Assessment of Profiler Performance for Construction Quality Control: Phase I

FINAL REPORT

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16. Abstract

This report describes a profiler verification experiment that tested the performance of inertial profilers on four pavement sections. The repeatability and reproducibility of profile and the International Roughness Index (IRI) measured by lightweight inertial profilers for construction quality control was of particular interest. The study included six lightweight inertial profilers, three high-speed inertial profilers, two walking-speed profilers, and a rod and level survey. The experiment demonstrated that repeatability of inertial profilers was compromised on the new concrete site with transverse tining, and was inadequate on the new concrete site with longitudinal tining. The experiment also demonstrated that inertial profilers are not able to reproduce profiles sufficiently when the position and severity of localized rough features is of interest. Poor performance on the concrete sites with coarse texture is attributed to the fact that the depth of tining and joints on new concrete are of the same scale as the height of longer wavelength features that are relevant to vehicle response.

Two potential solutions to these problems are possible. First, the sensor footprint of profilers could be altered to better represent the behavior of vehicle tires. This could improve the relevance of profile measurements over joints, transverse tining, and longitudinal tining. Second, a "tire bridging filter" could be applied to measured profiles. This filter should be customized to ignore narrow downward features that do not affect vehicle ride vibrations. This could improve the reproducibility and relevance of profile measurement over joints and transverse tining, but not over longitudinal tining.

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TABLE OF CONTENTS

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ACRONYMS

ACPA — American Concrete Pavement Association
ARRB — Australian Road Research Board
DOT — Department of Transportation
FHWA — Federal Highway Administration
HSP — High-Speed Profiler
ICC — International Cybernetics Corporation
IRI — International Roughness Index
JCS — James Cox and Sons
LISA — LIghtweight road Surface Analyzer
LWP — Lightweight Profiler
MCPA — Michigan Concrete Pavement Association
MDOT — Michigan Department of Transportation
RN — Ride Number
SSI — Surface Systems Instruments
WP — Walking Profiler

SUMMARY

This report documents a profiler verification experiment that tested the performance of inertial profilers on four pavement sections. The repeatability and reproducibility of lightweight profilers on new concrete with coarse texture was of particular interest. The study included six lightweight inertial profilers, three high-speed inertial profilers, two walking-speed profilers, a rod and level survey, and one profilograph. Tests were performed on four sites: (1) moderately rough asphalt of typical surface texture, (2) new longitudinally tined concrete, (3) moderately rough broom-finished concrete, and (4) new transversely tined concrete. Both new concrete sections were selected to assess the sufficiency of existing lightweight profilers on the market for use in construction quality control.

This study demonstrated that repeatability of high-speed and lightweight inertial profilers was compromised on the new concrete site with transverse tining, and was inadequate on the new concrete site with longitudinal tining. This study also demonstrated that high-speed and lightweight profilers are not able to reproduce profiles sufficiently when the spatial distribution of roughness is of interest. In other words, profilers did not agree on the position and severity of localized rough features. The level of reproducibility between inertial profilers demonstrated on smooth concrete with coarse texture needs improvement if they are to find acceptance for use in construction quality control and quality assurance. Poor reproducibility and reduced repeatability on the new concrete sites with coarse texture is attributed to the fact that the depth of tining and joints on new concrete are of the same scale as the height of longer wavelength features that are relevant to vehicle vibration response. These issues in profile measurement are likely to adversely affect the measurement of any profile-based index, such as the IRI and simulated profilograph index, and should be addressed so that profile measurements can better represent the experience of the traveling public.

Two potential solutions to these problems are possible. First, the sensor footprint of inertial profilers could be altered to better represent the enveloping and bridging behavior of vehicle tires. This has the potential to improve the relevance of profile measurements over joints, transverse tining, and longitudinal tining. Second, a “tire bridging filter” could be used in conjunction with a very small sensor footprint. If this filter is customized to ignore narrow downward features (e.g. cracks, grooves) that do not affect vehicle ride vibrations it could replace the moving average in the IRI and RN calculation procedures. This could improve the reproducibility and relevance of profile measurement over joints and transverse tining, but not over longitudinal tining.

Despite the current performance of profilers on new concrete, they hold great promise for efficient and meaningful construction quality control. To this end, the concrete pavement industry is committed to a second experiment in partnership with the profiler manufacturing industry. In this experiment, profiler vendors would be invited to demonstrate improvements to profiler technology that render them adequate for measurement of ride quality on new jointed concrete with coarse texture. Any profiler model that is able to demonstrate sufficient repeatability and can reproduce profile features that are relevant to vehicle response will be qualified by the ACPA for use on concrete pavement construction quality control.

