DEMONSTRATION OF LIGHTWEIGHT INERTIAL PROFILERS FOR CONSTRUCTION QUALITY CONTROL: STATUS REPORT

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ABSTRACT

The Federal Highway Administration, in partnership with the Road Profiler Users Group (RPUG), AASHTO, ACPA and NAPA solicited State DOTs for participation in projects to demonstrate the use of lightweight inertial profilers to measure pavement profile for construction quality control and acceptance. The objective of the demonstration projects was to field test and evaluate various lightweight non-contact profile measuring devices which will provide data on, 1) the most appropriate methods for measuring pavement smoothness, and 2) guidelines for smoothness specifications for both contractor quality control and agency acceptance testing. Ten states participated in this project in 1999.

This paper summarizes the results of the individual state evaluation reports received and makes recommendations concerning inertial profiler operation and calibration as well as proposed construction smoothness specifications based upon inertial profilers.

NOMENCLATURE

Repeatability: Ability of the same device to obtain similar test results.
Reproducibility: Ability of different devices to obtain similar test results.

INTRODUCTION

A national highway user survey was conducted to determine the general public satisfaction with the nation's highway system and to identify the public's priorities for highway improvements. This survey was conducted in 1995 under the oversight of the National Quality Initiative (NQI) Steering Committee. The survey indicated that improvements to pavement condition would most significantly increase public satisfaction with the highway system. Pavement smoothness was identified as one of the most important components of improved pavement condition (NQI

Steering Committee, 1996). A follow-up survey, conducted in 2000, indicated that improvements to pavement conditions would result in the greatest pay-off in traveler satisfaction (FHWA 2001).

To improve pavement condition, the Federal Highway Administration (FHWA) implemented a Pavement Smoothness Initiative. This initiative is a joint effort of FHWA, State Departments of Transportation (DOT) and the paving industry. The Pavement Smoothness Initiative represents a comprehensive approach to pavement smoothness.

OVERVIEW OF LIGHTWEIGHT PROFILER DEMONSTRATIONS

One component of the FHWA Pavement Smoothness Initiative is a showcase of state-of-the-art equipment for measuring pavement profile. Reliable and productive pavement profile measuring equipment is critical to implement a smoothness specification for pavement construction.

The most common type of pavement profile measuring equipment in use today is the California-type Profilograph (Baus 1999, Rizzo 2000). The profilograph is typically hand propelled and operates at walking speeds. The limitations of the profilograph include: slow operating speed and use of a profile trace based upon a 7.69 m rolling reference as opposed to a true profile, which is increasingly insensitive to roughness wavelengths longer than 7.69 m.

To address the need for a cost effective profile measuring device that could operate at higher speeds, produce true profiles, and capable of operating on newly constructed pavements, inertial pavement profilers used for pavement management roughness surveys were adapted for use during construction.

These devices, commonly called “lightweight profilers” consist of an accelerometer for relative reference, laser or infrared height sensor, and distance-measuring device are typically mounted on a lightweight vehicle such as a golf cart-type vehicle or bumper-mounted to any vehicle. The base cost of these lightweight profilers typically range from $45,000 to $65,000 (Larsen, 1999).

To demonstrate these lightweight profilers to state and local departments of transportation FHWA solicited for states interested in field-testing, evaluating and documenting the effectiveness of lightweight inertial profilers for construction quality control (FHWA 1998a). A total of ten states (Table 1) requested participation in this FHWA funded demonstration project.

Table 1: Summary of States participating in the lightweight profiler demonstration project.

STATE	DATE OF DEMONSTRATION
Arizona	April, 1999
Massachusetts	May, 1999
Indiana	June, 1999
Minnesota	June, 1999
Washington/Oregon	September, 1999
Connecticut	August, 1999
Arkansas	October, 1999
Virginia	October, 1999
Kansas	October/November, 1999

Scope and Objectives

The objective of the demonstration projects was to field test and evaluate various lightweight non-contact profile measuring devices which will provide data on, 1) the most appropriate methods for measuring pavement smoothness, and 2) guidelines for smoothness specifications for both contractor quality control and agency acceptance testing. The participating states were requested to submit projects that met the following criteria (FHWA, 1998):

- Project should be at least 1.6 km in length.
- Select a 160 m section for testing, should include a horizontal curve.
- Compare at least three lightweight profilers on same segment.
- Conduct at least 5 successive passes to compare repeatability.

