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Department of Transportation

Precision of High-Speed Inertial Profilers for Asphalt Pavement Smoothness Measurement

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1 EXECUTIVE SUMMARY

The Florida Department of Transportation conducted a study to assess the precision of the High-Speed Inertial Profilers (HSIP). The objective of this study was to evaluate the precision of the HSIP in terms of IRI and RN for determining the ride quality, or smoothness, of the newly constructed, overlaid, or rehabilitated flexible pavements. Eight HSIPs and four flexible pavement sections were selected for this experiment. The selected sections included two dense graded (DG) and two open graded (OG) surfaces with ride qualities similar to a new pavement. To keep the testing conditions as close to real-world conditions as possible, no pavement paint markings in the wheel paths were provided to assist drivers during the data collection. Profiler agreement in terms of repeatability and reproducibility was rated based on the International Roughness Index (IRI) and Ride Number (RN). This report presents a description of the testing program, the data collection effort, and the subsequent analysis and findings.

Overall, the HSIPs achieved high level of repeatability and reproducibility on both OG and DG pavement sections. The results indicated that regardless of the surface type, the respective IRI and RN results of two properly performed tests using the same HSIP on the same section should not differ by more than 1.8 inch/mile and 0.05, respectively, at a 95 percent confidence level. In addition, the respective IRI and RN results of two properly performed tests using two HSIPs on the same section should not differ by more than 3.4 in/mile and 0.08, respectively, at a 95 percent confidence level.

2 BACKGROUND

The Florida Department of Transportation (FDOT) annually evaluates over 40,000 lane miles of pavement across the state. The work entails evaluating the surface condition of the pavement in terms of roughness, cracking, and rutting, at the network level as well as at the project level. Many techniques have evolved for evaluating smoothness (or roughness), nearly all of which involve measuring the pavement profile defined as vertical deviations of the road surface along the direction of travel.

However, the pavement profile alone does not reveal much useful information unless it is transformed into a roughness index. Although various roughness indices exist, the International Roughness Index (IRI) and Ride Number (RN) are the primary ones used in the U.S. (*1*). The IRI summarizes the pavement roughness in terms of the theoretical response of a vehicle. The underlying IRI model is a series of differential equations that relate the motion of a simulated quarter-car mechanical system to a road profile. The IRI value is then computed as the accumulated suspension motion divided by the distance traveled for a single profile and has units of slope (*2*). The RN, on the other hand, estimates user perception of ride comfort and provides a prediction of a mean panel rating from pavement profile. It is an index without any units and can range from 0.0 to 5.0, where 5.0 represents a perfect ride and 0.0 corresponds to a virtually impassable road (*2*).

Currently, FDOT collects the pavement profiles using High-Speed Inertial Profilers (HSIP) as standardized in ASTM E 950 (*3*) and analyzes pavement roughness using RN, with the near future objective of implementing IRI for project smoothness acceptance on the State Highway System. Since smoothness is one of the most important factors to the roadway users, it is critical that (1) the roughness indices (IRI or RN) be repeatable and reproducible and (2) the variation of these indices that may be expected in practice be quantified.

3 OBJECTIVE AND SCOPE

The objective of this study was to evaluate the precision of the HSIP in terms of both IRI and RN for determining the ride quality, or smoothness, of the newly constructed, overlaid, or rehabilitated flexible pavements. The scope of the study is limited to the precision of the roughness indices (IRI and RN) obtained from the HSIP and will not address the precision of the actual pavement profiles. Therefore, within the context of this report, the term "precision of the HSIP" will be used interchangeably to indicate the precision of the roughness indices and it should not be confused with the precision of pavement profiles in terms of cross-correlation as used in some other literatures.

