DEPARTMENT OF TRANSPORTATION

Asphalt Real-Time Smoothness (ARTS) for Asphalt Paving

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The Transtec Group, Inc.

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16. Abstract (Limit: 250 words)

Real-Time Smoothness (RTS) measures pavement surface profiles during paving using sensors mounted on the back of a paver. The Federal Highway Administration (FHWA) has supported implementing RTS technology for concrete pavements through the SHRP2 Solutions program since 2014. Its study indicated that RTS technology's real-time diagnosis allows changing the paving operation to improve smoothness. This "proof-of-concept" research study aims to extend concrete RTS technologies to asphalt paving applications. The field demonstration results from two field projects show the feasibility of using asphalt Real-Time Smoothness (ARTS) to capture the roughness from various paving events. These results indicate some limitations of the ARTS prototype's measurements since the sensors were uncertified and mounted on a paver screed. The lessons learned from the demonstration projects are valuable for future ARTS technology and for further studies to improve asphalt pavement smoothness.

Asphalt Real-Time Smoothness (ARTS) for Asphalt Paving

Final Report

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EXECUTIVE SUMMARY

BACKGROUND

Real-Time Smoothness (RTS) is a technology used to measure pavement surface profile during paving using sensors typically mounted on the back of a paver. After an evaluation of RTS technology under the SHRP2 program from 2009 to 2011, the Federal Highway Administration (FHWA) supported the implementation of the technology for concrete pavements through the SHRP2 Solutions program and additional implementation efforts, which included field demonstrations, webinars, on-call support, and development of guidelines documents. The summary reports from these efforts indicate that RTS technology allows real-time (e.g., during paving) diagnosis of the impact of mix production and paving equipment settings and operations on the smoothness of the finished (hardened) concrete surface. This allows contractors to understand better changes that can be made to the paving operation to improve smoothness. The present study aims to extend current RTS technologies to asphalt paving.

METHODOLOGY

The technology resulting from this project was Asphalt Real-Time Smoothness (ARTS). The anticipated benefit of ARTS was identifying roughness sources from paver operation and roller compaction, allowing contractors to fine-tune adjustments to paver settings and rolling operations to improve smoothness. The characteristics of asphalt pavers, mainly the fluctuation of the screed, may limit the fine-tuning of smoothness to a procedural adaptation of the paving crew instead of a real-time adjustment. It was also recognized that other factors might influence smoothness, such as existing surface conditions. Current concrete RTS technology was re-designed to account for the differences between concrete and asphalt paving operations. The ARTS system was mounted to an articulating screed that encounters different dynamics than the rigid frame-mounted concrete paver RTS devices. Some factors considered for ARTS included adjusting the sensor mounting height on an asphalt paver to operate within the sensor's allowable temperature ranges and withstand airborne particulate, fumes, steam, smoke, dust, and vibration. Due to the project constraint, the ARTS prototype was uncertified under AASHTO 56 (AASHTO, 2018). It was assumed that the ARTS system had the same accuracy and performance as concrete RTS devices. Therefore, this project was a "proof-of-concept" study.

SUMMARY of RESEARCH RESULTS

An ARTS prototype was demonstrated at two field projects, one in 2021 and another in 2022. The goals of the demonstrations were successful, and the details were documented in the final report. Following is the summary.

Overall:

- The concept of ARTS can be realized in real-world paving jobs, as demonstrated in two field projects under this study.
- Demonstration project no. 1 was a local county paving job with a poor existing surface and challenging paving conditions such as vertical grade changes, cross slopes, intersections, and driveways. The ARTS and high-speed inertial profilers (HSIP) data reflected this project's high level of roughness, and the ARTS predicted, during paving, the roughness anticipated from the finished pavement surface.
- Demonstration project no. 2 was a typical highway mainline construction with Material Transfer Vehicle (MTV) on relatively flat terrain. The ARTS and HSIP data reflected the high smoothness of this project.

ARTS Sensors

- It should be stressed that the comments are limited to the selected ARTS prototype under this study and do not apply to other ARTS designs and solutions.
- The installation of the ARTS prototype on a paver required a specially designed bracket for a given screed model. The installation process was straightforward, so long as the paver or a power generator could provide the ARTS power supply.
- The ARTS cooling system prototype functioned well, as the temperatures around the sensors were kept under 120° F by a cooling system.
- The ARTS prototype required a distance measurement instrument (DMI) wheel that used a solid tire. The slight indent that the DMI wheel made on the fresh asphalt was eliminated after breakdown roller compaction.
- Due to mounting the ARTS sensors onto a screed, any large screed movements could invalidate the ARTS data. Such situations include screed movements at the beginning of paving and the transverse joint matching at the end of paving.
- Since the ARTS prototype was not certified under AASHTO R 56, the analysis results of the ARTS data can be considered relative values.

Paving Operation and ARTS Sensor Data

- The ARTS real-time data display reflected the changes in paver operations such as paver stops, slope control, grade control, spilled asphalt from the paver's hopper, asphalt trucker exchanges, vertical curves, cross slopes, etc. The effects were more pronounced when MTV was not used.
- However, some technical panel members had questions about the reliability of the high roughness from ARTS during demonstration project 2. Further investigation of the ARTS hardware and software changes between demonstrations 1 and 2 is thus warranted.

ARTS Data vs. HSIP Data

- The HSIP data are consistently smoother than the ARTS data. However, the roughness difference is much more significant for demonstration project 2 (surface layer placement on a highway paving job) than for demonstration project 1 (intermediate layer placement on a low-volume road).
- There is long wavelength content present in the ARTS data that is not present in the HSIP data.

RECOMMENDATIONS FOR FURTHER STUDY

The research team proposes the following recommendations for future ARTS development and implementation.

- An ARTS system can help identify paver equipment issues, settings, or operational practices in real-time during paving.
- An improved ARTS system would be less intrusive to paving operations with improved mounting designs to avoid paver operation inconvenience.
- Further field demonstrations should include various approaches for ARTS to encourage innovative solutions, especially to exclude the effects of screed movements.
- In addition to the report of AASHTO R54 IRI moving average as localized roughness, additional deviation reports (e.g., rolling straightedge simulation) are recommended to be included since some DOTs still use such requirements in their smoothness specification.
- Future field demonstrations should consider additional measurements, including the tow-point movements and screed/ARTS acceleration or movements, which could provide further insights into the benefits of ARTS.

- Future test plans should include focused analysis in areas where typical events such as truck exchange resulting in low mix levels in the hopper or hopper insert, turning with tow arm bearing against the mainframe, screed extending/retracting, head of the material fluctuation, varying paving speeds, screed movements, etc. These events could be manually induced, and the ARTS results could be documented and compared with results from controls or standard proper paving practices.
- Further observations should also be made before and after the changes of paver setting, such as re-positioning the sonic feed sensors and conveyor settings, tow to "hang up" on the frame, etc., to provide helpful information on the paver settings and operations effects on smoothness.
- Compare ARTS and HSIP data on the same surface for a relative baseline of error. Also, evaluate the wavelength range captured by ARTS systems.

RESEARCH STRATEGIC PRIORITIES AND BENEFITS

MnDOT Strategic Priorities

☒ Innovation and Future Needs

ARTS is an innovation to improve paving smoothness quality using modern sensor technologies. It has been a proven technology for concrete pavements for more than a decade, and this research demonstrates the extension of that technology to asphalt paving operations.

Benefits Description

Within certain limitations, ARTS's benefits include identifying the causes of roughness from the paver operations.

The ARTS measurements would help identify adjustments in the asphalt paving operation to improve pavement smoothness.

Expected Benefits

☒ Construction Savings: Corrective action (grinding, removal and replacement, etc.) is reduced for the finished surface to achieve specification requirements.

☒ Lifecycle: Improvement in as-constructed smoothness for longer pavement life. Smoother pavements tend to stay smoother longer and last longer.

☒ Operations and Maintenance Savings: Smoother pavements tend to last longer, requiring less maintenance and corrective action to improve smoothness.

☒ Technology: Real-time smoothness measurement technology using state-of-the-art pavement profiling sensors and real-time data analysis.

With further developments, ARTS can document roughness events during paving that can be fine-tuned to improve paving production consistency and smoothness. Therefore, ARTS will help improve as-constructed pavement smoothness to save construction costs, reduce lifecycle costs, save operation/maintenance costs, and improve paving technology.

RECOMMENDED IMPLEMENTATION STEPS

The potential implementation steps of ARTS include the following:

1. Further Study: Conduct further studies recommended above.
2. Outreach: Present ARTS findings and benefits to agencies and the industry through the NRRA Research Pay-Off webinar.
3. ARTS Rodeo: Conduct ARTS equipment round-ups to encourage innovation and improvements of ARTS solutions from multiple vendors if funding is available.
4. Integration with Other Intelligent Construction Technologies: To leverage ARTS' benefits by integration with other intelligent construction technologies, including paver-mounted thermal profiling (PMTP), intelligent compaction (IC), dielectric profile systems (DPS), etc., pending available research projects.
5. ARTS Knowledge-Based System: To consolidate ARTS technology information, benefits data, lessons learned, and successful practices into a knowledge-based system pending available research projects.

CHAPTER 1: INTRODUCTION

1.1 Background

Real-Time Smoothness (RTS) is a technology used to measure pavement surface profile during paving using sensors typically mounted on the back of a paver. After an evaluation of RTS technology under the SHRP2 program from 2009 to 2011, the Federal Highway Administration (FHWA) supported the implementation of the technology for concrete pavements through the SHRP2 Solutions program and additional implementation efforts, which included field demonstrations, webinars, on-call support, and development of guideline documents. The summary reports from these efforts indicates that RTS technology allows real-time (e.g., during paving) diagnosis of the impact of mix production and paving equipment settings and operations on the smoothness of the finished (hardened) concrete surface. This allows contractors to understand better changes that can be made to the paving operation to improve smoothness. The present study aims to extend current RTS technologies to asphalt paving.

1.2 Methodology

The technology resulting from this project is Asphalt Real-Time Smoothness (ARTS). The anticipated benefit of ARTS is identifying roughness sources from paver operation and roller compaction, allowing contractors to fine-tune adjustments to paver settings and rolling operations to improve smoothness. It is also recognized that other factors may influence smoothness, such as existing surface conditions. Current concrete RTS technology is re-designed to account for the differences between concrete and asphalt paving operations. Some factors considered for ARTS include adjusting the sensor mounting height on an asphalt paver to operate within the sensor's allowable temperature ranges and withstand airborne particulate, fumes, steam, smoke, dust, and vibration.

Due to the project constraint, the ARTS prototype was uncertified under AASHTO 56 (AASHTO, 2018). Therefore, this project was a "proof-of-concept" study. At some point before ARTS field demonstration one, members of the research group were made aware of the existence of a commercially available ARTS device by another vendor (Vendor B). The ARTS research group regrets that it could not accommodate the participation of Vendor B's device in this research due to budget and scope constraints.

1.3 REPORT STRUCTURE

This report includes the following chapters:

- Chapter 1 – Introduction
- Chapter 2 – ARTS Sensors
- Chapter 3 – Demonstration No. 1
- Chapter 4 – Demonstration No. 2
- Chapter 5 – Discussions

CHAPTER 2: ARTS SENSORS

2.1 ARTS SENSOR DESIGN

Vendor A designed two ARTS sensors and mounting elements for this study. Each ARTS sensor consists of three laser sensors used to produce a profile trace. Additional components of the system include the power supplies, data acquisition housing, cooling fans, chimneys, the distance measuring instrument (DMI) wheel, and a laptop computer. The sensor mounting design includes a steel frame assembly that fits into the paver screed's receiving brackets (Figure 1). The position of a paver's mounting bracket is specific to the paver brand and model, and Vendor A's mounting bracket was designed to be adjustable to fit varying screed widths and mounting heights. Figure 2 shows an example of the ARTS sensor mounting frame (in orange) and the paver's connection brackets (in blue). The intent is to use two ARTS sensors, one for the measurement along the left wheel path (LWP) and another for the right wheel path (RWP). Profile trace generation methodology uses the sensor heights to compute slopes between sensors, then produce the relative elevation profiles, similar to walking profilers.

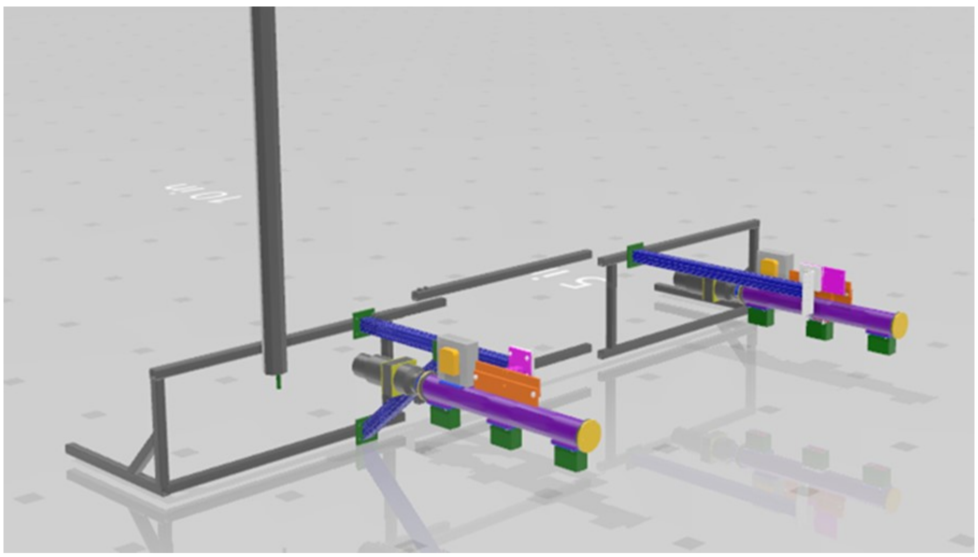


Figure 1. The design for the mounting brackets of two ARTS Sensors by Vendor A.

Figure 2. An example of the ARTS Sensors assembly (orange) and a paver screed connection brackets (blue).

2.2 ARTS SENSOR PROTOTYPE

Vendor A performed initial tests on the ARTS sensor prototypes by mounting two ARTS sensors onto a small utility vehicle (Figure 3).

Figure 3. Vendor A initial ARTS prototype tests with sensors mounted on a small utility vehicle.

The final mounting to the paver screed requires a short section of square steel tubing welded to the screed to receive the L-shaped mounting brackets. Figure 4 shows an ARTS sensor assembly connected to the paver's receiving bracket on the left side, similar to the sensor mounted on the right side of the paver.

A vital feature of the prototype, unique to ARTS sensors (vs. concrete RTS sensors), is a cooling fan and chimney used to keep the laser sensors cool when paving over a hot mat. The fan draws cooler air several feet above the surface through the chimney (corrugated black tubing shown in Figure 4), which passes over the laser sensor housing to keep it cooler.

Figure 4. ARTS sensor assembly by Vendor A connected to the receiving bracket on the left side of a paver screed.

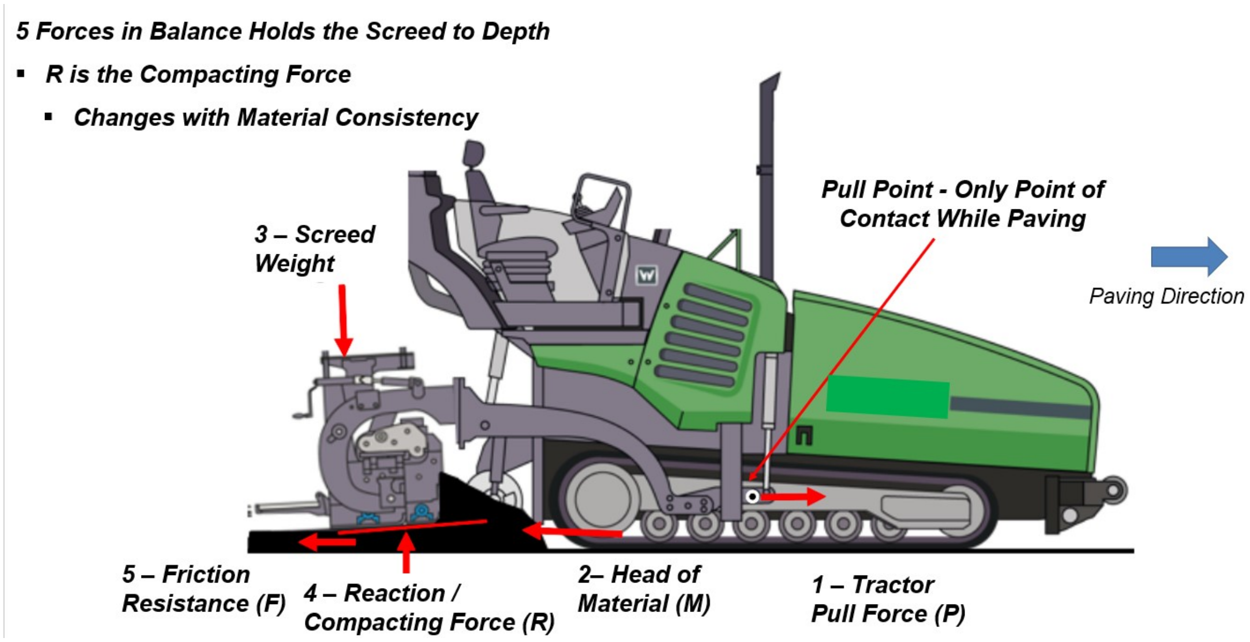
2.3 KNOWN ARTS SENSOR ISSUES

Based on the discussion between the research team and TAP, the Vendor's ARTS prototype had the following limitations:

- Since the ARTS prototype is for a feasibility study, it is not officially certified under AASHTO R 56 or ASTM E950.
- The ARTS prototype may move vertically with paver screed movements during the changes in paving depths.
- The ARTS prototype may tilt vertically with a paver screed changes in the angle of attack or joint matching during the paving.

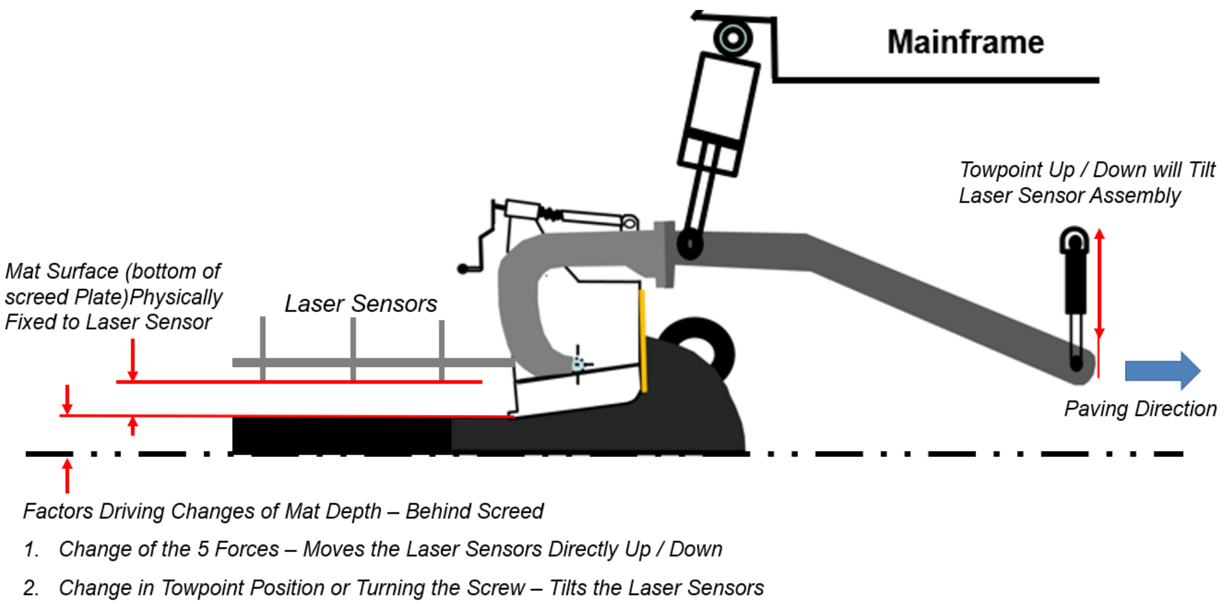
A paver screed is positioned by the balance of five types of forces during paving, including tractor pull force (P), weight/head of material (M), reaction/compaction force (R), and frictional resistance (F).

(Figure 5). The factors that cause changes in the mat depth behind the screed include changes in the five forces (moves the ARTS sensors up or down vertically) and tow point position or turning the depth screw (tilts the ARTS sensors). (Figure 6) (Narsingh, 2022) The blue arrows indicate the paving direction.



Source: (Narsingh, 2022A)

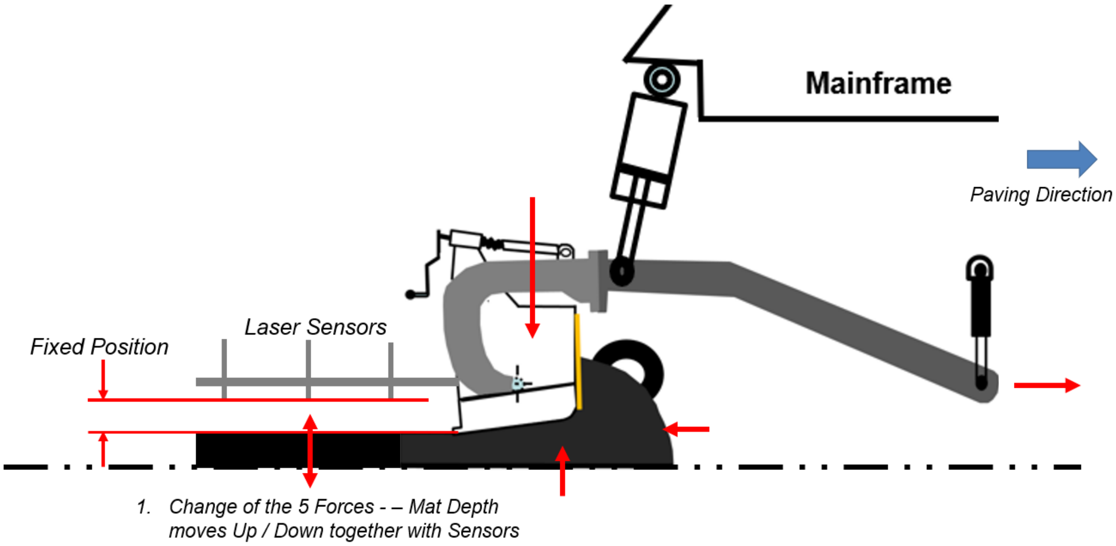
Figure 5. The five forces in balance hold the screed in a position.



Source: (Narsingh, 2022B)

Figure 6. The factors that caused changes in the mat depth behind the screed.

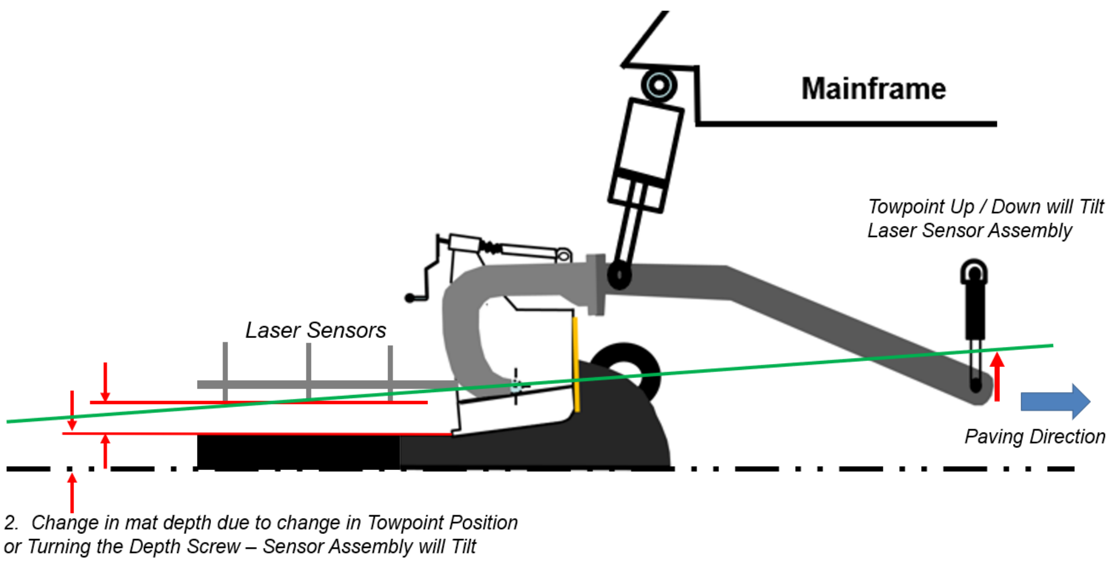
Change in mat depth due to changes in the five forces will cause a direct up or down movement of the sensors (Figure 7). Since the ARTS sensors are rigidly mounted to the screed plate, the relative distance between the bottom of the sensor and the mat should remain the same.



