TECHNICAL REPORT STANDARD PAGE

1. Title and Subtitle
Performance Index Rating and Maintenance Cost Assignment for Ramps, Acceleration Lanes, and Deceleration Lanes in Louisiana

2. Author(s)
Jun Liu, Ph.D., P.E.; Qiming Chen, Ph.D., P.E.

3. Performing Organization Name and Address
Louisiana Transportation Research Center
4101 Gourrier Avenue
Baton Rouge, LA 70808

4. Sponsoring Agency Name and Address
Louisiana Department of Transportation and Development
P.O. Box 94245
Baton Rouge, LA 70804-9245

5. Report No.
FHWA/LA.25/713

6. Report Date
July 2025

7. Performing Organization Code
LTRC Project Number: 22-1P
SIO Number: 22-1P/DOTLT1000431

8. Type of Report and Period Covered
Final Report
April 2022 – June 2025

9. No. of Pages
65

10. Supplementary Notes
Conducted in Cooperation with the U.S. Department of Transportation, Federal Highway Administration.

11. Distribution Statement

12. Key Words
Pavement smoothness; performance index; IRI; stop-and-go; special operational conditions; ramps

13. Abstract
Conventional high-speed inertial profilers provide valid international roughness index (IRI) measurements under favorable conditions but experience performance degradation at low speeds, during deceleration and acceleration, or when coming to a stop. Due to these limitations, Louisiana DOTD does not compute performance index (PI) values for certain highway sections, including ramps, acceleration lanes, and deceleration lanes, as conventional profilers fail to capture reliable IRI data under these conditions. The industry has recently introduced a Stop-and-Go (SAG) inertial profiler, designed to measure IRI across various operational conditions. The objectives of this study were to evaluate the performance of a SAG inertial profiler under various driving conditions on Louisiana roads and propose a method for measuring and characterizing IRI and PI values for ramps, acceleration lanes, and deceleration lanes to complement existing DOTD guidelines. The SAG inertial profiler was first compared with conventional high-speed inertial profilers under constant high-speed operation. Its repeatability and accuracy were then assessed under five different

operational conditions at two DOTD certification sites. The results demonstrated that the SAG inertial profiler can accurately and consistently measure pavement profiles under challenging operational conditions, including acceleration, deceleration, low-speed operation, and stop-and-go scenarios. This capability enables the profiler to obtain accurate IRI measurements for ramps, deceleration lanes, and acceleration lanes, facilitating direct PI calculations for these sections.

Project Review Committee

Each research project will have an advisory committee appointed by the LTRC Director. The Project Review Committee is responsible for assisting the LTRC Administrator or Manager in the development of acceptable research problem statements, requests for proposals, review of research proposals, oversight of approved research projects, and implementation of findings.

LTRC appreciates the dedication of the following Project Review Committee members in guiding this research study to fruition.

LTRC Administrator/Manager

Zhongjie Zhang, Ph.D., P.E.

Pavement and Geotechnical Research Administrator

Members

Christopher Cole

Mark Ordogne

Xingwei Chen

Jason Lacombe

Joshua Stutes

Clay Gottschalck

Christopher Brent Domingue

Scott Nelson

Directorate Implementation Sponsor

Chad Winchester, P.E.

DOTD Chief Engineer

Performance Index Rating and Maintenance Cost Assignment for Ramps, Acceleration Lanes, and Deceleration Lanes in Louisiana

By
Jun Liu, Ph.D., P.E.
Qiming Chen, Ph.D., P.E.

Louisiana Transportation Research Center
4101 Gourrier Avenue
Baton Rouge, LA 70808

LTRC Project No. 22-1P
SIO No. 22-1P/DOTLT1000431

conducted for
Louisiana Department of Transportation and Development
Louisiana Transportation Research Center

The contents of this report reflect the views of the author/principal investigator, who is responsible for the facts and the accuracy of the data presented herein.

The contents do not necessarily reflect the views or policies of the Louisiana Department of Transportation and Development, Federal Highway Administration, or Louisiana Transportation Research Center. This report does not constitute a standard, specification, or regulation.

July 2025

Abstract

Conventional high-speed inertial profilers provide valid international roughness index (IRI) measurements under favorable conditions but experience performance degradation at low speeds, during deceleration and acceleration, or when coming to a stop. Due to these limitations, Louisiana DOTD does not compute performance index (PI) values for certain highway sections, including ramps, acceleration lanes, and deceleration lanes, as conventional profilers fail to capture reliable IRI data under these conditions. The industry recently has introduced a Stop-and-Go (SAG) inertial profiler, designed to measure IRI across various operational conditions. The objectives of this study were to evaluate the performance of a SAG inertial profiler under various driving conditions on Louisiana roads and propose a method for measuring and characterizing IRI and PI values for ramps, acceleration lanes, and deceleration lanes to complement existing DOTD guidelines. The SAG inertial profiler was first compared with conventional high-speed inertial profilers under constant high-speed operation. Its repeatability and accuracy were then assessed under five different operational conditions at two DOTD certification sites. The results demonstrated that the SAG inertial profiler can accurately and consistently measure pavement profiles under challenging operational conditions, including acceleration, deceleration, low-speed operation, and stop-and-go scenarios. This capability enables the profiler to obtain accurate IRI measurements for ramps, deceleration lanes, and acceleration lanes, facilitating direct PI calculations for these sections.

Acknowledgements

This research project was funded by the Louisiana Department of Transportation and Development (DOTD) and the Louisiana Transportation Research Center (LTRC). The authors would like to express their gratitude to Moses Akentuna for initiating the project and acknowledge the valuable contributions of Terrell Gorham, Ray Kimble, and Biyuan Zheng.

Implementation Statement

The findings of this research project have significant potential for implementation in Louisiana's pavement management and maintenance practices. By integrating Stop-and-Go (SAG) inertial profiler technology, Louisiana DOTD can enhance the accuracy and consistency of IRI measurements for ramps, acceleration lanes, and deceleration lanes, which are currently excluded due to the limitations of conventional high-speed inertial profilers. This advancement would allow for direct performance index (PI) calculations for these roadway sections, leading to more data-driven maintenance decisions and equitable fund allocation. Additionally, incorporating SAG inertial profiling into DOTD certification procedures could improve the evaluation of inertial profilers under diverse operational conditions, ensuring more reliable pavement condition assessments. The findings of this study may contribute to an update of DOTD guidelines and specifications, promoting the integration of SAG inertial profilers into routine pavement evaluations and project planning throughout the state.

Table of Contents

List of Tables

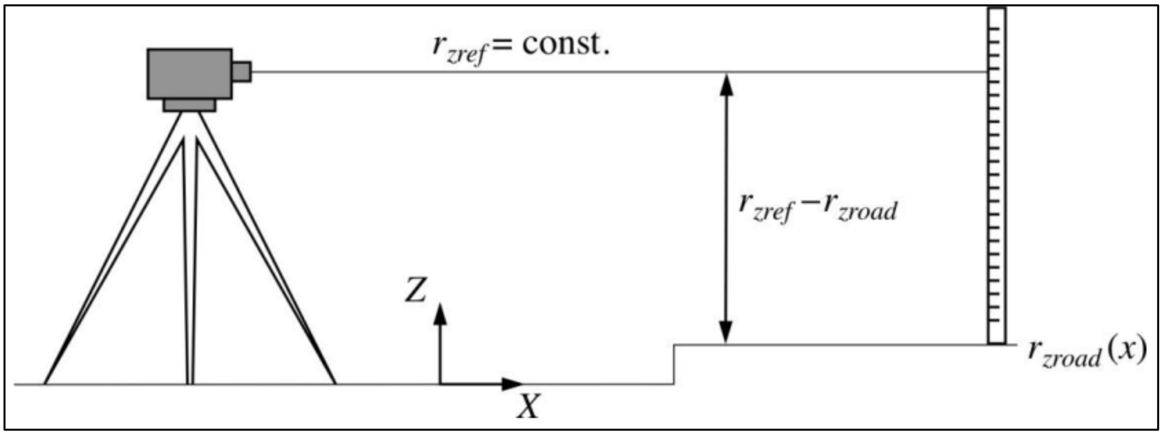
List of Figures

Introduction

Pavement smoothness measures the comfort level experienced by travelers when riding over pavement surfaces [1, 2, 3]. The term smoothness is often used interchangeably with roughness as a primary pavement performance indicator. According to ASTM E 867, roughness refers to “the deviations of a surface from a true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic loads, and drainage; for example, longitudinal profile, transverse profile, and cross slope” [4]. In addition to comfort, smoothness offers several benefits, including enhanced pavement performance and longevity, improved safety, and reduced fuel and maintenance costs [5, 6, 7, 8, 9]. State highway agencies routinely monitor pavement roughness to assess road network conditions, ensure construction standards are met, and allocate funds efficiently for maintenance, rehabilitation, and reconstruction efforts [10, 11, 12]. To support these objectives, the Louisiana Department of Transportation and Development (DOTD) systematically measures pavement roughness as part of its Pavement Management System (PMS). Roughness data is also a required performance metric in the Highway Performance Monitoring System (HPMS). The international roughness index (IRI), introduced by the World Bank in 1986, remains the most widely adopted standard for quantifying roughness and enabling consistent comparisons between road segments [1].

Over the years, pavement longitudinal profile measurement techniques have evolved significantly, progressing from basic manual methods, such as the rod and level, to walking profilers, and on to advanced automated systems like high-speed inertial profilers [13, 14, 15]. The rod and level, depicted in Figure 1, are traditional surveying instruments used for elevation measurement. The level establishes a reference elevation (r_{zef}), while readings from the rod determine the height relative to this reference (r_{zef} - r_{zroad}). A tape measure is then used to record the exact locations of the elevation points. This approach is classified as a static method since measurements are taken while the instruments remain stationary [3].

Figure 1. Rod and level method for pavement longitudinal profile [2]

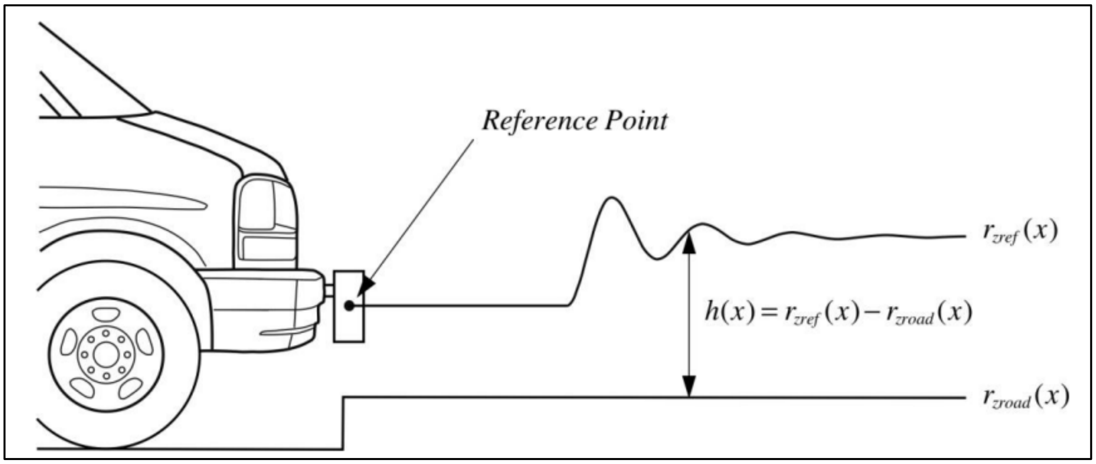


In the late 1960s, General Motors Research Laboratories developed the inertial profiler, enabling high-speed profiling for network-level pavement data collection. As illustrated in Figure 2, a typical high-speed inertial profiling system consists of three primary components [16, 17]:

1. An accelerometer, which records the motion of the vehicle frame and determines the elevation of a reference point. This elevation fluctuates in response to road roughness and is referred to as the floating reference height, $r_{zef}(x)$.
2. A height sensor, which measures the relative displacement between the vehicle frame and the road surface at specified intervals, $h(x)$.
3. A distance measuring instrument (DMI), which tracks the longitudinal distance traveled by the vehicle.

In General Motors' original design, a potentiometer connected to a road-following wheel served as the height sensor [2]. However, to prevent measurement inaccuracies due to wheel bouncing, testing had to be conducted at low speeds. Modern high-speed inertial profilers have since replaced this setup with non-contact laser sensors, which accurately measure the vertical distance from the profiler's reference point to the road surface.

Figure 2. High speed inertial profiler system for pavement longitudinal profile [2]

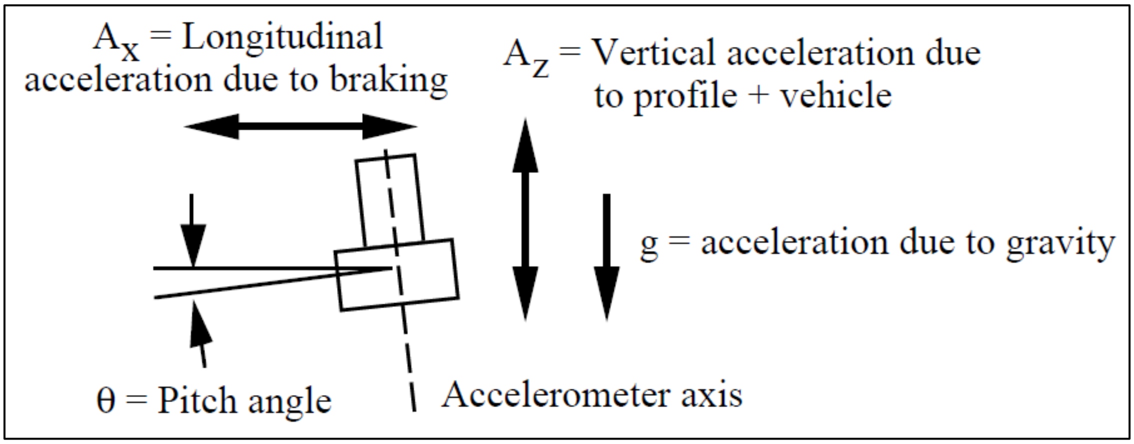


Sayers [3] noted that while high-speed inertial profilers may not accurately capture long-wavelength features such as grade and undulations spanning hundreds of feet, they are still capable of producing reliable profile statistics, including the IRI. Louisiana DOTD utilizes high-speed inertial profilers for network-level pavement roughness assessments.

The effectiveness of inertial profilers relies on maintaining a consistent high speed. At very low speeds, the vertical acceleration measured by the onboard accelerometers becomes minimal, making the vertical motion signal more susceptible to noise and sensor drift, which can lead to errors in height calculations. Ideally, speed variations would not affect profiling accuracy if (a) the accelerometer were perfectly aligned along a vertical axis or (b) the vehicle experienced no longitudinal acceleration [3]. However, these ideal conditions are not achievable in real-world scenarios.

