Continuous Asphalt Quality Measurements using Ground Penetrating Radar

Charles P. Oden, PhD, PE
Earth Science Systems, LLC
September 30, 2024

Abstract

Ground Penetrating Radar (GPR) is a non-contacting and non-destructive method that can be used to assess the quality of new asphalt pavements. GPR surveys can be made with antennas mounted on push carts, vehicles, or even roller compactors. Maps of compaction, roughness, thickness, and temperature can be made during the paving process which provide invaluable feedback for the construction process. The resulting maps can be used for quality control by the construction team, or for acceptance by the owner of the road. This method provides much more detail than conventional gauge measurements and core samples, and avoids the use of hazardous nuclear sources for density gauges and destructive core extraction.

The dielectric constant of the asphalt surface is determined from the amplitude of reflected radar waves, which increases as compaction increases. An asphalt mix calibration is used to convert the measured dielectric constant into compaction values which are then used to create maps of compaction. The height of the GPR antenna above the surface is measured by the time-of-flight of the radar wave. Using the geometry of the cart or vehicle and the antenna height measurements the profile of the road can be determined, which is then used to calculate roughness measurements. The measured time-of-flight of waves that penetrate the asphalt are also used to map the total thickness of the asphalt layers.

Introduction

The ESS Asphalt Pavement Scanner (APS) is a revolutionary new GPR system that provides detailed and comprehensive quality information for new asphalt mats without the use of nuclear sources. The standard pushcart configuration of the system is shown below in Figure 1, along with a typical real-time compaction map display on the tablet PC. The system can also be vehicle mounted using a standard two-inch trailer hitch. The scanner uses radar to measure compaction, roughness, and total mat thickness. A non-contacting IR temperature sensor is used to make temperature maps.

The heart of the APS system is a wireless scan head that contains a GPR, a non-contacting IR temperature sensor, and an advanced global navigation satellite system (GNSS) receiver. The scan head connects to a tablet PC via WiFi, eliminating the need for cumbersome and troublesome cables. The radar is a 2 GHz impulse system with bi-static antennas. The GNSS receiver receives signals from the GPS, GLONASS, BEIDOU, and GALILEO satellite constellations to achieve high accuracy positioning nearly anywhere. The system provides ~1 cm positional accuracy when connected to an RTK (real time kinematic) GPS base station or a CORS (continuously operating reference station) network via a cellular data connection on the tablet PC.

This paper demonstrates how maps and reports generated by the system are beneficial to builders who use them for both process control during construction, and to owners who use them for inspection and acceptance after construction. A short survey was conducted at a new subdivision under construction to illustrate these capabilities.

Figure 1. The left panel shows cart configuration of the Asphalt Pavement Scanner, and the right panel shows the tablet display with a map and histogram.

A county map of the survey site is shown in Figure 2. Each two-lane street was scanned with seven survey lines – three for each lane and one down the center joint. Four streets were scanned and each scan is labeled as Scan 1 – 4 as shown in Figure 2. The scanner location was measured with the internal GPS connected to an RTK base station providing accuracy of ~1 cm. Surveys were conducted at walking speed (5 km/h). This corresponds to a full-lane scan rate of about 1.6 km/h, which is faster than standard paving rates (0.5-1.0 km/h). It took approximately 3 hours to cover the site, resulting in approximately five km of continuous scan data. Normally when creating maps of compaction or other measurements, a satellite image showing existing roads is used as an underlay. But since this was a new subdivision, online satellite imagery only depicted open fields for the site and the the new road locations had not yet been captured. Therefore the county subdivision lot map in Figure 2 is used as an underlay for all of the APS data.

Figure 2. Subdivision planning map from county records.

Survey Results

The scanner makes four different measurements which are all useful for quality control during the paving process and can also be used as acceptance criteria. The results from each measurement are discussed in the following sections.

Compaction

Instead of nuclear radiation, the APS scanner uses the varying intensity of reflected radar waves from the asphalt surface to measure the dielectric constant of the mat, which increases as compaction increases. Then an asphalt mix specific calibration is used to determine compaction values from the dielectric measurements. With both the compaction and GNSS readings, compaction maps of new road construction can be generated. The APS system simultaneously measures the dielectric constant at sampling depths of 35 and 70 mm, and the appropriate measurement is used to make maps depending on the lift thickness. The American Association of State Highway and Transportation Officials (AASHTO) has defined standard practice PP-98 (AASHTO, 2019) for dielectric profiling of new asphalt mats.

The relationship between dielectric and compaction is different for each asphalt mix, and there are several methods available for determining this relationship. The selected method will depend on whether the data will be used for quality control or acceptance. Various theoretical relationships between dielectric constant of mixtures and compaction can be found in the literature. One example is the Bottcher mixing formula (Leng, 2011) which calculates the bulk dielectric properties from a mixture of aggregate, binder, and air. While this formula is useful for scientific study, it is impractical for field use. In practice, a linear approximation mapping dielectric to compaction provides more than sufficient accuracy.

The most accurate calibration method uses gyratory compactor pucks and is outlined by AASHTO standard test T-414 (AASHTO, 2024). This method is preferred when using APS measurements for acceptance. A group of gyratory compactor pucks (150 mm in diameter and nominally 100 mm tall) is created with each puck having a different density. Next, the dielectric constants of the pucks are measured with the APS scan head and a coupling cone (see Figure 3), and then the density/compaction values of the pucks are measured using industry standard water displacement methods such as AASHTO T-166 (AASHTO, 2022). Finally the dielectric and density values are entered into the software to obtain the linear mix calibration equation. If the mix calibration is done before conducting the survey, then compaction results will be available in real-time during the survey. Alternatively, if the pucks are not available prior to the survey, the mix calibration can be applied to the recorded measurements after the survey. If cores are used in place of gyratory compactor pucks, they need to be 150 mm in diameter and 75 to 125 mm tall, and the tops and bottoms of the cores must be cut flat to resemble a compactor puck.