Source: (Narsingh, 2022B)

Figure 7. The factors that move the ARTS sensors up or down.

A change in mat depth due to a change in the tow point position or changing the depth screw will cause the ARTS sensor to tilt relative to the horizontal mat surface. (Figure 8).



Source: (Narsingh, 2022B)

Figure 8. The factors that tilt the ARTS sensors.

Based on the understanding between the research team and TAP, the research team observed the above limitations during the data analysis and interpretation in this feasibility study.

CHAPTER 3: DEMONSTRATION NO. 1

3.1 OVERVIEW

The ARTS prototype was tested at the first demonstration project (Demo No.1) in Iowa from August 25 to 26, 2021. The goal was to test the sensor installation procedure, sensors operation, data collection, and analyze the data along with highspeed inertial profiler data and field observations.

3.2 FIELD PROJECT INFORMATION

Demo Project 1 was a Hot Mix Asphalt (HMA) resurfacing project. The project location terrain is relatively hilly with several curves. The existing bituminous surface was failing. This project did not include a smoothness requirement for acceptance. Both days of testing were performed on the base course with a nominal 2” thickness and paving widths varying between 12’ and 14’.

3.3 ASPHALT PAVING EQUIPMENT

The asphalt plant was located in the same county as the project site. The total daily tonnages were 2,632 and 1,551 for August 25 and 26, respectively. There were 16 trucks used for material delivery, with approximately 16 tons per truck. Material delivery used the end dump method directly into the paver hopper. No material transfer vehicles were used. The paver was a Caterpillar AP1000F with a Weiler SE10F screed and Willow Designs notched-wedge joint device. A contact ski automatic grade control device was used with the roadway centerline as the reference point. Automatic slope control was used to ensure the cross-slope, which controlled mat thickness along the shoulder. Three rollers were used for compaction. The breakdown roller was a Sakai SW880 double drum roller, the intermediate roller was a HAMM double drum roller, and the finishing roller was a HAMM HD+ 120i double drum roller. The breakdown and intermediate rollers operated at high frequency and low amplitude with 5 to 7 pass coverage.

3.4 ARTS SENSOR INSTALLATION EQUIPMENT

The ARTS system receiving brackets, designed explicitly for Caterpillar AP1000F pavers, were manufactured the week before the demo. The ARTS sensors were connected to the paver via the fabricated L-shape brackets.

The ARTS sensor assembly was connected the night before Demo No. 1. The left sensor was positioned approximately 6 ft from the right-side sensor (corresponding to wheelpath spacing) and approximately 4 ft behind the screed. The right-side sensor was positioned approximately 3.5 ft off the edge of the pavement (centerline) and 4 ft behind the screed. One of the ARTS sensors did not function due to a malfunctioning laser. The functioning ARTS sensor was installed on the paver’s right side on Day 1 (near the centerline) and the left side on Day 2 (near the shoulder).

The ARTS frame mounting and cabling were quick and straightforward. All equipment was mounted aft the screed catwalk, and cabling was run overhead to minimize interference for the paving crew. (Figure 9) The ARTS sensor mounting and connections before paving each day were also quick. Minor adjustment to the sensor mounting was required on Day 1 to ensure the sensors were within the operating working vertical measurement distance range (4”). The ARTS prototype's Acuity sensors were customized for high standoff height (13") and high resolution (.00023") within a 4" working range.

Figure 9. Demo No. 1 - ARTS sensor set up and operation.

The DMI was mounted behind the screed, roughly 1 ft from the right-side ARTS sensor. The DMI was equipped with a scraper to prevent the build-up of asphalt on the DMI’s wheel. (Figure 10) The paver operator would occasionally spray release agents on the wheel. A GPS receiver (not shown) was mounted near the paver operator’s station, approximately 17 ft ahead of ARTS sensors.

Figure 10. Demo No. 1 - ARTS Distance Measurement Instrument (DMI).

3.5 PAVING OPERATION AND ARTS DATA COLLECTION

3.5.1 Paving Operation

The paving operation for Day 1 (August 25, 2021) is summarized in Table 1.

Table 1. Paving operation for Day 1 (August 25, 2021)

Items	Descriptions
Weather	cloudy with occasional sunshine
Ambient temperature (low/high):	67/89 °F
Paved width	12 to 14 ft
Paving direction	southbound
Paving start	08:05 AM
Paving Ends	6:52 PM
Start Station	544+35
Stop Station	434+10
Length (ft)	11,025
Asphalt tonnage (tons)	2,632
ARTS Sensors	The functioning sensor was installed on the right side of the paver (i.e., near the left wheel path of the traffic direction)

The paving operation for Day 2 (August 26, 2021) is summarized in Table 2.

Table 2. Paving operation for Day 2 (August 26, 2021)

Items	Descriptions
Weather	Cloudy. Rained out at 1 PM.
Ambient temperature (low/high):	61/83 F °F
Paved width	12 to 14 ft
Paving direction	Southbound (in decreasing stationing numbers)
Paving start	07:30 AM
Paving Ends	1:09 PM (due to rain)
Start Station	434+10
Stop Station	368+00
Length (ft)	6,610
Asphalt tonnage (tons)	1,551
ARTS Sensors	The functioning sensor was on the left side of the paver (i.e., near the right wheel path of the traffic direction)

Paving conditions were challenging, with some areas consisting of steep vertical curves. The existing pavement surface was in poor condition, with significant potholes along the centerline and the shoulders. The old asphalt surface along the lane edge and shoulders over much of the project was missing, leaving new pavement on granular subbase material.

Widening of the existing surface resulted in significant mat thickness (up to 2’) at the shoulder edge over many areas. Pavement thickness was set at the design thickness at the roadway centerline and varied (to achieve design cross slope) at the shoulder edge. Thickness at the shoulder edge was highly variable, occasionally as thin as 0.5” and as great as 12”. Due to the high variability of mat thickness at the outside (shoulder) edge, material delivery spacing varied widely from approximately 35 ft to 75 ft per load and unpredictable yield calculation.

3.5.2 ARTS Data Collection Observations

The ARTS system operation is straightforward once the sensors and accessories are connected to the paver. Data collection is controlled on a Panasonic© Toughbook computer using Vendor A's data collection software. The computer was mounted to a stand attached to the RTS mounting frame, extending out in the shoulder for easier access. The ARTS computer monitor allows real-time analysis and visual display of results. Displays include tabs to select the profile trace, localized roughness (IRI) plot, Power Spectral Density (PSD) plot, Histogram, Defect Report, and Fixed Interval report. (Figure 11)

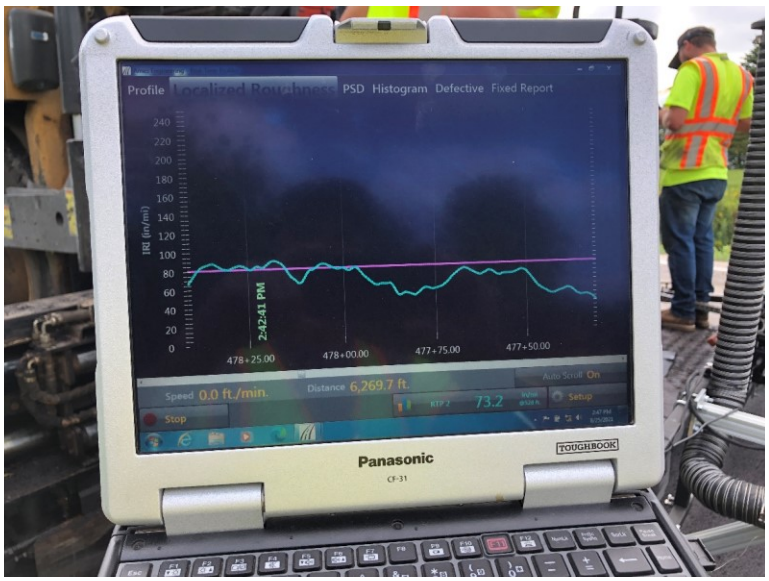


Figure 11. Demo No. 1 - ARTS displays real-time localized roughness (IRI) plots.

Sensor Movement: The ARTS support bracket was mounted to a receiving tube welded to the screed, creating stable support. The ARTS sensor moved slightly with any jolting movement of the screed (e.g., truck bumping the paver, dumping the wings, etc.). The paving crew occasionally stepped on the frame, but it did not cause any movement of the sensors. The ARTS frame and sensors generally jiggled every time the paver was bumped by a dump truck or when the hopper wings were dumped. This typically happened during paver stops to fill the paver hopper and therefore did not necessarily appear in profile data. Running the screed vibrators did not affect the ARTS smoothness readings as localized roughness.

DMI: The ARTS DMI wheel accumulated asphalt material but generally stayed clean when the paving crew regularly applied a release agent to the tire. The DMI left a track in the uncompacted pavement but was removed by the breakdown roller.

Temperatures: Under worst-case conditions, the ARTS sensor temperatures never exceeded roughly 110°F (with 120°F being the limit when the sensors may time out). The temperature difference between cloudy and sunny was about 5°F. Vendor A noted that changing the air intake chimney's color to white could further reduce incoming air temperatures. A sample of temperatures measured during the operation (using thermal imaging) was 158°F, 153°F, 148°F, and 247°F on the inside sensor housing, the middle sensor housing, the inside sensor housing, and the asphalt mat, respectively (Sp1, Sp2, Sp3, and Sp4 in Figure 12). The temperature on top of the ARTS sensor data acquisition housing drops to 93°F during operation (Figure 13).

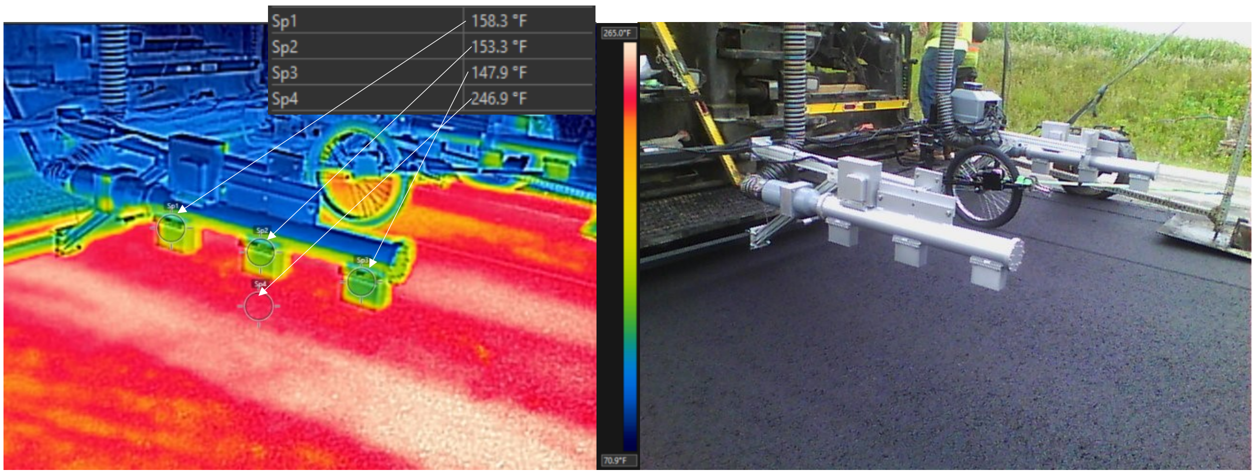


Figure 12. Demo No. 1 - Temperatures on the ARTS sensor housings and asphalt mat.

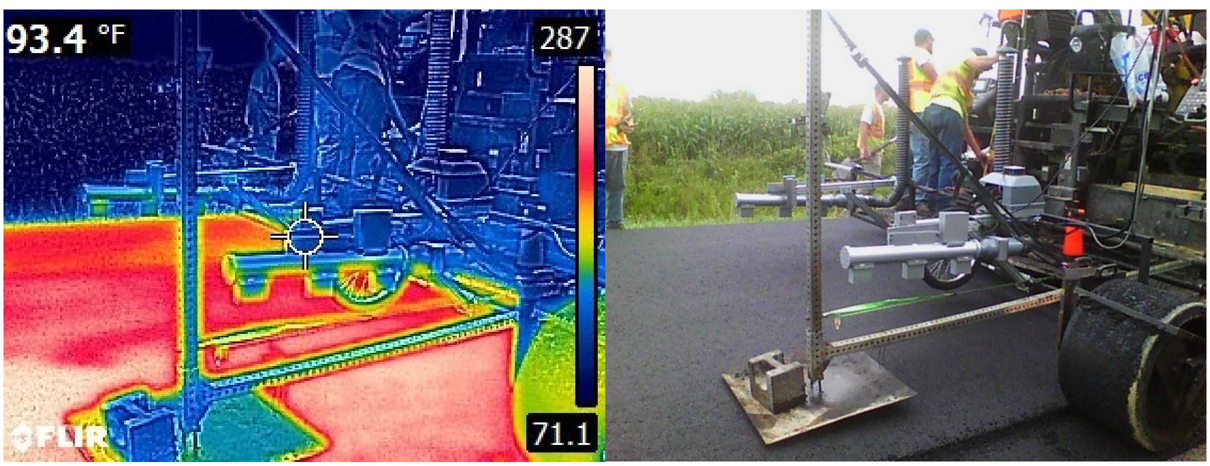


Figure 13. Demo No. 1 - Temperatures on top of the ARTS Sensor.

3.6 HSIP MEASUREMENT OPERATION

Vendor A's HSIP was used for final surface profiling each day. (Figure 14) HSIP data were collected in the opposite direction of paving (i.e., in the direction of traffic due to safety concerns). On Day 2, there were still areas with surface moisture from rain and roller water when HSIP data were collected.

Figure 14. Demo No. 1 - Vendor A's highspeed inertial profiler.

3.7 DATA ANALYSIS

3.7.1 Data Management

Paving was on the northbound (NB) lane, but the actual paving direction was southbound (against the traffic direction), and the stationing increased in the NB direction. Therefore, the LWP of the NB lane was close to the centerline on the side of the paver using automatic grade control, and the RWP on the paver side (shoulder side) using automatic slope control.

The working ARTS sensor was set up to collect data as follows: Day 1 measurement in LWP (in the traffic direction) and Day 2 measurement in RWP (in the traffic direction). HSIP data were collected in both the LWP and RWP in the direction of traffic. The profile length for Day 1 was 10,578 ft, and the profile length for Day 2 was 6,184 ft.

3.7.2 ARTS and HSIP Profiles

3.7.2.1 Day 1

The Day 1 ARTS and HSIP profiles for the LWP are shown in Figure 15, with a zoomed-in (0.1-mile section) shown in Figure 16. The overall profile trends (longer wavelength content) are very similar, but the HISP profile appears to pick up shorter wavelength content than the ARTS system.

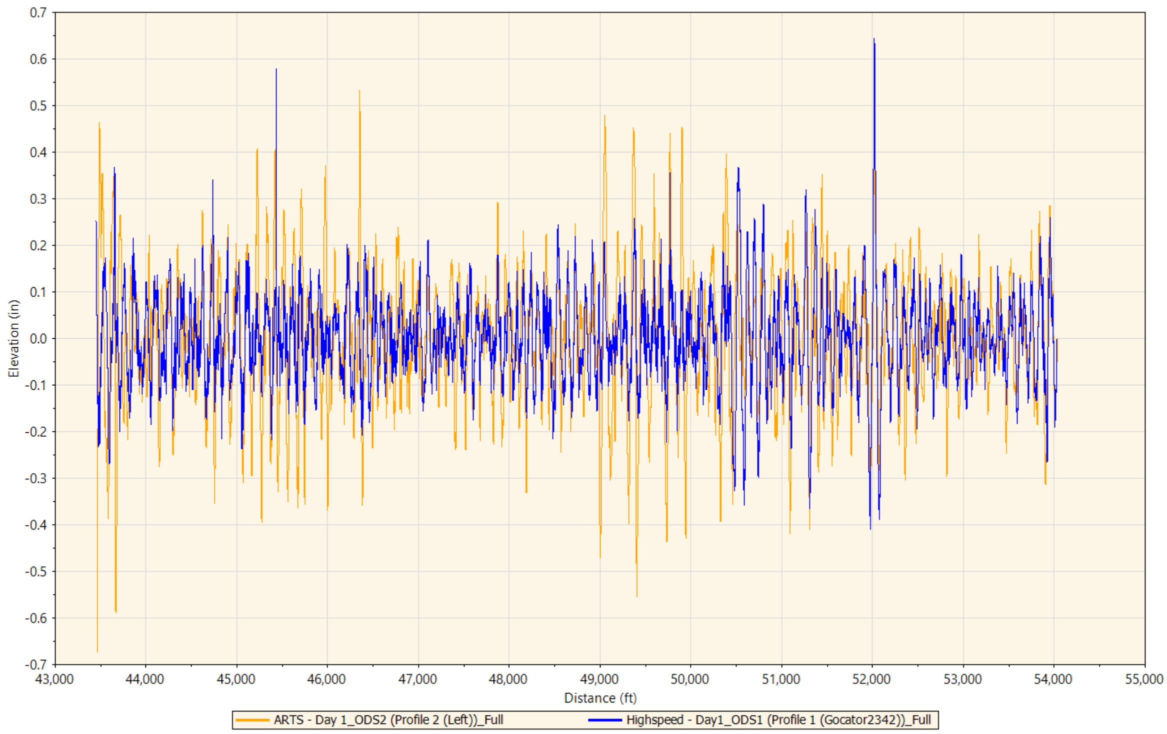


Figure 15. Demo No. 1 – Day 1 ARTS and HSIP profiles (LWP).

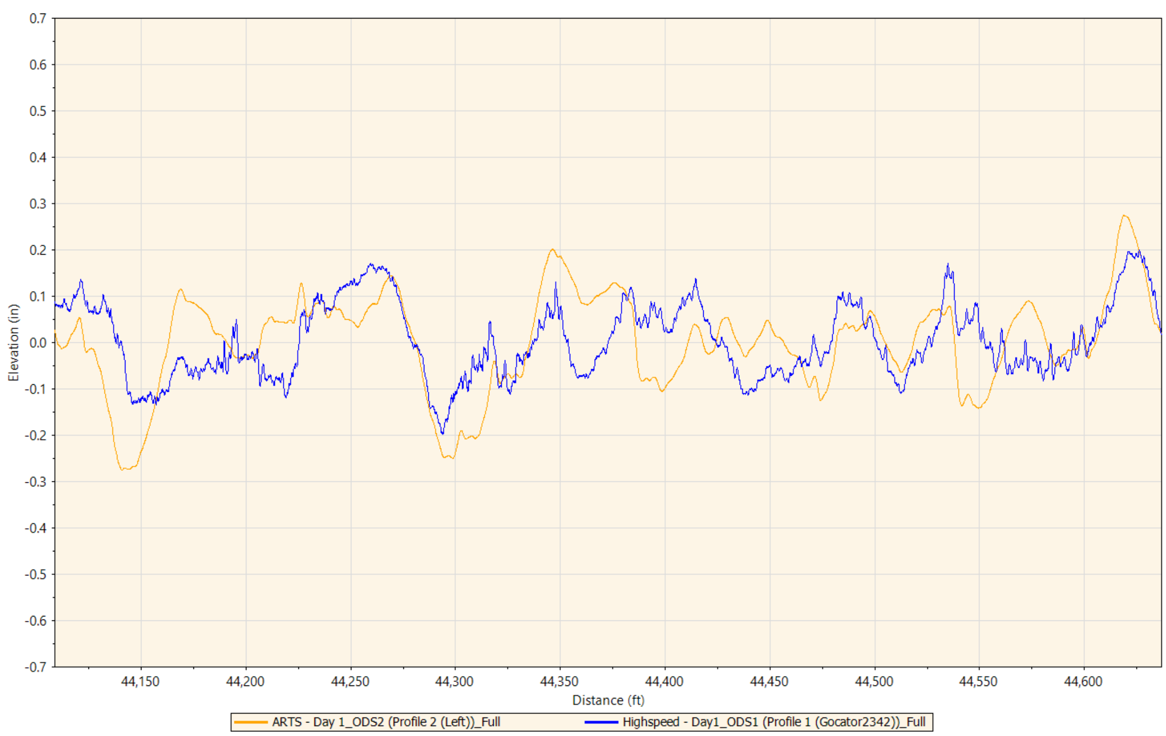


Figure 16. Demo No. 1 – 0.1-mile section of Day 1 ARTS and HSIP profiles (LWP).

3.7.2.2 Day 2

The Day 2 ARTS and HSIP profiles for the RWP are shown in Figure 17, with a zoomed-in (0.1-mile section) shown in Figure 18. Similar to Day 1 data, the overall profile trends (longer wavelength content) are very similar, but the HISP profile appears to pick up shorter wavelength content than the ARTS system.

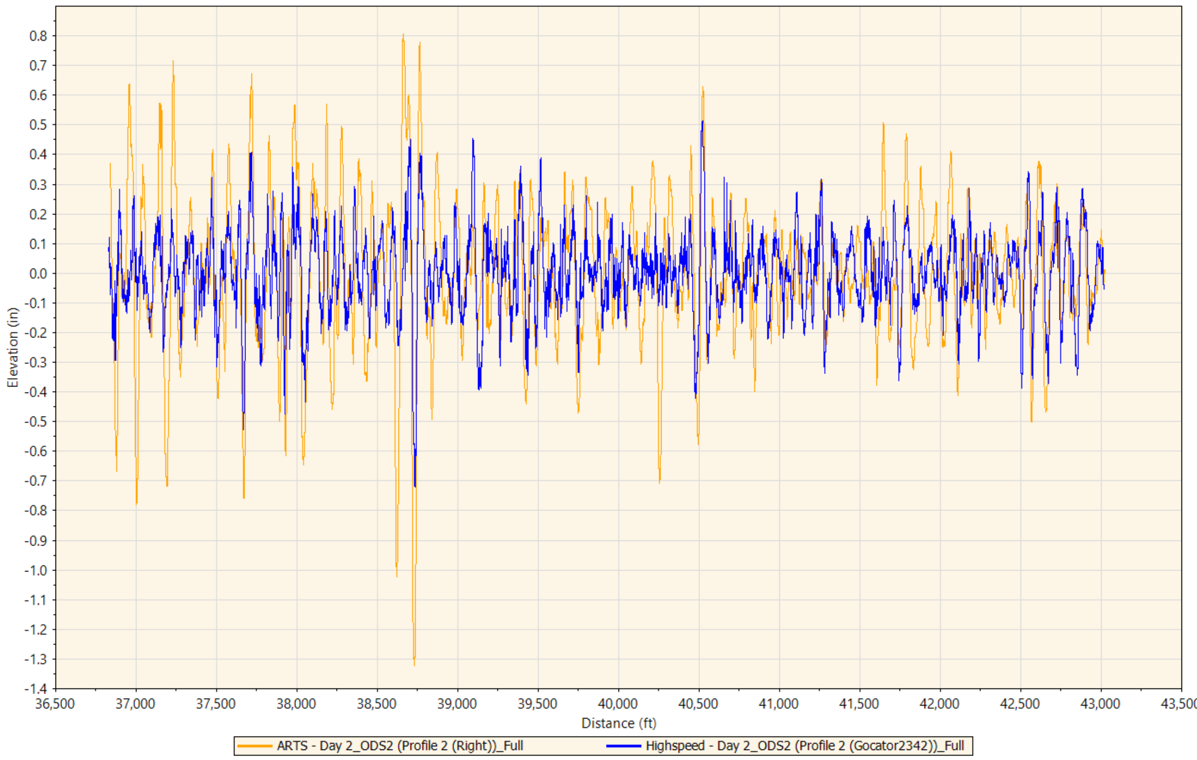


Figure 17. Demo No. 1 – Day 2 ARTS and HSIP profiles (RWP).

