Data was collected on East Main Road twice. The first time, the SIR-20 was used with a single 2.0 GHz horn antenna. The second time, a SIR-30 was used with three 2.0 GHz horn antennas. The purpose of using the SIR-30 was to be able to collect data at highway speeds while using three antennas, and to ensure that both systems produced the same data (the SIR-30 was first used with this project). Data from the right and left wheel paths was used in the analysis.

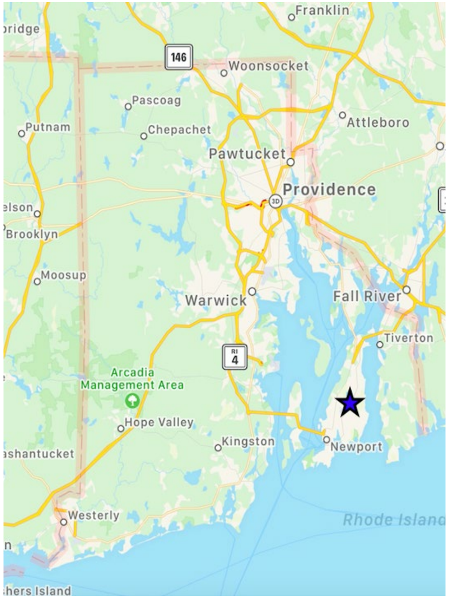

Figure 24: East Main Road location in Middletown/Portsmouth Rhode Island

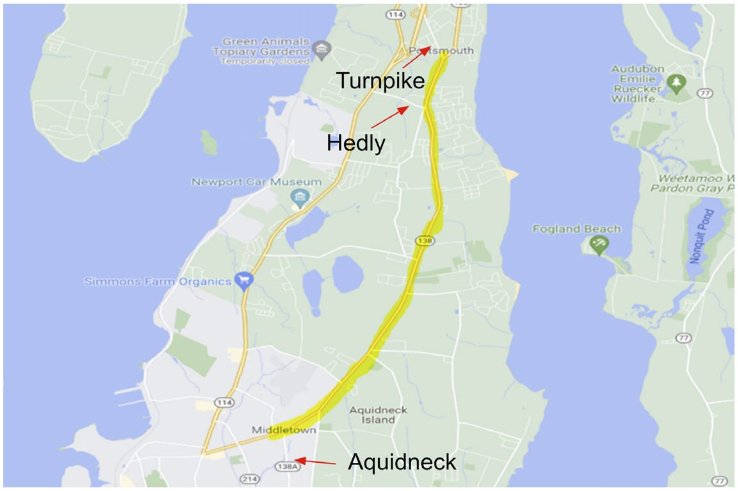

Figure 25: Limits encompassing approximately 6.5 miles of East Main Road

The same process of picking the surface and asphalt bottom layers in Radan as described in the previous section (Route 117), was performed for East Main Road. Both an asphalt thickness map and a variable dielectric map were created using Google Maps. Core locations were selected using the same process as described in the previous section, but they have not yet been collected. However, the validity of using Radan to estimate asphalt thickness was proven in the previous section. Since this section of roadway analyzed was quite lengthy (approximately 6.5 miles) ground artifacts were used to ensure accuracy when representing locations in Google Maps that were identified in the GPR d
ata. From the Route 117 analysis, it was noticed that new asphalt has a brighter reflection close to the surface. Using this information, new, resurfaced areas were used as landmarks for transcribing core locations and asphalt thicknesses into Google Maps.

Since the limits of data collection encompassed approximately 6.5 miles of roadway, a variety of road conditions were encountered. Areas where clusters of both high and low dielectrics were highlighted on the variable dielectric map created using Google Maps. These areas were found to correlate with poor surface conditions. Only the surface dielectrics (outputted directly from Radan) were analyzed since they appeared to be the same as the bottom of the asphalt, as shown and discussed in the previous section.

Figure 26 shows the surface dielectric values collected from each wheel path in the southbound left lane (lane 1. The dielectric values were normalized to the average dielectric (5.59) of this roadway. The red lines indicate the boundaries of +15% and -15% of the normalized dielectric. Areas on the graph that have clusters of dielectrics that stray outside of these red lines are indicated by the black rectangles. When viewing the surface of the roadway at these locations, it's clearly damaged. For example, Figure 27 is a Google Earth image showing the section of road that corresponds to the dielectric values in the first black rectangle at approximately 10500 feet from the graph's origin, in Figure 26. This further suggests that damaged areas will likely have higher dielectrics.