A more expedient mix calibration method uses a dielectric reading taken at a single location in the field that is combined with a nuclear gauge reading or core taken from the same location (see Figure 4). The slope of the mix calibration line is determined automatically by the software using the Bottcher mixing formula. It should be noted that while this approach is not as accurate as AASHTO T-414, it is quicker and more suitable for quality control applications. The biggest reason for the reduced accuracy has to do with the spacial variability of asphalt properties and different volumes of investigation for the different density measurement methods. For example, the volume of investigation of the APS is a 45 cm diameter cylinder with depth of 3.5 - 7 cm, while that of a nuclear density gauge can be loosely approximated by a 10 to 20 cm diameter half-sphere.

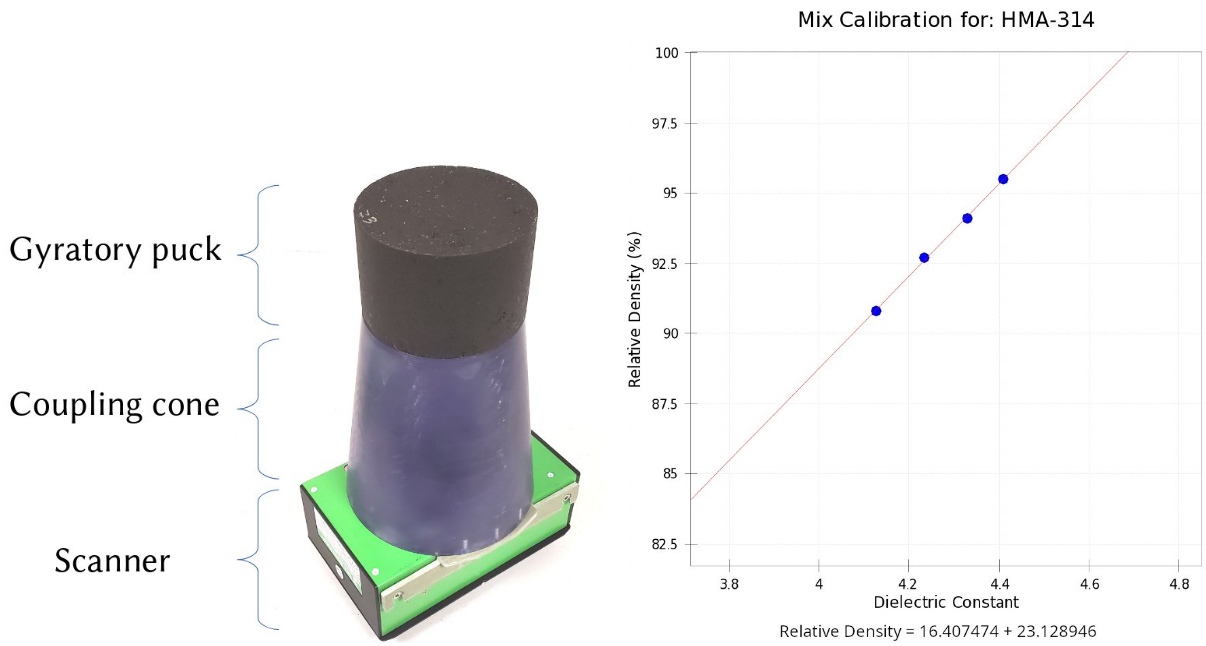

Figure 3. Using gyratory compactor pucks to determine the mix calibration for converting dielectric constant to compaction.

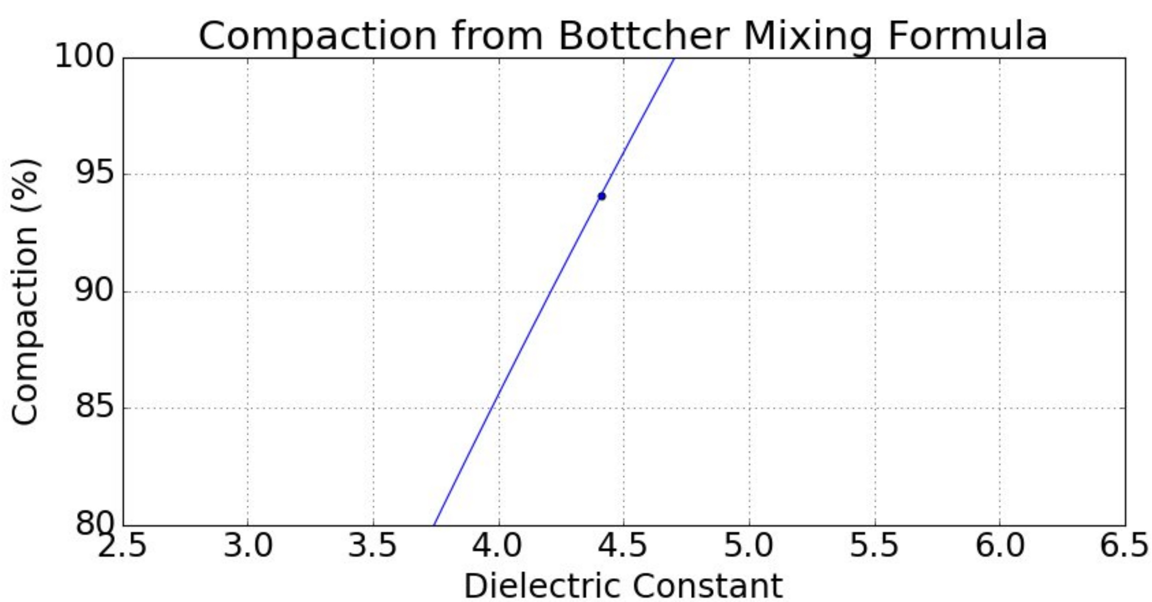

Figure 4. Asphalt mix calibration determined from a single density gauge reading of 95.8% and a dielectric constant of 4.73.

