SHRP2 Case Study
Infrared Thermal Profiler for Improving Mat Uniformity and Long-Term Performance

Technologies to Enhance Quality Control on Asphalt Pavements, R06C

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16. Abstract

Infrared (IR) technology was recommended for continued use as a product from the SHRP2 *Technologies to Enhance Quality Control on Asphalt Pavements (R06C)*. As part of that recommendation, field projects were completed to demonstrate the use and effectiveness of an IR asphalt pavement scanner for control of asphalt mixture temperature uniformity, and to confirm the short and long term benefits of the IR technology. A total of ten field demonstration projects and eight workshops were completed as part of the deployment effort for this product.

Density, mat temperatures, mixture segregation were recorded within each demonstration project. A summary of the demonstration projects and the data collected within each project were documented in a report entitled "Case Study: Infrared Thermal Profiler Deployment." The purpose of this report is to use the outcome from the ten field demonstration projects to estimate the increase in mat uniformity or reduction in potential mat defects and the increase in mat performance as a result of using the IR thermal profiler.

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SHRP2 Case Study: Infrared Thermal Profiler for Improving Mat Uniformity and Long-Term Performance

INTRODUCTION

In-place density is a critical factor in determining pavement durability in asphalt concrete (AC) mixtures. Localized non-uniform zones of the AC mat, often defined as segregation, are low-density areas. Although very localized, segregation is a major construction-related problem with an adverse impact on pavement service life. For example, figure 1 includes a photograph of two cores that exhibit longitudinal aggregate segregation at the surface of a mat.

The core to the right in Figure 1 clearly shows a concentration of coarse aggregate at the surface. This concentration of coarse aggregate caused a “weak” spot where a longitudinal crack started at the surface and is propagating downward through the AC.

The core to the left in figure 1 is similar, but the crack has propagated through all of the AC layers. In addition, the coarse aggregate have become dislodged by traffic and exhibits severe raveling along the longitudinal crack. This condition can occur in a few years after construction and require premature maintenance or rehabilitation.

Figure 1. Longitudinal Aggregate Segregation and Top-Down Cracking

The infrared (IR) scanner technology is being used to ensure these conditions are identified on a real time basis during the paving operation. The IR scanner is referred to as the IR paver mounted thermal profiler. The IR technology was demonstrated as part of the SHRP2 *Technologies to Enhance Quality Control on Asphalt Pavements (R06C)*. Ten field demonstration projects were completed to demonstrate the use and effectiveness of the IR thermal profiler for control of AC mixture temperature uniformity. Another objective of the field demonstration projects was to confirm the short and long-term benefits of the IR technology, which are listed below:

- Short or near-term benefits:

  - More uniformly constructed hot and warm-mix asphalt layers.
  - Higher or more uniform in-place field density.
  - Explanation of possible discrepancies between the contractor and agency test data.
  - Provide real-time results to facilitate immediate corrective actions to paving practices.
- Long-term benefits:
  - Less premature distress (raveling and cracking).
  - Longer lasting pavements with lower maintenance costs.

The agencies that participated in the field demonstration included: Alabama Department of Transportation (DOT), Alaska DOT, Eastern Federal Lands of FHWA, Illinois DOT, Maine DOT, Missouri DOT, New Jersey DOT, North Carolina DOT, Virginia DOT, and West Virginia DOT. Table 1 lists specific details for each demonstration project.

The purpose of this document is to focus on the long-term benefits of the technology to reduce maintenance costs and extend the life of the AC pavement by identifying and eliminating mat defects. A separate report focused on the short-term benefits and summarized application of the IR scanner technology (thermal profiler) to improve the uniformity of the AC mat during construction (Reiter, et al., 2017).

Table 1. Field Demonstration Projects and AC Layers Monitored with the Pave-IR Scan^{TM} System

Project	**Facility**	**Type**	**Layer Type**	**Thickness, in.**
Alabama DOT	Secondary Arterial	Mill and Overlay	Wearing Surface	1.5
Alaska DOT	Runway	Reconstruction	AC Base	3.0
	Taxiway		Binder Course	3.0
Eastern Federal Lands	Principle Arterial	New Construction	AC Base	3.0
			Intermediate	2.5
Illinois DOT	Secondary Arterial	Mill and Overlay	Wearing Surface	1.5
	Interstate	Mill and Overlay	Wearing Surface	1.5
Maine DOT	Interstate	Mill and Overlay	Wearing Surface	2.0
Missouri DOT	Interstate	Mill and Overlay	Wearing Surface	1.75
New Jersey DOT	Principle Arterial	Mill and Overlay	Wearing Surface	1.75
North Carolina DOT	Interstate	Reconstruction	Wearing Surface	1.5
Virginia DOT	Collector	Mill and Overlay	Wearing Surface	2.0
West Virginia DOH	Primary Arterial	New Construction	Drainage Layer	4.0
			AC Base	3.0

SEGREGATION AND LOW DENSITY

Getting proper density, free of segregation, is a key component to long-life AC mixtures. Most DOTs sample the AC mat by coring, which represents a small fraction of the area placed. The core density or percent compaction is used to determine if the AC mat meets the acceptance criteria. Localized segregation, however, may not decrease the density below the unacceptable value for an entire core, as shown in Figure 1, even if the core is located within the segregated area.

Some DOTs include segregation check procedures within their quality assurance (QA) program, because segregation has such a detrimental impact on long-term pavement performance. The procedures and test methods, however, only test a very small portion of the mat and will likely miss localized areas, even if those areas occur in a pattern or at cyclic intervals along the mat. In short, spot inspection methods risk overlooking problem areas and are labor intensive.

Localized areas with defects, like segregation, are usually identified through visual assessment. Visual inspection is a part of QA to identify and eliminate segregation. However, inspectors cannot always see anything unusual or defects in the AC mat. Contributing to the problem of seeing segregation is the increased use of night paving. Paving at night makes it difficult to visually see mat defects, and if you cannot see the defect, it is less likely to be eliminated. The visual subjective approach also leaves room for disputes between the agency and contractor because subjective procedures cannot be quantified.

The most common form of AC segregation is truck to truck segregation, also referred to as end of load segregation. Truck to truck segregation occurs at the start and/or end of the truckload, which can exhibit a higher amount of coarse aggregate depending on how the truck was loaded at the plant. These locations show up on the mat as regularly spaced defects and can vary from small areas on either side of the paver centerline to larger areas that extend across the width of the AC mat being placed.

Figure 2 shows the AC mat with different forms of segregation: truck to truck and longitudinal segregation. Determining the degree of segregation is difficult, at best, based on visual observations. A core was extracted from one of the areas exhibiting truck to truck segregation, which is also shown in Figure 2. An intact core was not recovered, suggesting severe segregation. The severity of segregation cannot be defined from visual observations. As such, it is in the best interest of the DOT and contractor to implement a procedure that can properly identify areas with segregation and low density areas, so they can be eliminated.

Areas with segregation deteriorate rapidly because of their lower density, higher permeability, and higher air voids that allow the entry of water and air. These areas are susceptible to premature and accelerated raveling and fatigue cracking. Early distress results in poorer ride quality and requires agencies to use resources earlier than planned to maintain an acceptable level of ride quality. Michigan DOT reported that construction defects associated with deterioration of the centerline joint, longitudinal cracks at the center of the paver (center lane cracks) and along the outside edges of the slat conveyor of the paver appeared on 100 percent of the flexible pavement and AC overlay projects exhibiting poor performance and requiring premature maintenance (Von Quintus and Perera, 2011).

Figure 2. Truck to Truck and Longitudinal Segregation

IR thermography is a technology that can be used to provide feedback in real time to paving crews through visual and quantitative outputs. The ten demonstration projects (see table 1) showed that IR imaging can be used to assess uniformity and/or defects during construction by monitoring the mat's surface temperature, while providing nearly 100 percent continuous coverage of the new AC mat. Mat defects are visually located on a real time temperature graph, and summarized in color coded tables to assist the paving crews.

Segregation shows up as cold spots or areas on an IR scan or photograph, and the severity of segregation is quantified by the magnitude of the temperature differential in localized areas or thermal streaks down the roadway. Essentially, the cold spot results in low-density areas of the compacted AC mat, and the thermal streaks result in a weakened plane down the roadway. The cold spots can also exhibit a coarser gradation and lower asphalt cement content increasing the susceptibility for raveling and cracking. The thermal streaks or longitudinal segregation results in a crack initiator (see figure 1).

MAT SURFACE TEMPERATURE-DENSITY RELATIONSHIP

The effect of temperature on AC density is well understood in a controlled environment or laboratory. As temperature increases, the density of the mixture increases under a specified compaction effort, because the viscosity of the asphalt decreases or the asphalt becomes more fluid. Figure 3 illustrates an increase in mat density with an increase in mat surface temperature for some lots from the Illinois and Missouri demonstration projects. An important observation is the scatter in the data, because there are many factors that affect density besides temperature that vary in the field (gradation, asphalt content, number of roller passes, lift thickness, etc.).

