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Implementing Dielectric Profiling Systems for Real-Time Quality Control

2023 Workshop

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Implementing Dielectric Profiling Systems for Real-Time Quality Control

2023 TRB Annual Meeting Workshop

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Contents

Introduction

This E-Circular is a summary of the 2023 TRB workshop on how Dielectric Profiling Systems (DPS) and Paver Mounted Thermal Profiling (PMTP) can be used to advance pavement quality measurement of the entire mat from a limited number of random post-construction measurements to near-continuous measurements in real time during construction. The original format was to be short presentations on the components of pavement quality assurance (process control, quality control [QC], and acceptance) measurements using DPS and PMTP followed by group breakout sessions to discuss and plan methods for effective implementation of the technologies. To collect the thoughts of attendees within the time constraints of the workshop, a link to a MentiPoll was given to the attendees with questions to be answered during each group of presenters.

The workshop moderator, Ervin Dukatz, gave a brief introduction of the workshop format and thanked the co-sponsoring TRB standing committees, Committee on Quality Assurance Management, Committee on Asphalt Pavement Construction and Rehabilitation, Committee on Production and Use of Asphalt, and Committee on Pavement Management Systems. Thanks were given to Tim Aschenbrener and the workshop committee, Dennis Dvorak, Adam Hand, Kyle Hoegh, Nima Kargah-Ostadia, and Jeff Withee for their work organizing this workshop. Additional recognition was given to Kye and Adam for running and summarizing the MentiPoll during the workshop. The workshop presenters and the chapters in this E-Circular are divided into three groups:

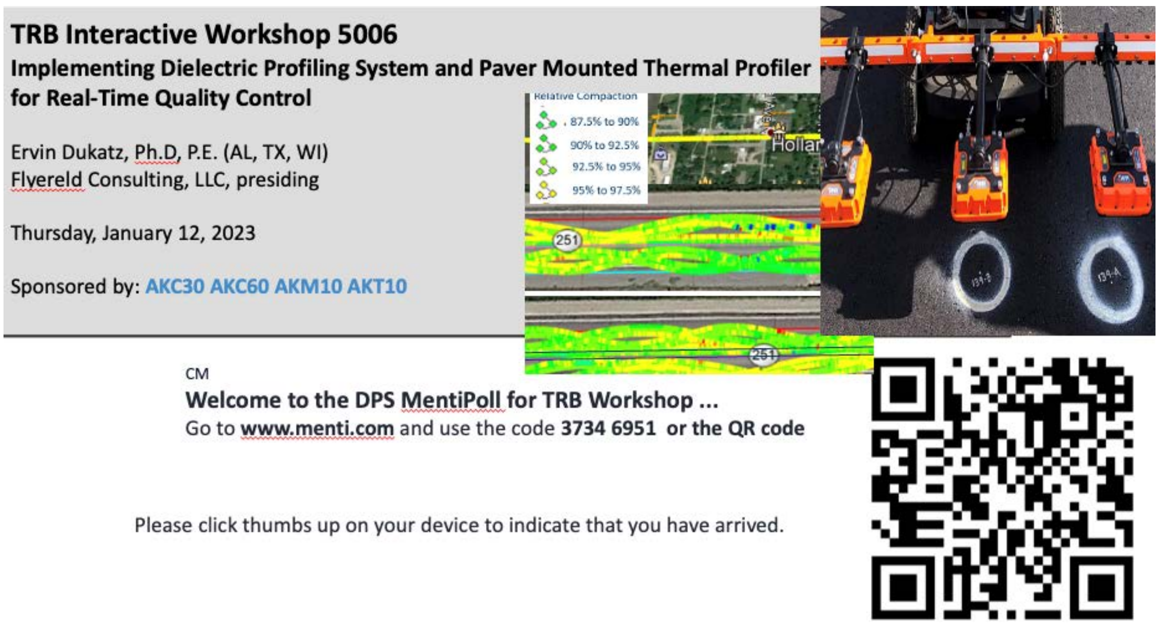
1. **Overview of DPS and PMTP**
   Department of Transportation Historical Perspective, *Curt Turgeon, Minnesota Department of Transportation*
   Improved Quality Control for Paving Operations: Contractor Perspective, *Bryce Wuori, Wuori Consulting, LLC*
   First MentiPoll Questions and Answers
2. **Overview of DPS and PMTP for State Highway Agencies**
   Dielectric Profiling Systems and Pavement Performance, *Craig Landefeld, Ohio Department of Transportation*
   Overview of DPS and PMTP for Pavement Performance, Sustainability, and Safety, *Kyle Hoegh, Minnesota Department of Transportation*
   Second MentiPoll Questions and Answers
3. **Implementing DPS and PMTP for Contractors**
   Implementing Dielectric Profile Systems and Paver Mounted Thermal Profiling: A Contractor Perspective, *Derek Frederixon, Mathy Construction Company*
   Implementing Intelligent Construction Technologies, *Forrest Hierholzer, Granite Construction*
   Third MentiPoll Questions and Answers

The seventh presentation on Acceptance Considerations and Ensuring Value for the Taxpayer Dollar could not be included in this E-Circular; however, a summary of the fourth

MentiPoll questions and answers are provided on page 54. The E-Circular concludes with information about additional resources on DPS and PMRP.

The views expressed in this E-Circular are those of individual workshop participants and do not necessarily represent the views of all workshop participants, the technical committee, or the Transportation Research Board.

The takeaways from this E-Circular for contractors will be how to improve their paving operations and increase profits with DPS and PMTP. For agencies, the takeaways will be the tools for them to sell the use of these technologies for process control today and acceptance in the future. The overall takeaway is: "The most sustainable pavement is the one that lasts the longest simply because it was built right."—Curt Turgeon.



Department of Transportation Historical Perspective

CURT TURGEON

Minnesota Department of Transportation

DIELECTRIC PROFILING SYSTEM AND PAVER MOUNTED THERMAL PROFILING SYSTEM—AND YOU MAY ASK YOURSELF, HOW DID WE GET HERE?

Often people get concerned about new technology because they think it is brand-new. This presentation will provide a brief history of PMTP, AASHTO-R110; Intelligent Compaction for Asphalt Pavements, AASHTO-R111; and Dielectric Profiling System, AASHTO-PP98. It starts with the State Pavement Technical Consortium, a pooled fund study. Materials engineers from Washington, Texas, California, Minnesota, and the universities from those states met every 6 months to discuss pavement problems and how to solve them. The report that kick-started the paver mounted thermal profiling was Construction-Related Asphalt Concrete Pavement Temperature Differentials and the Corresponding Density Differentials, by Kim A. Willoughby, et al. This was a multi-year study and note it was published in July 2001. This technology is not new. The study showed that measuring of lay-down temperature with an infrared camera and measuring of densities with a calibrated nuclear density gauge could be correlated to in-place pavement density (Figure 1). The study showed low pavement temperatures during compaction led to low densities and early pavement failures.

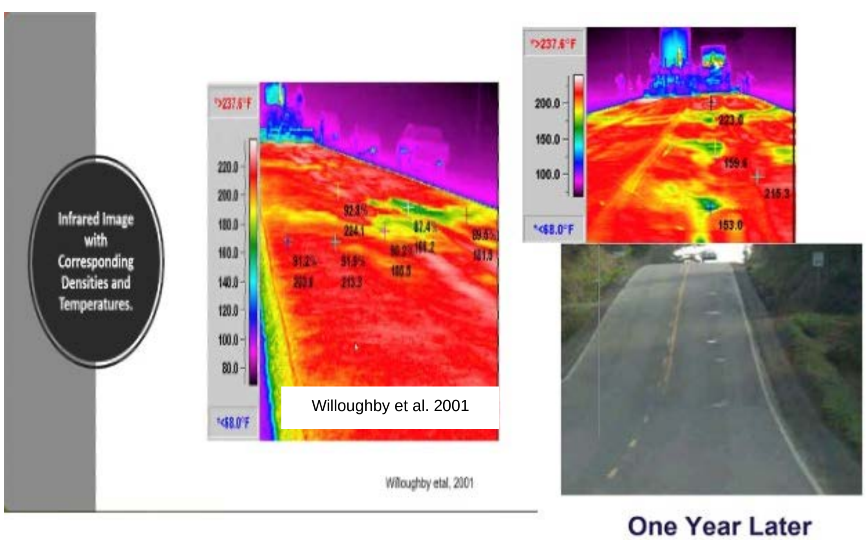


FIGURE 1 The birth of a pothole. Infrared images showing temperatures, corresponding densities, and performance.

The Texas Department of Transportation (TxDOT) took the first steps toward implementing monitoring pavement temperatures by writing a thermal profiling specification, TEX-244-F. The initial approach is summarized in Figure 2. TxDOT found out quickly that taking pictures behind a stopped paver just showed that the pavement cooled behind the paver and was not a fair presentation of paving. That has been carried forward to current specifications to just monitor moving pavers. The Texas Transportation Institute (TTI) developed the equipment and software to measure and display the pavement temperature in real time. Figure 3 is a picture of the first Pave IR (infrared) system in action for continuously monitoring pavement temperature behind the paver.

The second Strategic Highway Research Program (SHRP2) picked up on the idea of using infrared thermal scanning and the Minnesota Department of Transportation (MnDOT) volunteered to try out the improved software and an improved Pave IR bar mounted on the back of the paver (Figure 4). The results showed uniform temperatures resulted in uniform densities and better performing pavements.

MnDOT wanted to implement the technology but had many concerns including the ruggedness of the equipment. The IR bar has since been replaced with a less intrusive device with fewer wires to get crimped. MnDOT made a decision to show they were serious by providing a 5-year roadmap to full PMTP implementation in 2018. The key steps toward

FIGURE 2 Initial approach in Texas. **FIGURE 3 First Pave IR system.**

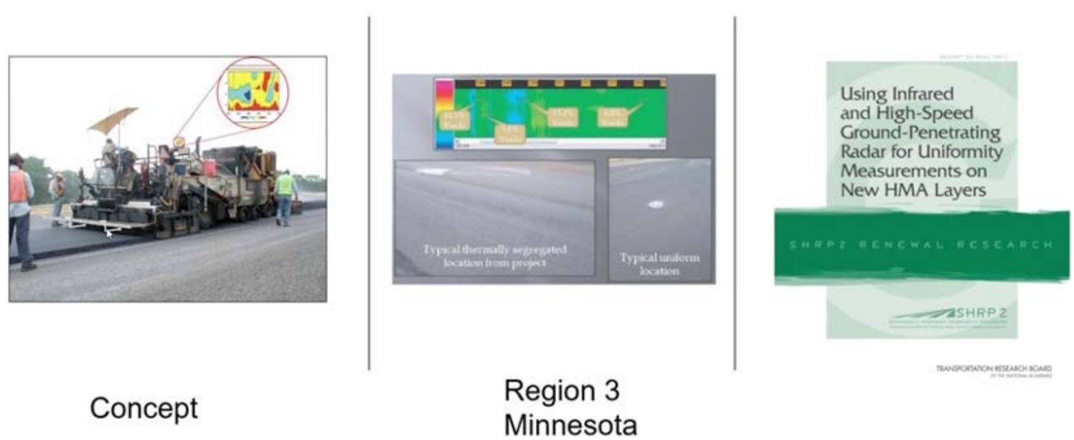


FIGURE 4 Pave IR for uniformity measurements.

implementation are shown in Figure 5. The goal was to engage both the contractors, MnDOT and vendors in implementing the “new technology.” They developed incentive/disincentive specifications to keep the contractors motivated. MnDOT spent a lot of time talking to contractors individually and in groups to understand the data and how the specification worked so there were no surprises; risk was limited for the department and the contractors; and system ruggedness and needed vendor support were determined. This was important so that everyone—contractors, vendors, and MnDOT—knew the amount of equipment, software, spare parts, and training were needed for fully functioning program.

The first intelligent compaction (IC) project in Minnesota started with measuring the stiffness of unbound base which proved to be very complicated because they tried to measure stiffness with the rollers. There was a long list of variables, not the least of which was that rollers are not manufactured to be QC testing platforms but are compaction machines. So, two identical rollers off the production line would not provide the exact same information. The(HMA) IC project start date was delayed from late summer until October, a time when it is hard to achieve density. Before agreeing to start the project, the contractor wanted the density specifications waived. MnDOT—not wanting to delay the project—made a deal with the contractor. If the contractor would use the IC equipment and the rollers followed the directions of “Big Mike,” there would be no density disincentives. The contractor agreed and at the end of the project all the cores passed density, and a few achieved density incentives. When the contractor asked Big Mike what he did with the rollers to achieve such good densities. He responded that all he needed was “roller operators who could count up to three.” MnDOT realized that they could track where the rollers had been, how many passes were made, and other information needed to keep the pavers moving to produce a uniform pavement.

IC implementation followed a process similar to that of PMTP (Figure 6). A couple of key factors are: communication to work through the kinks and keep the paver moving and the development of Veta software to store and analyze the data being collected by IC and PMTP. Both have been required on MnDOT paving projects since 2018.

FIGURE 5 PMTP implementation.

FIGURE 6 IC implementation.

In 2004 TTI was also developing a system for high-speed ground-penetrating radar (GPR), Figure 7. This system used radar antennas mounted on a van. The results were inconsistent, even with the antennas closely calibrated to each other. The problem was that the radar signal goes out in a cone shape and if there is not a uniform area under the cone, the reflectance times from the edges of the cone greatly affect the dielectric results. Another issue was that the original GPR systems were measuring differences in dielectric at the interface between surfaces. For pavement, we are only concerned about the surface layer.

Fast forward to today and the (RDM) systems are much closer to the ground and roll on solid tires. The antennas are tuned to measure the dielectric just below the pavement surface. So, if you go to an area where the dielectric is low and cut a core, the density is low. Likewise, if you go to an area where the dielectric is high and cut a core, the density will be high (Figure 8). These systems are an effective way of mapping the dielectric and cutting cores can be used to calibrate the systems to convert dielectric values into (pavement) densities. However, this was not an ideal situation. It required cutting cores to calibrate the system which increased the testing time needed on projects.

It was found that testing QC gyratory pucks could be used to make a density/air voids vs. dielectric calibration curve for each mix. Using time of flight measurements (TOF) through a precisely measured sample thickness, a dielectric could be determined for each mix design at differing air-void levels. This provided a method for real-time mapping of pavement density without the additional time needed for coring. Two manufacturers have developed equipment to measure the dielectric of gyratory compacted asphalt QC specimens (Figure 9). (Note: AASHTO T414 Determining the Dielectric Constant of Gyratory Compacted Asphalt Mixture Specimens Provisional is expected to be published July 2024).