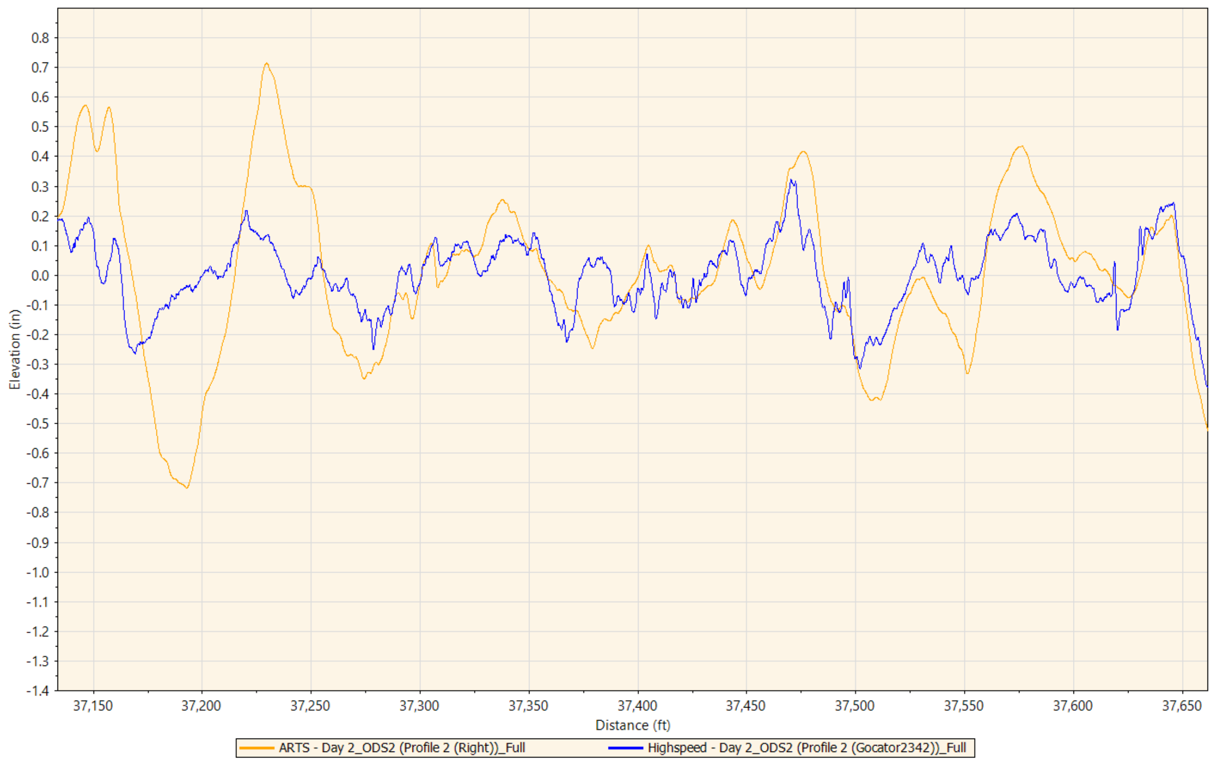


Figure 18. Demo No. 1 – 0.1-mile section of Day 2 ARTS and HSIP profiles (RWP).

3.7.3 Overall Ride Quality Analysis

Similar to the raw profiles, IRI values for the ARTS and HISP data are generally consistent, as shown in Figure 19. The overall IRI differences between HSIP and ARTS were -9% and 5% for Day 1 (LWP) and Day 2 (RWP), respectively. The RWP (slope-control side of the paver) roughness was 54% and 99% higher than the LWP (grade-control side of the paver) for Day 1 and Day 2, respectively.

Tests	Wheel Path	IRI (in/mi)	HSIP-ARTS (%	RWP-LWP (%)
ARTS - Day 1	LWP	71		
Highspeed - Day1	LWP	65	-9%	
Highspeed - Day1	RWP	100		54%
ARTS - Day 2	RWP	111		
Highspeed - Day 2	LWP	60		
Highspeed - Day 2	RWP	116	5%	95%

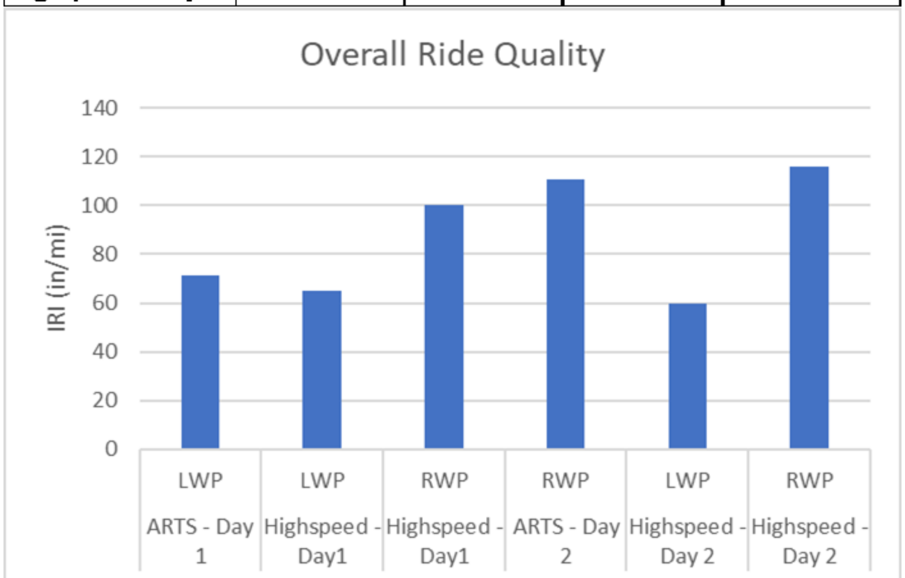


Figure 19. Demo No. 1 - Comparison of the overall roughness of ARTS and HSIP data.

Overall roughness measured by the ARTS system for Day 2 was higher than on Day 1 primarily because the functioning ARTS sensor was installed on the side of the paver with grade control (to match the adjacent pavement) on Day 1, and the side of the paver with slope control (to match the design cross-slope grade) on Day 2. The field team observed frequent and sometimes large tow point movements on the side of the paver using automatic slope control (shoulder edge), to which the higher roughness on that side of the paver can be attributed. The HSIP data confirmed this difference in roughness, with the RWP 54% and 95% rougher than the LWP for Day 1 and Day 2, respectively. HSIP data also revealed similar overall IRI between Day 1 and Day 2 for both the LWP and RWP.

On Day 1, the HSIP overall roughness was slightly lower (9%) than the ARTS, but on Day 2, the HSIP overall roughness was slightly higher (5%) than the ARTS. The difference between the roughness measured by ARTS and HSIP is likely due to roller compaction or measurement errors. The overall roughness can also be affected by compensating effects of various sections and factors. With such a limited amount of data (only two days of paving) and limited results, caution should be exercised in making definitive conclusions. The conservative conclusion is that ARTS and HSIP measurements are comparable (i.e., ARTS systems can accurately reflect final roughness after compaction). However, this does not mean compaction does not affect the final roughness. Day 2 paving, for example, consisted of more horizontal and vertical curves than Day 1, which may have contributed to some of the differences between Day 1 and Day 2.

3.7.4 Fixed Interval Ride Quality Analysis

3.7.4.1 Day 1

The 0.1-mile fixed-interval ride quality (IRI) report for Day 1 is shown in Figure 20. The IRI differences between (HSIP-ARTS) can be positive or negative. The differences range from +15% to -30%.

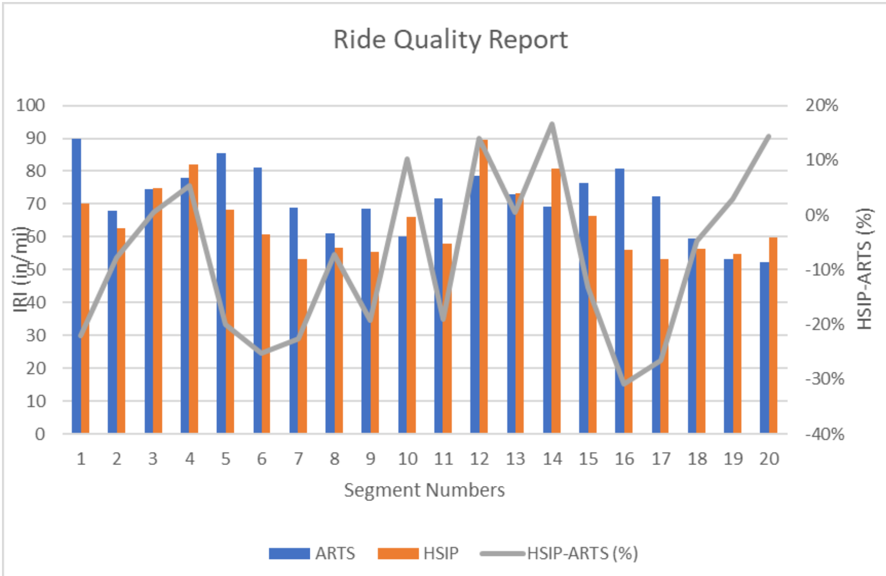


Figure 20. Demo No. 1 - Fixed-interval ride quality report for Day 1.

3.7.4.2 Day 2

The 0.1-mile fixed-interval ride quality (IRI) report for Day 2 is shown in Figure 21. The IRI differences between (HSIP-ARTS) can be positive or negative. The differences range from +45% to -20%.

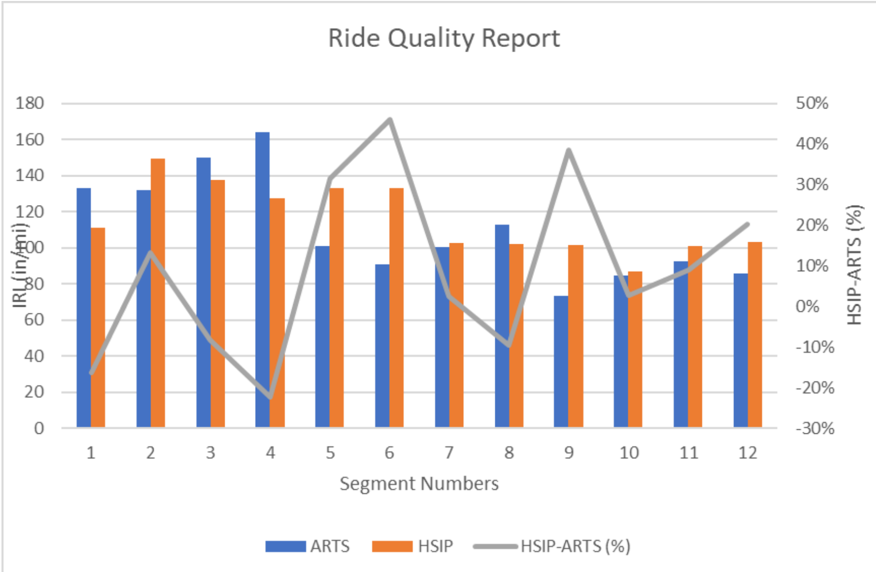


Figure 21. Demo No. 1 - Fixed-interval ride quality reports for Day 2.

3.7.5 Localized Roughness Analysis

3.7.5.1 Day 1

The Day 1 localized roughness report for the ARTS profile is shown in Figure 22. Localized roughness is identified using a continuous IRI report with a 25-ft baselength, the most common method used by state highway agencies.

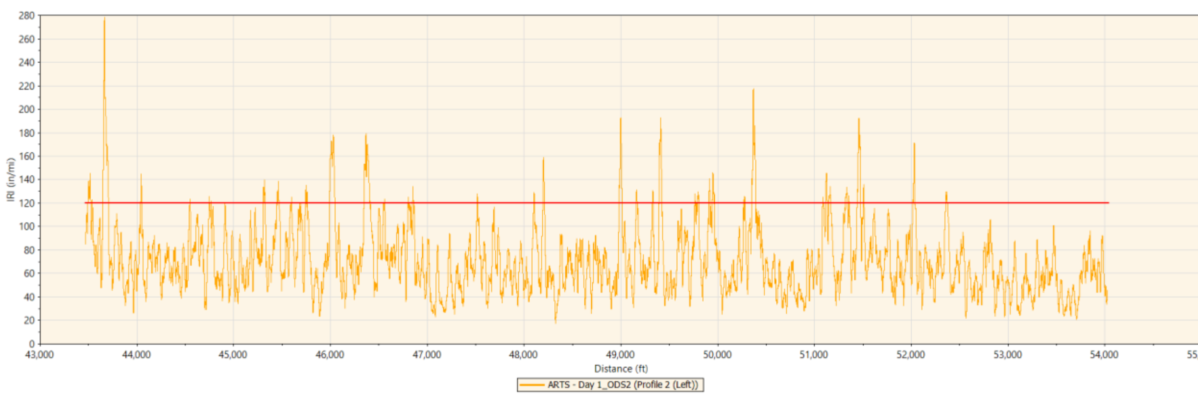


Figure 22. Demo No. 1 – Day 1 localized roughness report for the ARTS profile.

To correlate localized roughness to events occurring during paving, event logs were manually recorded during data collection and summarized in Table 3 (although some significant events were likely missed).

Table 3. Demo No. 1 - Event logs for Day 1 (August 25, 2021)

Station	Time	Notes/Event Markers	Notes
544+35	8:05A	Begin Paving	In the reversed order of stationing.
540+00	8:42A	BEGIN ARTS DATA COLLECTION (DMI = 0)	
535+00		DMI = 498’ (2’ diff.)	
520+00		DMI = 1,992’ (8’ diff.)	
505+00		DMI = 3,490’ (10’ diff.)	
486+17		DMI = Approx. 5400’. The shoulder pavement was thin after a very thick section.	There is no noticeable ARTS localized roughness.
480+00		DMI = 5,978’ (22’ diff.)	
479+78		DMI = ~6,000’ – The screed vibration was turned on (variable settings) for ~120.’	
475+00		DMI = 6,477’ (23’ diff.)	
465+00		DMI = 7,476’ (24’ diff.)	
445+00		DMI = 9,470’ (30’ diff.)	
436+65		DMI = 10,352’ The paver was stuck due to missed load dump in front of the paver. The paver was restarted after clearing material with a skid steer (about 11 min. later).	At 436+00, the ARTS’ localized roughness is about 275 in./mi., while the HSIP’s localized roughness is about 140 in./mi. Therefore, it may be due to the manual recording error.

Station	Time	Notes/Event Markers	Notes
		There are noticeable deviations in the pavement surface.	
434+10 (approx.)	6:52P	END RTS DATA COLLECTION, DMI = 10,557’	

The Day 1 localized roughness (IRI) report comparing the ARTS and HSIP profiles is shown in Figure 23. In general, the localized roughness of the ARTS profile is higher than the HSIP, with exceptions at station 453+68 and several instances between station 494+70 and station 509+84. However, no events were manually recorded in those areas, so the reason for these exceptions is unknown.

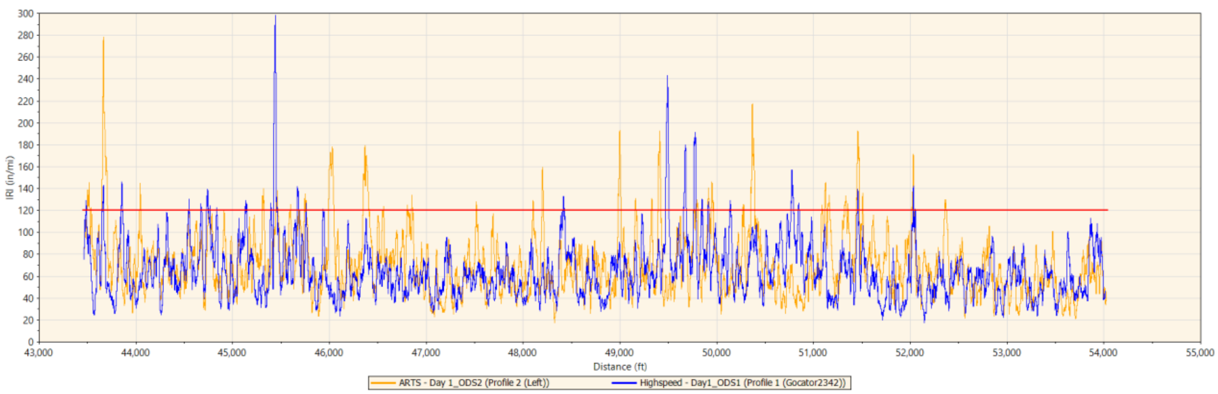


Figure 23. Demo No. 1 – Day 1 Localized roughness report for the HSIP profile.

A 120 in./mi. the threshold was used to assess the ALR from the Day 1 data as it is relatively smoother than Day 2. With the 120 in./mi. threshold, the number of ALR is 15 and 10 for ARTS and HSIP, respectively. They used a 5 ft. minimum length of ALR and the 120 in./mi. threshold, the number of ALR is 12 and 5 for ARTS and HSIP, respectively. Unlike the overall roughness analysis for the pavement length, the ALR reflects localized roughness issues likely correlated to construction artifacts. Based on this analysis, ALR is reduced from ARTS to HSIP measurements. However, based on a further detailed comparison, the ARTS ALR locations do not always match those from the HSIP. Some mismatched locations indicate that ALR picked up by ARTS may not be smoothed out by compaction, while some mismatched HSIP ALRs may be “caused” by compaction (e.g., rollers sitting on the hot mat). Therefore, a follow-up field study should use high-precision GPS on all equipment (paver, rollers, HSIP, ARTS) to better correlate the results.

3.7.5.2 Day 2

The Day 2 localized roughness report for the ARTS profile is shown in Figure 24. Similar to the overall roughness report, Day 2 ARTS data was generally significantly rougher than Day 1 as the ARTS sensor was located on the side of the paver controlled by the slope control.

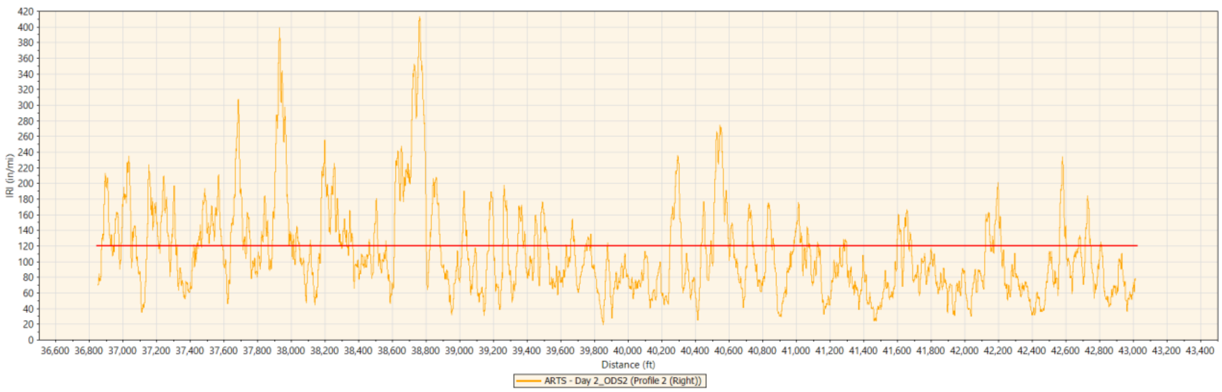


Figure 24. Demo No. 1 – Day 2 Localized roughness report for the ARTS profile.

Event logs were manually recorded on Day 2 and summarized in Table 4.

Table 4. Demo No. 1 - Event logs for Day 2 (August 26, 2021)

Station	Time	Notes/Event Markers	Notes
434+10	7:30A	Begin Paving	In the reversed order of stationing.
430+00	7:58A	BEGIN ARTS DATA COLLECTION (DMI = 0)	
428+75		DMI = ~125' – screed crank on the left side (manual adjustment?)	
425+00		DMI = 496' (4' diff.)	
420+00		DMI = 993' (7' diff.)	
410+00		DMI = 1,986' (14' diff.)	

Station	Time	Notes/Event Markers	Notes
Between 410+00 and 400+00		DMI = 2268' – paver stuck due to missed load dump in front of paver; restart after clearing material with a skid steer.	The ARTS' localized roughness is about 300 in./mi.
400+00		DMI = 2,989' (11' diff.)	
~395+00		Screed extensions out to ~14' paving width?	
~392+00		Screed extensions out to ~15' paving width?	
~387+00		Noticeable dip in profile at the driveway	The ARTS' localized roughness is about 400 in./mi.
380+00		DMI = 4979' (21' diff.)	
368+00 (approx.)	1:09P	END ARTS DATA COLLECTION, DMI = 6,176' (paving was stopped due to rain)	

A 200 in./mi. the threshold for ALR was used to assess the ALR for Day 2 data as it is significantly rougher than Day 1. With the 200 in./mi. threshold, the number of ALR is 21 and 32 for ARTS and HSIP, respectively. With the 200 in./mi. threshold and 5+ ft minimum length of ALR, the number of ALR are 17 and 23 for ARTS and HSIP, respectively. ALR increases from ARTS to HSIP measurements based on this analysis, which is the opposite of what was observed from Day 1 data and indicates that compaction may harm the smoothness. This is likely due to the highly variable depths of asphalt (from < 2" to 6"+ in the path of the ARTS sensor) as a result of running automatic slope control to establish the desired cross-slope in the mat. Based on the further detailed comparison, the ARTS ALR locations do not always match HSIP's. These mismatched locations indicate that ALR picked up by ARTS may not be smoothed out by compaction. In contrast, some mismatched HSIP ALRs may be "caused" by compaction (e.g., variable compaction due to variable mat thickness, rollers sitting on the hot mat, etc.).

CHAPTER 4: DEMONSTRATION NO. 2

4.1 OVERVIEW

The ARTS prototype was tested at the second field demonstration project in Wisconsin on June 2, 2022. The goal was to test the improved sensor installation procedure, sensor operation, data collection, and analyze the data along with HSIP data and field observations.

The ARTS Vendor added a software feature to easily insert event markers during data collection. The event keys and descriptions used during the demonstration are summarized in Table 5. This feature eliminated the manual notes and facilitated the correlation between the events and profile data.

Table 5. ARTS Event Markers

Event Key	Event Descriptions
Z	Paver Stop
X	Spill (Spills on the Grade in front of the paver (hopper flashing, MTV-related, truck dump on grade, etc.)
C	LT Ext Slope (Introduce slope in left screed extension)
V	RT Ext Slope (Introduce slope in right screed extension)
B	Vib On (Turn screed vibration on)
N	Vib Off (Turn screed vibration off)
M	Other (mark the event and manually enter the reason)

4.2 FIELD PROJECT INFORMATION

Demo Project 2 was another HMA resurfacing project. The project's terrain is relatively flat, and the existing asphalt base was visually smooth. This project included a smoothness requirement for acceptance. However, PMTP and IC were not used. Both days of testing were on the surface course placement of 1.75" thickness compacted (2.25" loose) and paving width of 12'.

4.3 ASPHALT PAVING EQUIPMENT

The total daily tonnage was 2,215 tons, delivered approximately 16 tons per truck. A Weiler material transfer vehicle (MTV) was used along with a hopper insert. The paver was a Caterpillar AP1000F wheeled paver with a Weiler screed and Willow Designs notched-wedge joint device. Two contact ski automatic grade control devices were used along the roadway centerline and the shoulder. The left ski appeared to have several unrounded wheels that slipped during the operation. (Figure 25) Three rollers were used for compaction, two for echelon breakdown, and one for finishing. All three were HAMM HD 120i double drum rollers. (Figure 27) A water truck sprayed water on the asphalt surface before the finishing compaction.

Figure 25. Demo No. 2 – Truck, MTV, and Paver Operations.

Figure 26. Demo No. 2 – ARTS Operations.

Figure 27. Demo No. 2 – Roller Compaction.

4.4 ARTS SENSOR INSTALLATION

The same receiving brackets from the first demonstration were re-used for the second demonstration. The two ARTS sensors were placed at the LWP and RWP of the paved lane.

4.5 PAVING OPERATION AND ARTS DATA COLLECTION

4.5.1 Paving Operation

Paving was conducted in two sections, the northern section and the southern section. Paving started on the passing lane in the northern section in the northbound direction. Both LWP and RWP ARTS sensors collected data. Once the northern section paving was completed, the paving equipment was mobilized to the southern end to continue paving. The paving continued on the driving lane in the northbound direction from the southern end of the project. The southern section consisted of two subsections separated by a bridge. Both ARTS sensors collected data. However, the ARTS data collection stopped around 3 PM due to a rain event. The paving operation for the northern and southern sections are summarized in Table 6 and Table 7, respectively.

Table 6. Paving operation for the northern section (June 2, 2022).

Items	Descriptions
Weather	sunshine
Ambient temperature (low/high):	NA
Paved width	12 ft
Paving direction	northbound
Paving start	07:40 AM
Paving Ends	11:00 AM
Start Station	411+06
Stop Station	435+09
Length (ft)	2,403
Asphalt tonnage (tons)	2,215 (northern section and southern section combined)
ARTS Sensors	Two ARTS sensors were installed at the LWP and RWP positions.