4 EQUIPMENT

For this study, a total of eight HSIPs were used for collecting the profile data used for calculating the roughness indices. The HSIP consists of full-size passenger van equipped with laser-based profile measuring sensors (Figure 1). Three narrow-footprint single-spot 32 kHz Selcom 5000 laser height sensors were mounted on the front bumper of the host vehicle. Two of the sensors are used to measure elevation profile traces in the left wheel path (LWP) and right wheel path (RWP) and they are spaced approximately 68 inches apart. The third sensor, mounted in the center of the bumper, is used primarily for rut depth measurement. The HSIP is outfitted with accelerometers mounted in tandem with the wheel path laser height sensors to compensate for the vehicle's vertical motion. The host vehicle is also equipped with a Distance Measuring Device (DMI) to measure traveled distance and a data acquisition system for collecting and storing the profile data. Although all of the HSIPs were from a single manufacturer, the HSIPs used for this study still included a variety of vehicle models, age, and most importantly, a range of sampling intervals approximately from 0.7 inch to 1.0 inch, as shown in Table 1.

Figure 1. FDOT High-Speed Inertial Profiler

Table 1. HSIP Vehicle and Sensor Information

HSIP Unit Number	Sampling Interval (inch)	Vehicle				Sensor Age (Years)		
		Year	Make	Model	Years in Service	LWP	Center	RWP
1	1.003	2009	Ford	E-350	3	3	3	3
2	0.874	2011	Ford	E-150	1	2	2	2
3	0.698	2010	Ford	E-150	2	5	2	2
4	0.873	2010	Ford	E-150	2	14	2	14
5	0.895	2008	Ford	E-150	4	4	4	4
6	0.738	2007	Ford	E-150	5	4	4	4
7	0.766	2003	Ford	E-350	8	1	1	1
8	0.815	2004	Ford	E-150	8	1	1	1

5 EXPERIMENTAL PROGRAM AND DATA COLLECTION

A total of four 1-mile long flexible pavement test sections were selected for this study. The selected sections represent typical smooth and medium smooth flexible pavements, and include two dense graded (DG) and two open graded (OG) surfaces. The surface roughness criteria in terms of IRI range used for the selection of the test sections are presented in Table 2. The criteria were imposed to ensure that the test sections represent the typical flexible pavements newly constructed, overlaid, or rehabilitated. The test sections were chosen to be on straight tangents of the roadway and were inspected to ensure they were free of any conditions or roadway features that might bias the results.

Table 2. Test Section Matrix

Surface Type	Surface Smoothness	IRI Range Criteria	Posted Speed Limit (mph)
Open Graded	Medium Smooth	60 – 80	60
	Smooth	< 50	50
Dense Graded	Medium Smooth	90 – 110	50
	Smooth	< 60	50

As shown in Figure 2, each test section included a minimum of 500 ft. lead-in and lead-out distance, and a 1-mile effective pavement length. The start and end limits were paint marked at the edge of the pavement as S1 and E1, respectively. A strip of retro-reflective tape was also placed in the middle of each tested lane at the S1 location to trigger the HSIP's data acquisition system. To keep the testing conditions as close to real-world conditions as possible, no wheel path tracking device was provided to assist drivers during the data collection.

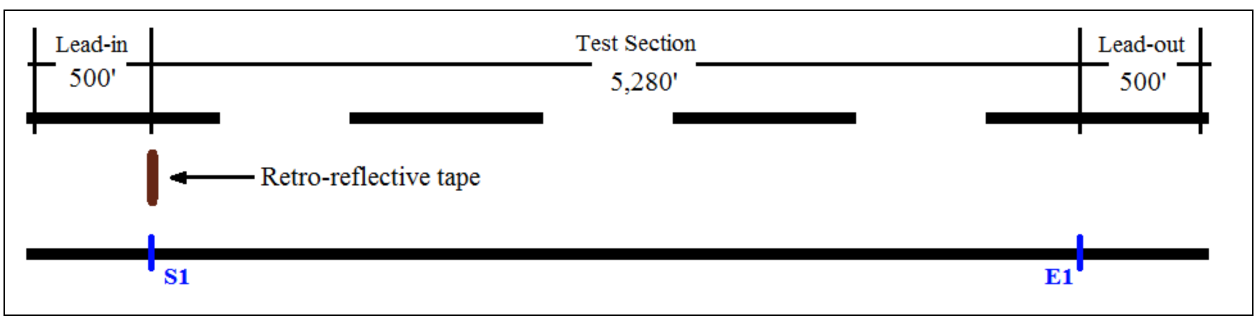


Figure 2. Test Section Layout

Prior to data collection, the DMI of each HSIP was calibrated over a one mile pavement section used for monthly distance calibration. All HSIPs were verified to measure the distance with a ± 0.15% of error or less, as specified in AASHTO R-56 (*4*). The data collection was triggered automatically by the retro-reflective tape placed at the S1 location and was terminated after travelling a distance of 1.0 mile as measured by the DMI. Each HSIP collected data in 10 repeat runs on each 1.0 mile test section at the posted speed, in accordance with ASTM E 950 (*3*).