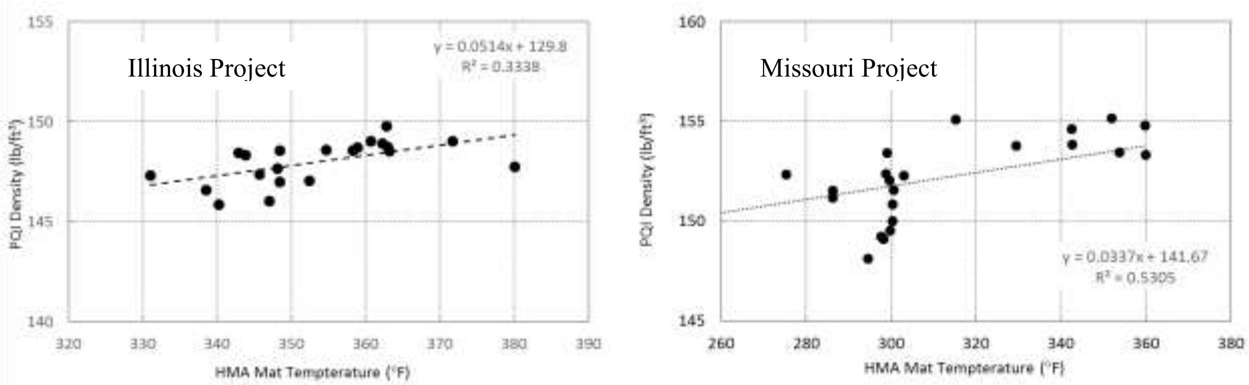


Figure 3. Mat Density Increasing with Higher Mat Surface Temperature Observed for Lots within the Illinois and Missouri Demonstration Projects

Mat density, however, did not always increase with increasing temperature. Figure 4 shows a decrease in mat density with increasing temperature from the North Carolina and Virginia demonstration projects, while figure 5 shows no statistical effect of temperature on the final density from the New Jersey and Missouri demonstration projects. These observations, however, do not imply mat surface temperature is insignificant relative to the quality of the mat.

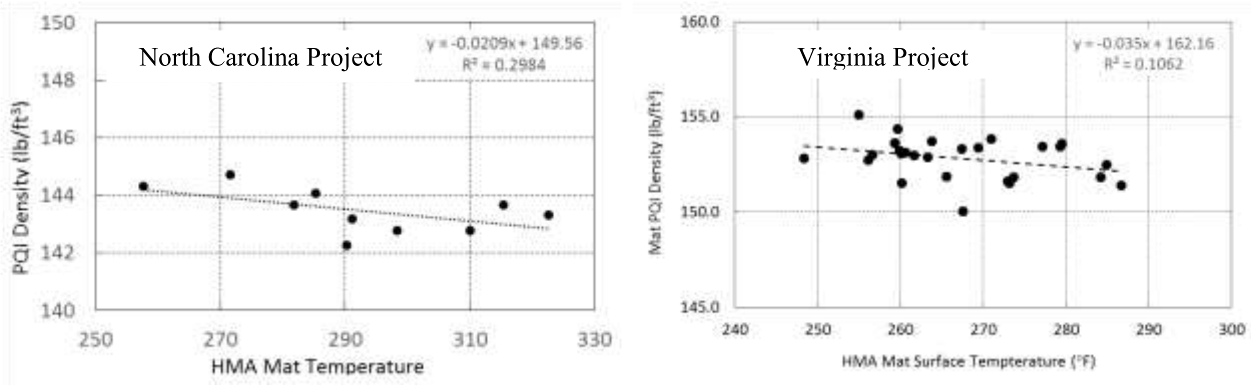


Figure 4. Mat Density Decreasing with Higher Mat Surface Temperature Observed for Lots within the North Carolina and Virginia Demonstration Projects

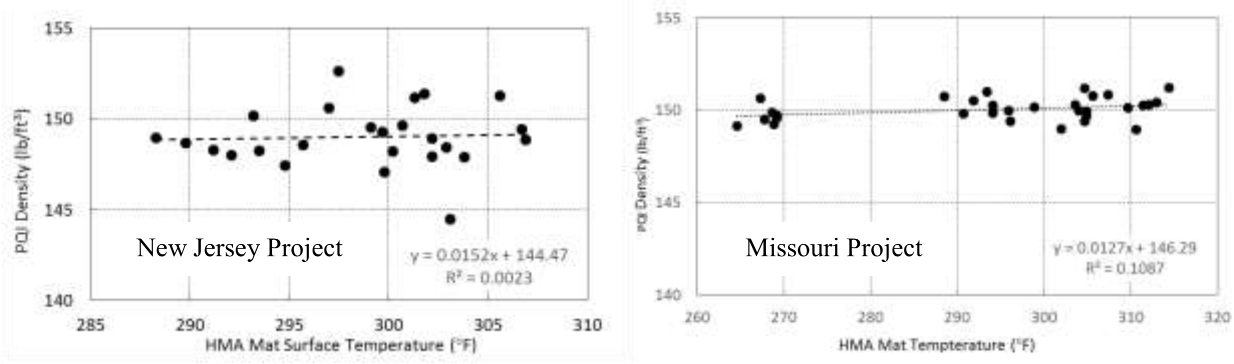


Figure 5. Mat Density decreasing with higher Mat Surface Temperature observed for Lots within the New Jersey and Missouri Demonstration Project

The next sections of this chapter illustrate examples of using temperature and density data to make decisions for improving mat uniformity by measuring mat surface temperature differentials.

MAT UNIFORMITY: TEMPERATURE AND DENSITY VARIATIONS

The temperature and density data collected during the field demonstration projects were segregated into three groups, which were related to the quality control (QC) procedures being used by the paving contractor:

1. Contractor was using a nuclear or non-nuclear density gauge to ensure mat density exceeded minimum value before moving to the next roller section in real time, referred to as aggressive QC program.
2. Contractor using density gauge to monitor mat density after finish rolling, referred to as monitor densities for QC.
3. Contractor not monitoring density during the rolling process, referred to as density tests (cores) after compaction.

Figure 6 shows the correspondence between the coefficient of variation (COV) of mat surface temperature and density. As shown, as the COV increased for mat temperature, the COV of mat density increased. The data for figure 6 was collected during the demonstration projects using the IR thermal profiler and a non-nuclear density gauge. Point measurements in a cluster, randomly selected, and identified from the IR thermal profiler were selected in comparing the temperature and density, as well as comparing the COVs.

The relationship in figure 6 shows the importance of controlling density through the control of mat surface temperature. This relationship becomes important for a percent within limits (PWL) type specification, or in other words, controlling the risk of the contractor for being penalized based on mat density. Specifically, the greater variations in mat surface temperatures results in greater variations in mat density, which results in a higher probability that the contractor could be penalized for insufficient mat density. This effect will be discussed in more detail in a latter next section of this chapter.

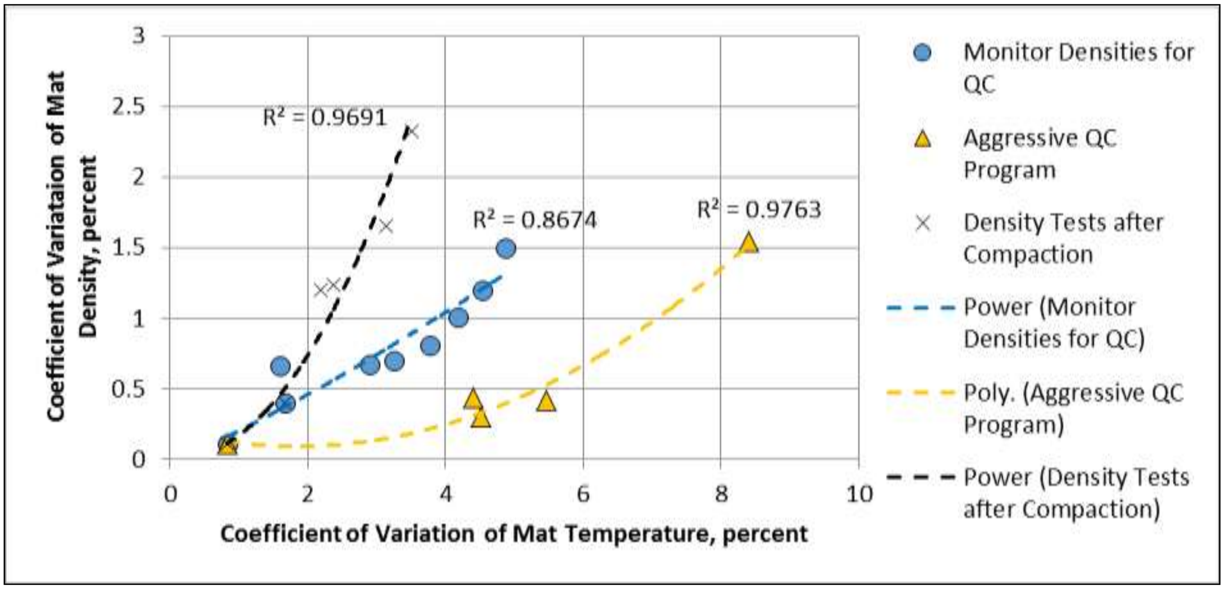


Figure 6. Coefficient of Variation of Mat Density as related to Coefficient of Variation of Mat Temperature

IDENTIFYING TEMPERATURE SENSITIVE ZONE

During the first day of the Virginia DOT demonstration, the contractor had some difficulty achieving the required density of the mat. The breakdown and finish rollers were kept longer within the start of the first lot, so the mat temperatures decreased which resulted in roller marks being left by the finish roller within the latter rolling zones. Figure 7 shows the correspondence between mat temperature and density within this lot of the northbound lane. As shown, the mat density decreased with an increase in temperature and then started to increase with the higher mat temperatures. It is expected that the intermediate and finish rollers rolled the mat within the temperature sensitive zone. Figure 8 shows the roller marks and checking left by the finish roller within this area.

The contractor later started making sure the mat surface temperatures being monitored by the IR thermal profiler were higher and the finish roller was kept closer to the paving operation. This eliminated the roller marks and checking that was observed in the AC mat.

The densities measured from cores exceeded the density to receive 100 percent pay for a couple of the demonstration projects exhibiting a high percentage of severe temperature differentials. For example, 82 percent of the Eastern Federal Land segments contained severe temperature differentials. The densities measured on the cores exceeded the value for the contractor to receive 100 percent pay. Figure 9 shows the relationship between temperature and mat density, as measured by the non-nuclear density gauge for the Eastern Federal Land project. As shown, the densities were found to vary significantly within the first lot. Cores were taken at random, but located in areas with the higher densities and/or lower temperature differentials. As such, these lots received 100 percent pay.