FIGURE 7 Initial GPR system and TOF details.

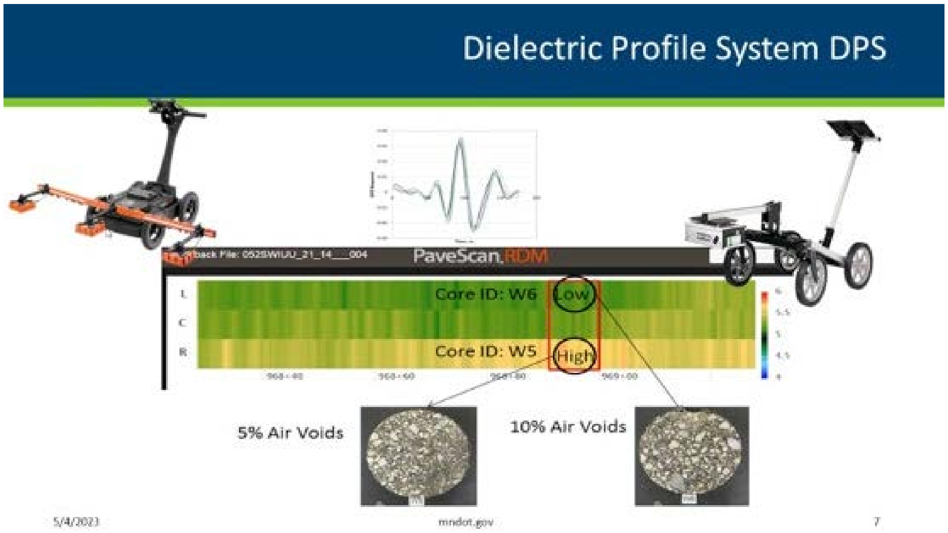


FIGURE 8 DPS scans and measured air voids.

FIGURE 9 Equipment to determine the dielectric constant of compacted asphalt specimens.

Entering continuous measured DPS and IC data into Veta for analysis, plots can be made showing uniformity of pavement density and compaction rolling throughout the project (as shown in Figure 10) for informational data collected by a contractor on whether a paving specification could be met. This data shows that where the specified three or more roller passes were made before the pavement temperatures dropped below 210ºF, satisfactory densities were achieved and provided an overall measure of pavement quality instead of the limited snapshots of random cores.

In summary, all this data can be used to construct more sustainable long lasting asphalt pavements. The question people are asking is: Is it possible to make longer lasting pavements.? The answer is: **Yes**, by incorporating all this knowledge and putting it into the paving process daily.

FIGURE 10 Example showing project meeting Caltrans specification.

The take aways from the 20+ years of development of these technologies are listed below. When you are collecting large amounts of data:

1. Be organized before collecting your data, AASHTO MP39-22 Guidance on Data Management.
2. Use the free Veta software, available from Intelligentconstruction.com.
3. Limit risk for all parties. Things will break! Don't throw all the risk on the contractor.
4. These concepts are **not** new.
5. The most sustainable pavement is the one that lasts longest simply because it was built right.

Figure 11 shows a roadmap of the Veta Virtual Roadway (BIM) showing what is currently available and what is planned.

FIGURE 11 Intelligent construction virtual roadway.

Improved Quality Control for Paving Operations

Contractor Perspective

BRYCE WUORI
Wuori Consulting, LLC

Intelligent construction technologies such as PMTP and DPS have become essential tools for contractors to improve the quality control processes of asphalt paving operations in the field. The following data and information are real-world examples of asphalt paving projects across multiple states that have utilized intelligent construction tools to enhance the quality of asphalt being placed in the field.

PMTP technology was used on projects in multiple states including Wyoming, North Dakota, Minnesota, Nebraska, and Texas (Figure 12). The PMTP technology assists users in quality control by providing real-time data on various aspects of the asphalt mat, such as temperature, consistency, and impacts from operational changes like paver stops and distribution processes. This data allows users to make proactive changes and trust that their operations are working at their full potential to achieve the highest quality possible (Figure 13).

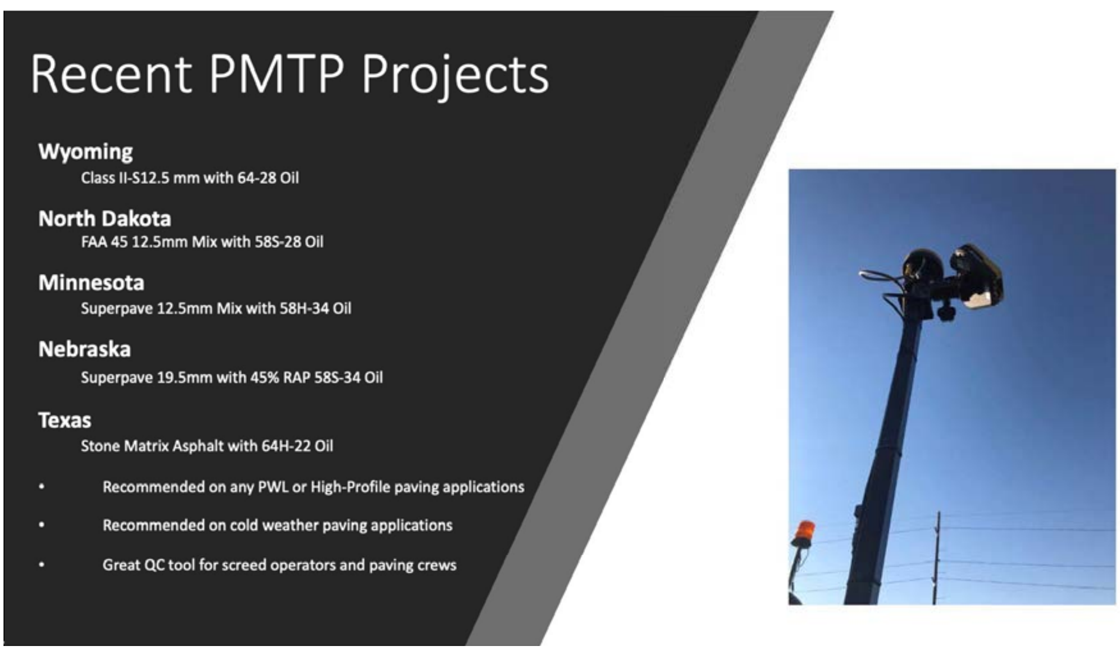


FIGURE 12 PMTP projects and picture of a scanning PMTP.

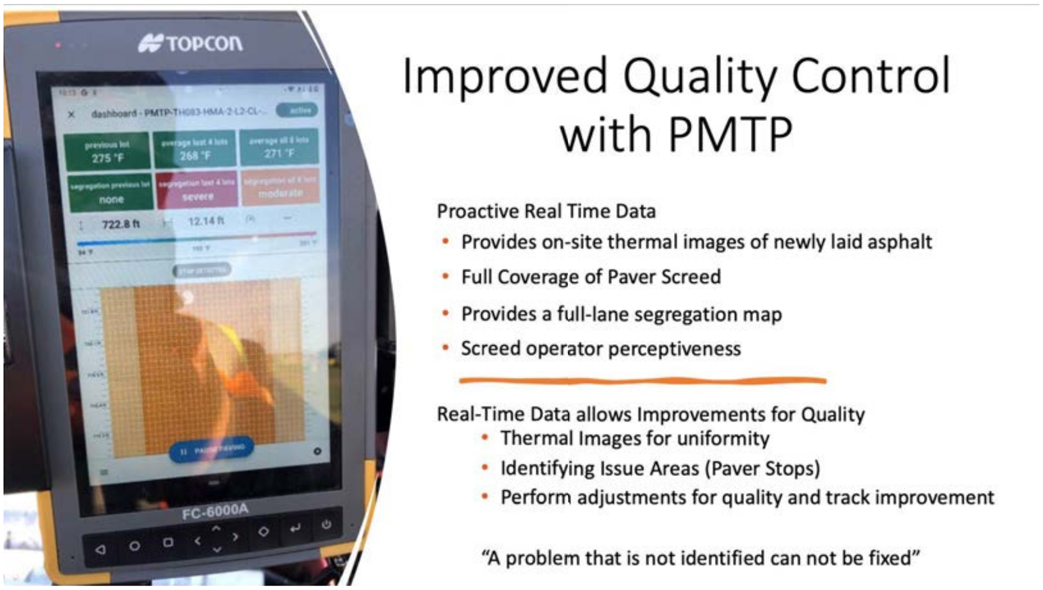


FIGURE 13 What was achieved using PMTP.

DPS is another intelligent construction technology that has gained immense popularity among paving contractors during the quality control processes of asphalt paving. DPS is used in place of traditional QC tools like the PQI (Pavement Quality Index) and Nuclear Density Gauge. Contractors are using this technology on projects in Wyoming, North Dakota, Montana, and many federal Airports (Figure 14).

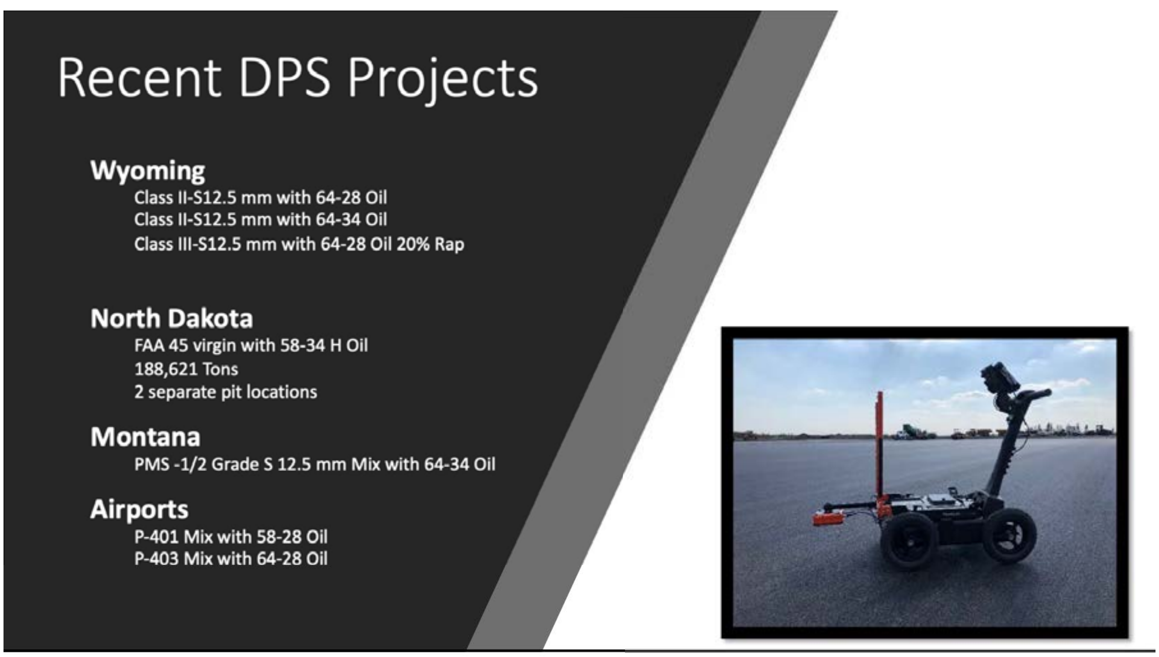


FIGURE 14 DPS projects and DPS.

DPS benefits the user during the quality control process by providing real-time data in the field. This data collection allows the users in the field to identify trends of low compaction or low quality by collecting more data in a faster process than traditional methods. The DPS technology has also been tested across multiple mix designs, AC oils, additives, and paving sections. These testing results have shown consistent data on the performance of the DPS technology in the quality control process (Figure 15).

The DPS technology is proving to be an important quality control tool during paving operations by providing continuous full coverage data in real time (Figure 16). This an advantage for the contractor in setting and checking roller patterns for uniformity. An example of using this data will be presented in Chapter 4 on longitudinal centerline density. Other contractor benefits are listed in Figure 17.

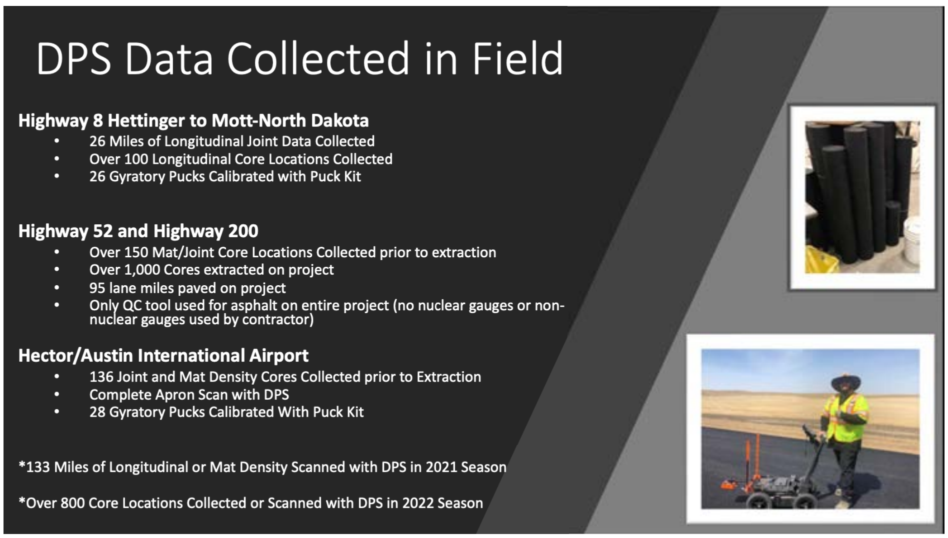


FIGURE 15 DPS project data collected.

FIGURE 16 What DPS provides for contractor quality control.

FIGURE 17 DPS contractor benefits.

As with any tool, DPS accuracy is controlled by understanding how the mix is being produced—what is the mix composition, has it changed, where is the mix being measured, and what is under the compacted mix being measured? A more complete list is provided in Figure 18.

The DPS technology is proving to be an important quality control tool during paving operations, but it does present some logistical challenges with the process of collecting data with the cart application in the field. Typically, current practice is one or two teams pushing the DPS behind the paving train which can create safety issues. The logistics around setting up safe construction zones for data collection have been identified as potential issues with the technology being adopted by the industry (Figure 19).