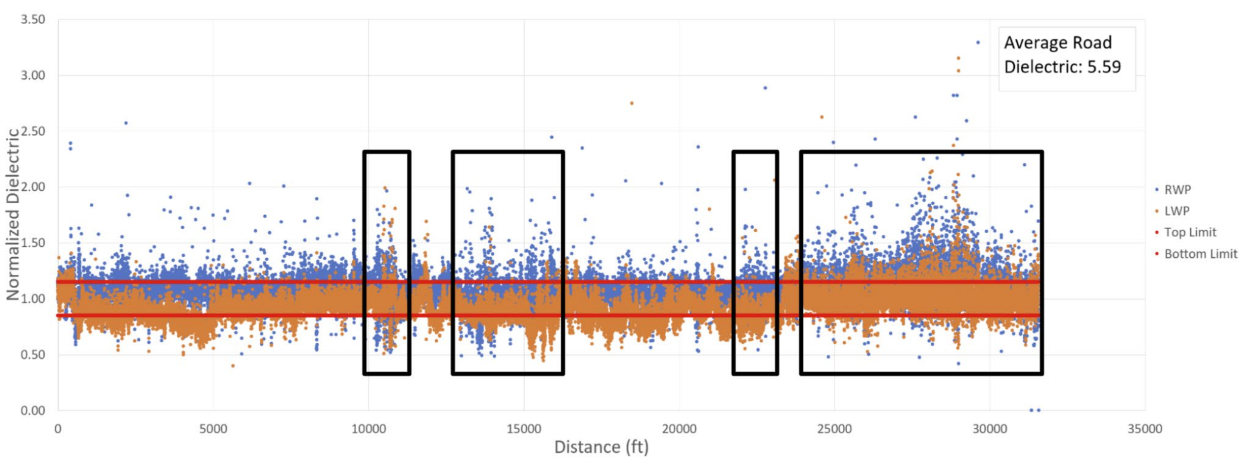

Figure 26: East Main Road surface dielectrics in each wheel path going Southbound

Figure 27: East Main Road surface photo from Google Street View of East Main Road Southbound lane 2

3.3 South of Commons Road, Little Compton

South of Commons Road is located in Little Compton, RI, as indicated with a star in Figure 28. The approximate limits of the data collected were between Commons Road and Brownell Road, as highlighted in Figure 29. South of Commons Road was selected for investigation due to the suspected presence of a high water table at this location. The road consisted of one northbound lane and one southbound lane. Data was collected using the SIR-30 with three 2.0 GHz horn antennas. After post-processing the data from each wheel path, it was found that the asphalt thickness was approximately 10 inches. It was also observed that the brightness of the reflection from the bottom of the asphalt layer was inconsistent, possibly as a consequence to the high water table. Similar to East Main Road, cores were identified but not collected from South of Commons Road, and asphalt thickness and dielectric maps were generated

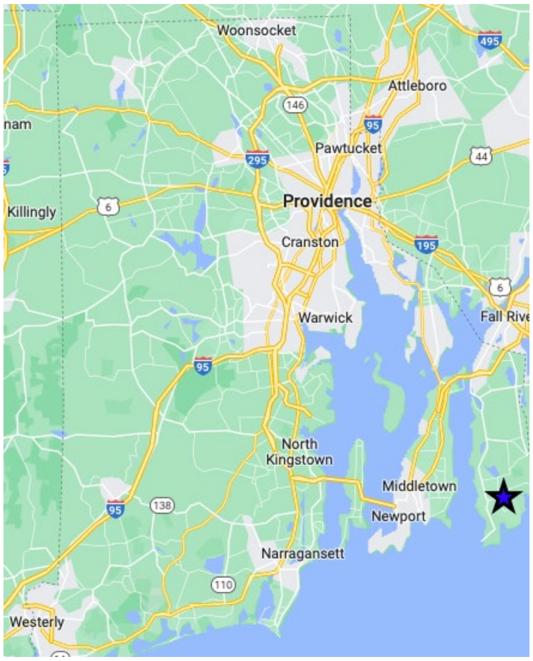

Figure 28: South of Commons Road location in Little Compton, RI

Figure 29: Limits encompassing approximately 1.1 miles of South of Commons Road

The presence of water can be identified where there are areas of high dielectrics. The dielectric values along this road were normalized to the road's average dielectric of 5.02, as shown in Figure 30. This figure shows the surface dielectrics collected from each wheel path in the southbound lane. It can be seen in Figure 30 that the right wheel path has consistently higher dielectrics than the left wheel path. It is hypothesized that this could be due to the crown of the road causing more water to collect in the right wheel path resulting in more damage to this portion of the road (See Figure 31). Clusters of dielectric values that are not within 15% of the average dielectric value for this roadway are shown in the black rectangles. It was suspected that the high water table could be the cause of the high dielectrics along the road. Although the dielectric values along this road weren't incredibly higher than the other roads studied, the high groundwater table could still be a contributing factor. Further observance after a rain event, and data collection during the wet spring season would be valuable to further conclusions.