To date final reports or draft final reports have been received from six participating states. The state's reports are summarized as follows:

OREGON/WASHINGTON DEMONSTRATION

Background

The Oregon Department of Transportation (ODOT) and Washington State Department of Transportation (WSDOT) cooperated in a joint profiler demonstration. There were test sections in both Oregon and Washington. The ODOT used a Dipstick® device to establish their baseline, while the WSDOT used their high-speed laser profiler to compare with the results from the lightweight profilers. Lightweight profilers participating in the Oregon/Washington demonstration are listed in Table 2 (Remily and Pierce, 2000).

Table 2: Lightweight Profilers participating in the Oregon/Washington State Demonstration

EQUIPMENT	MANUFACTURER
Model 6000 Lightweight Inertial Surface Analyzer LISA	Ames Engineering, Inc.
T6400 Lightweight Profilometer®	K.J. Law Engineers, Inc
Lightweight Profiler	International Cybernetics, Corp. (ICC)
ARRB TR-3LP (bumper mounted)	Trigg Industries International

Five test sections were laid out on Highway OR22, just east of Salem, OR. Two test sections were laid out in Washington on SR14 and SR205 near Vancouver, WA. The test section consisted of five sections with hot-mixed asphalt (HMA) pavement and two sections with PCC pavement. (Remily and Pierce, 2000)

Testing was preformed on all the Oregon test sections on one daywhile the Washington test sections were test the following day. The WSDOT high-speed profiler performed testing approximately one month later and the ODOT Dipstick performed testing approximately 4 months after the lightweight profilers. (Remily and Pierce, 2000)

Each lightweight profiler performed five replicate samples on the test sections. The WSDOT high-speed profiler performed three replicate samples on the test sections. Profile data from the right wheel path was used for comparison. (Remily and Pierce, 2000)

<u>Results</u>

Distance measurement: Only one device, other than the Dipstick, was consistently capable of measuring the length of the test section to within a reasonable tolerance despite the fact the length of each test section was clearly marked at approximately 200 m. Several of the devices were unable to determine the start and stop of the segment within approximately 25% of the measured distance, however there was consistency of measurement. Standard deviation of the distance measurement was typically below 0.5 m. Results are summarized in Table 3 (Remily and Pierce, 2000).

Table 3: Summary of distance measurements

DISTANCE MEASUREMENT (MEAN AND STANDARD DEVIATION, M)														
Section	OR Site 1		OR Site 2		OR Site 3		OR Site 4		OR Site 5		WA Site 1		WA Site 2	
	Dist.	SD	Dist.	SD	Dist.	SD	Dist.	SD	Dist.	SD	Dist.	SD	Dist.	SD
Vendor1	257.4	0.53	207.6	1.53	257.4	3.97	259.8	1.49	260.0	1.42	292.8	2.28	288.4	2.07
Vendor2	251.1	2.12	251.6	1.10	249.8	0.11	249.9	0.04	249.9	0.03	275.0	0.06	276.2	0.13
Vendor3	199.1	0.16	198.8	0.08	198.2	0.00	198.8	0.00	198.8	0.00	274.5	0.25	274.7	0.71
State 1	248.7	0.16	248.8	0.45	249.8	0.11	248.7	0.92	249.2	0.33	273.7	0.11	274.5	0.34
State 2	250.0	3.9	253.2	2.6	251.8	1.1	257.0	5.5	251.4	0.5	275.2	2.2	278.4	3.9
Dipstick	200	NA	200	NA	200	NA	200	NA	200	NA				

Roughness measurement: Results are summarized in Table 4 (Remily and Pierce, 2000).

Table 4: Summary of roughness measurements

DISTANCE MEASUREMENT (MEAN AND STANDARD DEVIATION, M)														
Section	OR Site 1		OR Site 2		OR Site 3		OR Site 4		OR Site 5		WA Site 1		WA Site 2	
	IRI	SD	IRI	SD	IRI	SD	IRI	SD	IRI	SD	IRI	SD	IRI	SD
Vendor1	1.23	0.04	1.49	0.07	1.39	0.03	1.92	0.03	1.06	0.01	1.43	0.03	1.10	0.02
Vendor2	1.65	0.62	1.21	0.03	1.31	0.06	2.42	0.08	1.23	0.53	1.47	0.03	1.14	0.02
Vendor3	1.54	0.13	1.22	0.13	1.62	0.19	2.15	0.08	1.13	0.06	1.97	0.09	1.24	0.03
State 1	1.13	0.03	1.06	0.03	1.28	0.02	1.37	0.09	0.77	0.05	1.30	0.05	0.83	0.03
State 2	1.45	0.17	1.44	0.08	1.77	0.08	1.79	0.06	1.00	0.06	1.80	0.07	0.90	0.03
Dipstick	0.80	NA	1.07	NA	1.03	NA	1.26	NA	0.83	NA	NA	NA	NA	NA

Conclusions

Remily and Pierce concluded that they did not have enough of a database to draw any conclusions concerning accuracy of these lightweight devices. However, it appears the various devices did not demonstrate reproducibility. Much of the reproducibility problems associated with this demonstration may be attributed to the differences in the test length. Many of the devices measured a test section of approximately 250 m while other devices measured 200 m. A possible explanation for the significant differences of the distance measurement was the use of manual versus automatic triggering to start and stop the test.