As the profiler vehicle encounters road roughness, it undergoes slight forward and backward pitch motions, subtly shifting the accelerometer’s orientation from a perfect vertical position. Additionally, changes in speed introduce longitudinal acceleration. When speed fluctuations are gradual, the resulting pitch angles and longitudinal acceleration remain small, typically less than one degree. However, braking or rapid deceleration amplifies both effects, increasing measurement inaccuracies. Figure 3 illustrates the potential errors introduced by vehicle pitch and longitudinal acceleration during profiling operations.

Figure 3. Pitch angle and longitudinal acceleration during braking [3]

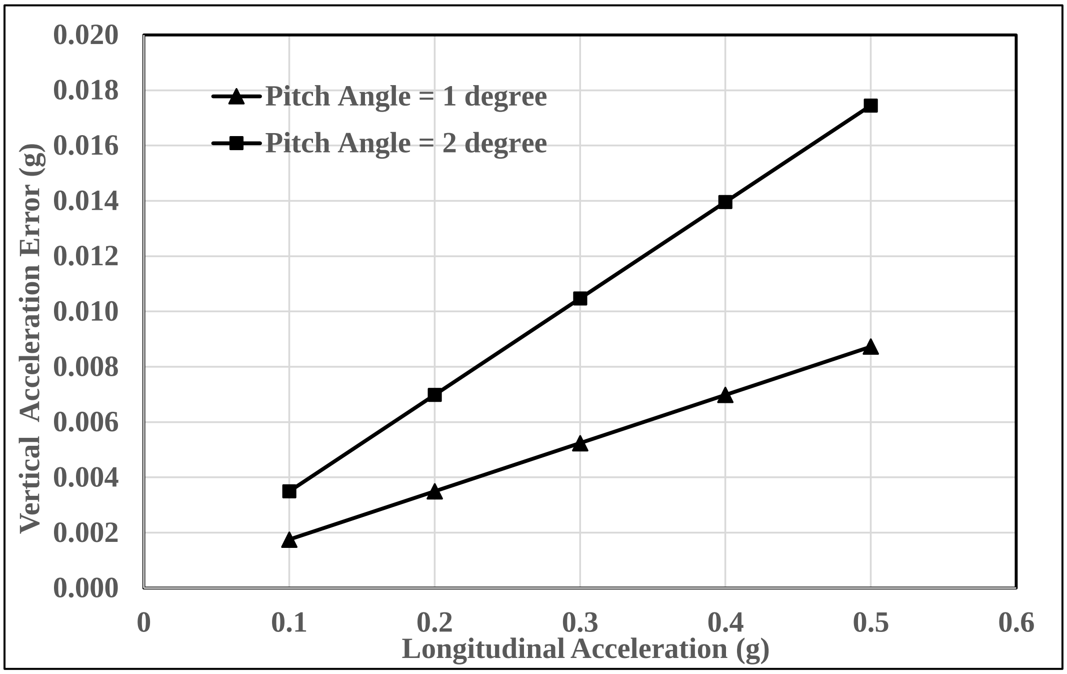


The accelerometer measures a combined acceleration that results from both vertical acceleration and longitudinal acceleration along its sensing axes.

$$A_{measured} = (A_Z - g)cos(\theta) + A_X sin(\theta)$$

Abrupt speed variations, especially in stop-and-go traffic common in urban areas, can substantially impact measured road profiles and ride quality metrics [18, 19, 20]. Figure 4 illustrates how vertical acceleration errors arise from both longitudinal acceleration and pitch angle variations. For instance, when a vehicle experiences a pitch angle of 3° combined with a longitudinal deceleration of 0.3 g, the resulting vertical acceleration error is approximately 0.01 g.

Figure 4. Vertical acceleration error caused by longitudinal acceleration



In NCHRP Project 10-93, Karamihas et al. highlighted the challenges of using inertial profilers on urban and other low-speed roadways, where profiling may need to occur at speeds below the typical valid operating threshold of approximately 15 mph (24 km/hr). In such environments, profilers frequently accelerate, decelerate, and come to a complete stop due to traffic signals, congestion, or safety concerns. These operational disruptions can introduce measurement errors exceeding acceptable limits for engineering applications [19].

Within the state highway system, these challenges are particularly relevant for ramps, acceleration lanes, and deceleration lanes. These roadway segments play a crucial role in traffic flow and safety, requiring regular maintenance to ensure optimal performance. However, the combination of slow-moving traffic and varying speed conditions in these areas makes it difficult to obtain accurate IRI measurements using conventional inertial profilers. As a result, assessing pavement conditions in these critical locations remains a significant challenge.

The performance index (PI) is a critical tool for highway systems, used to assess pavement deterioration and identify deficient sections requiring maintenance or rehabilitation. In Louisiana, PI ratings also support benefit-cost analyses and facilitate the comparison of pavement treatment strategies.

Currently, Louisiana DOTD does not compute PI values for highway sections such as ramps, deceleration lanes, and acceleration lanes due to invalid or missing IRI data. Given the limitations of high-speed inertial profilers, research has been conducted to address errors in profile measurement caused by adverse operational conditions, such as (a) low-speed operation, (b) acceleration, (c) deceleration, (d) stop-and-go operation, (e) profiling from a dead stop, and (f) operation on curves [2, 19]. Karamihas [2] proposed a twofold approach to addressing errors in inertial profiling. In the short term, he suggested combining custom numerical procedures with standard filtering techniques to minimize errors. For a long-term solution, he recommended enhancing the standard inertial profiler design by incorporating additional sensors to correct errors resulting from accelerometer misalignment and bias. Vendors of high-speed pavement profiling systems have been working to develop profilers capable of accurately measuring pavement roughness under these challenging conditions.

At the start of this project, Surface Systems & Instruments (SSI) was the only vendor offering such a system, branding it as the Zero-Speed Profiler (ZSP). By the time this report was written, multiple vendors had introduced similar systems under different names. For example, Pathway Services Inc. called its system the All-Speed Profiler (ASP), while ICC referred to its version as the Every-Speed Profiler (ESP).

The primary goal of this study was to evaluate these advanced systems for profiling on Louisiana roads. Successful implementation is expected to enable accurate and comprehensive measurement of the IRI for ramps, deceleration lanes, and acceleration lanes. This improvement will facilitate more precise PI calculations, supporting timely maintenance and rehabilitation efforts. Ultimately, this approach will help road agencies in Louisiana more effectively manage and maintain critical roadway components.

Objective

The objectives of this study were to:

1. Evaluate the performance of a Stop-and-Go (SAG) inertial profiler under various driving conditions on Louisiana roads;
2. Ascertain whether there are differences in IRI and PI values of Louisiana DOTD's analysis lanes compared to ramps, acceleration, or deceleration lanes;
3. Propose a method for measuring and characterizing IRI and PI values for ramps, acceleration, and deceleration lanes to complement existing DOTD guidelines.

Scope

The research team rented a SAG inertial profiler from the manufacturer for evaluation in this study. The initial assessment involved comparing its performance with conventional high-speed inertial profilers.

After the preliminary comparison, the SAG inertial profiler was tested under various operational conditions at two DOTD certification sites, focusing on repeatability and accuracy. Five specific conditions were examined:

1. Minimum operating speed (approximately 4 mph)
2. Deceleration
3. Acceleration
4. Stop-and-go
5. Stop-and-go with minimum operating speed

Following the certification trials, the SAG inertial profiler demonstrated its ability to accurately and consistently measure profiles under these specialized conditions. Based on these findings, it was then used to collect IRI readings for highway analysis lanes and their adjacent ramps.

The study further analyzed the differences in IRI and PI values between Louisiana DOTD's analysis lanes and adjacent sections, including ramps, acceleration lanes, and deceleration lanes. A discussion was provided on characterizing the IRI and PI values of these sections and their maintenance strategies.

Methodology

Currently, several manufacturers provide Stop-and-Go (SAG) inertial profilers, such as SSI, Ames Engineering, Dynatest, International Cybernetics Corporation, and Pathway Services. However, at the inception of this project in March 2022, only SSI's SAG systems were commercially available. SAG inertial profiler technology is advocated for measuring pavement roughness on highway ramps, acceleration and deceleration lanes, and under special operating conditions such as low speeds and stop-and-go scenarios.

For this project, an SSI SAG inertial profiler was rented for two rounds of testing: one in May 2022 and another in May 2024, each lasting one month. In May 2022, an initial comparison between the SAG inertial profiler and conventional inertial profilers was conducted. The SAG profiler executed initial runs with a single stop in the center of the test tracks to showcase its capabilities. In May 2024, a more extensive testing program assessed the SAG profiler's performance under special conditions such as low speeds and stop-and-go scenarios. Five specific operating conditions were considered: minimum operating speed (approximately 4 mph), deceleration, acceleration, stop-and-go, and stop-and-go with minimum operating speed. Additionally, differences in IRI values between Louisiana DOTD's analysis lanes and ramps or acceleration and deceleration lanes were analyzed during the second round of testing.

Initial SAG Inertial Profiler Comparison

The evaluation of the SAG profiler's performance began with a comparison between the SAG inertial profiler and conventional inertial profilers. The test sections for this comparison were all located in Baton Rouge; they included a concrete section on Burbank Drive, an asphalt section on Nicholson Drive, a concrete section on North Line Road near the LTRC Pavement Research Facility (PRF) in Port Allen, and an asphalt section on Ben Hur Road.

Three profilers were tested: (1) a conventional inertial profiler with a line laser from Fugro, (2) a conventional inertial profiler with a point laser manufactured by Dynatest, and (3) an SSI SAG inertial profiler. Testing was conducted at two constant high speeds for each of the four test sections, selected from an available range of 30, 40, 45, 50, and 55 mph based on prevailing traffic conditions. Specifically, 40 and 55 mph were used on the Burbank Drive test section, 40 and 50 mph on the Nicholson test section, 30 and 45 mph on the Ben Hur Road test section, and 30 and 40 mph on the North Line Road test section. Additionally, the

SAG inertial profiler was tested with a single stop at the center of the test sections, including Ben Hur Road and ALF Road in Port Allen, to demonstrate its capabilities.

Three test runs were conducted for each test section and speed. The IRI data was analyzed in 528 ft. segments for the one mi. test sections and averaged for each run. The comparison between the SAG inertial profiler and conventional inertial profilers was conducted using Analysis of Variance (ANOVA) analysis with a 95% significance level.

SAG Inertial Profiler Certification Under Various Operational Conditions (Repeatability and Accuracy)

In May 2024, a more extensive testing program to assess the SAG profiler's performance under special conditions such as low speeds and stop-and-go scenarios was conducted. Five specific operating conditions were considered: minimum operating speed (approximately 4 mph), deceleration, acceleration, stop-and-go, and stop-and-go with minimum operating speed.

Test Sections

Two Louisiana certification tracks that were selected by DOTD Materials and Testing Lab were used for the testing. The first test track is located on LA 414; see Figure 5. The test section is 1,128 ft. long and was newly overlaid with dense-graded asphalt mixtures. The surface was smooth, with no obvious distresses observed. To ensure consistent tracking of driving, the left wheel path (LWP) and right wheel path (RWP) were marked with blue paint; see Figure 5. The distance between the two wheel paths was approximately 69 in.

Figure 5. Location of certification site 1

The second section is located on LA 449; see Figure 6. The test section is 1,128 ft. long and was constructed with stone mastic asphalt (SMA). The LWP and RWP were marked with blue paint to ensure consistent tracking. The distance between the two wheel paths was approximately 69 in. It is noted that this section has a significant roughness difference between the wheel paths, with a transition gradient between 96-182 in./mi. Obvious cracks and potholes were observed on the RWP.

Figure 6. Location of certification site 2

Test Scenarios

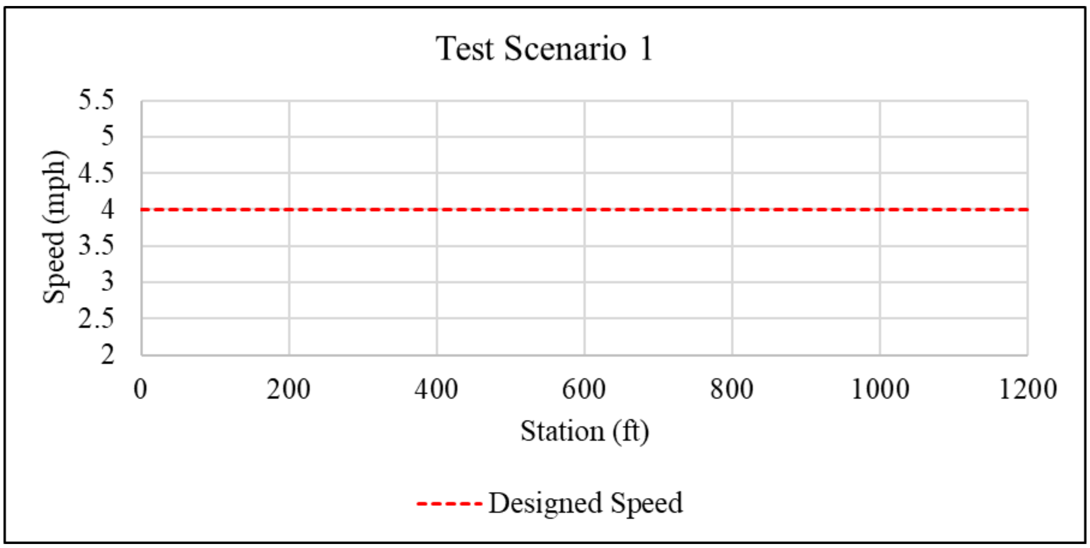
A tracking laser was used to ensure optimal tracking accuracy during tests. The laser setup was affixed as close to the driver's side wheel path (LWP) as possible on the vehicle's hood. The vehicle was driven slowly at an average speed of 4 mph along the track, ensuring it followed the painted line precisely. The vehicle was then brought to a stop, and the alignment of the LWP lasers with the painted line was inspected. If the lasers were centered on the painted line, three tracking laser dots were aligned at incremental, but visible, spacing along the left painted line. If the laser was not aligned, the vehicle proceeded further down the track, stopping and repeating the alignment process until the LWP profiler lasers were centered, after which the tracking lasers were aligned. It should be noted that the alignment of the LWP lasers with the painted line on the LWP does not necessarily guarantee the alignment of the RWP lasers with the painted line on the RWP. Two cones with reflective tape were placed at the start and end points of each test section. This allowed the profiler to automatically start and stop collecting profile data. Cones were placed beside the test section as landmarks to help profiler drivers achieve the required speed profiles.

The following five test scenarios were selected, as they represent challenges that occur in urban and low-speed conditions.

1. Creep under an average speed of 4 mph and a maximum speed of 5 mph for the entire track length;
2. Speed to 30 mph followed by a deceleration to 10 mph within 75 ft., then an acceleration back to 30 mph within 150 ft.;
3. Speed to 15 mph followed by an acceleration to 30 mph within 175 ft., then a deceleration back to 15 mph within 250 ft.;
4. Speed to 30 mph followed by a deceleration within 150 ft. to a stop. Hold for 60 sec. Then, an acceleration to 30 mph within 200 ft.; and
5. Speed to 30 mph followed by a deceleration within 150 ft. to a stop. Creep under 4 mph for 100 ft. Then, an acceleration back to 30 mph with 300 ft.