PURPOSE

The main purpose of this project is to motivate improvement in the repeatability, reproducibility, and accuracy of lightweight profilers on new concrete pavement. The project will be executed in two phases. The first phase, already complete, consisted of a limited profiler verification experiment. This experiment was performed to assess the repeatability and reproducibility of existing lightweight inertial profilers when they are operated on tined concrete. The experiment verified suspected problems caused by coarse texture. The experiment also helped to establish the methods that will be used in a more formal experiment planned for the second phase.

This report is the main product of the first phase. It will be used to provide feedback to profiler manufacturers on overall profiler performance and the degradation in profiler performance on tined concrete. Performance on new concrete is of particular interest because existing test procedures used to certify lightweight profilers rarely expose them to smooth pavement with coarse surface texture. The experiment in this phase showed that a profiler that achieves certified status on an asphalt pavement of dense-graded surface texture is not at all guaranteed to perform adequately on tined concrete.

The second phase will be a formal profiler certification experiment. Profilers that perform sufficiently well in the second phase will be “qualified” by the ACPA to its members for evaluating the smoothness of newly constructed concrete pavements. Manufacturers of lightweight profilers will be provided with this report and invited to participate in the second experiment. Hopefully, the results in this report and the prospect of access to the concrete pavement smoothness market will motivate necessary enhancements in existing lightweight profilers. The testing and data processing procedures for the second experiment will be defined and communicated to potential participants well in advance. This way, manufacturers seeking qualification can verify their performance before the official tests. Potential participants will also have the opportunity to review the procedures and provide feedback to the experiment organizers. The formal testing will commence when some manufacturers of lightweight profilers are prepared to demonstrate technological improvements that show promise for improved accuracy on coarse-textured concrete.

CONCEPTS

This section discusses the concepts of profiler accuracy, reproducibility, and repeatability, and the motivation for studying them.

Repeatability

Profiler repeatability is a rating of how well two measurements of the same segment of road by the same profiler under the same conditions can be expected to agree with each other. Checking the repeatability of a profiler is a simple matter of making several measurements with it on the same segment of road within a reasonable length of time. The level of agreement between the measurements is the repeatability. Testing repeatability is a good way to test the capability of a profiler, since a profiler’s precision (compared to the true profile) can never be any better than its repeatability. On the other hand, good repeatability does not guarantee accurate readings. Several profiler comparisons have been done in which very repeatable profilers were just reporting the same systematic errors in every measurement. (*1-5*) Nevertheless, for fairly accurate profilers, it is very useful to know how repeatable they are, so the index value that results from a single measurement is never interpreted as having greater precision than is justified by the device.

Repeatability is usually thought of as a property of a profiler alone, but it is actually a property of the profiler, the operating procedure, and the measurement environment together. For example, variations in lateral tracking of a profiler interact with transverse variations in pavement surface shape to degrade a profiler's ability to obtain repeatable measurements. This must be carefully acknowledged when only a single test site is used to rate profiler repeatability.

Reproducibility

Profiler reproducibility is a rating of how well two profiling devices are able to measure the same thing. Of course, if they are both measuring accurately they are also reproducible. If two profilers are compared and do not agree, the measurement was not reproduced, and at least one of them is incorrect. The consequence of poor reproducibility is that measurements from various devices do not mean the same thing and are not really using the same scale, even if the units are the same.

In this project, reproducibility between lightweight and high-speed profilers is of interest, as is reproducibility between lightweight profilers of various makes, and between lightweight profilers of the same make.

High-speed versus lightweight: Lightweight inertial profilers and high-speed inertial profilers work on the same set of principles, and measurements from them are supposed to have the same meaning. As such, they should agree with each other. This is very important for several reasons: (1) high-speed profilers are often used to audit measurements made by lightweight profilers for smoothness specifications, (2) high-speed profilers may be used for measurements of smoothness of pavement that is under warrantee, and (3) studies of roughness progression from cradle to grave often rely on measurements by both types of inertial profiler.

Different makes: Lightweight profilers of various makes are supposed to reproduce the same measurement under the same conditions. Since profilers made by different vendors use different components, software, and are assembled differently, they have not always demonstrated reproducibility.

Different profilers of the same make: Two profilers of the same make are more likely to agree with each other than two profilers of diverse make, since they are usually built with the same components and software. On the other hand, the performance of one or both of the devices may change over time if the system is not stable, or is not in good repair.