6 PRECISION ESTIMATES

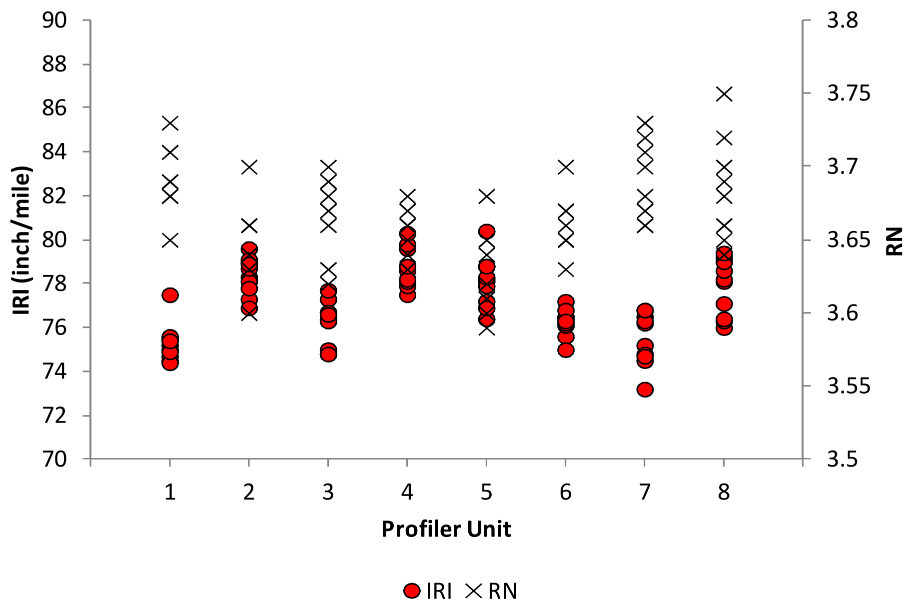
Precision is an estimate of the inherent random error and is one of the most important criteria for evaluating the adequacy of any testing device. ASTM C 670 states that an "acceptable difference between two test measurements" or the "difference two-sigma limit" (d2s), can be selected as an appropriate index of precision. The d2s index for a 95 percent confidence level can be calculated by multiplying the appropriate standard deviation or coefficient of variation (COV) by $2\sqrt{2}$ (*5*). The appropriate standard deviation and COV are those that represent the within and between unit variation from the multiple HSIP measurements. In this study, the above statistics were first obtained for each profiler and for each test section, and then pooled to result in an overall estimate of the within unit (repeatability) and between unit (reproducibility) variation as outlined in ASTM C 802 (*6*). The precision statement was then determined based on the pooled statistics.