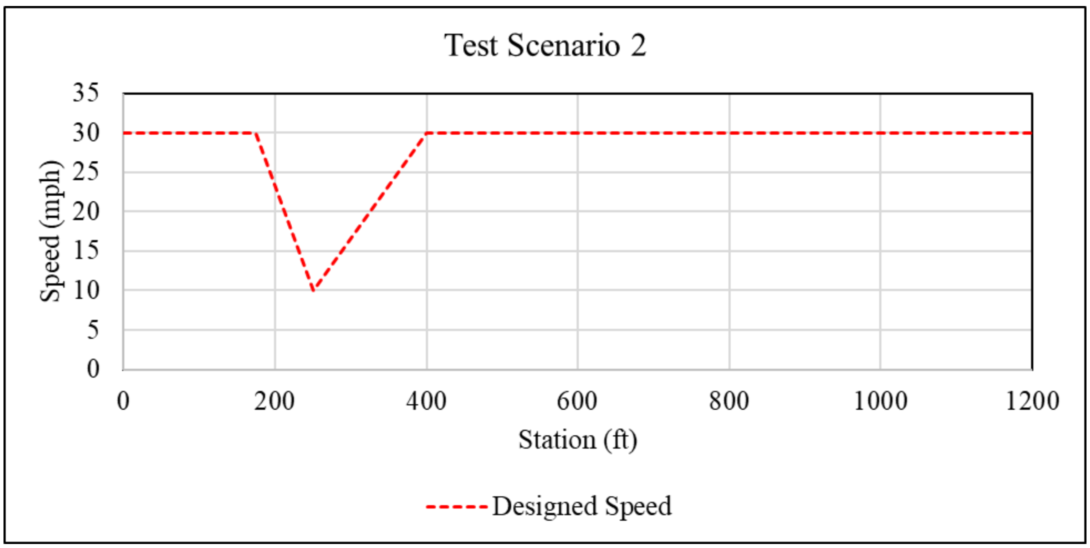
For test scenario 1, the operator was instructed to enter the test section at the idle speed of the host vehicle (approximately 4 mph) and maintain this speed until the end of the test section. Figure 7 shows the speed profile of test scenario 1. This scenario was designed to evaluate the performance of the SAG inertial profiler at very low speeds, specifically assessing its accelerometer sensitivity and ability to filter out drift effectively. According to the literature [2, 19], insufficient accelerometer sensitivity in SAG inertial profilers can introduce errors, gradually contaminating the waveband of interest due to dynamic misalignment. In dynamic conditions, misalignment occurs when the accelerometer shaft's axis of rotation deviates from that of its pedestal. Additionally, at extremely low speeds (approximately 3 mph), numerical integration issues can lead to accumulated drift, further affecting measurement accuracy.

Figure 7. Design speed profile of test scenario 1



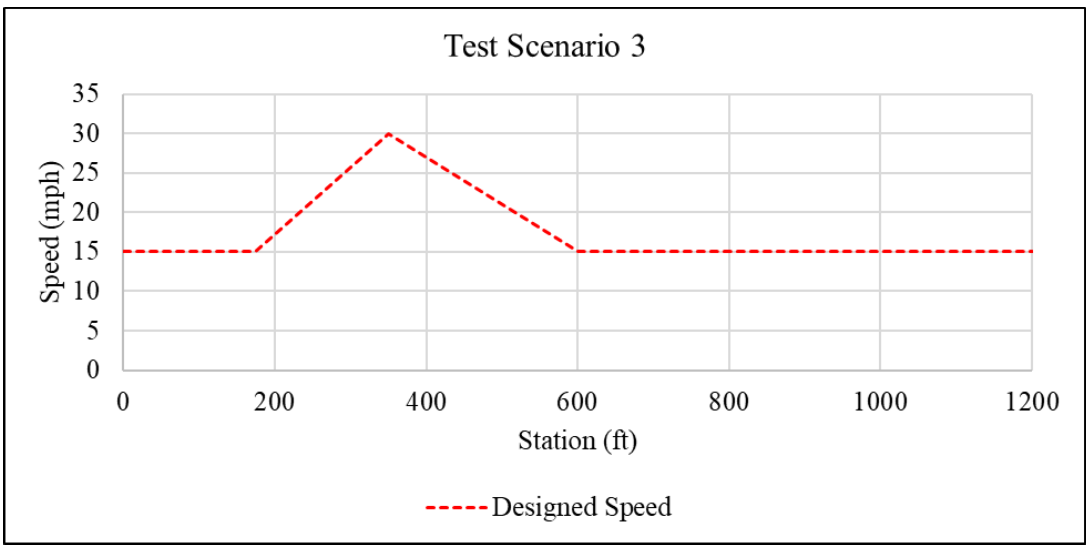
For test scenario 2, cones were placed at distances of 175, 250, and 400 ft. from the start of the test section. The operator was instructed to enter the test section at 30 mph. Upon reaching the first cone, the operator was instructed to begin braking to reduce the speed to 10 mph by the time the profiler reached the second cone. After passing the second cone, he or she was to accelerate back to 30 mph by the time the profiler reached the third cone and maintain that speed until the end of the section. Figure 8 shows the speed profile of test scenario 2. This test scenario was designed to evaluate the SAG inertial profiler's ability to minimize accelerometer errors caused by host-vehicle pitch during braking and acceleration. According to the literature [2, 19], factors such as integration drift, insufficient accelerometer sensitivity, and vehicle pitch during braking can introduce errors in pavement profile measurements.

Figure 8. Design speed profile of test scenario 2



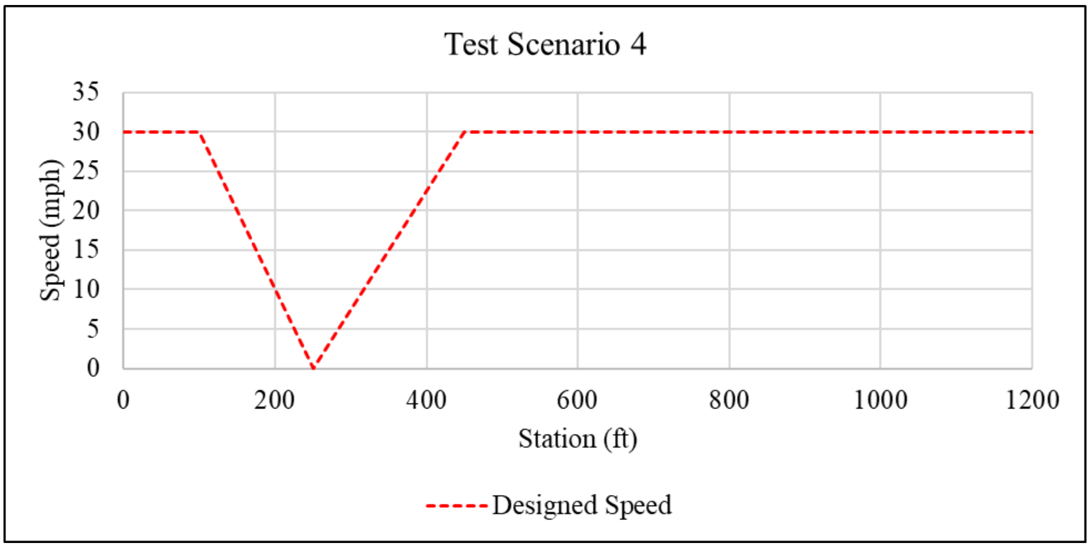
For test scenario 3, cones were placed at distances of 175, 350, and 600 ft. from the start of the test section. The operator was instructed to enter the test section at 15 mph and begin accelerating at the first cone to reach a speed of 30 mph by the time the profiler reached the second cone. After passing the second cone, the operator was instructed to reduce the speed back to 15 mph by the time the profiler reached the third cone and continue at that speed until the end of the section. Figure 9 shows the speed profile of test scenario 3. The test scenario 3 is the opposite of test scenario 2. It was designed to evaluate the effects of sequence of acceleration and deceleration on the SAG inertial profiler. Similar to test scenario 2, this test scenario also evaluated the SAG inertial profiler's ability to minimize accelerometer errors caused by host-vehicle pitch during braking and acceleration.

Figure 9. Design speed profile of test scenario 3



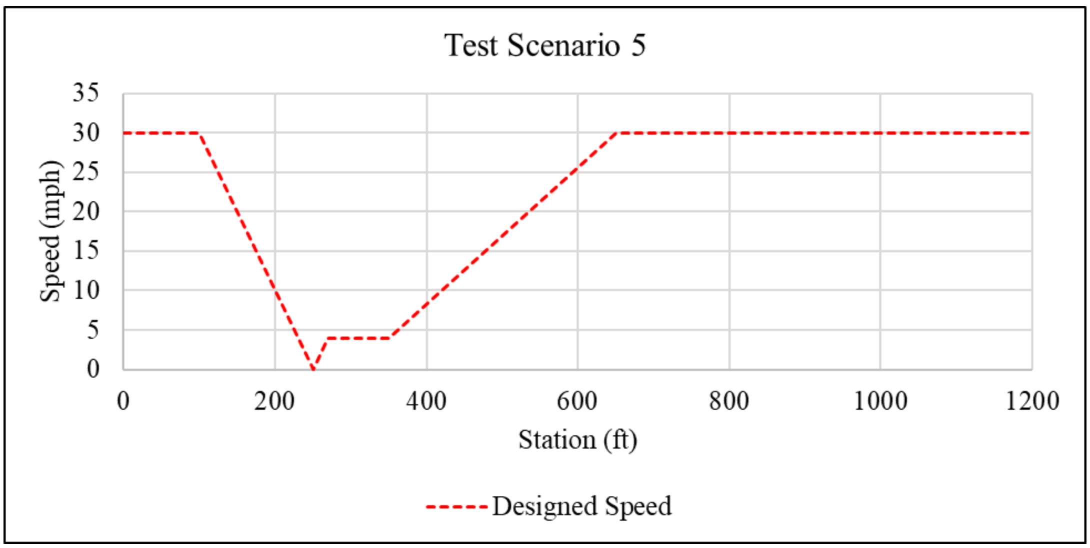
In test scenario 4, cones were placed at distances of 100, 250, and 450 ft. from the start of the test section. The operator was instructed to enter the test section at 30 mph, begin braking at the first cone, and come to a complete stop within 10 ft. of the second cone. The vehicle remained stopped for 60 sec. before accelerating back to 30 mph by the time it reached the third cone, maintaining that speed until the end of the section. Figure 10 shows the speed profile of test scenario 4. This test scenario was designed to evaluate the SAG inertial profiler's ability to minimize errors caused by integration drift during prolonged stops. According to the literature [2, 19], extended stops can generate excessive drift, potentially affecting the accuracy of pavement profile measurements.

Figure 10. Design speed profile of test scenario 4



In test scenario 5, cones were positioned at 100, 250, 350, and 650 ft. from the start of the test section. The operator entered the section at 30 mph, began braking at the first cone, and came to a complete stop within 10 ft. of the second cone, remaining stationary for 5 sec. The vehicle then proceeded at its idle speed (approximately 4 mph) for the next 100 ft. until reaching the third cone. From there, the operator accelerated back to 30 mph by the time the vehicle reached the final cone and maintained that speed through the remainder of the section. Figure 11 illustrates the speed profile for test scenario 5. This test scenario simulated driving in urban conditions, emphasizing abrupt changes in driving modes. It evaluates the SAG inertial profiler's ability to minimize errors caused by integration drift during prolonged stops, insufficient accelerometer sensitivity, limited drift-filtering capability, and host-vehicle pitch during braking and acceleration.

Figure 11. Design speed profile of test scenario 5



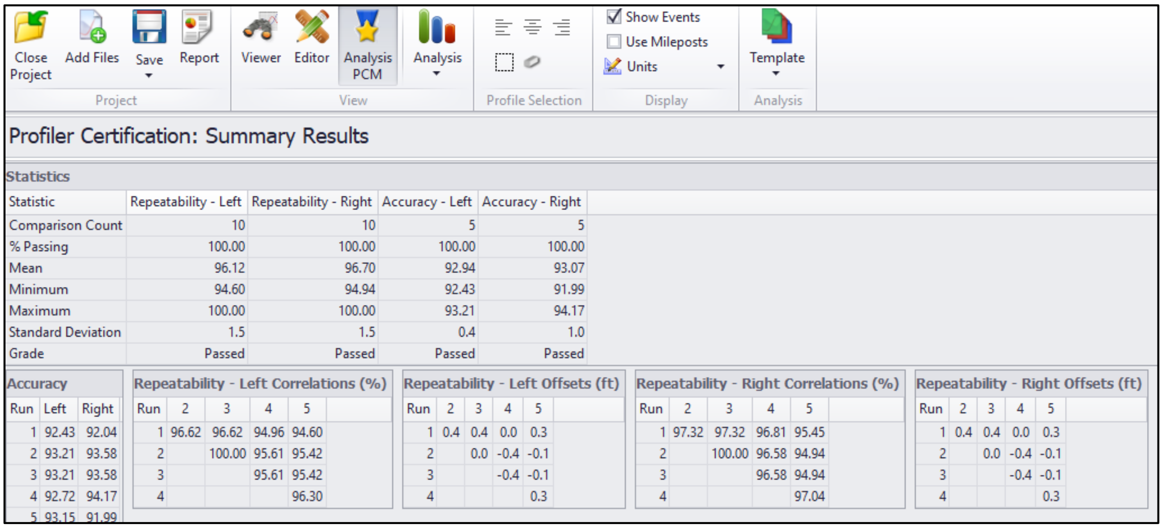
It is noted that operators were unable to precisely match the target speeds during certification runs. Therefore, a permissible speed tolerance was applied. The actual speed profiles for each run are provided in the Results chapter of this report.

Analysis Methods

Louisiana test method TR 644, "Determining the Longitudinal Profile Roughness of Traveled Surfaces Using Automated Profilers" [21], and AASHTO R 56, "Standard Practice for Certification of Inertial Profiling Systems" [22], were used to evaluate the repeatability and accuracy of the SAG inertial profiler. Louisiana test method TR 644 specifies that the standard deviation of the IRI results obtained from the profiler for each test scenario must not exceed 3 in./mi. to meet the repeatability requirement, and the average IRI value should be within ±6 in./mi. of the reference IRI, as determined from the reference device, to meet the accuracy requirement.

AASHTO R 56 employs cross-correlation to evaluate the performance of inertial profilers. In AASHTO R 56, cross-correlation is used as a quantitative method to compare the profile shape collected by a candidate profiler. The data from candidate profilers are assessed for repeatability—that is, how consistently the profiler produces similar results—and for accuracy—that is, how closely the profiler's measurements match those of a reference device. A cross-correlation score of 100.0 indicates two identical profiles. For certification based on IRI, AASHTO R 56 specifies a minimum mean repeatability cross-correlation score of 92.0. The goal of this criterion is for the IRI values from a candidate profiler to be within 5% of each other across all runs. AASHTO R 56 also sets a minimum mean accuracy cross-correlation score of 90.0, aiming for the candidate profiler's IRI value to be within 5% of the reference device's IRI. In addition to the repeatability and accuracy criteria, AASHTO R 56 requires verification of the candidate profiler's DMI accuracy, verification of the profiler's software for IRI computation, and verification that the profiler can pass both the block check and bounce test. These tests ensure that the laser displacement sensors and accelerometers are functioning correctly. In this study, cross-correlation analysis and IRI computation were performed using ProVAL 4.0, with the analysis based on IRI-filtered profiles as described in AASHTO R 56. Figure 12 shows an example of the summary result generated by ProVAL 4.0 software.