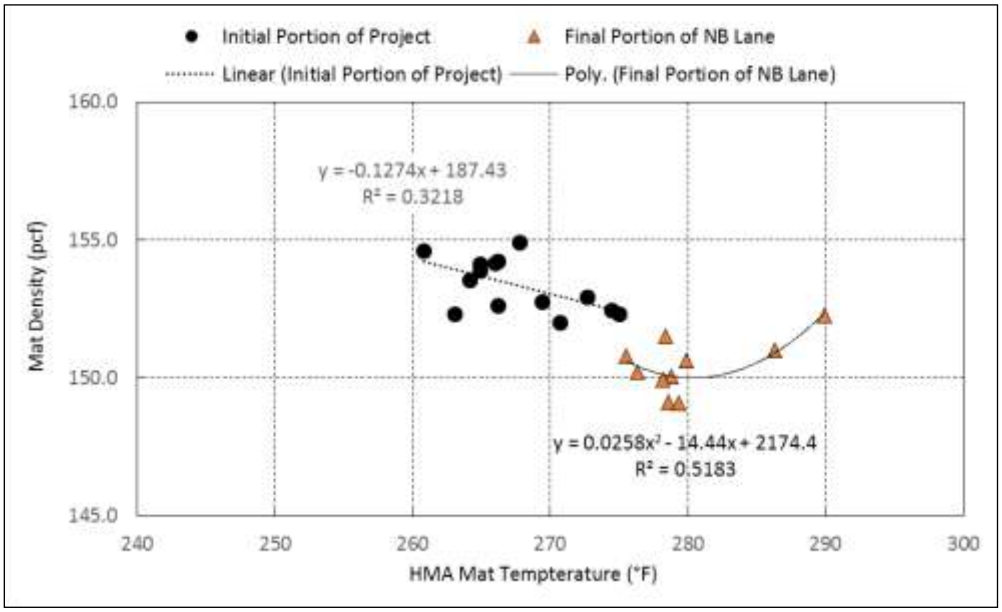


Figure 7. Illustration of the Mat Density for different Temperature Ranges

Figure 8. Roller Marks (photo on the left) and Checking (photo on the right) that Occurred in the Northbound Lane within the Temperature Sensitive Zone of the Mixture (see figure 7)

Even though 82 percent of the IR segments exhibited severe temperature differentials, the cold spots with or without segregation still represent a small portion of the mat. As such, the probability of drilling a core for acceptance in an area with minor temperature differential is higher than in areas with severe temperature differentials using random sampling methods.

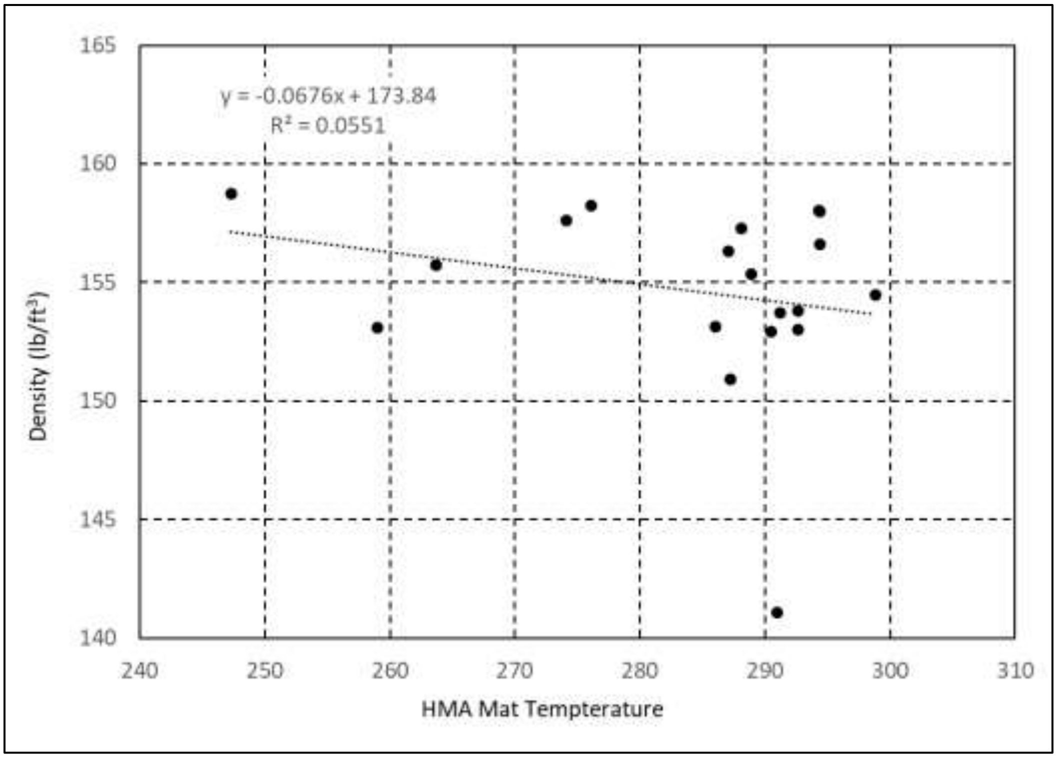


Figure 9. Comparison of Mat Density and Mat Surface Temperature observed for Lots within the Eastern Federal Land Demonstration Project

One of the evaluation factors for the demonstration projects was to compare the number and magnitude of penalized lots to the temperature differential magnitude or number of segments with severe temperature differentials. Most of the lots received 100 percent pay, regardless of the temperature differential, both in magnitude as well as in percentage of segments with sever temperature differential. As explained above, one reason for this observation is the truck to truck segregation and/or cold spots (starting and stopping the paver) identified by the IR thermal profiler were localized or small in comparison to the entire mat. This reason does not imply, however, that cyclic localized areas with insufficient density and/or high air voids have no impact on pavement performance or do not result in premature maintenance of the roadway.

REDUCING THE CONTRACTOR AGENCY'S RISK

This section discusses the importance and impact of controlling the COV of surface temperature and provides an example based on reducing the contractor's risk of being penalized because of increased uniformity of mat density using the PWL concept. Figure 6 provided the correspondence between the COVs of surface temperature and mat density.

At the beginning of the paving process for all demonstration projects, except for the Alaska and Alabama projects, the density of the mat was measured through the use of a non-nuclear density gauge, the Pavement Quality Indicator (PQI), and cores. The average standard deviation at the beginning of the project was 1.5 percent which decreased to 1.0 percent by watching the IR monitor and making decisions that reduced the temperature differential. Reduction in the number of severe temperature differentials and corresponding density COV was observed during the Eastern Federal Lands, Maine, North Carolina, Virginia, and West Virginia demonstration projects.

The average air voids, however, was about the same between using and not using the IR thermal profiler: 6.8 percent at the beginning and 6.5 percent after making adjustments to the paving process based on the IR thermal profiler. Table 2 provides a summary of the statistical values used for this example.

Table 2. Example: Summary of PWL Specification to Define of Risk of Contractor being Penalized

Air Voids	**IR Thermal Profiler Not Used for QC**	**IR Thermal Profiler Used for QC to Make Adjustments**
Upper Limit	8.0	8.0
Average	6.8	6.5
Standard Deviation	1.5	1.0
PWL	76	95
Percent Defective	24	5

Figure 10 shows the two density distributions or frequency diagrams for this example. The “no scanner used” represents the average distribution at the beginning, while the “scanner used” represents the average distribution after adjustments were made to the paving process (i.e.; Maine, North Carolina, Virginia, and West Virginia demonstration projects). Using an upper limit of 8 percent air voids, the percent defective and PWL values were calculated for this example (see table 2). As shown, the PWL was 76 percent at the beginning of the lot, while a PWL of 95 percent was calculated after making adjustments based on the IR thermal profiler.

In summary, the probability of the contractor being penalized by the agency is higher for the higher standard deviation than after making adjustments to the paving process that reduced the COV of the mat density (see figure 6).

Some points that need to be remembered in implementing the IR thermal profiler, as well as for long-term pavement performance, are noted below:

1. The contractor is not always in control of the on-site factors like traffic congestion that restricts delivery trucks from arriving at the paving site so the paver stops are minimized (i.e.; the Eastern Federal Lands project along US 1 in Virginia).

2. In some cases, the delivery trucks are independent contractors and requiring the delivery trucks to properly install and maintain the tarp is not under the control of the paving contractor (i.e.; the West Virginia project).
3. The level of risk a contractor is willing to take, relative to being penalized, will vary by contractor, project, and QA specifications (i.e.; the Maine and Missouri projects).
4. The IR thermal profiler only estimates mat uniformity immediately behind the paver. The thermal profiler will not identify the variability in density caused by the rollers operating in the temperature sensitive zone, using a non-uniform rolling pattern, or delaying the roller operation, for whatever reason (i.e.; the Virginia project).

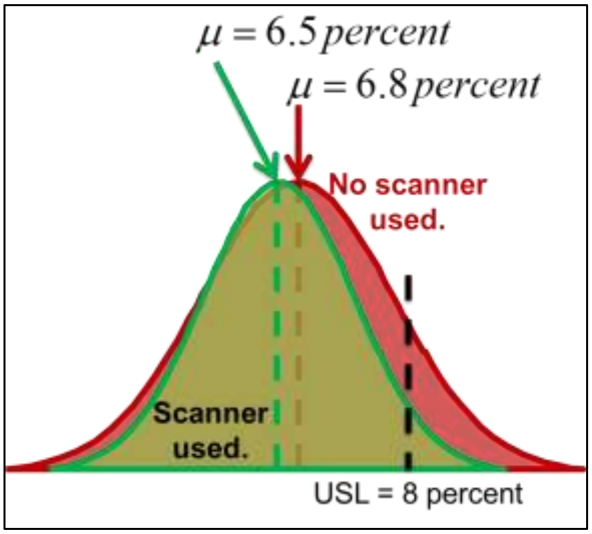


Figure 10. Example: Normal Distribution for Mat Air Voids with and without using the IR Thermal Profiler.