7 DATA ANALYSIS

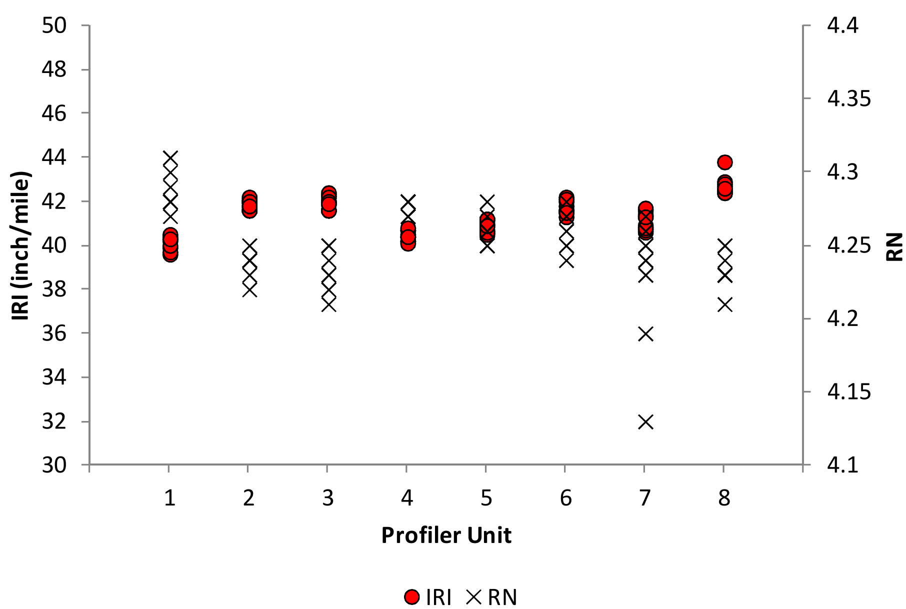
The raw profiles collected using the HSIPs were first processed at an interval of 6 inches using the manufacturer's software. Then, a 9.84-inch moving average filter and a 300-ft wavelength filter were applied to the profiles. Then, the IRI and RN values were computed in accordance with ASTM E 1926 (*7*) and ASTM E 1489 (*8*), respectively. To be consistent with the current FDOT procedure, the IRI and RN were calculated for each wheel path and then averaged. Figures 3 and 4 show the roughness indices calculated from the individual profiles for open and dense graded surfaces, respectively. Table 3 shows the summary of IRI and RN statistics for each HSIP.

ASTM C 802 states that the form of the precision statement should be determined based on the relationship between the average and the standard deviation or COV of the measurements (*6*). Since only two sections with different level of roughness were tested for each surface type, a trend could not be determined between the average and standard deviation. However, the relatively small values of standard deviation and COV shown in Table 3 indicate that the repeatability and reproducibility statements could be drawn independently of the average roughness indices.

Based on the summary statistics presented in Table 3, the standard deviations were pooled in accordance with ASTM C 802 to obtain the within and between unit variability (*6*). The pooled standard deviations were then multiplied by $2\sqrt{2}$ to reveal the necessary d2s statistics for repeatability and reproducibility. Table 4 summarizes the pooled statistics as well as the d2s statistics.