Figure 12. Profiler certification summary example from ProVAL 4.0 software



Profiler Certification: Summary Results

Statistics

Statistic	Repeatability - Left	Repeatability - Right	Accuracy - Left	Accuracy - Right
Comparison Count	10	10	5	5
% Passing	100.00	100.00	100.00	100.00
Mean	96.12	96.70	92.94	93.07
Minimum	94.60	94.94	92.43	91.99
Maximum	100.00	100.00	93.21	94.17
Standard Deviation	1.5	1.5	0.4	1.0
Grade	Passed	Passed	Passed	Passed

Accuracy

Run	Left	Right
1	92.43	92.04
2	93.21	93.58
3	93.21	93.58
4	92.72	94.17
5	93.15	91.99

Repeatability - Left Correlations (%)

Run	2	3	4	5
1	96.62	96.62	94.96	94.60
2		100.00	95.61	95.42
3			95.61	95.42
4				96.30

Repeatability - Left Offsets (ft)

Run	2	3	4	5
1	0.4	0.4	0.0	0.3
2		0.0	-0.4	-0.1
3			-0.4	-0.1
4				0.3

Repeatability - Right Correlations (%)

Run	2	3	4	5
1	97.32	97.32	96.81	95.45
2		100.00	96.58	94.94
3			96.58	94.94
4				97.04

Repeatability - Right Offsets (ft)

Run	2	3	4	5
1	0.4	0.4	0.0	0.3
2		0.0	-0.4	-0.1
3			-0.4	-0.1
4				0.3

Reference Device Selection

LA 414 Certification Site

A walking profiler was tested as a potential reference profiler in this study. These devices are well-established for accurately measuring pavement surface roughness and serve as a benchmark for assessing high-speed inertial profilers [13, 14, 15]. They are manually operated, with an individual moving the device along the pavement either by lifting and placing its “feet” or by guiding a rolling platform. Each movement, or “step,” precisely records the height difference or uses an accelerometer to capture the longitudinal profile [13, 14, 15].

On May 21, 2024, profile measurements were conducted using a walking profiler at the LA 414 certification site, covering both the left and right wheel paths with five replicate runs. The repeatability of the walking profiler’s measurements was assessed using AASHTO R 56 cross-correlation, with the results summarized in Table 1. The repeatability cross-correlation scores were 73 for the left wheel path and 89 for the right wheel path, both falling below the AASHTO R 56 requirement of 98. However, the standard deviation of the IRI results from the walking profiler was 1.4 in/mi. for the left wheel path and 1.5 in./mi. for the right wheel path, as shown in Table 2. These values meet the DOTD TR 644 requirements for high-speed inertial profilers. Notably, DOTD TR 644 does not specify repeatability requirements for reference equipment.

Table 1. Repeatability analysis results of walking profiler on May 21, 2024 (LA 414)

Statistic	**Repeatability— left wheel path**	**Repeatability— right wheel path**
Comparison Count	10	10
% Passing	0	0
Mean	73	89
Minimum	58	81
Maximum	86	93
Standard Deviation	12	4

Table 2. IRI Results of Walking Profiler on May 21, 2024 (LA 414)

	IRI (in/mi)	
Replicate runs	Left wheel path	Right wheel path
1	46.0	60.6
2	47.9	59.5
3	47.4	57.5
4	49.3	57.0
5	49.4	58.1
Average	48.0	58.5
Standard Deviation	1.4	1.5

Two additional attempts to use the walking profiler were conducted on June 3, 2024, and June 6, 2024. The repeatability analysis results for these attempts are presented in

Table **3** and Table 4, respectively. As the tables demonstrate, neither attempt met the AASHTO R 56 requirements for a reference device.

Table 3. Repeatability analysis results of walking profiler on June 3, 2024 (LA 414)

Statistic	**Repeatability— left wheel path**	**Repeatability— right wheel path**
Comparison Count	3	3
% Passing	0	0
Mean	88	85
Minimum	87	82
Maximum	89	89
Standard Deviation	1	4

Table 4. Repeatability analysis results of walking profiler on June 6, 2024 (LA 414)

Statistic	Repeatability— left wheel path	Repeatability— right wheel path
Comparison Count	3	3
% Passing	0	0
Mean	85	91
Minimum	80	89
Maximum	92	93
Standard Deviation	6	2

According to AASHTO R 56, a device qualifies as a reference device if it achieves at least 98% repeatability across at least three runs. In other words, a device with a repeatability score of 98% meets reference-level repeatability and can be used to collect baseline reference profiles. In this study, the SAG inertial profiler was tested at a constant high speed (40 mph), with ten replicate runs conducted. The results, presented in Table 5, show that the SAG inertial profiler achieved 98% repeatability, confirming its capability to serve as a reference-level device. Therefore, the profiles obtained from the constant high-speed runs of the SAG inertial profiler were used as reference profiles for accuracy evaluation under various special operation conditions at the LA 414 certification site.

Table 5. Repeatability analysis results of high speed profiler (LA 414)

Statistic	Repeatability— left wheel path	Repeatability— right wheel path
Comparison Count	45	45
% Passing	100	100
Mean	98	98
Minimum	95	94
Maximum	99	99
Standard Deviation	1	1

LA 449 Certification Site

Both the walking profiler and the SAG inertial profiler at constant high speed were evaluated as potential reference profilers. The results are presented in Table 6 and Table 7, respectively. As the tables demonstrate, neither met the AASHTO R 56 requirements for a reference device. Consequently, the accuracy evaluation of the SAG inertial profiler under various special operating conditions at the LA 449 certification site could not be conducted due to the absence of a reference profile.

Table 6. Repeatability analysis results of walking profiler (LA 449)

Statistic	Repeatability—left wheel path	Repeatability—right wheel path
Comparison Count	10	10
% Passing	0	0
Mean	96	93
Minimum	94	86
Maximum	97	97
Standard Deviation	1	4

Table 7. Repeatability analysis results of high speed profiler (LA 449)

Statistic	Repeatability—left wheel path	Repeatability—right wheel path
Comparison Count	10	10
% Passing	0	0
Mean	95	88
Minimum	90	78
Maximum	97	95
Standard Deviation	2	5

Project Testing

After the certification trials, the SSI SAG inertial profiler was used to collect project data to ascertain whether there are differences in the IRI values of Louisiana DOTD's analysis lanes compared to ramps, acceleration, or declaration lanes. Five projects were tested on I-10 and I-12. Below is the list of the projects that were tested in this project.

1. I-10, Eastbound, Exit 173, 1-mi. travel lane (outside lane) before the exit and ramp at the exit. Concrete surface.
2. I-10, Eastbound, Exit 179, 1-mi. travel lane (outside lane) before the exit and ramp at the exit. Concrete surface.
3. I-10, Eastbound, Exit 194, 1-mi. travel lane (outside lane) before the exit and ramp at the exit. Asphalt surface.
4. I-10, Eastbound, Exit 206, 1-mi. travel lane (outside lane) before the exit and ramp at the exit. Asphalt surface.
5. I-12, Westbound, Exit 2B, 1-mi. travel lane (outside lane) before the exit and ramp at the exit. Concrete surface.

Results

This section presents the results of the comparison between the SAG inertial profiler and conventional high speed inertial profilers; an evaluation of the SAG inertial profiler under various operating conditions in terms of repeatability and accuracy; and differences in the IRI values of Louisiana DOTD's analysis lanes compared to ramps, acceleration, or declaration lanes, as measured by the SAG inertial profiler.

Initial SAG Inertial Profiler Comparison

Figure 13 and Figure 14 present the comparison of the SSI SAG inertial profiler with LTRC's and Fugro's conventional high-speed inertial profilers at constant operating speeds of 40 mph and 55 mph, respectively, on the Burbank test section. The IRI values were calculated and averaged every 528 ft., with the left and right wheel path values further averaged for analysis. The error bars in the figures indicate the standard deviations of three replicate runs. The results showed that the SSI SAG inertial profiler had similar IRI values as those measured from LTRC's and Fugro's conventional high-speed inertial profilers at speeds of both 40 mph and 55 mph. The IRI variations at bridge locations could be attributed to driving wander. Fugro's conventional high-speed inertial profiler showed consistently higher IRI values, followed by the SSI SAG inertial profiler and LTRC's conventional high-speed inertial profiler.

The Analysis of Variance (ANOVA) is a statistical method used to compare the means of multiple groups and determine whether the differences between them are statistically significant. The ANOVA results, presented in Table 8 and Notes: "SS": sum of squares; "df ": degrees of freedom; "MS": mean square; "F": F-statistic, calculated by dividing the mean square between groups (or treatments) by the mean square within groups (or error); P-value: a smaller p-value (typically < 0.05) indicates statistical significance; F crit: Critical F value, the threshold value used to determine statistical significance.

Table 9 indicates no statistically significant differences among the IRI values measured by the three different inertial profilers. Additionally, the operational speeds had no significant effect on the averaged IRI results for the Burbank test section.

Figure 13. IRI comparison of inertial profilers at 40 mph on Burbank test section

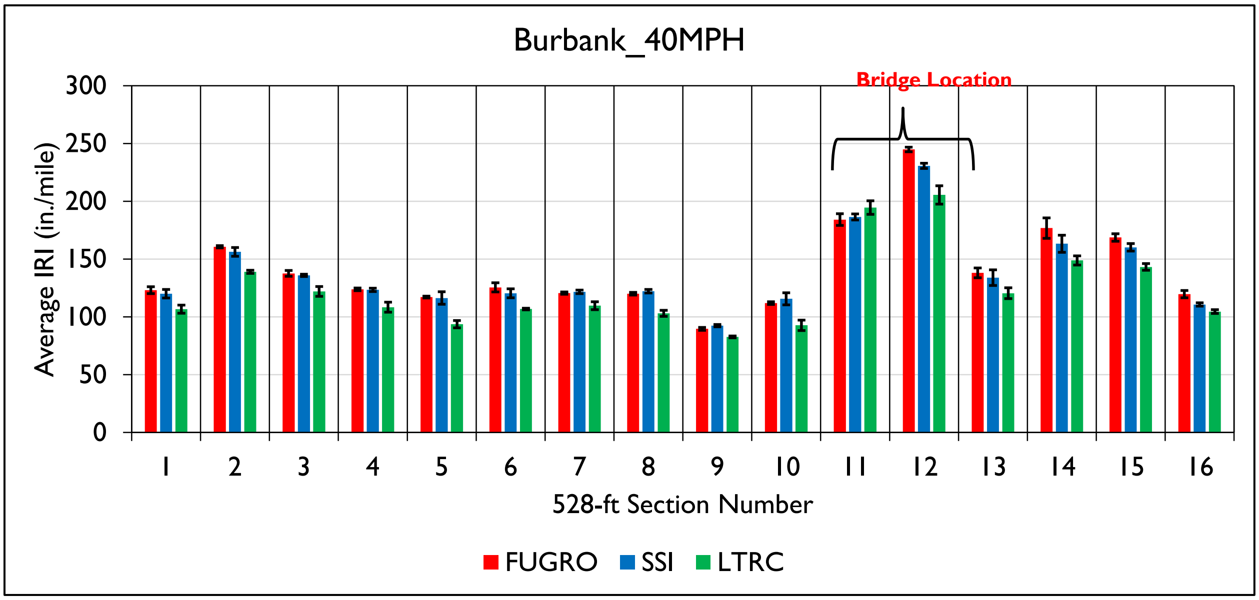


Figure 14. IRI comparison of inertial profilers at 55 mph on Burbank test section

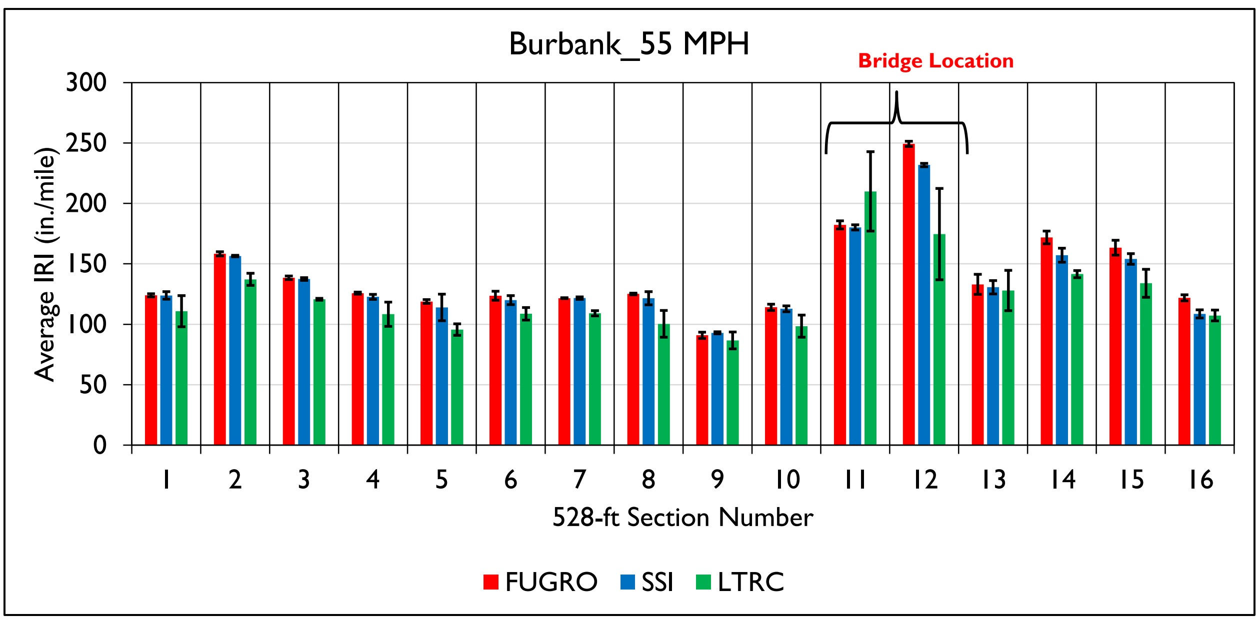


Table 8. ANOVA analysis of IRI comparison of inertial profilers at 40 mph on Burbank test section

Groups	**Count**	**Sum**	**Average**	**Variance**		
FUGRO	17	2391	141	1341		
SSI	17	2334	137	1108		
LTRC	17	2094	123	1152		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2932.240	2	1466.120	1.222	0.304	3.191
Within Groups	57610.655	48	1200.222			
Total	60542.895	50				

Notes: "SS": sum of squares; "df ": degrees of freedom; "MS": mean square; "F": F-statistic, calculated by dividing the mean square between groups (or treatments) by the mean square within groups (or error); P-value: a smaller p-value (typically < 0.05) indicates statistical significance; F crit: Critical F value, the threshold value used to determine statistical significance.

