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Advancements in Profiler Certification

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16. Abstract

Repeatable, accurate, and reproducible measurement of a pavement's longitudinal profile is essential to supporting state and federal efforts related to the functional quality of the road system. A key ingredient to ensuring repeatable, accurate, and reproducible profile measurements is a robust profiler certification program that is based on AASHTO R 56, "Standard Practice for Certification of Inertial Profiling Systems." Under this standard, operators of inertial profilers are tested on their ability to operate the equipment and collect high-quality profile data. In recent years, the technology for inertial profilers has advanced to allow for stop-and-go operation, which is not fully addressed in the current version of AASHTO R 56. The current study was conducted to support the implementation of updated profiler certification methods that, in turn, yield high-quality measurements of roughness throughout a pavement's life. The study featured a national profiler roundup at the Illinois Certification and Research Track in the fall of 2024. This pilot certification event included 42 profilers operating on six pavement surfaces, followed by R 56 cross-correlation analysis of the collected profile data and comparison to the R 56 repeatability and accuracy standards. The testing included certification of vehicle-mounted profilers for constant-speed operation, certification of profilers for urban and low-speed operation, and certification for walking-speed profilers. This report details the profiler roundup and results and provides recommendations for advancing certification procedures and protocols in the future.

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The following were members of the Technical Review Panel (TRP):

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- Steven Miles, Ohio Department of Transportation
- Everett Schmitz, Pathway Services
- Larry Scofield, International Grooving and Grinding Association
- Larry Wiser, Federal Highway Administration

The authors of this report are grateful to the Illinois Department of Transportation (IDOT) for providing access to the Illinois Certification and Research Track (ICART) for this research. The authors are also grateful to the contractors, profiler manufacturers, state departments of transportation, and Federal Highway Administration (FHWA) for lending their staff and equipment to the research effort, as well as the profiler drivers and operators who traveled to ICART for their time, patience, expertise, and, in some cases, help in placing the chalk line.

Ken Winzeler, Nicholas Krueger, and Mark Gilbert from the University of Michigan Transportation Research Institute and Steve Karamihas from Applied Pavement Technology (APTech) measured reference profiles with the FHWA Urban and Low-Speed Profiler and the FHWA Benchmark Profiler (BP). Abhik Borthakur and Dylan Schmidt from APTech and John Senger from IDOT assisted with the painstaking process of measuring profile with the FHWA BP.

Abhik Borthakur and Steve Karamihas from APTech and John Senger from IDOT marked the test sections and prepared the site.

Abhik Borthakur, Brian Feighan, Arturo Espinoza, Steve Karamihas, and Dylan Schmidt from APTech and Brian Schleppi from VIHSC ran the testing with inertial profilers, walking-speed profilers, and stop-and-go profilers.

EXECUTIVE SUMMARY

Repeatable, accurate, and reproducible measurement of a pavement's longitudinal profile is essential to supporting management of road networks and construction quality control and quality assurance (QC/QA) for smoothness of new pavement surfaces. In particular, road agencies require accurate measurements of the International Roughness Index (IRI) to quantify the roughness of roadways. The IRI is calculated from the longitudinal profile, and an accurate underlying longitudinal profile is needed to identify the roughest areas within a road surface, recognize the source of the roughness, and either identify a corrective strategy or address the cause.

This study demonstrated profiler certification methods that ensure high-quality roughness measurements (e.g., IRI) by emphasizing accurate longitudinal profiles. The demonstrations support the refinement of regional or national profiler certification procedures at the Illinois Certification and Research Track (ICART), among other sites. This research examined profiler certification methods for three types of profilers: (1) conventional inertial profilers, (2) inertial profilers with enhancements for urban and low-speed operation, and (3) walking-speed profilers.

Testing was performed in a road profiler comparison experiment at ICART from October 28 to November 16, 2024. The experiment used six test surfaces at ICART: dense-graded hot-mix asphalt, stone-matrix asphalt, microsurface, transversely tined jointed concrete, continuously reinforced diamond-grooved concrete, and continuously reinforced diamond-ground concrete.

The experiment established profile accuracy using comparisons to reference profile measurements collected at the start of the experiment. The Federal Highway Administration (FHWA) Benchmark Profiler (BP) and the FHWA Urban and Low-Speed Profiler (ULSP) collected the reference measurements. The BP has a pedigree as the reference profile measurement device in several previous road profiler comparison experiments, and the ULSP demonstrated close agreement to the BP on the six test sections. In addition to the reference profilers, the experiment included 28 high-speed profilers, 3 lightweight profilers, and 11 walking-speed profilers.

Certification testing of conventional inertial profilers confirmed the sensitivity of profile measurement accuracy to pavement macrotexture type and the need to test the accuracy of profilers on each type of macrotexture they may encounter in the field. The experiments also demonstrated the need to calibrate instruments for longitudinal distance measurement preceding the collection of profile for certification.

Certification testing of profilers for urban and low-speed operation demonstrated the need to require accurate profile measurement during operation at low speed, during braking, and through stops. At the time of writing, the existing standard placed accuracy thresholds on the measurement of roughness rather than the profile. The test data included measurement of roughness that satisfied the accuracy criterion based on profile measurements that were less accurate than the expectation for conventional inertial profilers. Updating the standard to require accurate profile measurement at low speed, during braking, and through stops is warranted.

Testing of conventional inertial profilers under the standard conditions used to evaluate profilers for urban and low-speed operation demonstrated the types of profile measurement errors they typically encounter. This research demonstrated a method to establish areas near braking and stops where erroneous measurements appear, which should be excluded from segment-wide roughness reporting.

Testing of walking-speed profilers showed that not all inclinometer-based profilers used as reference devices offered reference-level accuracy on all test surfaces. Anecdotally, slower and smoother operation of these devices improved their performance. The analysis also revealed the need to calibrate the longitudinal distance measurement instrument on each test surface.

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LIST OF ACRONYMS

AASHTO	American Association of State Highway and Transportation Officials
BP	Benchmark Profiler
DGR	diamond ground
DGV	diamond grooved
DMI	distance measurement instrument
DOT	department of transportation
FHWA	Federal Highway Administration
HMA	hot-mix asphalt
ICART	Illinois Certification and Research Track
IDOT	Illinois Department of Transportation
IRI	International Roughness Index
MAP-21	Moving Ahead for Progress in the 21st Century Act
MS	microsurface
PSD	power spectral density
QC/QA	quality control and quality assurance
SMA	stone-matrix asphalt
TT	transversely tined
ULSP	Urban and Low-Speed Profiler

CHAPTER 1: INTRODUCTION

MOTIVATION

Repeatable, accurate, and reproducible measurement of a pavement's longitudinal profile is essential to supporting two important state and federal obligations to measure the functional quality of roadways: management of the road network and quality control and quality assurance (QC/QA).

First, management of the road network requires roughness measurements collected on a comparable scale over time and among various agencies. Regulations under the Moving Ahead for Progress in the 21st Century Act (MAP-21) (§1104 and §1203) require states to meet minimum standards for pavement performance (including roughness) or lose flexibility in the use of their highway funds (GPO 2012a, 2012b, 2012c). Under this legislation, states are now required to report the International Roughness Index (IRI) on an expanded National Highway System network. The IRI is typically calculated from longitudinal profile measured by inertial profilers, but the expanded network includes a high proportion of urban and low-speed roadways, posing a challenge for conventional inertial profilers in collecting meaningful data.

Second, construction QC/QA often includes measurement of surface roughness, which in turn determines positive or negative pay adjustments to a bid price based on the IRI. In this function, contractor roughness measurements must be accurate to ensure appropriate pay adjustments and consistent with owner/agency measurements to avoid disputes. Repeatable, accurate, and reproducible measurement of the underlying profile used to calculate the IRI is needed to maximize the value of roughness measurements. High-quality pavement profiling helps pavement engineers locate surface irregularities, diagnose and quantify roughness, and adjust construction and rehabilitation processes to improve ride quality.

The Advancements in Profiler Certification research demonstrates profiler certification methods that ensure high-quality roughness measurements (e.g., IRI) by emphasizing accurate longitudinal profiles. The demonstrations support the refinement of regional or national profiler certification procedures at the Illinois Certification and Research Track (ICART), among other sites. The results also produced recommendations for updates to American Association of State Highway and Transportation Officials (AASHTO) profile measurement standards.

SCOPE

This study demonstrated and documented profiler certification methods for implementation in regional or national profiler certification at sites such as ICART. The field demonstrations included three categories of testing:

1. **Certification of vehicle-mounted profilers for constant-speed operation:** This testing included commercially available high-speed inertial profilers and lightweight inertial profilers, which are mounted to conventional road vehicles and all-terrain vehicles, respectively.

Currently, high-speed inertial profilers collect most of the longitudinal profile data used to support roughness assessment of in-service roads.

Collectively, high-speed inertial profilers and lightweight inertial profilers collect most of the longitudinal profile data used for construction QC/QA on newly placed or rehabilitated road surfaces. Lightweight inertial profilers are used in the QC/QA function to operate safely within limited space on construction sites. They are also used to obtain concrete pavement profile measurements before they can support the weight of a high-speed profiler.

Certification for constant-speed operation testing also included prototypes of noninertial high-speed profilers. These profilers were mounted to host vehicles that could operate in live traffic but measured profile using a different measurement principle (and sensor set) than inertial profilers.

2. **Certification of profilers for urban and low-speed operation:** This included testing with staged speed conditions that often cause errors in measurements by inertial profilers. Test procedures evaluated whether specially equipped profilers can obtain valid profiles under adverse speeds and determined the limitations of conventional inertial profilers.

   Conventional inertial profilers provide accurate measurements at constant or nearly constant operating speed but are unable to measure valid profiles under adverse conditions, such as operating at very low speed, operating during heavy braking, or stopping within the section of interest. Inertial profiler manufacturers offer systems with additional sensors and specialized algorithms for mitigating or eliminating errors during adverse speed conditions.

3. **Certification of walking-speed profilers:** This testing evaluated commercially available and prototype walking-speed profilers that collect reference measurements for certification. Certification of walking-speed profiler testing also evaluated walking-speed profilers that collect profile on construction sites or bridge decks where the use of vehicle-mounted profilers is impractical.

Testing was conducted at ICART in Trenton, Illinois. Site setup, experimental protocols, and analysis procedures used methods appearing in AASHTO R 56-25, “Standard Practice for Certification of Inertial Profiling Systems” (AASHTO 2025) and in testing and analysis plans written for profile comparison studies conducted under Transportation Pooled Fund Study TPF-5(063) (Karamihas et al. 2013, 2015).

The Federal Highway Administration (FHWA) Benchmark Profiler (BP) measured reference profiles in the left wheel track of each test section. The FHWA Urban and Low-Speed Profiler (ULSP) measured reference profiles in the right wheel track of each test section.

LITERATURE REVIEW

Appendix A presents a bibliography pertaining to (1) past profiler comparison experiments, (2) methods for quantifying the agreement between measured profiles, and (3) profiler certification.

This research used AASHTO R 56-25 as a baseline for testing and analysis methods, because it is the prevailing standard for profiler certification. Further, the literature search revealed that past research supports many of the testing and analysis methods in R 56-25. The following are important aspects of the research approach adopted from the literature and practiced in AASHTO R 56-25:

- **Testing on diverse surface types:** Surface texture affects the repeatability and accuracy of road profile measurements. In particular, the interaction of a profiler's footprint with surface macrotexture affects its ability to determine road surface elevation (Perera and Karamihas 2014). For profilers that sense the road with optical or laser sensors, such as inertial profilers, macrotexture affects the net height of the road surface measured within the area of light projected to the road surface. For profilers that contact the road surface, such as inclinometer-based profilers, macrotexture affects the way in which the supports settle over the road surface (Karamihas 2025). This research examines the accuracy and repeatability of profilers over six macrotexture types.

- **Testing inertial profilers at more than one speed:** Several past profiler comparison studies and research into profile measurement quality suggest that inertial profilers perform differently at different travel speeds (Perera 2007; Perera and Karamihas 2017a; Perera and Kohn 1994, 1995). Further, collection of repeated measurements by the same profiler often reveals potential sources of error without the need for comparison to a reference measurement (Perera and Kohn 1994, 1995).

- **Marking a wheel track for certification testing:** Several publications recommend the use of pavement marking to assist operators with lateral tracking during profiler certification testing (Perera 2007, 2018; Fernando and Leong 1997; El-Korchi 2000; Sjogren et al. 2008). The site preparation for this research includes placement of markings to assist profiler operators with lateral tracking.

- **Designation of a reference profiler:** Profiler certification requires a candidate profiler to reproduce the output of a reference profile measurement device (Perera 2018; Fernando and Leong 1997). This research uses a robotic reference profile measurement device (the FHWA BP) from several past profile comparison studies, as described in Chapter 2. This research also uses a vehicle-mounted reference profile measurement device (the FHWA ULSP), which has demonstrated reference-level agreement to the FHWA BP on the test sections used in this research.

- **Cross correlation of profile after application of the IRI algorithm:** This research examines the repeatability and accuracy of profilers by comparing measured profiles rather than comparing summary index values. This is needed to avoid reporting satisfactory agreement due to a compensating error when two profiles include the same level of overall roughness. Agreement between profiles creates more confidence that roughness measurements will agree under a broader range of field conditions.

Karamihas (2005) presented a detailed review of methods for quantifying the accuracy and repeatability of profile measurement devices. According to that study, this research quantifies agreement between two profiles using cross correlation of IRI filter output. High cross correlation of IRI-filtered profiles ensures that the severity, shape, and longitudinal layout of roughness within the profiles that affect the IRI agree. The cross-correlation algorithm yields an agreement score between two profiles, which ranges from −1 to 1. A score of 1 represents perfect agreement (Karamihas 2004).

Cross correlation of two profiles measured by the same device under the same conditions quantifies repeatability, and cross correlation of a profile from a given device to the reference profile quantifies accuracy. This report provides repeatability and accuracy scores using the average agreement scores when multiple profile measurements are available.

To examine the influence of longitudinal distance measurement errors on repeatability and accuracy of profile, cross correlation is calculated in two ways:

1. With distance measurement instrument (DMI) adjustment: Reporting the highest level of cross correlation found with modest shifting of the starting point measured by one of the profiles and modest adjustments to the recording interval of one of the profiles.

2. Without DMI adjustment: Reporting the highest level of cross correlation found with modest shifting of the starting point measured by one of the profiles.

Appendix B provides details about the cross-correlation algorithm and the interpretation of agreement scores derived from cross correlation.

REPORT ORGANIZATION

Chapter 2 describes the work conducted to support the three profile certification testing types performed in this research, including the planning and organization, site preparation at ICART, and collection of reference measurements. Chapter 3 describes the certification testing of vehicle-mounted profilers for constant-speed operation, the analysis methods, and the results. Chapter 4 describes certification testing of profilers for urban and low-speed operation, the analysis methods, and the results. Chapter 5 describes the certification testing of walking-speed profilers, the analysis methods, and the results. For each type of testing, the corresponding chapter presents observations related to testing operations and analysis results as well as suggestions for implementation in profiler certification procedures at ICART and other regional or national profiler certification facilities. Chapter 6 summarizes the recommendations from Chapters 3 through 5 and specifically addresses recommendations for updates to AASHTO R 56-25.

Appendix A provides a bibliography pertaining to profiler compassion experiments and profiler certification practices. Appendix B provides details about the cross-correlation algorithm and relates cross-correlation levels between profiles to expected disagreement in overall IRI. Appendix C provides a layout of the ICART facility and close-up photos of the test surfaces used in this research. Appendix D provides instructions for executing speed profiles used in the certification for urban and low-speed operation testing with speed profile plots.

CHAPTER 2: EXPERIMENTAL SETUP

PLANNING AND ORGANIZATION

All measurements took place from October 21 to November 14, 2024. Reference profile measurements were taken during the week of October 21, 2024. Participants' profile testing commenced on October 28, 2024.

The organizers of the experiments used a broad announcement to recruit participants representing profiler manufacturers, profile measurement service providers, paving contractors, state departments of transportation (DOTs), and the FHWA. The announcement described the research goals, location, and timing. Initially, the organizers intended to partition each week to test profiler types in the following order: certification for constant-speed operation testing of high-speed profilers, certification for constant-speed operation testing of lightweight profilers, certification of walking-speed profiler testing, and certification for urban and low-speed operation testing. However, the team adjusted the testing order to accommodate the mix of profilers scheduled for each week and crews arriving with more than one type of testing to perform.

Several participating profilers conducted both certification for constant-speed operation and certification for urban and low-speed operation testing. To optimize efficiency and minimize downtime, the team sometimes did certification for constant-speed operation testing in the morning and certification for urban and low-speed operation testing with the same profilers in the afternoon. The next morning, certification for urban and low-speed operation testing was conducted with the same profilers so that they could then go home.

Before the experiment, participants were given a testing and analysis plan. This plan detailed the location, testing procedures (such as the required number of runs and their speeds), check-in and safety protocols, plans for the test section markings, standard data submission protocols (such as naming and format requirements), reference measurements, and analysis for each testing category. Virtual information sessions were held on October 18 and 25, 2024, to present the testing and analysis plan details and answer questions.

Table 1 lists the profilers that participated in the testing and categorizes them by profiler type and their operating organization. Several operators also requested certification under the prevailing rules from the 2024 ICART certification season. This was accommodated because the certification procedure relied on a subset of the certification for constant-speed operation testing. Thirty-one high-speed and lightweight profilers participated in the certification for constant-speed operation testing. Eleven of the 31 profilers participated in certification for urban and low-speed operation testing. Two of the 11 profilers were conventional inertial profilers with no special hardware or software to mitigate errors under adverse speed conditions. Seven of the 11 profilers were inertial profilers augmented with additional sensors and processing algorithms intended to measure valid profiles at very low speed, during braking, or with stops. The remaining two were prototypes, measuring profile using a principle of operation not classified as inertial profiling.

Table 1 also distinguishes production profilers from prototype designs that remained under development. Results for all the profilers are anonymized; this report addresses the performance of participating profilers as a group to evaluate and refine the testing procedures. Assessments relevant to the status of the prevailing fleet of in-service profilers address only production devices.

Table 1. Participants in the Certification Experiments

Development Status	Profiler Type	Organization Type	Count	ICART Cert. Testing	CULSO Testing
Production	High speed	State DOT	9	5	4
Production	High speed	Manufacturer	8	8	5
Production	High speed	FHWA	4	–	–
Production	High speed	Contractor	3	3	–
Production	High speed	Service provider	1	1	–
Production	Lightweight	Contractor	2	2	–
Production	Lightweight	State DOT	1	1	–
Production	Walking speed	State DOT	5	–	–
Production	Walking speed	Manufacturer	3	–	–
Prototype	High speed	Manufacturer	3	1	2
Prototype	Walking speed	Manufacturer	3	–	–

CULSO = Certification for urban and low-speed operation.

ICART OVERVIEW AND TEST SECTION DETAILS

Testing took place at ICART in Clinton County, Illinois. ICART is located at 13255 Crackerneck Road outside of Trenton, Illinois, where Crackerneck Road intersects US-50. ICART is a closed facility with three lanes of test pavement on a 3/4 mile tangent section along US-50. At the time of writing, it is composed of 21 test cells that provide a range of the surface properties necessary to support pavement surface characteristics research. The test cells include multiple material types, pavement designs, roughness levels, macrotexture types, and synthetic distresses. Appendix C provides a schematic of test cells at ICART. ICART also includes a wider area of pavement at each end of the track, allowing an easy change in test vehicle direction.

Testing included six surface types:

1. **Dense-graded hot-mix asphalt (HMA)**: 9.5 mm nominal maximum aggregate size with 0% asphalt binder replacement.

2. **Stone-matrix asphalt (SMA)**: 12.5 mm nominal maximum aggregate size with 0% asphalt binder replacement.

3. **Microsurface (MS)**: A traditional microsurfacing mix with calcined bauxite as part of the aggregate and No. 4 sieve missing as part of the gradation.

4. **Diamond ground (DGR)**: This section appears on a continuously reinforced concrete pavement. The original concrete surface was floated without additional texturing. The surface was blanket ground with 4 ft wide grinding heads and gang-mounted diamond saw blades with a rate of 50 blades per foot.

5. **Diamond grooved (DGV)**: This section appears on a continuously reinforced concrete pavement. The concrete was textured with a turf drag and cured prior to the diamond grooving. The turf drag is made of 0.85 in. synthetic blades and was specified to have 7,200 blades per square foot. The grooving pattern produced longitudinal grooves 1/8 in. wide and 3/16 ± 1/16 in. deep, with a lateral spacing of 3/4 in.

6. **Transversely tined (TT)**: This section appears on a jointed plain concrete pavement. The joints are unsealed and appear 12 ft apart. The specification for tines was 1/10 to 1/8 in. wide and 1/8 to 3/16 in. deep. The tines were placed with an irregular spacing and a net frequency close to eight tines per foot.