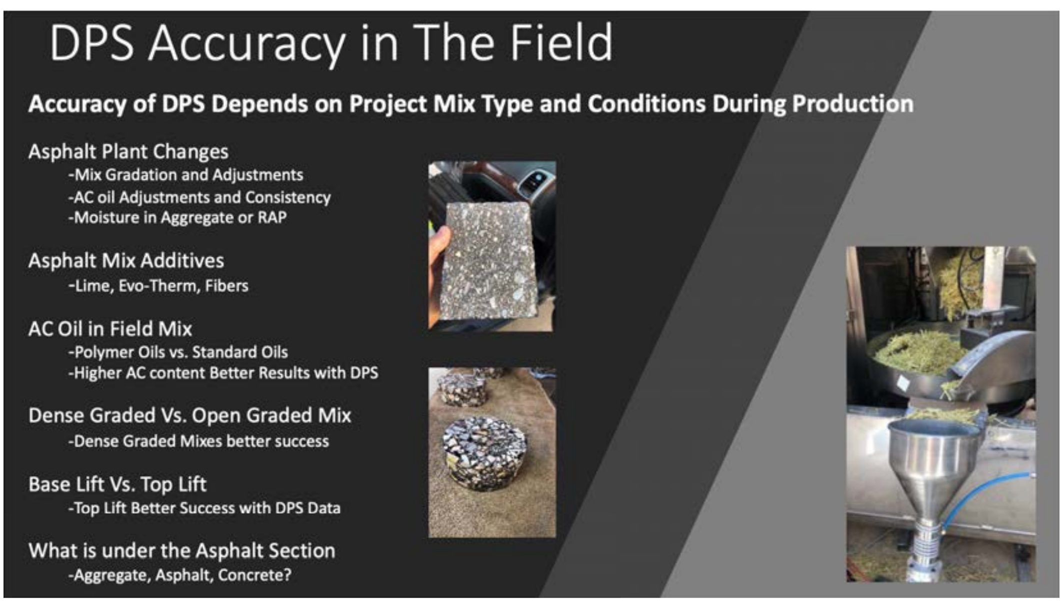


FIGURE 18 Factors that affect DPS results.

FIGURE 19 DPS field logistics.

One solution that is being explored is to mount the DPS units on the finish compaction rollers. While mounting the DPS on a roller does solve the safety and coverage issues, it creates additional issues including linking DPS and IC roller time stamps, water from the roller, and DPS signal distortion from other equipment.

For the contractor, the following are benefits of using DPS technology:

- Full assessment of the asphalt with continuous coverage.
- Great tool for quality control and roller pattern setup.
- Nondestructive testing method.
- Equipment and software are user friendly with proper training.
- Proactive identification of compaction issues.

The challenges to be considered before implementing are:

- Construction logistics.
- Cost compared to other tools.
- Operator safety.
- Accuracy and calibrations (bad data in, bad data out).
- Field condition variables (weather, asphalt mix design, pavement section).

In conclusion, DFPS and PMTP intelligent construction technologies provide users with the data needed to make proactive decisions to improve quality in the field, but they do come with challenges of implementation, training, and costs to the user as well. Overall, for the contractors on projects discussed, use of these technologies lead to successful projects achieving bonuses.

First MentiPoll Questions and Answers

The attendees were asked to identify themselves as an (state) agency, contractor, consultant, federal, industry (manufacturer or association) representative.

Q1: WHAT WOULD BE THE BEST USE OF DPS AND PMTP FOR YOUR AGENCY OR COMPANY?

Responses (57):

Agency (9):

- Use as bid items to provide data to support implementation
- Measure consistency in real time
- Keep production team aware of their processes in real time

Contractors (5):

- Use as a QC tool for (paving) process improvement
- Use as (standard practice) tool(s) for making real-time process improvement changes
- Contractors collect data and agency verifies

Federal (1):

- Assessment of pavement compaction

Dielectric Profiling Systems and Pavement Performance

CRAIG LANDEFELD

Ohio Department of Transportation

INTRODUCTION

Like most other state departments of transportation, the Ohio Department of Transportation (ODOT) deals with pavement performance issues resulting from segregation and other defects during placement. These defects lead to premature failures, resulting in costly pavement repairs, and loss of pavement life. To address these issues, ODOT has begun piloting PMTP Systems and DPS on projects around the state. These technologies allow for more comprehensive measurement of process control and pavement quality during construction. To date, ODOT has not fully implemented either technology, but the lessons learned have led to changes in specifications and implementation plans are currently being developed with industry.

WHAT IS DPS?

Dielectric profiling systems are a nondestructive density measurement tool that utilizes advanced ground-penetrating radar technology to measure the dielectric value of the asphalt. That dielectric can then be correlated to density or air voids. DPS offers continuous measurement of the pavement surface and allows for the collection of thousands of data points, compared to the current ODOT practice of collecting 10 density cores in a lot. An abbreviated list of DPS benefits and different vendor systems can be found in Figure 20.

WHY DPS? PAVEMENT DEFECTS

ODOT faces many pavement distress issues that are often related to defects built in during construction. These issues include potholes and delamination, accelerated raveling, longitudinal joint deterioration, and poor ride quality. Examples of pavement distresses encountered on ODOT roads can be found in Figure 21.

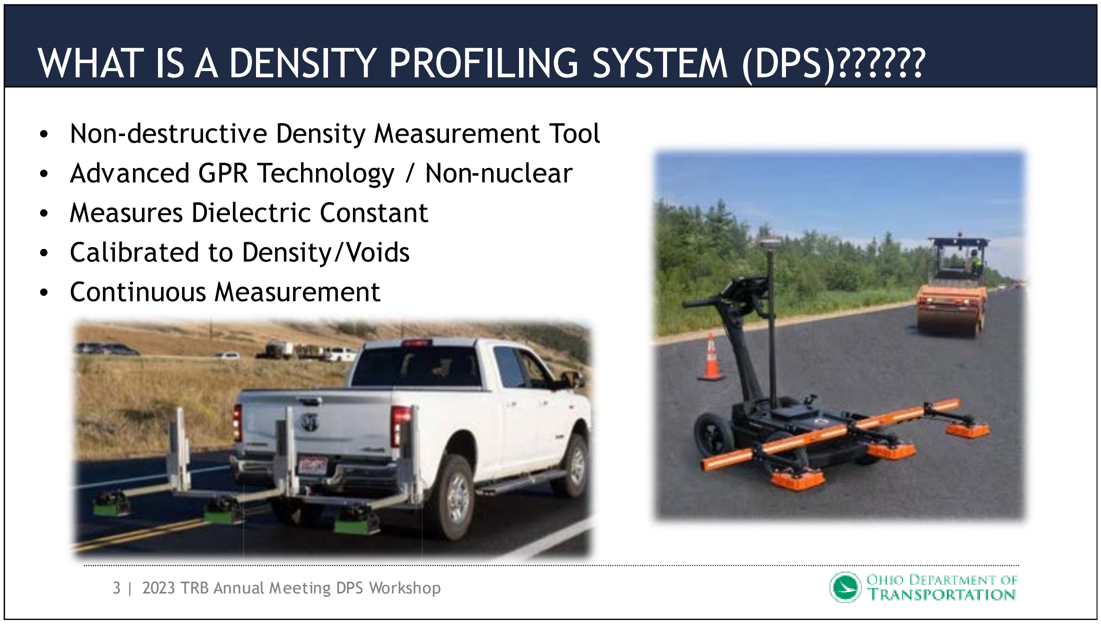


FIGURE 20 What is a DPS?

FIGURE 21 Pavement defects on ODOT roadways.

These defects can have huge financial impacts. The majority of ODOT's minor rehabilitation projects consist of an asphalt overlay with full and partial depth repairs. As noted in Figure 22, ODOT estimates annual expenditures of over $30 million on repairs in 2021. Reducing these costly, and many times preventable, repairs would allow ODOT to reinvest these dollars elsewhere on the network. Additionally, loss of service life due to defects has substantial financial impacts. Based on current funding levels, each year of service life lost equates to over $55 million dollars.

OHIO DPS PILOTS

ODOT has been conducting DPS pilots since 2018, capturing data on nearly 20 projects throughout the state. In general, DPS has correlated very well with cores taken on the pilot projects. R^2 correlation values with DPS routinely exceed correlations with other gauge density testing devices. While correlations have been positive, results of density distribution comparisons of Core Percent Within Limits (PWL) data and DPS results have been mixed. Based on observations of core locations, we suspect that PWL calculations may be biased by random sampling locations that are not truly representative of the lot, and by the limited number of samples that are being collected. Examples of project core calibrations and observed density distributions can be found in Figures 23 and 24.

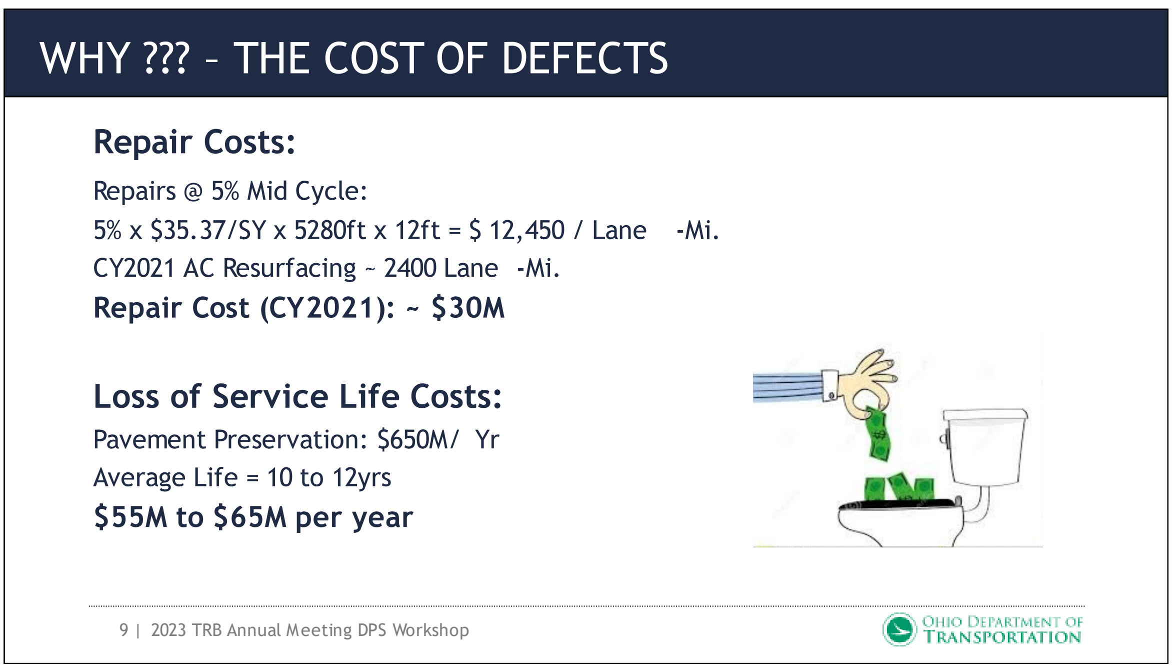


FIGURE 22 The potential cost of defects.

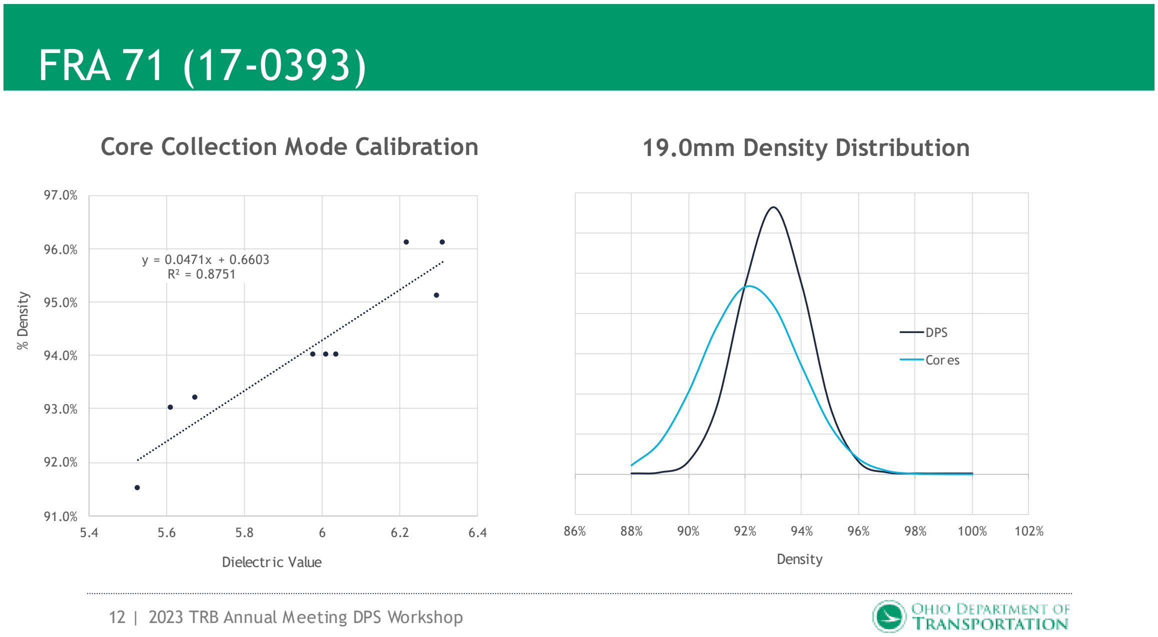


FIGURE 23 FRA71 DPS data distributions.