Table 9. ANOVA analysis of IRI comparison of inertial profilers at 55 mph on Burbank test section

Groups	**Count**	**Sum**	**Average**	**Variance**		
FUGRO	17	2393	141	1305		
SSI	17	2313	136	1066		
LTRC	17	2088	123	947		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2952.268	2	1476.134	1.334	0.273	3.191
Within Groups	53096.605	48	1106.179			
Total	56048.873	50				

Figures 15 and 16 compare the SSI SAG inertial profiler with LTRC's and Fugro's conventional high-speed inertial profilers at constant operating speeds of 40 mph and 50 mph, respectively, on the Nicholson test section. The results show that the SSI SAG inertial profiler produced IRI values comparable to those measured by the LTRC and Fugro profilers at most sections for both speeds. However, the profilers' operator reported experiencing driving wander, which may have contributed to the significant variance in repeated runs and differences in IRI readings among the three tested inertial profilers in certain sections.

Figure 15. IRI comparison of inertial profilers at 40 mph on Nicholson test section

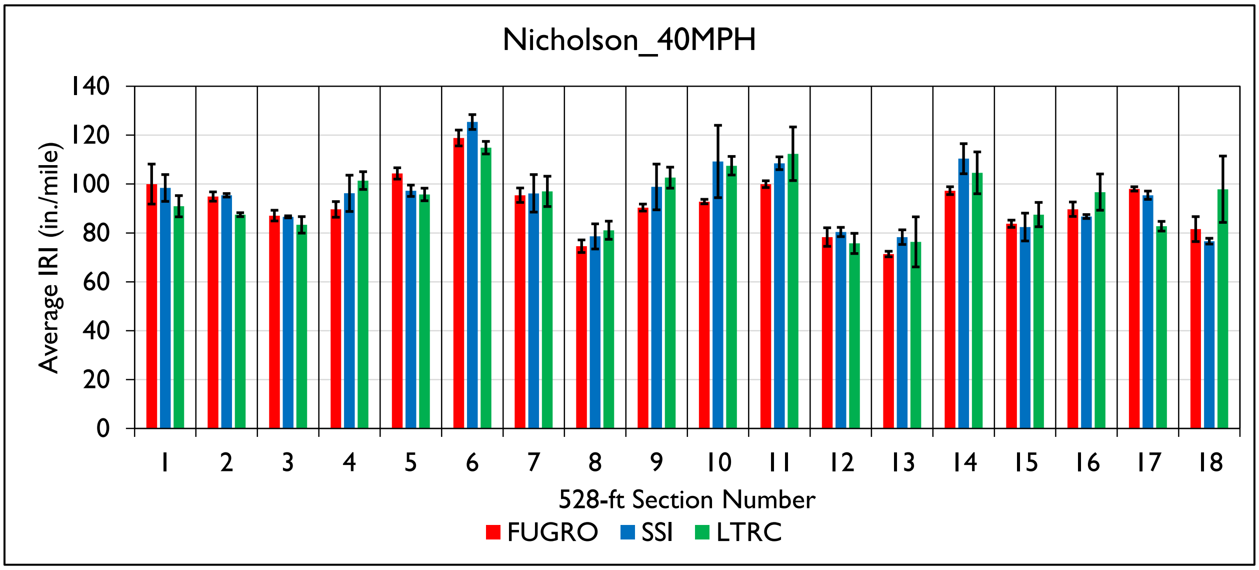


Figure 16. IRI comparison of inertial profilers at 50 mph on Nicholson test section

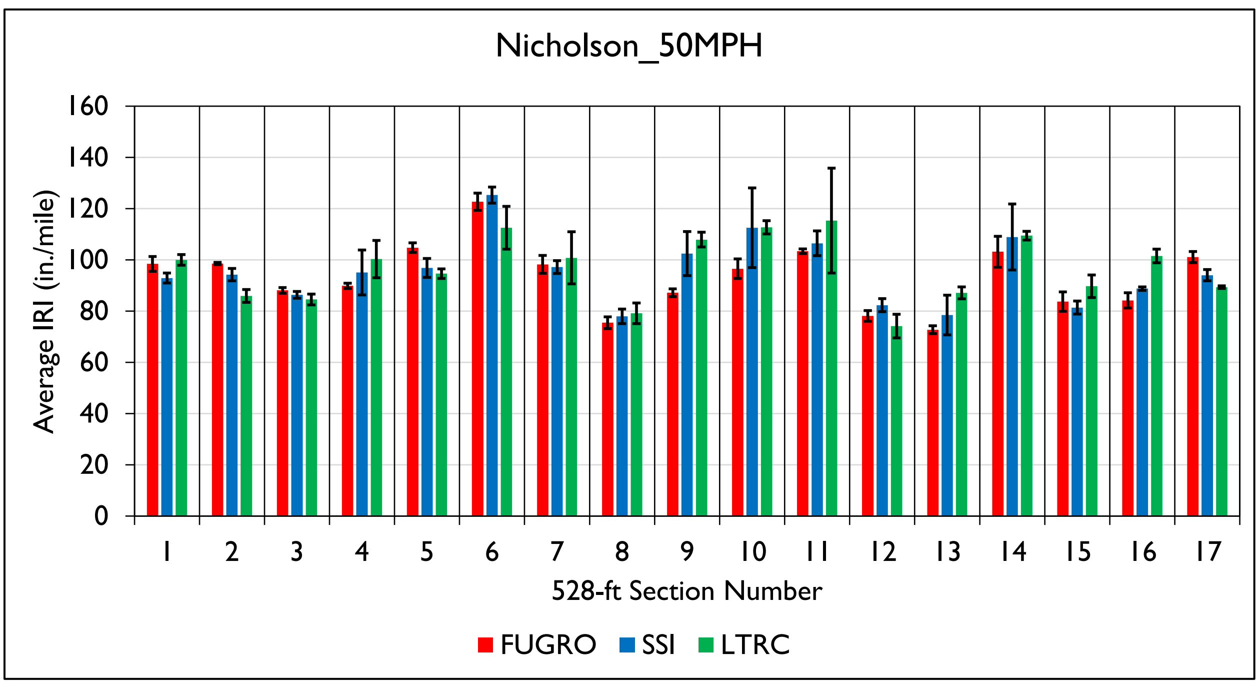


Table 10 and Table 11 present the ANOVA results for the IRI readings obtained from the three inertial profilers on the Nicholson test section at constant operating speeds of 40 mph and 50 mph, respectively. The analysis indicates no significant differences among the mean

IRI readings of the three profilers. Further, the operating speed had no statistically significant effect on the IRI measurements.

Table 10. ANOVA analysis of IRI comparison of inertial profilers at 40 mph on Nicholson test section

Groups	**Count**	**Sum**	**Average**	**Variance**		
FUGRO	18	1648	92	130		
SSI	18	1701	94	175		
LTRC	18	1696	94	140		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	94.857	2	47.428	0.320	0.728	3.179
Within Groups	7568.207	51	148.396			
Total	7663.064	53				

Table 11. ANOVA analysis of IRI comparison of inertial profilers at 50 mph on Nicholson test section

Groups	**Count**	**Sum**	**Average**	**Variance**		
FUGRO	17	1586	93	161		
SSI	17	1621	95	165		
LTRC	17	1645	97	155		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	103.172	2	51.586	0.321	0.727	3.191
Within Groups	7702.566	48	160.470			
Total	7805.738	50				

Figure 17 and Figure 18 compare the SSI SAG inertial profiler with LTRC's and Fugro's conventional high-speed inertial profilers at constant operating speeds of 30 mph and 45 mph, respectively, on the Ben Hur Road test section. In addition to the constant speed runs, the SSI SAG inertial profiler was tested with a single stop at the center of the test section. The results indicate that the SSI SAG profiler produced IRI values comparable to those measured by the LTRC and Fugro profilers in most sections at both constant operational speeds. However, sections with potholes exhibited significant variance in IRI readings across repeated runs, as well as differences among the three profilers in certain areas. Notably, the single-stop operation of the SSI SAG inertial profiler did not affect the IRI results along the test section.

Tables 12 and 13 present the ANOVA results for the IRI readings obtained from the three inertial profilers on the Ben Hur Road test section at constant operating speeds and the SSI SAG profiler's single-stop operation. The analysis revealed no significant differences among the mean IRI readings of the three profilers. Additionally, the results confirmed that the single-stop operation of the SSI SAG inertial profiler had no impact on its IRI measurements.

Figure 17. IRI comparison of inertial profilers at 30 mph on Ben Hur Road test section

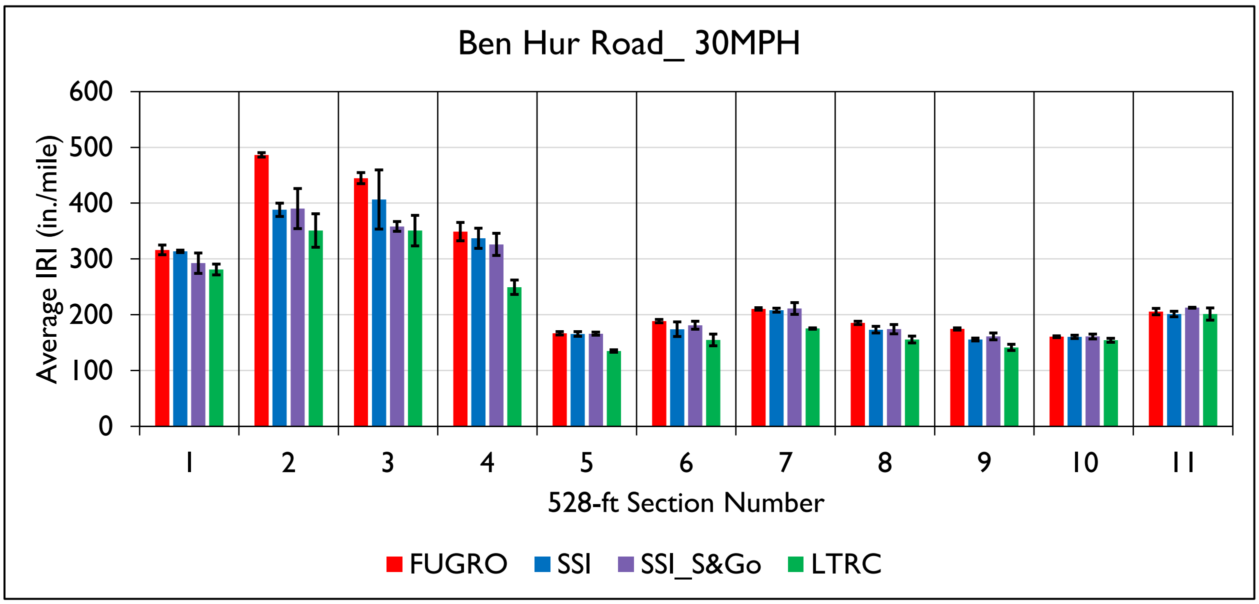


Figure 18. IRI comparisons of inertial profilers at 45 mph on Ben Hur Road test section

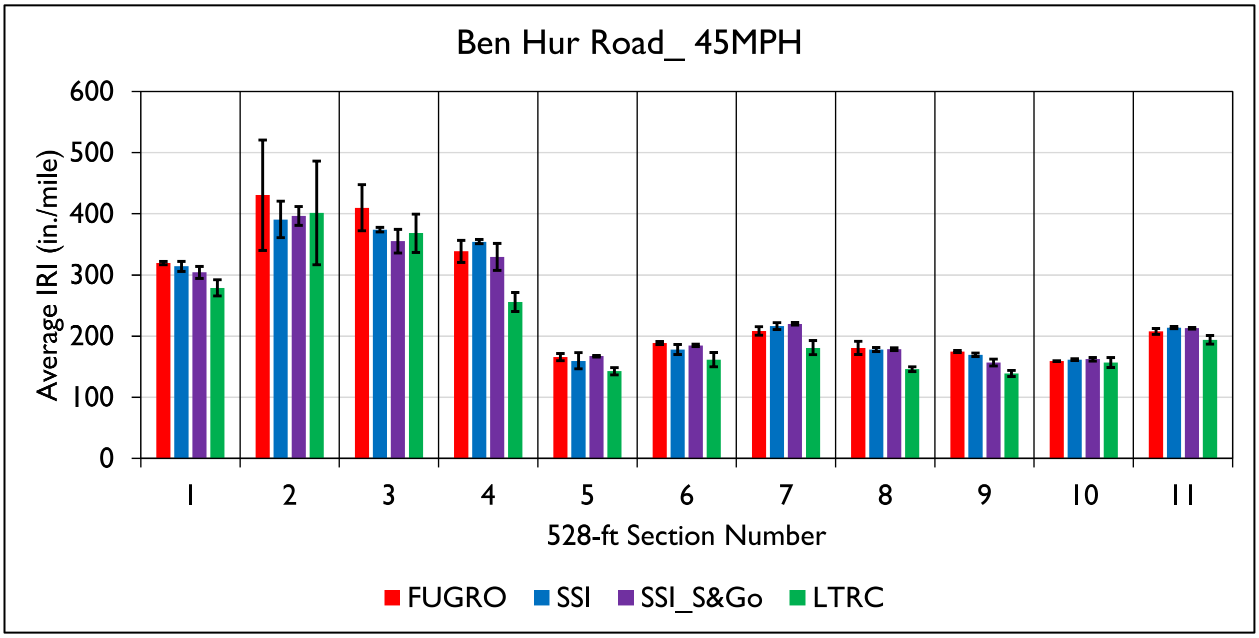


Table 12. ANOVA analysis of IRI comparison of inertial profilers at 30 mph on Ben Hur Road test section

Groups	Count	Sum	Average	Variance		
FUGRO	11	2888	263	13843		
SSI	11	2683	244	9468		
SSI_S&Go	11	2634	239	7397		
LTRC	11	2350	214	6685		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	13436.975	3	4478.992	0.479	0.699	2.839
Within Groups	373937.791	40	9348.445			
Total	387374.765	43				

Table 13. ANOVA analysis of IRI comparison of inertial profilers at 45 mph on Ben Hur Road test section

Groups	Count	Sum	Average	Variance		
FUGRO	11	2783	253	10379		
SSI	11	2709	246	8547		
SSI_S&Go	11	2667	242	7614		
LTRC	11	2424	220	8733		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	6579.485	3	2193.162	0.249	0.862	2.839
Within Groups	352738.766	40	8818.469			
Total	359318.251	43				

Figure 19 and Figure 20 compare the SSI SAG inertial profiler with LTRC's and Fugro's conventional high-speed inertial profilers at constant operating speeds of 30 mph and 40 mph, respectively, on the North Line Road test section. Similarly, the SSI SAG Inertial profiler was tested with a single stop at the center of the test section. The results indicate that the SSI SAG profiler produced IRI values comparable to those measured by the LTRC and Fugro profilers at both constant operational speeds. The single-stop operation of the SSI SAG inertial profiler did not affect the IRI results along the test section. The ANOVA analysis revealed no significant differences among the mean IRI readings of the three profilers. Additionally, the results confirmed that the single-stop operation of the SSI SAG inertial profiler had no impact on its IRI measurements, as shown in Table 14 and Table 15.