KANSAS DEMONSTRATION

Background

The Kansas Department of Transportation (KDOT), in cooperation with the Kansas State University, Department of Civil Engineering conducted a lightweight profiler demonstration with three lightweight profilers. These devices were compared to the KDOT South Dakota-type profiler, a K.J. Law T6500 high speed profiler, and a California-type profilograph. Lightweight profilers participating in the Kansas Demonstration are summarized in Table 5 (Boyer, et al. 2001)

Table 5: Lightweight Profilers participating in the Kansas Demonstration

EQUIPMENT	MANUFACTURER
Model 6000 Lightweight Inertial Surface Analyzer LISA	Ames Engineering, Inc.
T6400 Lightweight Profilometer®	K.J. Law Engineers, Inc
Lightweight Profiler	International Cybernetics, Corp. (ICC)
Light Weight Profiler	Surface Systems and Instruments, Inc. (SSI)

Six test sections of approximately 325 m length were laid out in three locations near Topeka, Kansas. The all test sections were PCC pavements constructed between July 2, 1999 and October 23, 1999 (Boyer, et al. 2001).

Testing was conducted at the four test sections on different days in October and November, 1999. The KDOT California Profilograph and the KDOT high-speed profiler performed testing on all test sections (Boyer, et al. 2001).

Each Lightweight profiler performed three replicate profile measurements in the left and right wheel path of both the left and right lanes of these four lane highways. The two high-speed profilers performed five replicate tests, while the KDOT California-type profilograph performed one test in each wheel path.

Results

Not all lightweight profilers participated in profile testing at all three sites. Mean IRI obtained from the lightweight profilers compared favorably with the KDOT South Dakota-type Profiler. Mean Profile Index (PI) values using zero blanking band (0.0_{BB}) from the lightweight profilers compared favorably to the KDOT California-type profilograph. Standard deviations of the test results for the lighweight profilers and the high-speed profilers were not provided in the draft final report. Mean roughness values are summarized in Tables 6 and 7.(Boyer, et al. 2001).

Table 6: Summary of roughness measurements (IRI, m/km)

ROUGHNESS MEASUREMENT, AVERAGE RIGHT AND LEFT WHEEL PATH (IRI, M/KM)						
Section	Vendor 1	Vendor 2	Vendor 3	Vendor 4	Vendor 1 (high Speed)	State Profiler
Valencia, Rt	1.61	1.61	1.60		1.51	1.67
Left lane	1.20	1.16	1.18		1.19	1.26
K-4, Right.	1.53	1.56	1.62		1.47	1.61
Left lane	1.14	1.17	1.17		1.17	1.29
K-99, Right		1.13	1.13			1.07
Left lane		1.13	1.17			1.13
K-185, Rt.		1.09	1.05			1.08
Left lane		1.05	1.09			1.04
McD Crk, Rt		1.92				1.88
Left lane		1.49				1.51
Marshall F. Rt.		1.77				1.72
Left lane		1.67				1.61
Exit318 West, Rt				1.48		1.22
Left lane				1.35		1.21
Exit 318 East, Rt				1.37		1.37
Left lane				1.35		1.23

Table 7: Summary of roughness measurements ($PI_{0.0BB}$, m/km)

ROUGHNESS MEASUREMENT, AVERAGE RIGHT AND LEFT WHEEL PATH ($PI_{0.0BB}$, M/KM)							
Section	Vendor 1	Vendor 2	Vendor 3	Vendor 4	Vendor 1 (high speed)	State Profiler	State Profilograph
Valencia, Rt	0.45	0.47	0.41		0.42	0.56	0.47
Left lane	0.32	0.31	0.30		0.30	0.42	0.33
K-4, Right.	0.39	0.41	0.38		0.31	0.58	0.38
Left lane	0.26	0.28	0.26		0.21	0.43	0.45
K-99, Right		0.37	0.37			0.42	0.33
Left lane		0.36	0.35			0.36	0.36
K-185, Rt.		0.31`	0.30			0.35	0.26
Left lane		0.28	0.26			0.35	0.28
McD Crk, Rt		0.51				0.64	0.37
Left lane		0.36				0.51	0.48
Marshall F. Rt.		0.47				0.60	0.46
Left lane		0.49				0.56	0.46
Exit318 West, Rt				0.40		0.39	0.36
Left lane				0.32		0.37	0.31
Exit 318 East, Rt				0.36		0.42	0.33
Left lane				0.32		0.38	0.30