Table 7. Paving operation for the southern section (June 2, 2022).

Items	Descriptions
Weather	Sunshine, then cloudy and rain at 3 PM
Ambient temperature (low/high):	NA
Paved width	12 ft
Paving direction	Northbound
Paving start	12:00 PM
Paving Ends	3:00 PM (ARTS sensors stopped collecting data, but paving resumed after the rain)
Start Station	154+04 (section 1), 181+00 (section 2)
Stop Station	176+53 (section 1), 214+11 (section 2)
Length (ft)	2,250 ft (section 1) and 3,311 ft (section 2)
Asphalt tonnage (tons)	2,215 (northern section and southern section combined)
ARTS Sensors	Two ARTS sensors were installed at the LWP and RWP positions.

4.5.2 ARTS Data Collection

Figure 28 shows the paving operation and ARTS data collection setup for paving of both the northern and southern sections, which was virtually identical to Demo Project 1.

Figure 28. Demo No. 2 -ARTS data collection during paving.

During the operation, temperatures were monitored using thermal imaging. A sample of these temperatures revealed 124.2°F, 131.2°F, 114.8°F, and 232.5°F on the inside sensor housing, the middle sensor housing, the inside sensor housing, and the asphalt mat, respectively, as shown in Figure 29 (Sp1, Sp2, Sp3, and Sp4).

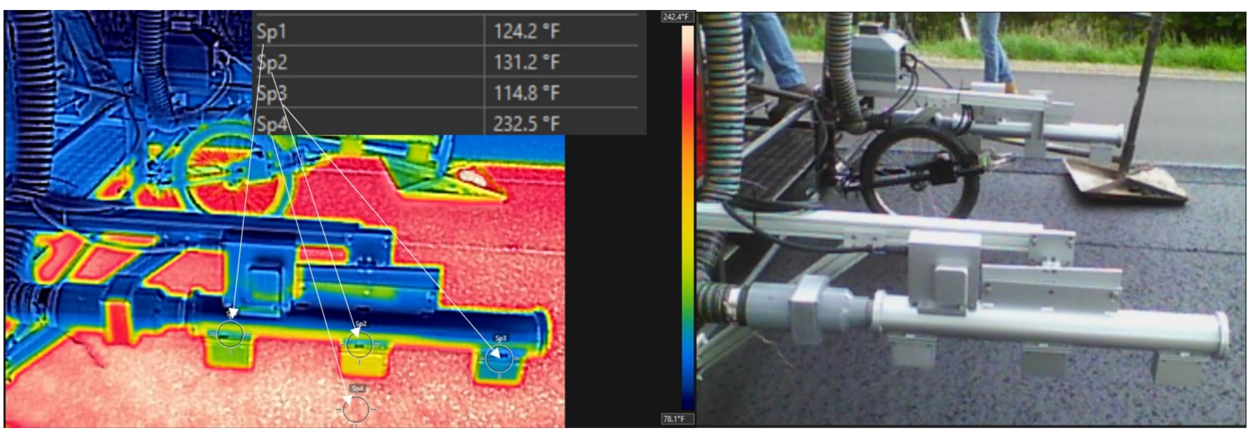


Figure 29. Demo No. 2 - Temperatures on the ARTS sensor housings and asphalt mat.

4.6 HSIP MEASUREMENT OPERATION

Vendor A's HSIP collected profiles from finished pavement surfaces for the northern and southern sections. During the HSIP operation for the northern section, the HSIP needed to stop at a ramp to wait for passing traffic. The HSIP data in this stop-and-go area was excluded from the analysis.

4.7 DATA ANALYSIS

4.7.1 Data Management

The ARTS and HSIP data were collected along the LWP and RWP in the northern and southern sections on June 2, 2022.

The profile length for the northern section was 2,400 ft long. Both ARTS and HSIP data were extracted into two sub-sections for further comparison and analysis: northern section 1 (N1) (414+00 to 423+00, 900 ft) and northern section 2 (N2) (426+45 to 432+79, 634 ft), corresponding to sections on either side of the HSIP stop-and-go area.

The profiles for the southern sections were collected in two sections, separated by a bridge. The profile length for southern section 1 (S1) is 2,250 ft long, and 3,311 ft for southern section 2 (S2). The ARTS and HSIP data for the first 159 ft of S1 were excluded to avoid ARTS data disturbance, though the HSIP data also showed high roughness.

4.7.2 ARTS and HSIP Profiles

4.7.2.1 Northern Sections

The ARTS raw data were imported into ProVAL with start and stop GPS locations, event markers, and the begin and end stations. The ARTS start distance was offset by 41,106 ft to indicate stationing. Since the ARTS profiles were unfiltered, a Butterworth[1] high-pass filter with a 100-ft cutoff was applied to the raw profiles, as shown in Figure 30. Profile 1 and Profile 2 are LWP and RWP profiles, respectively.

[1] Butterworth filter is a ProVAL function to filter out the wavelength contents of a profile. Refer to the ProVAL users' manual for details (https://www.roadprofile.com/proval-software/current-version/).

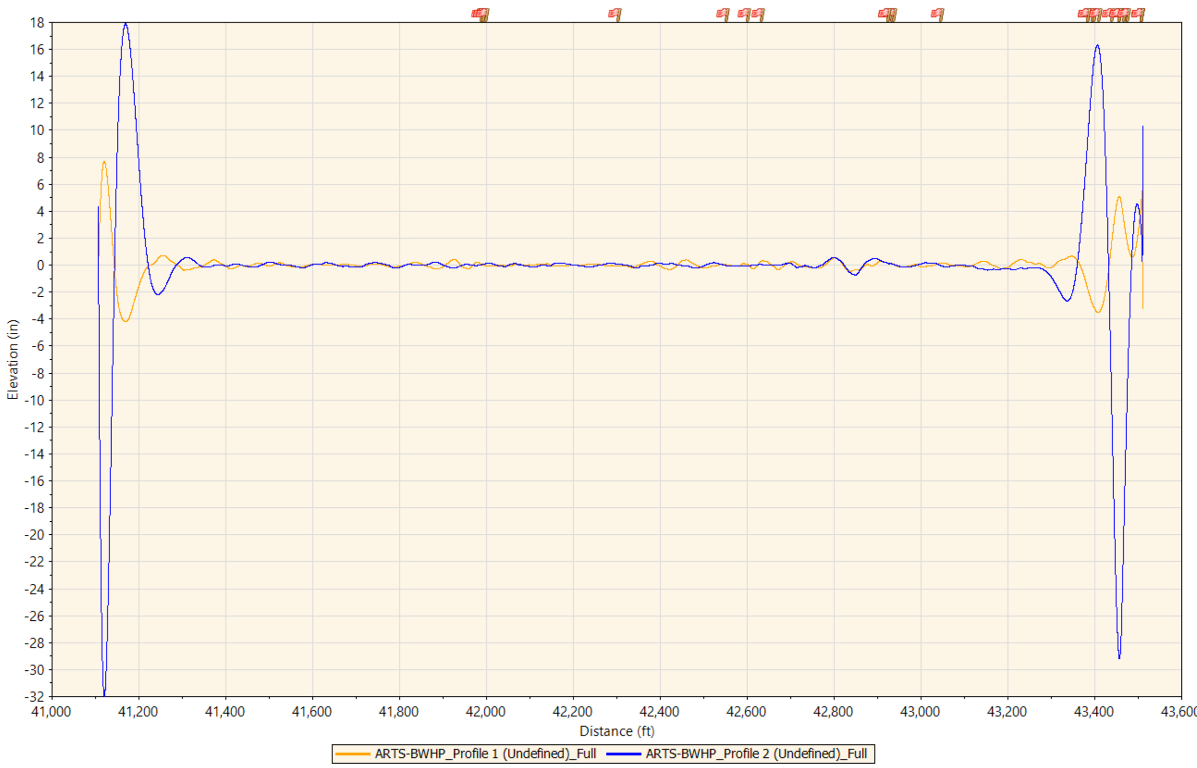


Figure 30. Demo No. 2 - ARTS profiles for the combined northern section.

Zooming in on the drastic change area towards the end of the profile in Figure 30, these changes started at the event when the paver resumed paving after a stop. Then, there are multiple stop-and-go events and a ski issue afterward, as indicated by the event marker flags in Figure 31. The changes are more drastic for the RWP profile than the LWP profile. There were also vertical screed movements at the end of the north section to tie in with the bridge, which may have caused the ARTS system movements and abnormal data.

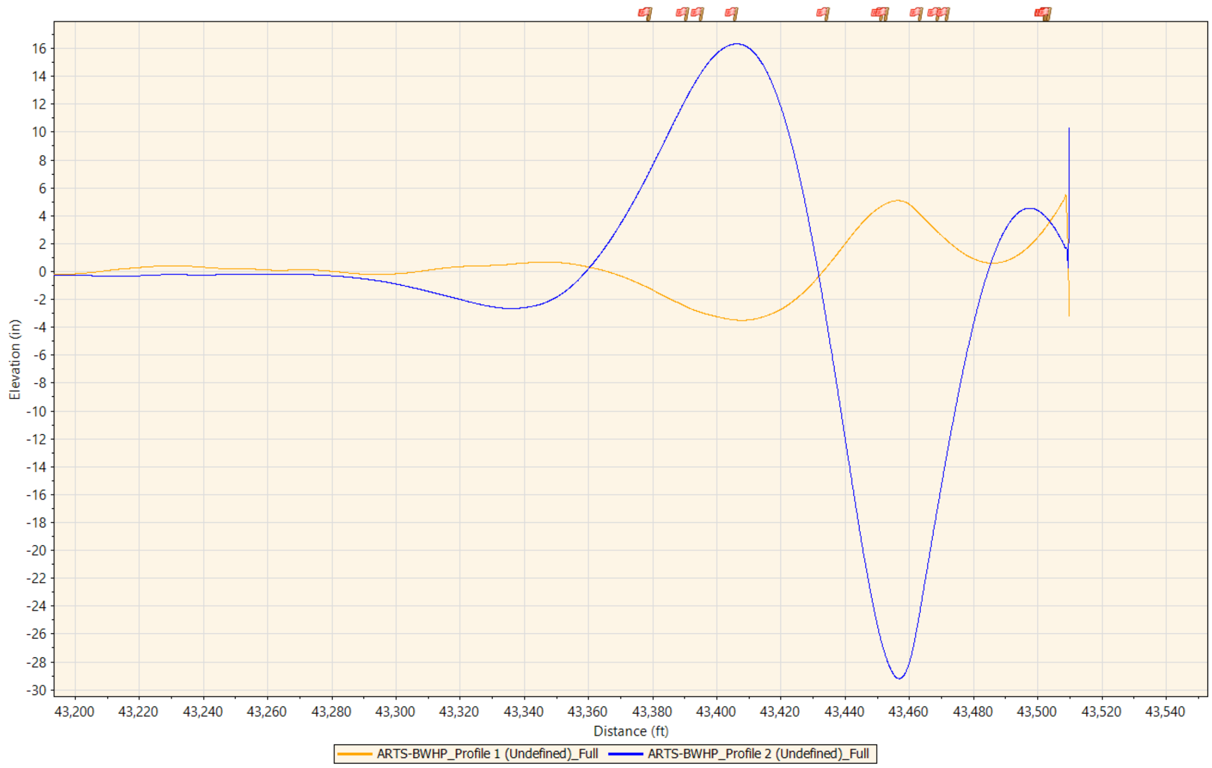


Figure 31. Demo No. 2 - Filtered ARTS profile with stationing, zoomed in at the end of the northern section.

The contractor stopped the paver about 20 ft from the bridge tie-in location and switched from automatic grade control (contact ski) to automatic slope control to tie into the bridge deck (Figure 32). A screed takes roughly 4 to 5 times the tow-arm length (~40 to 50 ft) to stabilize. This observed roughness may result from WisDOT's exclusion for smoothness requirements 25 ft offset from a structure. If the exclusion distance was 50 ft, contractors may start this bridge tie-process at the 50-ft offset, which would provide a greater distance for the screed to reach equilibrium, resulting in a smoother transition or tie-in to the bridge deck.

Figure 32. Demo No. 2 – Bridge Deck Tied-in.

Figure 33 shows the HSIP profiles for the northern section after high-pass filtering with a 100-ft cutoff and distance offset to indicate stationing. The HSIP data included a stop-and-go area at a cross-over ramp for passing traffic. Therefore, this area was defined as exclusion, and two sub-sections were defined before and after this area for the analysis.

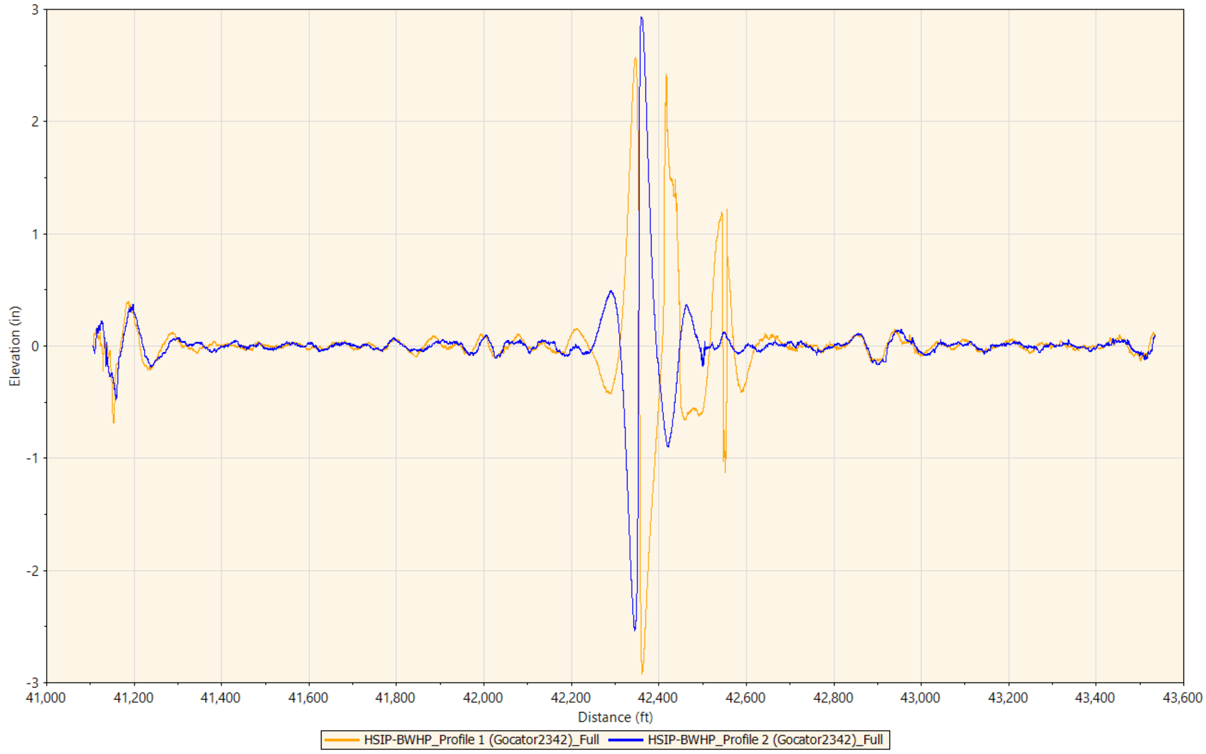


Figure 33. Demo No. 2 - HSIP profile for the northern section.

4.7.2.2 Southern Sections

The Southern Section 1 (S1) ARTS raw data files were imported into ProVAL with start and stop GPS locations, event markers, and the beginning and end stations. The ARTS start distance was offset by 15,404 ft to indicate stationing. Since the ARTS profiles were unfiltered, a Butterworth[2] high-pass filter with a 100-ft cutoff was applied to the raw profiles, as shown in Figure 34.

[2] Butterworth filter is a ProVAL function to filter out the wavelength contents of a profile. Refer to the ProVAL users' manual for details (https://www.roadprofile.com/proval-software/current-version/).

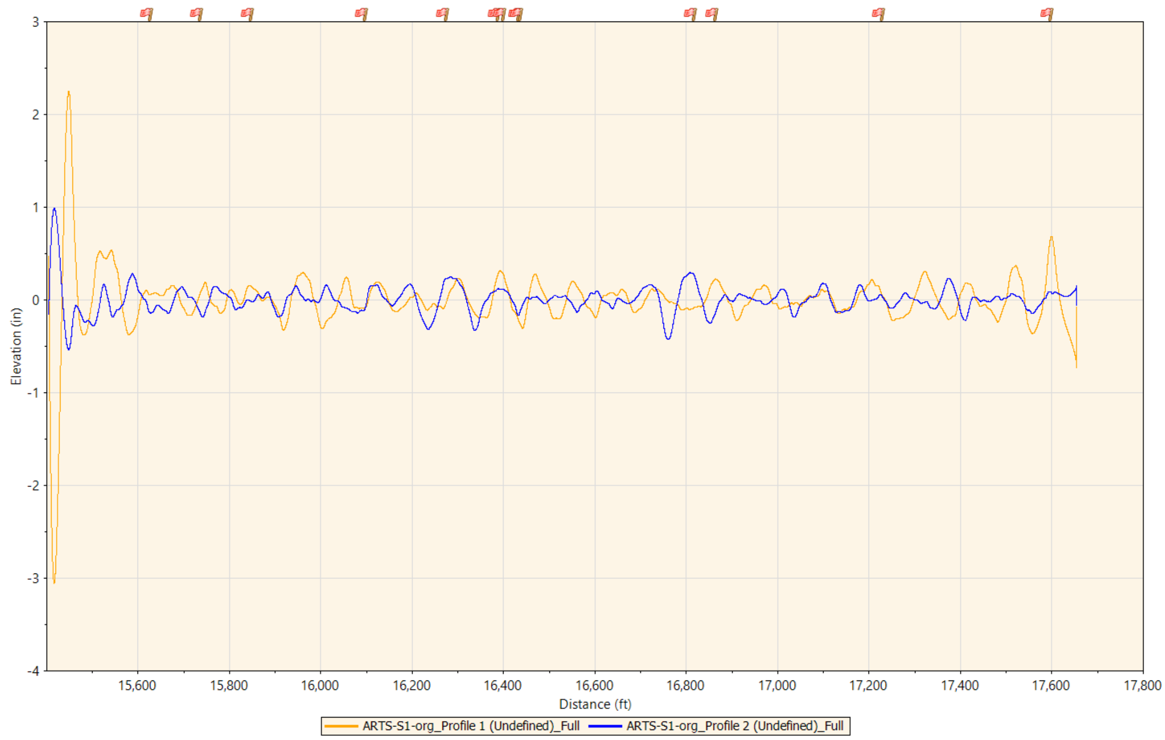


Figure 34. Demo No. 2 - ARTS profile for southern section 1.

The S1 HSIP profiles were, likewise, high-pass filtered with a 100-ft cutoff, and the distance was offset to indicate stationing, as shown in Figure 35.

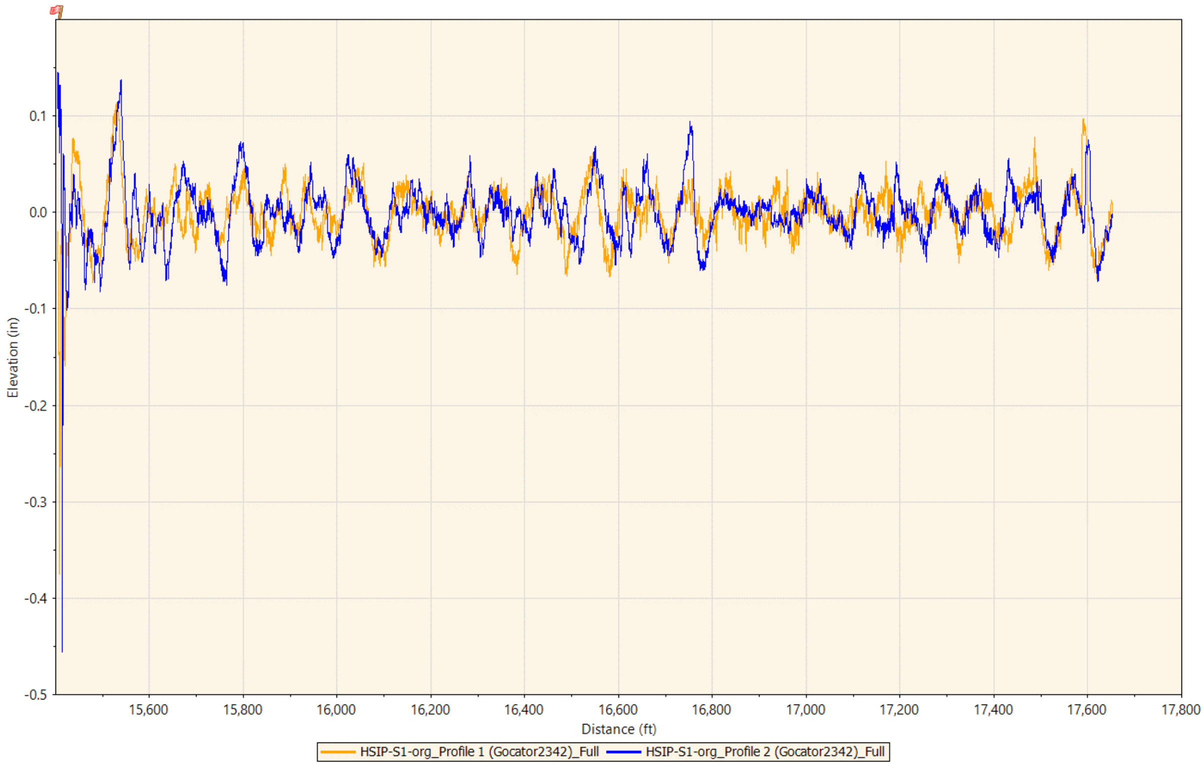


Figure 35. Demo No. 2 – HSIP profile for southern section 1.

The Southern Section 2 (S2) ARTS raw data files were imported to ProVAL with start and stop GPS locations, event markers, and the beginning and end stations. The ARTS start distance was offset by 18,100 ft to indicate stationing. Since the ARTS profiles were unfiltered, a Butterworth[3] high-pass filter with a 100-ft cutoff was applied to the ARTS raw profiles, as shown in Figure 36.

[3] Butterworth filter is a ProVAL function to filter out the wavelength contents of a profile. Refer to the ProVAL users' manual for details (https://www.roadprofile.com/proval-software/current-version/).

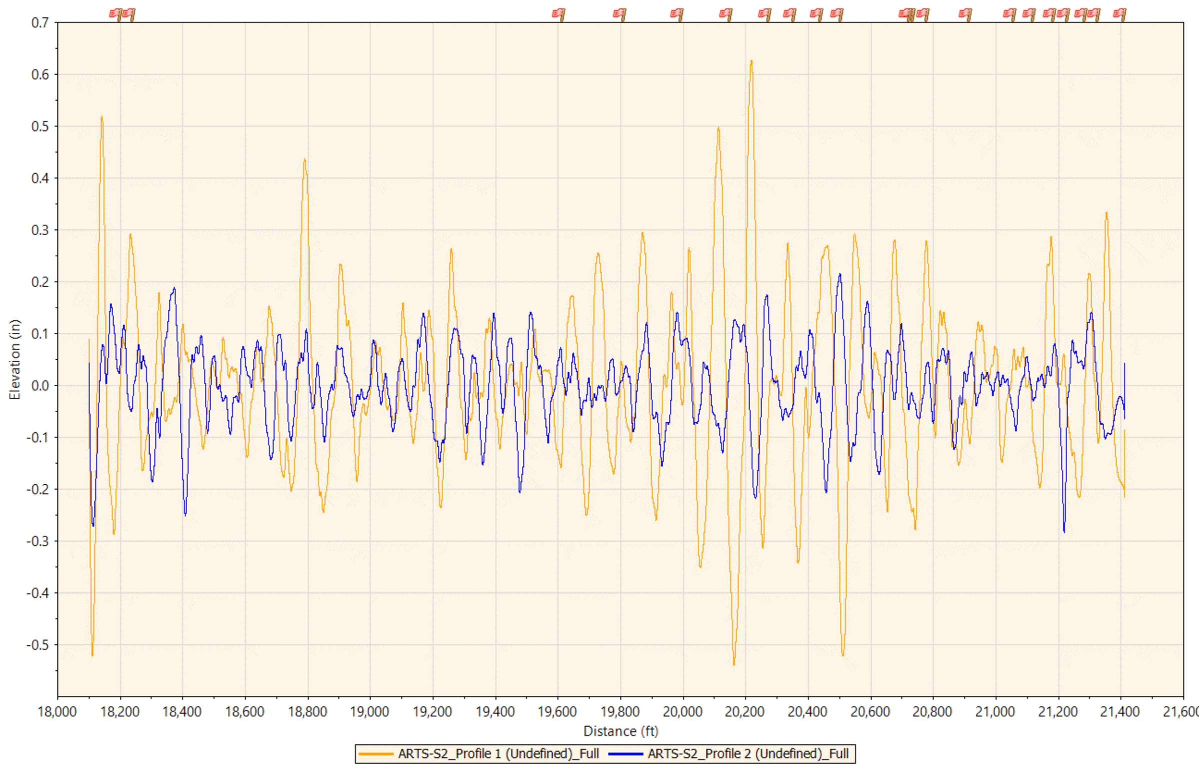


Figure 36. Demo No. 2 - ARTS profiles for southern section 2.