Figure 19. IRI comparisons of inertial profilers at 30 mph on North Line Road test section

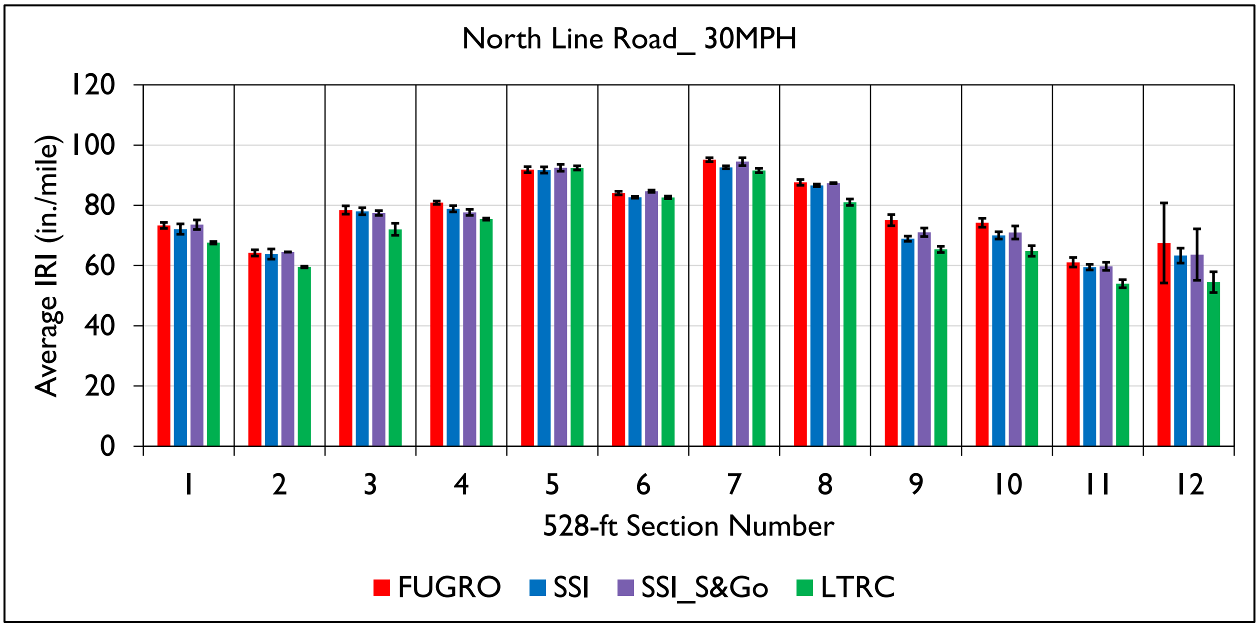


Figure 20. IRI comparison of inertial profilers at 40 mph on North Line Road test section

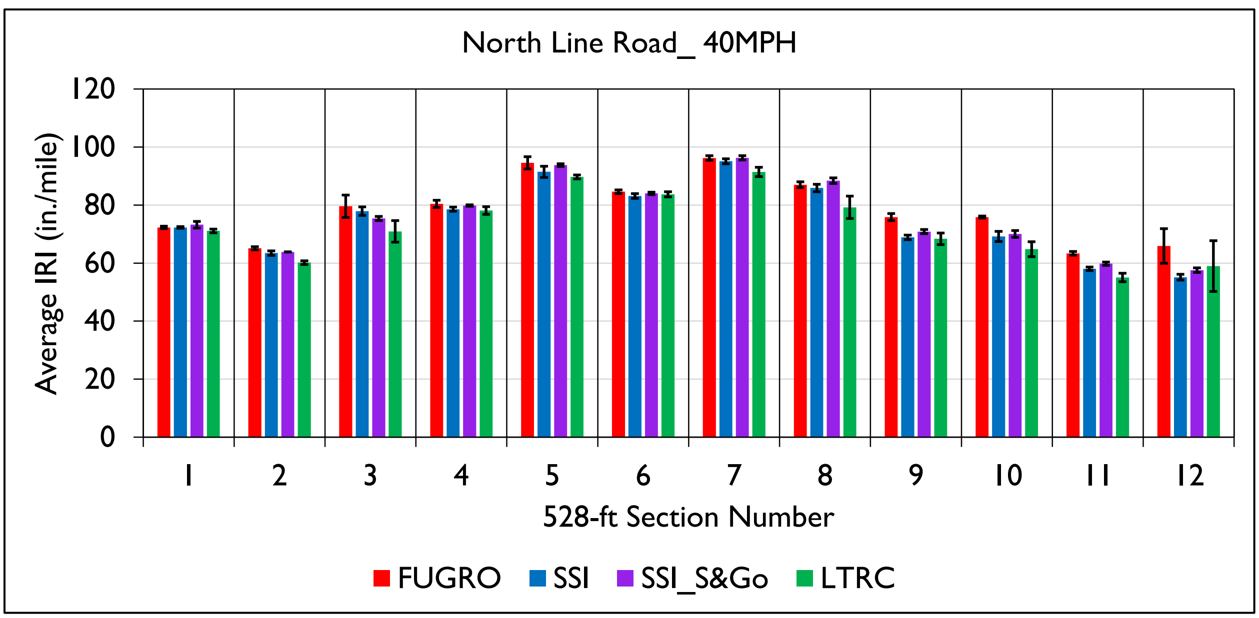


Table 14. ANOVA analysis of IRI comparison of inertial profilers at 30 mph on North Line Road test section

Groups	**Count**	**Sum**	**Average**	**Variance**		
FUGRO	12	933	78	114		
SSI	12	908	76	125		
SSI_S&Go	12	917	76	130		
LTRC	12	861	72	173		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	243.1652	3	81.055	0.598	0.620	2.816
Within Groups	5963.187	44	135.527			
Total	6206.353	47				

Table 15. ANOVA analysis of IRI comparison of inertial profilers at 40 mph on North Line Road test section

Groups	**Count**	**Sum**	**Average**	**Variance**		
FUGRO	12	941	78	119		
SSI	12	899	75	161		
SSI_S&Go	12	913	76	162		
LTRC	12	872	73	143		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	207.8968	3	69.299	0.473	0.702	2.816
Within Groups	6440.117	44	146.366			
Total	6648.014	47				

SAG Inertial Profiler Certification Under Various Operational Conditions (Repeatability and Accuracy)

In this study, the Louisiana test method TR 644, "Determining the Longitudinal Profile Roughness of Traveled Surfaces Using Automated Profilers," and AASHTO R 56, “Standard

Practice for Certification of Inertial Profiling Systems," were used to evaluate the repeatability and accuracy of the SAG inertial profiler.

LA 414 Certification Site

Figure 21 through Figure 25 illustrate the speed profiles of the SAG inertial profiler across various testing scenarios. While the actual speed profiles did not fully meet the designed speed profiles, they remained sufficiently within compliance to allow for a meaningful assessment of the SAG inertial profiler's performance in each scenario.