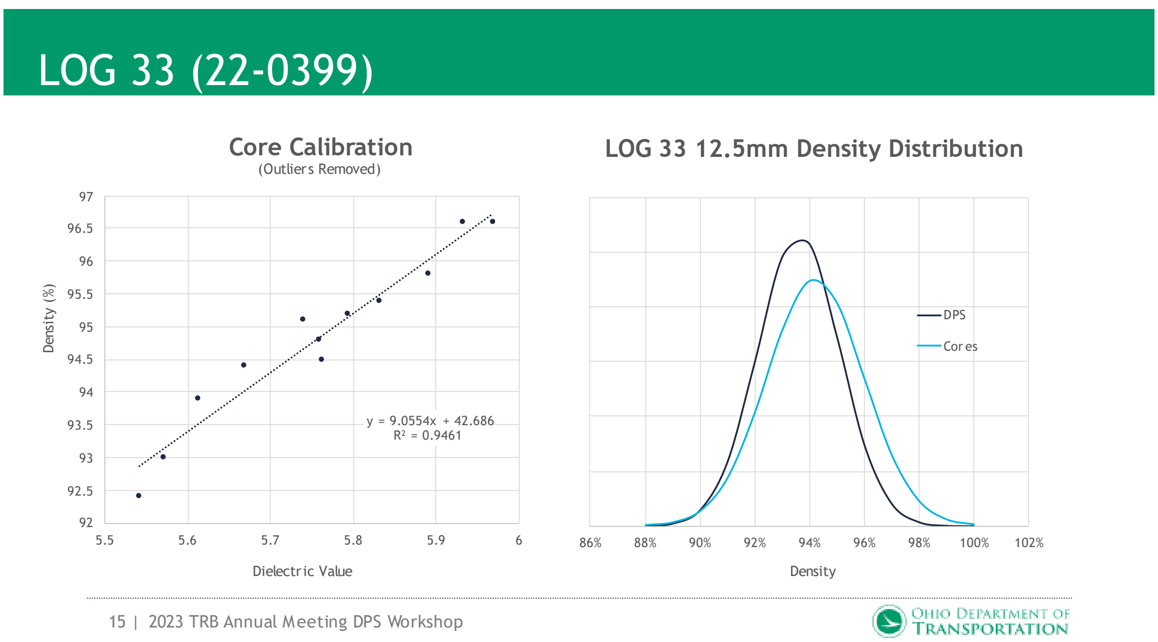


FIGURE 24 LOG33 DPS data distributions.

In 2022, ODOT also piloted DPS and PMTP on the same resurfacing project. The PMTP measures the temperature directly behind the paver without the need to correlate any data. ODOT has found the PMTP device useful to recognize, diagnose, and correct placement issues during construction. Figure 25 shows a paver stop on the LOG33 pilot project. In this instance there was both thermal and physical segregation at this location. The temperature dropped to 180 °F and density to 85%. Through the DPS and PMTP pilots conducted, ODOT has found that segregation at truck changes is one of the biggest sources of built-in defects that we face. By advancing quality control and acceptance requirements through PMTP and DPS, ODOT believes we can have a substantial impact on pavement performance.

DPS CHALLENGES

While correlations and data collection have gone well on pilots, ODOT faces challenges in implementing DPS technology. One set of challenges is with the DPS units themselves. ODOT's DPS units have struggled with sensor connectivity in cooler temperatures, leaving the units inoperable. We believe these issues have been corrected with vendor updates, but further testing is required. The sensors are also sensitive to changes in height and that has caused comparison issues within the data. Currently, we believe the DPS units lack the ruggedness for day-to-day use on construction projects at a large scale.

To implement DPS, ODOT will need to be able to complete quality assurance on the DPS data collected by the contractor. While working on quality assurance on the DPS data, ODOT has experienced noticeable shifts in the dielectric data when the same area is collected by multiple units by the same vendor (i.e., regardless of who is operating the unit). We believe this

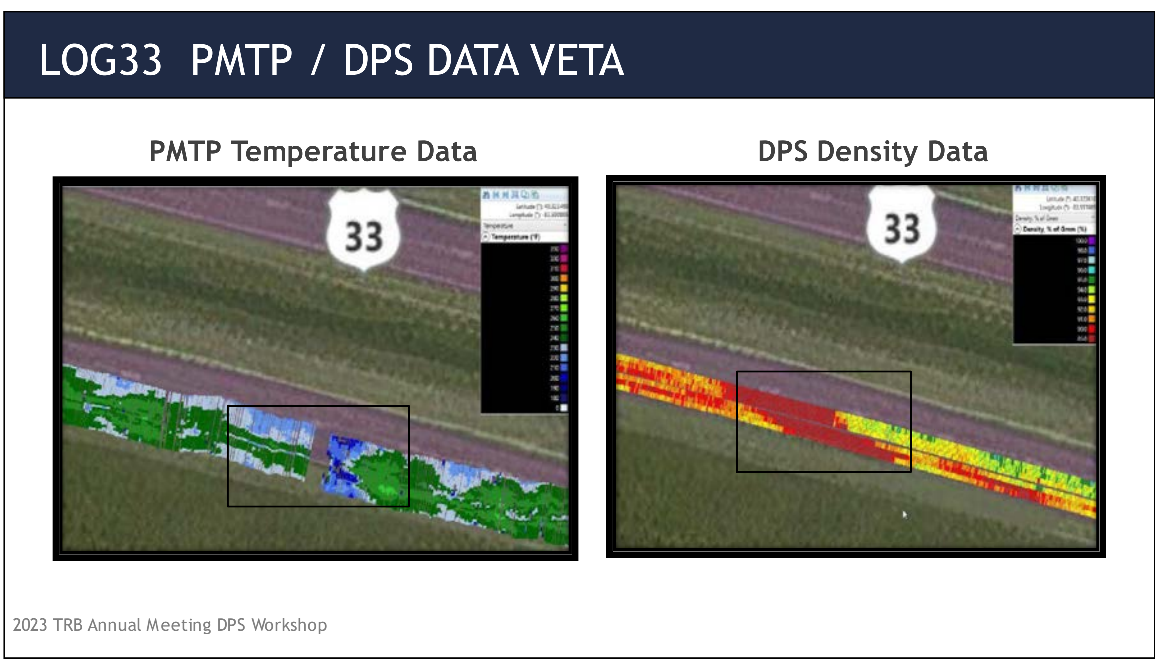


FIGURE 25 PMTP and DPS comparison at a paver stop.

issue has been corrected by the DPS vendor based on our latest collection efforts, but the data will need to be monitored for quality.

Last, the DPS units collect dielectric data, not density data. Because the dielectric measurements must be correlated to density, this opens another point of contention. ODOT has piloted correlation curves using field cores and lab gyratory samples with varying degrees of success. Fortunately, these correlations are being thoroughly investigated by other members of the pooled fund study and the DPS manufacturers as well. This research includes methods that will greatly reduce the number of correlation cores that have been necessary in the past. A summary of the challenges with DPS implementation and charts depicting the shifts in data observed can be found in Figure 26.

CONCLUSIONS

ODOT deals with pavement performance issues resulting from segregation and other defects during placement. To address these issues, ODOT has piloted PMTP and DPS technologies across the state with PMTP beginning in 2014 and DPS in 2018. Both technologies offer promising results when it comes to improving mat consistency and reducing thermal and physical segregation. ODOT believes that implementation of technologies like these can reduce the number of repairs on future projects and those conducted by internal maintenance forces. ODOT also hopes that this will increase the service life of pavements allowing for funding to be redirected as needed to maintain our network as efficiently as possible.

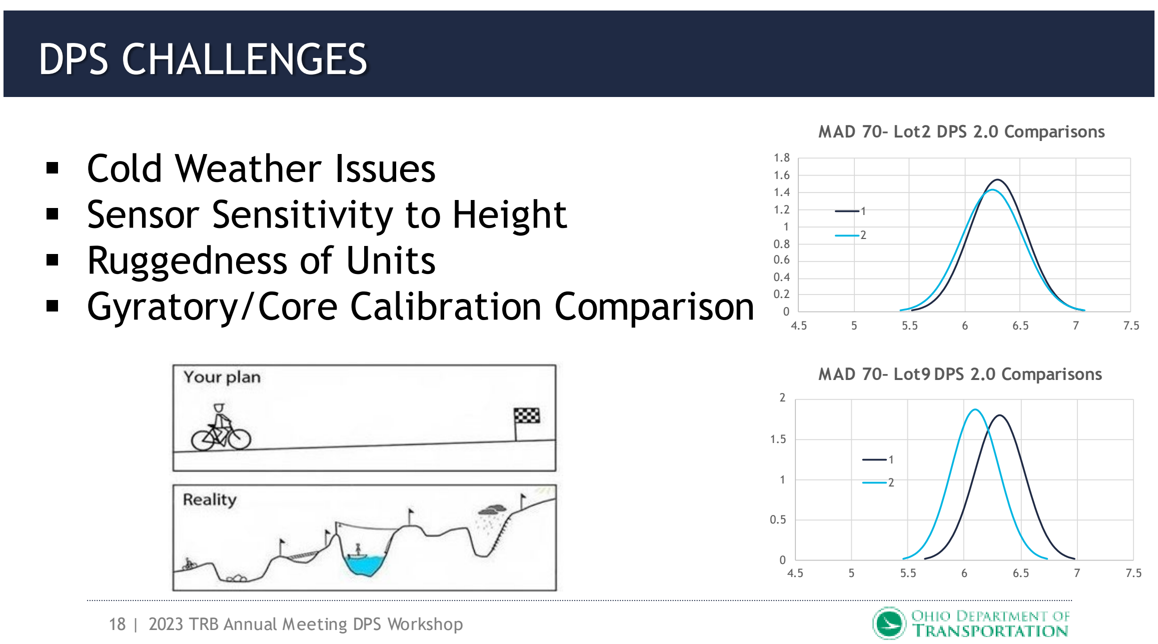


FIGURE 26 Challenges ODOT faces in implementing DPS.

Overview of DPS and PMTP for Pavement Performance, Sustainability, and Safety

KYLE HOEGH

Minnesota Department of Transportation

INTRODUCTION

Dielectric (a.k.a Density) profiling systems are a means of collecting continuous dielectric measurements that have been used by various state agencies as a means of evaluating compaction of freshly placed asphalt pavements. Recently, this has been the subject of a national pooled fund effort, Continuous Asphalt Mixture Compaction Assessment Using Density Profiling System [TPF-5(443)], with the general objectives of further advancing the systems based on the needs from participants, supporting communication, providing training and technical assistance, and conducting marketing efforts to make industry aware of the current capabilities. For the Minnesota Department of Transportation (MnDOT), full implementation of PMTP and other intelligent construction technologies (ICT) like intelligent compaction, the value ultimately comes down to the ability to geospatially assess the DPS density results and compare them with other ICT for insight into improved practices leading to process improvements for consistent properly compacted and longer lasting pavements that improve the sustainability of the road network.

WHAT WE MEASURE

At MnDOT, the current procedure of three-cart passes provides a “full coverage” map of the 12-ft. lane since the cart used has three 1.5-ft. spaced sensors giving 2 joint (0.5 and 11.5 ft. offset from centerline) and 7 mat (2, 3.5, 4.5, 6, 7.5, 8.5, and 10 ft.) lines of data throughout the project. There are various ways of converting the dielectric constant to density (see publications posted on the pooled fund website: http://www.dot.state.mn.us/materials/dps/publications.html). Then the resulting data can be presented on a colormap scale such as that shown in Figure 27 with warmer colors indicating higher density and cooler colors indicating lower density. (Note: This same relative relationship can be obtained by mapping dielectric constant assuming no major changes to the production mix composition is occurring). There are some seemingly random lower density locations mapped by the DPS.

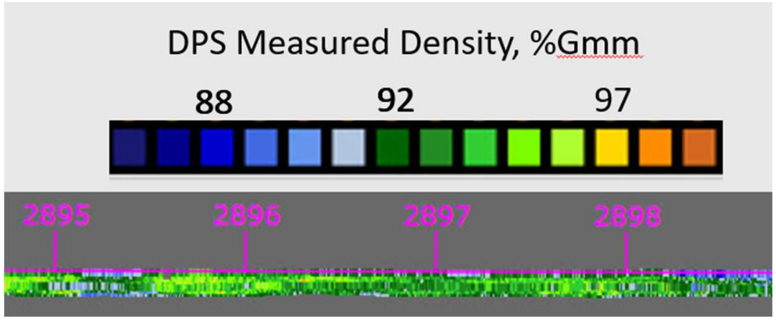


FIGURE 27 Example full coverage geospatially placed density map.

Upon closer inspection, however, when compared to PMTP measurements mapped on the same section of pavement, however, these lower density spots are in fact not random. It can be observed from the low-density location comparison with PMTP data that the low density in this case was a direct result of the colder mix being placed (Figure 28). This is one of many reasons that can cause low density in a pavement. A better performing, more sustainable road network can be achieved if this type of technology is used to limit the frequency of these types of occurrences.

ON-SITE USE FOR PROCESS IMPROVEMENTS

Ideally, identification of the potential for process improvements should be communicated early in the day of pavement construction to allow for same-day changes that improve the pavement in a timely manner. Figure 29 shows an example DPS on-site analysis of percent conformance (above 92 %Gmm for joint and above 93 %Gmm for mat) broken down by 100-ft. sublots, as well as a scatter plot of the same morning of paving. The joint percent conformance approached as low as 10% in to lower 80s stationing of the project.

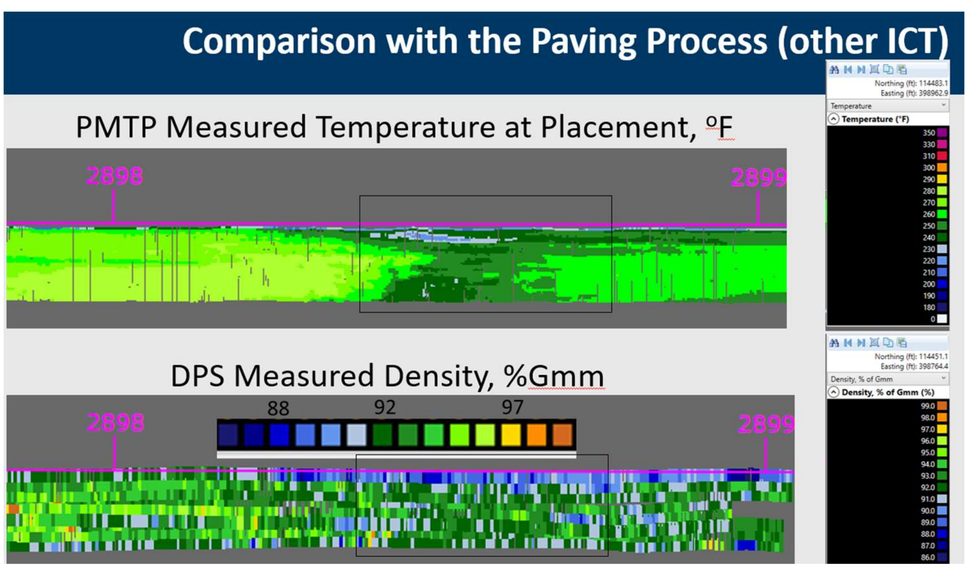
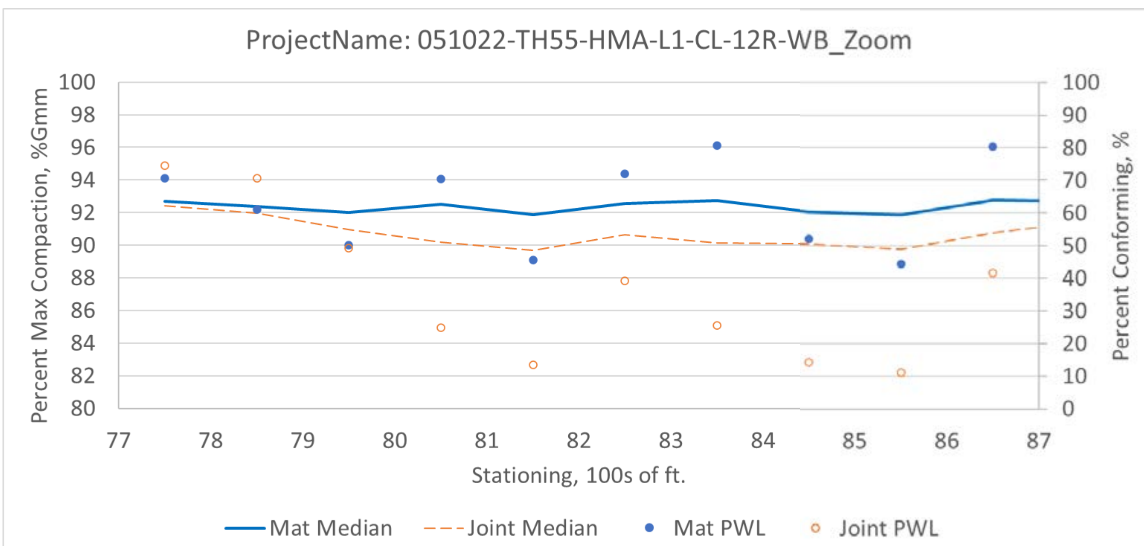


FIGURE 28 Comparison with the paving process (PMTP in this case).