The S2 HSIP profiles were, likewise, high-pass filtered with a 100-ft cutoff, and the distance was offset to indicate stationing, as shown in Figure 37. Section 2 was defined from 18,100 ft to the end.

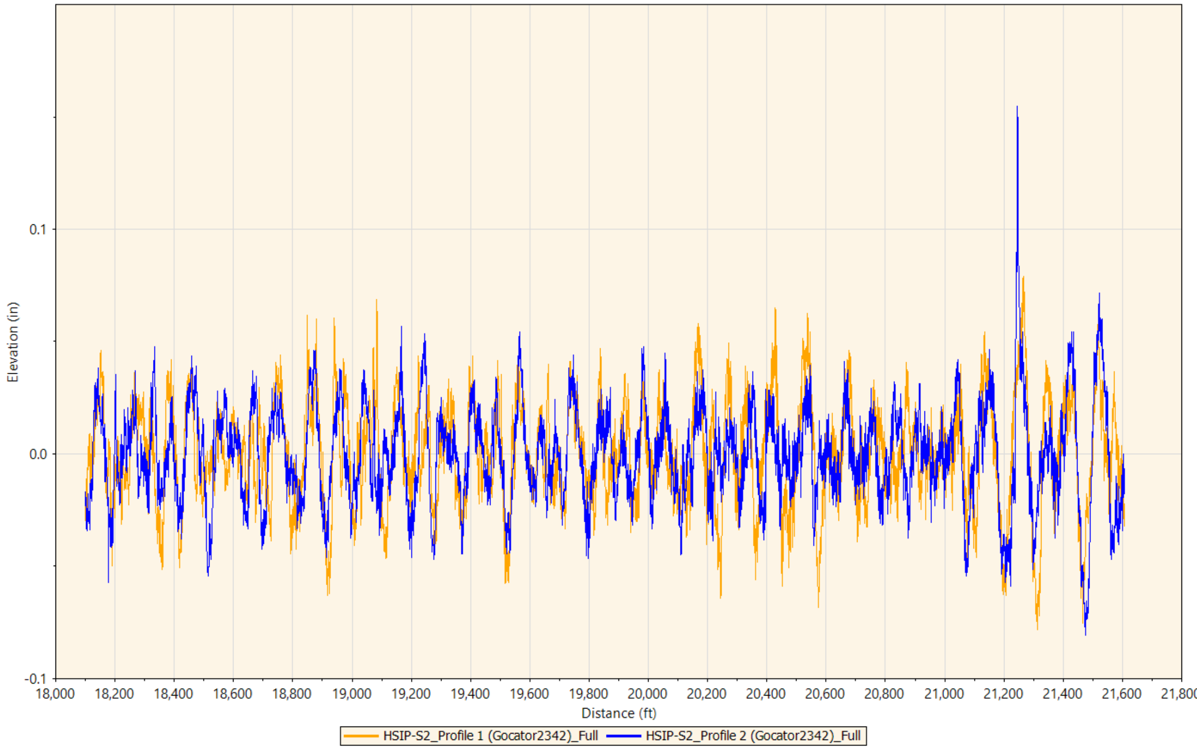


Figure 37. Demo No. 2 – HSIP profile for southern section 2.

4.7.3 Overall Ride Quality Analysis

Unlike the overall ride quality (IRI) values from Demo Project 1, the ARTS and HISP overall ride quality are significantly different, as shown in Table 8. Overall, IRI differences between HSIP and ARTS data are approximately 50%, as shown in Table 8 and Figure 38. The ARTS LWP IRI is consistently higher than the RWP IRI. Also, roughness levels are very low compared with Demo Project No. 1.

Table 8. Summary of overall ride quality (IRI) values for Demo Project 2.

Test Sections	LWP IRI (in/mi)	LWP (HSIP-ARTS) IRI Difference (%)	RWP IRI (in/mi)	RWP (HSIP-ARTS) IRI Difference (%)
ARTS-N1	50	NA	42	NA
HSIP-N1	25	-50%	26	-38%
ARTS-N2	66	NA	49	NA
HSIP-N2	30	-55%	27	-45%
ARTS-S1	49	NA	40	NA
HSIP-S1	25	-49%	24	-39%
ARTS-S2	57	NA	35	NA
HSIP-S2	24	-58%	21	-41%

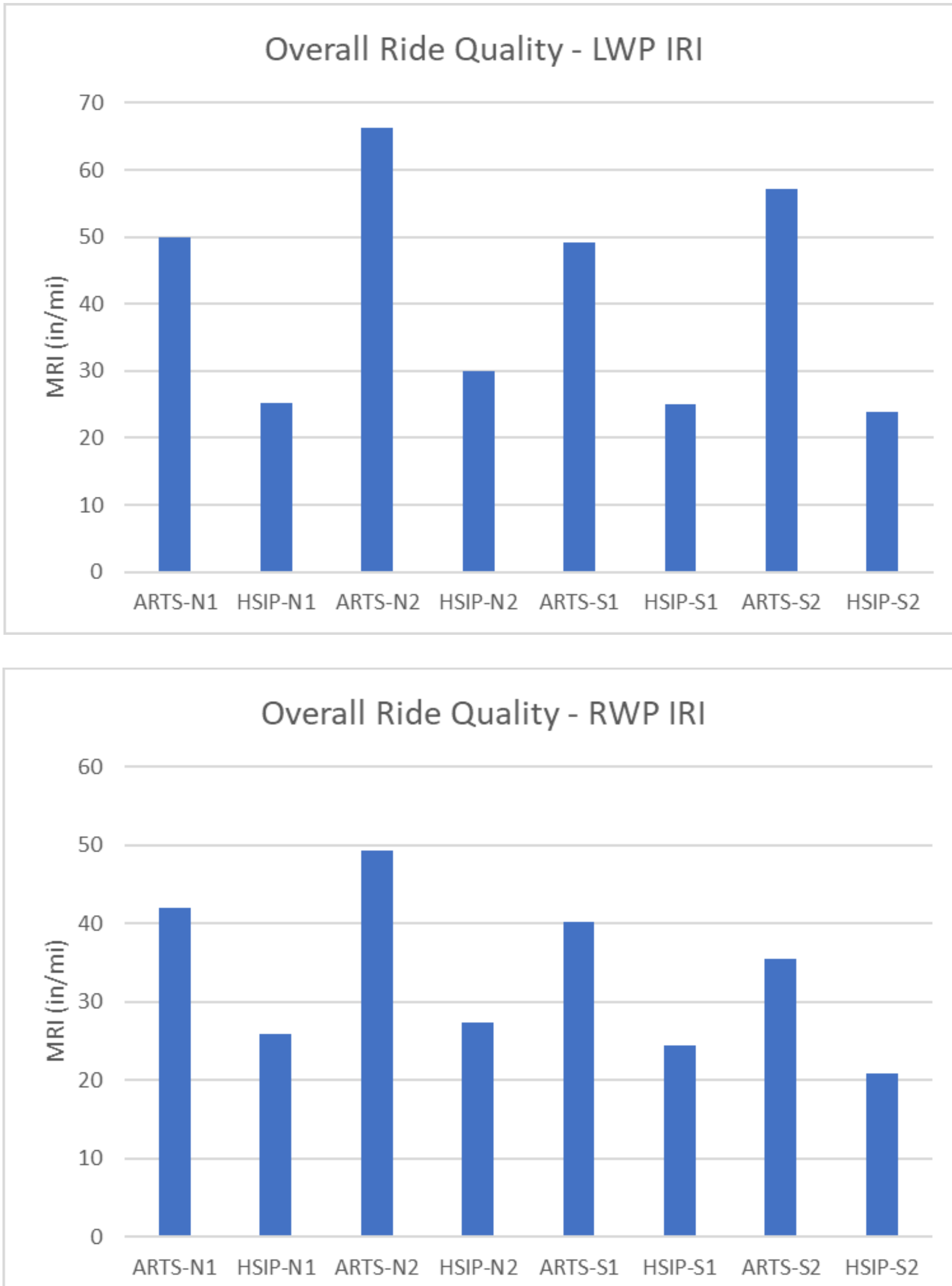


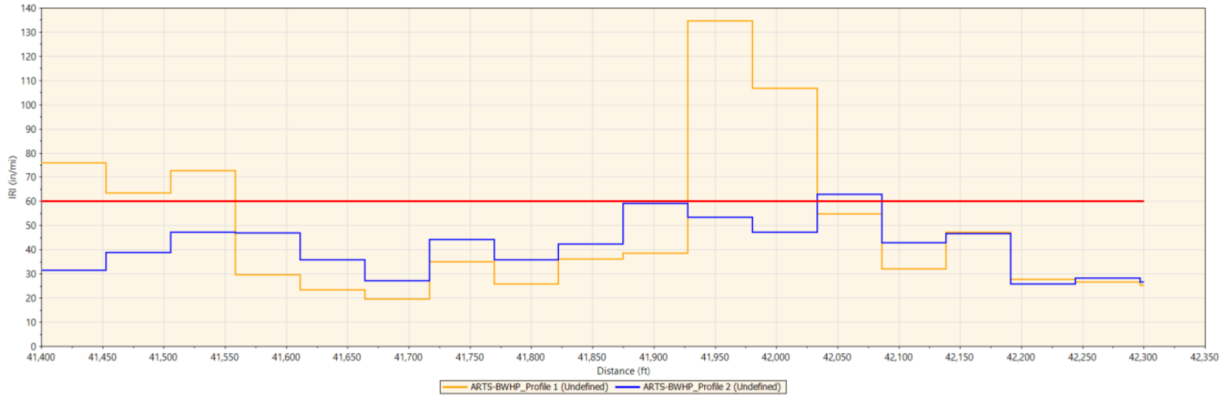
Figure 38. Demo No. 2 - Overall IRI differences between HSIP and ARTS data.

4.7.4 Fixed Interval Ride Quality Analysis

4.7.4.1 Northern Sections

SECTION 1

Figure 39 compares fixed-interval IRI results between ARTS (top chart) and HSIP (bottom chart) for northern section 1, using a 52.8-ft segment and 60 in/mi threshold for reference. The high IRI in the LWP of the ARTS data may be due to the spilled asphalt, as recorded in the event log. The HSIP data shows that the roughness in this area was much lower for the HSIP profiles, likely due to “smooth-out” by compaction.



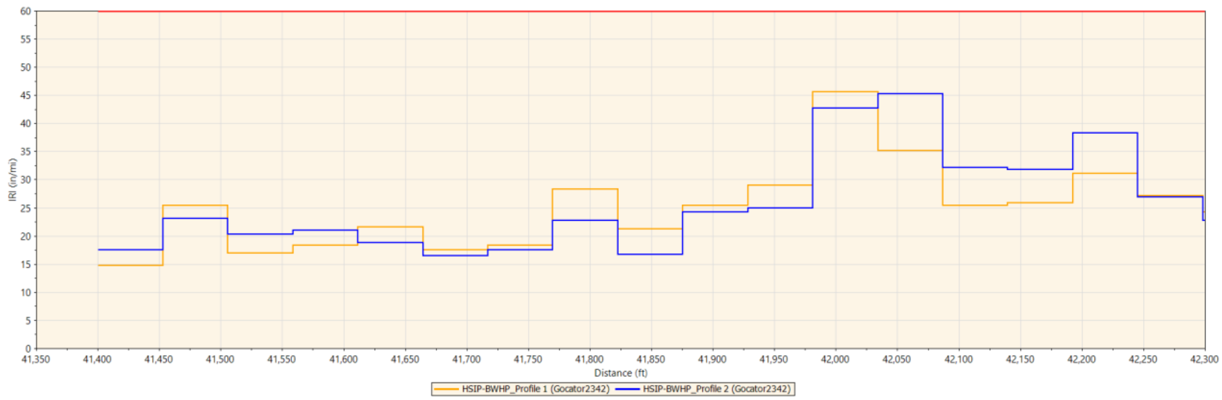
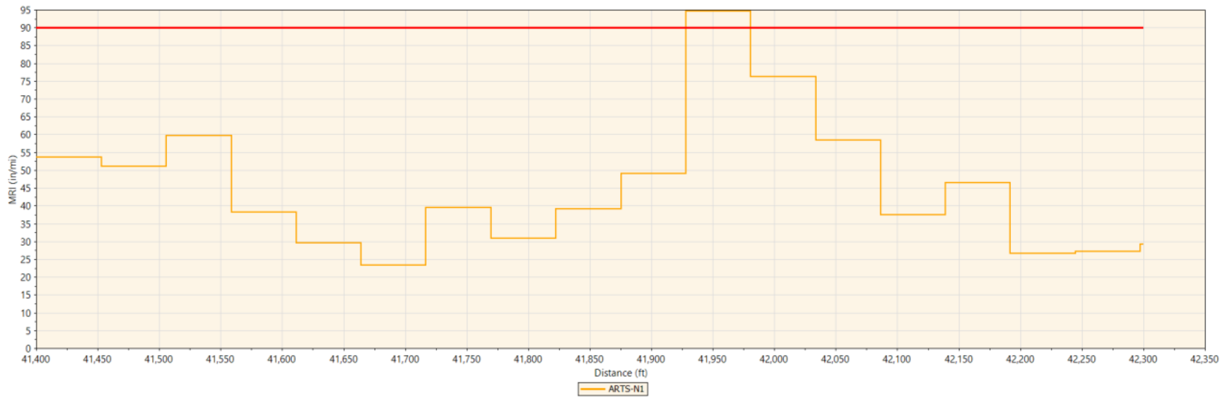


Figure 39. Demo No. 2 – Comparison of fixed-interval IRI for ARTS (top chart) and HSIP (bottom chart) data for northern section 1.

To simplify the comparison, Figure 40 shows a fixed-interval report for the MRI with a 52.8 ft segment length and 90 in/mi threshold for reference for the ARTS and HSIP data. Figure 41 shows a side-by-side comparison of the results, indicating that the HSIP roughness was much lower.



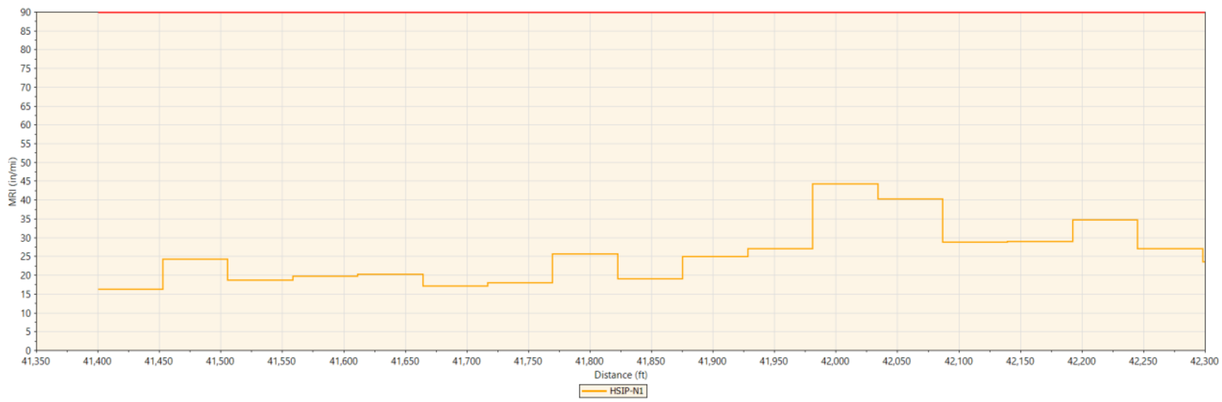


Figure 40. Demo No. 2 –Fixed-interval MRI plots for ARTS (top) and HSIP (bottom) data for northern section 1.

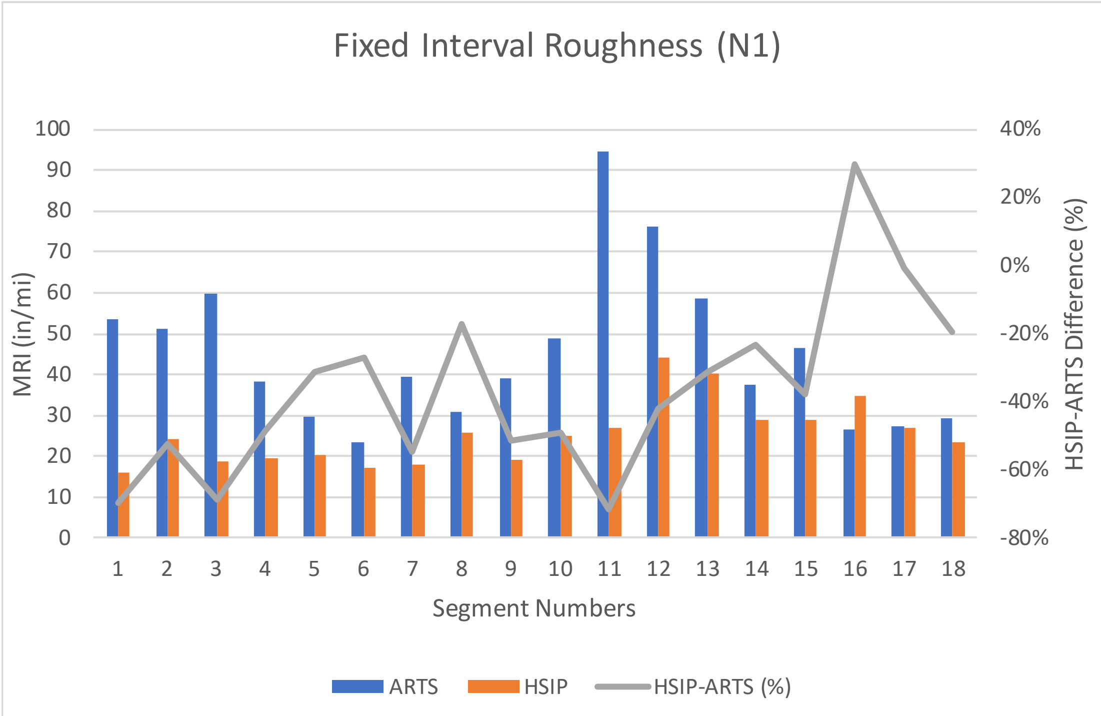
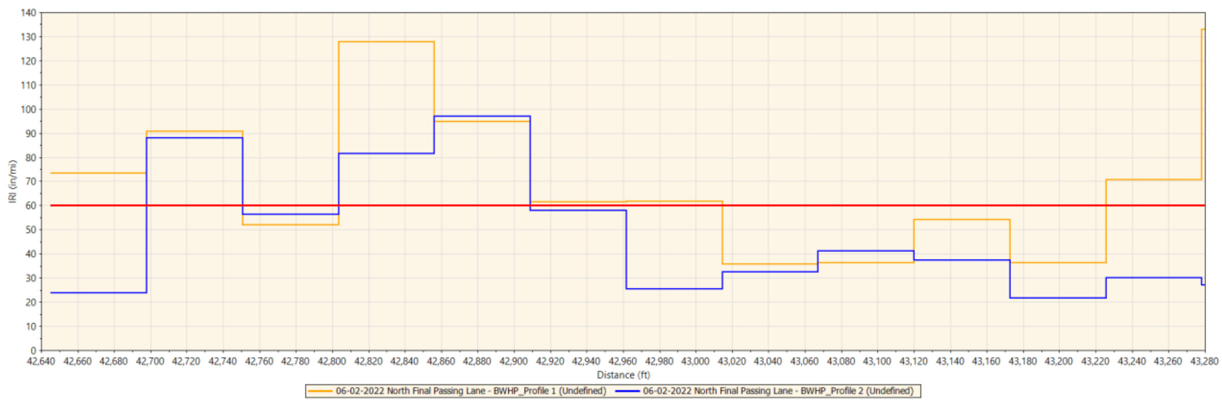


Figure 41. Demo No. 2 – Comparison of fixed-interval MRI values for ARTS and HSIP data for northern section 1.

Figure 42 compares fixed interval IRI between ARTS (top chart) and HSIP (bottom chart) for northern section 2, using a 52.8-ft segment and 60 in/mi threshold for reference. These charts show that the HSIP roughness was much lower than ARTS.



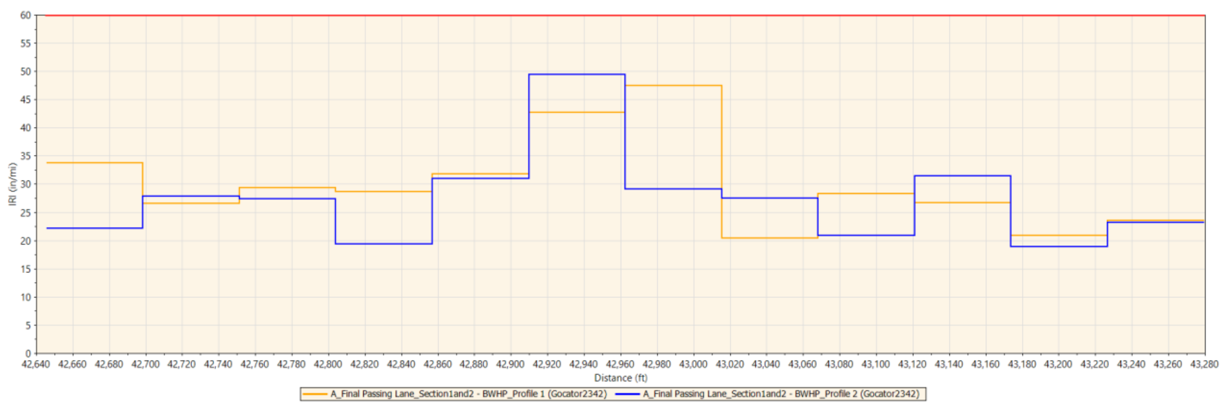
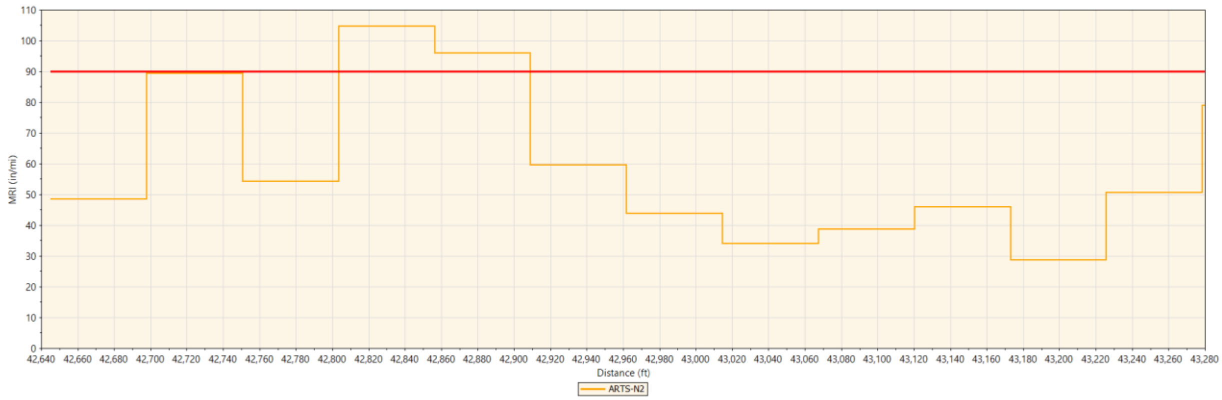


Figure 42. Demo No. 2 – Comparison of fixed-interval IRI for ARTS (top) and HSIP (bottom) data for northern section 2.

Figure 43 shows a fixed-interval report for the MRI with a 52.8 ft segment length and 90 in/mi threshold for reference for the ARTS and HSIP data. A side-by-side comparison of the results in Figure 44 indicates that the HSIP roughness was much lower.