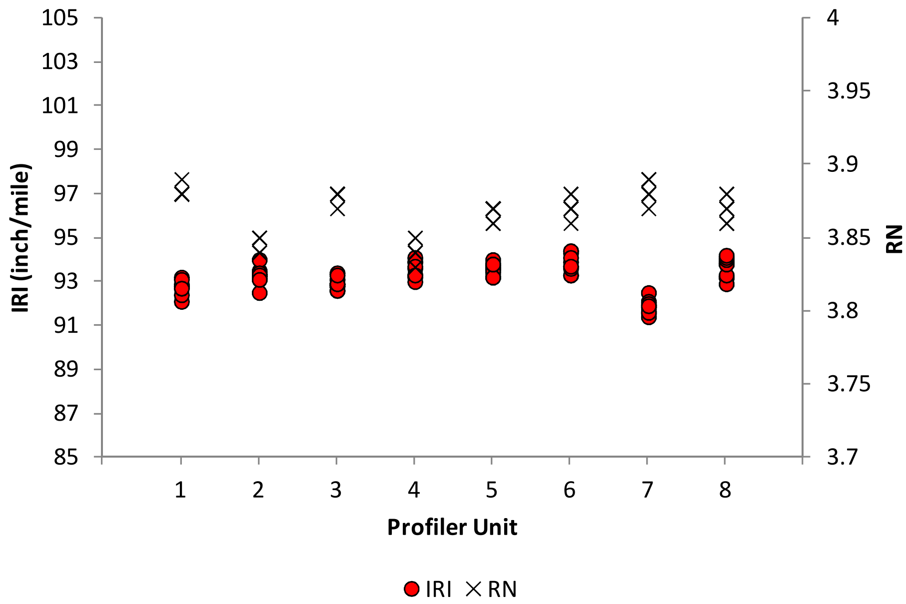


(a) Medium Smooth Test Section

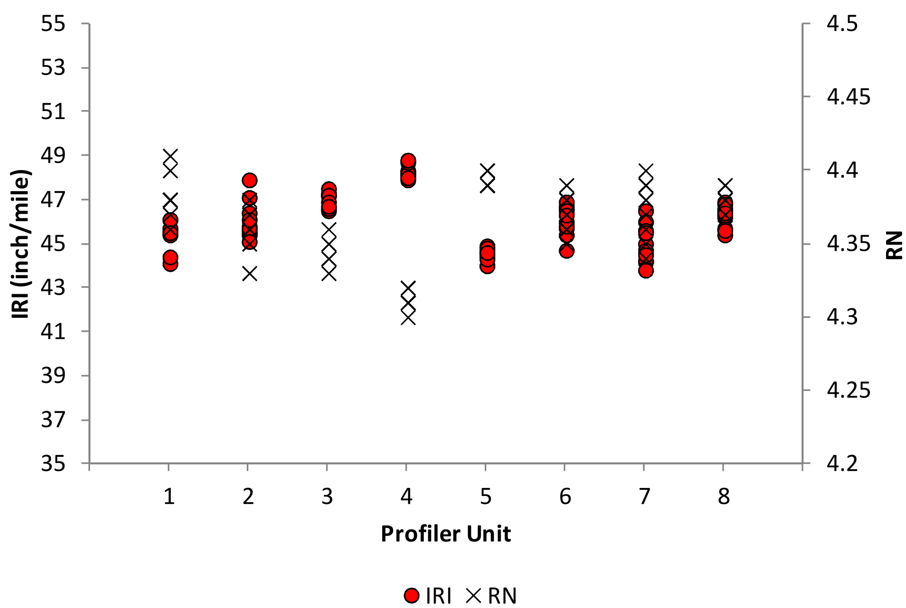


(b) Smooth Test Section

Figure 3. IRI and RN Values from the Individual Profiles of the Open Graded Sections



(a) Medium Smooth Test Section



(b) Smooth Test Section

Figure 4. IRI and RN Values from the Individual Profiles of the Dense Graded Sections

Table 3. Summary Statistics for IRI and RN

Roughness Index	Surface Type	Surface Smoothness	Statistics	HSIP							
				1	2	3	4	5	6	7	8
IRI (inch/mile)	Open Graded	Medium Smooth	Average	75.3	78.4	76.2	78.8	78.1	76.3	75.5	77.8
			Std. Dev	0.9	0.9	1.0	0.9	1.1	0.6	1.2	1.3
			COV (%)	1.2	1.1	1.3	1.1	1.4	0.8	1.6	1.6
		Smooth	Average	40.1	41.9	42.0	40.4	40.9	41.7	41.1	42.7
			Std. Dev	0.3	0.2	0.3	0.2	0.3	0.3	0.4	0.4
			COV (%)	0.8	0.5	0.7	0.6	0.7	0.7	1.0	1.0
	Dense Graded	Medium Smooth	Average	92.8	93.3	92.9	93.5	93.6	93.9	91.9	93.6
			Std. Dev	0.3	0.4	0.3	0.4	0.3	0.4	0.3	0.5
			COV (%)	0.3	0.4	0.3	0.4	0.3	0.4	0.3	0.5
		Smooth	Average	45.4	46.1	47.0	48.3	44.5	46.1	45.0	46.2
			Std. Dev	0.7	0.9	0.3	0.3	0.3	0.7	0.9	0.5
			COV (%)	1.4	1.9	0.7	0.6	0.7	1.5	1.9	1.1
RN	Open Graded	Medium Smooth	Average	3.7	3.6	3.7	3.7	3.6	3.7	3.7	3.7
			Std. Dev	0.02	0.03	0.03	0.02	0.03	0.02	0.03	0.03
			COV (%)	0.58	0.72	0.77	0.47	0.77	0.52	0.77	0.92
		Smooth	Average	4.3	4.2	4.2	4.3	4.3	4.3	4.2	4.2
			Std. Dev	0.01	0.01	0.02	0.01	0.01	0.01	0.04	0.01
			COV (%)	0.33	0.21	0.36	0.12	0.22	0.29	1.00	0.30
	Dense Graded	Medium Smooth	Average	3.9	3.8	3.9	3.8	3.9	3.9	3.9	3.9
			Std. Dev	0.00	0.01	0.00	0.01	0.00	0.01	0.01	0.01
			COV (%)	0.08	0.13	0.08	0.15	0.11	0.15	0.17	0.19
		Smooth	Average	4.4	4.4	4.3	4.3	4.4	4.4	4.4	4.4
			Std. Dev	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01
			COV (%)	0.32	0.31	0.19	0.15	0.12	0.28	0.45	0.19