The asphalt mix calibration assumes that there is no water in the mix, and it is therefore important to conduct the APS surveys soon after the last roller pass. Surveys conducted the following day run the risk of added moisture to the new asphalt pavement due to rain or dew events. The APS system has been designed to run as part of the paving train so that real-time information can be provided to the construction team.

At this survey site a single gauge reading was used to obtain the mix calibration (see Figure 4), and the resulting mix calibration was used to obtain the compaction values shown in Figures 5-7 below. Because the gauge had a measurement depth of 10 cm, the 7 cm deep APS readings are shown. In Figure 5, each reading is plotted successively for all seven survey lines in Scan 4 (the high dielectric readings at the end of each line occurred at locations where the cart rolled off the edge of new pavement between scan lines). The common problem of under-compaction at joints in the mat can be seen in the lower compaction values obtained along line 4 which straddled the center joint. The lower compaction along the joints can also be seen in Scans 1 – 4 in Figure 6, and more detail can be seen in Figure 7 which shows the compaction for Scan 4.

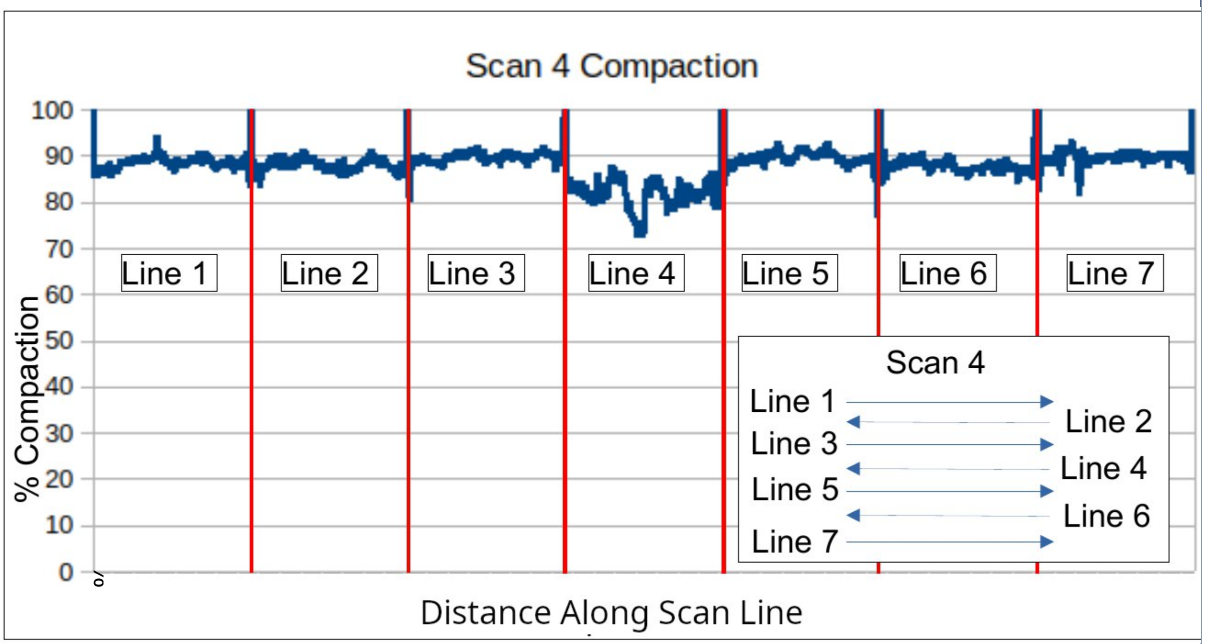

Figure 5. Compaction readings from all lines in Scan 4 where the spikes indicate the change between scan lines. Lower compaction values are evident along scan line 4 that traverses the center joint.

Figure 6. Compaction values obtained from the three inch depth readings [81% 97%], horizontal and vertical map axes in feet.