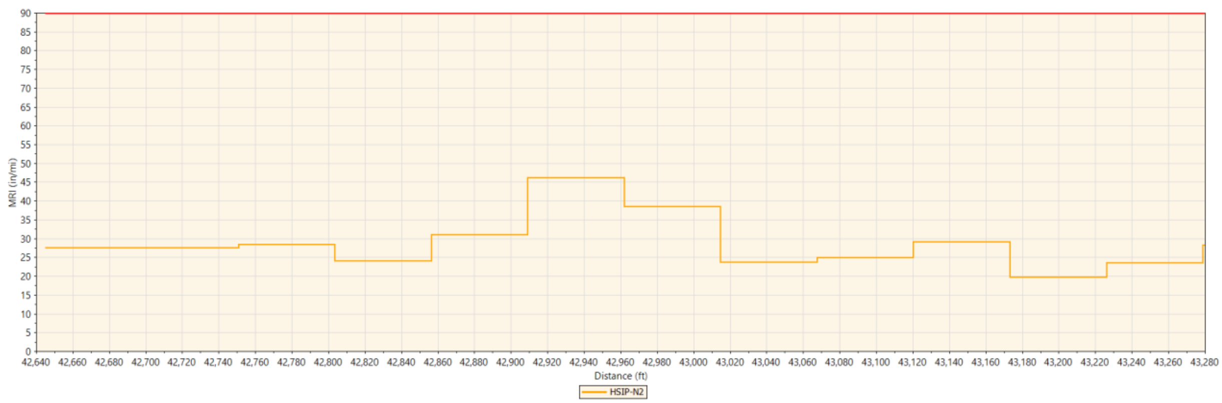


Figure 43. Demo No. 2 – Comparison of Fixed interval MRI plots for ARTS (top chart) and HSIP (bottom chart) data for northern section 2.

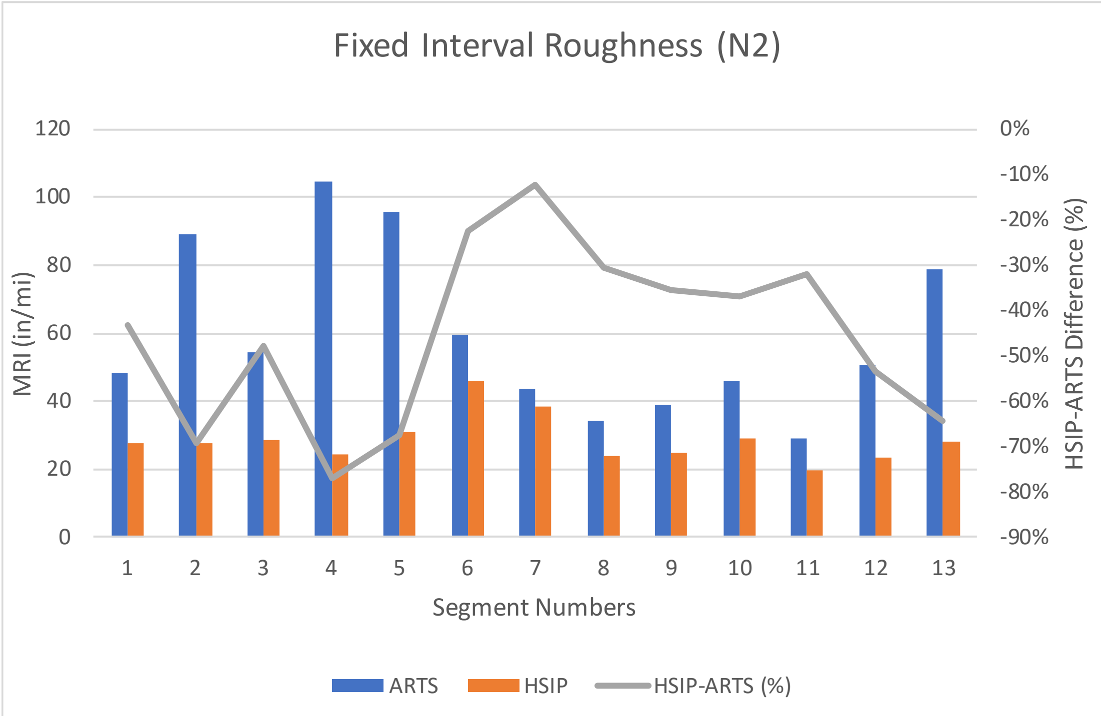


Figure 44. Demo No. 2 – Comparison of fixed-interval MRI values for ARTS and HSIP for northern section 2.

4.7.4.2 Southern Sections

SECTION 1

Figure 45 shows the fixed-interval IRI report for the ARTS (top chart) and HSIP (bottom chart) data for northern section 2, using a 52.8-ft segment and 60 in/mi threshold for reference. These charts show that the HSIP roughness is much lower than ARTS roughness.

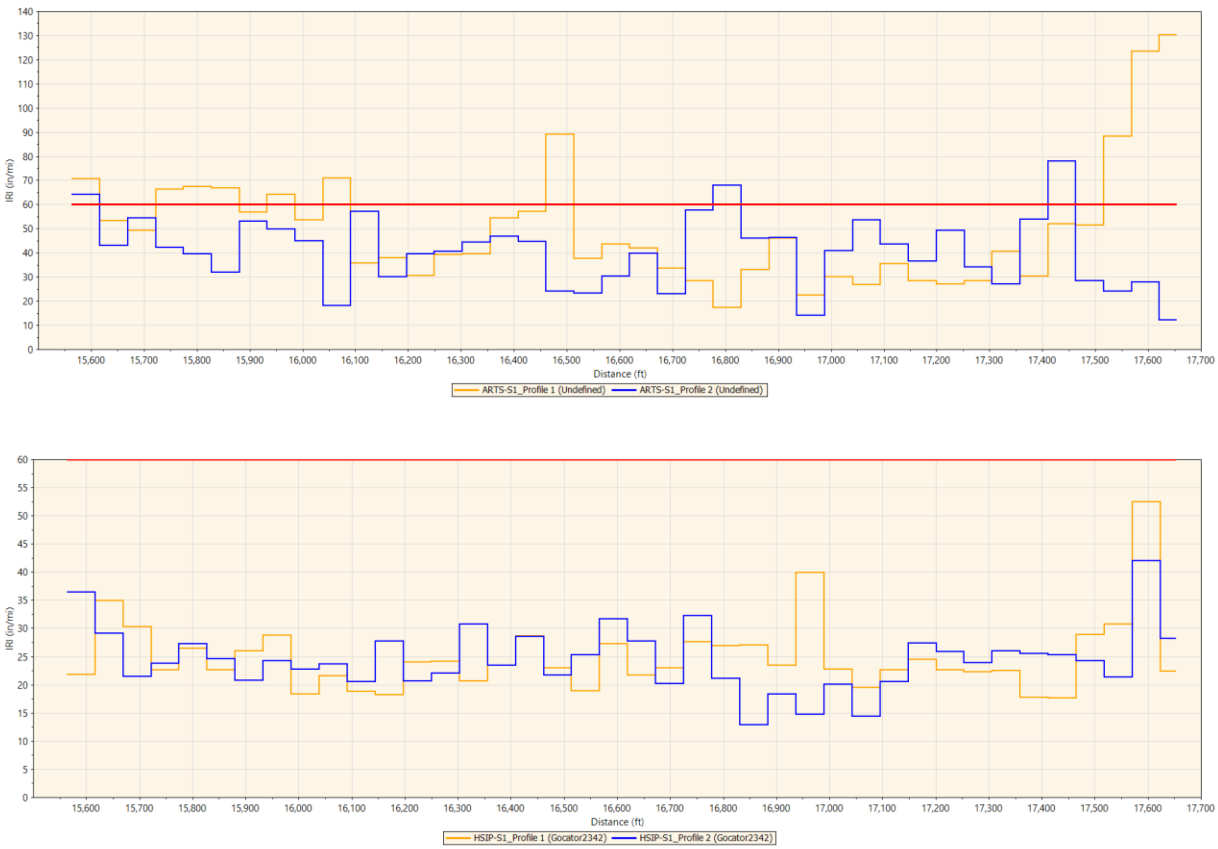
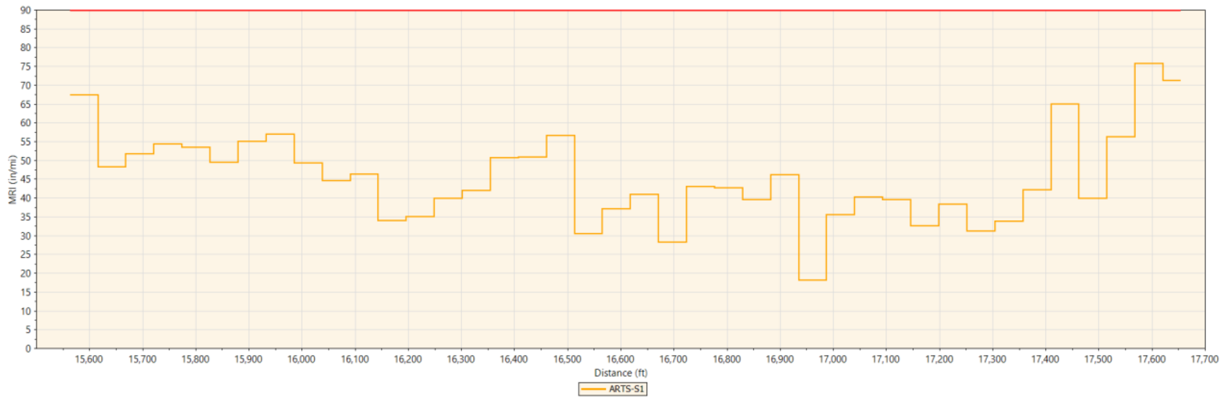


Figure 45. Demo No. 2 – Comparison of fixed-interval IRI for ARTS (top) and HSIP (bottom) for southern section 1.

To simplify the comparison, Figure 46 shows a fixed-interval report for MRI with a 52.8 ft segment length and 90 in/mi threshold for reference. Figure 47 shows a side-by-side comparison of the results, indicating that the HSIP roughness was much lower.



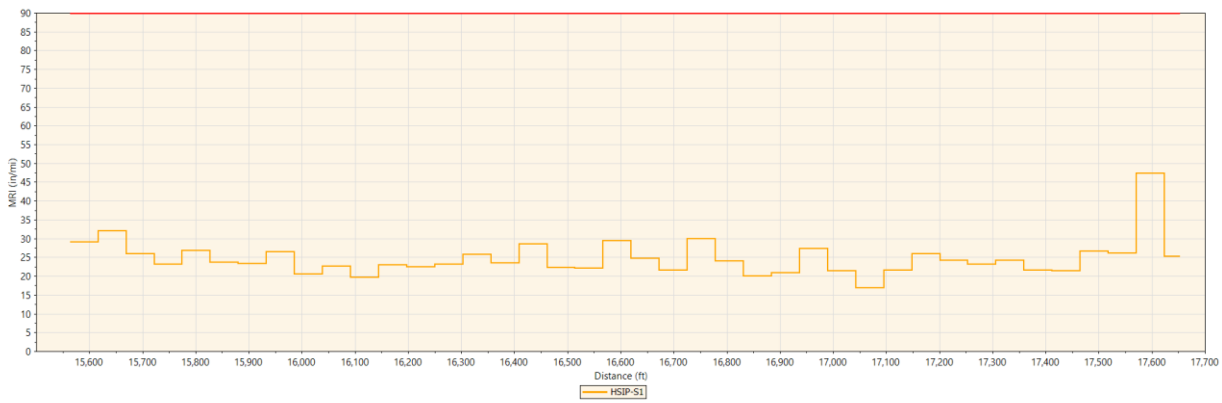


Figure 46. Demo No. 2 – Comparison of fixed interval MRI plots for ARTS (top) and HSIP (bottom) data for Southern section 1.

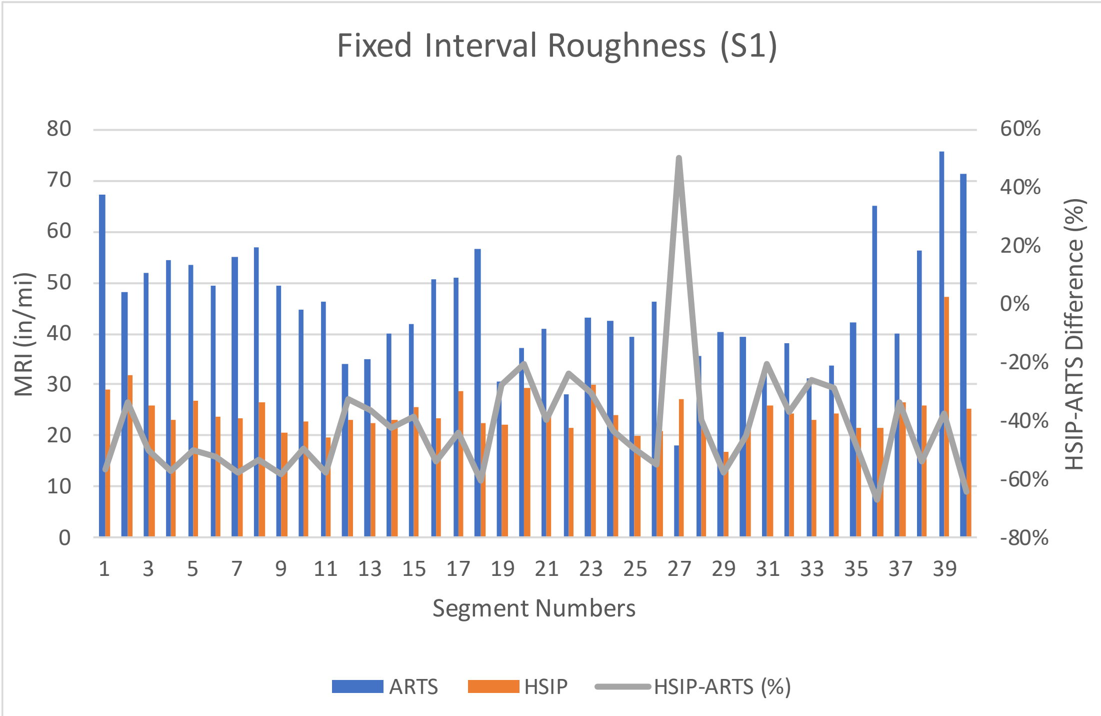
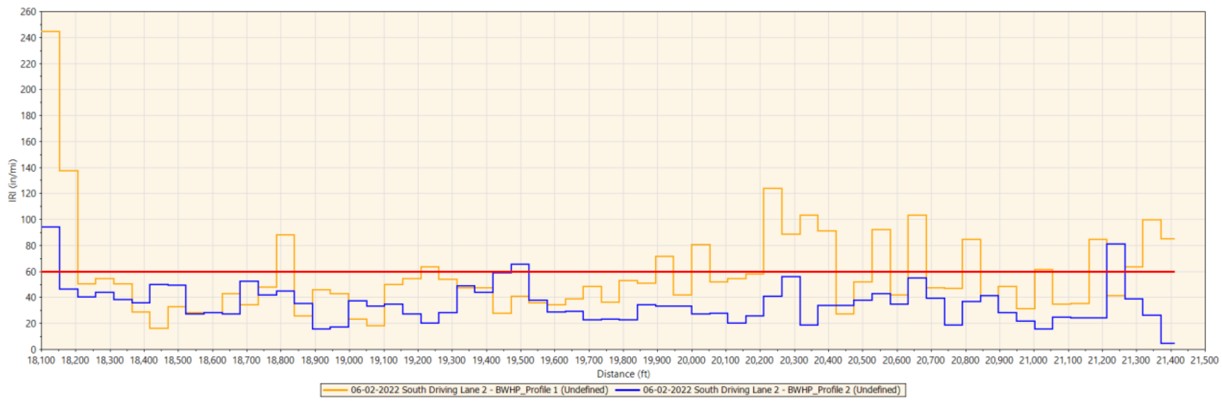


Figure 47. Demo No. 2 – Comparison of fixed-interval MRI values for ARTS and HSIP data for southern section 1.

Figure 48 shows the fixed-interval IRI reports for ARTS (top chart) and HSIP (bottom chart) data for northern section 2, using a 52.8-ft segment length and 60 in/mi threshold for reference. The ARTS RWP roughness is generally lower than LWP, possibly due to the LWP being close to the high side on several super elevation sections. These charts show that the HSIP roughness was much lower than ARTS roughness.



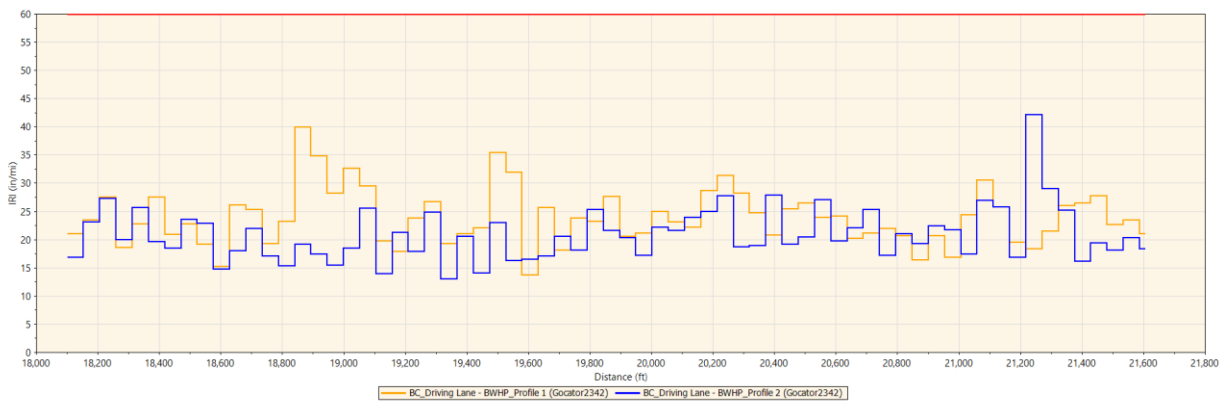
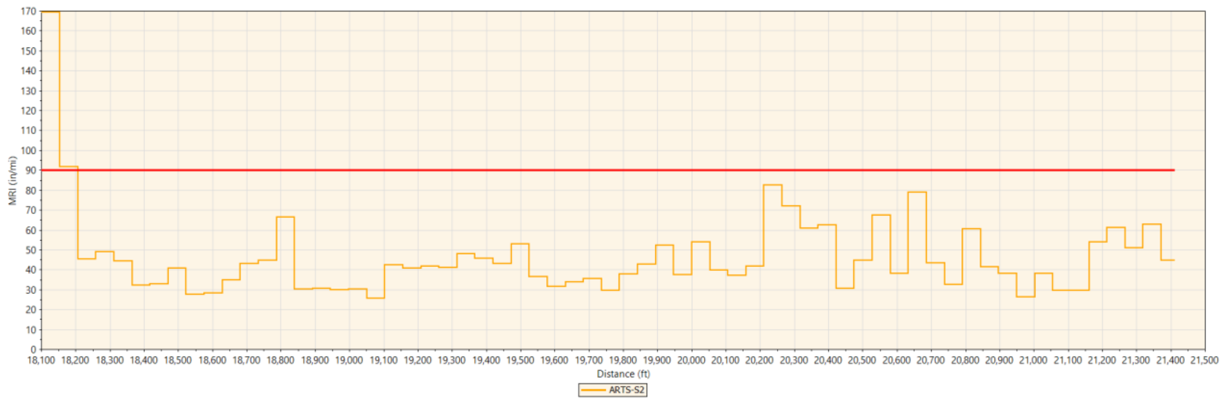


Figure 48. Demo No. 2 – Comparison of fixed-interval IRI for ARTS (top) and HSIP (bottom) for southern section 2.

Figure 49 shows a fixed-interval report for the MRI with a 52.8 ft segment length and 90 in/mi threshold for reference for the ARTS and HSIP data. A side-by-side comparison of the results in Figure 50 indicates that the HSIP roughness was much lower than the ARTS roughness.



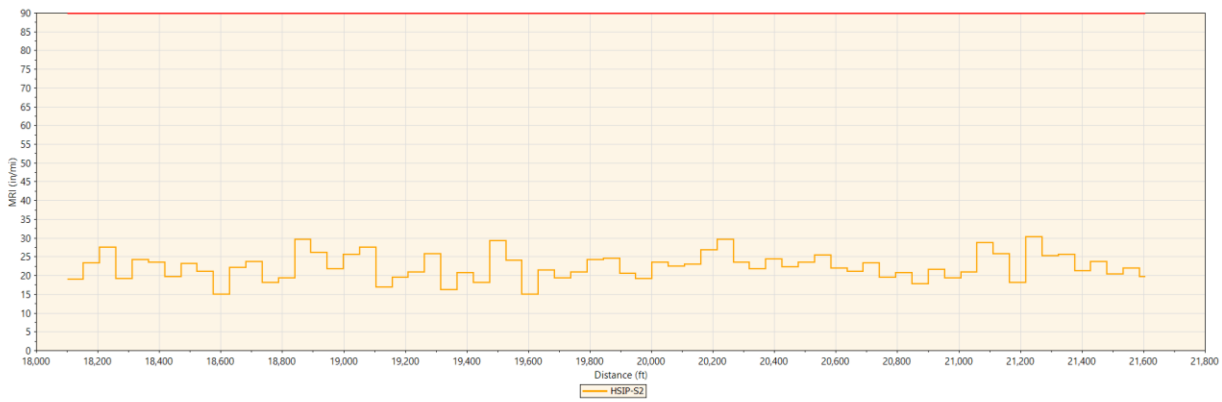


Figure 49. Demo No. 2 – Comparison of fixed-interval MRI plots for ARTS (top) and HSIP (bottom) data for Southern section 2.

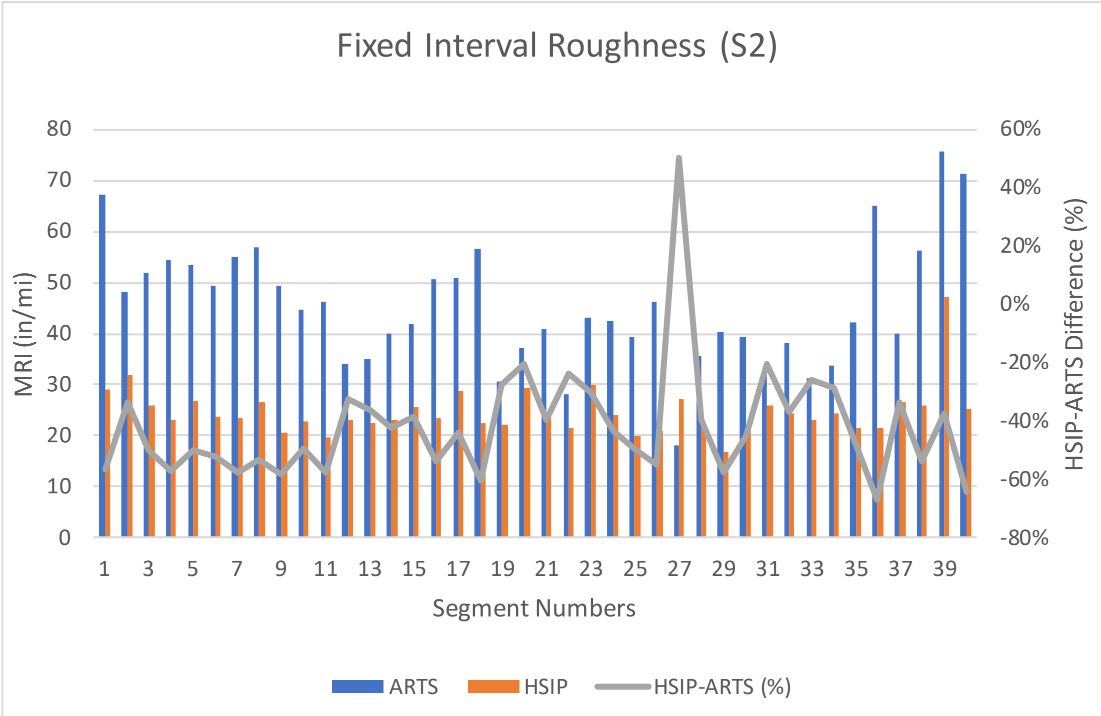


Figure 50. Demo No. 2 – Comparison of fixed-interval MRI values for ARTS and HSIP data for Southern section 2.

4.7.5 Localized Roughness Analysis

4.7.5.1 Northern Sections

The localized roughness report shows the extremely high values at the beginning and end of the northern sections before data extraction for the subsequent comparison, as shown in Figure 51. After removing the sections at the extreme ends, the data appears more reasonable, as shown in Figure 52.