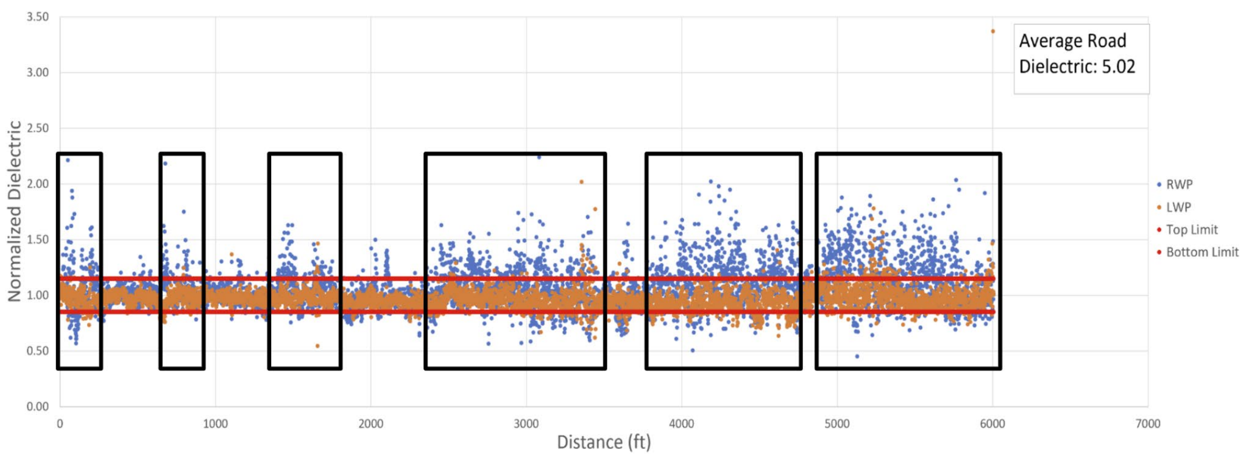

Figure 30: South of Commons Road surface dielectrics in each wheel path going Southbound

Figure 31. South of Commons Road Southbound condition

Chapter 5: Conclusions and Recommendations

The primary findings of this project are as follows:

- High dielectric constant suggests road damage and/or high groundwater
- Good agreement between Radan and ground truth data in determining asphalt thickness
- GPR can be used to locate areas of roadway with a composite base
- GPR can be used for choosing optimate core locations
- GPR serves as a promising tool to determine asphalt thickness and damage
- GPR can be useful in resurfacing design

The use of GPR allowed for the estimation and interpretation of pavement thickness and dielectric constant, ultimately aiding in the determination of the condition of a road. URI and RIDOT worked in collaboration to identify candidate roads with varying conditions and collect the data utilized for this project. The data was collected using both a SIR-20 and SIR-30 survey system and was post-processed using GSSI's software system, Radan. The data was collected from state-owned roads in various towns throughout Rhode Island, with a focus on Route 117 in Warwick, East Main Road in Middletown/Portsmouth, and South of Commons Road in Little Compton. The accuracy of determining pavement thickness via GPR was investigated by comparing estimated pavement thickness values from GPR with cores collected from strategic locations along the roadway. Using GPR to detect moisture-related damage was also performed by observing the trends of dielectric constant values and locating areas with abnormally high values. Google Maps was used to create user-friendly interactive maps that display the pavement thickness and dielectric values along the roads. This information can also be converted into the RIDOT's GIS-based inventory to aid in the process of planning for reconstruction or rehabilitation. The objective of this project was to use GPR as a nondestructive process for collecting and interpreting pavement thickness and moisture related damage. The information obtained will allow the RIDOT to optimize their system of planning for future pavement related projects.

It is proposed that the Little Compton sites could be great candidates for repeated measurements over time due to the high variability of asphalt dielectric constant and asphalt layer reflection in Radan, as well as the presence of high groundwater table. Additional data could be collected from these roads to monitor the impact, if any, of high groundwater table on the overall condition of the road over a period of time. This information could also be inputted into an interactive map for visual understanding or the GIS-based inventory for organization and future planning of rehabilitation.

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