Figure 21. Speed profiles for test scenario 1

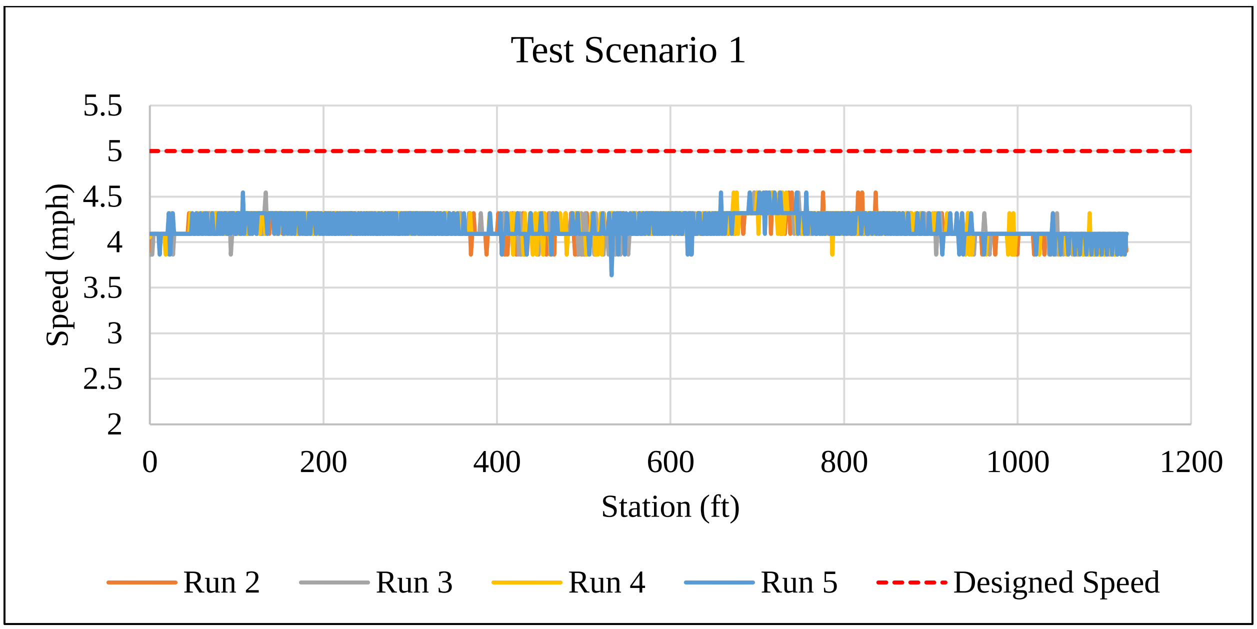


Figure 22. Speed profiles for test scenario 2

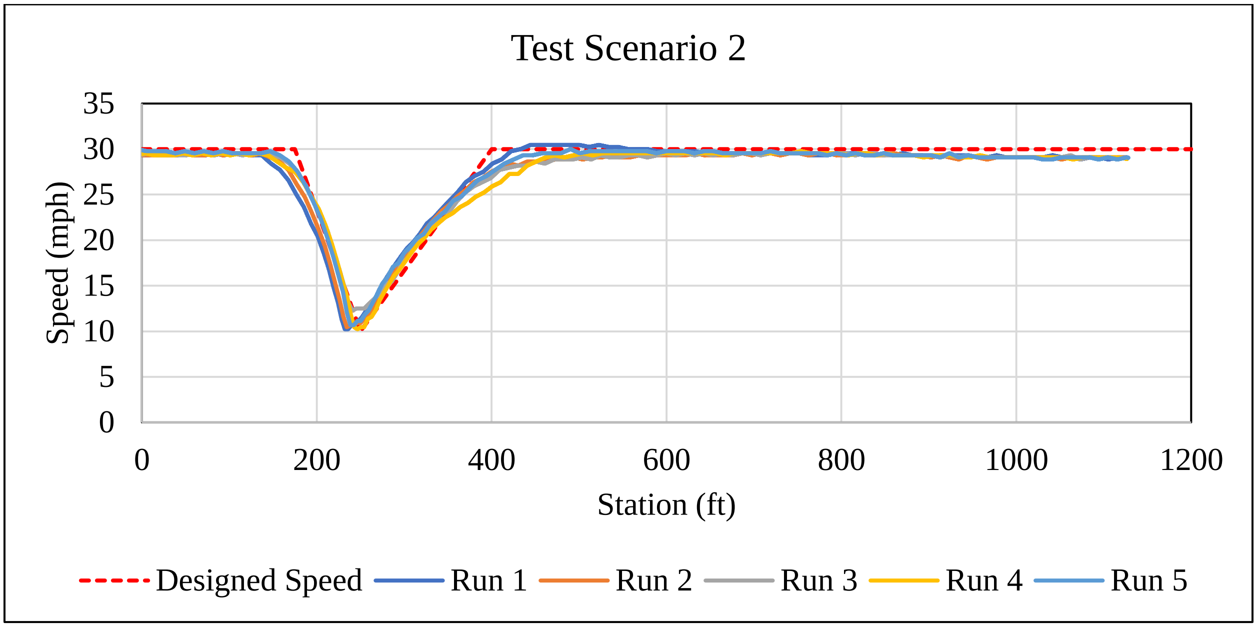


Figure 23. Speed profiles for test scenario 3

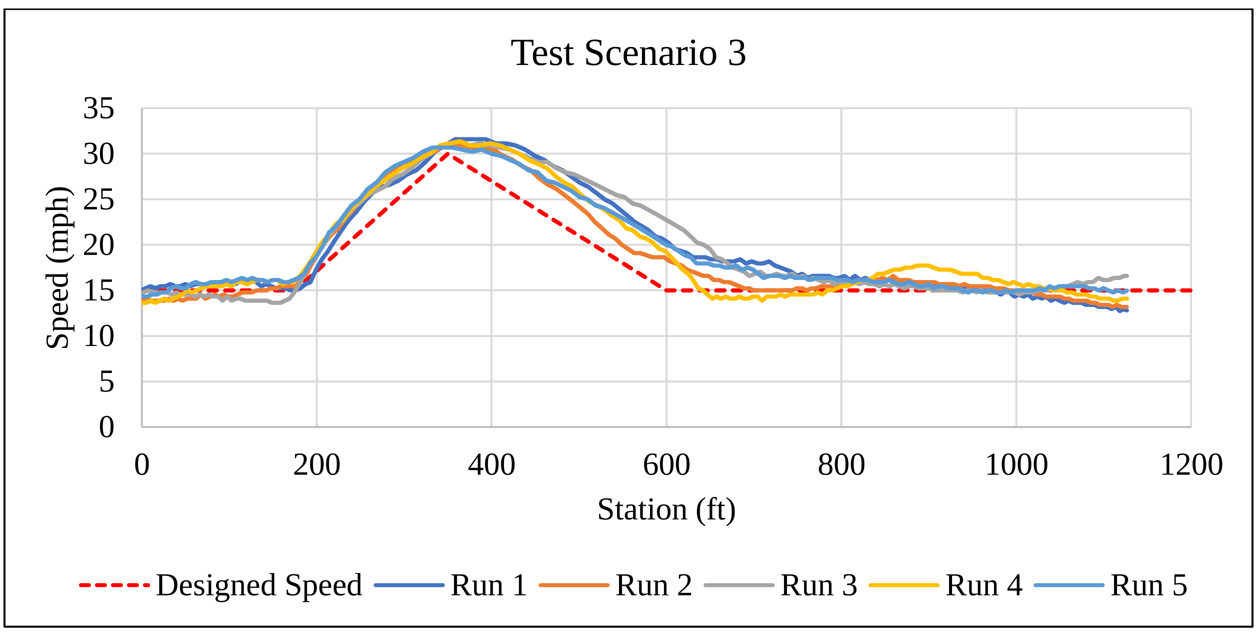


Figure 24. Speed profiles for test scenario 4

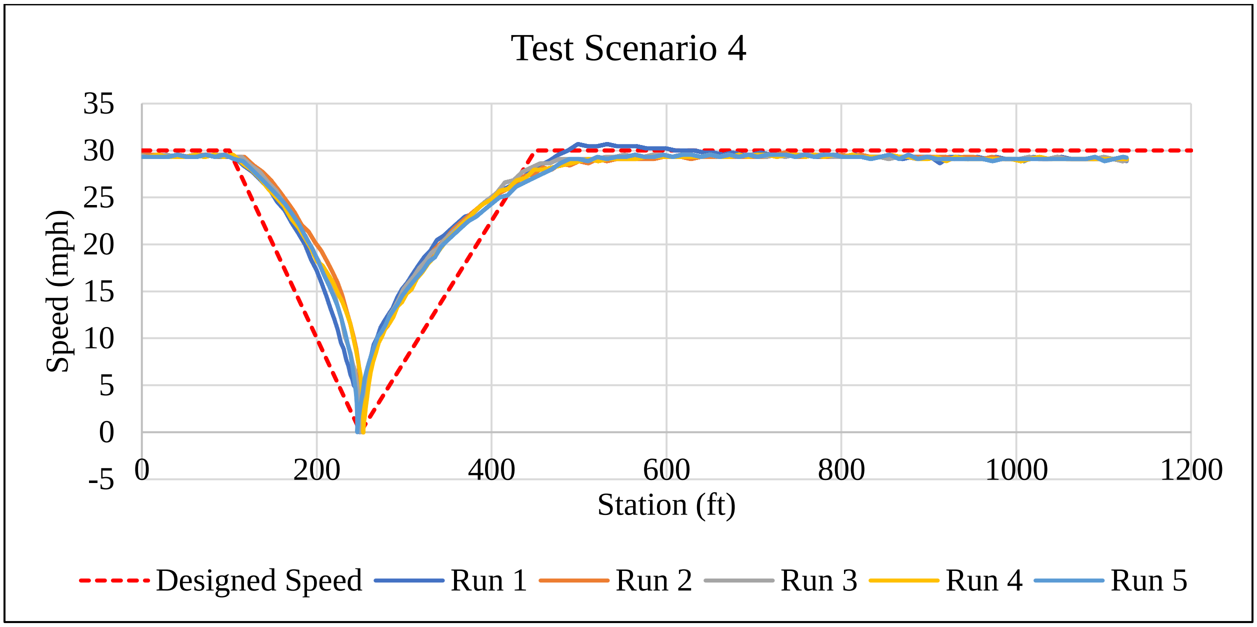
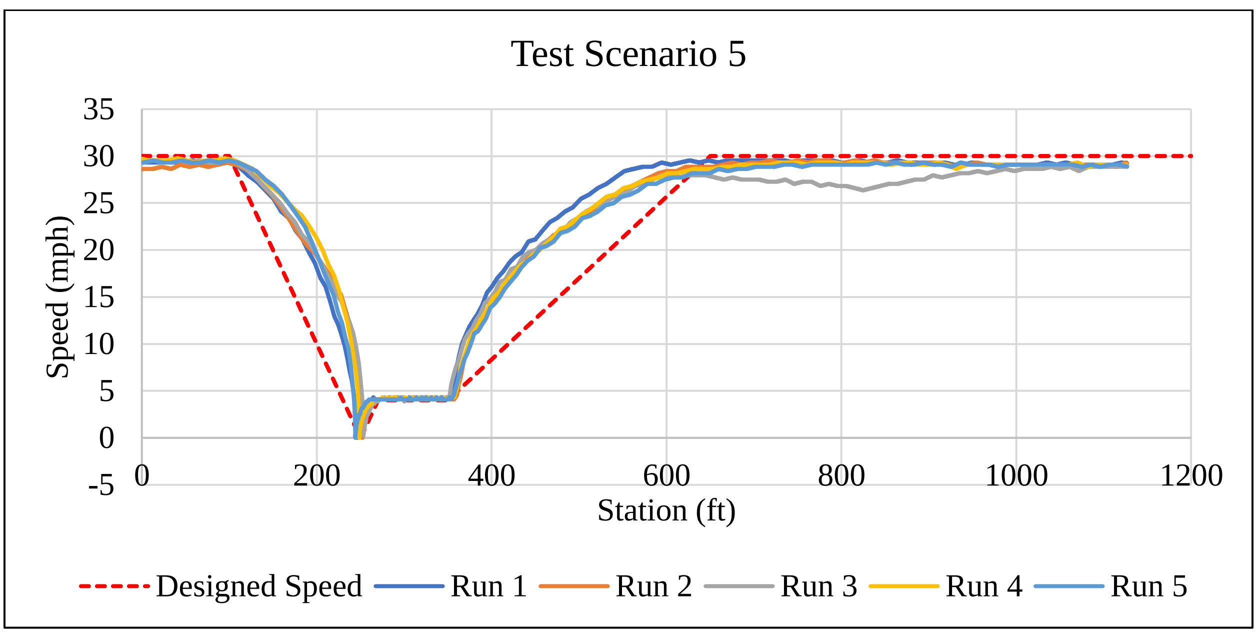


Figure 25. Speed profiles for test scenario 5



DOTD TR 644 establishes repeatability and accuracy criteria for profiler performance. To meet the repeatability requirement, the standard deviation of IRI results for each test scenario must not exceed 3 in./mi. For accuracy compliance, the average IRI value must fall within ±6 in./mi. of the reference IRI, as determined by a reference profiler. As outlined in the Methodology section, the profiles measured at a constant high speed of 40 mph from SSI SAG inertial profiler were designated as reference profiles for the LA 414 certification site. Table 16 presents the IRI values calculated from these reference profiles.

Table 16. IRI values from reference device on LA 414 certification site

Replicate Runs	IRI (in./mi.)	
	Left wheel path	Right wheel path
1	44.1	58.9
2	44.2	59.1
3	44.1	59.2
4	43.7	58.7
5	43.7	59.5
6	44.3	59.5
7	44.1	59.4
8	43.7	59.0
9	44.1	59.4
10	43.9	59.6
Average	44.0	59.2
Standard Deviation	0.22	0.28

Table 17 through Table 21 summarize the repeatability and accuracy evaluation of the SAG inertial profiler under various test scenarios at the LA 414 certification site, following DOTD TR 644 standards. The standard deviation of the IRI results for each scenario remained below 1 in./mi. for both wheel paths, ensuring compliance with the repeatability requirement. Additionally, the average IRI values for both the left and right wheel paths across all test scenarios fell within ±6 in./mi. of the reference IRI, as determined by the reference profiler, satisfying the accuracy requirement of DOTD TR 644.

Table 17. Repeatability and accuracy based on DOTD TR644, test scenario 1 on LA 414 certification site

Wheel Path	Repeatability		Accuracy		
	Standard Deviation (in./mi.)	Met DOTD TR 644?	Average Test IRIs (in./mi.)	Difference between averages of test and walking profiler IRIs (in./mi.)	Met DOTD TR 644?
Left	0.24	Yes	43.9	0.0	Yes
Right	0.32	Yes	57.8	1.4	Yes

Table 18. Repeatability and accuracy based on DOTD TR644, test scenario 2 on LA 414 certification site

Wheel Path	Repeatability		Accuracy		
	Standard Deviation (in./mi.)	Met DOTD TR 644?	Average Test IRIs (in./mi.)	Difference between averages of test and walking profiler IRIs (in./mi.)	Met DOTD TR 644?
Left	0.48	Yes	44.5	0.6	Yes
Right	0.68	Yes	58.9	0.4	Yes

Table 19. Repeatability and accuracy based on DOTD TR644, test scenario 3 on LA 414 certification site

Wheel Path	Repeatability		Accuracy		
	Standard Deviation (in./mi.)	Met DOTD TR 644?	Average Test IRIs (in./mi.)	Difference between averages of test and walking profiler IRIs (in./mi.)	Met DOTD TR 644?
Left	0.51	Yes	43.5	0.5	Yes
Right	0.64	Yes	58.7	0.5	Yes

Table 20. Repeatability and accuracy based on DOTD TR644, test scenario 4 on LA 414 certification site

Wheel Path	Repeatability		Accuracy		
	Standard Deviation (in./mi.)	Met DOTD TR 644?	Average Test IRIs (in./mi.)	Difference between averages of test and walking profiler IRIs (in./mi.)	Met DOTD TR 644?
Left	0.60	Yes	45.1	1.1	Yes
Right	0.70	Yes	59.1	0.1	Yes

Table 21. Repeatability and accuracy based on DOTD TR644, test scenario 5 on LA 414 certification site

Wheel Path	Repeatability		Accuracy		
	Standard Deviation (in./mi.)	Met DOTD TR 644?	Average Test IRIs (in./mi.)	Difference between averages of test and walking profiler IRIs (in./mi.)	Met DOTD TR 644?
Left	0.55	Yes	45.5	1.6	Yes
Right	0.40	Yes	58.9	0.3	Yes

AASHTO R 56 employs cross-correlation to evaluate the performance of inertial profilers, providing a quantitative comparison of the profile shape collected by a candidate profiler. A cross-correlation score of 100.0 indicates identical profiles. For IRI-based certification, AASHTO R 56 establishes a minimum mean repeatability cross-correlation score of 92 and a minimum mean accuracy cross-correlation score of 90. Table 22 through Table 26 present the repeatability and accuracy assessment of the SAG inertial profiler under various test scenarios at the LA 414 certification site, in accordance with AASHTO R 56 standards. Typically, up to five collection files were analyzed for each test scenario, resulting in ten repeatability comparisons and five accuracy comparisons. However, in some cases, only four collection files were used due to significant discrepancies between the test speed profile and the design speed profile, leading to six repeatability comparisons and four accuracy comparisons in those instances.

The results indicate that test scenarios 2-5 met the AASHTO R 56 requirements, achieving a repeatability score of 92 and an accuracy score of 90. However, as shown in Table 22, the accuracy of both wheel paths in test scenario 1 did not meet the required thresholds. This discrepancy may be attributed to a misalignment in tracking the reference line. Additionally, the GPS-based distance measurement instrument exhibited a high standard deviation. This issue may have stemmed from a combination of low GPS reception and low speed, preventing the inertial navigation system from effectively compensating for errors.

Table 22. Repeatability and accuracy based on AASHTO R 56, test scenario 1 on LA 414 certification site

Statistic	Repeatability		Accuracy	
	Left	Right	Left	Right
Comparison Count	6	6	4	4
% Passing	100	83.33	25	50
Mean	95.75	95.51	88.26	86.6
Minimum	92.78	91.75	82.55	78.3
Maximum	97.29	97.9	94.38	93.73
Standard Deviation	1.8	2.3	5	6.8

Table 23. Repeatability and accuracy based on AASHTO R 56, test scenario 2 on LA 414 certification site

Statistic	Repeatability		Accuracy	
	Left	Right	Left	Right
Comparison Count	10	10	5	5
% Passing	100	100	100	100
Mean	95.54	96.15	95.82	96.2
Minimum	93.47	92.27	92.74	93.41
Maximum	97.48	97.87	97.3	97.81
Standard Deviation	1.4	1.7	1.8	1.7

Table 24. Repeatability and accuracy based on AASHTO R 56, test scenario 3 on LA 414 certification site

Statistic	Repeatability		Accuracy	
	Left	Right	Left	Right
Comparison Count	10	10	5	5
% Passing	100	100	100	100
Mean	95.36	95.41	95.38	96.18
Minimum	93.37	93.03	93.12	93.62
Maximum	97.03	99.04	96.62	97.59
Standard Deviation	1.3	1.8	1.4	1.6

Table 25. Repeatability and accuracy based on AASHTO R 56, test scenario 4 on LA 414 certification site

Statistic	Repeatability		Accuracy	
	Left	Right	Left	Right
Comparison Count	10	10	5	5
% Passing	100	100	100	100
Mean	94.84	97.29	94.47	97.25
Minimum	92.62	96.66	92.26	96.54
Maximum	97.15	97.78	96.44	97.93
Standard Deviation	1.5	0.4	1.8	0.5

Table 26. Repeatability and accuracy based on AASHTO R 56, test scenario 5 on LA 414 certification site

Statistic	Repeatability		Accuracy	
	Left	Right	Left	Right
Comparison Count	10	10	5	5
% Passing	100	100	100	100
Mean	94.36	96.85	93.15	96.69
Minimum	92.86	95.76	92.04	96.25
Maximum	96.28	98.28	95.45	97.26
Standard Deviation	1	0.7	1.4	0.5

LA 449 Certification Site

The same tests and analyses conducted at the LA 414 certification site were performed at the LA 449 certification site. However, as noted in the Methodology section, this study was unable to identify a suitable reference profiler for LA 449. As a result, only repeatability analyses were conducted at this site.

Tables 27 through 31 present the repeatability evaluation of the SAG inertial profiler under various test scenarios at the LA 449 certification site, following DOTD TR 644 standards. The standard deviation of the IRI results remained below 3 in./mi. for the left wheel path but exceeded 3 in./mi. for the right wheel path. As a result, the SAG inertial profiler met the DOTD TR 644 repeatability requirement for the left wheel path but did not meet the standard for the right wheel path under various test scenarios.

Table 27. Repeatability based on DOTD TR 644, test scenario 1 on LA 449 certification site

Wheel Path	Repeatability		
	Average Test IRIs (in./mi.)	Standard Deviation (in./mi.)	Met DOTD TR 644?
Left	97.2	1.34	Yes
Right	120.2	4.09	No

Table 28. Repeatability based on DOTD TR 644, test scenario 2 on LA 449 certification site

Wheel Path	Repeatability		
	Average Test IRIs (in./mi.)	Standard Deviation (in./mi.)	Met DOTD TR 644?
Left	95.6	1.48	Yes
Right	124.2	7.08	No

Table 29. Repeatability based on DOTD TR 644, test scenario 3 on LA 449 certification site

Wheel Path	Repeatability		
	Average Test IRIs (in./mi.)	Standard Deviation (in./mi.)	Met DOTD TR 644?
Left	96.9	2.57	Yes
Right	116.4	6.94	No

Table 30. Repeatability based on DOTD TR 644, test scenario 4 on LA 449 certification site

Wheel Path	Repeatability		
	Average Test IRIs (in./mi.)	Standard Deviation (in./mi.)	Met DOTD TR 644?
Left	93.7	1.02	Yes
Right	122.2	5.79	No

Table 31. Repeatability based on DOTD TR 644, test scenario 5 on LA 449 certification site

Wheel Path	Repeatability		
	Average Test IRIs (in./mi.)	Standard Deviation (in./mi.)	Met DOTD TR 644?
Left	94.4	1.26	Yes
Right	126.3	6.67	No

Table 32 through Table 36 present the repeatability assessment of the SAG inertial profiler under various test scenarios at the LA 449 certification site, following AASHTO R 56 standards. Consistent with the DOTD TR 644 evaluation, the profiler did not meet the repeatability requirement for the right wheel path across multiple test scenarios. Additionally, it failed to meet the standard for the left wheel path under test scenarios 3 and 5.