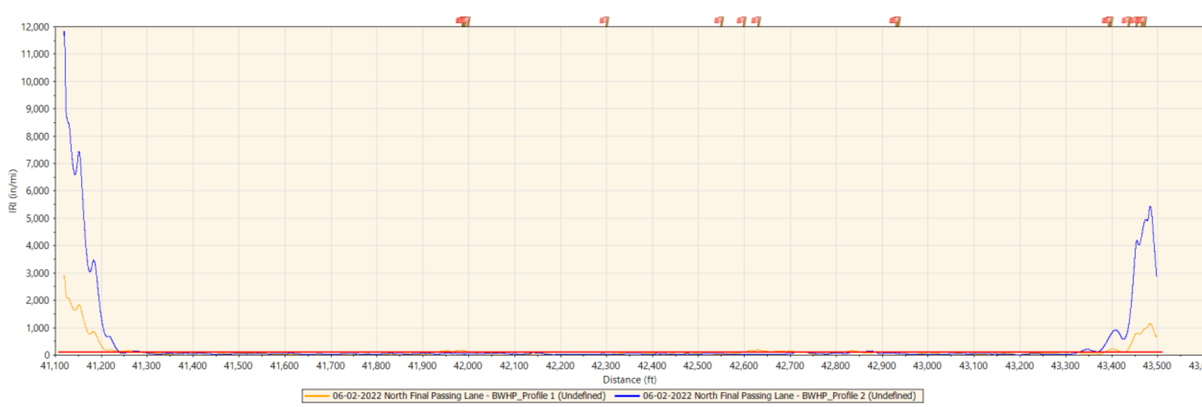


Figure 51. Demo No. 2 - ARTS localized roughness at ends of northern sections.

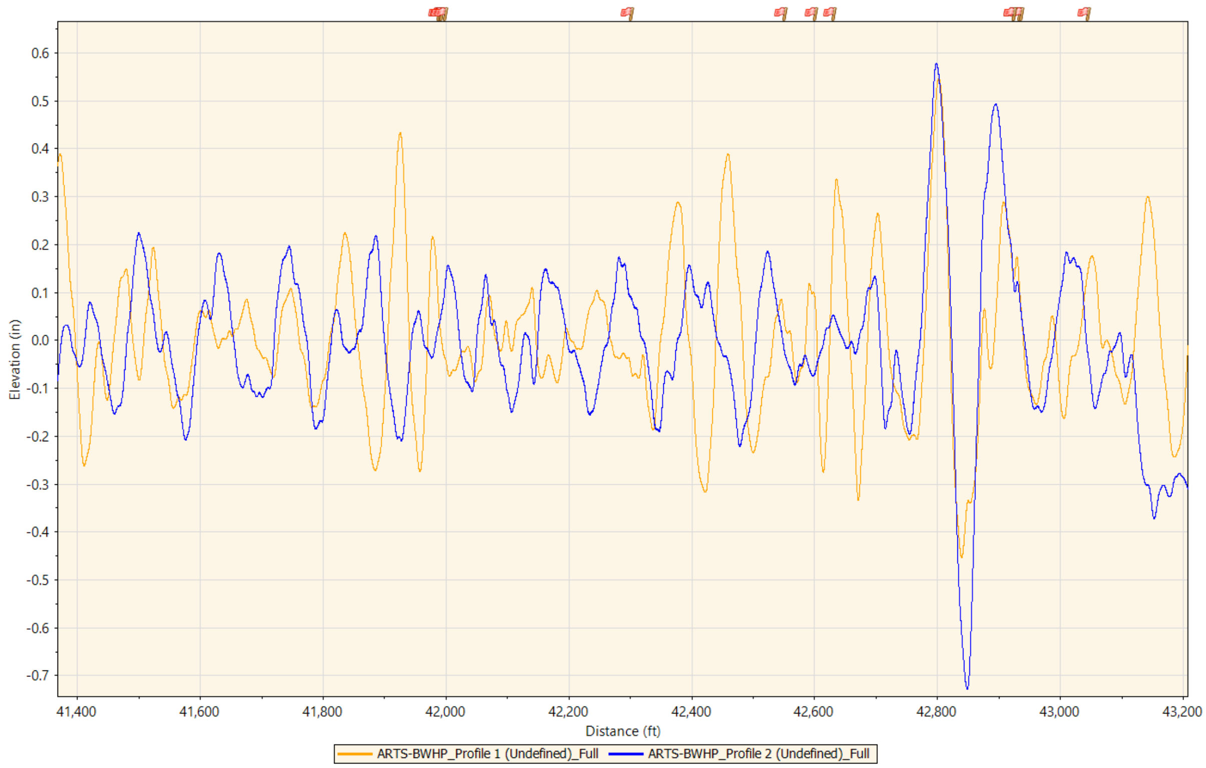


Figure 52. Demo No. 2 - ARTS elevation plot for northern section- cropped to exclude the beginning and end high roughness areas.

The event logs and observed roughness are summarized in Table 9.

Table 9. Demo No. 2 - ARTS event markers and observed roughness for the northern section.

Distance (ft)	Name	Notes
41983.36	KEY X (Spill)	LWP ALR is much higher than RWP ALR
41986.18	KEY X (Spill)	LWP ALR is much higher than RWP ALR
41988.17	KEY X (Spill)	LWP ALR is much higher than RWP ALR
41994.56	KEY X (Spill)	LWP ALR is much higher than RWP ALR
42296.94	KEY B (Vib on)	Both LWP and RWP ALR are similar

Distance (ft)	Name	Notes
42547.05	KEY C (LT Ext Slope)	Both LWP and RWP ALR are similar
42595.75	KEY V (RT Ext Slope)	LWP ALR is much higher than RWP ALR
42626.69	KEY V (RT Ext Slope)	LWP ALR is much higher than RWP ALR. No noticeable change in RWP ALR.
42920.03	Stopped at 8:57 AM	ALR ~ 80 in./mi. No noticeable changes.
42920.11	Resume at 9:03 AM	Same as above
42928.24	KEY Z (Stop)	No noticeable changes.
42931.89	KEY M (Other)	Same as above
43039.9	Left side tow arm pushed inwards against paver in a right-hand turn	ALR ~ 40 in./mi. very smooth. Very odd.
43377.71	Stopped at 9:23 AM	ALR ~ 200 in./mi. RWP ALR starts to rise to very high values after this event.
43377.95	Resume at 9:23 AM	Starting from here, the screed may move due to the change to slope control. The ARTS measurement may no longer be valid.
43389.73	KEY Z (Stop)	
43394.13	KEY M (Other)	

Distance (ft)	Name	Notes
43404.83	stop and start event was added late	ALR ~ 900 in./mi. (unrealistic) ALR starts to rise to very high values after this event, esp. for the RWP.
43433.45	KEY X (Spill)	
43450.38	KEY C (LT Ext Slope)	
43451.95	Stopped at 9:27 AM	ALR ~ 3,755 in./mi. (unrealistic) ALR starts to rise to very high values after this event, esp. for the RWP.
43451.95	Resume at 9:27 AM	
43462.57	KEY Z (Stop)	
43467.88	KEY M (Other)	
43470.79	skis going up end lip	ALR ~ 4,821 in./mi. (unrealistic) ALR starts to rise to very high values after this event, esp. for the RWP.
43501.39	Stopped at 9:30 AM	No ALR report since < 25 ft.
43501.48	Resume at 9:30 AM	
43501.48	Stopped at 9:30 AM	No ALR report since < 25 ft.
43501.73	Resume at 9:30 AM	
43502.39	Stopped at 9:30 AM	No ALR report since < 25 ft.

Distance (ft)	Name	Notes
43502.47	Resume at 9:30 AM	

In the northern section, ARTS and HSIP show high roughness at the beginning, as shown in Figure 53.

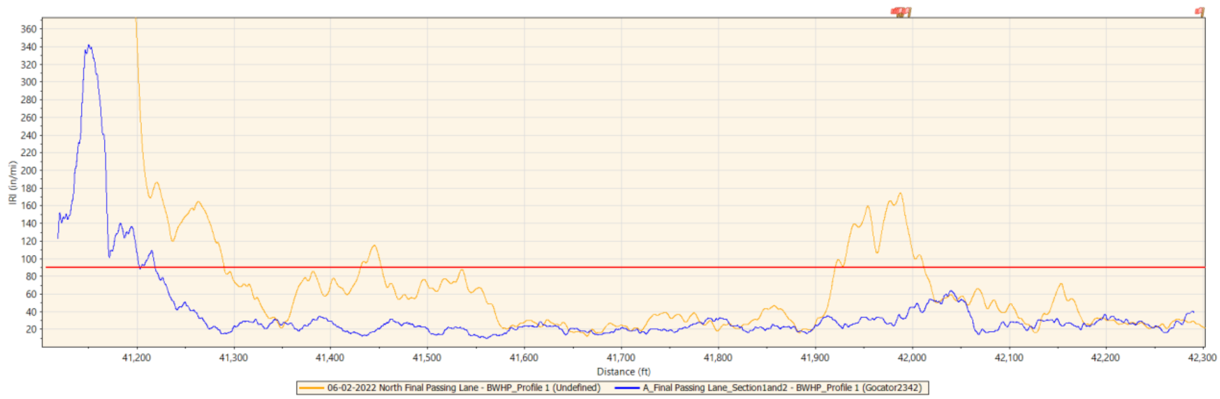


Figure 53. Demo No. 2 - ARTS and HSIP LWP localized roughness for the northern section - zoomed in to the beginning with high roughness areas.

ARTS and HSIP data also showed high roughness at the northern end of the northern section, as shown in Figure 54. This location is where the contractor tied in with the bridge with slope control instead of grade control, which moved the screed and the ARTS sensors.

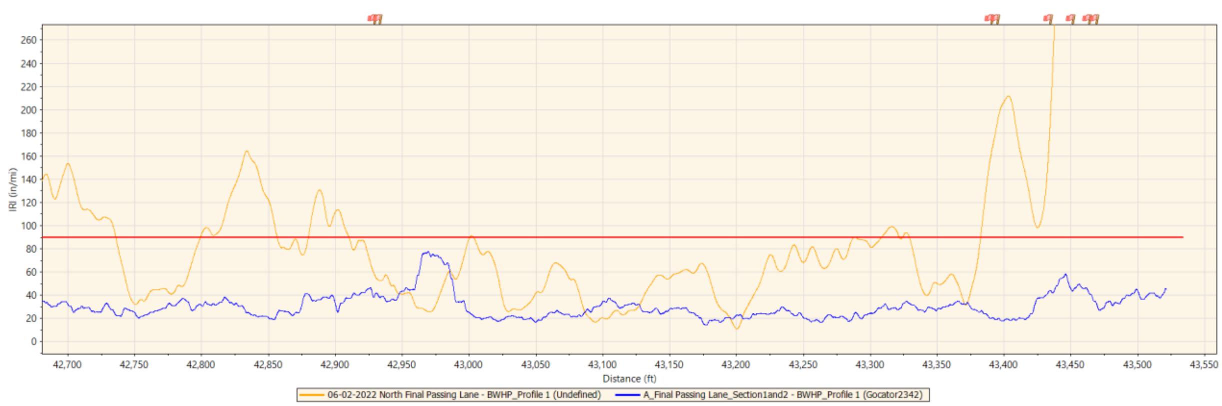


Figure 54. Demo No. 2 - ARTS and HSIP LWP localized roughness - zoomed in to the high roughness areas at the end of the northern section.

Figure 55 shows the ALR report for Section 1 for both the ARTS and HSIP data. HSIP ALR is much lower than ARTS ALR, likely due to compaction effects. The cyclic ALR pattern in the ARTS RWP is not present in the HSIP data. The high LWP ALR in the ARTS data between Station 41900 and 42000 is also not present in the HSIP data. The ARTS and HSIP ALR tend to converge in some areas, such as Station 42021-42050 and 42180 – 42283.

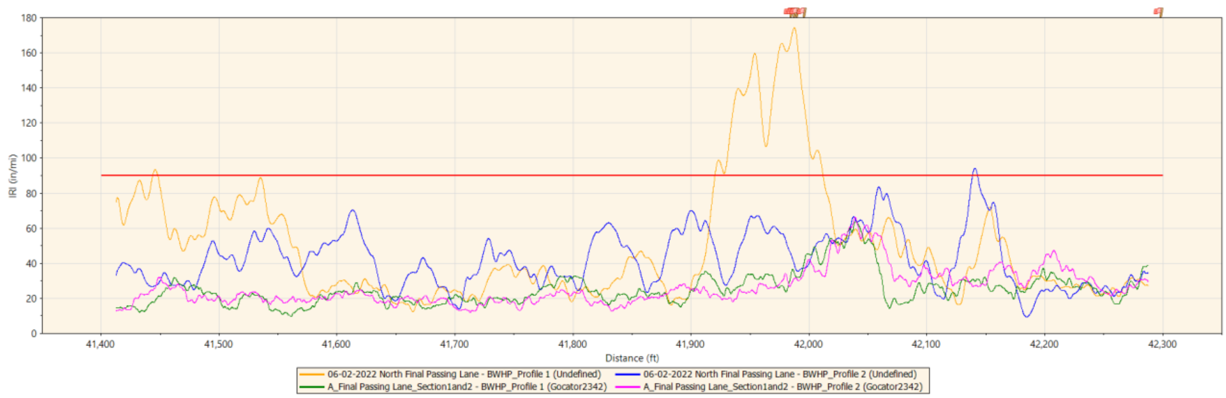


Figure 55. Demo No. 2 – Comparison of localized roughness from ARTS and HSIP for northern section 1.

Figure 56 shows ALR for Section 2 for both the ARTS and HSIP data. Section 2 displays similar ALR trends to that of Section 1.

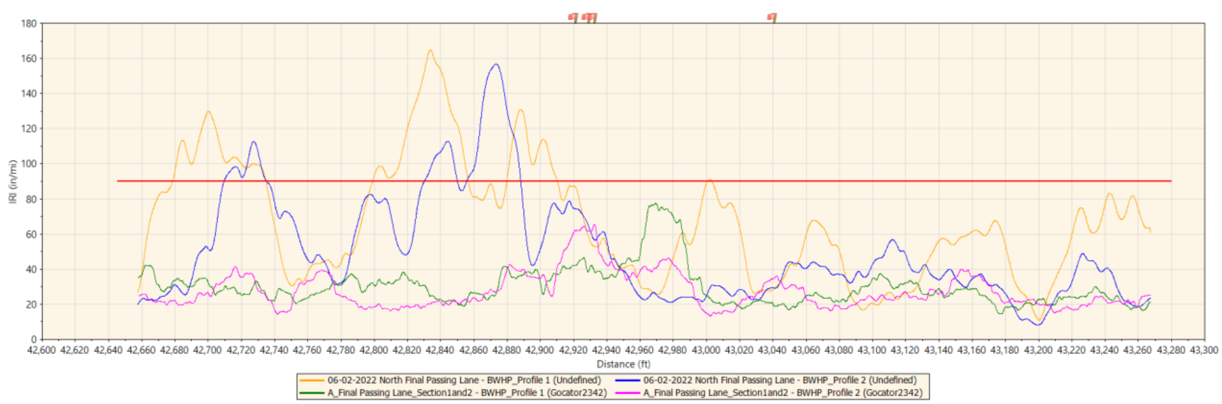


Figure 56. Demo No. 2 – Comparison of localized roughness from ARTS and HSIP for northern section 2.

4.7.5.2 Southern Sections

SECTION 1

The ARTS localized roughness report for southern section 1 is shown in Figure 57. The extremely high localized roughness at the beginning section may be due to false data collection (e.g., due to the movement of the ARTS sensors-screed assembly) and needs to be excluded from the analysis.

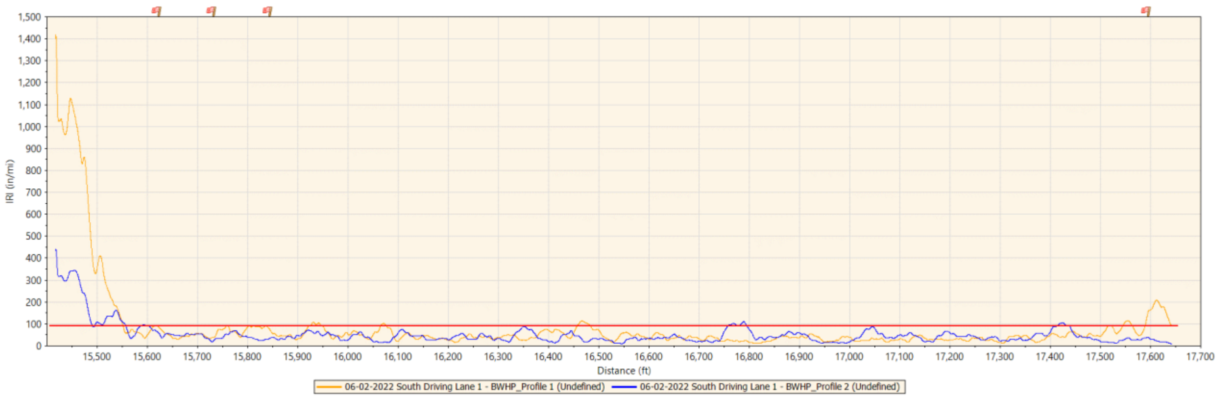


Figure 57. Demo No. 2 - ARTS localized roughness for southern section 1.

The event logs and observed roughness for southern section 1 are summarized in Table 10.

Table 10. Demo No. 2 - ARTS event markers and observed roughness for southern section 1.

Distance (ft)	Name	Notes
15620.27	KEY V (RT Ext Slope)	RWP ALR drops
15728.86	KEY B (Vib on)	Both LWP and RWP ALR increase
15840.85	KEY X (Spill)	RWP ALR increases a little, but LWP ALR drops.
16090.39	Raised left side of the screed	ALR for LWP and RWP cross over at 40 in./mi. Then, the RWP's ALR increased and peaked at 70 mi./mi. after 20 ft.
16268.67	right side screed down slightly	ALRs are 54 and 39 in./mi. for RWP and LWP. Both RWP and LWR's ALR decrease afterward.
16382.23	Right-hand side tow point rubbing against paver frame, left-hand turn	ALRs are 30 and 67 in./mi. for RWP and LWP. The RWP's ALR decreases.
16394.01	right tow point oscillating about 1hz	ALRs are 28 and 74 in./mi. for RWP and LWP.
16426.12	turned off automatic sonic control, right side screed vibration stopped	ALRs are 49 and 61 in./mi. for RWP and LWP.
16430.52	sonic control back on, screed vibration back on	ALRs are 51 and 57 in./mi. for RWP and LWP. Then RWP's ALR rises slightly to peak at 68 in./mi. Before dropping, while LWP's ALR decreases, then increases when the RWP's ALR is at the peak of 68 in./mi. Then, RWP's ALR decreases to extremely low values.

Distance (ft)	Name	Notes
16811.37	automatic control off	ALRs are 32 and 13 in./mi. for RWP and LWP. The RWP dropped from the peak of 110 in./mi. About 20 ft. earlier.
16856.83	auto control back on, modified settings	ALRs are almost identical at 40 in./mi. for RWP and LWP. RWP's ALR increases slightly afterward, but LWP's ALR remains similar.
17222.1	small spill right-hand side	ALRs are 40 and 33 in./mi. for RWP and LWP. RWP's ALR increased and peaked at 52 in./mi. about 15 ft later.
17592.09	KEY Z (stop)	LWP ALR increases

The comparison of localized roughness between ARTS and HSIP is shown in Figure 58. Generally, HSIP roughness is much lower than ARTS.

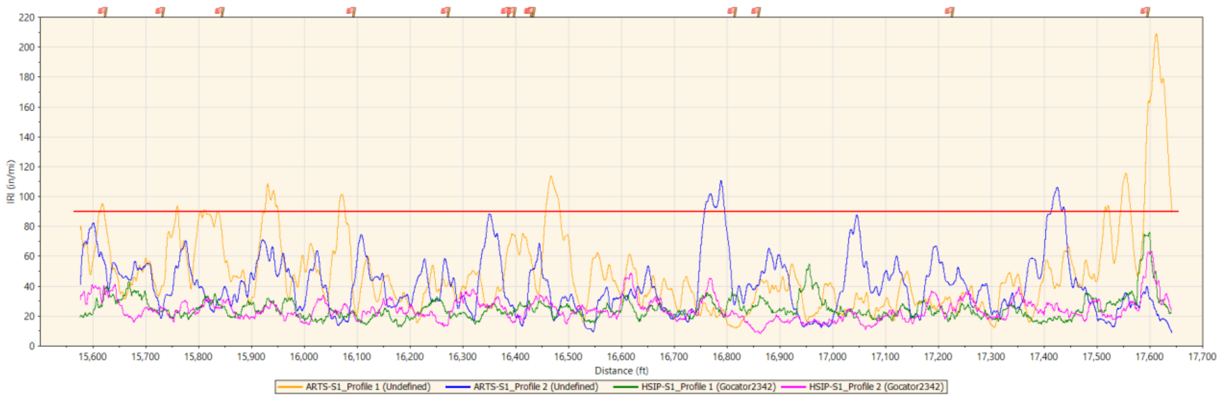


Figure 58. Demo No. 2 – Comparison of the localized roughness for ARTS and HSIP data for southern section 1.

SECTION 2

The ARTS localized roughness for southern section 2 is shown in Figure 59. The extremely high localized roughness at the beginning section may be due to the false data collection (e.g., from the movement of the ARTS sensors at startup) and needs to be excluded from the analysis.

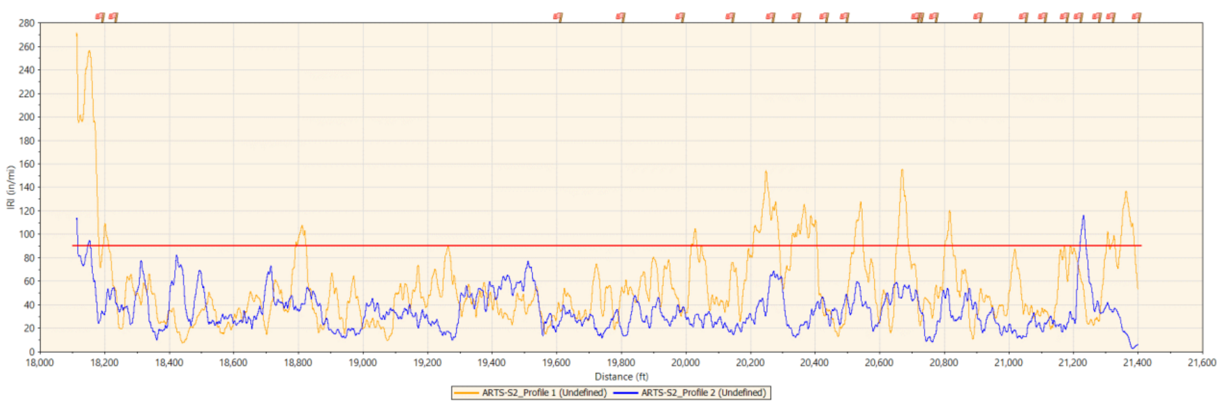


Figure 59. Demo No. 2 - ARTS localized roughness for southern section 2.

The event logs and observed roughness for southern section 2 are summarized in Table 11.

Table 11. Demo No. 2 - ARTS event markers and observed roughness for southern section 2.

Distance (ft)	Latitude	Longitude	Name	Notes
18187.77	45.14699	-89.6415	changed automatic control system settings	ALRs are 44 and 77 in./mi. for RWP and LWP. RWP's ALR decreased afterward, but LWP's ALR increased.
18229.66	45.1471	-89.6416	auto control was changed back to the original settings, no longer in a turn	ALRs are 52 and 60 in./mi. for RWP and LWP. Both RWP and LWP's ALRs decreased afterward to very low levels (37/17 in./mi.).
19605.18	45.15071	-89.6431	begin truck dump	ALRs are 22 and 41 in./mi. for RWP and LWP. Both RWP and LWP's ALRs increased afterward to peak at 39/54 in./mi. after 15 ft and 20 ft, respectively
19800.54	45.15123	-89.6433	begin truck dump	ALRs are 18 and 54 in./mi. for RWP and LWP.
19984.38	45.15171	-89.6435	begin truck dump	ALRs are 30 and 34 in./mi. for RWP and LWP.
20140.34	45.15212	-89.6437	begin truck dump	ALRs are 19 and 73 in./mi. for RWP and LWP.
20263.95	45.15245	-89.6437	begin truck dump	ALRs are 66 and 113 in./mi. for RWP and LWP.