A key aspect of testing reproducibility is the operator. Profilers that are operated by their manufacturers should be thought of as representing their maximum capability. A profiler manufacturer is likely to employ an expert operator that will recognize measurement problems readily, and will avoid adverse measurement conditions and use a device that is in good repair. Profilers that are operated by common users will more closely represent their likely field performance, even though the technicians will be aware that they are involved in an experiment. In light of this, an experiment that addresses reproducibility should consider who is operating the profilers, and field capability (using "real" operators) should be treated as a different type of performance rating than the maximum potential of the device (using expert operators).

Accuracy

Profiler accuracy is a rating of how closely a profiling device measures the true profile and the resulting true index value. Accuracy can only be judged if a profile measurement is considered to be correct. It is then called a "reference measurement". The accuracy of a measurement under study is then judged by its ability to reproduce the reference.

Reference Profile Measurement

In the past, the most common method of obtaining a reference profile measurement is to perform a rod and level survey. Since rod and level measurements are very time consuming, they are rarely performed at a sufficiently short sample interval to serve as a complete reference measurement. The large rigid footprint under the rod also complicates the interpretation of the resulting profile. Each reading may be the true elevation of some point under the footprint of the rod, but the collective set of readings may not make up a profile with direct relevance to the end use.

Devices such as the DipStick, the ARRB Walking Profiler, the SurPro 1000, and the RoadPro have been used in place of a rod and level survey to speed up the process of getting a reference measurement. Like a rod and level survey, these devices may all produce output with a consistent and well-defined relationship to the true profile. They may not, on the other hand, reproduce each other's measurements. This is because they each have a unique way of sensing the pavement surface. The merits of each device's "footprint" depends on the end use of the profile. For example, an index that is meant to predict vehicle response may require that narrow, concave profile features are ignored if a tire would bridge over them. In contrast, measurements intended to identify slab shapes in jointed concrete pavement are much more useful in they include dips at the contraction joints.

Until the end use of a profile measurement is defined, a proper reference measurement can not be selected as a benchmark for profile accuracy. A reference device and measurement procedure can only be endorsed if it has a direct link to the intended interpretation of the output profile. Short of that, the "reference" devices listed above are simply alternative ways of getting a profile, and comparison to them is only a measure of reproducibility, rather than accuracy.

THE EXPERIMENT

The main portion of this experiment took place in July 9-10, 2002. It included 4 sites that represented a diverse range of surface texture, and thirteen devices. Of the thirteen devices eleven were classified as profilers, including six lightweight inertial profilers, three high-speed profilers, and two walking-speed profilers. A reference profile was obtained via rod and level survey. A profilograph also participated. A collection of photos of the devices and test pavements are provided in Appendix D.

Devices

Overall, four broad classes of profiler participated in this experiment: (1) static, (2) walking-speed, (3) lightweight inertial, and (4) high-speed inertial. The experiment sought to test the performance of lightweight profilers. Thus, it included at least one lightweight profiler from each manufacturer. No effort was made to include a comprehensive set of high-speed or walking-speed devices, but profiler owners who knew about the experiment offered to include some of them for various reasons. The Michigan DOT high-speed profiler was specifically invited to the experiment because plans have been discussed for using it to audit contractor's measurements, and it may be used in the future for enforcement of warrantees.

Table 1 lists the devices by class and the organization that operated them. Many of the profilers did not have a model number, because the name of the manufacturer is enough to identify them. The table also lists a handle for each device used in summary tables throughout this report.

Table 1. Devices that participated in the study.

Device		Operated By:	Handle
Static			
0	Rod and Level	CJ Engineering & Const. Services	Rod and Level
Walking Speed			
1	SurPro 1000	International Cybernetics Corp.	SurPro 1000
2	ARRB Walking Profiler	Pennsylvania DOT	ARRB WP
Lightweight Inertial			
3	International Cybernetics Corp.	Pennsylvania DOT	ICC LWP
4	Dynatest/KJL6400	Dynatest	Dyn/KJL 6400
5	Surface Systems Instruments	Surface Systems Instruments	SSI, LWP
6	Lightweight Inertial Surface Analyzer (LISA) Model 6000	Ames Engineering	LISA, Ames
7	LISA	Tony Angelo Cement Construction	LISA, Angelo
8	LISA	John Carlo Construction	LISA, Carlo
High-Speed Inertial			
9	Michigan DOT	Michigan DOT	MDOT, HSP
10	Dynatest RSP5051	Dynatest	Dynatest 5051
11	Surface Systems Instruments	Surface Systems Instruments	SSI, HSP
Profilograph			
12	James Cox and Sons	John Carlo Construction	JCS, PG

In addition to the profilers, one profilograph participated in the study. Profilographs fall into an entirely different category of instrument, because they do not purport to measure the road surface shape without distortion. (*6*) The profilograph participated to demonstrate the systematic difference between the way its measuring wheel senses the pavement and the narrow footprint used in some inertial profilers. This is of particular interest when measurements from a profiler are entered into a profilograph simulation.