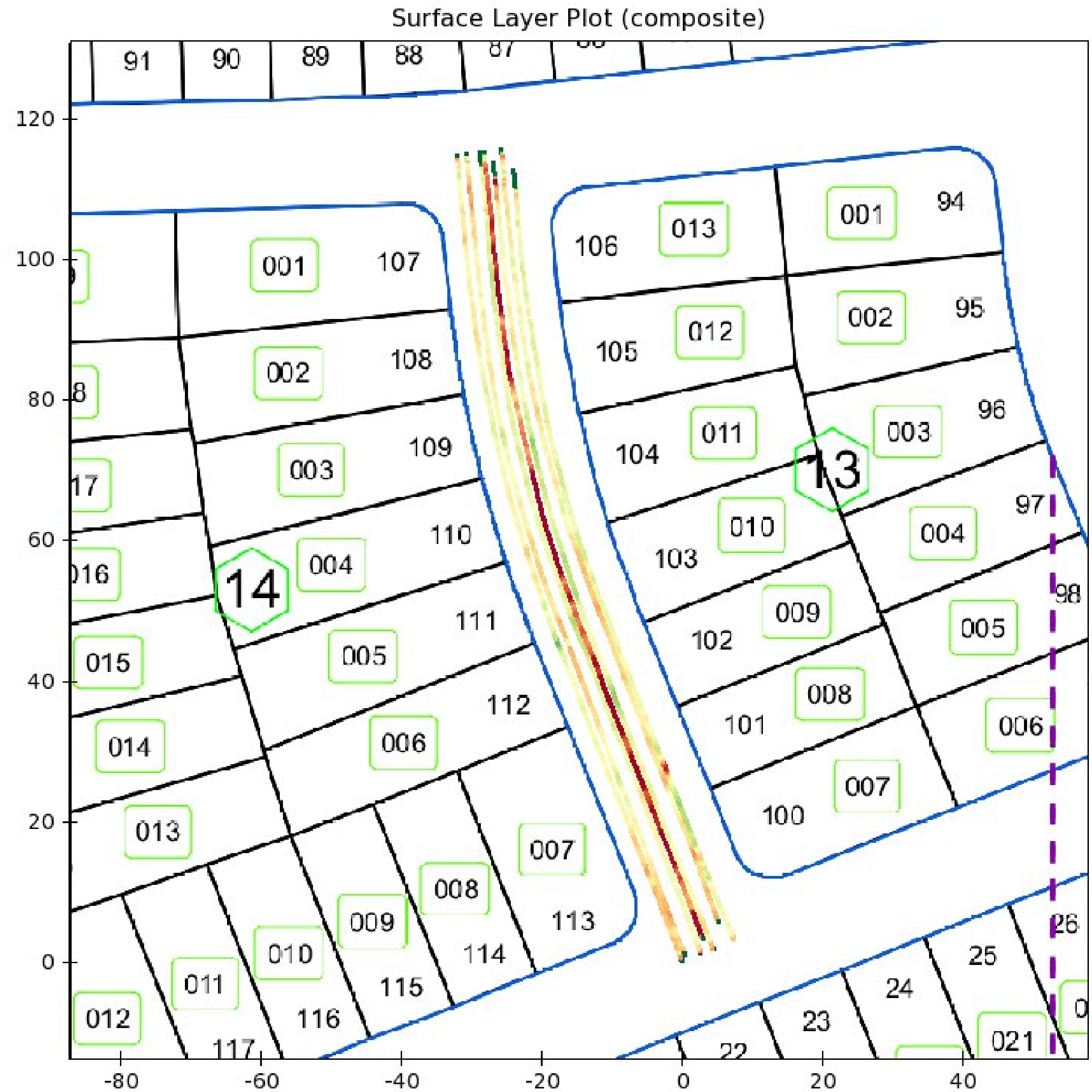

Figure 7. Compaction values obtained from the three inch depth readings for Scan 4 [81% 97%], horizontal and vertical axes in feet. The center of the road along the joint shows lower compaction than the rest of the road (red versus yellow).

Surface Roughness

The APS also measures the height of the scan head above the surface using radar. With this measurement and consideration of the wheel geometry of the cart, the surface profile can be calculated (Sayers and Karamihas, 1998). This is similar to the measurements made by California Profilograph or a rolling straight edge. A standard indicator of roughness is the International Roughness Index (IRI), which is calculated from the surface profile measurement. The APS provides and IRI measurement is a useful quality indicator that measures roughness in m/km. Due to wheel base length limitations, the APS IRI measurements have reduced sensitivity to the long period undulations of the roadway. As a result, IRI measurements made from vehicles have more fidelity than those taken from a push cart.

Nowadays, the state of the practice for roughness testing is to conduct inertial profiler surveys sometimes days after the construction phase has been completed. These inertial profilers must be annually certified according to the American Society for Testing and Materials E-950 specification (ASTM, 2022) using data collected on an approved test track, such as the MnRoad test track operated by the Minnesota Department of Transportation. Although the APS uses the previously used rolling straight-edge method, the E-950 test criteria are still valid and were used to evaluate the APS IRI measurements. Figure 8 shows the IRI results from a series of repeat runs on the MnRoad test track using the APS system mounted on a pickup truck. These runs were evaluated using the industry standard ProVal software which uses ASTM E-950 to assess repeatability and accuracy. All of the runs passed the repeatability criterion with typical correlation coefficients of 98%. However, the APS IRI measurements differed from the reference laser inertial profiler values by about 10% which is outside the acceptable range for acceptance applications. Nevertheless the availability of real-time IRI measurements during the paving operation is very useful for quality control purposes.