Distance (ft)	Latitude	Longitude	Name	Notes
20343.83	45.15267	-89.6438	begin truck dump	ALRs are 15 and 100 in./mi. for RWP and LWP.
20431.02	45.1529	-89.6439	KEY X (Spill)	
20494.23	45.15307	-89.6439	begin truck dump	ALRs are 48 and 30 in./mi. for RWP and LWP.
20714.57	45.15367	-89.644	begin truck dump	ALRs are 51 and 60 in./mi. for RWP and LWP.
20724.28	45.1537	-89.644	KEY X (Spill)	An unknown event causes ALRs to decrease to very low levels (< 10 in./mi. for RWP).
20770.23	45.15371	-89.644	KEY X (Spill)	
20906.28	45.15371	-89.644	screed up a little	ALRs are 27 and 34 in./mi. for RWP and LWP. LWP's ALR increased afterward and peaked at 54 in./mi. 6 ft later.
21047.15	45.15371	-89.644	begin truck dump	ALRs are 13 and 35 in./mi. for RWP and LWP.
21108.04	45.15371	-89.644	small spill	ALRs are 22 and 34 in./mi. for RWP and LWP. No noticeable changes afterward.

Distance (ft)	Latitude	Longitude	Name	Notes
21174.07	45.15371	-89.644	spray encoder wheel	ALRs are 20 and 88 in./mi. for RWP and LWP.
21218.45	45.15371	-89.644	KEY X (Spill)	RWP ALR increases
21274.7	45.15371	-89.644	KEY X (Spill)	LWP and RWP ALRs cross-over, then LWP ALR increases
21317.34	45.15371	-89.644	KEY X (Spill)	LWP ALR is high
21398.3	45.15371	-89.644	rain	Stop ARTS data collection But paving resumed after the rain

The comparison of localized roughness between ARTS and HSIP is shown in Figure 60. Generally, HSIP roughness is much lower than ARTS.

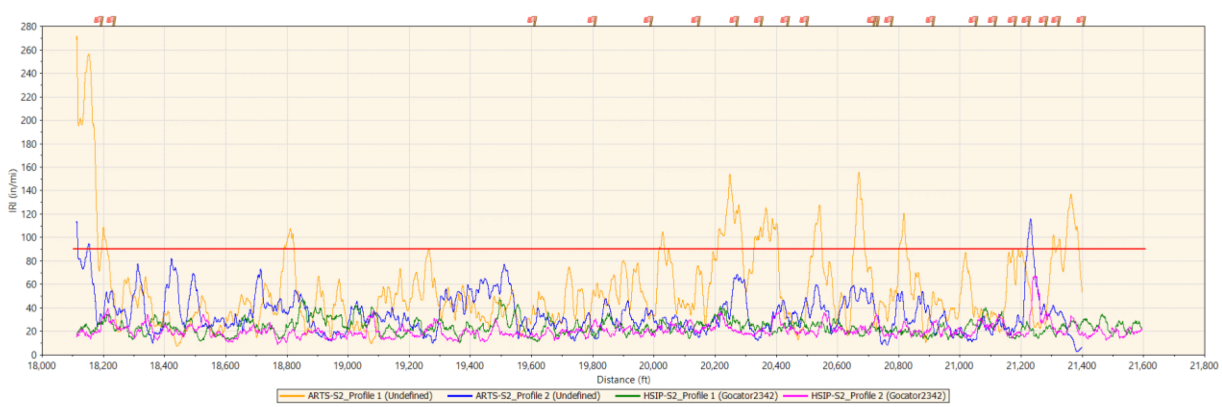


Figure 60. Demo No. 2 – Comparison of the localized roughness for ARTS and HSIP data for Southern section 2.

4.7.6 Power Spectral Density (PSD) Analysis

4.7.6.1 Northern Sections

SECTION 1

Figure 61 compares the PSD analysis for the ARTS and HSIP data for northern section 1. Note that much of the longer wavelength content in the ARTS data is not present in the HSIP data.

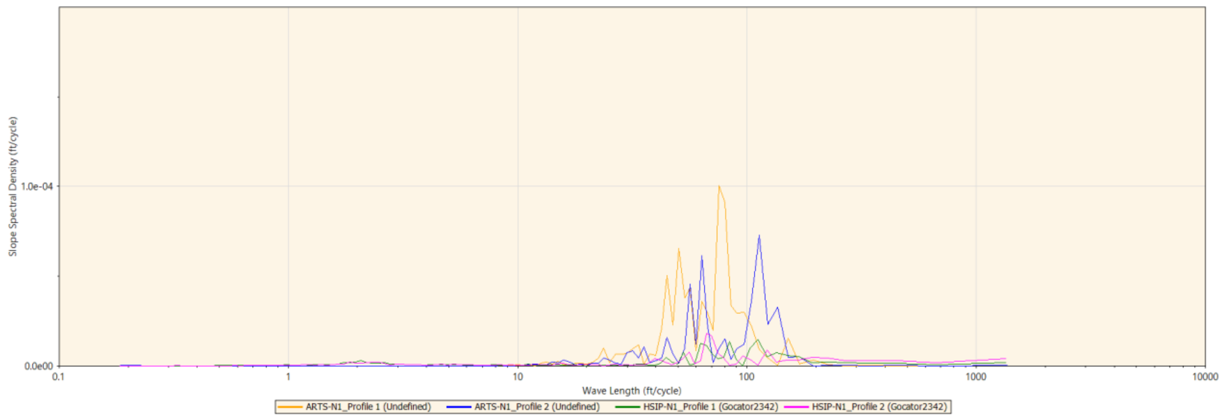


Figure 61. Demo No. 2 – Comparison of PSD between ARTS and HSIP for northern section 1.

SECTION 2

Figure 62 compares the PSD analysis for the ARTS and HSIP data for northern section 2. Similar to Section 1, much of the longer wavelength content in the ARTS data is not present in the HSIP data.

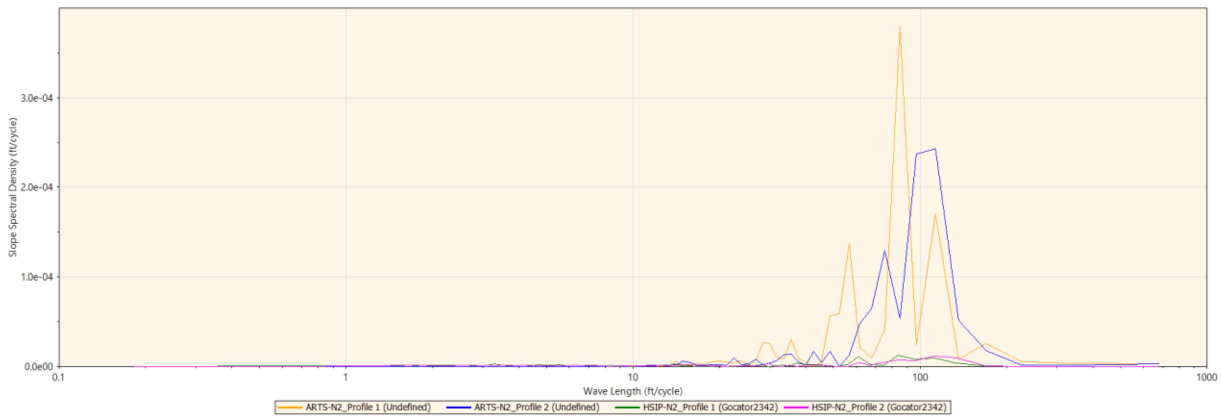


Figure 62. Demo No. 2 – Comparison of PSD between ARTS and HSIP for northern section 2.

4.7.6.2 Southern Sections

SECTION 1

Figure 63 compares the PSD analysis for the ARTS and HSIP data for southern section 1. The ARTS PSD shows significantly higher values than HSIP between 10 ft and 100 ft, which is the opposite for wavelengths below 10 ft. This indicates that the roller compaction likely reduced the wavelength between 10 and 100 ft.

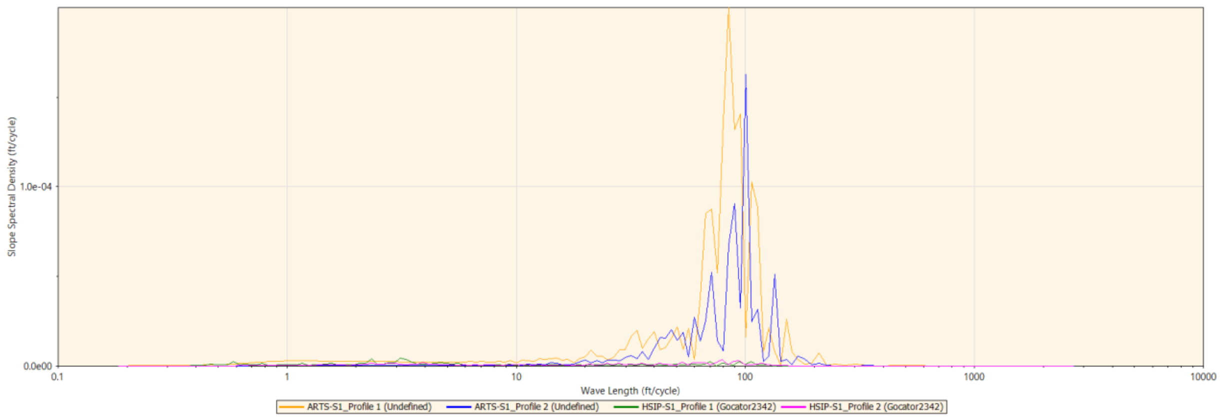


Figure 63. Demo No. 2 – Comparison of PSD between ARTS and HSIP for southern section 1.

SECTION 2

Figure 64 compares the PSD analysis for the ARTS and HSIP data for southern section 2. Similar to section 1, the ARTS PSD shows significantly higher values than HSIP between 10 ft and 100 ft, although it is more pronounced in the LWP. Again, this indicates that the roller compaction likely reduced the wavelength between 10 and 100 ft.

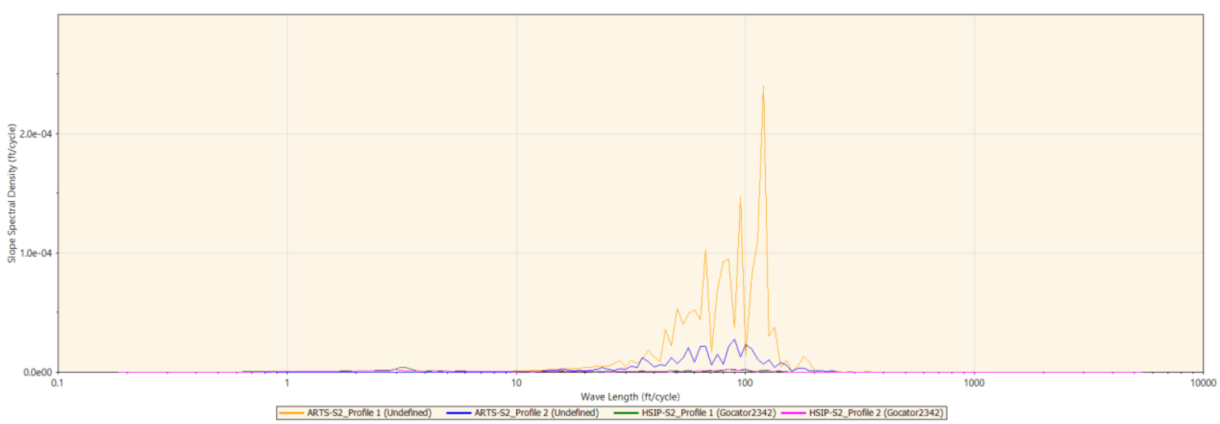


Figure 64. Demo No. 2 – Comparison of PSD between ARTS and HSIP for southern section 2.

CHAPTER 5: DISCUSSION

The following are discussions among the research team partners and TAP members regarding the ARTS demonstration findings.

5.1 MAJOR DIFFERENCES BETWEEN DEMO 1 AND DEMO 2

Demo 1 was a rural paving project with hills and valleys. Demo 2 was a typical highway construction with relatively straight lines of paving. The observed roughness events and levels were different between Demo 1 and Demo 2. Therefore, caution must be taken when interpreting the results from both demos.

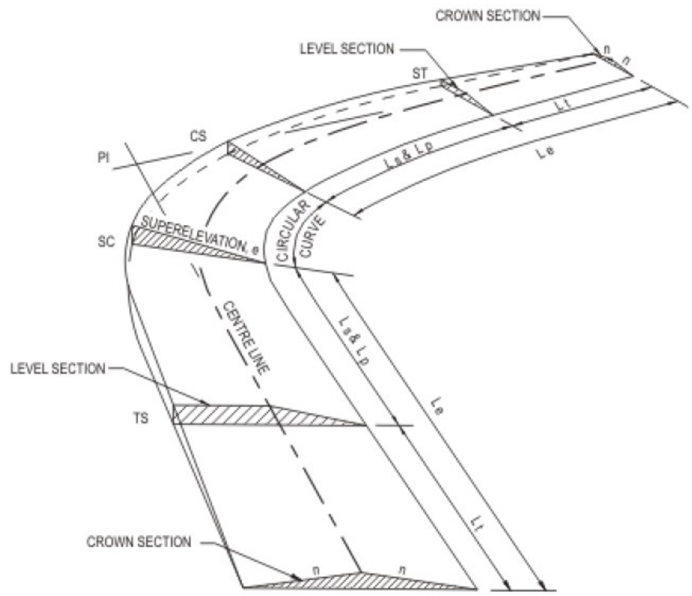
5.2 EFFECTS OF PAVER SETTINGS AND CALIBRATION ON SMOOTHNESS

For Demo 2, the automatic grade control system was calibrated earlier in the season but not before this demonstration. There could be a mechanical or electrical issue, or the tow point solenoid valve may need replacement. Different dead-bands and valve speed settings were adjusted before this demonstration, but no different results. Due to the rigid mounting of the ARTS sensors to the screed, the ARTS measurements could be amplified during the tow-point “hunting” or “adjusting to achieve equilibrium” but not necessarily reflected in the actual asphalt mat’s roughness. This may explain the significant differences between ARTS and HSIP roughness for Demo 2 but not for Demo 1. However, the above observation and analysis can be limited due to excellently smooth pavements (IRI in 20’s in./mi.) for Demo 2.

5.3 PAVER OPERATION’S EFFECTS ON SMOOTHNESS

For Demo 2, the head of material (mix height) appeared to have an issue that the right-side conveyor/auger speed did not change after adjusting the feed system to maintain a constant (and equal) head of material on both sides, including re-positioning the sonic feed sensors and conveyor settings. Therefore, the right-side feed was not controllable, resulting in a higher head of material on the right side. This equates to the expectation of more variability in the right wheel path. This appeared to be a machine issue with the right-side feed system control.

Another factor influencing left-side and right-side real-time smoothness is when the paver goes through a superelevation. This causes the tow to “hang up” on the frame due to a thick after-market nylon block, and then the tow arms flick when they break free of the friction on the tractor frame. Two or three super-elevated sections may result in higher roughness in the high-side wheel path. The contractor noticed approximately 5 to 10 in/mile higher IRI on the “high side,” where this effect was happening on other projects. (Figure 65 and Figure 66) Based on results from Section 4.7.3, the ARTS’ LWP IRI is consistently higher than the RWP IRI.



Source: (Mansell, 2022)

Figure 65. Paving through superelevation may cause contact between the paver's tow arm and frame at the high side – Part 1.

Source: (Mansell, 2022)

Figure 66. Paving through superelevation may cause contact between the paver's tow arm and frame at the high side – Part 2.

5.4 EFFECTS OF USING MTV

Demo 2 used an MTV for material delivery, but Demo 1 used an end dump. The truck exchanges were noticeable in the ARTS data for Demo 1 but not in Demo no. 2. However, if the hopper of MTV was running low, truck exchanges may still have effects even with MTV. Any possible variation in the head of material (mix height) at the screed may also affect the results.

5.5 SCREED AND ARTS SENSORS' MOVEMENTS

The screed's movements would affect the ARTS sensors' measurement as the ARTS sensors are rigidly connected to the screed. A such limitation was discussed in Chapter 2. It was also observed during Demo 2's northern section testing. The ARTS data within the areas of screed movement need to be excluded from the analyses.

5.6 GENERAL DISCUSSION

This study will help the industry understand the following asphalt paving issues to fine-tune further operations to maximize as-constructed smoothness. Due to the known limitations of the current ARTS sensors (Chapter 2), the following descriptions are limited to the observations of the two field demonstrations and cannot be generalized.

- Can the ARTS sensors be positioned to identify paving issues (equipment setup, condition, or operation), such as segregation (gearbox, end of the load), truck bumps, etc.?
  >> The ARTS data reflected on some of these events (e.g., Demo 1) but not the cases when MTV reduces or eliminates the effects of those events (e.g., Demo 2). Also, the ARTS sensors are limited to measuring only the two-wheel tracks instead of the entire mat width.
- Can the ARTS sensors help identify the causes of localized roughness (short wavelength) by the paver, the roller, or both?
  >> Both the ARTS and HSIP data are needed to investigate these questions. Generally, the localized roughness is higher in ARTS data than in the HSIP. However, this does not necessarily indicate the effects of compaction to reduce localized roughness due to the mounting design of the ARTS sensors attached to the screed.
- Can the ARTS sensors identify long-wavelength roughness and whether it is caused by paver operation? The factors include screed angle of attack, auger speed/position, smoothness electronics for joint matching, skis (contact vs. non-contact) for longitudinal smoothness, slope control, and so forth.
  >> Based on the PSD results, the ARTS sensors data did identify long wavelengths by the paving operation. There were significant differences in roughness between grade control (with contact skis) and slope control (e.g., Demo 1). The long-wavelength content was reduced by rolling (e.g., Demo 1). However, the other factors mentioned in this question were not completely identified during the demonstrations. For future study, improved ARTS mounting mechanism and other

essential measurements such as recorded tow point movement data and the changes in screed angle of attacks will provide additional insights.

- What is the effect of paver speed vs. roller speed on smoothness?
  >> The paver speed was approximately constant (e.g., 24 ft/min. for Demo 2). The roller speeds or impacts per foot were not monitored with IC. Therefore, limited results from the field demonstration.
- Is the asphalt pavement surface smoother directly behind the paver or after rolling?
  >> The limited demonstration data show that the asphalt surface was smoother after rolling based on comparing the ARTS and HSIP data.
- What is the influence of the smoothness of the underlying surface? Is it more important for the rollers to compact to a consistent height (datum) or a consistent thickness that mirrors the underlying surface?
  >> Based on qualitative observation, the underlying surface does influence the smoothness, as shown during Demo 1. However, the high roughness from Demo 1 may also be influenced by a more challenging paving conditions such as vertical grades. The roller compaction question is beyond the project scope and should be more adequately answered by 3D paving project data.

CHAPTER 6: CONCLUSIONS

An ARTS prototype was designed, produced, and tested at two field demonstration projects. The goal was to prove the concept's feasibility and better understand the capabilities and limitations of a selected prototype. The following conclusions can be drawn based on qualitative field observations and quantitative data analysis.

Overall:

- The concept of ARTS can be realized in real-world paving jobs, as demonstrated in two field projects under this study.
- Demonstration project no. 1 was a local county paving job with a poor existing surface and challenging paving conditions such as vertical grade changes, cross slopes, intersections, and driveways. The ARTS and HSIP data reflected this project's high level of roughness, and the ARTS accurately predicted, during paving, the roughness anticipated from the finished pavement surface.
- Demonstration project no. 2 was a typical highway mainline construction with MTV on relatively flat terrain. The ARTS and HSIP data reflected the high smoothness of this project.

ARTS Sensors

- It should be stressed that the comments are limited to the selected ARTS prototype under this study and do not apply to other ARTS designs and solutions.
- The installation of the ARTS prototype on a paver required a specially designed bracket for a given screed model. The installation process was straightforward, so long as the paver or a power generator could provide the ARTS power supply.
- The ARTS prototype functioned well, as the temperatures around the sensors were kept under 120 °F by a cooling system.
- The ARTS prototype required a DMI wheel that used a solid tire. The slight indent that the DMI wheel made on the fresh asphalt was eliminated after the breakdown roller compaction.
- Due to mounting the ARTS sensors onto a screed, any large screed movements could invalidate the ARTS data. Such situations include screed movements at the beginning of the paving and the transverse joint matching at the end of the paving.
- Since the ARTS prototype was not certified under AASHTO R 56, the analysis results of the ARTS data can be considered relative values.

Paving Operation and ARTS Sensor Data

- The ARTS real-time data display reflected the changes in paver operations such as paver stops, slope control, grade control, spilled asphalt from the paver’s hopper, asphalt trucker exchanges, vertical curves, cross slopes, etc. The effects were more pronounced when MTV was not used.

- However, some technical panel members have questions about the reliability of the high roughness from ARTS during demonstration project 2. Further investigation of the ARTS hardware and software changes between demonstrations 1 and 2 is thus warranted.

ARTS Data vs. HSIP Data

- The HSIP data are consistently smoother than the ARTS data. However, the roughness difference is much more significant for demonstration project 2 (surface layer placement on a highway paving job) than for demonstration project 1 (intermediate layer placement on a low-volume road).
- The long wavelength content of the ARTS roughness behind the paver was reduced by roller compaction, as reflected in the HSIP data.

CHAPTER 7: RECOMMENDATIONS

The research team proposes the following recommendations for future ARTS development and implementation.

- An ARTS system can help identify paver equipment issues, settings, or operational practices in real time during paving.
- An improved ARTS system would be less intrusive to paving operations with improved mounting designs to avoid paver operation's inconvenience.
- Further field demonstration should include various approaches for ARTS to encourage innovative solutions, esp. to exclude the effects of screed movements.
- In addition to the report of AASHTO R54 IRI moving average as localized roughness, additional deviation reports (e.g., rolling straightedge simulation) are recommended to be included since some DOTs still use such requirements in their smoothness specification.
- Future field demonstrations should consider additional measurements, including the tow-point movements and screed/ARTS acceleration or movements, which could provide further insights into the benefits of ARTS.
- Future test plans should include focused analysis in areas where typical events such as truck exchange resulting in low mix levels in the hopper or hopper insert, turning with tow arm bearing against the mainframe, screed extending/retracting, head of material fluctuation, varying paving speeds, screed movements, etc. These events could be manually induced, and the ARTS results can be documented to compare with results from controls or standard proper paving practices.
- Further observations should also be made before and after the changes of paver setting, such as re-positioning the sonic feed sensors and conveyor settings, tow to “hang up” on the frame, etc., to provide helpful information on the paver settings and operations effects on smoothness.

CHAPTER 8: BIBLIOGRAPHY

AASHTO. (2018). *Standard Practice for Accepting Pavement Ride Quality When Measured Using Inertial Profiling Systems* (R 54-14). Washington, DC: AASHTO.

AASHTO. (2018). *Standard Practice for Certification of Inertial Profiling Systems* (R 56-14). Washington, DC: AASHTO.

ASTM. (2018). *Standard Test Method for Measuring the Longitudinal Profile of Traveled Surfaces with an Accelerometer-Established Inertial Profiling* (E950-09). West Conshohocken, PA: ASTM.

Dukatz, E. (2021). Communication with the ARTS technical panel.

FHWA. (2022). *Proven Technologies to Identify Surface Irregularities that can Impact Concrete Pavement Smoothness and Provide the Opportunity for Corrections in Real-Time, Tools to Improve PCC Pavement Smoothness During Construction (R06E)*. Retrieved from https://www.fhwa.dot.gov/goshrp2/Solutions/Renewal/R06E/Tools_to_Improve_PCC_Pavement_Smoothness_During_Construction

Mansell, T. (2022). Communication with the ARTS technical panel.

Narsingh, L. (2022a). *Paving 101 - Fundamentals of Paving & Screed Choices.* Paper presented at the Minnesota Transportation and Expo conference, May 18. Retrieved from https://www.is-ic.org/wp-content/uploads/2022/05/MTCE2022-ISIC-5-Narsingh.pdf

Narsingh, L. (2022b). Communication with the ARTS technical panel.

Rasmussen, R. O., Torres, H. N., Karamihas, S. M., Fick, G., & Sohaney, R. C. (2013). Real-Time Smoothness Measurements on Portland Cement Concrete Pavements During Construction (SHRP 2 report, S2-R06E-RR-1). Washington, DC: The National Academies Press. https://doi.org/10.17226/22767

Transtec Group. (2022). Profile Viewing and Analysis (ProVAL) software. Retrieved from https://www.roadprofile.com/