LONG-TERM PAVEMENT PERFORMANCE

The ten demonstration projects were constructed in 2015 to 2017 construction seasons, so the time since construction is too short to quantify long-term performance of AC mixtures placed using the IR thermal profiler in comparison to those placed using traditional QA methods. To quantify the performance of the mixtures, historical data, experience of the authors, and extrapolation methods were used to estimate the difference in performance between the QA procedures using and excluding use of the IR thermal profiler to make decisions about mat quality in real time.

More importantly, pavement performance is not going to increase or maintenance costs decrease simply because the IR thermal profiler is used on a project. The contractor must take some corrective action when cold spots or moderate to severe temperature differentials are observed on the IR monitor along a project.

TEMPERATURE DIFFERENTIALS: CAUSE AND EFFECT

Tables 3 and 4 include a summary of the results and specific factors observed from each demonstration project. As shown, the percent of severe temperature differentials varied significantly between the different demonstration projects. The other important observation is that thermal streaks were not observed consistently on any of the demonstration projects. Thermal streaks were observed on the Alabama and New Jersey projects, but only at the start of a lot. Shortly after paving began, the thermal streaks were not noticeable or identifiable on the IR monitor.

Table 3. Summary of Overall Results from Demonstration Projects, including Paver Stops

Demonstration Project	Delivery Truck Type	MTV Included	Percent Severe Temp. Differentials	Thermal Streaking
Alaska	Bottom-Dump	Windrows	17	None
Alabama	End Dump	Yes	4	None
Maine	End Dump	Yes	5	None
Virginia	End Dump	Yes	5	None
North Carolina	End Dump	Yes	18	None
New Jersey	End Dump	Yes	21	None
Missouri	End Dump & Flow Boys	Yes	25	None
West Virginia	End Dump	Yes	5	None
West Virginia	***End Dump***	***No***	***41***	***None***
Illinois	***End Dump***	***No***	***40***	***None***
Eastern Federal Lands	***End Dump***	***No***	***83***	***None***

Table 4. Summary of Total Number of Increments and the Number of Increments within each Temperature Differential Category for the Individual Demonstration Projects

Paver Stops	Total Number of Increments	Number of Increments within Temp. Regimes			Thermal Streaking
		Minor	Moderate	Severe	
Alaska DOT Project					
Excluded	36	27	9	0	None
Included	36	22	8	6	None
Alabama DOT Project					
Excluded	48	34	14	0	None
Included	47	34	11	2	None
Virginia DOT Project					
Excluded	84	72	10	2	None
Included	84	71	9	4	None
North Carolina DOT Project					
Excluded	126	95	24	7	None
Included	126	79	24	23	None
West Virginia DOH Project; without MTV					
Excluded	99	0	74	25	None
Included	99	0	58	41	None
West Virginia DOH Project; with an MTV					
Excluded	159	133	19	7	None
Included	159	104	47	8	None
Maine DOT Project					
Excluded	579	546	25	8	None
Included	579	494	56	28	None
New Jersey DOT Project					
Excluded	262	188	49	25	None
Included	262	163	43	56	None
Missouri DOT Project					
Excluded	816	648	135	33	None
Included	816	440	170	206	None
Eastern Federal Lands Project					
Excluded	108	2	24	82	None
Included	108	2	16	90	None
Illinois DOT Project					
Excluded	1,520	218	761	541	None
Included	1,502	196	708	598	None

Table 3 also identifies the type of delivery truck and the impact of using a Material Transfer Vehicle (MTV) on the percentage of severe temperature differentials. As shown, the percentage of severe temperature differentials were significantly lower for the demonstration projects employing the use of an MTV.

The factors included in the analysis of the impact of using IR thermal profiler on a project included: reduced maintenance and/or extended service life, International Roughness Index (IRI) or smoothness, raveling, fatigue cracks, and longitudinal cracks. Rutting, bleeding or flushing and other distortion types of distress are not significantly affected by segregation or severe temperature differentials in the AC mat and are not included in the discussion.

Reduced Maintenance and Extended Service Life

One of the sources for evaluating maintenance costs between projects was obtained through the Quebec Ministry of Transportation in Canada. Quebec collected data on multiple projects with and without longitudinal thermal streaks. Mat surface temperatures were collected with an IR camera, as opposed to the use of the IR scanner or thermal profiler. Those projects exhibiting thermal streaks also exhibited longitudinal cracking along the thermal streak shortly after construction. The longitudinal cracks usually appear after the first couple of winters and certainly in less than 5 years. Projects without thermal streaks did not exhibit longitudinal cracks shortly after construction. Quebec's policy is to seal linear cracks once they occur to prevent water from entering the pavement structure.

Other agencies have also tracked increased maintenance costs and/or reduced service life in AC pavements and overlays related to truck to truck and longitudinal segregation. Many agencies report shorter service lives and/or higher maintenance costs on projects exhibiting segregation and/or severe temperature differentials throughout the life of the pavement. For truck to truck segregation, the more common maintenance strategy is to do a mill and fill or place a micro-surfacing depending on traffic and other factors.

International Roughness Index

The International roughness index (IRI) is an important factor in terms of pavement performance and life cycle cost analysis. It is well known that an AC wearing surface with a lower IRI value at construction will remain smoother and exhibit lower vehicle operating costs until pavement distresses start to occur and then the surface becomes rougher.

IRI was requested for all field demonstration projects to determine if use of the IR scanner reduced the IRI or increased smoothness of the AC mat by making the right decision at the right time. IRI is used by many agencies in the acceptance procedures for the wearing surface of AC pavements and overlays. Of the 10 field demonstration projects, however, only five included IRI within their acceptance procedure for the final lift of the demonstration projects: Maine, Missouri, New Jersey, North Carolina, and Virginia. The IR scanner was used throughout the project, so there is no direct comparison between the IRI values measured on the wearing surface with and without the use of the IR scanner.

Verbal information was obtained from the Missouri DOT on a project where the IR scanner was used to determine the locations where the paver stopped. IRI measurements were made along the project and the areas where the paver stopped were compared to the areas where continuous paving occurred. Missouri DOT reported an increase in IRI values over 10 percent where the paver stopped creating a cold spot in comparison to those areas where the paver continued without stopping and without cold spots.

Longitudinal Cracking

The potential for longitudinal cracking in dense-graded mixtures along a project at or below the surface increases where thermal streaks occur. Thermal streaks typically occur in three areas relative to the paver: under the gear box or center of the paver which results in center lane longitudinal cracks; adjacent or along the outside edges of the slat conveyor which results in longitudinal cracks adjacent to the wheel paths; and near the ends of the auger which result in longitudinal cracks just outside the wheel path.

Thermal streaks caused by a consistent temperature differential parallel to the paving direction with and without longitudinal segregation causes a weakened plane at which a crack initiates at the surface. If the consistent temperature differential down the mat is caused by segregation, accelerated crack deterioration will occur with the loss or dislodging of the coarse aggregate (see figure 1). If the thermal streak is not caused by longitudinal segregation, however, a crack will still appear but accelerated crack deterioration will not occur. It is the opinion of the authors that most thermal streaks are a result of longitudinal segregation.

Figure 11 shows longitudinal cracks in locations where thermal streaks were identified. It is important that the longitudinal cracks caused by longitudinal segregation be sealed as soon as possible to reduce or mitigate the loss of coarse aggregate along the crack.

Fatigue Cracking

The potential for fatigue cracking along a project with dense-graded mixtures at or below the pavement surface increases with an increase in air voids or reduction in density. The extent and severity of area fatigue cracking depends on the extent of the segregation and magnitude of the air voids.

Area fatigue cracking is heavily dependent on air voids and asphalt content of dense-graded mixtures, especially if that segregated area is near the bottom of the layer. As air voids increase and/or as asphalt content or asphalt film thickness decreases, the adhesion between the asphalt and aggregate decreases resulting in greater extents and a higher severity of cracking. The potential for fatigue cracking for the demonstration projects was defined by truck to truck segregation and/or stopping the paver and letting the AC mixture cool in localized areas without mixture segregation but still resulting in cold spots.

Figure 11. Longitudinal Cracks from Thermal Streaks during Construction.

Figure 12. Raveling of the Wearing Surface from a Cold Spot during Construction.

Raveling of Wearing Surface

The potential for raveling along a project with dense-graded wearing surfaces increases with an increase in air voids or reduction in density. Figure 12 shows raveling that has occurred in an area with a cold spot (probably from truck to truck segregation). The extent and severity of raveling depends on the extent of the segregation and magnitude of the air voids.

Raveling is difficult to estimate but is heavily dependent on air voids and asphalt content of dense-graded mixtures at the surface. As air voids increase and/or as asphalt content or asphalt film thickness decreases, the adhesion between the asphalt and aggregate decreases resulting in a higher severity of raveling. The potential for raveling in wearing surfaces for the demonstration projects was defined by truck to truck segregation resulting in cold spots.