Summary Statistics PaveScan RDM Statistics Loaded

Distance Range	Start Station	End Station	Min Lat Offset	Max Lat Offset	Mat PWL	Joint PWL	Mat Median	Joint Median	Mat St Dev	Joint St Dev
Segment	76+00	77+00	0	12R	53.39	60.61	92.09	91.38	1.09	1.33
Segment	76+00	77+00	0	12L	84.15	69.82	92.99	91.62	1.04	1.1
Segment	77+00	78+00	0	12R	70.64	74.45	92.68	92.42	1.25	1.65
Segment	77+00	78+00	0	12L	61.33	74.95	92.3	91.79	1.16	1.13
Segment	78+00	79+00	0	12R	60.9	70.53	92.36	91.95	1.27	1.57
Segment	78+00	79+00	0	12L	75.53	62.38	92.68	91.46	1.01	1.28
Segment	79+00	80+00	0	12L	42.89	66.37	91.8	91.64	1.05	1.31
Segment	79+00	80+00	0	12R	49.97	49.23	91.99	90.97	1.06	1.13
Segment	80+00	81+00	0	12R	70.41	24.82	92.51	90.18	0.98	1.52

(a)

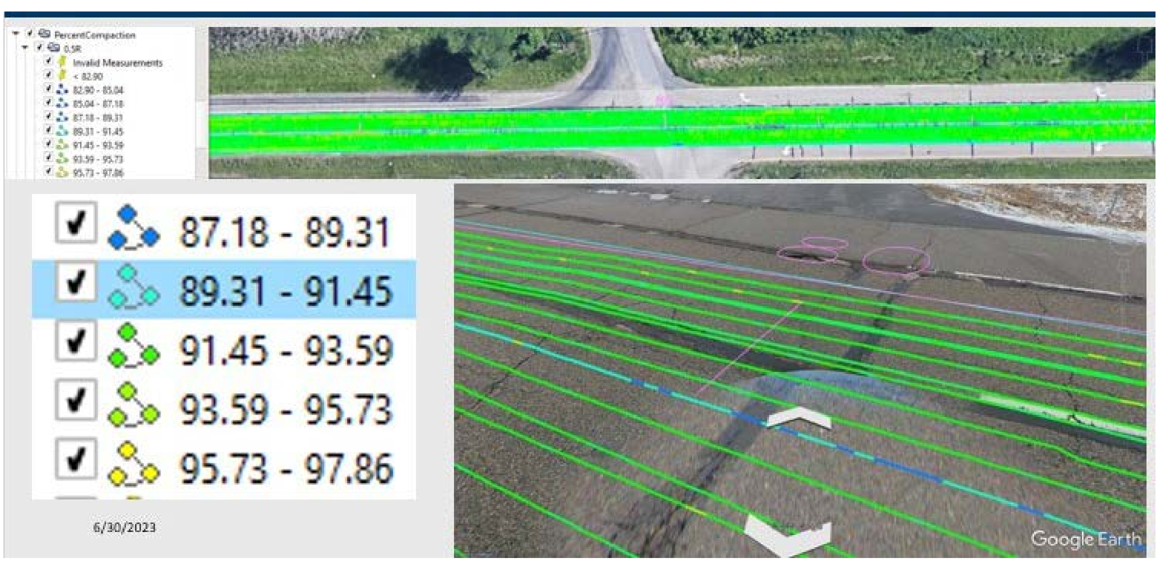


(b)

FIGURE 29 Poor joint density observed in DPS: a) on-site summary analysis and b) Excel plot of percent conformance and average density in 1 station lots: (*a*) Percent conformance analysis obtained on the DPS data collection software the day of paving and (*b*) Median density (%Gmm) (line), and percent conformance (circles) output for mat (blue) and joint (orange) collected at the beginning of the paving day.

Figure 30 shows a breakdown of where the low density was occurring on the project including the on-site drop in dielectric from the scatterplot, as well as the results of opening the same set of data in Google Earth using the exported .kmz files. The low spots were observed occurring on the right side of the centerline joint looking up station. This information was communicated to the paving foreman, who suggested that there may be some bridging occurring when compacting that side of the joint and went back to the paving operation to make the necessary corrections.

(a)



(b)

FIGURE 30 On-site analysis indicating the geospatial location of the low density: (a) a. On-site indication of lower density by the DPS sensor located 6 inches right of the centerline joint and (b) Google Earth image of the low density observations located right of the centerline 6 inches.

Figure 31 shows a plot of the DPS measured results toward the beginning and toward the end of paving that day (percent conformance and average 1 station lot %Gmm). The end of the day paving showed joint density similar to the mat, and joint percent conforming above 60% in all locations, while most were around 80% conformance. This was a significant improvement over the beginning of paving which showed significantly lower %Gmm at the joint and most lots below 40% conformance. This type of improvement in density should lead to a longer lasting more sustainable pavement.

POST-SITE ANALYSIS FOR PROCESS IMPROVEMENTS

Occasionally, the on-site analysis alone does not provide sufficient information to make the necessary process improvements. In these cases, a comparison of DPS density results with other ICT technologies like PMTP or IC can lead to process improvements that allow for consistently properly compacted asphalt mats. Figure 32 shows an example, following top to bottom, where a low-density spot indicated by the DPS can be traced to a paver stop and low temperature location when comparing with PMTP. N this example, the DPS user determined the cause of the low density by conducting a video call with the PMTP user evaluating both technologies in an intelligent construction data management and analysis software, Veta.

One example where this type of comparison led to process improvements was on an echelon paving project where there were periodic low-density locations at the joint. This case study was also highlighted in the pooled fund sponsored DPS Digest series, in an article titled, “Contractors, Ask Yourselves One Question: Are you Feeling Lucky?” (http://www.dot.state.mn.us/materials/dps/digest.html). Figure 33 shows a summary of the information that was communicated to the contractor after a day of paving, where the density 6 inches left of centerline was significantly lower than the other offset locations.

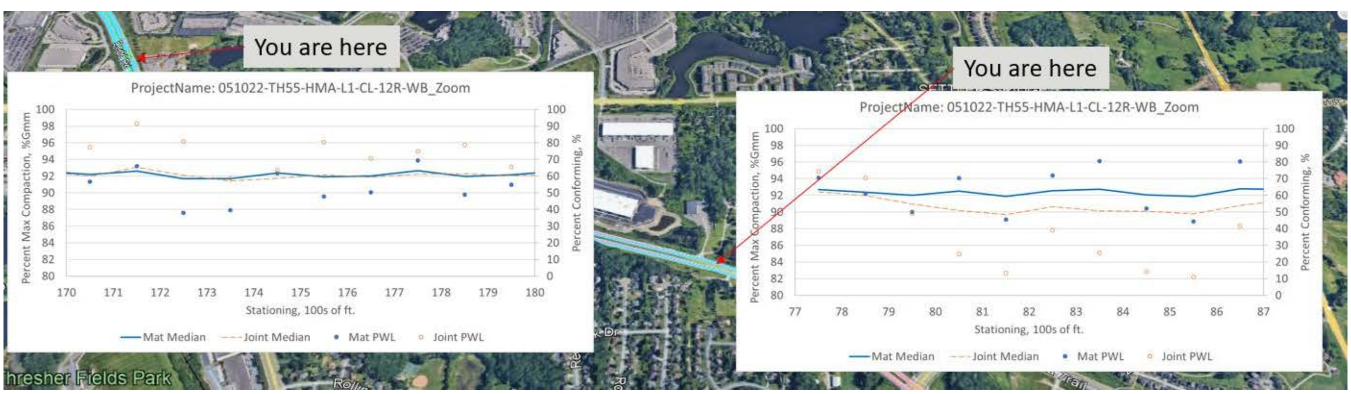


FIGURE 31 Improvement in density resulting from process improvements initiated by DPS information communicated to the contractor.

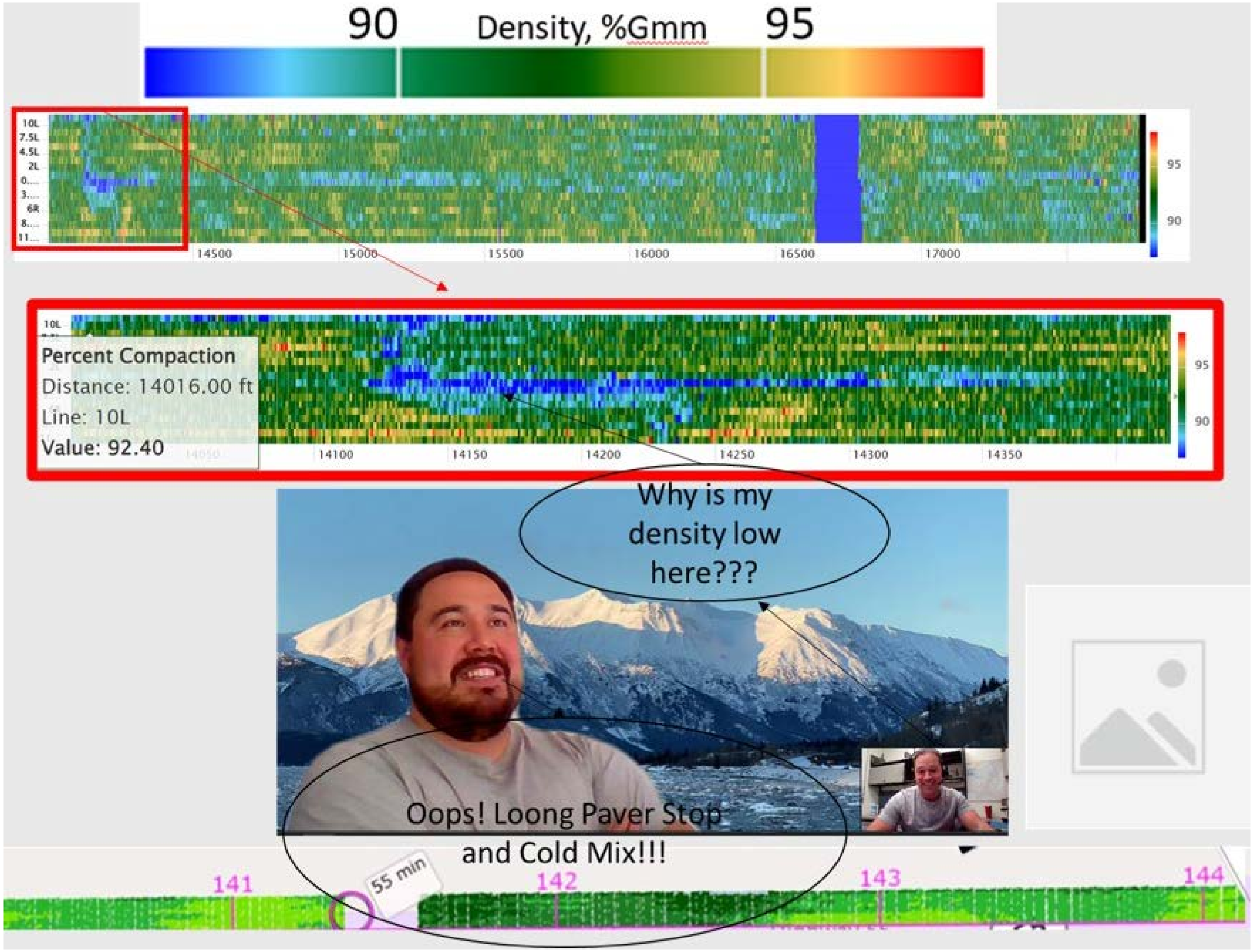


FIGURE 32 Poor joint density observed in DPS, an on-site summary analysis.

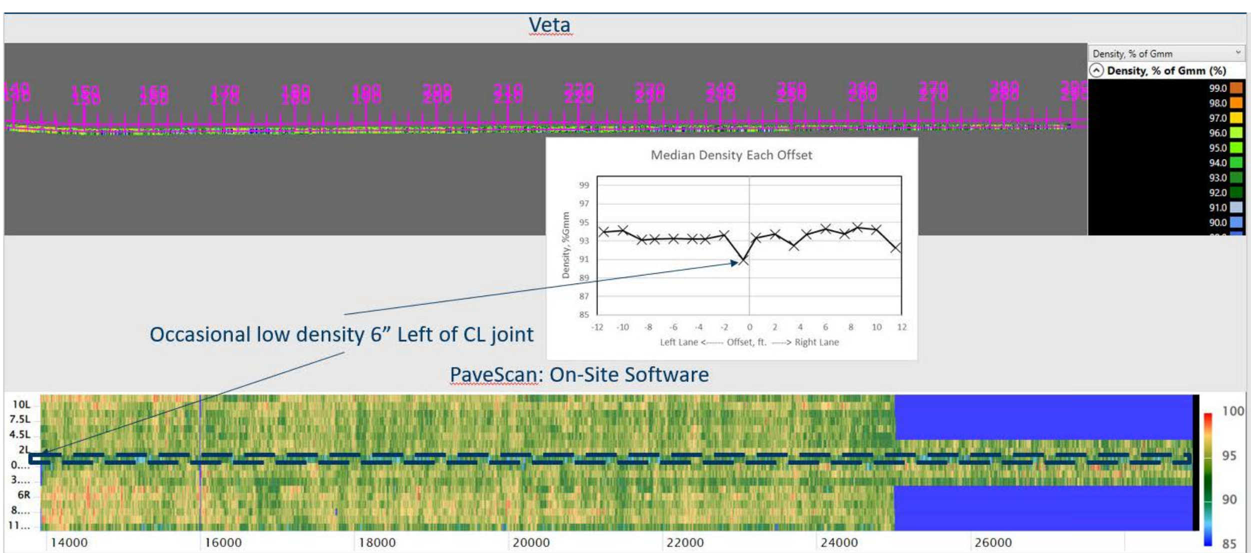


FIGURE 33 Veta and on-site analysis indicating the geospatial location of the low density on the left lane centerline joint.