The test sections were selected to approximate the recommendations in Karamihas (2005) for certification of reference profilers. They provide a broad range of macrotexture types, including positive isotropic (e.g., MS), negative isotropic (e.g., SMA), longitudinal (e.g., DGV), transverse (e.g. TT), and a baseline with less aggressive macrotexture (e.g., HMA). The DGR section, which is another example of longitudinal texture, was included because it had low roughness.

Table 2 lists the GPS coordinates of the test section endpoints in the WSG84 datum. All test sections appeared in the eastern half of the facility. Table 2 also provides the length of each test section as measured by steel tape and adjusted for ambient temperature. The HMA and SMA surfaces, adjacent to each other, were combined into a single long test section. This allowed for diagnosing the accuracy of long wavelength content in measured profiles. Analysis was performed using the entire test section and subsections that included SMA and HMA only. The SMA section covered the initial 490 ft of the SMA/HMA section, and the HMA section covered the final 490 ft of the SMA/HMA section.

Table 2. Test Section Endpoints

Test Section	Start Longitude (deg)	Start Latitude (deg)	End Longitude (deg)	End Latitude (deg)	Length (ft)
SMA/HMA	−89.6437649	38.6159336	−89.6401782	38.6158698	1025.3
MS	−89.6391967	38.6158522	−89.6379164	38.6158295	366.0
DGR	−89.6394067	38.6158732	−89.6412072	38.6159054	514.7
DGV	−89.6425021	38.6159285	−89.6442226	38.6159591	491.6
TT	−89.6393863	38.6158065	−89.6411049	38.6158373	491.2

SITE PREPARATION

The team selected wheel tracks that were 2.65 in. wide with their centers situated 67 3/4 in. apart. The tracks were placed approximately 33 7/8 in. from the lane center of each test section. Dashed longitudinal guide marks were painted beside the left wheel track of each test section to assist the participants with lateral tracking. The markings were placed 7 in. to the right of the left wheel track of interest using a GPS-guided painting robot.

Transverse markings were placed to identify the starting and ending point of each test section. Figure 1 provides a schematic (not to scale) of the markings placed in the left wheel track of each test section. The precise starting point of each test section was at the aft (trailing) edge of the starting stripe, and the precise ending points were at the fore (leading) edges of the ending stripe. These points were used as landmarks for section length measurements using steel tape. Figure 2 provides a downstream view of the starting point and longitudinal guide stripe on the SMA section.

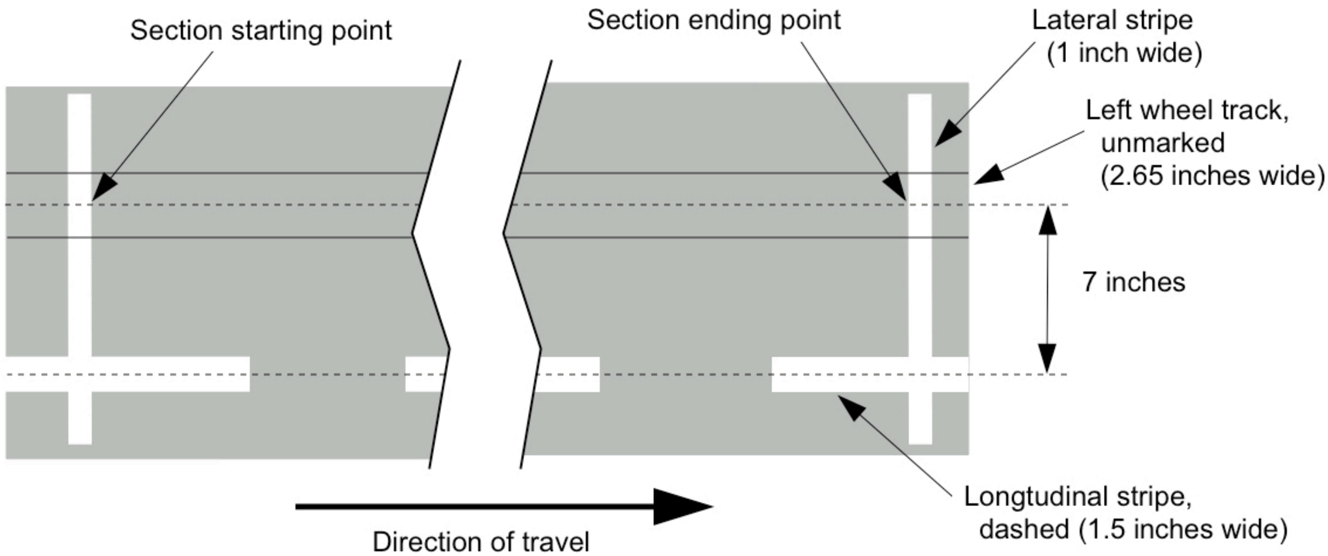

Figure 1. Illustration. Test section marking schematic.

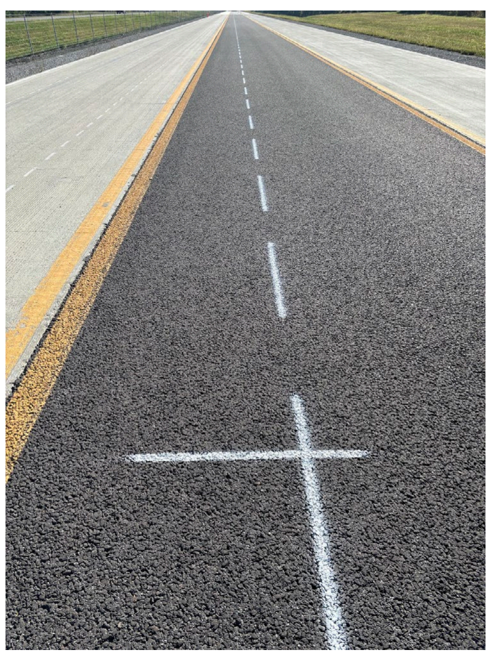

Figure 2. Photo. Test section starting point and longitudinal guide marks.

Figure 3 depicts the test section arrangement, including the direction of travel and the approximate paint marking locations. The test section arrangement facilitated efficient measurement by vehicle-mounted profilers. The SMA/HMA and MS test sections appeared in succession in the center lane and ran from west to east. The DGV and DGR test sections appeared in succession in the north lane and ran from east to west. The TT test section appeared in the south lane and ran from east to west. This was done to maximize the number of sections that could be measured during each host vehicle loop over the track.

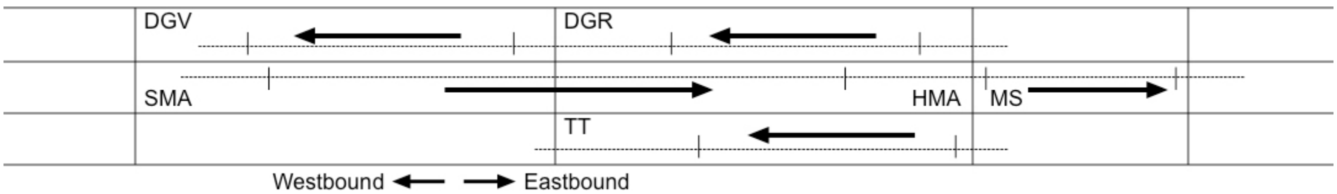

Figure 3. Illustration. Test section layout.

The longitudinal guide stripe in the center lane ran continuously through all three test sections, with the longitudinal guide stripe in the north lane running continuously through both test sections. The guide stripe also began at least 150 ft upstream of the first test section that appeared in each lane. With this layout, operators of vehicle-mounted profilers had the option to measure the profile of one or more of the test sections traveling in one direction and one or more of the test sections in the other direction's return pass.

Markings were also placed on a 1,000 ft long section for DMI calibration. This section was at the far west end of the track to keep it separated from the profile measurement test sections. Landmarks were painted 200, 528, and 1,000 ft from the start to accommodate various DMI calibration practices. An additional landmark was placed 100 ft from the start at the request of one participant. The first three quarters of the DMI calibration section appeared within an SMA test cell, with the last quarter appearing within a test cell with artificial rutting.

REFERENCE PROFILE MEASUREMENT

FHWA Benchmark Profiler

The FHWA BP was built in 2007–2009 to measure accurate longitudinal profiles and used as a standard for comparison to candidate reference profilers in 2009–2015 (Karamihas 2009, 2011; Karamihas et al. 2013; Perera and Karamihas 2017a) and used as a standard for comparison to production high-speed inertial profilers in 2015 (Perera and Karamihas 2017b). Winkler et al. (2013) describes its measurement principle and its operation. During this 2024 testing, the FHWA BP collected reference measurements in the left wheel track.

Figure 4 shows the BP cart and tripod at the start of the MS section. The tripod supported a laser, which projected a horizontal line to establish a stable reference plane for the cart. The cart then moved along the wheel track of interest using nylon-coated steel tape as a steering guide, combining the output of a wheel encoder and detection of landmarks on the guide tape to measure its longitudinal position. During this time, the cart measured its vertical position and orientation relative to the reference laser line by detecting its projection on a set of targets within a "light tunnel" at the back. Vertical position of the road surface below the reference laser line projection was measured using a RoLine laser, which was directly below the reference laser line targets. The RoLine used a 2.65 in. wide swatch with a fixed lateral distance beside the guide tape to determine road surface height.

Figure 4. Photo. BP operating at the start of the MS section.

Depending on atmospheric conditions, the BP can measure valid profiles only when the cart is within 50 ft of the tripod. As a result, measurement of an entire test section requires the use of several tripod setups to capture subsection profiles: 12 to 25 endpoints, depending on the conditions. Construction of the complete profile also requires the use of a rod and level survey to anchor the subsection endpoints in a common coordinate system.

FHWA Urban and Low-Speed Profiler

The FHWA ULSP, an augmented version of a typical high-speed inertial profiler, collected reference profile measurements in the right wheel track. The ULSP was designed to overcome measurement errors that typical inertial profilers experience at low travel speed, during braking, and in stop-and-go operation (Karamihas 2021a, 2021b). Figure 5 shows the ULSP parked for a bounce test on the SMA portion of the SMA/HMA section. The ULSP sensor set includes real-time kinematic corrected GPS, GPS pitch-and-roll attitude measurement, fiber optic gyroscopes for measurement of pitch-and-roll rate, an inertial navigation system, rotational encoders on both rear wheels, and an optical fifth wheel for longitudinal distance measurement.

Figure 5. Photo. ULSP on the SMA/HMA section.

BP and ULSP Comparison

Table 3 presents results for cross correlation of IRI filter output for repeatability of each device and agreement between them. (See Appendix B for details about the cross-correlation algorithm.) Repeatability results are the average of the three possible comparisons among the three repeat measurements over each test section. Agreement results are the average of the nine possible comparisons of each of the three profiles measured by the BP to each of the three profiles measured by the ULSP. In addition to the sections listed in Table 2, results are reported for the first and last 488.8 ft of the SMA/HMA test section, which were SMA only and HMA only.

Table 3. Cross-Correlation Results for the BP and ULSP, Left Wheel Track

Test Section	BP Repeatability	BP vs. ULSP Agreement	ULSP Repeatability
SMA/HMA	0.994	0.984	0.988
HMA	0.987	0.980	0.993
SMA	0.995	0.990	0.986
MS	0.993	0.989	0.990
DGR	0.993	0.980	0.981
DGV	0.995	0.981	0.975
TT	0.996	0.988	0.990

Note that the repeatability scores for the BP are not true repeatability. Although the three profile measurements each use a different set of passes over each subsection by the BP cart, they each use the same steel tape and tripod setup, which guarantees consistent tracking among the three passes. Karamihas and Gilbert (2026) describe recent upgrades to the BP and ULSP preceding this research and their comparison at ICART in detail. For this research, the reference profile for the left wheel track was selected from the three passes by the BP, while the reference profile for the right wheel track was selected from the three passes by the ULSP.

CHAPTER 3: CERTIFICATION OF HIGH-SPEED AND LIGHTWEIGHT PROFILERS

The certification for constant-speed operation testing of vehicle-mounted profilers emphasized the application and refinement of methods in AASHTO R 56-25 for high-speed and lightweight profilers.

PARTICIPANTS

The certification for constant-speed operation testing evaluated 31 profilers. This group of profilers included 3 lightweight inertial profilers, 25 high-speed inertial profilers, and 3 prototype high-speed profilers. Not all the prototype high-speed profilers used the same measurement principle as inertial profilers.

Contractors operated two lightweight inertial profilers. However, representatives from the equipment manufacturers were on hand the day of the testing and assisted the contractors with the measurements. State DOT personnel operated the other lightweight inertial profiler.

State DOT personnel operated 9 of the 25 production high-speed inertial profilers. Equipment manufacturers operated 8 high-speed inertial profilers, contractors operated 4, and the data collection contractor for the FHWA Long-Term Pavement Performance program operated 4.

Operators of 22 of the participating profilers requested official certification under the procedures used in the 2024 ICART certification season. Descriptions of the additional procedures applied to support 2024 ICART certification appear in the Test Conditions section.

TEST CONDITIONS

The testing program included measurements in all five test sections. The testing program required lightweight profilers to perform five repeated passes on each section at a typical running speed. The testing program required high-speed profilers to perform five repeated passes over each test section at two speeds: 25 mi/hr and 50 mi/hr.

Certification under the 2024 ICART procedures used results from the DGR section, the TT section, and the HMA portion of the SMA/HMA section. The procedure for 2024 ICART certification permitted operators to conduct eight passes at each test speed and based certification on scores from the best five passes from each speed. Consequently, several operators opted to perform more than five passes over those three test sections, and in some cases all the test sections, at each speed.

All participating profilers identified the starting and ending locations of the test sections using photocells that detect reflective landmarks. At the start of each test day, observers placed posts with reflective tape at the left lane edge to mark the starting and ending point of each test section. Figure 6 shows a post at the starting point of the SMA/HMA section, with the profilers traveling from left to right.

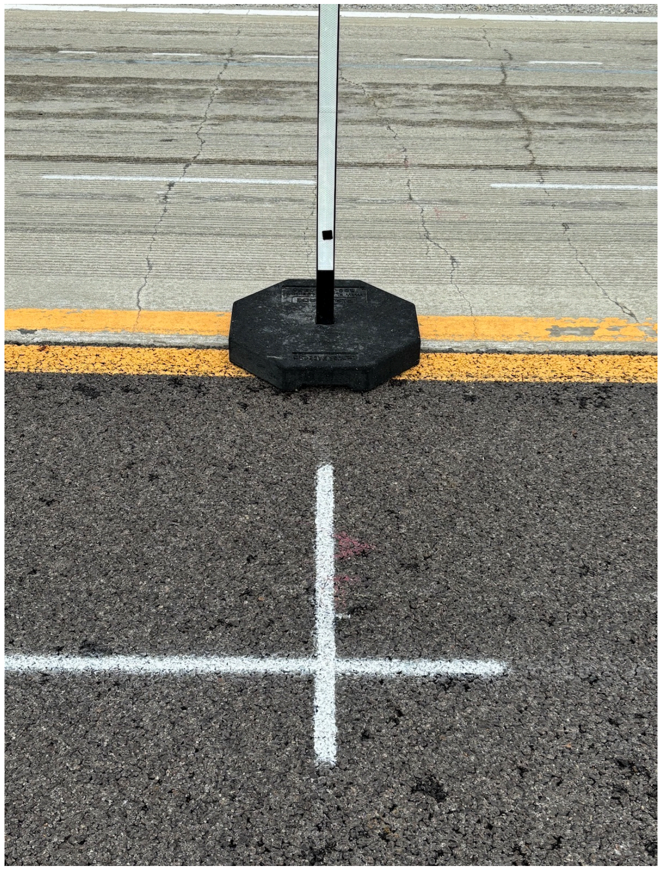

Figure 6. Photo. Triggering post at the start of the SMA/HMA section.

Every test section included a dashed longitudinal guide stripe 7 in. to the right of the left wheel track. The 7 in. offset placed the stripe near the center of the driver position for high-speed profilers and avoided the possibility of detrimental interaction between the markings and optics of the profilers' height sensors.

OPERATIONS AND SAFETY

Calibration and System Checks

The research did not require operators to conduct any system checks, such as bounce tests or block tests, before measuring the test sections. However, the 2024 ICART Profiler Certification Procedures required observers to witness the operator performing a bounce test and a block test. As such, the 22 profiler operators interested in certification conducted bounce and block tests on the concrete pad at the west end of the track. Operators of the other profilers performed system checks at their own discretion.

Neither the research plan nor profiler certification required operators to perform DMI calibration. Most operators performed at least one pass for DMI calibration; some operators performed several passes for DMI calibration. Some operators performed DMI calibration over a length of 528 ft, others over a length of 1,000 ft.

Test Runs

Testing of lightweight profilers took place on October 29 and November 7, 2024. Observers closed the portion of the track near the test sections to full-sized vehicles while the lightweight profilers operated. On October 29, two lightweight profilers operated simultaneously without interfering with each other. All lightweight profilers changed direction on their returns without driving to the ends of the track.

Testing of high-speed profilers took place October 28 to 29, November 6 to 7, and November 11 to 14, 2024. Each profiler performed the testing in loops from the west to the east end of the track and back. Typically, operators started each loop at the wide concrete pad at the west end of the track. They measured the SMA/HMA section or the MS section (or both) while traveling east in the center lane. They proceeded to the wide concrete pad at the east end of the track to change direction. During the westbound return, they either measured the TT section in the south lane or measured the DGR or DGV section (or both) in the north lane.

In most cases, profilers performed their testing in groups, and an observer coordinated the runs. The largest number of profilers operating at once was six. During coordinated operation, the profilers queued at the west end of the track. An observer released each profiler after the previous profiler had proceeded far enough along the track to avoid interaction between them. All profilers waited at the east end of the track until the last profiler arrived, when they began to conduct westbound passes one by one, which was coordinated by an observer at the east end.

Platooning of multiple profilers required cooperation and communication. All observers and profiler operating crews carried handheld two-way radios to help avoid clashes between vehicles. Most profiler drivers were cooperative and quickly learned to observe the rules for looping over the track without intervention. The safest and most efficient operation with multiple profilers occurred when all vehicles operated at the same speed in each loop. In the November test dates, profiler operators were asked to wait until every profiler completed their runs at 25 mi/hr before any runs at 50 mi/hr began.

Triggering

Difficulties with triggering at test section boundaries slowed progress on October 29 and November 6. First, no platoon could operate unless all the profilers used triggers on the same side of the lane. Placing triggers on both sides would have caused too much potential for detection of a trigger from a test section in another lane. For example, while using triggers on the left side only, one profiler detected triggers from the TT section in the south lane while attempting to measure the DGR section in the north lane.

Second, several profilers were unable to reliably detect the reflective tape on the posts. Some operators used their own posts with solid reflectors; Figure 7 shows an example. Ad hoc testing showed that most devices detected solid reflectors more reliably.

Figure 7. Photo. Triggering post with a solid reflector.

Third, testing five sections in three lanes within a longitudinal distance of 2,000 ft confused a few operators because the purpose of each post was not always clear. This was somewhat mitigated by providing a schematic of the test section layout with the travel direction for each lane. However, ad hoc installation of reflective numbers on the posts revealed that visible signs identifying the start and end of a test section helped operators know when to arm their systems for triggering.

Finally, the DMI calibration section was within the area where vehicles looped over the test sections. In some cases, platoons of profilers needed to stop operating to wait for another profiler to place or move the triggering posts at the DMI test section.

Lateral Tracking

Several profiler operators recognized the potential influence of lateral tracking on their repeatability and accuracy scores. The left and right wheel tracks were 67 3/4 in. apart, and operators of systems with adjustable lateral sensor spacing moved their sensors accordingly. Operators who could not adjust to a sensor spacing of 67 3/4 in. attempted to align their left-side sensors with the left wheel track as accurately as possible. Some operators installed hood-mounted lasers on the profiler host vehicle that projected visible dots along the desired location of the longitudinal marking stripe to help them pilot on the correct lateral position. Some operators used a forward-facing camera with a dashboard-mounted monitor for assistance whereas others applied ad hoc markings to their windshield or hood for assistance.

RESULTS

Table 4 summarizes the number of measurements collected by the 28 commercially available inertial profilers on each test section. The table lists the number of runs on each section from high-speed profilers at 25 mi/hr and high-speed profilers at 50 mi/hr. Each high-speed profiler performed five to eight repeated passes at each speed over each test section. The table also lists the number of runs on each section from lightweight profilers. Two of the lightweight profilers ran at 25 mi/hr, and the other ran at 10 mi/hr. Each lightweight profiler performed five or six repeated passes over each section.