Conclusions

Boyer reported that based upon a Analysis of Variation (ANOVA) and a Least Square Means (LSMeans) approach, the lightweight profilers produces statistically similar results when reporting as Profile Index. However, the results were slightly higher than PI results of the manual profilograph reduced using ProScan. Boyer further concludes that three of four lightweight profilers produced statistically similar results when reported as IRI. However, significant differences were observed between results obtained from two high-speed profilers and one lightweight profiler.

VIRGINIA DEMONSTRATION

Background

The Virginia Department of Transportation (VDOT) and the Virginia Transportation Research Council (VTRC) cooperatively conducted a study to determine the repeatability (precision) and accuracy (bias) of various lightweight profilers with the objective of making a recommendation to procure a lightweight profiler for conducting construction acceptance testing in Virginia. The VDOT compared the IRI obtained from the lightweight devices as well as the VDOT high-speed profiler to the Dipstick®. The lightweight profilers participating in the Virginia Demonstration are listed in Table 8 (Elfino and McGhee, 2001).

Table 8: Lightweight Profilers participating in the Virginia Demonstration

EQUIPMENT	MANUFACTURER
Model 6000 Lightweight Inertial Surface Analyzer LISA	Ames Engineering, Inc.
T6400 Lightweight Profilometer®	K.J. Law Engineers, Inc
ROSAN	Surfan Engineering & Software

The Virginia demonstration was conducted on four test sections of 153.8 m length. Each device performed five repeat tests on one wheel path. These profiles were then broken into five, 30.8 m test segments. The IRI developed from each device was compared for each of these 100 test segments. To eliminate the error potentially associated with proprietary data reduction or reporting, raw profiles were uploaded to an independent profile analysis program developed by the University of Michigan's Transportation Research Institute (UMTRI) (Elfino and McGhee, 2001).

Results

Elfino and McGhee normalized the results, by dividing the replicate tests for each device by the mean and subtracting 1.0 to cluster the results around 0.0. Using this analysis, a device with a high degree of repeatability would have a narrow, normal distribution curve, while a device with low repeatability would have a broad, normally shaped distribution.

The VTRC high speed profiler demonstrated the "narrowest" distribution, however two lightweight profilers demonstrated more symmetric balance around 0.0. Table 9 lists the standard deviations obtained from the different device and the percent within 2% limit and 5% limits (Elfino and McGhee, 2001).

Table 9. Repeatability Analysis - IRI

INSTRUMENT	NO. OF TESTS	STD. DEV. (%)	WITHIN 2% (COUNT/%)	WITHIN 5% (COUNT/%)
Vendor 1	100	6.58	31	66
Vendor 2	100	6.18	31	67
Vendor 3	100	7.04	28	56
VTRC high-speed	100	4.25	41	75

To determine the accuracy or bias of the lightweight profilers the IRI results obtained were normalized against the reference device, the Dipstick®. A positive bias indicates the device tends to report higher IRI results than the reference, negative bias indicates the device tends to report IRI results lower than the reference. The results of the accuracy analysis as compared to the Dipstick® are shown in Table 10. (Elfino and McGhee, 2001)

Table 10. Accuracy Analysis - IRI

INSTRUMENT	NO. OF TESTS	BIAS (%)	WITHIN 5% (COUNT/%)	WITHIN 25% (COUNT/%)
Vendor 1	100	8.91	31	90
Vendor 2	100	2.10	32	99
Vendor 3.	100	13.65	26	82
VTRC high speed	100	2.20	34	96

<u>Conclusions</u>

Elfino and McGhee concluded that lightweight profilers are more than capable of serving as a tool to support construction quality control, based upon the precision and bias analysis of the IRI results. However, the researchers recommend full-size, high-speed inertial profilers for routine acceptance testing and production ride quality surveys.