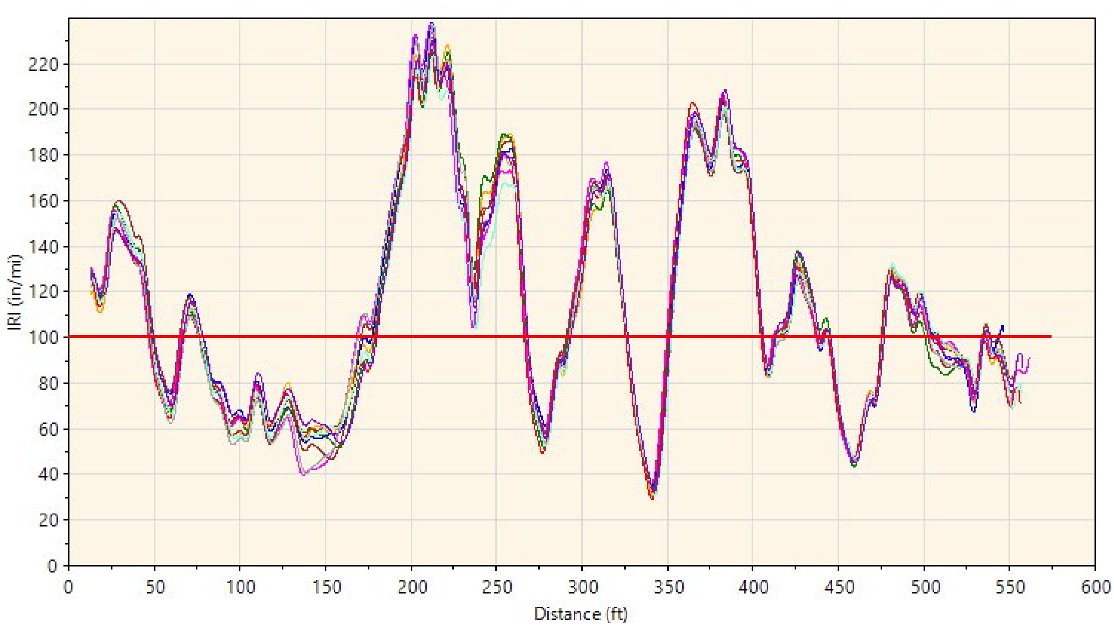

Figure 8. Repeat continuous IRI measurement made by the APS system in the MnRoad test track (100 in/mi is about 1.58 m/km, and 500 feet is about 150 m).

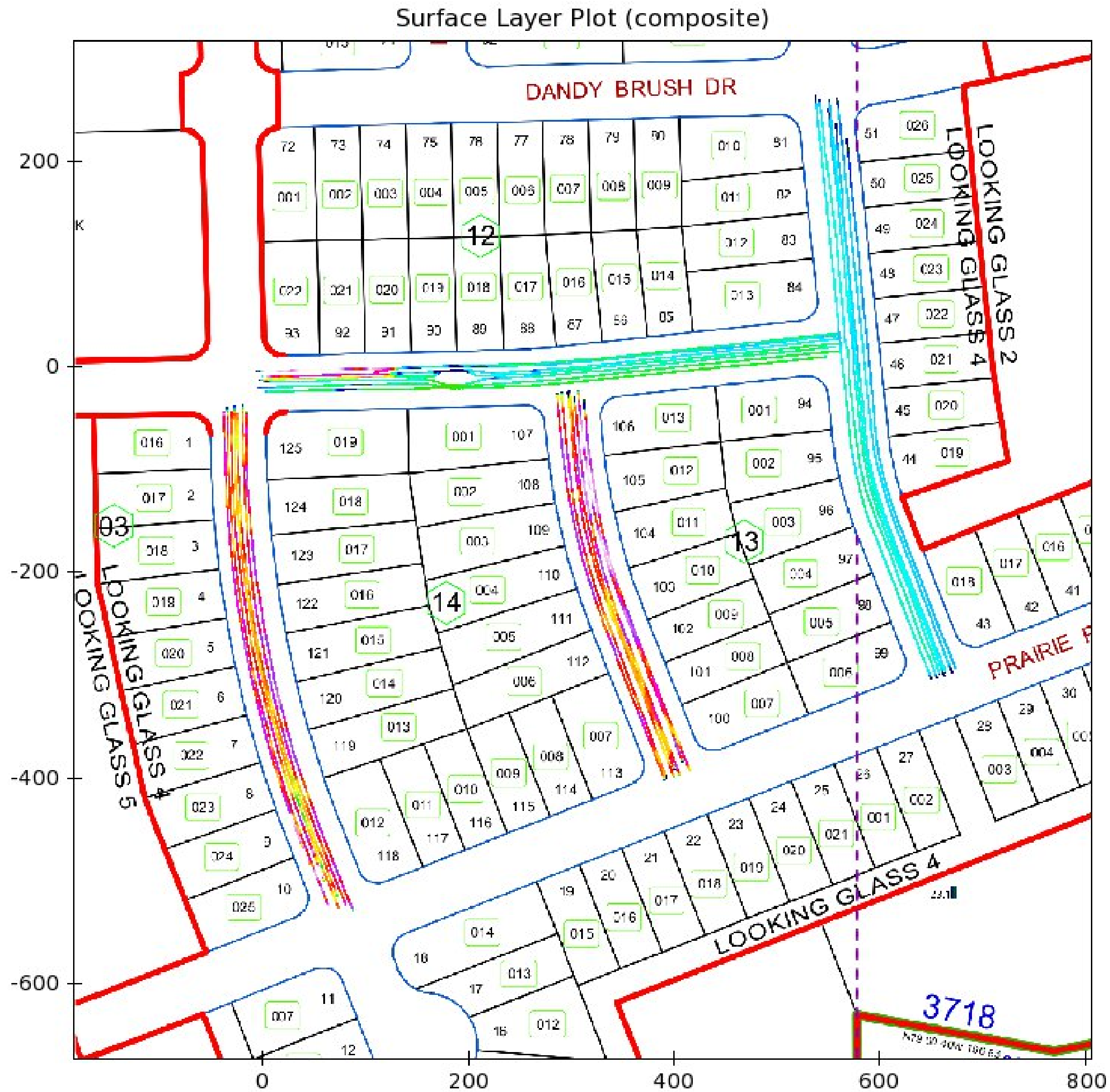

Figure 9. Surface temperature [23C 50C], horizontal and vertical axes in feet.