While there were some other findings with PMTP and other ICT technology, Figure 34 shows the specific information that was communicated to the contractor. One specific location where the field core used for incentive/disincentive happened to be approximately 50 ft. short of one of the low-density spots that were periodically occurring on the left lane centerline joint. While the random core location luckily did not fall in the poor density location (as can be observed from the top figure), a core within the spot about 100 ft. farther would have likely resulted in a deduct. These periodic low-density locations corresponded primarily with periodic locations where the breakdown roller was not getting sufficient passes at the joint, as can be observed by the lower breakdown roller pass counts (red and orange) near the joint. Ideally, echelon paving is two pavers working simultaneously to pave both lanes as close as possible to one another.

MnDOT presented the findings to the contractor who diagnosed potential causes and proposed plans to improve joint densities. The contractor suggested possible causes of the periodic low spots were a new breakdown roller operator not rolling part of the joint when changing directions, and the inconsistent spacing ranging up to 250 ft. between the pavers. Figure 35 shows the roller changing directions at a paver, but leaving part of the hot joint uncompacted when the pavers were spaced over 200 ft. apart. This problem was corrected by coaching the inexperienced roller operator and keeping the second paver within 150 ft. of the first paver to give the roller operator time to roll these uncompacted spots. After the contractor incorporated these lessons learned, MnDOT used a DPS to measure an adjacent part of the project. According to MnDOT findings, “the DPS results showed that the lower density locations associated with an inexperienced roller operator and inconsistent distance between echelon pavers were significantly improved.”

As shown in the examples above, the pilot projects using DPS along with other technologies like PMTP and IC provide insight to improve the paving process. Continued improvement in how these technologies can be used together to provide information to road builders promises to allow for better performing, more sustainable pavements into the future.

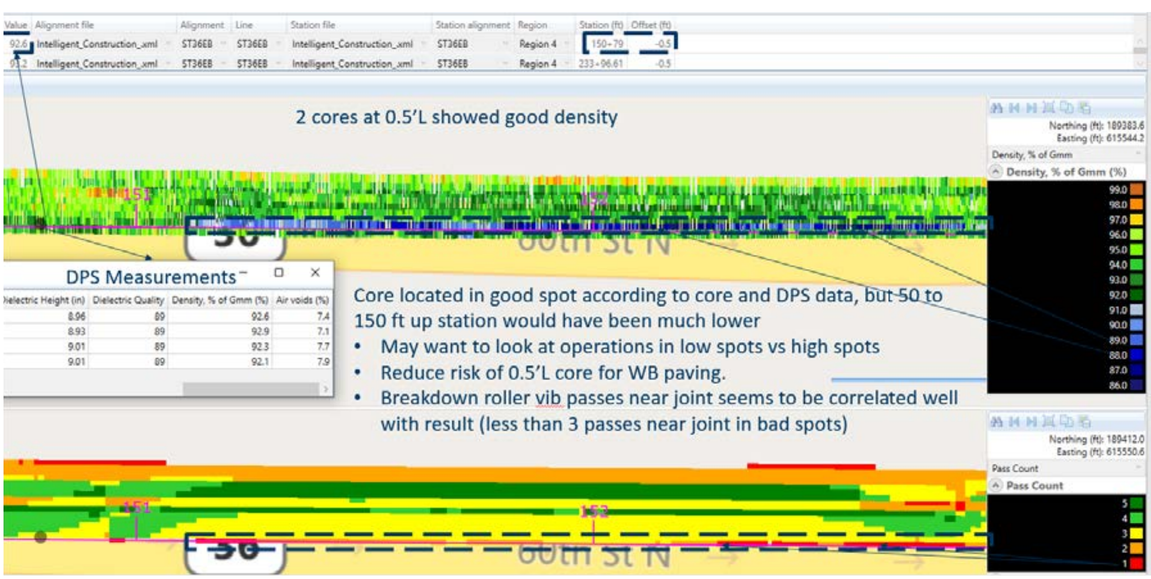


FIGURE 34 Lack of breakdown roller passes near the joint causing lower density.

FIGURE 35 Low density area corresponding to roller direction change locations.

Second MentiPoll Questions and Answers

Q2: WHAT DATA AND DATA COLLECTION METHODS ARE NEEDED TO ILLUSTRATE PAVEMENT PERFORMANCE? RESPONSES (22):

Agency (3):

- Condition data collected over time compared to DPS and PMTP (e.g., improved pavement density, smoothness, slope, and no segregation)

Contractors (2):

- Longer lasting pavements produced by proactive process control

Consultant (2):

- Less isolated defects
- Less maintenance

Federal (1):

- Less rework

Unk (13):

- Automated data entry and analysis
- Data to illustrate (improved) material performance
- (Collect) Underlying surface quality data
- Use of crowd source data to obtain continuous pavement performance data
- GIS-based virtualization tools that overlap construction data with (pavement) performance data

Q3: HOW COULD DPS AND PMTP HELP SUSTAINABILITY AND SAFETY? RESPONSES (21):

Agency (3):

- Pavements with longer life cycle are a huge improvement in sustainability
- Less frequent resurfacing reduces worker exposure

Contractors (2):

- Improves safety by reducing people on road coring/nuclear density readings
- Improved pavement density, smoothness, longer lasting roads

Consultant (2):

- Less isolated defects; less maintenance

Federal (1):

- Extended pavement life; less construction time and better safety

Unk (13):

- Sustainability, better performance, better service life, reduced carbon footprint
- Safety: less exposure to live traffic

Implementing Dielectric Profile Systems and Paver Mounted Thermal Profiling

A Contractor Perspective

DEREK FREDERIXON
Mathy Construction Company

OVERVIEW

Mathy Construction Company and its divisions have been using PMTP systems since at least 2010 and have had a DPS system since 2020. When implemented correctly, both systems are great tools to improve the quality of hot mix asphalt (HMA) pavements. This presentation will go over implementing both technologies as a contractor and will touch on project preparation, data collection and analysis, challenges, benefits to the contractor, and final thoughts regarding the technologies and implementation.

PROJECT PREPARATION—DPS

One of the biggest advantages DPS technology offers is the ability to establish dielectric constants for the mix design prior to placing the mix on a project. This means is that when you start a project and bring out the DPS, you can have a reasonable level of confidence that the percent density the DPS is telling you is accurate and will be representative of any cores taken for acceptance. As a contractor, having a tool that can accurately predict density prior to cutting any cores greatly reduces risk upon project startup. It helps us quickly amend our processes to achieve maximum compaction and incentives. Figure 36 goes through the process of establishing the dielectric constants using lab batched or plant mixed material.

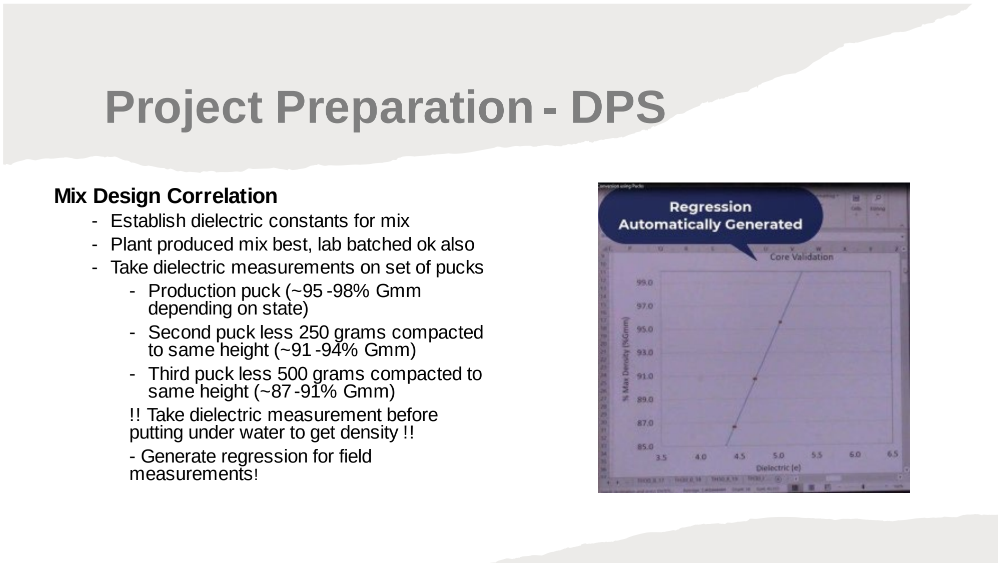


FIGURE 36 Establishing dielectric regression.

PROJECT PREPARATION—PMTP

Prior to starting a project with PMTP the equipment needs to be installed on the paver. Installations are generally different for each paver make and model. Paver modifications may be required to supply the correct electrical connections and mounting of the PMTP hardware. You will want to start installing the equipment at least one week prior to when you want to use it so that you can make necessary equipment modifications and manufacture any additional hardware you may need. Other considerations need to be made regarding paver skis and attachments that may impact the PMTP's ability to scan. In Figure 37 you can see that the camera is on an adjustable pole, you can also see the non-contact ski. By adjusting the length of the camera pole you can avoid scanning the bar for the ski. In Figure 40 the poles holding the ski pan are bent outward, which is another solution to avoid scanning the ski equipment. Display mounting and other access required for paving personnel should also be considered.

PROJECT PREPARATION—DATA MANAGEMENT

DPS and PMTP systems both generate thousands of rows of data and there needs to be a plan in place prior to starting a project on how to manage that data (Figure 38). There should be a plan for file naming, data storage and access, and data sharing. There should also be a plan for recording and storing other project information that may be useful when analyzing the data such as weather, paving data (speed, trucking), plant data (moistures, blend changes), break downs, or any other information that may be relevant to analysis and troubleshooting. AASHTO has a draft specification for Material Delivery Management Systems that provides standardized formats for digitalized communication that, when complete, should help with the data management for DPS, PMTP, and other intelligent construction technologies.

FIGURE 37 PMTP installation.

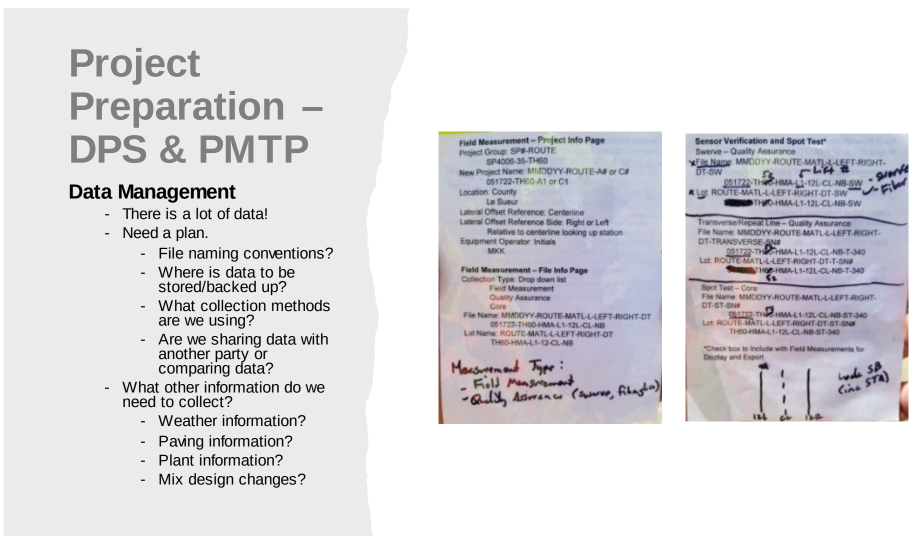


FIGURE 38 Data management.

DATA COLLECTION—DPS

There are several different types of data collection methods that have been developed for use with the DPS depending on what part of the pavement you are interested in and how much analysis you want to do (Figure 39). Total coverage of the mat generates the most data and most complete picture of pavement quality, but sometimes you may just want to focus on a specific area like the joints or areas that had problem cores. With the different methods of data collection for DPS, each project should be customized to match the needs of the project. Another important key to data collection is consistency in where you are testing. Trying to always test approximately the same distance from the paving train will generate the most consistent data.

FIGURE 39 DPS data collection methods.

DATA COLLECTION—PMTP

Data collection for the PMTP is straight forward (Figure 40). You need to enter your station and direction into the controller and beyond that it is mostly just adjusting your settings for temp ranges. A broader temp range will show mostly major temp differences from things like paver stops or end of load segregation. Smaller temp ranges will help you identify slight discrepancies in screed angles and offsets. Best practice is to start with a larger temp range so that you can identify more major problems first. Once any major problems are addressed, slowly reduce the temp range so that you can identify the smaller discrepancies that may be caused by screed or paver settings that are slightly off.

FIGURE 40 PMTP data collection using traditional skis and pans.

DATA ANALYSIS

DPS and PMTP both generate a lot of data, but that data is only useful if you can successfully analyze it (Figure 41). Veta is a free program developed for use in intelligent construction and can be used to analyze both DPS and PMTP as well as IC data. Other applications such as Google Earth and Microsoft Excel can also be used successfully, especially when analyzing smaller projects and data sets. As contractors, we want to analyze the data in real time on the project so that we can make process changes timely. Real-time data analysis requires training personnel to read the displays on the equipment so that they understand what they are looking at. For DPS, you generally should be training the QC technician running the equipment and the project manager and foreperson to analyze the display data—they are the personnel best suited for adjusting rolling patterns or paving operations. For PMTP the screed person should be trained as well as the foreman and project manager. Training the screed person to analyze the display data is crucial to maximizing the effectiveness of PMTP.