PAVEMENT PERFORMANCE AND DATA SUMMARY FROM DEMONSTRATION PROJECTS

The impact of the severe temperature differentials on the expected performance were estimated based on the cause and extent of temperature differentials. The following sections are a summary of each demonstration project as related to a decrease in service life and/or increase in maintenance of the layers that were monitored with the IR thermal profiler. The projects are organized by layer type: wearing surface and the lower layers. The wearing surfaces are susceptible to raveling, while the lower layers are not. An explanation or definition of each parameter included in the summaries is listed below:

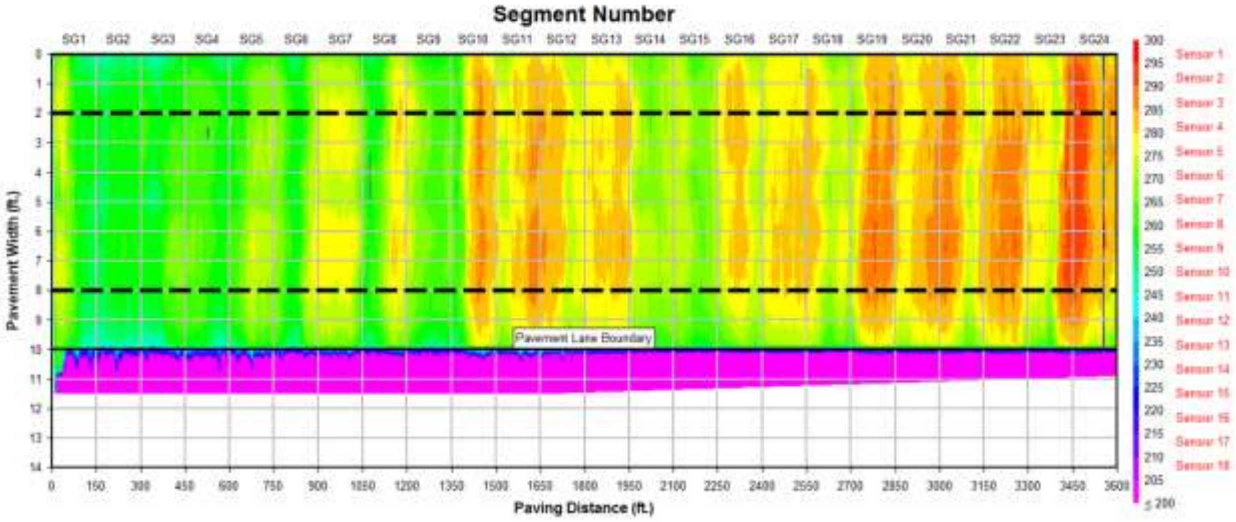
- Example temperature contours represents a typical temperature contour extracted from the IR data during paving.
- Percent of segments with different temperature differentials was taken directly from the field demonstration report summarizes and data collected along each project.
- Percent mat area within a specific temperature category is estimated based on the type of temperature differential and its magnitude and extent from the temperature contours for each project. This parameter was included to try and quantify the area of the mat susceptible to increased distress, if any.
- Cause of temperature differential is defined and estimated based on observations made by project personnel on site during construction.
- Average and standard deviation of density represents the density measurements made with the non-nuclear density gauge after compaction or final rolling. The densities summarized do not include the values measured by the agency for acceptance purposes.
- Average mat surface temperature represents the mean average segment temperatures and their variability measured by the IR thermal profiler.

Wearing Surfaces

The following presents a summary of the observations for all of the demonstration projects for which the IR thermal profiler was used to monitor and make decisions based on placement of wearing surfaces.

Alabama Demonstration Project

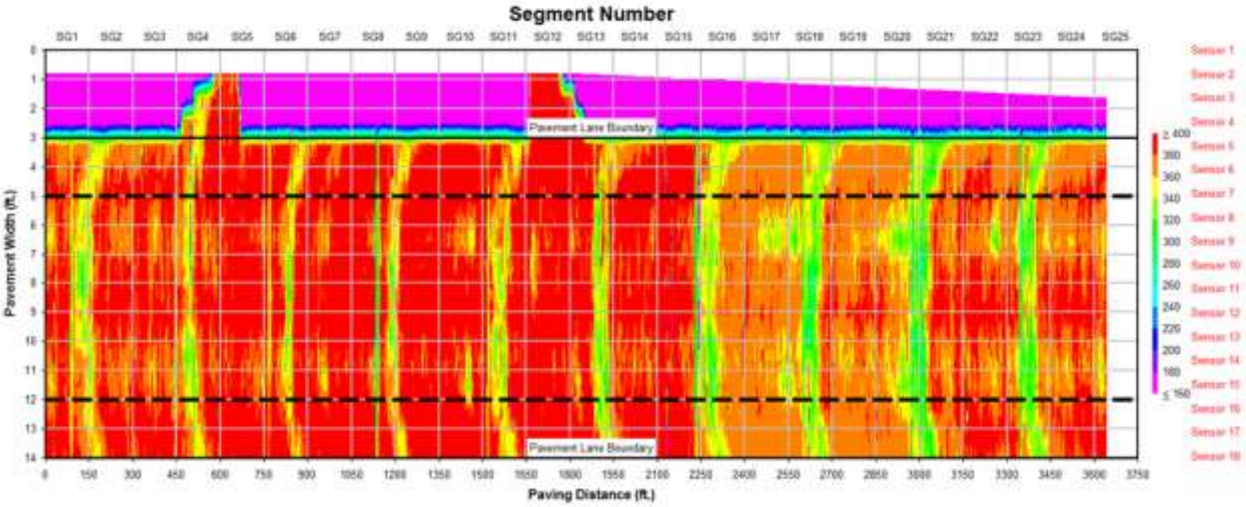
Temperature contour from one IR section of the Alabama demonstration project; end dump trucks and a MTV used to place the AC overlay (wearing surface).



Temperature Differential Category	Percent of IR Segments, including Paver Stops, %	Percent of Total Mat Area, %
Minor	73	84
Moderate	23	15
Severe	4	< 1
Cause of Severe Temperature Differentials	Most severe temperature differentials were in those areas where paver stopped and screed heater increased temperature of mat. As such, they are hot spots, rather than cold spots. Areas with moderate temperature differentials were a result of minor end of load segregation.	
Mat Properties	**Average**	**Standard Deviation**
Density	NA	NA
Surface Temperature	274	7.5
Distress	**Probable Effect of Temperature Differential on Performance or Specific Distress**	
Fatigue Cracking	None.	
Longitudinal Cracking	None.	
Raveling	None.	
IRI	Minor: slight increase in IRI confined to those areas where the paver stopped.	

Illinois Demonstration Project, Secondary Arterial Route IL 116

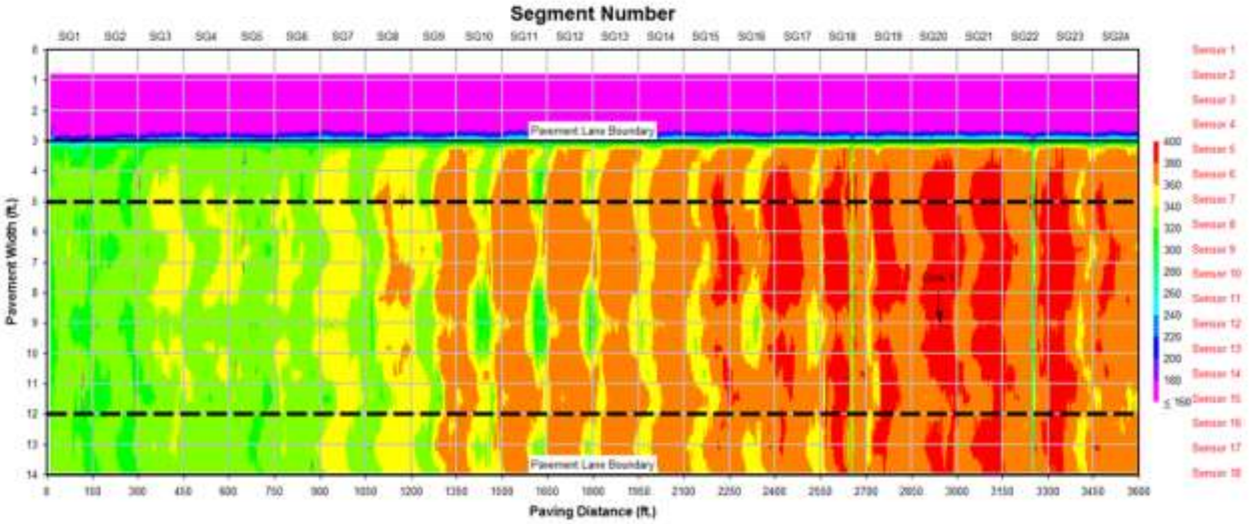
Temperature contour from one IR section of the Illinois demonstration project; end dump trucks used without an MTV to place the thin, fine-grained AC overlay (wearing surface) along Route IL 116.



Temperature Differential Category	Percent of IR Segments, including Paver Stops, %	Percent of Total Mat Area, %
Minor	8	30
Moderate	32	25
Severe	60	45
Cause of Severe Temperature Differentials	Most severe temperature differentials were in areas where the paver stopped and between the trucks. The AC wearing surface is a thin, fine-graded mixture. As such, the mixture is susceptible to accelerated cooling behind the screed. Mat temperatures were very high.	
Mat Properties	**Average**	**Standard Deviation**
Density	NA	NA
Surface Temperature	358	17.3
Distress	**Probable Effect of Temperature Differential on Performance or Specific Distress**	
Fatigue Cracking	Moderate; between truck loads.	
Longitudinal Cracking	None.	
Raveling	None.	
IRI	Minor: few paver stops; most of the severe temperature differentials were a result of the high mix temperatures and a thin, fine-grained overlay being susceptible to accelerated cooling.	