CONNECTICUT DEMONSTRATION

<u>Background</u>

The Connecticut Department of Transportation (ConnDOT) conducted a demonstration of lightweight profilers to determine if lightweight profilers could be used in lieu of or in conjunction with the ConnDOT high-speed profiler for quality assurance testing of HMA pavement in Connecticut. The ConnDOT high-speed profiler is an Automatic Road Analyzer (ARAN) manufactured by Roadware Group, Inc. Lightweight profilers participating in the Connecticut demonstration are listed in Table 11. A ConnDOT ARAN device also conducted profile measurement of these test sections for comparison (Larsen, 1999).

Table 11: Lightweight Profilers participating in the Connecticut demonstration

EQUIPMENT	MANUFACTURER
Model 6000 Lightweight Inertial Surface Analyzer LISA	Ames Engineering, Inc.
T6400 Lightweight Profilometer®	K.J. Law Engineers, Inc
Lightweight Profiler	International Cybernetics, Corp. (ICC)
Pathrunner LITE (PSI-35)	Pathways Services, Inc.
ARRB TR-3LP	Trigg Industries International, Inc.(distributor)

Three test sections of 162.5 m were laid out within the limits of one recent HMA paving project on CT Route 9 near Cromwell/Berlin, CT. The left and right wheel paths in the right lane were marked with paint to facilitate repetitive tracking of profilers. (Larsen, 1999).

To establish a baseline the ConnDOT ARAN vehicle performed profile measurement before, during and after the lightweight profilers performed testing. Additionally, the ARRB TR Walking Profilers owned by Massachusetts Highway Department performed profile measurements for comparison purposes. Each device vendor performed testing on different days during the July and August, 1999. (Larsen, 1999).

Each lightweight profiler and the ConnDOT owned high-speed profiler performed ten replicate tests on each wheel path of three test sections. The State profiler performed two profile tests on each test section.

Results

The mean roughness value and standard deviation obtained for each wheel path and the average of the left and right wheel paths are reported in Table 12. As the State profiler did not perform at least three profile measurements, no standard deviation is provided (Larsen, 1999).

Table 12: Summary of IRI data

ROUGHNESS MEASUREMENT, IRI MEAN AND STANDRARD DEVIATIONS (M/KM)												
Equipment	Section 1, Left		Section 1, Right		Section 2, Left		Section 2, Right		Section 3, Left		Section 3, Right	
	IRI	SD	IRI	SD	IRI	SD	IRI	SD	IRI	SD	IRI	SD
State #5a	1.16	0.02	1.88	0.06	1.53	0.04	2.05	0.08	1.09	0.02	1.10	0.06
Vendor #1	1.12	0.02	1.63	0.08	1.41	0.01	1.63	0.04	0.82	0.02	1.03	0.02
Vendor #2	1.36	0.08	1.80	0.07	1.44	0.02	1.78	0.03	0.55	0.02	1.06	0.02
Vendor #3	1.12	0.05	1.63	0.08	1.42	0.08	1.85	0.07	0.98	0.06	1.14	0.08
Vendor #4	1.01	0.05	1.34	0.05	1.39	0.11	1.36	0.05	0.98	0.06	1.12	0.12
State #5b	1.14	0.03	1.85	0.05	1.55	0.03	2.01	0.05	1.09	0.02	1.12	0.02
Vendor #5	1.09	0.12	1.74	0.10	1.51	0.01	1.91	0.08	0.87	0.03	1.10	0.03
State #5c	1.16	0.03	1.80	0.06	1.55	0.03	1.94	0.04	1.09	0.03	1.12	0.04
State profiler	1.23		1.85		1.57		1.91		1.09		1.17	

Conclusions

Larsen concluded that IRI data provided by the vendors showed reasonable repeatability. Larsen hypothesized that significant differences in IRI results between left and right wheel path and the inability to exactly duplicate a line through ten replicate tests, contributed significantly to the observed differences between tests. Larsen also concluded that based upon an analysis of variance (ANOVA) of the IRI reported for each test section, significant differences between devices were obtained. Larsen recommended that ConnDOT continue use of the ConnDOT high-speed profiler for pavement quality assurance during the 2000 construction season.

INDIANA DEMONSTRATION

Background

The Indiana Department of Transportation (INDOT) in cooperation with Purdue University, Department of Civil Engineering, conducted a lightweight profiler demonstration with four lightweight profilers. These devices were compared to the INDOT California-type profilograph, the INDOT high-speed profiler, and a precision rod and level survey of the test sections. Lightweight profilers participating in the Indiana demonstration are summarized in Table 13 (Mondal, et al., 2000)

Table 13: Lightweight Profilers participating in the Indiana demonstration

EQUIPMENT	MANUFACTURER
Model 6000 Lightweight Inertial Surface Analyzer LISA	Ames Engineering, Inc.
T6400 Lightweight Profilometer®	K.J. Law Engineers, Inc
Lightweight Profiler	International Cybernetics, Corp. (ICC)
Pathrunner LITE (PSI-35)	Pathways Services, Inc.