CHALLENGES

As with any technology, DPS and PMTP are not without their challenges (Figure 42). As mentioned, these systems generate a lot of data and managing that is the biggest challenge we face. Connectivity between GPS and sensors is also a common problem for both systems. GPS and Sensor connectivity issues are your typical electronics issues where a plug fails or gets wet, or a wire breaks. They are generally easy to fix once the issue is tracked down. Training can also be a challenge for both systems. There are not a lot of people familiar with the

FIGURE 41 Data management programs.

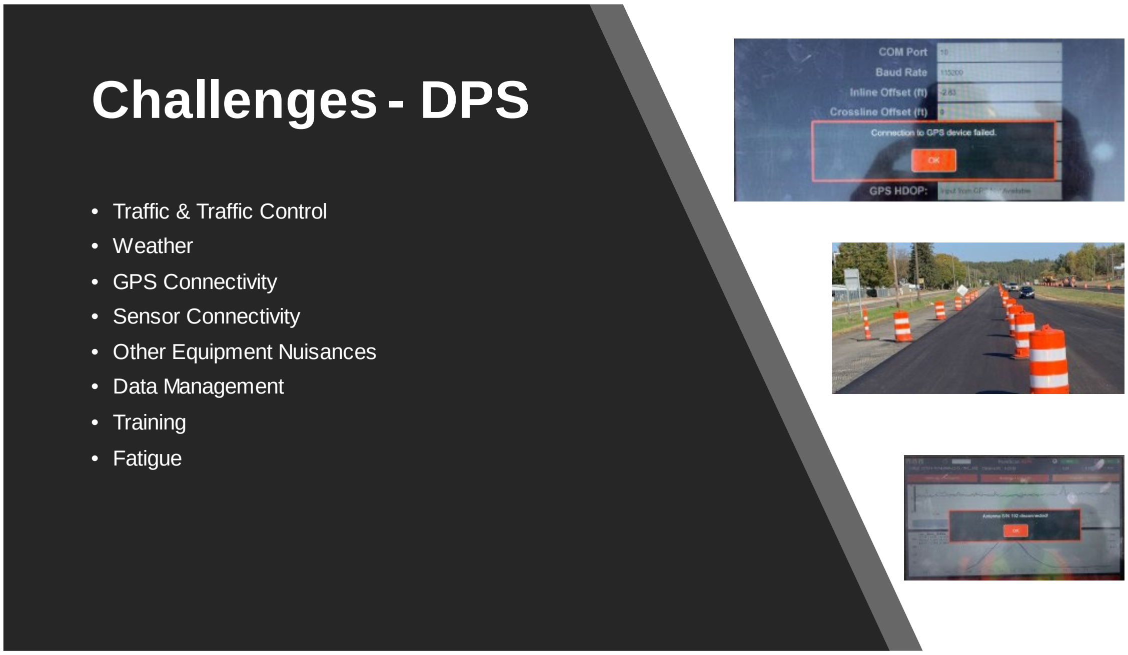


FIGURE 42 DPS challenges.

equipment and even less people familiar with using Veta or the other analysis tools. Demand for both technologies continues to grow so finding enough people to train new employees and employees new to the technology can prove difficult.

DPS also has its own set of challenges such as operator fatigue. The standard DPS setup utilizes a 4-wheeled cart that houses the sensors, battery, and other equipment. When doing full coverage for a road, the technician needs to walk the entire length of what has been paved a minimum of three times which can get to be tiring during full production. Efforts are being made to mount the system on different vehicles to help solve this issue. Weather can also be a challenge with the DPS. Dielectric measurements are very sensitive to moisture, after a rain event it can take several days or weeks for that moisture to leave the pavement. This can throw off the dielectric constants developed in the lab. This is one reason that staying a consistent distance behind the paving train is important as it will minimize any pavement that can't be measured after a rain event.

CONTRACTOR BENEFITS

When contractors are going to purchase new technology, we need to know how it is going to benefit us and if that benefit is going to be greater than the cost of implementing the technology (Figure 43). For DPS, having the ability to generate dielectric constants prior to starting a project so that you are reasonably confident that your density is accurate is a major benefit and reduces the amount of risk we carry on the first day of production. In Wisconsin we do 750-ton test strips, if we can eliminate the need to remove and replace one test strip it pays for the equipment.

These technologies also give us much more data than cores, nuke gauges, or non-nuke gauges. That data can be accessed in real time and on a digital mapping display that gives us a much broader picture of what is happening with our pavement. Having this data in an easy-to-understand format and in real time helps us make better decisions on our process changes which ultimately helps us produce higher quality pavements that earn more incentives.

These tools can also be used to help train personnel. The PMTP is one of the best tools we have for training screed persons who understand basic screed principals and are ready to increase their knowledge on the more technical changes associated with the screed. Being able to see the thermal segregation and how small changes to the screed affect the mat helps them more deeply understand how the screed works. The DPS can also give a full picture of the density of the roadway which allows you to point out areas that are consistently getting missed or where you are consistently having problems. It also allows you to see if a problem area is just an anomaly and can save you from making an adjustment that may not be warranted. When you can combine both systems, it helps contractors analyze the whole process and define areas that need improvement.

FINAL THOUGHTS

Implementation of DPS and PMTP are not cookie cutter and can be challenging at times, but when implemented and understood, they become great tools for helping improve the quality of pavements and are well worth the investment (Figure 44).

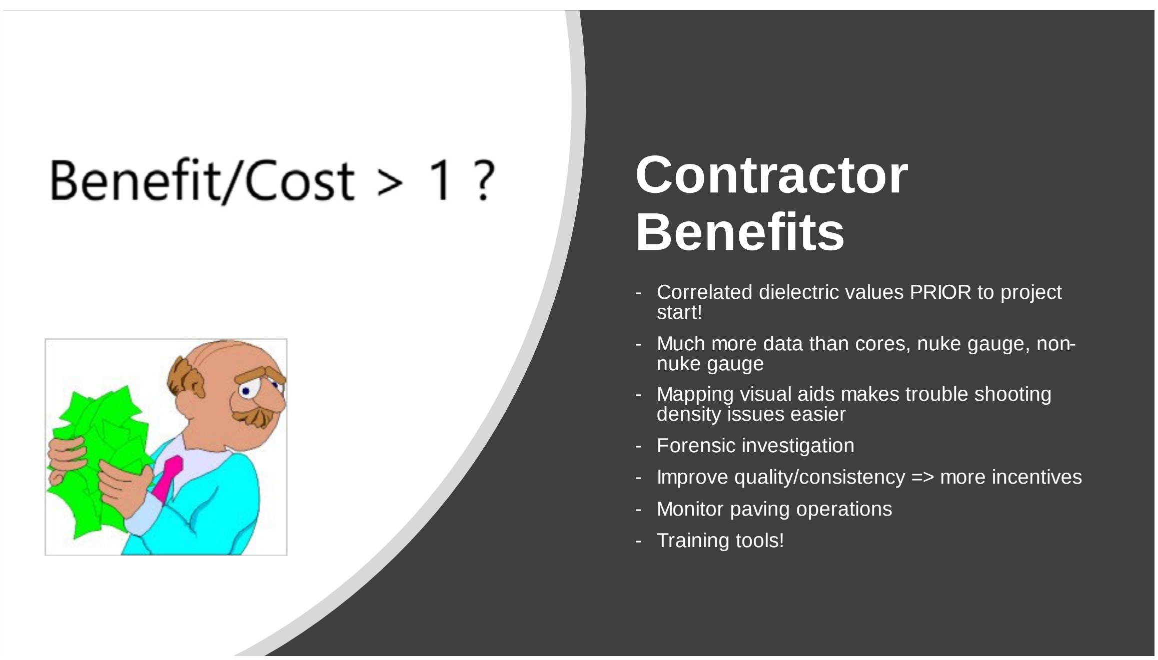


FIGURE 43 Contractor benefits.

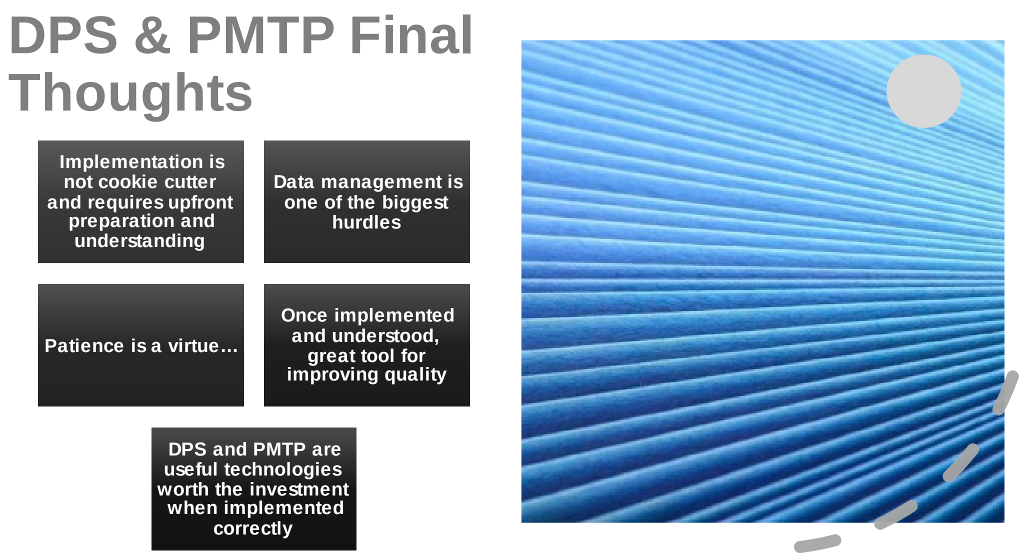


FIGURE 44 Final thoughts.

Implementing Intelligent Construction Technologies

Forrest Hierholzer

Granite Construction

PROJECT OVERVIEW

During the 2022 paving season, Granite Construction utilized DPS, PMTP, and IC equipment for projects in California and Washington to better understand the technologies and how they can be used as process control tools to improve compliance with specifications and maximize material-related bonuses. Within the Pacific Northwest Region, Granite has invested heavily in IC and PMTP equipment. The DPS on the other hand was a relatively new technology to Granite and was loaned from the FHWA Mobile Asphalt Technology Center's equipment loan program (https://www.fhwa.dot.gov/pavement/asphalt/matc/equipment-loan-program.cfm). During the equipment loan period, Granite was able to collect DPS, PMTP, and IC data on five mill and fill projects containing various asphalt mixture designs and materials.

In California, DPS data collection was the primary focus and data was collected on a gap graded rubberized asphalt mixture, an asphalt mixture containing warm mix additives and a standard dense graded asphalt mixture. In Washington, DPS, PMTP, and IC data were collected on two projects containing polymer modified dense graded asphalts. During these various projects, Granite worked alongside many local municipalities and state agencies and provided several demonstrations of the DPS calibration and data collection processes as shown in Figures 45 and 46.

FIGURE 45 DPS demonstration with the City of San Jose.

FIGURE 46 DPS demonstration with Caltrans and the City of Bakersfield.

DPS TRAINING, ASSEMBLY AND CALIBRATION

Training took place after the DPS data was received and was conducted by consultants contracted by the FHWA. This was a free-of-charge training sponsored by the FHWA's equipment loan program. Training proved to be a very important first step and needed to take place to ensure that personnel understood device assembly, sensor calibration, and sensor validation before using the equipment out on a project. Training also provided peace of mind to the contractor that the collected data was reliable data. Device assembly was very straight forward and was a brief 5-minute process. Seldom did issues occur during this process and when they did, they were typically caused by a loose connection. Sensor calibration was also a relatively quick 10-minute process that included an air calibration, metal plate calibration, and a DMI calibration (Figure 47). Sensor validation took the longest amount of time and consisted of a swerve, repeat line and a HDPE (high-density polyethylene) block test. On several occasions, these tests had to be performed multiple times to conform to the manufacturers recommended dielectric tolerances.

FIGURE 47 Performing the air and metal plate calibration process.

DPS FIELD CORE AND PUCK KIT CALIBRATIONS

Calibrations were performed to understand the mixture-specific relationship between density and dielectric. During the loan period, the Field Core and Puck Kit calibration methods were performed on almost every project. The Field Core calibration process consisted of taking dielectric measurements in the field before coring and determining density. The Puck Kit calibration process consisted of measuring the dielectric of gyratory compacted specimens in the lab, followed by density measurements. While the Field Core method was desired due to its actual relationship to in-place asphalt density, the Puck Kit method was easier and faster to perform and could be completed prior to stepping foot onto the project. Both methods produced similar results, but on many occasions the slope of the Field Core calibration was flatter than the slope of the Puck Kit calibration. Although the reason for this was not fully understood, the difference in slope between the calibration methods, as shown in Figure 48, could significantly impact project density. None the less, the density information collected on each project proved to be valuable and has since been used to inform and train project personnel.

VETA ANALYSIS

After collecting various intelligent construction data on each project, the data was analyzed using the Veta software. This software provided the ability to analyze DPS, PMTP, and IC data all in one place. It also provided great visuals which have since been used as training tools. This software was used to better understand the relationship between density and IC pass count, density and IC temperature, density and PMTP temperature, and variances in density measurements across the mat.

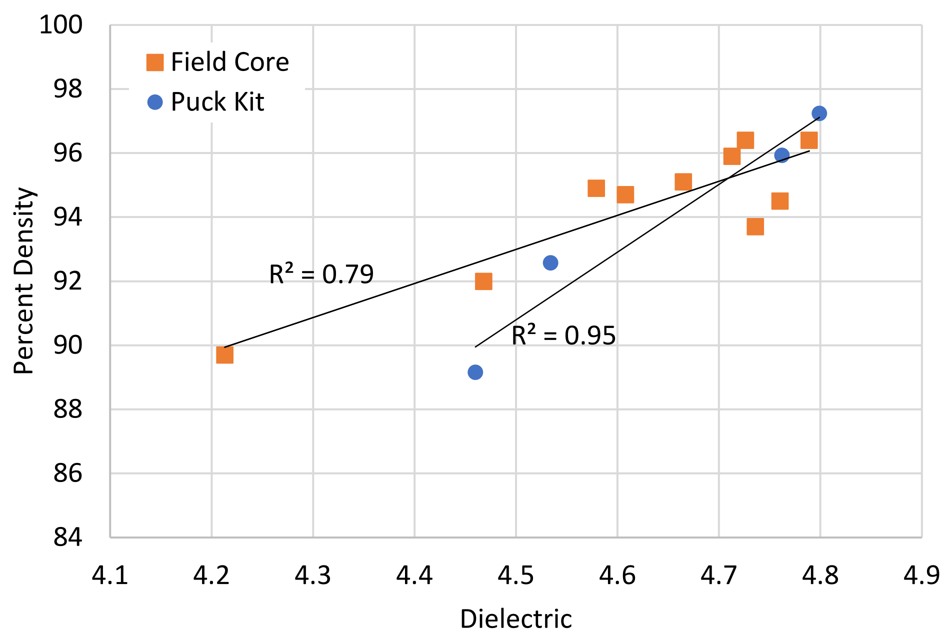


FIGURE 48 Field Core and Puck Kit density vs. dielectric relationships.