Illinois Demonstration Project, Interstate Route I-155

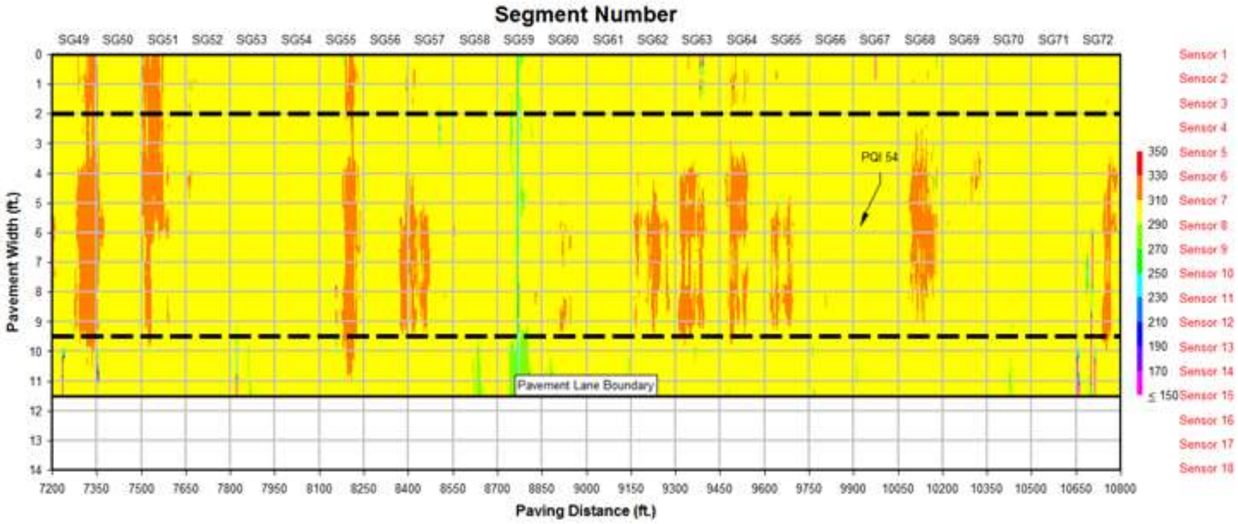
Temperature contour from one IR section of the Illinois demonstration project; end dump trucks used without an MTV to place the AC overlay (wearing surface) along Interstate 155.



Temperature Differential Category	**Percent of IR Segments, including Paver Stops, %**	**Percent of Total Mat Area, %**
Minor	13	40
Moderate	47	35
Severe	40	25
Cause of Severe Temperature Differentials	Most severe temperature differentials were in those areas where paver stopped and reflect the difference in mixture temperatures between trucks, rather than cold or hot spots. Mat temperatures were very high.	
Mat Properties	**Average**	**Standard Deviation**
Density	148	1.1
Surface Temperature	360	10.6
Distress	**Probable Effect of Temperature Differential on Performance or Specific Distress**	
Fatigue Cracking	Moderate; between truck loads.	
Longitudinal Cracking	None.	
Raveling	None.	
IRI	Moderate: increase in IRI because of temperature difference between truck loads and areas where the paver stopped.	

Maine Demonstration Project, Interstate Route I-95

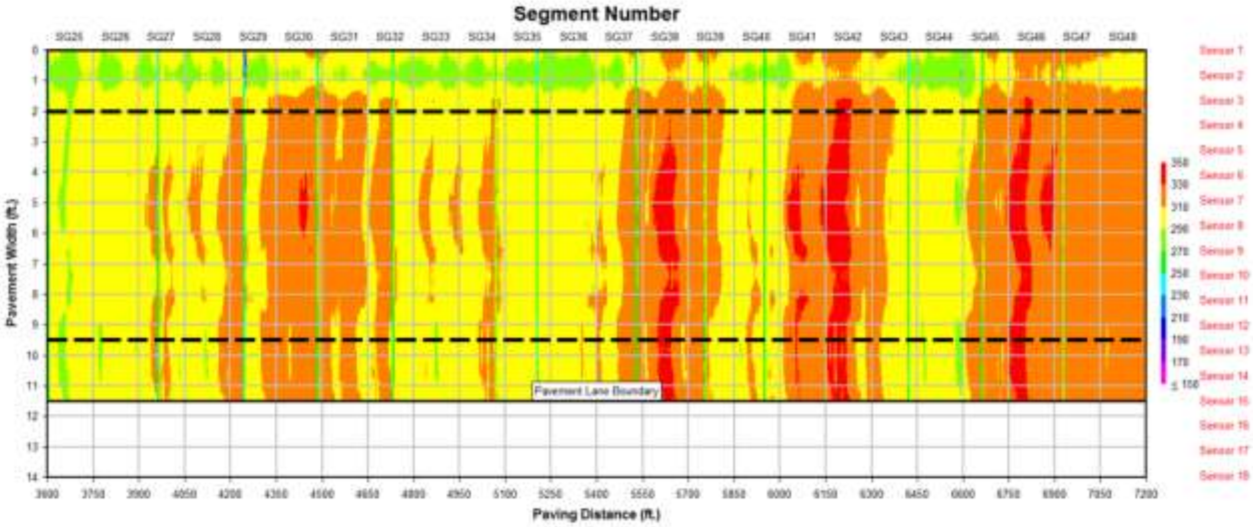
Temperature contour from one IR section of the Maine demonstration project; end dump trucks used with an MTV to place the AC overlay (wearing surface) along Interstate 95.



Temperature Differential Category	**Percent of IR Segments, including Paver Stops, %**	**Percent of Total Mat Area, %**
Minor	85	95
Moderate	10	4
Severe	5	1
Cause of Severe Temperature Differentials	Most severe temperature differentials were in those areas where paver stopped and/or temperature differences between truck loads.	
Mat Properties	**Average**	**Standard Deviation**
Density	146	2.4
Surface Temperature	276	6.7
Distress	**Probable Effect of Temperature Differential on Performance or Specific Distress**	
Fatigue Cracking	None.	
Longitudinal Cracking	None.	
Raveling	None.	
IRI	Minor or slight increase in IRI because of temperature difference between truck loads and areas where the paver stopped.	

Missouri Demonstration Project, Interstate Route I-29

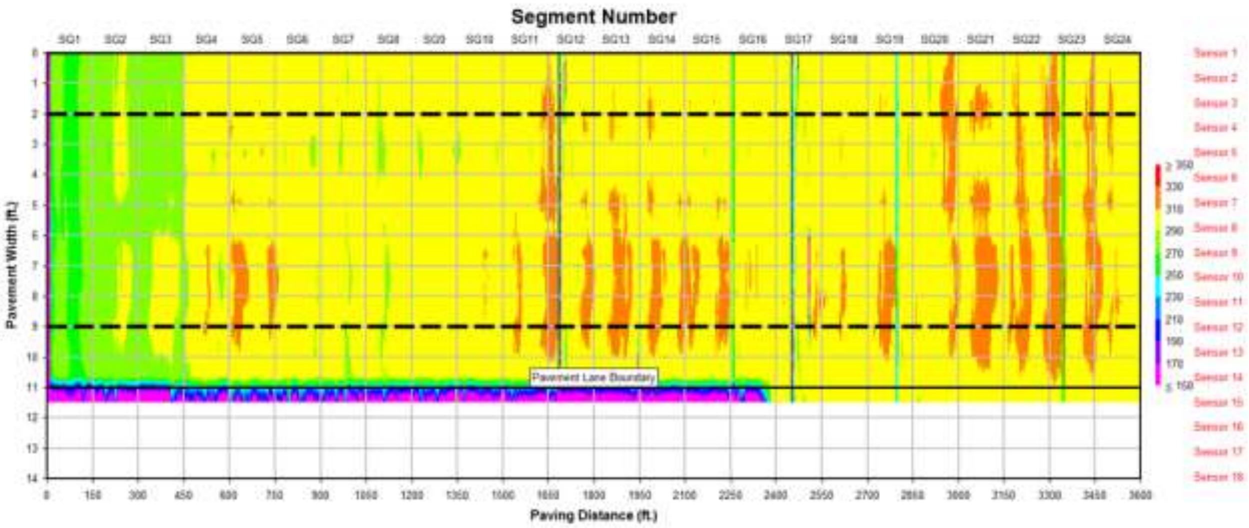
Temperature contour from one IR section of the Missouri demonstration project; end dump and flow boys or horizontal discharge trucks used with an MTV to place the AC overlay (wearing surface) along Interstate 29.



Temperature Differential Category	**Percent of IR Segments, including Paver Stops, %**	**Percent of Total Mat Area, %**
Minor	54	70
Moderate	21	15
Severe	25	15
Cause of Severe Temperature Differentials	Most severe temperature differentials were in those areas where paver stopped and/or temperature differences between truck loads, rather than cold spots.	
Mat Properties	**Average**	**Standard Deviation**
Density	146	2.3
Surface Temperature	306	17.4
Distress	**Probable Effect of Temperature Differential on Performance or Specific Distress**	
Fatigue Cracking	None.	
Longitudinal Cracking	None.	
Raveling	None.	
IRI	Moderate increase in IRI because of temperature difference where the paver stopped.	