It is important to note that this certification site exhibits a significant difference in roughness between the left and right wheel paths, with a transition gradient ranging from 96-182 in./mi. Visible cracks and potholes on the right wheel path likely contributed to the variability in profile measurements. When capturing profiles over the same pavement segment, one pass may record a height value within a distress pit, while another may not, leading to substantial discrepancies between repeated profiles.

Therefore, the low repeatability scores observed at this site do not necessarily indicate poor performance of the SAG inertial profiler. Instead, the findings suggest that pavement sections with extensive distresses, such as cracking and rutting, are not suitable for use as certification sites for inertial profilers.

Table 32. Repeatability based on AASHTO R 56, test scenario 1 on LA 449 certification site

Statistic	Repeatability—left wheel path	Repeatability—right wheel path
Comparison Count	10	10
% Passing	60	30
Mean	92.95	88.2
Minimum	87.55	81.94
Maximum	97.15	93.62
Standard Deviation	3.4	4

Table 33. Repeatability based on AASHTO R 56, test scenario 2 on LA 449 certification site

Statistic	Repeatability—left wheel path	Repeatability—right wheel path
Comparison Count	10	10
% Passing	70	10
Mean	93.15	82.61
Minimum	88.64	72.49
Maximum	95.22	93.33
Standard Deviation	2.2	6.9

Table 34. Repeatability based on AASHTO R 56, test scenario 3 on LA 449 certification site

Statistic	Repeatability—left wheel path	Repeatability—right wheel path
Comparison Count	10	10
% Passing	30	0
Mean	90.17	82.85
Minimum	84.22	71.61
Maximum	95.08	91.64
Standard Deviation	3.2	6.9

Table 35. Repeatability based on AASHTO R 56, test scenario 4 on LA 449 certification site

Statistic	Repeatability—left wheel path	Repeatability—right wheel path
Comparison Count	6	6
% Passing	66.67	16.67
Mean	93.13	85.05
Minimum	91.29	76.77
Maximum	94.99	94.68
Standard Deviation	1.5	6.8

Table 36. Repeatability based on AASHTO R 56, test scenario 5 on LA 449 certification site

Statistic	Repeatability—Left wheel path	Repeatability—Right wheel path
Comparison Count	10	10
% Passing	40	10
Mean	91.22	85.18
Minimum	87.33	72.36
Maximum	95.28	92.27
Standard Deviation	2.9	6.2

Project Testing

Following the certification trials, the SAG inertial profiler demonstrated its capability to accurately and consistently measure profiles under various special operational conditions, including acceleration, deceleration, low-speed operation, and stop-and-go scenarios. Based on these findings, the SAG inertial profiler was utilized to collect IRI readings for highway analysis lanes and their adjacent ramps. Table 37 presents a comparison of overall IRI values between travel lanes and ramps across various projects. The results indicate that, contrary to current DOTD practice, which assumes similar IRI values for both, the ramps did not exhibit the same or comparable IRI levels as the travel lanes. Observations from the five projects in this study revealed that ramps generally had higher IRI readings than the corresponding travel lanes. It is noted that the project I-10 Exit 206, Eastbound exhibited a lower IRI value on the ramp compared to the travel lane, likely due to a rehabilitation performed on the ramp in 2016.

Table 37. Overall IRI comparison between travel lanes and ramps for various projects

Project Name	Surface Type	Overall IRI (in./mi.)			
		Left wheel path		Right wheel path	
		Travel Lane	Ramp	Travel Lane	Ramp
I-10 Exit 173, Eastbound	Concrete	116.4	185.4	116.1	191.1
I-10 Exit 179, Eastbound	Concrete	106.7	133.4	114.8	133.0
I-10 Exit 194, Eastbound	Asphalt	113.4	161.1	127.2	195.9
I-10 Exit 206, Eastbound	Asphalt	104.2	80.1	96.9	88.6
I-12 Exit 2B, Eastbound	Concrete	127.2	200.6	118.6	183.4

Louisiana Performance Index

The performance index (PI) rating of pavements is a critical tool for highway systems, used to estimate the extent of deterioration and identify deficient sections requiring improvement. In Louisiana, the PI rating also supports benefit-cost analyses and enables the comparison of pavement treatment strategies. Accurate PI data reporting is essential for equitable fund allocation and effective pavement maintenance and preservation efforts. The PI rating system assesses the overall pavement condition on a scale of 0 to 100, with 100 representing new roads in excellent condition. PI values are calculated based on the pavement type (flexible, composite, or rigid) using a combination of the IRI and measured pavement distress values. Distress indexes incorporated into PI calculations include alligator cracking, random cracking (transverse and longitudinal cracking for flexible pavements), patching, and rutting indexes. Figure 26 presents the Louisiana DOTD scale for rating the PI of different types of roads.

Figure 26. Louisiana DOTD performance index scale

Rating	INTERSTATES	NHS	RHS & SHS
VERY GOOD	100-96	100-95	100-95
GOOD	95-90	94-88	94-85
FAIR	89-76	87-70	84-65
POOR	75-65	69-60	64-50
VERY POOR	64-0	59-0	49-0

Equations for computing PI values for different pavement types are provided below:

For flexible pavements:

$$PI = max\{min(RNDM, ALCR, PTCH, RUFF, RUT), [AVG(RNDM, ALCR, PTCH, RUFF, RUT) - 0.85STD(RNDM, ALCR, PTCH, RUFF, RUT)]\}$$

For composite pavements:

$$PI = max\{min(RNDM, PTCH, RUFF, RUT), [AVG(RNDM, PTCH, RUFF, RUT) - 0.85STD(RNDM, PTCH, RUFF, RUT)]\}$$

For jointed concrete pavements:

$$PI = max\{min(LONG, TRAN, PTCH, RUFF), [AVG(LONG, TRAN, PTCH, RUFF) - 0.85STD(LONG, TRAN, PTCH, RUFF)]\}$$

For continuous reinforced concrete pavements:

$$PI = max\{min(LONG, PTCH, RUFF), [AVG(LONG, PTCH, RUFF) - 0.85STD(LONG, PTCH, RUFF)]\}$$

where,
Max = maximum;
Min = minimum;
STD = standard deviation;
$RNDM$ = random cracking index;
$LONG$ = longitudinal cracking index;
$TRAN$ = transverse cracking index;
$ALCR$ = alligator cracking index;
$PTCH$ = patching index;
$RUFF$ = roughness index; and
RUT = rutting index.

Potential Improvement Using the SAG Inertial Profiler

The primary reason DOTD does not calculate PI for ramps and similar sections is the lack of valid IRI data. However, this study demonstrated that the SAG inertial profiler can accurately and consistently measure profiles under special operational conditions, including:

1. Acceleration and deceleration;
2. Low-speed operation; and
3. Stop-and-go scenarios.

This capability suggests that the SAG inertial profiler can be used to obtain accurate IRI measurements for ramps, deceleration lanes, and acceleration lanes, allowing direct PI calculations for these sections. By using accurate PI values, these special highway sections can be evaluated independently, rather than assuming they share the same maintenance trigger values and treatment costs as the analysis lane. While the same methodologies for triggering maintenance and allocating treatment costs can still apply across all roadway sections, the actual treatment costs and maintenance needs should be assessed separately for ramps and adjacent lanes.

Conclusions and Recommendations

Based on the study results and analysis, the following conclusions can be drawn:

- The SAG inertial profiler can produce IRI values comparable to those measured by the conventional high speed inertial profilers at constant high operational speeds.
- Operational speed had no significant impact on the average IRI results obtained from the SAG inertial profiler when operating at a constant high speed.
- The single-stop operation of the SAG inertial profiler had no impact on its IRI measurements.
- The SAG inertial profiler demonstrated accurate and consistent profile measurements under special operational conditions, including acceleration, deceleration, low-speed, and stop-and-go scenarios, at the LA 414 DOTD certification site. These results suggest that the profiler is suitable for obtaining reliable IRI measurements on ramps, deceleration lanes, and acceleration lanes throughout Louisiana.
- Pavement sections with extensive distresses, such as cracking and rutting, are not suitable for use as certification sites for inertial profilers.
- Ramps did not demonstrate the same or comparable IRI levels as travel lanes.

The following recommendations are provided:

- The SAG inertial profiler can be used to obtain accurate IRI measurements for ramps, deceleration lanes, and acceleration lanes.
- The performance index (PI) for special highway sections, including ramps, deceleration lanes, and acceleration lanes, can be reliably determined using valid IRI readings obtained from the SAG inertial profiler and calculated with existing DOTD equations.
- Actual treatment costs and maintenance needs should be assessed separately for ramps and adjacent travel/analysis lanes.
- DOTD may consider adopting SAG inertial profilers for network-level pavement smoothness evaluations to improve the accuracy of condition assessments, particularly for special highway sections such as ramps, deceleration lanes, and acceleration lanes.

- When utilizing SAG inertial profilers, DOTD should update certification procedures to ensure the more effective evaluation of inertial profilers across various operational conditions.

Acronyms, Abbreviations, and Symbols

Term	Description
AASHTO	American Association of State Highway and Transportation Officials
ALCR	Alligator cracking index
cm	centimeter(s)
df	Degree of Freedom
DOTD	Louisiana Department of Transportation and Development
FHWA	Federal Highway Administration
F	F-statistic
F crit	Critical F value
ft.	foot (feet)
in.	inch(es)
IRI	International Roughness Index
IP	Inertial Profiler
LONG	Longitudinal cracking index
LTRC	Louisiana Transportation Research Center
LWP	Left Wheel Path
Max	Maximum
Min	Minimum
MS	Mean Square
NHS	National Highway System
PI	Performance Index
PTCH	Patching Index
P-value	A statistic value indicating statistical significance
RHS	Regional Highway System
RNDM	Random cracking index
RUFF	Roughness index
Rut	Rutting Index
RWP	Right Wheel Path
SAG	Stop-and-Go

Term	Description
SHS	State Highway System
SS	Sum of square
STD	Standard deviation
TRAN	Transverse cracking index

References

[1] M. W. Sayers, “On the Calculation of International Roughness Index from Longitudinal Road Profile,” *Transportation Research Record*, vol. 1501, pp. 1-12, 1998.

[2] S. M. Karamihas, “Improving the Quality of Inertial Profiler Measurements at Low Speed, During Braking, and through Stops, Report No. FHWA-RC-21-0001,” Federal Highway Administration, Vancouver, WA, 2020.

[3] M. W. Sayers, “The Little Book of Profiling: Basic Information about Measuring and Interpreting Road Profiles,” University of Michigan, Ann Arbor, Transportation Research Institute, 1998.

[4] ASTM E 867, “Standard Terminology Relating to Vehicle-Pavement Systems,” ASTM International, West Conshohocken, PA, 2023.

[5] A. Louhghalam, M. Akbarian and F. J. Ulm, “Roughness-Induced Pavement–Vehicle Interactions: Key Parameters and Impact on Vehicle Fuel Consumption,” *Transportation Research Record,* vol. 2525, no. 1 pp. 62–70, 2015.

[6] M. Sime, G. Bailey, E. Y. Hajj and R. Chkaiban, “Impact of Pavement Roughness on Fuel Consumption for a Range of Vehicle Types,” *Journal of Transportation Engineering, Part B: Pavements,* vol. 147, no. 3, pp. 04021022, 2021.

[7] J. Lee, M. Abdel-Aty and E. Nyame-Baafi, “Investigating the Effects of Pavement Roughness on Freeway Safety Using Data from Five States,” *Transportation Research Record*, vol. 2674, no. 2, pp. 127–134, 2020.

[8] X. Wang, V. V. Gayah and S. I. Guler, “Integration of Pavement Roughness into Safety Performance Functions of Two-Lane Rural Roads in Pennsylvania,” *Journal of Transportation Engineering, Part B: Pavements*, vol. 150, no. 2, pp. 04024016, 2024.

[9] J. Hu, X. Gao, R. Wang and S. Sun, “Research on Comfort and Safety Threshold of Pavement Roughness,” *Transportation Research Record*, vol. 2641, no. 1, pp. 149–155, 2017.

[10] D. K. Merritt, G. K. Chang and J. L. Rutledge, “Best Practices for Achieving and Measuring Pavement Smoothness: A Synthesis of State-of-Practice, Report FHWA/LA.14/550,” Louisiana Transportation Research Center, 2015.

[11] P. A. Serigos, B. A. Visintine, A. L. Simpson, G. R. Rada, and J. L. Groeger, “Quality Management Program for Pavement Condition Data Collected on the National Highway System,” *Transportation Research Record,* vol. 2672, no. 40, pp. 155–165, 2018.

[12] J. Tsai, Z. Wang and R. C. Purcell, “Improving GDOT’s Highway Pavement Preservation, Research Project No. 05-19,” Georgia Department of Transportation, Office of Maintenance, 2010.

[13] J. C. Wambold, L. E. Defrain, R. R. Hegmon, K. Macghee, J. Reichert and E. B. Spangler, “State of the Art of Measurement and Analysis of Road Roughness,” *Transportation Research Record*, vol. 836, pp. 21–29, 1981.

[14] S. Islam, W. G. Buttlar, R. G. Aldunate and W. R. Vavrik, “Measurement of Pavement Roughness Using Android-Based Smartphone Application,” *Transportation Research Record,* vol. 2457, no. 1, pp. 30–38, 2014.

[15] M. A. Bidgoli, A. Golroo, H. S. Nadjar, A. G. Rashidabad and M. R. Ganji, “Road Roughness Measurement Using a Cost-Effective Sensor-Based Monitoring System,” *Automation in Construction*, vol. 104, pp. 140–152, 2019.

[16] A. Nazef, A. Mraz, S. Iyer and B. Choubane, “Semi-Automated Faulting Measurement for Rigid Pavements: Approach with High-Speed IPData,” *Transportation Research Record*, vol. 2094, no. 1, pp. 121–127, 2009.

[17] S. Kouchaki, J. A. Prozzi, A. de Fortier Smit and P. Buddhavarapu, “Assessment of Using Inertial Profilers to Measure Ride Quality on Short Projects,” *Transportation Research Record,* vol. 2641, no. 1, pp. 177–184, 2017.

[18] S. A. Dyer and J. S. Dyer, “Implementation Problems in Inertial Road-Profiling: An Overview,” in *2008 IEEE Instrumentation and Measurement Technology Conference*, pp. 1520–1525, 2008.

[19] R. Guo, Z. Yu and Y. Zhou, "Development and Preliminary Evaluation of a Varying-Speed Road Profiler," *Journal of Testing and Evaluation,* vol. 48, no. 5, pp. 3479–3489, 2020.

[20] S. M. Karamihas, M. E. Gilbert, M. A. Barnes and R. W. Perera, "Measuring, Characterizing, and Reporting Pavement Roughness of Low-Speed and Urban Roads, NCHRP Project No. 10-93," 2019.

[21] DOTD TR 644, "Method of Test for Determining the Longitudinal Profile Roughness of Traveled Surfaces using Automated Profilers," Louisiana Department of Transportation and Development, Baton Rouge, LA, 2017.

[22] AASHTO R 56, "Standard Practice for Certification of Inertial Profiling Systems," American Association of State Highway and Transportation Officials, Washington, D.C., 2014.