Table 4. Pooled Statistics for IRI and RN

Roughness Index	Surface Type	Surface Smoothness	Average	Pooled Standard Deviation		Overall Pooled Standard Deviation				d2s limit			
				Within Unit	Between Unit	Within Unit		Between Unit		Within Unit		Between Unit	
IRI (inch/mile)	Open	Medium Smooth	77.0	1.0	1.7	0.7	0.6	1.3	1.2	2.1	1.8	3.8	3.4
		Smooth	41.3	0.3	0.9								
	Dense	Medium Smooth	93.2	0.4	0.7	0.6		1.1		1.4		3.0	
		Smooth	46.1	0.6	1.3								
RN	Open	Medium Smooth	3.7	0.03	0.03	0.02	0.02	0.03	0.03	0.06	0.05	0.09	0.08
		Smooth	4.3	0.02	0.03								
	Dense	Medium Smooth	3.9	0.01	0.02	0.01		0.02		0.03		0.07	
		Smooth	4.4	0.01	0.03								

8 PRECISION STATEMENTS

Based on the d2s statistics calculated above, the following precision statements are drawn from the study.

8.1 Repeatability (Within-Profiler Precision)

On open graded surfaces, the respective IRI and RN results of two properly performed tests using the same HSIP on the same section should not differ by more than 2.1 inch/mile and 0.06, respectively, at a 95 percent confidence level. On dense graded surfaces, the respective IRI and RN results of two properly performed tests using the same HSIP on the same dense graded section should not differ by more than 1.4 inch/mile and 0.03, respectively, at a 95 percent confidence level.

For practical purposes, it can also be concluded that the differences in the repeatability criteria of IRI and RN from two different surfaces (open and dense) are negligible and hence the results can be pooled once again to yield a single repeatability statement, regardless of the surface type. The overall within unit pooled standard deviation was determined to be 0.6 inch/mile and 0.02 for IRI and RN, respectively. Therefore, the respective IRI and RN results of two properly performed tests using the same HSIP on the same section should not differ by more than 1.8 inch/mile and 0.05, respectively, at a 95 percent confidence level.

8.2 Reproducibility (Between-Profiler Precision)

On open graded surfaces, the respective IRI and RN results of two properly performed tests using two HSIPs on the same open graded section should not differ by more than 3.8 inch/mile and 0.09, respectively, at a 95 percent confidence level. On dense graded surfaces, the respective IRI and RN results of two properly performed tests using two HSIPs on the same dense graded section should not differ by more than 3.0 inch/mile and 0.07, respectively, at a 95 percent confidence level.

As it was the case for the repeatability statement and by virtue of the same argument presented above, the reproducibility statements for open and dense graded surfaces can be combined for practicality. The overall between unit pooled standard deviation was determined to be 1.2 inch/mile and 0.03 for IRI and RN, respectively. Therefore, the respective IRI and RN results of two properly performed tests using two HSIPs on the same test section should not differ by more than 3.4 inch/mile and 0.08, respectively, at a 95 percent confidence level.

9 SUMMARY AND CONCLUSIONS

The present study was conducted to assess the level of precision of FDOT HSIPs for evaluating the roughness of flexible pavements in Florida. Four 1-mile test sections were selected to cover typical surface textures for newly constructed, overlaid, or rehabilitated pavements, including two dense graded and two open graded surfaces with roughness levels ranging from smooth to medium-smooth. The collected profile data was used to evaluate repeatability and reproducibility based on IRI and RN indices, and the corresponding precision statements have been developed.

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11 DISCLAIMER

The content of this paper reflects the views of the authors who are solely responsible for the facts and accuracy of the data as well as for the opinions, findings and conclusions presented herein. The contents do not necessarily reflect the official views or policies of FDOT. This paper does not constitute a standard, specification, or regulation. In addition, FDOT assumes no liability for its contents or use thereof.

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