Temperature

The scanner has a non-contacting IR temperature sensor whose measurements can be used as an indicator for non-uniformity of the mix during paving. For example, mix problems such as segregation often manifest as temperature anomalies. In Figure 9, the cooler parts of the image (blues and greens) correspond to pavement that was placed the day prior to the APS survey, and the hotter regions (purples and reds) were placed on the day of the survey. For Scan 1, the north-west part of the scan area was placed the same day that the APS scan was conducted. In Scans 2 and 3, some temperature variations can be seen which may be due to uneven heating and/or uneven mixing. Areas with anomalies like this should be visually inspected to look for segregation or other mix defects.

When the scanner is mounted on a roller compactor, the temperature readings indicate to the roller operator when the mat is within or outside the proper temperature for compaction.

Asphalt Thickness

The radar reflections from the top and bottom of the asphalt mat can be used to measure the overall thickness of the mat. When the subgrade material below the asphalt has different properties (dielectric or moisture) than the mat, a radar wave reflection from the bottom of the mat can be seen as shown in Figure 9. By measuring the travel time difference between the top and bottom of asphalt, and using the measured dielectric constant, the thickness of the mat can be measured. Figure 10 shows the asphalt thickness for all of the scanned areas. Note that this is the thickness to the depth where the material properties change, which in most cases is the base of the asphalt. This measures the combined thickness of all lifts in the asphalt sequence and is not able to distinguish thickness of individual lefts. Although uncommon, in some cases the dielectric properties of the subgrade are similar to those of the asphalt, and the reflection off of the base of the asphalt may be too weak to measure thickness. GPR cross sections as shown in Figure 9 show mat thickness in real-time. The process of creating thickness maps however, does not occur in real-time like the other measurements described in this paper. Thickness maps require an additional post processing step to pick the surface and subsurface horizons after the data have been recorded.

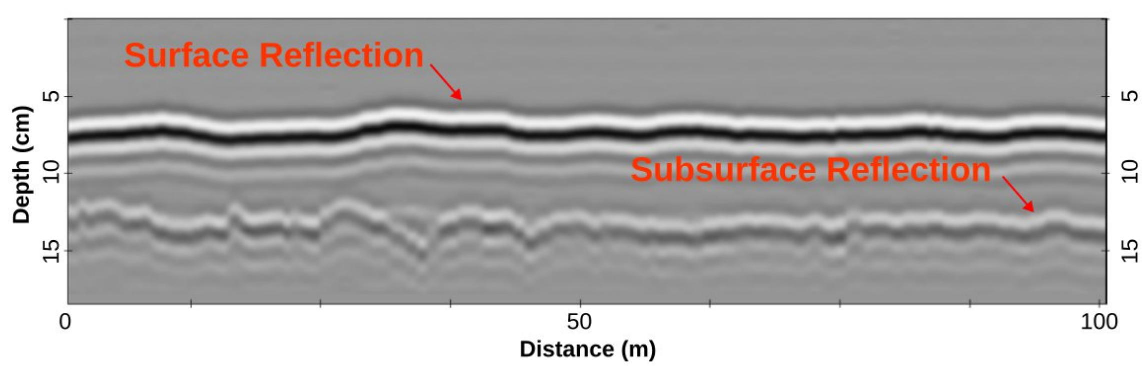

Figure 9. GPR cross section showing the surface reflection and the subsurface reflection off of the base of the asphalt mat.