Table 4. Inertial Profiler Measurements of Each Test Section

Test Section	Lightweight	High Speed (25 mi/hr)	High Speed (50 mi/hr)
SMA/HMA	16	147	148
MS	16	144	148
DGR	15	147	132
DGV	15	145	132
TT	16	141	133

Accuracy Scores without DMI Correction

Figure 8 shows a distribution of accuracy scores on the left wheel track of the HMA test section for each group of passes without DMI correction. Figure 8 includes results from 53 groups: two speeds for each of the 25 high-speed profilers plus one speed for each of the 3 lightweight profilers. Each accuracy score is the average of the five to eight accuracy scores for each group.

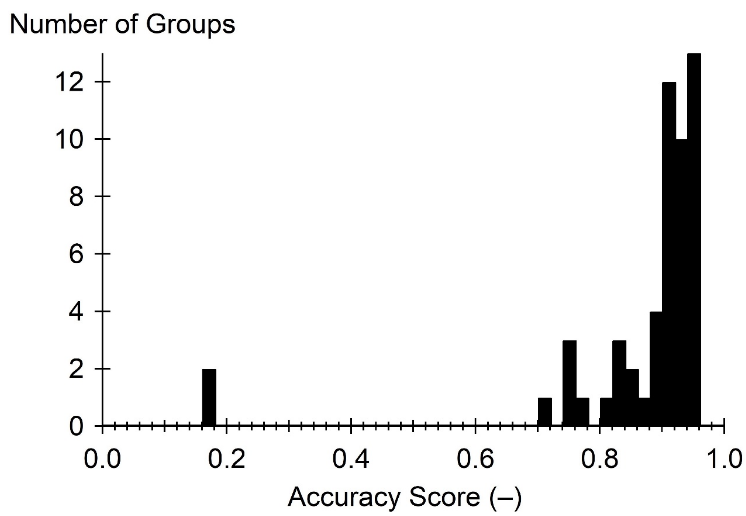

Figure 8. Graph. Distribution of accuracy scores without DMI correction, HMA, left wheel track.

Table 5 summarizes the distribution of accuracy scores without DMI correction for each wheel track of each test section. The table lists the median, high, and low accuracy scores among the 53 groups for each wheel track. The table also lists the number of groups that achieved an accuracy score above various thresholds.

AASHTO R 56-25 requires an accuracy score above 0.90 for profiler certification. Karamihas (2004) recommended an accuracy score threshold of 0.94 for profilers that make “project-level” measurements, such as profile measurements for construction quality control and quality assurance. Out of 53 groups shown in Figure 8, 35 produced an accuracy score greater than 0.90, 23 produced an accuracy score above 0.92, and 13 produced an accuracy score above 0.94. The accuracy scores in Table 5 show that profilers can achieve accuracy scores above 0.94 or above an intermediate threshold of 0.92.

Table 5. Summary of Accuracy Scores without DMI Correction

Test Section	Wheel Track	Median	High	Low	Count >0.90	Count >0.92	Count >0.94
SMA/HMA	Left	0.898	0.981	0.150	26	20	17
SMA/HHA	Right	0.897	0.981	0.132	26	23	15
SMA	Left	0.882	0.982	0.199	23	22	18
SMA	Right	0.857	0.973	0.188	13	8	6
HMA	Left	0.918	0.960	0.170	35	23	13
HMA	Right	0.925	0.966	0.175	36	32	19
MS	Left	0.920	0.991	0.185	35	27	22
MS	Right	0.908	0.986	0.344	27	23	9
DGR	Left	0.956	0.981	0.206	36	34	32
DGR	Right	0.911	0.980	0.235	28	25	22
DGV	Left	0.898	0.980	0.136	26	21	14
DGV	Right	0.845	0.953	0.041	15	11	3
TT	Left	0.957	0.990	0.201	42	37	33
TT	Right	0.909	0.965	0.448	28	20	11

Accuracy Scores with DMI Correction

Figure 9 shows a distribution of accuracy scores for the left wheel track of the HMA test section for each group of passes with DMI correction. The two groups with agreement scores below 0.2 in Figure 8 (which did not include DMI correction) improved to values greater than 0.7 with DMI correction applied. Those groups correspond to a profiler that operated with a DMI calibration error of more than 10%.

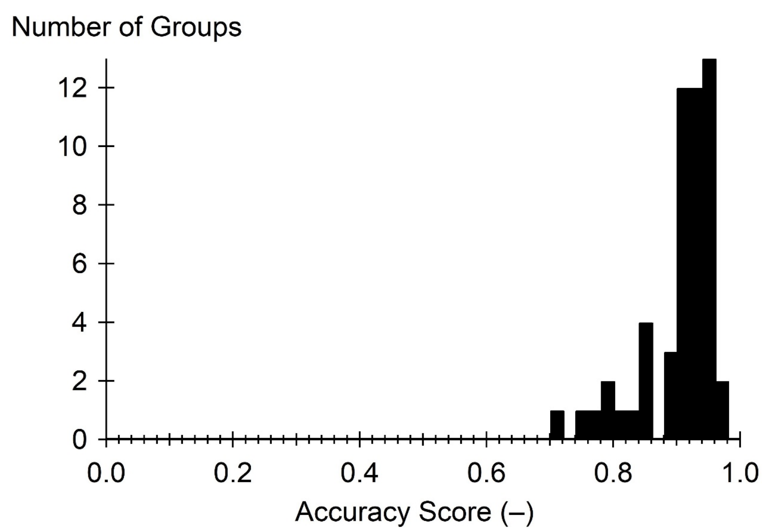

Figure 9. Graph. Distribution of accuracy scores with DMI correction, HMA, left wheel track.

Table 6 summarizes the distribution of accuracy scores with DMI correction for each wheel track of each test section. Table 6 confirms a net improvement in accuracy scores on all test sections. On most test sections, the number of groups with an accuracy score greater than 0.90 increased when the DMI correction was applied. This result illustrates the need for DMI calibration before collecting profile for certification.

Table 6. Summary of Accuracy Scores with DMI Correction

Test Section	Wheel Track	Median	High	Low	Count >0.90	Count >0.92	Count >0.94
SMA/HMA	Left	0.930	0.982	0.724	38	29	20
SMA/HHA	Right	0.931	0.982	0.782	39	33	21
SMA	Left	0.889	0.984	0.642	25	25	18
SMA	Right	0.872	0.973	0.629	17	11	6
HMA	Left	0.923	0.963	0.705	39	27	15
HMA	Right	0.937	0.967	0.783	41	39	24
MS	Left	0.931	0.991	0.730	37	30	25
MS	Right	0.913	0.989	0.757	31	24	12
DGR	Left	0.958	0.982	0.307	39	35	32
DGR	Right	0.912	0.981	0.348	28	26	22
DGV	Left	0.910	0.980	0.138	29	25	14
DGV	Right	0.869	0.953	0.047	16	11	4
TT	Left	0.960	0.991	0.674	46	39	35
TT	Right	0.910	0.966	0.599	28	20	12

The results listed in Table 6 are a summary of 4,233 profile comparisons. In each comparison, the algorithm determines the DMI correction required to maximize agreement with the reference profile. The algorithm applied a DMI correction greater than 10% for 158 of the comparisons. Those cases correspond to a single device. The algorithm applied a correction greater than 0.5% in an additional 45 of the comparisons. Five of the high-speed profilers account for those cases. Those profilers routinely exhibited DMI errors over 0.25%. AASHTO R 56-25 requires DMI accuracy of 0.15% or better. With the six profilers that had the highest levels of DMI error removed, the algorithm applied a DMI correction of more than 0.15 in 391 of the remaining 3,349 comparisons.

Applying the DMI correction caused the greatest increase on the SMA/HMA test section, because accuracy scores are more sensitive to DMI errors on longer test sections. The other test sections better represent the expected influence of DMI errors on profiler certification results because they are closer to the typical length used in profiler certification.

Surface Texture

The fewest groups with an accuracy score above 0.90 occurred for profiles measured on the SMA and DGV section. All but four of the commercially available profilers that participated in the certification for constant-speed operation testing used height sensors with the same footprint as the reference profilers. In particular, the profilers used line lasers that projected light to the road surface over a width of 4 in. However, two differences with the reference profilers negatively affected the accuracy scores, particularly on the SMA and DGV surfaces.

First, the profilers with line lasers typically used an algorithm for determining the height of the road surface within a 4 in. wide footprint that was provided by the laser manufacturer. The reference profilers used a customized bridging algorithm that the laser firmware did not include (Karamihas 2005).

Second, many of the profilers mounted their line lasers with a different orientation than the reference profilers. The reference profilers measured the road surface using line lasers mounted perpendicular to the direction of the travel. Many of the profilers mounted their line lasers at an angle that was less than 90 degrees, and in some cases less than 30 degrees, relative to the direction of travel.

Figure 10 shows a distribution of accuracy scores for the left wheel track of the DGV test section for each group of passes with DMI correction. The lowest eight accuracy scores in the figure correspond to groups of passes measured by profilers with lasers that use a narrower footprint. On the DGV surface, the narrower-footprint lasers often switched from detecting the plateaus to detecting the bottom of the grooves.

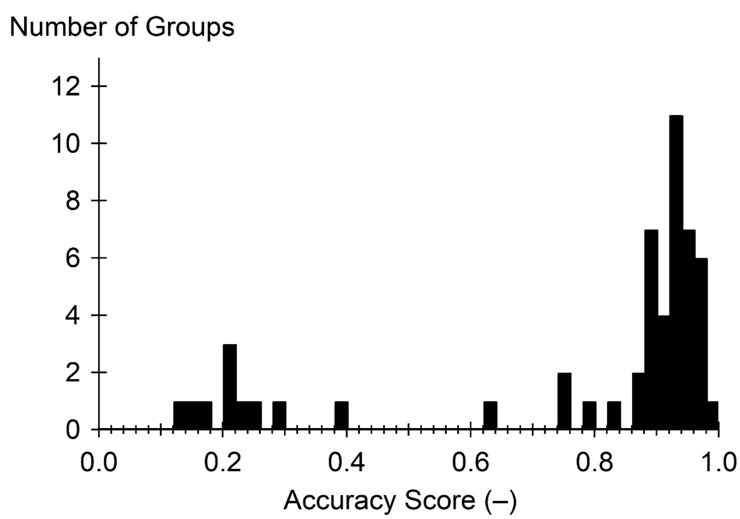

Figure 10. Graph. Distribution of accuracy scores without DMI correction, DGV, left wheel track.

Figure 11 shows three profile measurements over a portion of the left wheel track of the DGV test section: one pass by the reference profiler and two passes by a profiler with a narrow-footprint height sensor. For ease of interpretation, the plots are high-pass filtered using a cutoff wavelength of 200 ft and offset vertically from each other. Intermittent dips up to 20 ft wide and 0.12 in. deep appear in the two profiles measured with a narrow footprint.

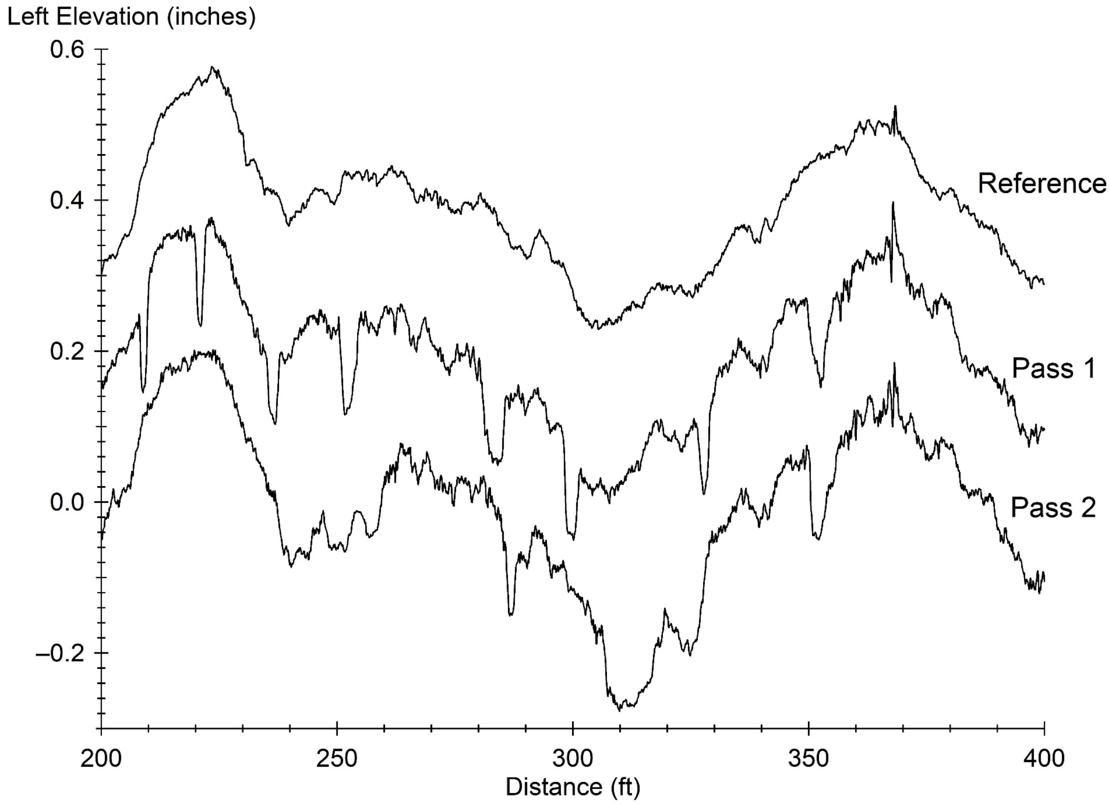

Figure 11. Graph. Three profiles measured over a portion of the DGV section.

Changes with Time

Diurnal changes in the true profile of the TT section affected the accuracy scores. For example, the ULSP collected reference measurements between 3 p.m. and 4 p.m. on October 21, 2024. Passes with accurate lateral tracking in that time interval produced agreement scores above 0.98. However, passes from different times of day did not agree as well with one another as passes collected at the same time of day.

Figure 12 compares the power spectral density (PSD) plot for the right profile from the reference pass by the ULSP, which occurred at 3:49 p.m., to the PSD plot from a pass by the ULSP at 6:34 p.m. The PSD functions differ the most at wavelengths equal to the joint spacing on the TT section and half of the joint spacing. Changes in slab curl account for the change in content at these wavelengths.

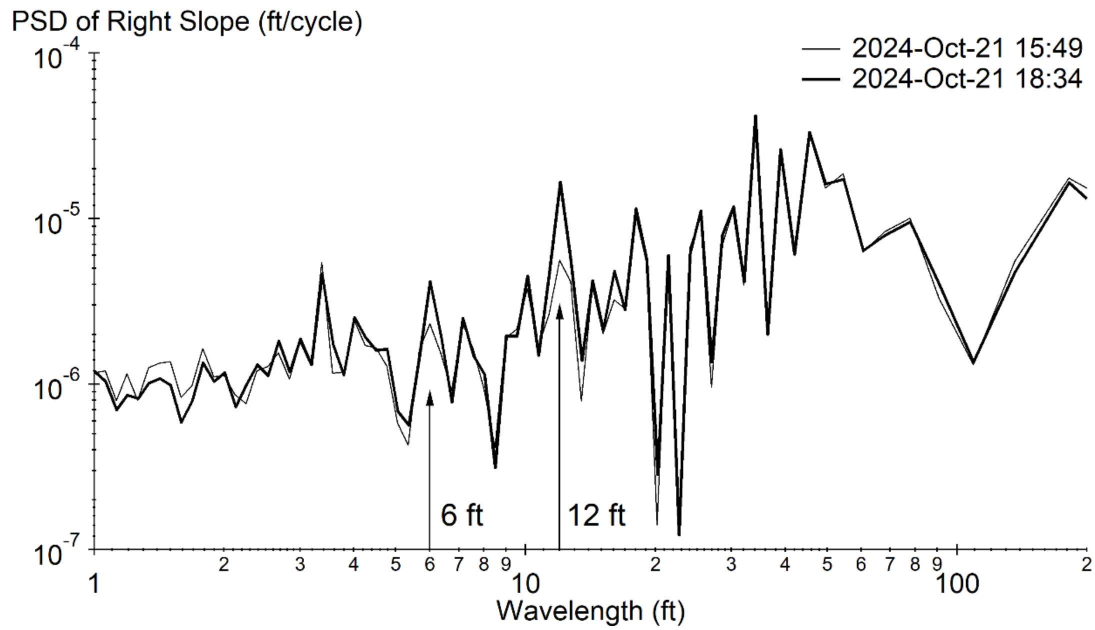

Figure 12. Graph. PSD plot for right profile measurements of the TT section at different times.

The earlier pass shown in Figure 12 occurred when the air temperature was 78°F and under a clear sky. Both conditions reduced the prevailing upward curl of the pavement slabs. The later pass occurred within minutes of civil twilight, and the air temperature had reduced to 64°F. As such, the profile of the test section included a higher level of upward slab curl. Due to the change in the true profile, the agreement score of the two runs reduced to 0.917.

Further examination of profiles measured at different times showed that greater changes occurred on the profile of the right wheel track than in the left wheel track. This is because the left side of the lane is tied to the left shoulder, whereas the right side of the lane is free.

Repeatability Scores

Figure 13 shows a distribution of repeatability scores for the left wheel track of the HMA test section for each group of passes without DMI correction. In this context, a group is a set of 5 to 8 passes by a profiler at 1 test speed. Figure 13 includes results from 53 groups: 2 speeds for each of the 25 high-speed profilers plus 1 speed for each of the 3 lightweight profilers. Each repeatability score is the average of the individual repeatability scores for each group. For example, the repeatability score for 5 passes is the average from the 10 possible comparisons among the 5 measured profiles.

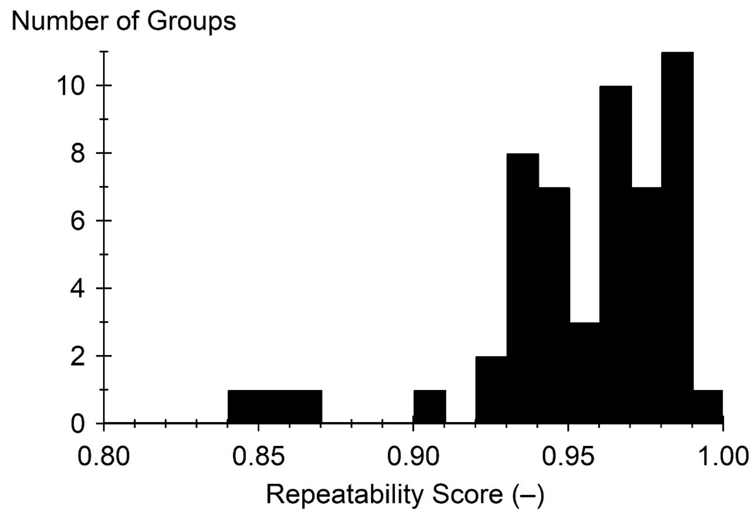

Figure 13. Graph. Distribution of repeatability scores without DMI correction, HMA, left wheel track.

Table 7 summarizes the distribution of repeatability scores without DMI correction for each wheel track of each test section. The table lists the median, high, low, and repeatability scores among the 53 groups for each wheel track. The table also lists the number of groups that achieved a repeatability score above various thresholds.

AASHTO R 56-25 requires a repeatability score above 0.92 for profiler certification. Of the 53 groups shown in Figure 13, 49 produced a repeatability score greater than 0.92. Karamihas (2004) recommended a repeatability score threshold of 0.94 for profilers that make project-level measurements, such as profile measurements for construction quality control and quality assurance. Of the 53 groups shown in Figure 13, 49 produced a repeatability score greater than 0.92 and 39 produced a repeatability score greater than 0.94. Table 7 shows that profilers can achieve repeatability scores above 0.94.

Table 8 summarizes the distribution of repeatability scores with DMI correction for each wheel track of each test section. Using the DMI correction did not change the number of groups with a repeatability score greater than 0.92.