Six test sections of 162.5m length were laid out at various locations around West Lafayette, IN. Three test sections consisted of PCC pavement and three test section consisted of HMA pavement. The types of facilities included Interstate expressway and city streets. Additionally, to simulate a bump or bridge approach some profile tests included wood boards of 10mm and 20mm thickness which the profilers were to pass over during profile data collection (Mondal, et al. 2000)

Testing was conducted on June 24 –25, 1999. All profile measurements were conducted at the same time (Mondal, et al. 2000)

Each lightweight device performed five replicate tests in a cycle with the other vendors at each test section. Testing cycle order was determined by random drawing. At Site #1 the precision rod and level survey was conducted once and the INDOT California-type profilograph performed four replicate tests. At Site #2 a 20mm thick plywood board was placed across the lane to simulate a bump of bridge approach. Seven tests were performed with the board, three tests were performed without the board. At Site #3, a 10mm wood board was placed in the left wheel path to simulate a bump or bridge approach. Five tests were conducted with the board, five without the board. Each vendor analyzed the measured profile in terms of IRI, Profile Index with 5mm blanking band ($PI_{5.0mm\ bb}$) and Profile Index with 0.0mm blanking band ($PI_{0.0mm\ bb}$) (Mondal, et al. 2000).

Results

The mean roughness value (IRI) and standard deviation obtained for the left wheel path for each test section are reported in Table 14. The mean roughness value Profile Index with 0.0mm blanking band as reported by the vendors is summarized in Table 15. The data for the tests performed at Site #2 and Site #3 with the wood boards are summarized in Table 16 (Mondal, et al. 2000).

Table 14: Summary of IRI data

ROUGHNESS MEASUREMENT, IRI MEAN AND STANDRARD DEVIATIONS (M/KM)												
Equipment	Site #1 PCC		Site #2 HMA		Site #3 HMA		Site #4 HMA		Site #5 PCC		Site #6 PCC	
	IRI	SD	IRI	SD	IRI	SD	IRI	SD	IRI	SD	IRI	SD
Vendor #1	1.69	0.08	0.93	0.02	2.08	0.11	1.45	0.06	1.03	0	1.22	0.08
Vendor #2	2.40	0.05	0.62	0.02	2.33	0.02	1.60	0.05	0.70	0.03	0.87	0.02
Vendor #3	2.42	0.02	0.50	0.02	2.61	0.07	1.61	0.02	0.68	0.02	0.90	0.02
Vendor #4	2.45	0.05	0.55	0.08	2.43	0.05	1.69	0.05	0.82	0.11	0.95	0.02
State profiler	2.64	0.03	0.73	0.24	3.19	0.08	1.80	0.11	1.06	0.03	1.15	0.07
Profilograph*	2.97	0.03										
Rod/Level	1.42	NA										

* NOTE: The profilograph trace was digitized and the subsequent profile analyzed using RoadRuf software from UMTRI. The resulting IRI is <u>not</u> a valid result since the profilograph does not produce a "true profile."

Table 15: Summary of $PI_{0.0mm\ bb}$ data

ROUGHNESS MEASUREMENT, $PI_{0.0mm\ bb}$ MEAN AND STANDRARD DEVIATIONS (M/KM)												
Equipment	Site #1 PCC		Site #2 HMA		Site #3 HMA		Site #4 HMA		Site #5 PCC		Site #6 PCC	
	PI	SD	PI	SD	PI	SD	PI	SD	PI	SD	PI	SD
Vendor #1	0.42	0.05	0.08	0.02	0.57	0.02	0.36	0.02	0.20	0.02	0.27	0.03
Vendor #2	1.20	0.02	0.22	0.03	0.89	0.02	0.58	0.03	0.30	0.02	0.36	0.02
Vendor #3	1.47	0.02	0.11	0.00	1.00	0.07	0.62	0.02	0.25	0.02	0.36	0.32
Vendor #4	1.25	0.00	0.13	0.02	0.90	0.02	0.61	0.02	0.07	0.00	0.35	0.03

Table 16: Summary of IRI and PI data for test sections using wood board in profile