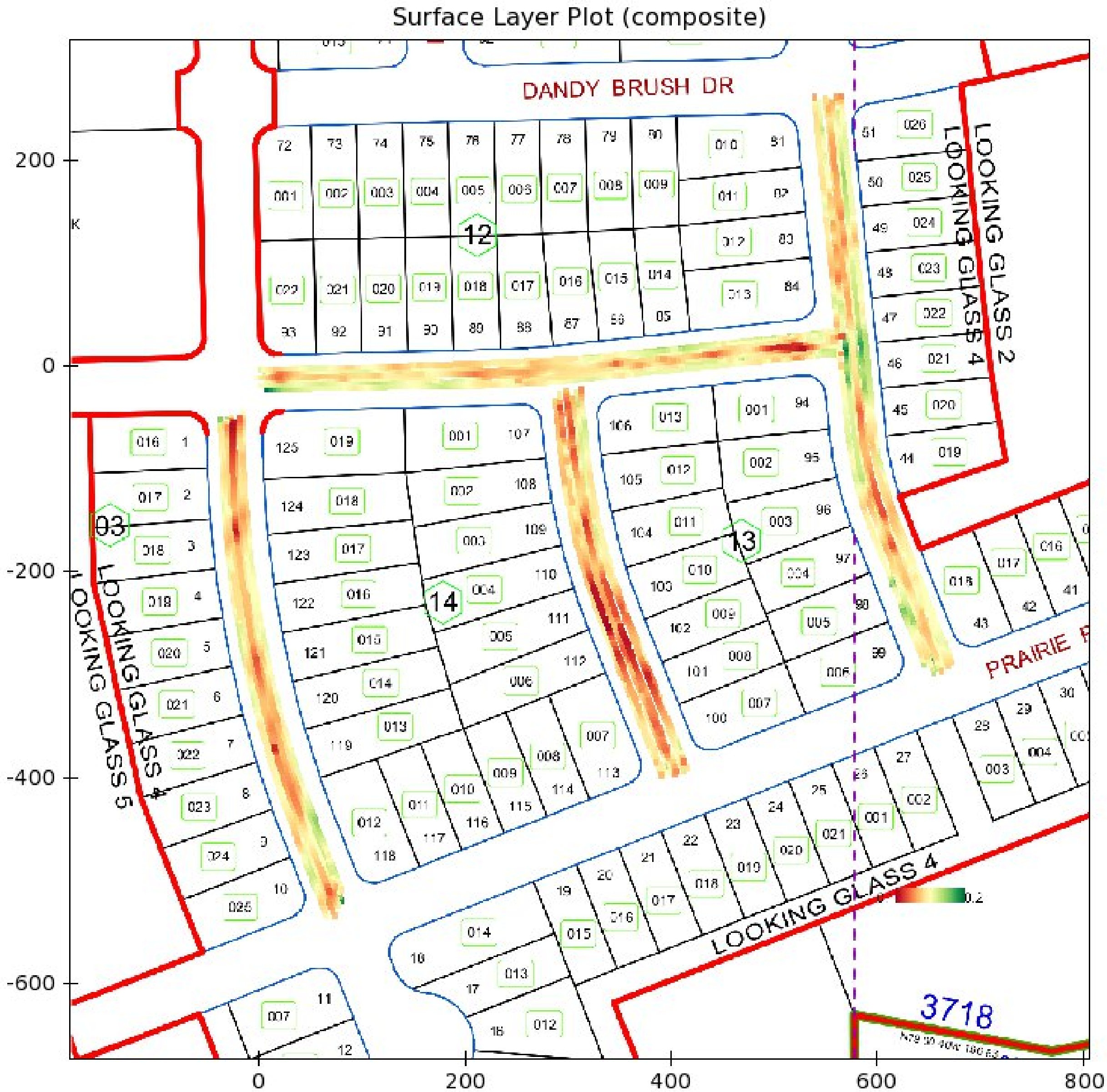

Figure 10. The asphalt thickness at this site is nominally 12 cm thick (yellow), with some localized minor deviations. [7 — 30 cm], horizontal and vertical map axes in feet.

Maps and Reports

The APS system displays real-time maps of compaction, roughness, and temperature on the tablet PC screen as data are being recorded. Figure 11 shows a real-time map with the compaction color overlay on the left, and a histogram of compaction on the right. Users can also generate histograms and calculate percent within limits (PWL) for compaction, thickness, and roughness. The PWL values are often used to determine incentives and penalties in paving contracts. Due to the large number of samples and locations tested with the APS, the results more truly represent the in-place material and provide a valuable tool to reduce the risk assumed by both the buyer and the contractor. In other words it will be less likely for the contractor to be falsely penalized for acceptable work and for the buyer to pay for defective work.

Figure 11. Screen shot of real-time compaction map along with a histogram of measured compaction values.

The APS system also supports industry standard software that has been developed under support from the U.S. Federal Highway Administration. These software packages support a wide variety of intelligent compaction measurements and can be freely downloaded (see Veta, 2023, and ProVal, 2024). These software packages offer advanced processing, data filtering, and mapping capabilities.

- **Veta** is a standardized software tool developed by The Transtec Group, funded jointly by MnDOT and FHWA for geospatial data management, viewing, analysis, and reporting. This software is used to display temperature, compaction, and stiffness data that are recorded by instruments mounted on screeds and roller compactors. Like the APS software, the Veta software overlays data onto Google Map satellite views; and it also allows users to combine data collected from a wide variety of intelligent compaction sensors that may be mounted on different platforms (asphalt delivery trucks, screeds, roller compactors, survey vehicles, etc.).

- **<u>ProVal</u>** (Profile Viewer and Analyzer) is a software that was initially developed to provide a means to view and analyze pavement profiles efficiently and robustly, as part of the Federal Highway Administration (FHWA) smoothness initiative.

At the end of each survey line, the APS system automatically exports a .pdf summary report with a map along with Veta and ProVal files. Figure 12 shows an example of the mapping capability of the Veta software. Additionally, the APS software can create reports and data exports in several alternative file formats.