Table 7. Summary of Repeatability Scores without DMI Correction

Test Section	Wheel Track	Median	High	Low	Count >0.90	Count >0.92	Count >0.94
SMA/HMA	Left	0.965	0.992	0.818	41	38	35
SMA/HHA	Right	0.962	0.993	0.825	42	39	36
SMA	Left	0.950	0.988	0.745	36	31	29
SMA	Right	0.929	0.989	0.691	34	31	23
HMA	Left	0.962	0.989	0.851	50	49	39
HMA	Right	0.973	0.995	0.896	52	50	48
MS	Left	0.951	0.993	0.592	42	37	30
MS	Right	0.942	0.992	0.567	44	39	28
DGR	Left	0.982	0.996	0.321	39	36	36
DGR	Right	0.946	0.993	0.364	37	36	30
DGV	Left	0.936	0.990	0.172	36	32	24
DGV	Right	0.913	0.989	0.157	27	22	16
TT	Left	0.978	0.996	0.866	51	51	45
TT	Right	0.954	0.994	0.820	45	41	33

Table 8. Summary of Repeatability Scores with DMI Correction

Test Section	Wheel Track	Median	High	Low	Count >0.90	Count >0.92	Count >0.94
SMA/HMA	Left	0.967	0.991	0.818	42	39	35
SMA/HHA	Right	0.967	0.994	0.825	45	41	37
SMA	Left	0.951	0.988	0.745	36	32	29
SMA	Right	0.929	0.989	0.691	33	31	23
HMA	Left	0.962	0.989	0.851	50	49	39
HMA	Right	0.973	0.994	0.897	52	50	48
MS	Left	0.954	0.993	0.608	43	37	31
MS	Right	0.943	0.992	0.584	44	40	28
DGR	Left	0.983	0.995	0.194	39	36	36
DGR	Right	0.946	0.993	0.399	37	36	30
DGV	Left	0.937	0.990	0.208	36	32	23
DGV	Right	0.895	0.990	0.186	26	22	16
TT	Left	0.978	0.996	0.866	51	51	46
TT	Right	0.955	0.994	0.820	46	41	33

RECOMMENDATIONS

The following practices are recommended for profiler comparison testing with lightweight and high-speed profilers:

- Assign an observer to help ensure the safety of the operators and to instruct them in the expected testing procedures.
- Issue communication devices (e.g., handheld two-way radios) to the operators of each profiler.
- Close the area of the track where the profilers operate to all other traffic.
- Do not allow any traffic, such as a different profiler returning from a completed run, to appear in a lane adjacent to a profiler that is making measurements.
- Use compatible measurement speeds when a set of profilers operates in a platoon.
- Do not allow profilers to turn around within test sections where stable surface characteristics are needed. In the experiment described here, the observers found evidence of changes to the right wheel track of the MS section caused by a high-speed profile making three-point turns on it.
- Provide a location outside of the profile measurement area for DMI calibration and profiler system checks, if possible. In this experiment, individual operators struggling with DMI calibration held up testing by others in multiple situations.

The following additional practices are recommended for certification testing with lightweight and high-speed profilers:

- Provide highly visible markings directly within the wheel tracks of interest. In this experiment, markings appeared 7 in. to the right of the left wheel track. Several participants expressed a preference for markings within the wheel tracks so they could adjust their systems for assisting the driver more readily.
- Standardize the lateral spacing between wheel tracks.
- Standardize the test-section length. This experiment used irregular test section lengths that were not shared with the profiler operators. This technique provided a way to test DMI accuracy. However, six of the high-speed profilers exhibited a high level of DMI error that they would have recognized in their first run if the test section lengths were known.
- Provide highly visible landmarks that clarify the starting and ending points of test section boundaries. Also, provide a clear diagram to operators that shows the location and direction of measurements for each test section.
- Obtain posts for automated triggering at test section endpoints with solid reflectors that are compatible with as many of the photocells used in practice as possible.

CHAPTER 4: CERTIFICATION FOR URBAN AND LOW-SPEED OPERATION

The certification for urban and low-speed operation experiment evaluated procedures recently added to AASHTO R 56-25. The added testing and analysis procedures verify the ability of specially equipped profilers to obtain valid profiles under adverse speed conditions and determine the conditions under which a conventional inertial profiler does not measure valid profiles. AASHTO R 56-25 describes these procedures in Sections 8.2.4 to 8.2.5 and 8.3.3 to 8.3.7. This chapter addresses the implementation of the field test procedures, analysis methods, and profile measurement accuracy and repeatability requirements.

PARTICIPANTS

The certification for urban and low-speed operation testing evaluated 11 profilers: 10 commercially available systems and 1 prototype system. State DOT personnel operated 4 of the 10 commercially available systems, and equipment manufacturers operated the remaining 6. All 10 commercially available systems included conventional inertial profiler sensors.

Two systems, which were operated by state DOT personnel, were conventional inertial profilers. Nine systems incorporated enhancements intended to support valid measurement of profile under conditions that cause errors in conventional inertial profilers, such as operation at low speed, during heavy braking, and through stops. Typical enhancements included additional sensors and specialized processing algorithms. Some of the systems incorporated the enhancements only as a distinct mode of operation, which was selected at the start of each run. Other systems detected adverse conditions in real time and switched to using an enhanced mode during those intervals.

Testing the nine enhanced systems provided an opportunity to verify that they could collect valid profile during adverse speed conditions. Testing the two conventional systems provided a way to examine their limitations and define the range of profile near adverse events, such as stops, that should be marked as invalid during production operation.

TEST CONDITIONS

The certification for urban and low-speed operation experiment took place on October 29, November 7, and November 12, 2024. The testing was conducted on the SMA/HMA test section, which was 1,025.3 ft long. The test runs required initiation of speed changes or stops at specific landmarks. Figure 14 shows the layout of the landmarks. A post with a sign was placed at each landmark.

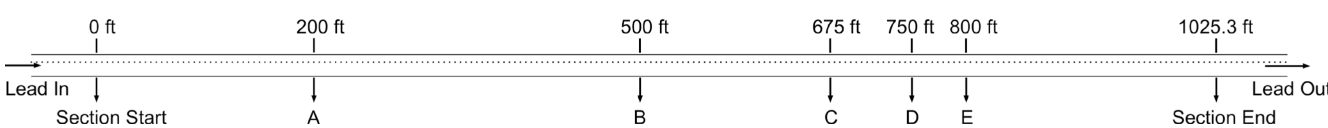

Figure 14. Illustration. Landmarks used in the certification experiment for urban and low-speed operation.

Testing required measurement of the profile while piloting over the test section with five speed profiles:

1. **Constant speed**: Operation at a constant speed between 40 mi/hr and 45 mi/hr over the length of the test section.
2. **Low speed**: Operation at an average speed between 2 mi/hr and 4 mi/hr over the test section with no instantaneous speed over 5 mi/hr.
3. **Braking**: Braking from 30 mi/hr to 15 mi/hr over a 75 ft long interval from Landmark C to Landmark D.
4. **Stop**: A 60-second stop at Landmark D preceded by braking from 30 mi/hr starting at Landmark B.
5. **Stop with creep**: Braking from 30 mi/hr starting at Landmark B and stopping at Landmark D, followed by 5 seconds at rest at Landmark D, travel below 5 mi/hr past Landmark E, and finally a gentle acceleration and travel to the end of the test section.

Four participants attempted an additional (optional) speed profile with braking—long braking: Braking from 45 mi/hr to 10 mi/hr over a 250-ft-long interval from Landmark B to Landmark D.

Appendix D provides detailed instructions to operators for the six speed profiles and idealized plots of speed versus time and speed versus distance.

One of the participants operating a conventional inertial profiler performed additional constant speed runs at 6, 10, 17, and 20 mi/hr to help define the minimum speed that the device produced a valid profile. (See the Low-Speed Performance section of this chapter.)

The original test plan required three passes conforming to the specification for each of the five required speed profiles. The plan permitted operators to make five attempts to achieve three specification-compliant samples of each speed profile. Table 9 lists the number of attempts at each speed profile made by the operators of each device, identifying each device using a letter designation to maintain anonymity.

Table 9. Passes Attempted by Each Device

Speed Profile	A	B	C	D	E	F	G	H	I	J	K
Constant Speed	3	3	3	2	3	3	3	2	3	4	3
Low Speed	5	3	5	3	5	5	5	5	5	5	5
Braking	6	8	5	7	7	7	7	5	5	6	5
Stop	5	5	5	4	5	5	5	4	5	5	5
Stop with Creep	5	5	5	5	5	5	5	5	5	5	5

Most operators chose to complete five passes with the low-speed, stop, and stop-with-creep speed profiles. All operators attempted the braking speed profile at least five times; some opted to exceed five attempts.

OPERATIONS AND SAFETY

On each test date, three or more profilers participated in the testing simultaneously. Three observers helped execute the testing program: one at the west end of the test track, one at the east end of the test track, and one in the adjacent lane near Landmark D. The observer held the profilers on a pad at the west end of the track and released them one at a time. Each time a profiler reached the end of the test section, the observer released the next profiler. Profilers used the east end of the track to turn around and gathered there until the last profiler in the group arrived. At that point, the observer at the east end of the track released the group to platoon to the west end of the track and repeat the cycle.

The observer at Landmark D manipulated the signs to help operators execute each speed profile. This observer operated a "shot clock" during the stop runs that showed the profiler operator a countdown from 60 seconds after coming to a stop and signaled profiler operators after 5 seconds had elapsed during their stop within the stop with creep runs.

All participants and observers carried handheld two-way radios. Certification for urban and low-speed operation testing with multiple profilers ran more efficiently when all profilers attempted the same type of speed profile in the same loop. This way, an announcement by an observer could inform the entire group about which speed profile to execute, and each operator better understood how to judge when the preceding profiler would clear the test section. A disadvantage of that approach is that crews who complete their passes for one type of speed profile with fewer attempts than others must wait for the others to finish before proceeding to the next type of speed profile.

Preparation for each test day required approximately 1 hour to place the landmarks, set up the shot clock, discuss safety and operations with the participants, and answer questions about the required speed profiles. Once the test runs began, completing them took at least 3 hours on each testing day.

RESULTS

Five types of analysis were performed on the data provided by the participants:

1. Inspection of speed profiles for compliance with the specifications for each type of run.
2. Calculation of accuracy scores for each group of passes.
3. Calculation of repeatability scores for each group of passes.
4. Comparison of short-interval roughness profiles from each pass to short-interval roughness profiles from reference measurements.
5. Demonstration of the low-speed limit of a conventional inertial profiler.

Inspection of Speed Profiles

Out of the total group, seven operators provided records of speed versus distance at a constant distance interval with each measured elevation profile. Five of them also provided a record of time versus distance as an additional output channel. One provided speed versus time at a constant time interval in a separate record from speed versus distance. Although the records of speed versus distance were provided using the same distance interval as the profile elevation data, five of the seven operators provided profiles and speed records in different files. For example, all participants provided elevation profiles in Engineering Research Division (ERD) or pavement profile file (PPF) format, but some provided speed records in comma-delimited text (TXT) or comma-separated value (CSV) files.

For the seven devices that provided speed records, the data were inspected for compliance with the specifications.

For the low-speed runs, the specifications required an average speed of 2 to 4 mi/hr and no instantaneous speed greater than 5 mi/hr. All speed records met both requirements. Operators typically chose a speed near 3 mi/hr and maintained it consistently within the test section.

For the constant-speed runs, the specifications required a speed of approximately 40 or 45 mi/hr. The use of two speeds was due to ambiguity in the instructions provided at the test site. All speed records confirmed travel over the test section at a constant speed of approximately 40 or 45 mi/hr.

For the stop runs, the specifications required speed greater than 30 mi/hr from the start of the section until Landmark B and a stop within 10 ft of Landmark D followed by a continued stop for at least 60 seconds. All available records of speed versus time confirmed the stopping duration for the corresponding runs. Figure 15 provides a sample inspection of speed versus distance for a stop run by one of the profilers. The black lines illustrate the speed specifications; the black line from 740 to 760 ft shows the specified window for the stopping location. All available records of speed versus distance showed correct stopping locations.

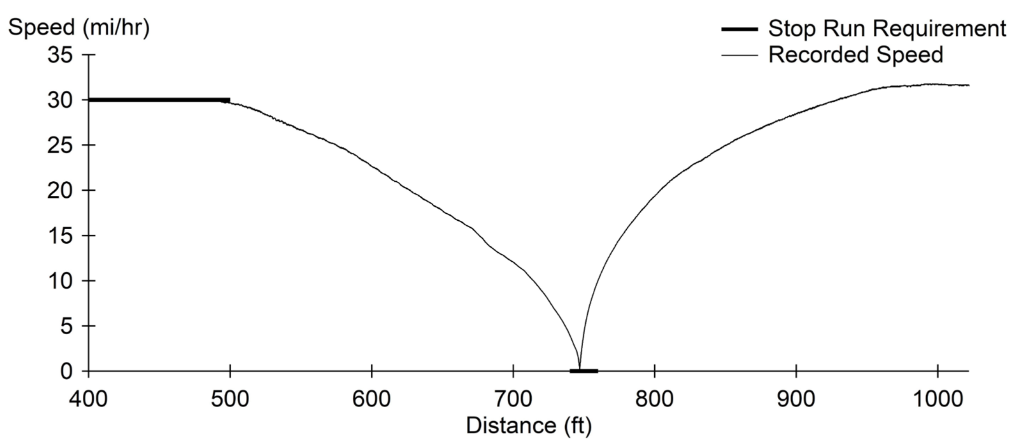

Figure 15. Graph. Speed profile for a stop run.

In Figure 15, the Stop Run Requirement line from 400 to 500 ft shows the minimum speed that profilers must maintain over that interval. Fewer than half of the speed records adhered to this criterion. Some profilers maintained a speed just below 30 mi/hr over that interval and correctly initiated braking after passing Landmark B at the 500 ft mark. Others initiated braking slightly ahead of Landmark B, as shown in Figure 15.

AASHTO R 56-25 recommends braking from 30 mi/hr to a stop over 200 ft, which is an average deceleration of 0.15 g. In previous research using the AASHTO procedure, operators chronically initiated braking before the proper location (Harris and Karamihas 2025). This research extended the distance to 250 ft, which reduced the required deceleration to 0.12 g but did not eliminate issues with early braking.

For the stop-with-creep runs, the specifications required speed exceeding 30 mi/hr from the start of the section until Landmark B, a stop within 10 ft of Landmark D, a continued stop for at least 5 seconds, and travel from Landmark D to Landmark E after the stop at a speed below 5 mi/hr. Figure 16 shows compliant speed profiles from five passes by the same operator.

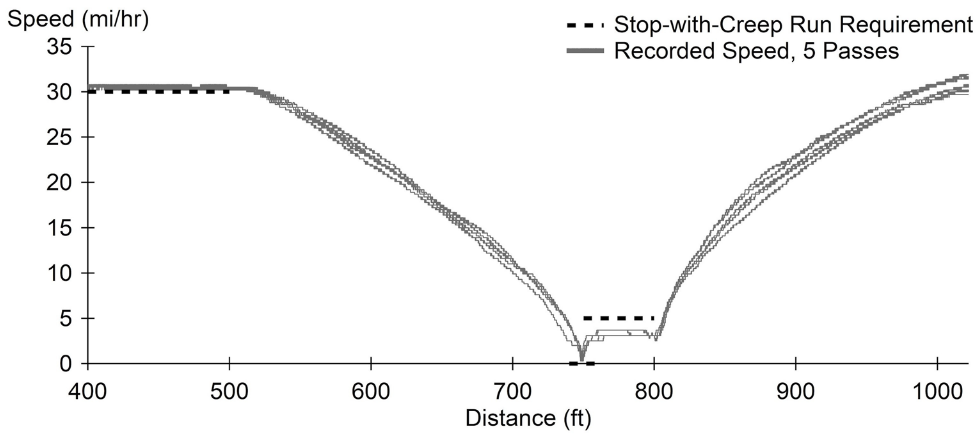

Figure 16. Graph. Speed profiles for a set of stop-with-creep runs.

All available records of speed versus time for the stop-with-creep runs confirmed the stopping duration for the corresponding runs. All available records of speed versus distance showed correct stopping locations and confirmed travel below 5 mi/hr over the 50 ft following the stop. However, the same operators that recorded low entry speed or early braking in the stop runs also recorded the same results in the stop-with-creep runs.

For the braking runs, the specifications required speed exceeding 30 mi/hr from the start of the section until after reaching Landmark C and then speed under 15 mi/hr when crossing Landmark D. Only three of the operators that provided speed records demonstrated adherence to these specifications in three or more of their braking runs. No operator succeeded in every pass, with early braking being the most common issue.

In 38 of the 45 braking runs with available speed profiles, the operator achieved the required speed reduction over the required net distance of 75 ft or less. Figure 17 provides an example. The speed crosses below the 30 mi/hr threshold early, and the speed passes below the 15 mi/hr threshold early. In this pass, the driver achieved a net speed reduction from 30 to 15 mi/hr over 51 ft. A majority of the unsuccessful runs would qualify under specifications that allow for a modest location shift of the 75 ft braking interval.

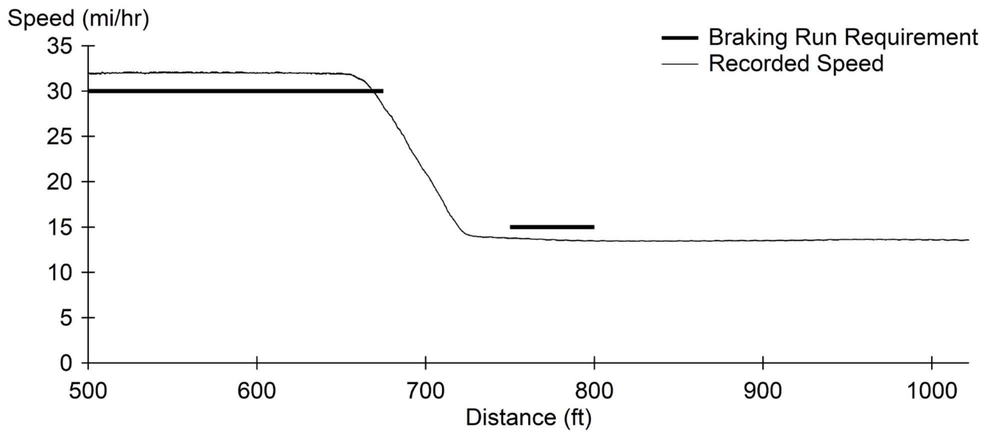

Figure 17. Graph. Speed profile for a braking run with early braking.

Braking from 30 to 15 mi/hr over 75 ft requires an average deceleration of 0.3 g. Several drivers mentioned difficulty in attempting to execute the braking runs to specification. Some operators attempted one or two long-braking runs, which also require a high average deceleration (0.257 g). However, these operators found them more comfortable to execute because the braking occurred over a greater distance.

Braking from 45 to 15 mi/hr over 200 ft presents a potentially satisfactory alternative to the current specification for the braking speed profile, as drivers may find these requirements easier to execute. This alternative uses an already-required landmark for the stop and stop-with-creep runs. It also preserves two important properties of the existing braking speed profile: (1) average deceleration of 0.3 g and (2) braking to a speed that is not below the lower valid speed of operation for typical inertial profilers.

However, braking over a longer distance may present less of a challenge to profile measurement accuracy. Karamihas (2021a) and Herra Gomez (2022) observed that braking causes the largest errors in inertial profiler measurements at the location where the brakes are released while the vehicle is pitched forward due to the deceleration before releasing the brakes. Modification of the braking speed profile to use a longer braking interval may reduce the severity of this combination.

Accuracy Scores

This section presents accuracy scores using comparison of profiles over the HMA section, which covered the final 490 ft of the SMA/HMA section. The experiment's profile measurements covered the entire SMA/HMA section. The accuracy scores cover only the HMA section to help improve the relevance of the results in three ways:

1. Comparison of profiles over the 1,025.3 ft covered by the SMA/HMA section reduced the sensitivity of the accuracy scores to errors caused by braking and stops. This occurred because it included more length over the first half with constant-speed operation.

2. Heavy braking and stops introduced a longitudinal shift into profiles measured using rotational encoders for travel distance. In those profiles, the DMI correction procedure could align the measured profiles with the reference profile before or after the area near Landmark D but not both. Comparison of profile over a longer section exacerbates the effect of misalignment on accuracy scores, even if the vertical measurements within the profile do not include errors.

3. Some profilers demonstrated difficulty with accuracy on the SMA portion of the SMA/HMA section.

Table 10 lists the accuracy score for the left wheel track calculated with DMI correction for each set of passes by each commercially available profiler. Each accuracy score is the average of two to seven individual accuracy scores for the passes performed with each speed profile. For example, the accuracy score for Device A for constant-speed runs is the average of individual accuracy scores for three passes. In contrast, the accuracy score for Device A for stop runs is the average of individual accuracy scores for five passes. (See Table 9.) Table 11 lists the accuracy score for the right wheel track calculated with DMI correction for each set of passes by each commercially available profiler. Tables 10 and 11 identify each device using a letter designation to maintain anonymity.

AASHTO R 56 requires accuracy scores of 0.90 for profile measurements performed at constant speed. Tables 10 and 11 show accuracy scores of 0.90 or greater in bold. Devices A and B produced scores below 0.90 for all speed profiles except constant speed. Devices A and B were conventional inertial profilers.

Only Devices C and I produced accuracy scores above 0.9 for all speed profiles in both wheel tracks. However, taken as a group, the specially equipped profilers (Devices C to J) demonstrate that accuracy scores above 0.9 are within reach for many of the devices.