New Jersey Demonstration Project, Interstate Route US-130

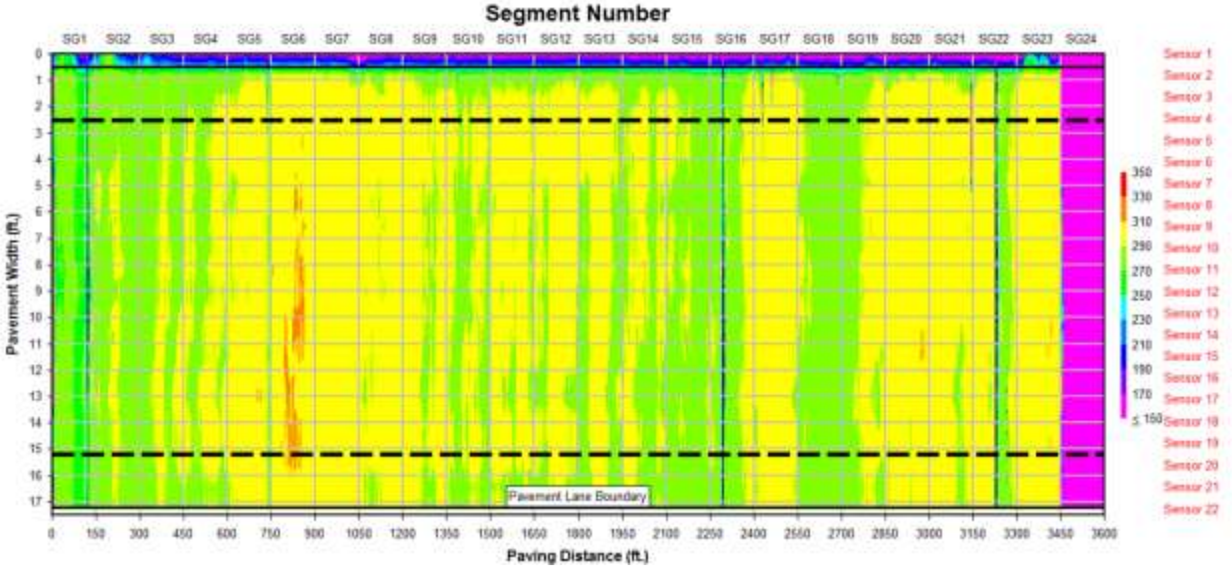
Temperature contour from one IR section of the New Jersey demonstration project; end dump trucks used with an MTV to place the AC overlay (wearing surface) along US 130.



Temperature Differential Category	**Percent of IR Segments, including Paver Stops, %**	**Percent of Total Mat Area, %**
Minor	62	80
Moderate	17	10
Severe	21	10
Cause of Severe Temperature Differentials	Most severe temperature differentials were in those areas where the paver stopped and the screed heater increased the temperature of mat, and/or mix temperature differences between truck loads. As such, some are hot spots, rather than cold spots.	
Mat Properties	**Average**	**Standard Deviation**
Density	156	1.8
Surface Temperature	294	9.1
Distress	**Probable Effect of Temperature Differential on Performance or Specific Distress**	
Fatigue Cracking	None.	
Longitudinal Cracking	None.	
Raveling	None.	
IRI	Minor increase in IRI because of temperature difference where the paver stopped and temperature differences between truck loads.	

North Carolina Demonstration Project, Interstate Route I-40

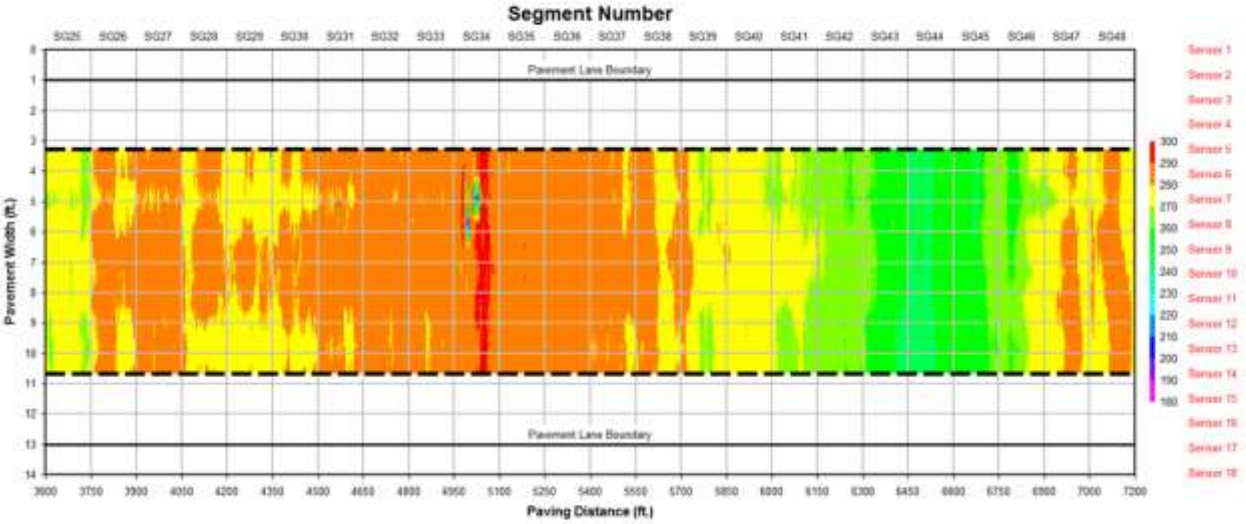
Temperature contour from one IR section of the North Carolina demonstration project; end dump trucks used with an MTV to place the AC wearing surface along Interstate 40.



Temperature Differential Category	**Percent of IR Segments, including Paver Stops, %**	**Percent of Total Mat Area, %**
Minor	63	85
Moderate	19	10
Severe	18	5
Cause of Severe Temperature Differentials	Most severe temperature differentials were in those areas where the paver stopped and the screed heater increased the temperature of mat, localized end of load segregation, and/or temperature differences between the trucks. As such, some are hot spots, rather than cold spots.	
Mat Properties	**Average**	**Standard Deviation**
Density	144	0.8
Surface Temperature	292	13.8
Distress	**Probable Effect of Temperature Differential on Performance or Specific Distress**	
Fatigue Cracking	Minor, because of random/localized end of load segregation.	
Longitudinal Cracking	None.	
Raveling	Minor, because of random/localized end of load segregation.	
IRI	Minor increase in IRI because of temperature difference where the paver stopped and temperature differences between truck loads.	

Virginia Demonstration Project, Interstate Route US-15

Temperature contour from one IR section of the Virginia demonstration project; end dump trucks used with an MTV to place the AC overlay (wearing surface) along US 15.



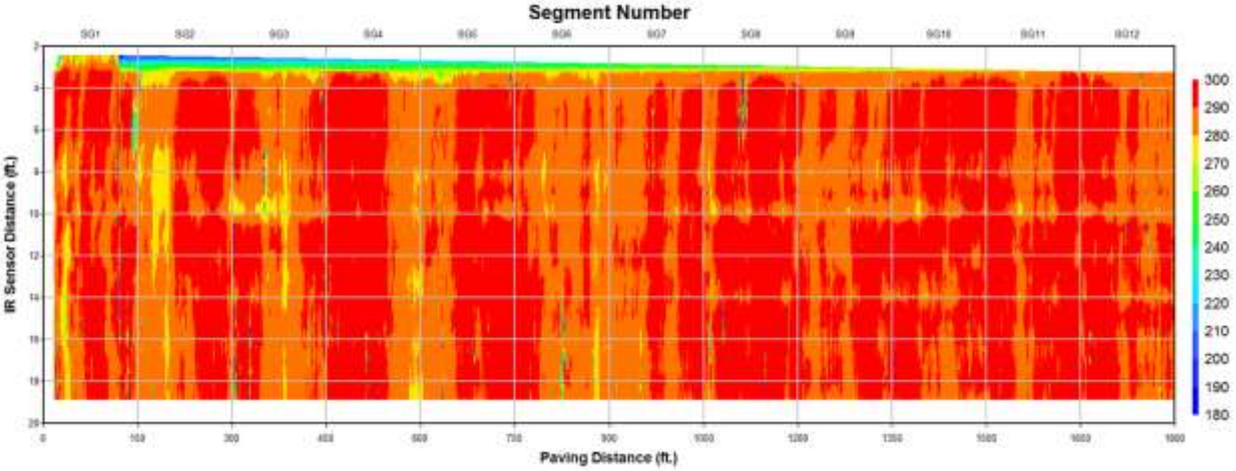
Temperature Differential Category	**Percent of IR Segments, including Paver Stops, %**	**Percent of Total Mat Area, %**
Minor	85	94
Moderate	11	5
Severe	5	1
Cause of Severe Temperature Differentials	Most severe temperature differentials were in those areas where the paver stopped and/or temperature differences between truck loads.	
Mat Properties	**Average**	**Standard Deviation**
Density	152	1.7
Surface Temperature	274	9.5
Distress	**Probable Effect of Temperature Differential on Performance or Specific Distress**	
Fatigue Cracking	None.	
Longitudinal Cracking	None.	
Raveling	None.	
IRI	Minor increase in IRI because of temperature difference where the paver stopped and temperature differences between truck loads.	

Lower AC Layers

The following presents a summary of the observations for all of the demonstration projects for which the IR thermal profiler was used to monitor and make decisions based on placement of AC layers below the wearing surface.