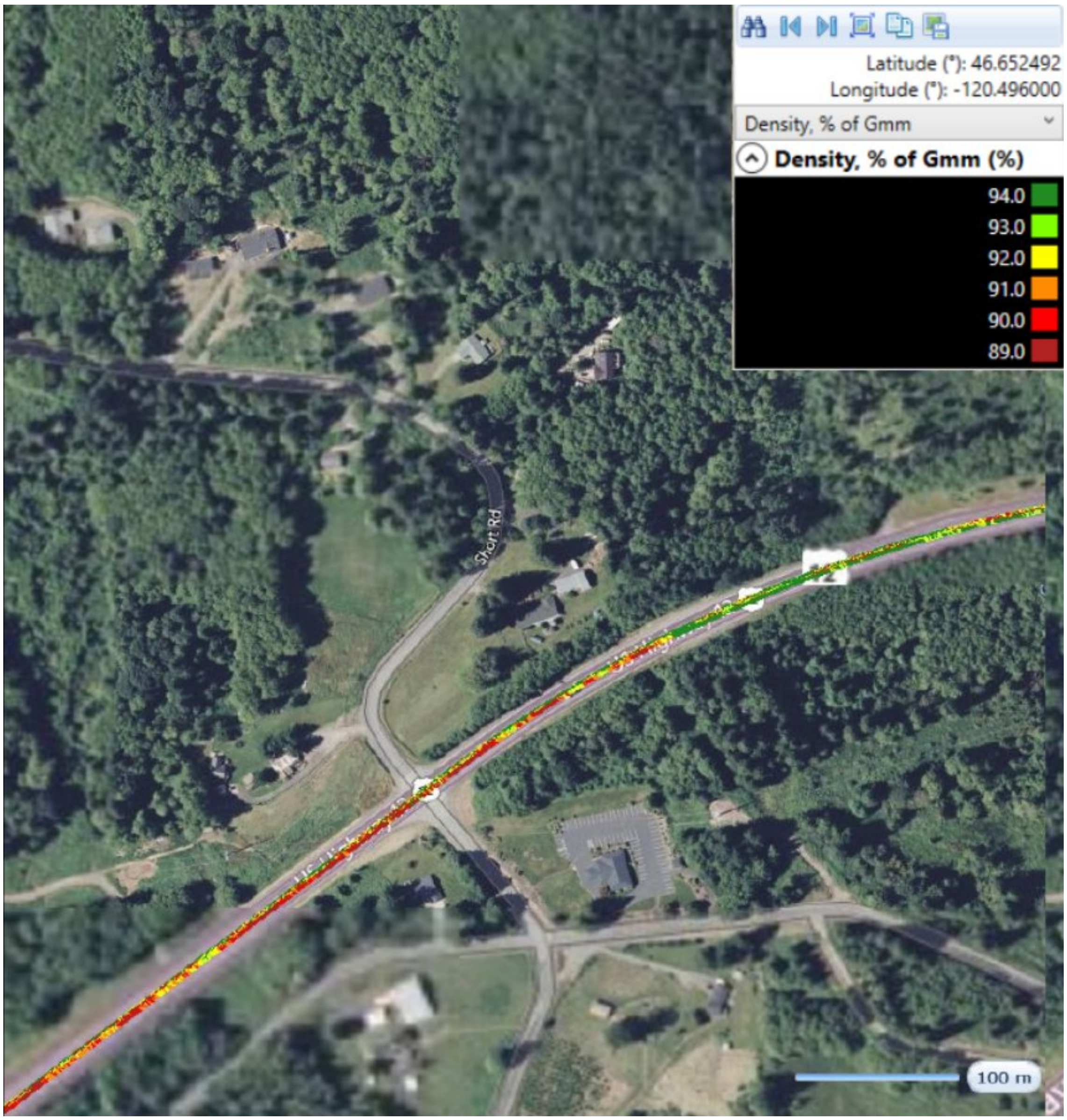

Figure 12. A screen shot of APS scans along a highway in the Veta software.

Conclusions

Continuous compaction measurements from the APS system are a significant shift from traditional nuclear gauge and coring methods. Continuous coverage provides a much more representative indicator of the quality of the paving job. The hazards and special training required for nuclear density gauges is no longer necessary. Continuous compaction measurements also reduce the need to destructively extract cores from newly constructed roads.

A mix specific calibration is needed for every asphalt mix. Some transportation departments will require a daily mix calibration or a new calibration for every 1000 tons of asphalt. An important consideration is that dielectric measurements should be made soon after and at least on the same day that the last roller has completed its passes. The reason is that any moisture on the asphalt adversely affects the dielectric measurement and is not accounted for in the mix calibration. Moisture from rain events and dew events should be avoided. The APS is designed to be part of the paving train so that real-time information can be provided to the road builders.

The ability of the APS system to collect so many useful measurement from a single pass is truly revolutionary. Although there are other instruments available to measures asphalt compaction, surface roughness, asphalt thickness, and surface temperature, no other instrument can provide all of these measurements continuously from a single pass. The APS provides the data needed by builders to develop processes to meet specifications and demonstrate compliance. Owners and transportation departments can use the APS to ensure that the entire asset was built properly rather than only verifying a few data points from gauge measurements or cores. With more and more transportation departments moving to contracts with both incentives and disincentives based on percent-within-limits measurements, the APS is becoming an invaluable tool for both contractors and owners.

References

AASHTO, 2019, Standard Practice for Asphalt Surface Dielectric Profiling System using Ground Penetrating Radar, AASHTO Designation PP 98-19, American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO, 2024, Determining the Dielectric Constant of Compacted Asphalt Mixture Specimens, AASHTO Designation T 414-24, American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO, 2022, Standard Method of Test for Bulk Specific Gravity (Gmb) of Compacted Asphalt Mixtures Using Saturated Surface-Dry Specimens, AASHTO Designation T 166-22, American Association of State Highway and Transportation Officials, Washington, DC.

ASTM, 2022, Standard Test Method for Measuring the Longitudinal Profile of Traveled Surfaces, ASTM Designation E-950, ASTM International, West Conshohocken, PA.

Leng, Z., 2011, Prediction of In-Situ Asphalt by Mixture Density Using Ground Penetrating Radar: Theoretical Development and Field Verification, PhD Thesis, University of Illinois at Urbana-Champaign, 144 p.

Sayers, M.W. and Karamihas, M.S., 1998, The Little Book of Profiling. The Regent of the University of Michigan, Ann Arbor.

Veta, 2023, Veta 8.0 desktop software, The Transtec Group, Austin, TX, https://www.intelligentconstruction.com/veta-8-0-released/.

ProVal, 2024, PROfile Viewing and AnaLysis, The Transtec Group, Austin, TX, https://www.thetranstecgroup.com/resources/software/proval/.