Table 10. Accuracy Scores with DMI Correction for Each Speed Profile, Left Wheel Track

Speed Profile	A	B	C	D	E	F	G	H	I	J
Constant Speed	**0.930**	**0.932**	**0.959**	**0.915**	0.793	**0.939**	**0.922**	**0.921**	**0.930**	**0.933**
Low Speed	0.835	0.079	**0.951**	0.888	**0.947**	0.879	**0.942**	0.461	**0.939**	**0.930**
Braking	0.358	0.675	**0.944**	0.776	**0.927**	0.892	**0.900**	**0.912**	**0.924**	0.811
Stop	0.157	0.194	**0.956**	0.794	**0.934**	**0.905**	0.868	0.894	**0.925**	0.853
Stop with Creep	0.167	0.186	**0.956**	0.799	**0.933**	**0.910**	0.860	0.889	**0.920**	0.861

Bolded values indicate accuracy scores of 0.90 or greater.

Table 11. Accuracy Scores with DMI Correction for Each Speed Profile, Right Wheel Track

Speed Profile	A	B	C	D	E	F	G	H	I	J
Constant Speed	**0.947**	**0.943**	**0.962**	**0.920**	0.848	**0.958**	**0.954**	**0.932**	**0.910**	**0.943**
Low Speed	0.897	0.052	**0.969**	**0.926**	**0.959**	**0.900**	**0.965**	0.752	**0.935**	**0.953**
Braking	0.227	0.705	**0.958**	0.789	**0.945**	**0.930**	**0.940**	**0.919**	**0.922**	0.777
Stop	0.214	0.200	**0.959**	0.832	**0.943**	**0.935**	**0.919**	**0.912**	**0.913**	0.859
Stop with Creep	0.211	0.195	**0.959**	0.820	**0.933**	**0.949**	**0.915**	**0.901**	**0.919**	0.896

Bolded values indicate accuracy scores of 0.90 or greater.

Repeatability Scores

Table 12 lists the repeatability score for the left wheel track calculated with DMI correction for each set of passes by each commercially available profiler. Each repeatability score is the average of 2 to 28 individual repeatability scores for combinations of passes performed with each speed profile. For example, the repeatability score for Device A in constant-speed runs is the average of individual repeatability scores for three combinations of passes (1 and 2, 1 and 3, 2 and 3), whereas the repeatability score for Device A in stop runs is the average of individual repeatability scores for 10 possible combinations of two of the five passes. (See Table 9.) Table 13 lists the repeatability score for the right wheel track calculated with DMI correction for each set of passes by each commercially available profiler. Tables 12 and 13 identify each device using a letter designation to maintain anonymity.

Table 12. Repeatability Scores with DMI Correction for Each Speed Profile, Left Wheel Track

Speed Profile	A	B	C	D	E	F	G	H	I	J
Constant Speed	**0.992**	**0.945**	**0.991**	**0.974**	0.845	**0.983**	0.909	**0.945**	**0.961**	**0.954**
Low Speed	0.855	0.118	**0.988**	0.918	**0.971**	**0.965**	**0.979**	0.260	**0.989**	**0.971**
Braking	0.736	0.691	**0.980**	0.898	**0.959**	0.892	**0.929**	**0.935**	**0.930**	0.917
Stop	**0.946**	0.789	**0.983**	0.844	**0.959**	**0.947**	**0.932**	**0.931**	**0.961**	**0.960**
Stop with Creep	0.763	0.750	**0.979**	0.904	**0.970**	**0.952**	**0.921**	**0.944**	**0.974**	**0.964**

Bolded values indicate repeatability scores of 0.92 or greater.

Table 13. Repeatability scores with DMI Correction for Each Speed Profile, Right Wheel Track

Speed Profile	A	B	C	D	E	F	G	H	I	J
Constant Speed	**0.997**	**0.942**	**0.994**	**0.983**	0.868	**0.992**	**0.962**	**0.958**	**0.989**	**0.969**
Low Speed	0.905	0.108	**0.992**	**0.950**	**0.979**	**0.977**	**0.989**	0.589	**0.986**	**0.971**
Braking	0.787	0.684	**0.980**	0.902	**0.961**	**0.926**	**0.957**	**0.956**	**0.940**	0.887
Stop	0.802	0.752	**0.980**	0.919	**0.978**	**0.954**	**0.969**	**0.968**	**0.955**	**0.939**
Stop with Creep	0.897	0.698	**0.987**	**0.926**	**0.973**	**0.971**	**0.963**	**0.959**	**0.979**	**0.966**

Bolded values indicate repeatability scores of 0.92 or greater.

AASHTO R 56 requires repeatability scores of 0.92 for profile measurements performed at constant speed. Tables 12 and 13 show repeatability scores of 0.92 or greater in bold.

Devices A and B produced repeatability scores below 0.92 for all speed profiles except constant speed and stop. Devices A and B were conventional inertial profilers. The high repeatability score for Device A using the stop speed profile represents impressive repetition of the same measurement errors in the profiles in every pass.

Only Devices C and I produced repeatability scores above 0.92 for all speed profiles in both wheel tracks. However, taken as a group, the specially equipped profilers (Devices C to J) demonstrate that repeatability scores above 0.92 are within reach.

Device E produced accuracy scores above 0.9 and repeatability scores above 0.92 for the low-speed, braking, stop, and stop-with-creep runs. However, it produced accuracy scores and repeatability scores below 0.90 for runs at constant speed. Constant-speed runs are considered a nominal operating condition. Because certification testing using the low-speed, braking, stop, and stop-with-creep speed profiles is time consuming, acceptable scores for constant-speed runs should serve as a prequalification for testing using other speed profiles.

Short-Interval Roughness Profiles

AASHTO R 56-25 includes testing of valid operation due to stop-and-go operation and testing of valid operation due to stop-and-go and minimum speed operation. The procedures for these two types of testing resemble testing with the stop and stop-with-creep speed profiles demonstrated in this research. AASHTO R 56-25 does not place requirements on accuracy scores of measured profile based on cross correlation. Instead, it requires that short-interval roughness profiles measured in each pass agree to within 30 in./mi over the length of the profile.

Figure 18 compares the right short-interval roughness profile for a stop-with-creep run by Device D to that of the reference device on the HMA section. A short-interval roughness profile presents IRI values averages over a short length versus distance. Figure 18 shows short-interval roughness profiles using an averaging window of 25 ft. As such, each point in each plot represents the average IRI for a pavement length spanning from 12.5 ft upstream to 12.5 ft downstream.

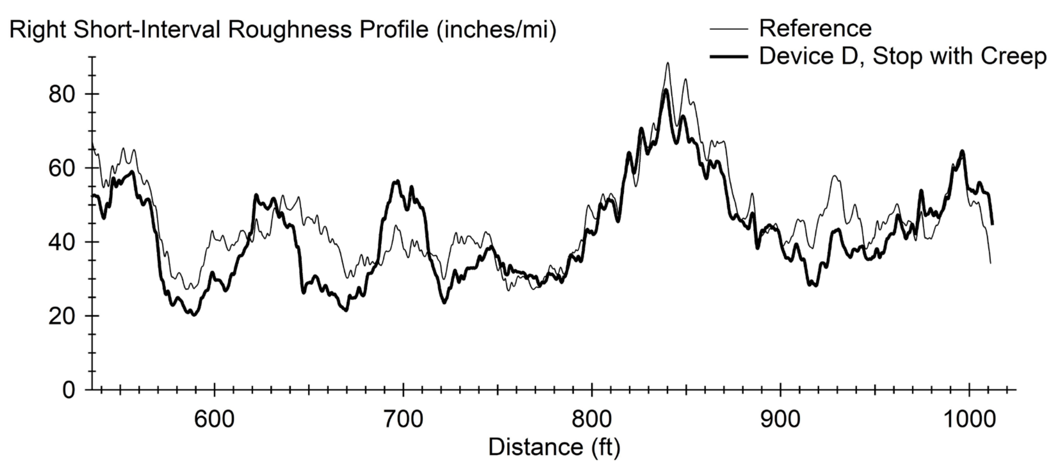

Figure 18. Graph. Short-interval roughness profile comparison.

AASHTO R 56-25 deems any area where the short-interval roughness profile differs from the reference value by more than 30 in./mi as invalid. No area shown in Figure 18 satisfies this criterion. However, the accuracy score for the profile that produced Figure 18's short-interval roughness profile was 0.766; the overall IRI values differ by 7.8%, and differences in the details of the short-interval roughness profile signify differences in the underlying profile.

Karamihas et al. (2019) based the recommended requirement for agreement in short-interval roughness profiles within 30 in./mi on experiments that did not include devices with additional sensors for collecting valid profile through stops. Rather, the previous research sought to encourage the development of conventional inertial profilers with special algorithms to mitigate the measurement of severe artificial roughness at stopping locations. Since commercially available profilers have exceeded that capability, accuracy score requirements for the measurement of accurate profiles are warranted.

For conventional inertial profilers, the methodology used in AASHTO R 56-25 provides a way to identify the range within measured profiles near a stop or heavy braking to mark as invalid. Figure 19 provides an example of artificial roughness caused by heavy braking. The figure compares a profile measurement by Device A at constant speed to a pass using the braking speed profile. Artificial profile curvature in the profile where the braking ended (Landmark D at 750 ft) causes most of the measurement errors associated with braking. However, the high-pass filters applied by the profiler spread the influence of the error in the raw elevation profile over an area exceeding 400 ft in length.

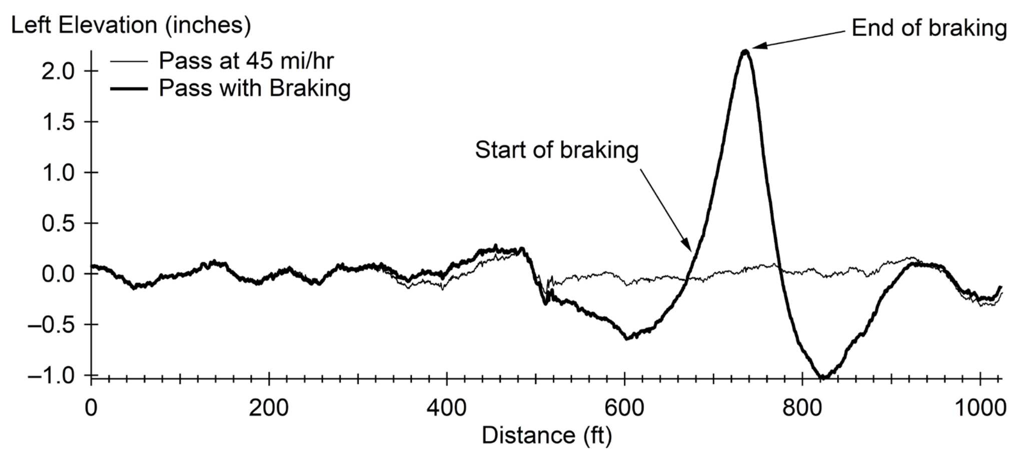

Figure 19. Graph. Elevation profile measurements with and without braking.

Figure 20 compares the short-interval roughness profiles of the two passes illustrated in Figure 19. A comparison of the short-interval roughness profiles shows the range with the profile where braking affected content that contributed to the IRI. For Device A, the area extends from 40 ft upstream of the location where the braking ended to at least 75 ft downstream of the location where the braking ended. In the area more than 40 ft upstream of the end of braking, the short-interval roughness profiles agree. In the area more than 75 ft downstream of the end of braking, the roughness profiles agree, except for a longitudinal shift caused by a downward bias in longitudinal distance measurement during braking.

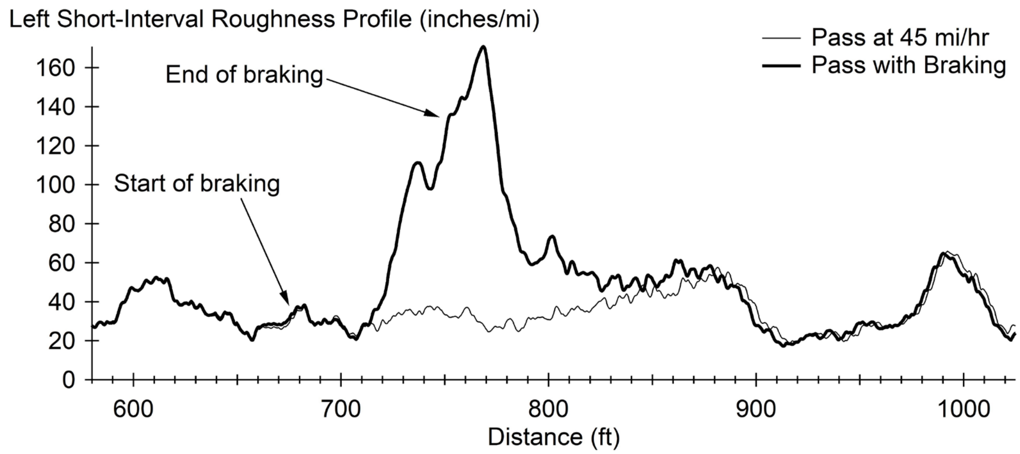

Figure 20. Graph. Short-interval roughness profile measurements with and without braking.

Low-Speed Performance

Device A collected additional profiles at 6, 10, 17, and 20 mi/hr to help define the minimum speed at which it measured valid profiles. Device A also collected repeated passes at 45 mi/hr in the constant-speed runs. Device A collected repeated passes at 3 mi/hr in the low-speed runs and at 25 mi/hr and 50 mi/hr in the certification for constant-speed operation experiment. Table 14 presents the number of passes, accuracy scores, and average IRI values from each test speed of Device A. The accuracy scores and average IRI values are calculated for the left wheel track of the HMA section. Accuracy scores included DMI correction because of the sensitivity of longitudinal distance measurement to speed.

Table 14. IRI and Accuracy Scores at Various Speeds for Device A

Speed	Passes	Accuracy Score	Average IRI
3	3	0.820	41.4
6	1	0.912	38.4
10	1	0.930	36.6
17	1	0.927	36.4
20	1	0.956	37.1
25	7	0.936	36.3
45	3	0.930	36.5
50	8	0.937	36.4

Table 14 presents anecdotal evidence of the effect of the speed on the accuracy of Device A on the HMA test section. The limited data suggest that the accuracy scores may diminish for speeds below 10 mi/hr and pass under the accuracy threshold used in AASHTO R 56 at 3 mi/hr. For this (limited) set of runs, the IRI increases as speed decreases below 10 mi/hr.

Karamihas et al. (2019) reported that the longest wavelength a conventional inertial profiler measures accurately decreases with travel speed. Figure 21 provides an example of this phenomenon for profile measurements by Device A at 45 and 3 mi/hr. The profiles measured short-wavelength content (e.g., the features that reverse over shorter distances) consistently at both speeds. However, the profile measured at 3 mi/hr includes additional long-wavelength roughness relative to the profile measured at 45 mi/hr. Some of the spurious long-wavelength roughness in the profile measured at 3 mi/hr affects the content that contributes to the IRI, which accounts for the reduction in accuracy score.

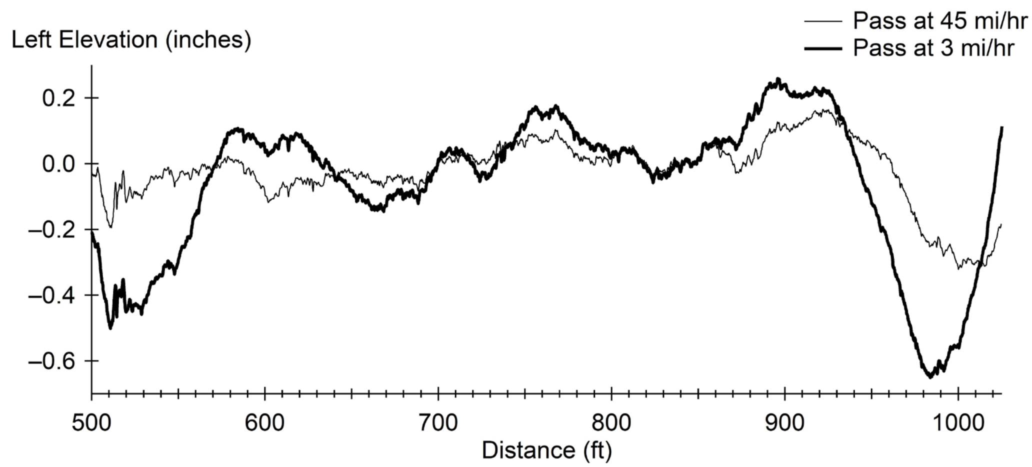

Figure 21. Graph. Elevation profile measurements at 45 mi/hr and 3 mi/hr.

RECOMMENDATIONS

The following practices are recommended for certification for urban and low-speed operation testing:

- Assign an observer to help ensure the safety of the operators and to instruct them on the expected speed profiles, testing procedures, and safety rules.
- Provide operators with a clear diagram that shows the meaning and location of each landmark within the test section.
- Issue communication devices (e.g., handheld two-way radios) to the operators of each profiler.
- Use compatible speed profiles when a set of profilers operates in a platoon.
- Provide highly visible landmarks that clarify the start and end points of test section boundaries and all the landmarks used to execute the required speed profiles. If needed, display signs only at the landmarks that are required during testing with each speed profile. For example, during stop runs, remove the signs at Landmarks A, C, and E, because only Landmarks B and D are needed.
- Use an observer to verify the duration of the stops during the stop and stop-with-creep runs if the profiler under test is unable to provide a record of speed versus time.

The following modifications to AASHTO R 56-25 are recommended:

- For conventional inertial profilers, maintain the use of short-interval roughness profiles to determine the area around stops and release of the brakes where measurement of the IRI is invalid.

- For specially equipped profilers that purport to measure valid profile under adverse speed conditions, require accuracy and repeatability scores from cross correlation above a minimum threshold for the low-speed, braking, stop, and stop-with-creep speed profiles. Use the same thresholds for required accuracy and repeatability scores for constant-speed operation.

- Change the test section length to 528 ft. Maintain sufficient lead in and lead out.

- Provide an area for operators to practice executing the required speed profiles before the certification testing. If possible, provide the area for practice on a pavement section other than the section used for certification. The practice section provides three opportunities for operators: (1) rehearsal of the speed profiles, (2) prequalification based on agreement between profiles measured at constant speed and profiles from passes measured using the other speed profiles, and (3) practice maintaining accurate lateral tracking.

- Establish an additional speed profile for operation with braking that requires a change in speed from 45 to 15 mi/hr over 200 ft. This version of the long-braking speed profile provides a potential substitute for the current braking speed profile that is easier to execute, does not require an additional landmark, and may be safer. Additional testing is needed to verify that measuring valid profile using the long braking speed profile implies the same level of satisfactory field performance as the current braking speed profile.

The following modifications to AASHTO M 328-14 (2022) are recommended:

- Establish a standard protocol for profilers to store and export records of speed and time versus distance.

- Specify the maximum distance interval and resolution for reporting speed and time. It should also specify a file format for reporting speed and time versus distance.

- Note that ASTM E2560-17 includes a provision for appending signals stored at a constant distance interval to the end of PPF files used to store elevation profile (ASTM 2017).

CHAPTER 5: CERTIFICATION OF WALKING-SPEED PROFILERS

PARTICIPANTS

The certification of walking-speed profilers experiment included 11 devices, 8 of which were rolling inclinometer-based profilers designed to produce reference measurements for certification. The manufacturers of these 8 inclinometer-based profilers operated 3 of the devices while personnel from state DOTs operated the other 5. Three prototype walking-speed profilers were also included, some of them intended for operation on closed bridge decks and within construction sites. This chapter presents the results of the commercially available inclinometer-based profilers.

TEST CONDITIONS

Testing took place on October 30, November 8, and November 13, 2024, and required three repeated measurements over the left wheel track of the five test sections. However, rain interrupted the November 13 testing, leaving the two profilers operating that day to execute only a subset of the required runs.

On October 30 and November 7, the participants and researchers collaborated to place a chalk line in the wheel track of each test section. Figure 22 shows a portion of the SMA section's chalk line. Operators needed a chalk line as a guide because the dashed longitudinal guide mark for vehicle-mounted profilers appeared 7 in. to the right of the wheel track of interest.

Figure 22. Photo. Chalk line placed to guide walking-speed profilers on the SMA section.

On November 13, a participant attached a screw that extended 7 in. to the right of the centerline at the mid-wheelbase position of the walking-speed profilers. These screws provided ad hoc pointers, which allowed the operators to use the dashed longitudinal guide mark, rather than chalk line, for piloting.

OPERATIONS AND SAFETY

Most of the operators performed DMI calibration before they began the required profile measurement runs. Some operators performed the DMI calibration over a length of 100 ft, others over a length of 528 ft, and still others over a length of 1,000 ft. In a few cases, operators returned to recalibrate the DMI after observing inconsistent measurement of longitudinal distance during repeated runs over the same test section.

The test plan did not place any requirements on the speed of operation during the measurements. Operators selected their speed based on a combination of experience and manufacturer recommendations. Several operators performed loop closure as a means of quality control on some or all measurements. Loop closure is a return pass over a test section from the end to the beginning. It provides the operator with a means to evaluate, and potentially compensate for, a difference in the net elevation changes between the forward and return passes.