Alaska Demonstration Project, Anchorage Airport

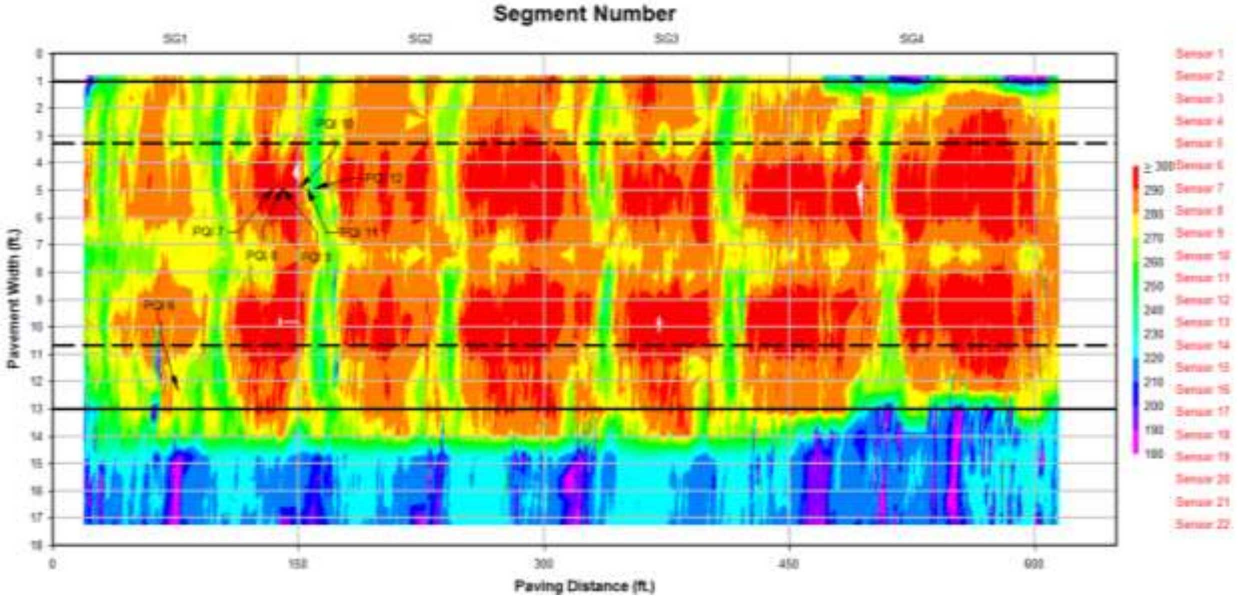
Temperature contour from one IR section of the Alaska demonstration project; belly dump trucks used to place the AC base and binder layers along the runway and taxiway reconstruction.



Temperature Differential Category	Percent of IR Segments, including Paver Stops, %	Percent of Total Mat Area, %
Minor	61	75
Moderate	22	15
Severe	17	10
Cause of Severe Temperature Differentials	Most severe temperature differentials were in those areas where the paver stopped and/or temperature differences between truck loads.	
Mat Properties	**Average**	**Standard Deviation**
Density	NA	NA
Surface Temperature	295	5.9
Distress	**Probable Effect of Temperature Differential on Performance or Specific Distress**	
Fatigue Cracking	Minor, because of temperature differences between truck loads.	
Longitudinal Cracking	None.	
Raveling	NA	
IRI	NA	

Eastern Federal Lands Demonstration Project, Route US 1

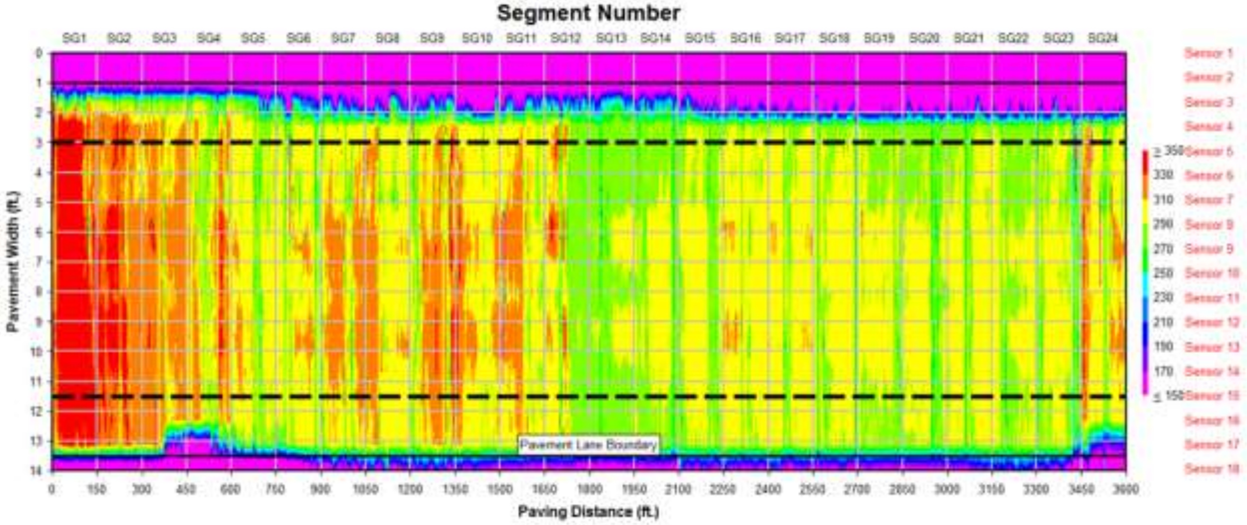
Temperature contour from one IR section of the Eastern Federal Lands demonstration project; end dump trucks used to place the AC base and binder layers along US 1 reconstruction.



Temperature Differential Category	**Percent of IR Segments, including Paver Stops, %**	**Percent of Total Mat Area, %**
Minor	2	20
Moderate	22	15
Severe	76	65
Cause of Severe Temperature Differentials	Most severe temperature differentials were in those areas where the paver stopped, end of truck segregation, and/or temperature differences between truck loads.	
Mat Properties	**Average**	**Standard Deviation**
Density	154	3.2
Surface Temperature	269	9.3
Distress	**Probable Effect of Temperature Differential on Performance or Specific Distress**	
Fatigue Cracking	High, because of end of load segregation.	
Longitudinal Cracking	None.	
Raveling	NA	
IRI	NA	

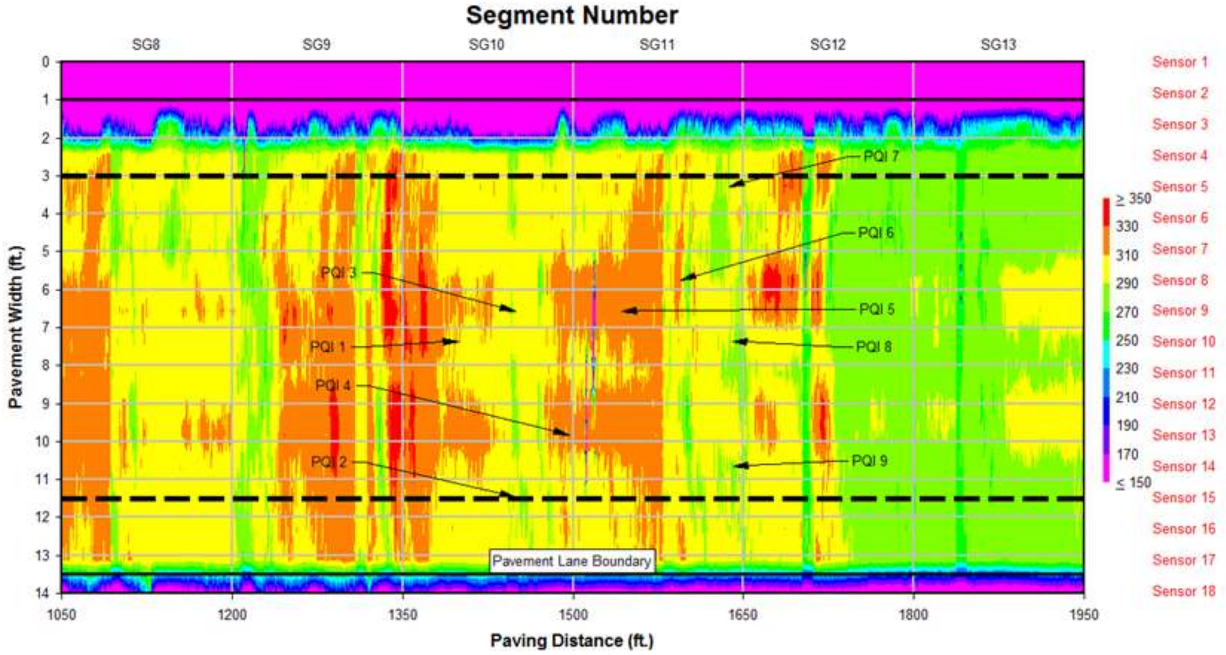
West Virginia Demonstration Project, Route US 1

Temperature contour from one IR section of the West Virginia demonstration project; end dump trucks without an MTV used to place the AC base layers along US 1 reconstruction.



Temperature Differential Category	**Percent of IR Segments, including Paver Stops, %**	**Percent of Total Mat Area, %**
Minor	0	25
Moderate	59	45
Severe	41	30
Cause of Severe Temperature Differentials	Most severe temperature differentials were in those areas where the paver stopped, end of load segregation, and/or temperature differences between truck loads.	
Mat Properties	**Average**	**Standard Deviation**
Density	146	1.1
Surface Temperature		
Distress	**Probable Effect of Temperature Differential on Performance or Specific Distress**	
Fatigue Cracking	Moderate, because of end of load segregation.	
Longitudinal Cracking	None.	
Raveling	NA	
IRI	NA	

Temperature contour from one IR section of the West Virginia demonstration project; end dump trucks with an MTV used to place the AC base layers along US 1 reconstruction.



Temperature Differential Category	**Percent of IR Segments, including Paver Stops, %**	**Percent of Total Mat Area, %**
Minor	65	80
Moderate	30	20
Severe	5	< 1
Cause of Severe Temperature Differentials	Most severe temperature differentials were in those areas where the paver stopped and/or temperature differences between truck loads.	
Mat Properties	**Average**	**Standard Deviation**
Density	146	1.1
Surface Temperature		
Distress	**Probable Effect of Temperature Differential on Performance or Specific Distress**	
Fatigue Cracking	None.	
Longitudinal Cracking	None.	
Raveling	NA	
IRI	NA	

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Reiter, Joseph, Harold L. Von Quintus, and Paul Dalbey, "Case Study: Infrared Thermal Profiler Deployment," Report Number XXX, Strategy Highway Research Program, Federal Highway Administration, U.S. Department of Transportation, Washington, DC, September 15, 2017.

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