ROUGHNESS MEASUREMENT, IRI AND $PI_{0.0mm\ bb}$ MEAN AND STANDRARD DEVIATIONS (M/KM)								
Equipment	Site #2 HMA		Site #2 HMA		Site #3 HMA		Site #3 HMA	
	IRI	SD	PI	SD	IRI	SD	PI	SD
Vendor #1	3.45	0.38	1.07	0.03	2.34	0.08	0.57	0.02
Vendor #2	1.49	0.06	0.53	0.03	2.37	0.05	0.96	0.02
Vendor #3	0.50	0.02	0.17	0.02	2.70	0.14	0.94	0.05
Vendor #4	1.33	0.06	0.43	0.02	2.56	0.03	0.90	0.03
State profiler	1.04	0.31			3.24	0.09		

<u>Conclusions</u>

Mondal concluded that based upon the comparison of the standard deviations the lightweight profilers exhibited good repeatability over a large range of roughness observed at the test sites. Mondal also concluded that the lightweight profilers did not correlate well with the INDOT high-speed profiler. Comparisons of the profiles showed good individual profiler repeatability. Mondal's analysis showed that the lightweight profilers exhibited poor reproducibility or between vendor consistency.

Mondal developed a draft smoothness specification based upon IRI for HMA pavements and PI with 0.0mm blanking band for PCC pavement. However, Mondal recommends that INDOT retain a PI-based smoothness specification, using 0.0mm blanking band, until lightweight profiler technology is further refined.

MASSACHUSETTS DEMONSTRATION

Background

The Massachusetts Highway Department (MHD) in cooperation with Worchester Polytechnic Institute, Department of Civil and Environmental Engineering, conducted a profiler demonstration with ten high speed profilers representing six manufacturers, four lightweight profiler representing three manufacturers, and one manually-operated profiler. These devices were compared to the ARRB Walking profiler (MHD reference device) and a precision rod and level survey. Lightweight profilers participating in the Massachusetts demonstration are summarized in Table 17 (El-Korchi, 2000)

Table 17: Lightweight Profilers participating in the Massachusetts demonstration

EQUIPMENT	MANUFACTURER
Model 6000 Lightweight Inertial Surface Analyzer LISA	Ames Engineering, Inc.
T6400 Lightweight Profilometer® (two devices participated)	K.J. Law Engineers, Inc
Lightweight Profiler	International Cybernetics, Corp. (ICC)

Four test sites with two test sections each were established in the vicinity of Devens, MA. Test sections were between 322 and 383 m in length. The test sections consisted of HMA pavement. Both wheel paths were clearly marked with paint as were the beginning and ending locations. Testing was conducted on May 11-12, 1999(El-Korchi, 2000).

Each lightweight profiler performed ten replicate tests, while the manual devices performed three replicate tests on each test section. A precision rod and level survey was conducted at one test site. To eliminate the error potentially associated with proprietary data reduction or reporting, raw profiles were uploaded to RoadRuf software for consistent analysis (El-Korchi, 2000).

Results

Mean roughness (IRI) and standard deviation obtained for the right wheel path from each lightweight profiler and the reference devices for each test section are reported in Tables 18a and Table 18b.

Table 18a: Summary of roughness measurements

ROUGHNESS MEASUREMENT, IRI MEAN AND STANDRARD DEVIATIONS (M/KM)								
Equipment	Airport #1		Airport#2		Barnum #1		Barnum#2	
	IRI	SD	IRI	SD	IRI	SD	IRI	SD
Vendor #1	2.07	0.07	2.47	0.08	2.54	0.08	2.67	0.09
Vendor #2	1.56	0.02	2.02	0.01	2.21	0.03	2.41	0.02
Vendor#3	1.67	0.02	2.24	0.04	2.27	0.04	2.42	0.03
Vendor#4	1.68	0.01	2.12	0.01	2.27	0.01	2.49	0.01
Walking Profiler	1.66	0.02	1.96	0.02	2.24	0.01	2.42	0.02
Rolling Dipstick								

Table 18b: Summary of roughness measurements

ROUGHNESS MEASUREMENT, IRI MEAN AND STANDRARD DEVIATIONS (M/KM)								
Equipment	McArthur #1		McArthur #2		McPherson #1		McPherson #2	
	IRI	SD	IRI	SD	IRI	SD	IRI	SD
Vendor #1	1.63	0.05	2.15	0.06	2.24	0.07	1.89	0.03
Vendor #2	1.43	0.01	2.03	0.01	2.02	0.01	1.71	0.03
Vendor#3	1.54	0.02	2.12	0.03	2.14	0.03	2.03	0.04
Vendor#4	1.57	0.01	2.27	0.02	2.27	0.01	1.91	0.01
Walking Profiler	1.51	0.03	2.18	0.02	2.05	0.02	1.76	0.01
Rolling Dipstick	1.51	0.01			2.08	0.06		