It is important to note that testing with walking-speed profilers requires a generous allocation of time. The allotted time should provide for at least two DMI calibration runs, loop closure for every profile measurement run, a walking speed of 0.5 mi/hr during data collection, and additional time for the operator to save and inspect the profile after each run. Six walking-speed profilers completed the entire testing program on October 30. Although the observers and participants collaborated to keep all six profilers as active as possible, the testing spanned nearly 9 hours after completing the chalk line placements.

To ensure the safety of those involved, instructions to participants requested minimal use of full-sized vehicles within the walking-speed profiler area of the test track. Additionally, full-sized vehicles were restricted to a maximum speed of 15 mi/hr. Operators performed their measurements within view of an observer, and all participants and observers carried handheld two-way radios.

RESULTS

Table 15 lists the number of passes collected by each commercially available inclinometer-based profiler. Table 15 also identifies each profiler using a letter code to maintain anonymity. The profilers identified by these letters are different from those in Chapter 4. This section presents the average repeatability scores and accuracy scores for each set of listed passes.

Table 15. Passes Collected by Each Production Walking-Speed Device

Test Section	A	B	C	D	E	F	G	H
SMA/HMA	3	3	3	3	2	3	3	3
MS	3	0	3	3	0	5	3	3
DGR	3	1	3	3	0	3	3	3
DGV	3	1	3	3	1	3	3	3
TT	3	0	3	3	0	3	2	3

Table 16 lists the repeatability score calculated without DMI correction for each profiler's set of passes. In most cases, the repeatability score is the average of three individual scores produced by comparing profiles from Pass 1 to Pass 2, from Pass 1 to Pass 3, and from Pass 2 to Pass 3.

Table 16. Repeatability Scores without DMI Correction

Test Section	A	B	C	D	E	F	G	H
SMA/HMA	0.939	0.945	0.829	0.958	0.914	0.942	0.951	0.959
SMA	0.940	0.930	0.829	0.960	0.958	0.922	0.951	0.948
HMA	0.926	0.926	0.764	0.927	0.841	0.933	0.945	0.961
MS	0.952	–	0.850	0.972	–	0.959	0.954	0.977
DGR	0.873	–	0.699	0.946	–	0.903	0.918	0.927
DGV	0.966	–	0.864	0.972	–	0.947	0.942	0.968
TT	**0.993**	–	0.646	**0.994**	–	**0.987**	**0.991**	**0.991**

Bolded values indicate repeatability scores of 0.98 or greater.

Table 17 lists the repeatability score calculated with DMI correction for each profiler's set of passes. The greatest improvement to an average repeatability score caused by DMI correction was 0.008, which occurred on the set of passes from Device C on the TT section. Excluding the passes from Device C on the TT section, DMI correction caused the largest improvement in average repeatability scores for each device on the SMA/HMA section. Repeatability scores were more sensitive to longitudinal distance measurement errors on the SMA/HMA section because it was a longer section than the others. On a longer test section, the same DMI error-level percentage causes a higher level of misalignment to accumulate.

Table 17. Repeatability Scores with DMI Correction

Test Section	A	B	C	D	E	F	G	H
SMA/HMA	0.943	0.945	0.832	0.959	0.915	0.944	0.954	0.965
SMA	0.940	0.930	0.829	0.960	0.958	0.923	0.952	0.949
HMA	0.926	0.926	0.766	0.928	0.841	0.933	0.946	0.964
MS	0.952	–	0.850	0.972	–	0.960	0.954	0.977
DGR	0.873	–	0.699	0.947	–	0.904	0.918	0.927
DGV	0.966	–	0.865	0.973	–	0.948	0.945	0.970
TT	**0.993**	–	0.654	**0.994**	–	**0.987**	**0.994**	**0.991**

Bolded values indicate repeatability scores of 0.98 or greater.

Table 18 lists the accuracy score calculated without DMI correction for each set of passes by each profiler. The accuracy score is the average of individual scores produced by comparing the profile from each pass to the profile measured by the BP.

Table 19 lists the accuracy score calculated with DMI correction for each profile's set of passes. DMI correction caused the largest improvement in average accuracy scores for each device on the

SMA/HMA section. As with the change in repeatability scores with DMI correction applied, observation of the largest improvement on the SMA/HMA section is attributed to section length.

Table 18. Accuracy Scores without DMI Correction

Test Section	A	B	C	D	E	F	G	H
SMA/HMA	0.941	0.871	0.890	0.921	0.832	0.813	0.929	0.844
SMA	0.956	0.936	0.897	0.960	0.917	0.910	0.935	0.855
HMA	0.930	0.843	0.769	0.894	0.795	0.814	0.930	0.892
MS	0.956	–	0.910	0.940	–	0.906	0.958	0.935
DGR	0.896	0.852	0.754	0.942	–	0.868	0.900	0.928
DGV	0.948	0.923	0.874	0.931	0.902	0.847	0.948	0.919
TT	0.961	–	0.815	0.973	–	0.967	0.977	0.963

Bolded values indicate accuracy scores of 0.98 or greater.

Table 19. Accuracy Scores with DMI Correction

Test Section	A	B	C	D	E	F	G	H
SMA/HMA	0.945	0.947	0.891	0.962	0.919	0.935	0.937	0.924
SMA	0.957	0.947	0.898	0.963	0.932	0.927	0.937	0.868
HMA	0.931	0.888	0.770	0.925	0.843	0.903	0.932	0.947
MS	0.956	–	0.913	0.970	–	0.953	0.963	0.972
DGR	0.896	0.853	0.754	0.943	–	0.869	0.901	0.930
DGV	0.948	0.934	0.874	0.940	0.936	0.901	0.952	0.934
TT	0.961	–	0.819	**0.993**	–	**0.986**	0.979	**0.989**

Bolded values indicate accuracy scores of 0.98 or greater.

Karamihas (2004, 2005) recommends accuracy and repeatability scores of at least 0.98 for reference profilers. Tables 16 through 19 show scores exceeding 0.98 in bold. No accuracy score exceeded 0.98 without DMI correction, and no accuracy or repeatability score exceeded 0.98 on any test section except TT. Anecdotally, the operators that produced the highest accuracy and repeatability scores pushed their profilers as slowly and smoothly (e.g., without longitudinal acceleration) as possible.

Detailed assessment of the results and inspection of profiles from each device produced the following observations. First, DMI errors differed for each profiler depending on the test section. The algorithm that calculates an accuracy score with DMI correction reports the DMI adjustment that produces the highest score. For five of the profilers, the optimal DMI adjustment for measurements on the SMA section was more than 0.1% higher than the optimal DMI adjustment on the HMA section. This means that correction to the total length of the profile was at least 0.5 ft greater on the SMA section than on the HMA section. Note that operators measured profiles on the SMA and HMA sections in one long pass.

Next, the operator of Device C discovered a problem with the profile measured in the third pass on the TT section. The profile from that pass included an excessive level of spurious short-wavelength content (i.e., chatter). The source of the error is not known. With that pass removed, the average accuracy score for the other two passes exceeds 0.97.

Profiles from Device C included a high level of content at a wavelength equal to the circumference of the supporting wheels. This is most likely caused by one or more of the supporting wheels being out of round. Although the sensitivity of the IRI to roughness at that wavelength is small, vertical and longitudinal acceleration of the profiler's inclinometer may affect measurement quality at other wavelengths. Further, the inconsistent relationship between wheel rotation and distance will cause longitudinal distortion in the measured profiles.

RECOMMENDATIONS

The following practices are recommended for profiler comparison testing with walking-speed profilers:

- Assign an observer to help ensure the safety of the operator (noting that walking-speed profiler operators are unable to observe their surroundings).
- Learn and follow the instructions in the manual.
- Provide highly visible markings directly within the wheel track of interest, using a solid marking if possible.
- Pilot the device slowly and at a constant walking speed, imposing as little change in the tilt of the device as possible.
- Store the device without resting it on its supporting wheels, periodically inspecting the power spectral density plots for high content at a wavelength equal to the circumference of the supporting wheels.
- Close the test section to all traffic during operation of the profiler, avoid traffic in adjacent lanes to the greatest extent possible, and impose a low speed limit (e.g., 15 mi/hr or lower) for all vehicles operating near the test section.

The following additional practices are recommended when a walking-speed profiler is designated as a reference device:

- Calibrate the DMI of walking-speed profilers on each section of interest or a section with the same material and surface macrotexture type. Alternatively, verify the accuracy of the DMI over a short segment within each test section of interest.
- Use a walking-speed profiler with a real-time display of speed to assist the operator.
- Perform at least three repeated passes over each test section. If the three profiles do not produce an average repeatability score of 0.98 or greater, address the cause.

CHAPTER 6: SUMMARY AND RECOMMENDATIONS

SUMMARY

This study demonstrated and evaluated profiler certification methods for implementation at ICART. The field demonstrations included three categories of testing:

1. **Certification for constant-speed operation:** This testing evaluated the performance of profilers used to measure roughness for pavement network evaluation, project-level pavement evaluation, and construction QC/QA while operating and constant speed. Certification for constant-speed operation testing included 3 lightweight inertial profilers, 25 high-speed inertial profilers, and 3 prototype high-speed profilers. The testing included measurements on a diverse set of macrotexture types composed of positive isotropic, negative isotropic, longitudinal, transverse, and a baseline with less aggressive macrotexture. The testing also included a very smooth test section. Testing of high-speed profilers included measurements at 25 mi/hr and 50 mi/hr.

2. **Certification for urban and low-speed operation:** This testing evaluated the performance of profilers operating under adverse speed conditions that caused measurement errors in conventional inertial profile measurements, such as low speed, with braking, or with stops. Certification for urban and low-speed operation testing included 11 high-speed profilers: 2 conventional inertial profilers and 9 profilers with enhancements to improve accuracy under adverse speed conditions. The experiment included measurement of profile while operating under staged versions of adverse speed conditions, including operation below 5 mi/hr, operation with braking of 0.3 g, operation with long stops, and operation with a stop followed by travel at a low speed.

3. **Certification for walking-speed profilers:** This testing evaluated the performance of 8 inclinometer-based profilers and 3 prototype profilers. The testing included the same 6 test sections as in the certification for constant-speed operation testing.

All three types of testing adopted aspects of certification practices recommended in AASHTO R 56-25, including testing on a diverse set of surface types and comparison of profile, rather than summary roughness index, to quantify the repeatability and accuracy of profilers. Cross correlation of IRI-filtered profile provided the ratings of agreement between profiles. Appendix B describes the details of the algorithm used in this research.

The study targeted the use of 5 passes under each speed condition for testing the repeatability of vehicle-mounted profilers and 3 passes for testing the repeatability of walking-speed profilers. The study compared measured profiles to reference profile measurements to establish the accuracy of each profiler. The FHWA Benchmark Profiler and FHWA Urban and Low-Speed Profiler collected reference measurements for all three types of testing. These two devices demonstrated reference-level repeatability and reference-level agreement in a recent comparison study at ICART on the same six test surfaces used for the certification for constant-speed operation testing (Karamihas and Gilbert 2026).

RECOMMENDATIONS

Chapters 3, 4, and 5 provide recommendations related to the certification for constant-speed operation, certification for urban and low-speed operation, and certification of walking-speed profiler testing, respectively. The recommendations in Chapters 3 through 5 address test conditions, testing operations, safety, and analysis methods. This section summarizes the most critical recommendations for each category.

Test Conditions

For vehicle-mounted profilers, perform certification testing at a minimum of two speeds. If possible, use two speeds that differ by a factor of two or more. Testing at two speeds helps reveal and diagnose measurement errors associated with inaccurate sensor calibration, signal latency, and signal processing errors that are less obvious when testing at one speed.

In certification for urban and low-speed operation testing, demonstration of the newly adopted methods in AASHTO R 56-25 confirmed their practicality. However, four suggestions for updates are offered:

1. Evaluate profiler accuracy and repeatability using a 528 ft section of the measured profiles.
2. Consider a modified version of the braking run with reduction in speed from 45 mi/hr to 15 mi/hr over 200 ft. More testing is needed to confirm that the modified speed profile presents the same challenge to profilers as the current version does.
3. Require the same accuracy score and repeatability score for certification used in adverse speed conditions as is used for constant-speed certification. When a profiler fails to achieve a passing accuracy score, use the requirement for short-interval roughness profile accuracy to within 30 in./mi to identify areas of highly inaccurate roughness for leave-outs.
4. Update AASHTO M 328-14 to require storage of speed and time versus distance to support certification for urban and low-speed profile measurement and automated identification of areas with inaccurate roughness measurement in conventional inertial profilers.

Results of the certification for constant-speed operation and certification of walking-speed profiler testing confirmed the difference in accuracy of many profilers on different surface types. For example, certification on any one of the following macrotexture types does not ensure accurate measurement of profile on any of the others: isotropic negative, isotropic positive, longitudinal, and transverse. Thus, to the extent possible, certify profilers on the full range of macrotexture types they will encounter in the field.

As an alternative, regularly test each profiler make or design on a comprehensive set of surfaces in national type testing experiments or profiler roundups. In these tests, establish the baseline capability of each profiler design using expert operators. Perform regular certification under a subset of conditions with regular operators to establish the status of individual profilers and their operators.

Lateral tracking errors and changes to the profile with time affected perceived profile measurement accuracy. Results from testing on a jointed concrete test section demonstrated a change in its profile over an interval of 3 hours. Several operators employed lasers, cameras, or windshield markings to improve their tracking accuracy. Regional profiler certification programs should attempt to quantify the sensitivity of each test section used for certification to changes with time and lateral tracking position using a controlled set of reference-quality profile measurements.

This research did not include measurements on rough test sections. Further work is needed to establish a testing methodology or roughness levels needed for certification of profilers for network-level roughness measurements.

Testing Operations

Automated triggering at test section starting and ending points expedited the analysis of measured profiles. To support the use of automated triggering, obtain a set of posts with solid reflectors that are compatible with as many of the profile measurement devices' triggering sensors as possible. Further, using visible labels on the posts to help operators of vehicle-mounted profilers recognize the start and end of each test section, and distinguish test sections, helps expedite testing with vehicle-mounted profilers. For all types of testing, provide a clear diagram of the layout and testing direction and review it with profiler operators before collecting measurements.

If possible, provide a test section for DMI calibration and practice executing certification for urban and low-speed operation speed profiles away from the certification test sections so that those operations do not interfere with the measurements used for certification.

Safety

Communicate safety rules to operators before entering the test facility. Issue handheld radios to all participants in the testing, or establish some other method to allow all participants and observers to communicate within the test facility. If any person within the facility is working or testing outside of a full-sized vehicle, close the area to traffic or establish a very low speed limit for any passing vehicle.

Analysis Methods

Continue to report agreement between profile measurements using cross correlation of IRI-filtered profiles. If other roughness index options enter common practice, use the filter or algorithm associated with the new index in place of the IRI algorithm. Certify profilers based on cross correlation without DMI correction. Report cross-correlation results with DMI correction if needed to help operators diagnose low accuracy scores and repeatability scores.

Not all the inclinometer-based profilers demonstrated reference-level accuracy and repeatability on all the test surfaces in this research. Further examination is needed to either improve their performance or adapt certification programs that use inclinometer-based devices to their current performance.

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APPENDIX B: CROSS CORRELATION

This appendix provides details about the algorithm used to quantify the agreement between profiles. This research used cross correlation of IRI-filtered profiles to generate agreement scores between profiles (Karamihas 2004). This study reports three types of agreement score:

Accuracy: Comparison of a profile measurement to the reference profile.

Reproducibility: Comparison of a profile measurement from one profiler to a measurement from another profiler, or comparison of measurements from the same profiler under difference conditions, such as two different speeds.

Repeatability: Comparison of two measurements from the same profiler.

When individual agreement scores are available for multiple pairs of profiles, this report provides the average agreement score. For example, 5 repeated passes by a candidate profiler produce 5 individual accuracy scores when each is compared to the reference profile. The accuracy score is the average of the 5 individual scores. The repeatability score is the average of each of the 10 possible pairs among the 5 profiles. If another profiler collects 5 repeated passes on the same test section, the reproducibility score between the 2 sets is the average of the 25 possible pairs using 1 pass from each profiler.

CALCULATION PROCEDURE

Cross-correlate a profile from a profiler (hereafter referred to as the candidate profile) to a reference profile as follows:

Step 1: Identify the reference profile.

Designate the reference profile (Q), recorded at a constant interval of δ_Q. The profile shall begin at a longitudinal reference location of 0, which corresponds to the section start. Denote each profile point with an indexed value, starting at $Q(0)$ and ending at $Q(N_{QRaw})$, where $N_{QRaw}+1$ is the number of samples in the reference profile.

Step 2: Identify the candidate profile.

Designate a candidate profile (P), recorded at a constant interval of δ_P. Crop the profile (P) so that it begins at the test section starting point. Terminate the profile at the test section ending point. Denote each profile point in the cropped profile with a subscript, starting at $P(0)$ and ending at $P(N_{PRaw})$, where $N_{PRaw}+1$ is the number of samples in the candidate profile.

Step 3: Apply the IRI algorithm to each profile.

Note that the IRI algorithm will produce a filtered profile with the same recording interval as the input profile. However, the filtered profile will contain slightly fewer samples than the input profile, because the IRI algorithm truncates up to 0.8202 ft at the end. The filtered reference profile and the filtered candidate profile will have N_{QFilt} +1 and N_{PFilt} +1 points, respectively.

Step 4: Upsample the filtered profiles to a common sample interval.

Use linear interpolation to upsample the profiles to a common interval of δ. The upsampled reference profile (q) will have N_q+1 samples, where (Figure 23):

$$N_q = \text{trunc}(N_{QFilt}\delta_Q/\delta)$$

Figure 23. Equation. Where statement number of samples in reference profile (*q*).

The trunc function truncates its argument to the next-lowest integer. Similarly, the upsampled candidate profile (p) will have N_p+1 samples, where (Figure 24):

$$N_p = \text{trunc}(N_{PFilt}\delta_P/\delta)$$

Figure 24. Equation. Where statement for number of samples in candidate profile (*p*).

Step 5: Cross-correlate the candidate profile to the reference profile over a range of longitudinal offsets.

Cross-correlate the filtered and upsampled candidate profile (p) to the filtered and upsampled reference profile (q) several times over a range of longitudinal offsets.

Do this by shifting the longitudinal distance referencing for the candidate profile (p) by various amounts, ranging from $-X_{off}$ to X_{off}. An index value of 0 denotes the section start. When the candidate profile (p) shifts longitudinally by a distance in the downstream direction, the new index value of the first point is (Figure 25):

$$N_{off} = \text{trunc}(X_{off}/\delta)$$

Figure 25. Equation. Shift in the index value of the first point.

When the candidate profile (p) shifts upstream by the same distance, the first point has an index value equal to $-N_{off}$.

Step through the possible range of starting index offset values (m) from $-N_{off}$ to N_{off} and cross-correlate p to q.

Cross-correlate over the overlapping portion of the profiles at each step. For an offset index value of m, the correlation covers a range of index values from N_{start} to N_{end} as shown in Figure 26:

$$N_{start} = \max(m, 0)$$

$$N_{end} = \min(N_p - m, N_q)$$

Figure 26. Equation. Starting and ending index values for cross correlation.

As a function of the offset index value (m), the cross correlation is (Figure 27):

$$\rho(m) = \frac{1}{\max(\sigma_p, \sigma_q)^2} \sum_{i=N_{start}}^{N_{end}} (p(i+m) - \mu_p)(q(i) - \mu_q)$$

Figure 27. Equation. Cross correlation as a function of the offset index value (*m*).

Where (Figure 28):

$$\mu_p = \frac{1}{N_O} \sum_{i=N_{start}}^{N_{end}} p(i+m)$$

$$\mu_q = \frac{1}{N_O} \sum_{i=N_{start}}^{N_{end}} q(i)$$

$$\sigma_p = \sqrt{\frac{1}{N_O} \sum_{i=N_{start}}^{N_{end}} (p(i+m) - \mu_p)^2}$$

$$\sigma_q = \sqrt{\frac{1}{N_O} \sum_{i=N_{start}}^{N_{end}} (q(i) - \mu_q)^2}$$

$$N_O = N_{end} - N_{start} + 1$$

Figure 28. Equation. Where statement equations for Equation 23 cross correlation.

Step 5: Report the agreement score.

The agreement score is the highest value of ρ among all the values of m.

In cases where a candidate profile is compared to another candidate profile, rather than a reference profile, replace the reference profile in the procedure with one of the candidate profiles.

INTERPRETATION

Karamihas (2025) reports that a high agreement score between profiles means that the overall IRI value and the details that contribute to roughness agree. The algorithm for computing agreement scores penalizes disagreement in the shape, severity, and relative position of rough features within the two profiles under comparison. Figure 29 compares an IRI-filtered reference profile measurement to a pass by an inertial profiler that produced an accuracy score of 0.978. The two traces are barely distinguishable. The overall IRI values agree to within 1.5%.