DPS VS. IC PASS COUNT

Project data was used to better understand how density is influenced by roller pass count. On several projects, roller pass count was thought to be the culprit of low asphalt density. Figure 49 displays density and pass count data from a project that struggled to meet density requirements. Density issues were first identified on this project from measurements taken using the nuclear density gauge and were later validated with the density data collected from the DPS, which showed density values initially ranging from 89% to 92%.

It was also later determined that the total pass count for the same section of highway was between 4 and 12 passes. Figure 50 displays density and pass count information after operational changes were made approximately a quarter mile up the roadway from the section of roadway displayed in Figure 49. Changes to the operation included slowing down the paver speed, increasing the number of passes made by the breakdown and intermediate rollers, and moving the breakdown roller closer to the paver and heat. When compared to Figure 49, Figure 50 shows a drastic increase in density ranging from 92% to 94%. Figure 50 also shows a drastic increase in the total number of passes (12–20) made by the rollers. In both figures it can been seen that as the total number of passes increases, so does the density.

Figure 49 Density (left) vs. total pass count (right).

FIGURE 50 Density (left) vs. total pass count (right).

DPS VS. IC TEMPERATURE

Projects data was also used to better understand how density is influenced by breakdown and intermediate compaction temperatures. For this analysis, a filter was used to display pass count data within Veta when the asphalt material was greater than 210 °F. Figure 51 displays the filtered density and pass count data for the same section of roadway shown in Figure 49. For this section, only one pass was made when the asphalt temperature was greater than 210 °F.

On the contrary, Figure 52 displays the same section of roadway as shown in Figure 50, after the operational changes (slowing down the paver speed, increasing the number of passes made by the breakdown and intermediate rollers, and moving the breakdown roller closer to the paver and heat) were made. For this section of roadway, there are upward of four passes being made when the material is greater than 210°F. This data suggests that the total number of passes and the number of passes at a greater temperature are both important factors for achieving density.

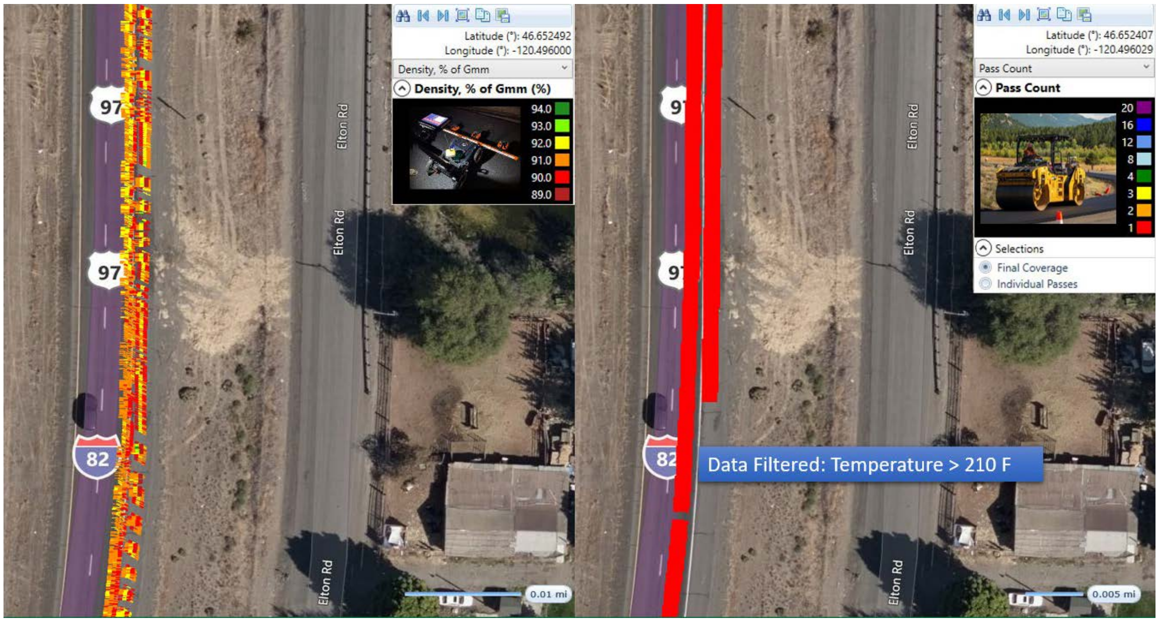


FIGURE 51 Density (left) vs. filtered total pass count (right).

FIGURE 52 Density (left) vs. filtered total pass count (right).

DPS VS. PMTP

Project data was also used to better understand how paver stops influence asphalt density. After analyzing the DPS and PMTP data, it became evident that paver stops had a significant influence on asphalt density. Figure 53 illustrates density and PMTP temperature data and the circled area within the figure is the location of a 50-minute paver stop. At this location, the density (89-90%) and the PMTP temperature (140-160 °F) are low and outside the minimum specification requirements. For the paver stop locations analyzed on this project, it was observed (as illustrated in Figure 54) that longer paver stops resulted in lower asphalt density.

The IC pass count data for this location suggests that adequate roller coverage was achieved. It was also observed that the low-density area resulting from the paver stop was double or triple the low temperature area. Figure 53 shows the area affected by low temperature extending approximately 10 feet, whereas the area affected by low density extending approximately 20 - 30 feet. This suggests that paver stop not only affects density directly behind the screed but extends some distance beyond. This may be caused by interruptions in the rolling pattern and not being able to roll close behind the paver while the equipment is stopped.

EDGE AND MAT DENSITY

Project data was also used to better understand the variation of density across the mat and the influence confinement has on density. Figure 55 shows significant differences in average density for a 1500-foot section of roadway between the unconfined edge (89.8%) and the confined edge (93.9%). On this section of roadway, no significant rolling pattern differences from the unconfined edge to the confined edge were indicated by the IC data. This data suggests that additional passes and a change to the rolling pattern may have been necessary to improve density on the unconfined edge.

FIGURE 53 Density vs. PMTP temperature.

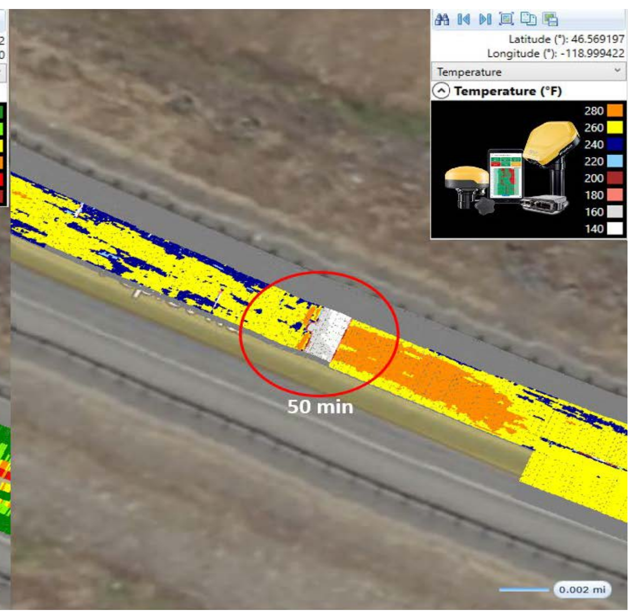


FIGURE 54 Density vs. paver stop duration.

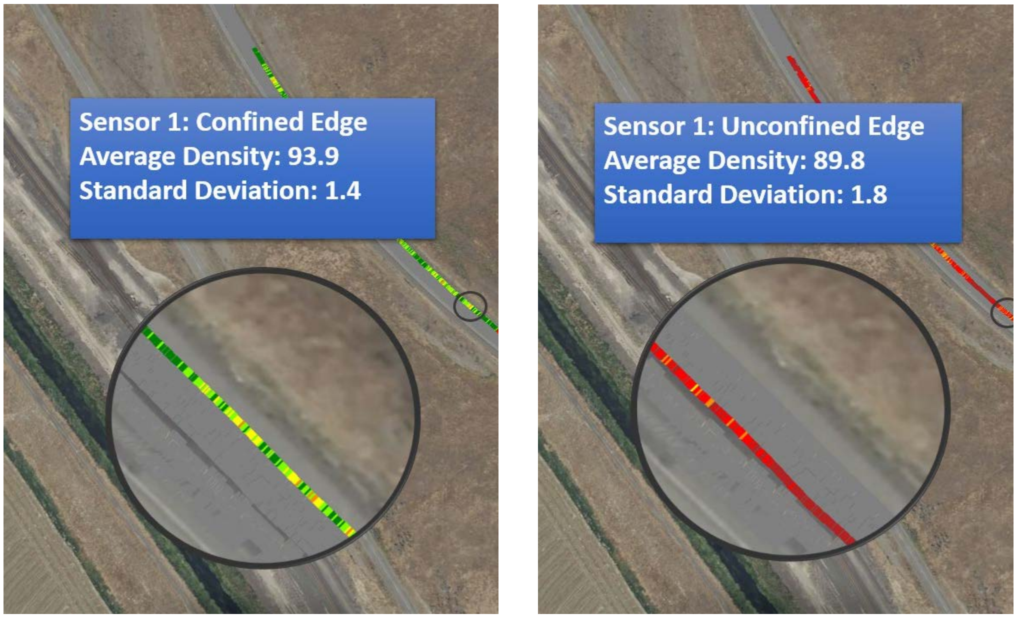


FIGURE 55 Confined edge density (left) vs. unconfined edge density (right).

CONCLUSION

Intelligent construction technologies such as DPS, PMTP, and IC are all tools that gather useful paving and compaction-related information that can be used to make critical operational changes and decisions. If utilized properly, these tools may help to improve compliance to specifications and maximize material-related bonuses. They may also provide extra insight and information that may not have been captured otherwise.

Considerations around changes and adjustments to existing specifications should be made if these intelligent construction technologies are to be used for quality control or quality assurance purposes. The purpose of these changes and adjustments would be to make achievable specifications that balance the risk between agencies and contractors. Further research should also be done to investigate differences identified between DPS calibration methods. It is also suggested that the intelligent construction technologies discussed in the above sections be paired with one another when used. The most useful information gathered throughout the duration of the projects was when multiple intelligent construction technologies were used in conjunction.

Third MentiPoll Questions and Answers

Q4: HOW WOULD YOU SELL DPS AND PMTP TO YOUR AGENCY/COMPANY? Responses (34):

Academic (1):

- Show them a summary of this workshop

Agency (8):

- (“Show me the money”) Explain monetary benefits and pavement improvement
- Show advantage of continuous measurements vs. random spot tests
- Implement by requiring as QC tool

Consultant (1):

- Lower LCC; fewer work zones

Contractors (4):

- Improved pavement quality and incentives
- Reduced disincentives (preventing one dispute could pay for the equipment)

Federal (1):

- Save money in long term with increased pavement life

Unk (19):

- Book, file,(e-circular) with project examples and data
- Show (positive) ROI
- Ability to make real-time/live decisions

Q5: HOW WOULD YOU IMPLEMENT THE TECHNOLOGY (WHAT ARE PROBABLE ROADBLOCKS AND SOLUTIONS)? Responses (34):

Academic (1):

- Workshops and webinars

Agency (8):

- Need a champion; Roadblocks are available responses; confidence in measurements
- Implement with Pilot projects
- Roadblock is contractor hesitancy

Consultant (1):

- Fewer disputes
- Roadblocks are the technology, personnel, and initial cost of equipment

Contractors (4):

- Show how can reduce costs and improve profits
- Roadblocks are equipment costs and personnel, data collection and analysis

Federal (1):

- Save money in long term with increased pavement life
- Roadblocks are (management) lack of understanding, contractor resistance

Unk (19):

- Tighter specifications with targets and incentives so contractors need the equipment
- Separate pay item for using the equipment
- Roadblocks are cost and knowledge-training

Fourth MentiPoll Questions and Answers

NOTE: A seventh presentation on Acceptance Considerations and Ensuring Value for the Taxpayer Dollar, could not be included in this E-Circular; however, a summary of the fourth MentiPoll questions and answers are provided below.

Q6: WHAT ARE THE BIGGEST CHALLENGES AND RISKS IN USING THESE TECHNOLOGIES FOR ACCEPTANCE/ PAYMENT? (FOR OWNERS/AGENCIES? FOR CONTRACTORS?) Responses (18):

Agency (4):

- FHWA interpretation of CFR for QA
- Accuracy and proficiency of equipment users
- SOP for when data can't be collected due to weather, equipment failure

Consultant (1):

- Abuse of black box component and moisture

Contractors (1):

- Meeting CFR

Federal (2):

- Accuracy of data for acceptance
- Verification process for data acceptance

Unk (10):

- Agency verification and validation of contractor data
- Confidence in accuracy, consistency, repeatability, training, and qualifications of operators
- Costs
- Equipment limitations and unpredicted events

Conclusion

Work is continuing on these technologies. Links for more information follow. What needs to be realized is that improvements come with an initial cost, that over time yields savings just in pavement maintenance and user costs from traffic interruptions for maintenance that will pay back more than the initial costs to monitor constructing a uniform pavement. Indeed, some of the testing will reduce testing costs and increase worker safety by removing the need to core brand-new pavements. This idea of measuring pavement uniformity will require another paradigm shift away from assuming spot tests represent the whole.

LINKS TO CURRENT INFORMATION ON DPS AND PMTP

- Continuous Asphalt Mixture Compaction Assessment Using Density Profiling System [TPF-5(443)] https://www.dot.state.mn.us/materials/dps/index.html
- Homepage for NRRA Intelligent Construction Team: https://www.dot.state.mn.us/mnroad/nrra/structure-teams/intelligent-construction/index.html
- Reports on using DPS, PMTP and other intelligent construction technologies: https://www.fhwa.dot.gov/pavement/asphalt/matc/technical-documents.cfm
- A Practice for Including Intelligent Construction Equipment in Quality Assurance Programs: https://www.fhwa.dot.gov/pavement/pub_details.cfm?id=1153