Inertial profilers typically utilize a high-pass filter to remove the long wavelengths from a profile. Long wavelength should be removed because 1) they do not impact ride quality and 2) they are not accurately determined by inertial profilers. Different manufacturers of lightweight profilers utilize different high-pass filters and cutoff wavelengths. To determine if the type of high-pass filter and cutoff wavelength has an impact on the profile reported or the ride statistic, a convergence study was conducted. The profiles were analyzed using different lead-in distances and overlaid to determine where the profiles converged. The length of lead-in required to obtain similar profiles is summarized in Table 19 (El-Korchi, 2000).

Table 19: Summary of convergence study

Recommended lead-in for different high-pass filters, m		
Filter	Convergence length	Lead-in recommendation
30.4 m (100 ft) high-pass	15.2 m (50 ft)	30.4 m (100 ft)
91.4 m (300 ft)high-pass	45.7m (150 ft)	45.7 m (150 ft)
95.7 m (314 ft) high pass third order butterworth	36.6 m (120 ft)	38.3 m (125 ft)
91.4 m (300 ft) high-pass third order butterworth	91.4 m (300 ft)	91.4 m(300 ft)
61 m (200 ft) high-pass	45.7 m (150 ft)	45.7 m (150 ft)

Conclusions

El-Korchi recommended that when conducting precision (repeatability) analysis using the IRI statistic, the standard deviation of repeat runs should not exceed 0.05m/km (3in/mile). One lightweight profiler was only able to achieve this level of precision on two of eight test sections. Three lightweight profilers were able to achieve this level of precision in eight of eight instances.

El-Korchi found that profiles of test section are influenced by the upstream profile. Therefore, it is necessary to consider the effect of this lead-in profile when determining the precision and accuracy of the resulting profile measurements. Recommended lead-in distances for different high-pass filters are provided.

El-Korchi also recommended that to compare profiles between devices, both profiles should be filtered with the same cutoff wavelength and filter.

CONCLUSIONS

The objectives of the lightweight profiler demonstration were to field test and evaluate various lightweight profilers and provide data on the most appropriate methods for measuring pavement smoothness and to develop guidelines smoothness specifications for contractor quality control and agency acceptance.

The results to date are mixed. However, there does appear to be sufficient data to make general findings and recommendations.

Repeatability

The lightweight profilers evaluated in these six demonstration projects had reasonable repeatability. Using the Massachusetts standard for satisfactory precision (SD <=0.05 m/km) it is determined that in Oregon/Washington project the lightweight profilers met this standard on 10 of 21 test sections. One device was only able to achieve a standard deviation of 0.05m/km or less on one of seven test sections.

In the Connecticut demonstration the lightweight profilers achieved a satisfactory precision on 17 of 30 test sections. One device was only able to achieve satisfactory precision on one of six test sections.

In the Indiana demonstration, lightweight profilers were able to achieve satisfactory precision on 18 of 24 test sections. One device achieved satisfactory precision in three of six cases. This device also reported significantly different IRI measurements than the other lightweight profilers

In Massachusetts, lightweight profilers were able to achieve satisfactory precision on 26 of 32 test sections. However, it should be noted that one device contributed all unsatisfactory tests. This device also reported significantly different IRI measurements for the test sections than the other lightweight profilers or the reference device.

It is not known if the device that achieved poor repeatability results in these demonstrations was the same device or from the same manufacturer.

Reproducibility

None of the researchers concluded that there was sufficient reproducibility (agreement) between the devices tested to recommend a State DOT to proceed with a quality control/quality assurance (QC/QA) type specification for pavement smoothness using a lightweight profiler. With QC/QA specifications, states agencies will accept test results submitted by a contractor subject to verification testing. However, with the satisfactory repeatability demonstrated by most lightweight profilers, a smoothness specification with a State DOT performing the acceptance testing is recommended.

The apparent lack of reproducibility could be related to different profile filtering methods, possibly insufficient lead-in distance to the test section, and possibly length of sample section. These conclusions are supported by the relatively better results reported for the Massachusetts demonstration project where effect of lead-in was evaluated and longer test sections were used. In Massachusetts, all profiles were analyzed using a common profile analysis software to minimize the impact of proprietary filtering processes. Reproducibility using these lightweight profilers should be achieved once effective equipment calibration, verification, operator certification programs, and standardized testing and analysis protocols are developed and implemented.

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