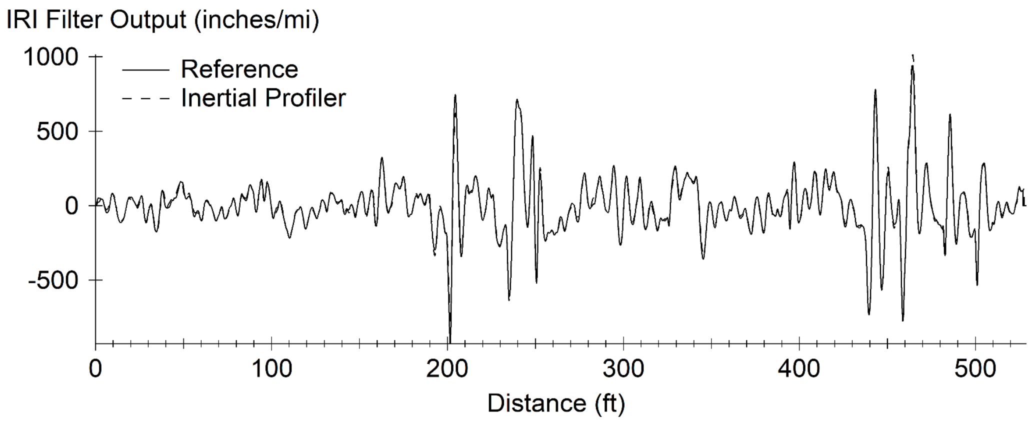

Figure 29. Graph. IRI-filtered traces with a high agreement score.

Figure 30 compares the same IRI-filtered reference profile measurement to a pass by an inertial profiler that produced an accuracy score of 0.729. In this case, the overall IRI values disagree by more than 4%. In addition, the distribution of roughness within each profile is different.

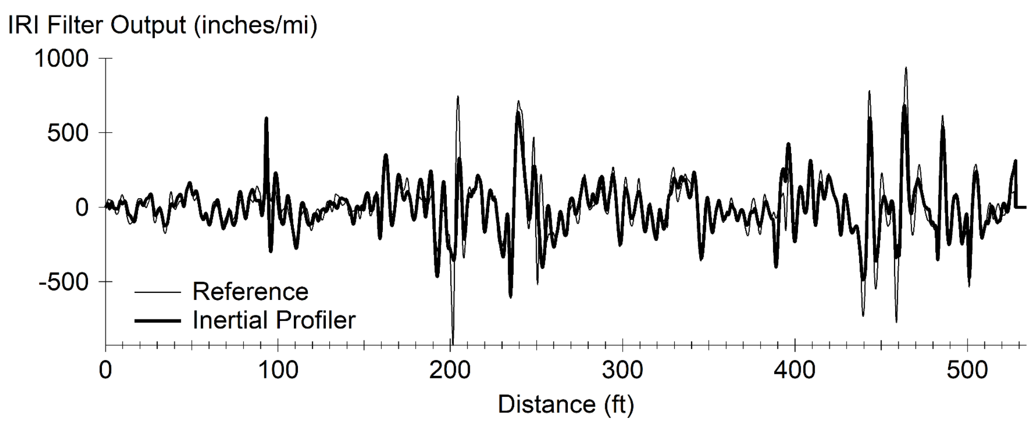

Figure 30. Graph. IRI-filtered traces with a low agreement score.

LONGITUDINAL DISTANCE MEASUREMENT (DMI) ERRORS

DMI errors affect the agreement scores produced by the cross-correlation algorithm. Figure 31 compares the reference profile from Figures 29 and 30 to a copy of itself with a longitudinal distance measurement error of 1% imposed on it. That is, the DMI Error trace is the reference profile with the longitudinal sampling interval increased by 1%. Although the shape of the two IRI-filtered traces is the same, they are aligned in only one location within the measurement range. The longitudinal misalignment between features grows with distance from the point of alignment. The agreement score between the two traces in Figure 31 is 0.647.

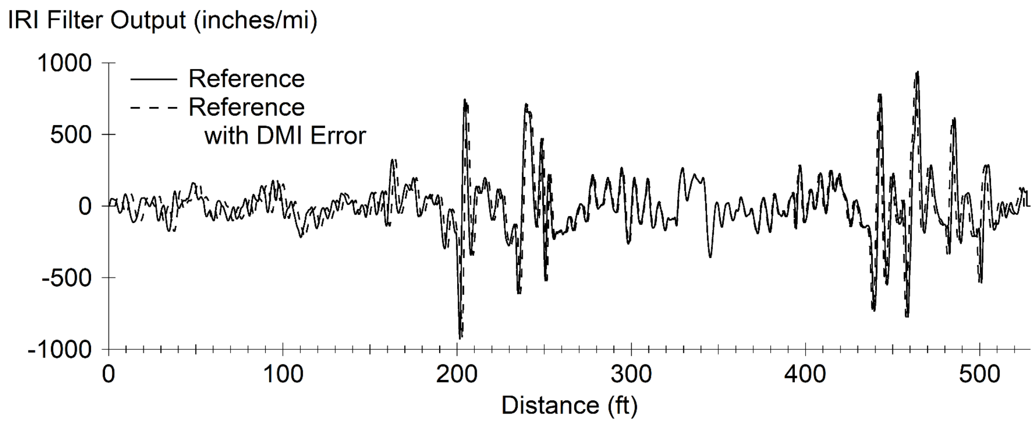

Figure 31. Graph. IRI-filtered traces with and without DMI error.

Figure 32 demonstrates the potential influence of DMI error on agreement scores on the left wheel track of the HMA section and the DGR section measured in this research. For each section, the figure shows the agreement score when the reference profile is compared to a copy with a DMI error introduced.

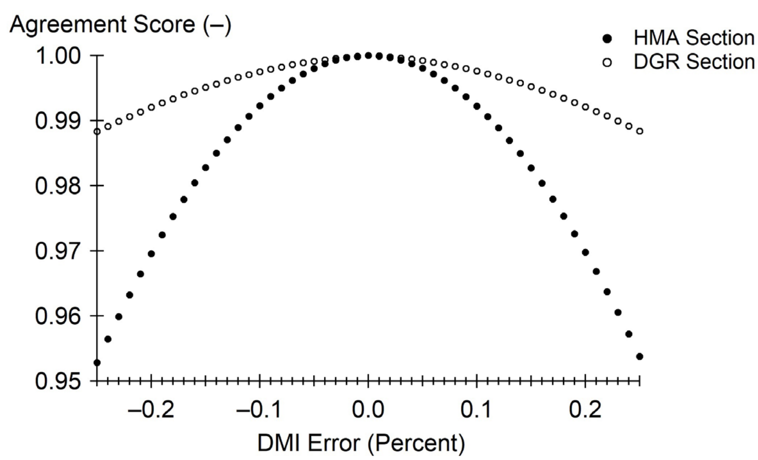

Figure 32. Graph. Change in agreement score with DMI error, HMA and DGR section.

AASHTO R 56-25 requires candidate profiles to demonstrate DMI accuracy to within 0.15%. Table 20 lists the agreement score that results from comparing reference profiles from each wheel track of each test section to a copy with a DMI error of 0.15%. Agreement scores on the SMA/HMA exhibit the highest sensitivity to DMI error because the SMA/HMA section is longer than the others. As a result, a much greater level of misalignment occurs at the ends for the same level of DMI error. Among the remaining sections, accuracy scores on the HMA and SMA sections are the most sensitive to DMI errors, because the largest share of roughness is caused by short-wavelength content. Accuracy scores on the DGR section are the least sensitive to DMI errors, because the largest share of roughness is caused by long-wavelength content.

Table 20. Effect of DMI Error on Agreement Scores

Test Section	Wheel Track	Agreement Score, 0.15% DMI Error
SMA	Left	0.984
SMA	Right	0.980
HMA	Left	0.983
HMA	Right	0.984
MS	Left	0.987
MS	Right	0.988
DGR	Left	0.995
DGR	Right	0.995
DGV	Left	0.986
DGV	Right	0.988
TT	Left	0.990
TT	Right	0.992
SMA/HMA	Left	0.949
SMA/HMA	Right	0.950

To account for the sensitivity of agreement scores to DMI error, all agreement scores were calculated twice:

- Without DMI adjustment: This is the agreement score produced by the calculation procedure described previously.
- With DMI adjustment: This is the agreement score produced by repeating Steps 3 through 5 in the calculation procedure, with adjustments to the value of δ_P of −1 to 1% in increments of 0.004%. The agreement score with DMI adjustment is the highest agreement score found among all the adjusted values of δ_P. One of the profilers in this study exhibited DMI error greater than 1%, and a larger range of adjustments was used.

RELATIONSHIP TO IRI AGREEMENT

This section examines the relationship between disagreement in overall IRI and agreement score between profiles using profile measurements from this research. This section compares percentage difference in IRI to agreement score for every possible pair of profiles measured by commercially available profilers or the reference profilers on both wheel tracks of the SMA, HMA, MS, DGR, DGV, and TT test sections. Table 21 lists the number of passes used from each wheel track of each test section.

Table 21. Passes Collected on Each Wheel Track of Each Test Section

Test Section	Passes, Left Wheel Track	Passes, Right Wheel Track
SMA	350	327
HMA	349	326
MS	329	309
DGR	311	292
DGV	313	293
TT	308	291

In each wheel track, the number of possible pairs available is $N(N\text{-}1)/2$, where N is the number of passes (e.g., the passes in the left wheel track of the SMA section for 61,075 possible pairs). The total number of profile pairs for the 10 wheel tracks was 601,389.

For each profile pair, the agreement score with DMI correction was calculated. Figure 33 shows the distribution of agreement scores using increments of 0.01 unit wide. Of the 601,389 values represented, 433,733 (72.1%) exceed 0.8 and 269,572 (44.8%) exceed 0.9.

Each agreement score was matched to the IRI values from the profiles in the associated pair. The IRI values were calculated with the DMI adjustment and offset adjustment applied and only over the overlapping portion of the profile that generated the agreement score.

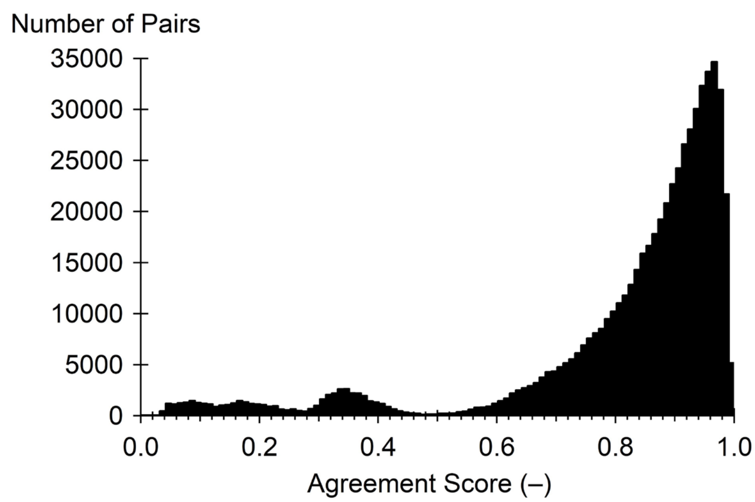

Figure 33. Graph. Distribution of agreement scores.

Figure 34 shows a subset of the results for comparisons of candidate profiles to reference profiles. The figure compares absolute IRI error to accuracy score for 3,561 comparisons. Note that the analysis included 3,786 comparisons, but only 3,561 comparisons fall within the plotted range. Figure 34 shows that the maximum level of error increases as the accuracy score decreases.

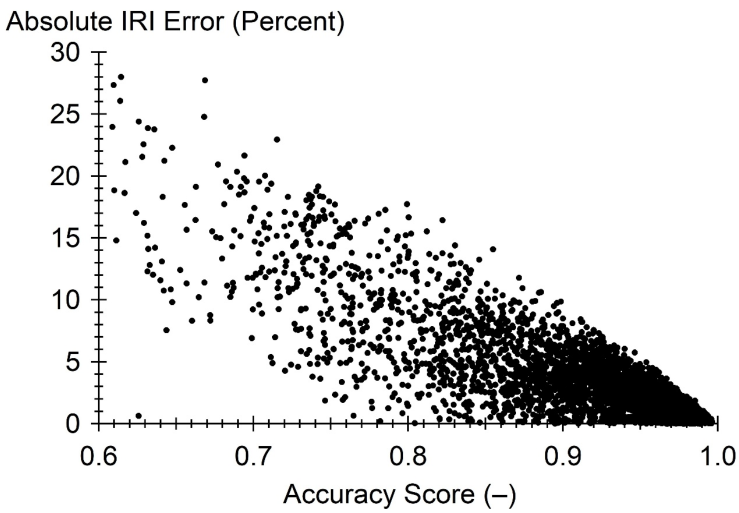

Figure 34. Graph. Comparison of absolute IRI error to accuracy score.

To relate absolute IRI disagreement to agreement score for the full set of comparisons, root mean square and 95th percentile IRI disagreement were calculated for increments of agreement 0.01 unit wide. Figure 35 provides a sample distribution for the range of agreement score from 0.93 to 0.94. This distribution includes absolute IRI disagreement from 30,172 profile comparisons with a root mean square of 2.99% and a 95th percentile value of 5.14%.

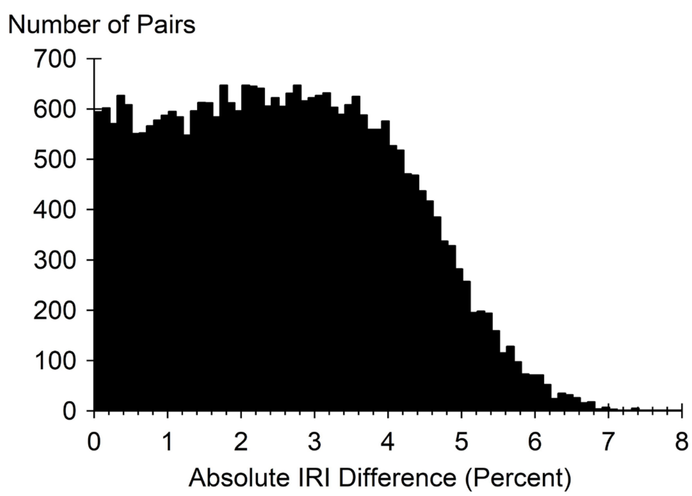

Figure 35. Graph. Sample distribution of absolute IRI disagreement.

Table 22 presents the root mean square and 95th percentile IRI disagreement for each increment of agreement score from 0.8 to 1. IRI disagreement statistics increase systematically as the range of agreement score decreases. The results in Table 22 provide bounds on the disagreement in IRI values expected at each level of agreement score.

Table 22. IRI Disagreement Statistics Versus Agreement Score

Agreement Score Range	Number of Pairs	RMS Absolute IRI Error (%)	95th Percentile Absolute IRI Error (%)
0.99–1.00	5,275	0.49	0.95
0.98–0.99	21,815	0.88	1.65
0.97–0.98	32,036	1.35	2.39
0.96–0.97	34,771	1.79	3.12
0.95–0.96	33,808	2.21	3.80
0.94–0.95	32,437	2.62	4.51
0.93–0.94	30,172	2.99	5.14
0.92–0.93	28,173	3.33	5.70
0.91–0.92	26,716	3.65	6.30
0.90–0.91	24,369	3.98	6.91
0.89–0.90	22,803	4.31	7.50
0.88–0.99	20,931	4.62	8.02
0.87–0.98	19,344	4.92	8.51
0.86–0.97	17,924	5.20	8.92
0.85–0.96	16,752	5.54	9.47
0.84–0.95	16,005	5.93	10.02
0.83–0.94	14,405	6.39	10.67
0.82–0.93	12,946	6.92	11.60
0.81–0.92	11,907	7.46	12.52
0.80–0.91	11,144	7.84	13.19

APPENDIX C: ICART LAYOUT AND PHOTOS

Figure 36 shows a layout of the test sections at ICART. Figures 37 through 44 are photos of test section surfaces and markings.

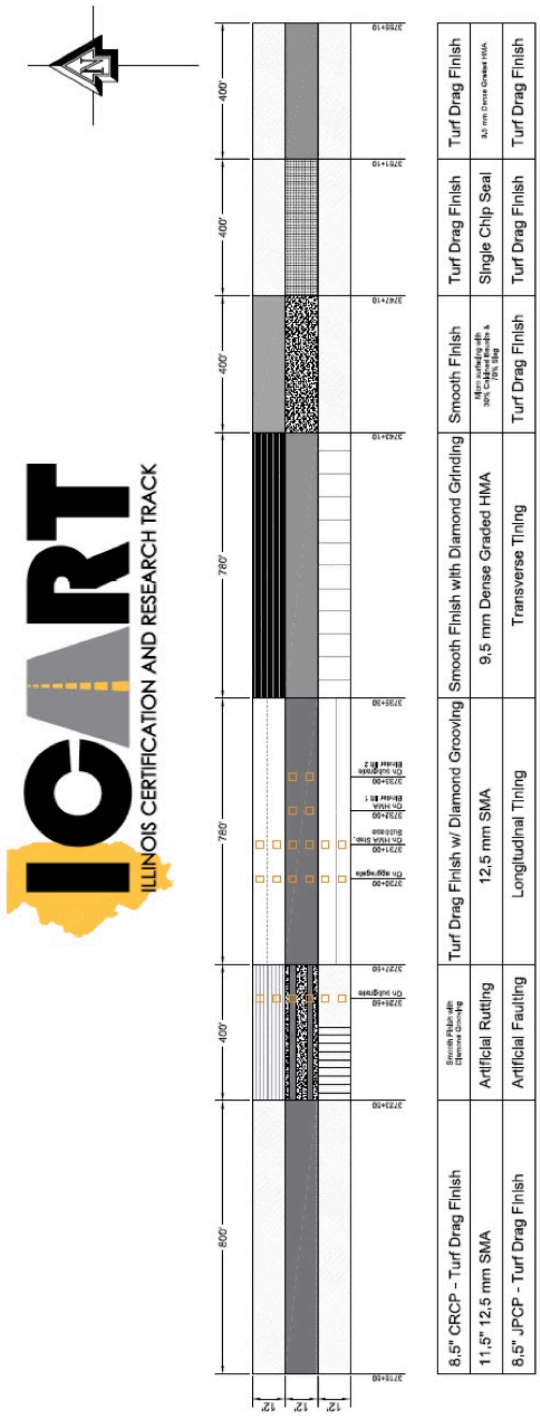

Figure 36. Illustration. ICART layout.

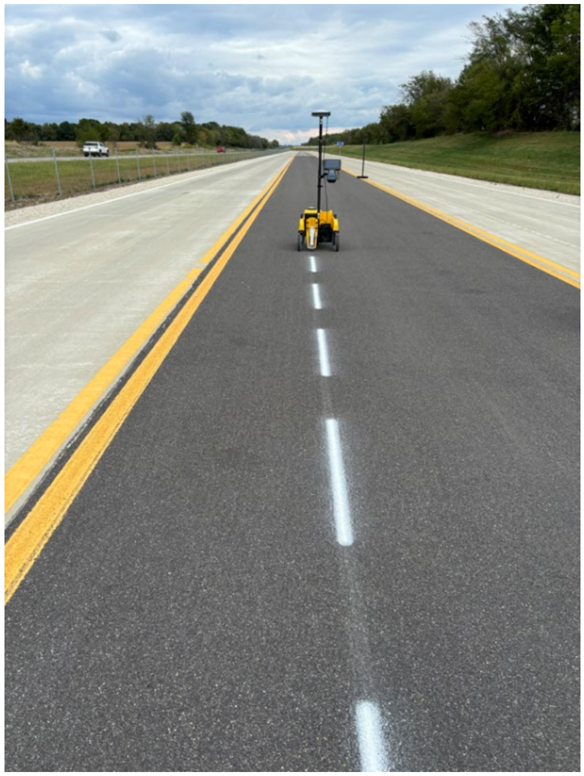

Figure 37. Photo. Painting robot used to mark a guide 7 in. right of the left wheel track.

Figure 38. Photo. BP guide tape at a test section lead-in.

Figure 39. Photo. DGV section starting location.

Figure 40. Photo. DGR section starting location.

Figure 41. Photo. TT section starting location.

Figure 42. Photo. MS section starting location.

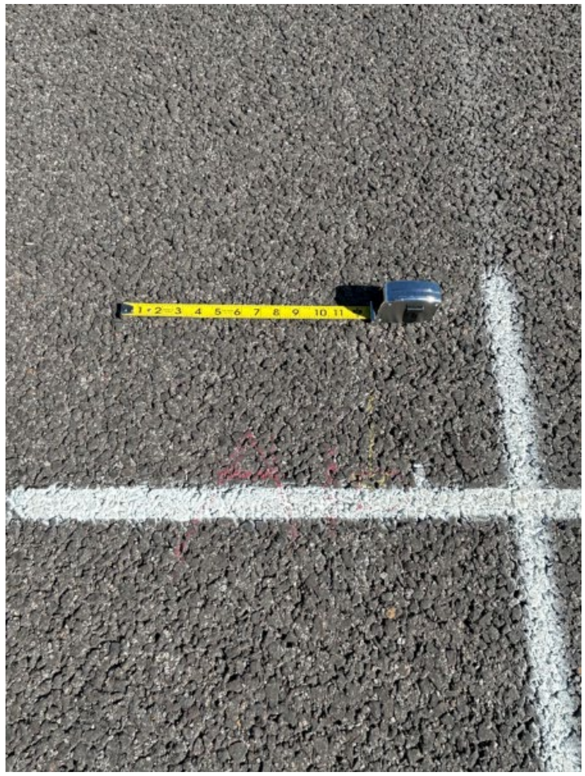

Figure 43. Photo. SMA/HMA section starting location.

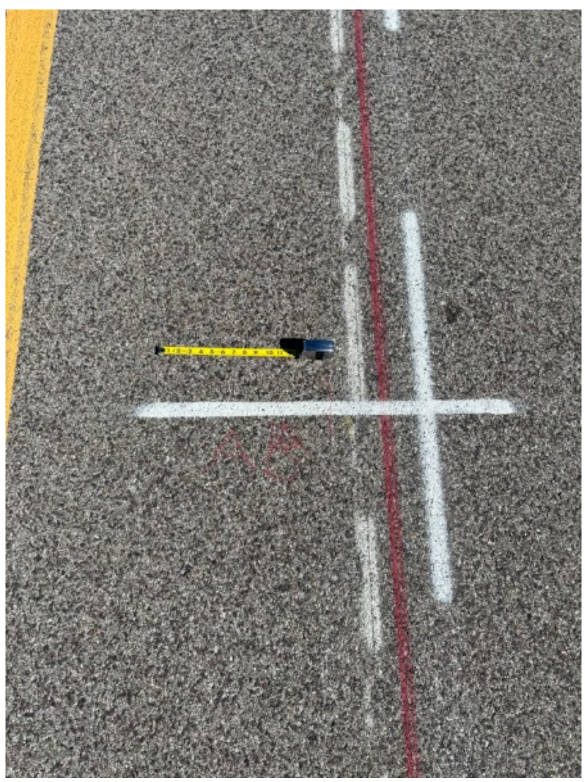

Figure 44. Photo. SMA/HMA section ending location.

APPENDIX D: CERTIFICATION FOR URBAN AND LOW-SPEED OPERATION TESTING INSTRUCTIONS AND SPEED PROFILE PLOTS

This appendix details the instructions provided to operators who participated in the certification for urban and low-speed operation experiment. The instructions include updates to reflect adjustments made during the testing.

Testing included three passes conforming to each of the five speed profiles:

1. **Constant speed:** Pass over the test section at a constant speed from 40 mi/hr to 45 mi/hr, using cruise control if possible.

2. **Low speed:** Pass over the test section at very low speed. The desired speed is 3 mi/hr, but if the idle speed of the vehicle is greater than 3 mi/hr, travel at the idle speed. The average speed for each run must be 2 mi/hr to 4 mi/hr, and the speed must not exceed 5 mi/hr at any location. Figures 45 and 46 provide ideal speed profiles versus distance and time for the low-speed runs.
   Note: Acceptance of the run will depend on running at an average speed below 4 mi/hr and registering no speed of 5 mi/hr and above.

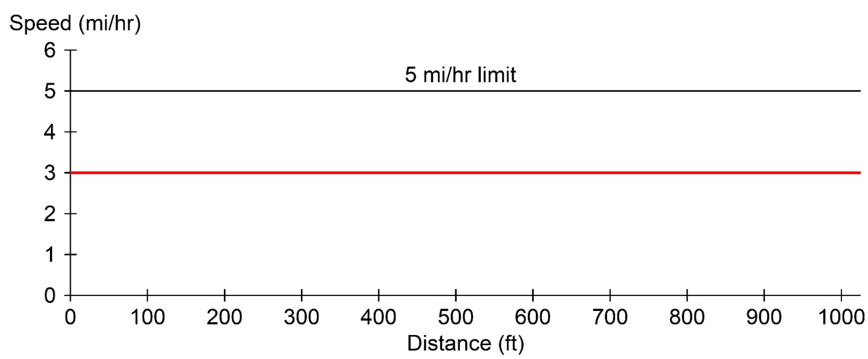

Figure 45. Graph. Low-speed run, idealized speed profile versus distance.

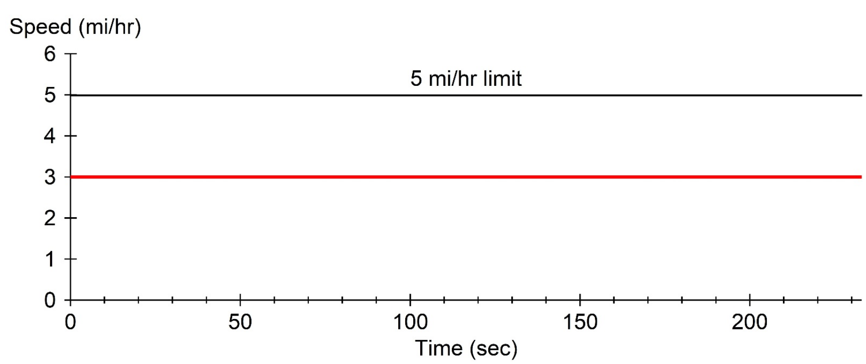

Figure 46. Graph. Low-speed run, idealized speed profile versus time.

3. **Braking:** Enter the test section at a speed of at least 30 mi/hr. Maintain a speed of at least 30 mi/hr until reaching Landmark C. Upon reaching Landmark C, decelerate smoothly to a speed of 15 mi/hr or less at Landmark D. Traverse the rest of the test section at a speed of 15 mi/hr or less. Figures 47 and 48 provide ideal speed profiles versus distance and time for the braking runs.
Note: A change in speed from 30 mi/hr to 15 mi/hr over the distance from Landmark C to Landmark D corresponds to an average deceleration of 0.3 g.
Note: Acceptance of the run will depend on maintaining speed above 30 mi/hr from the start of the section up to Landmark C and registering a speed below 15 mi/hr while crossing Landmark D.

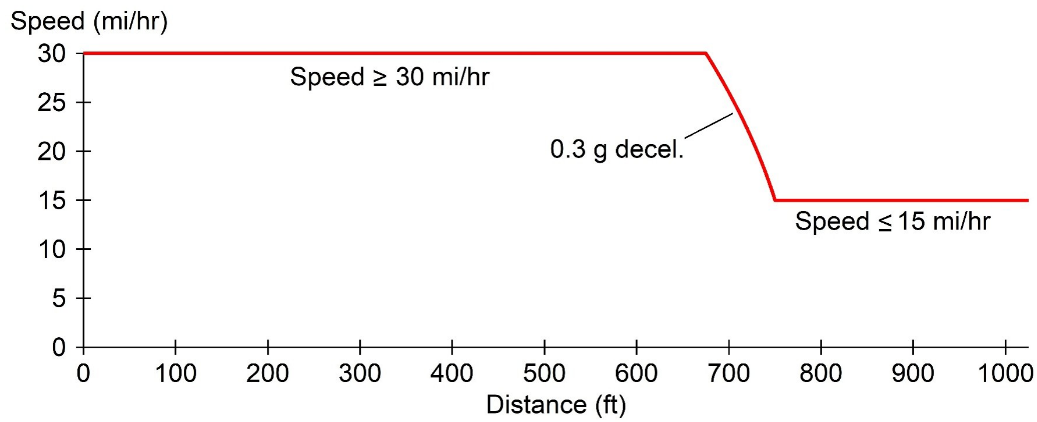

Figure 47. Graph. Braking run, idealized speed profile versus distance.

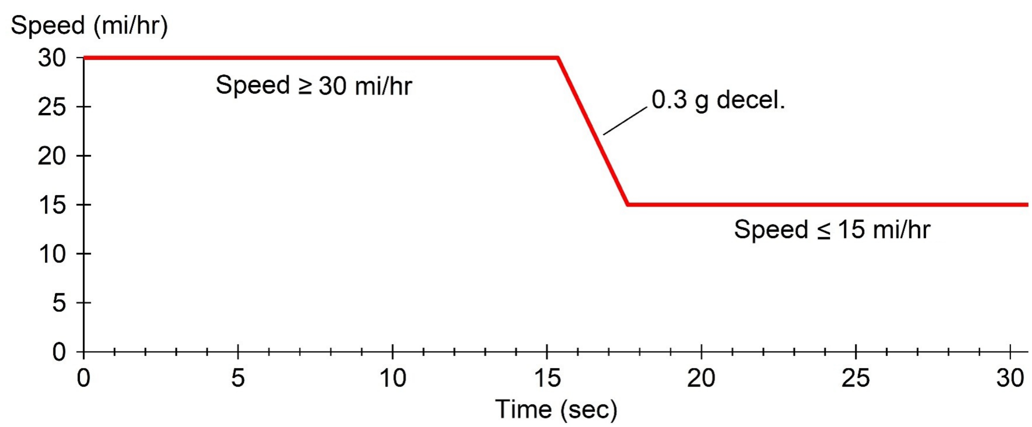

Figure 48. Graph. Braking run, idealized speed profile versus time.

4. **Stop:** Enter the test section at a speed of at least 30 mi/hr. Maintain a speed of at least 30 mi/hr until reaching Landmark B. After passing Landmark B, decelerate to a stop within 10 ft of Landmark D. Remain at the stop for at least 60 seconds. After the 60-second wait, accelerate gently to 30 mi/hr and continue to traverse the rest of the test section. Figures 49 and 50 provide ideal speed profiles versus distance and time for the stop runs.
Note: A change in speed from 30 mi/hr to 0 mi/hr over the distance from Landmark B to

Landmark D corresponds to an average deceleration of 0.12 g.
Note: Acceptance of the run will depend on maintaining speed above 30 mi/hr from the start of the section up to Landmark B, stopping within 10 ft of Landmark D, and remaining still after stopping for 60 seconds or more.
Note: A visible clock will display a countdown to help the operator determine when 60 seconds have passed.

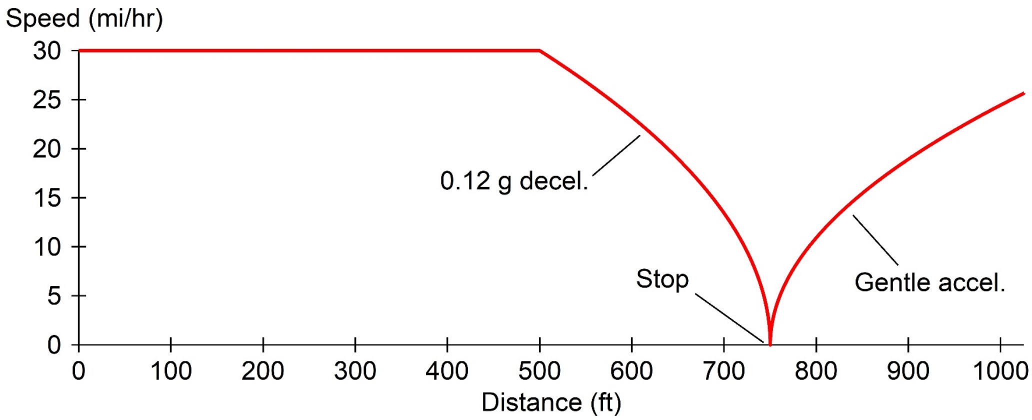

Figure 49. Graph. Stop run, idealized speed profile versus distance.

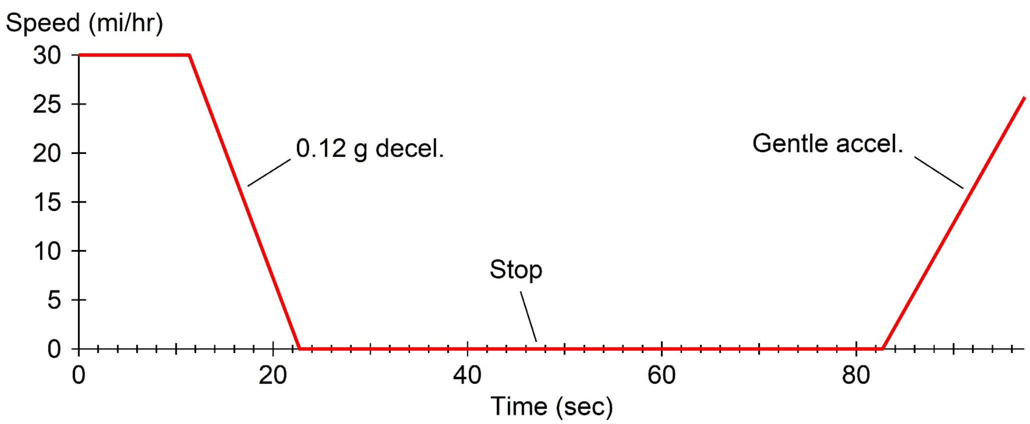

Figure 50. Graph. Stop run, idealized speed profile versus time.

5. **Stop with creep:** Enter the test section at a speed of at least 30 mi/hr. Maintain a speed of at least 30 mi/hr until reaching Landmark B. After passing Landmark B, decelerate to a stop within 10 ft of Landmark D. Remain at the location of the stop for at least 5 seconds. After the 5-second wait, proceed to Landmark E at a speed of no greater than 5 mi/hr. Once Landmark E is passed, accelerate gently to 30 mi/hr or less and continue to traverse the rest of the test section. Figures 51 and 52 provide ideal speed profiles versus distance and time for the stop with creep runs.
Note: Acceptance of the run will depend on maintaining speed above 30 mi/hr from the start of the section up to Landmark B, stopping within 10 ft of Landmark D, remaining still for

5 seconds or more, and registering a speed of 5 mi/hr or less between Landmark D and Landmark E.

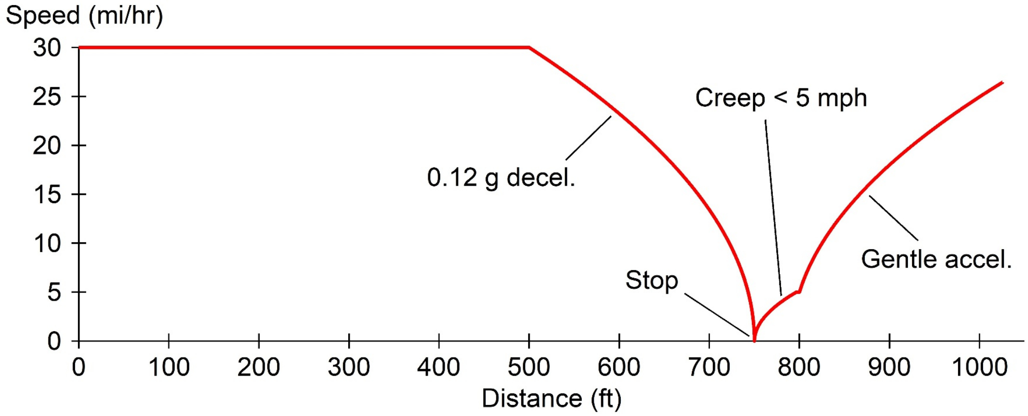

Figure 51. Graph. Stop with creep run, idealized speed profile versus distance.

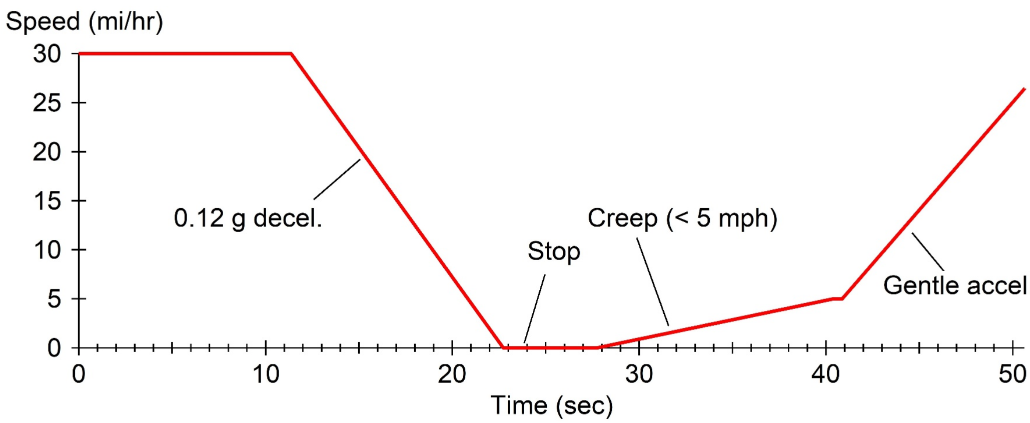

Figure 52. Graph. Stop with creep run, idealized speed profile versus time.

Testing also included passes conforming to an optional sixth speed profile:

6. **Long braking:** Enter the test section at a speed of at least 45 mi/hr. Maintain a speed of at least 45 mi/hr until reaching Landmark B. Upon reaching Landmark B, decelerate smoothly to a speed of 10 mi/hr or less at Landmark D. Traverse the rest of the test section at a speed of 20 mi/hr or less. Figures 53 and 54 provide ideal speed profiles versus distance and time for the long braking runs.
   Note: A change in speed from 45 mi/hr to 10 mi/hr over the distance from Landmark B to Landmark D corresponds to an average deceleration of 0.257 g.
   Note: This optional braking test is included to determine whether operators can execute the braking more reliably if braking occurs over a longer distance than the other braking test.
   Note: Acceptance of the run will depend on maintaining a speed above 45 mi/hr from the start of the section up to Landmark B and registering a speed below 10 mi/hr at Landmark D.

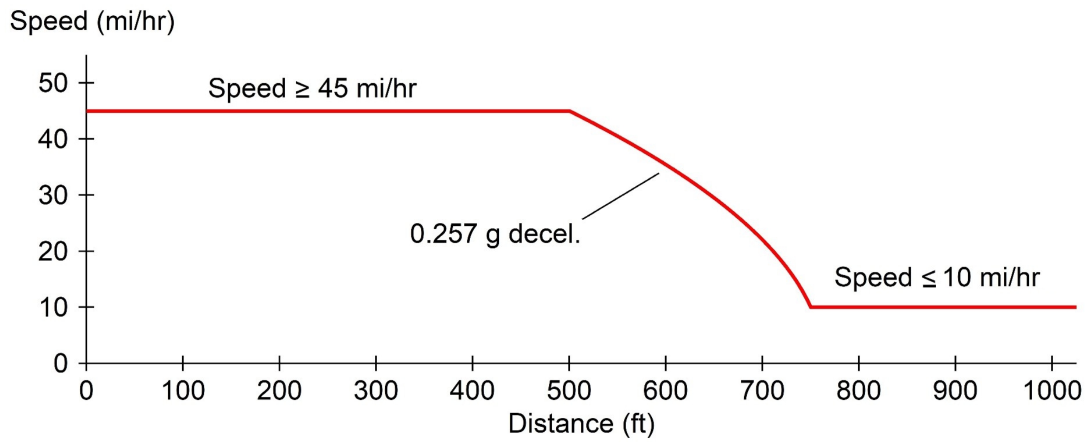

Figure 53. Graph. Long braking run, idealized speed profile versus distance.

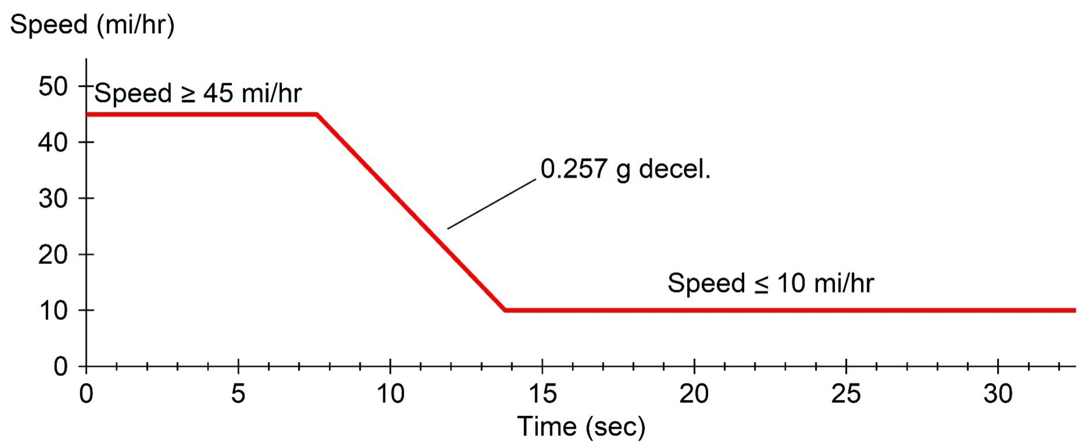

Figure 54. Graph. Long braking run, idealized speed profile versus time.

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