Rod and level surveys were performed on three of the four sites within two weeks of the rest of the measurements. These were done using a Zeiss Digital Level, model number DINI22. The level is calibrated to read a rod that was marked with a bar code. It was last calibrated on June 3, 2002. Each survey reading was recorded with the following procedure:

- A technician placed the rod in the proper position along a steel tape, which was fixed adjacent to the wheel path.
- The technician adjusted the angle of the rod until it is completely upright. When a bubble indicator was satisfactorily centered, the operator holded the rod in place and looked forward toward the level.
- When the level operator saw that the rod operator was looking forward, a button was pushed to instigate elevation readings.
- The digital level took 10 readings. If the standard deviation of the readings was less than 0.004 inches (1/10 mm), the average elevation, standard deviation, and horizontal distance was recorded. If the standard deviation was too high, the level operator asked for a new set of readings. Horizontal distance was recorded to the nearest 0.4 inches (1 cm).
- When a proper reading was recorded, the level operator waved the rod operator to place the rod in the next location.

The vast majority of readings were recorded in the first try. A few of them were repeated because they violated the limit on standard deviation. One of the causes of excessively high standard deviation for the 10 readings was a change in ambient light. This occurred only on site 2 (described below) because of passing trucks to the west late in the day. Another cause was aggressive convection currents. The surveys were timed to avoid these problems when it was possible. In rare cases, the angle of attack of the level needed adjustment, because the rod had moved (laterally) out of its range.

Whenever it was possible, the time of day of the survey incorporated the time the profilers were used. Unfortunately, the surveys usually took about 8 hours per site.

Test Sites

The testing covered four pavement sections in southeastern Michigan. The sites were primarily selected to cover a diverse range of surface texture, and included a section of asphalt with typical surface texture, longitudinally-tined concrete, broom-finished concrete, and transversely-tined concrete. The specific locations were, in part, sites of opportunity because they all had to be available with some form of existing traffic control over the same few days.

Site 1 was on an access road at the Lansing Airport. It was included in the experiment for several reasons. First, the Michigan DOT was using it as a profiler verification site, and had taken a reference profile measurement with a rod and level in the summer of 2000. The site was well marked with a guide stripe near the right wheel path and highly visible marks every 100 feet over 1000 feet of pavement. Second, the site was very sparsely traveled, such that the only traffic that appeared during the experiment was one airport security vehicle. (The pavement started near an unused building, and terminated at a guard rail.) Third, it was an asphalt concrete site with typical fine aggregate at the surface. The site was moderately rough (~150 in/mi). A smooth site would have been more ideal, but this site offered a safe measurement environment and good contrast to the coarse-textured sites.

The wheel path of interest selected for this site was 4 to 12 inches to the right of the guide stripe. This position was selected to avoid the influence on the measurement of the stripe, and of some pk nails placed far to the right as survey reference marks. The portion of the site used for this experiment started at the "300 foot" marker, end extended for 528 feet afterward.

Site 2 was on a new longitudinally-tined jointed reinforced concrete pavement. The tines were 3/4 inch apart and ranged in depth from 1/8 to 3/16 inch. The slabs were 27 feet long throughout the site, except for the slabs surrounding an expansion joint 419 feet and 8 inches from the site starting point. This joint was about 1 5/8 inches wide. The contraction joints were, on average, about 1/2 inch wide. Although the site was broom cleaned, the joints were filled with slurry so that the reservoir was rarely more than 1/4 inch deep. The site appeared in the far right lane on a new construction job along I-75 northbound, just south of M-10 near Bay City. The site was 528 feet long, starting at a joint at station 91+292. The wheel path of interest was on the right side, 107 inches from the left slab edge. The majority of devices reported IRI values near 90 in/mi on this site.

Site 3 was an access road inside the General Motors Proving Grounds in Milford. It was jointed concrete pavement with a broom finish and extruded material (tar) at some of the joints. The joints were spaced about 23.5 feet apart. The wheel path of interest was on the right side, 107 inches from the left slab edge. This site was chosen because it was concrete, but provided a unique surface texture to the two concrete highway pavements. It was also an ideal place to test because it was completely isolated from traffic. The site was moderately rough, and had an IRI value of about 135 in/mi.

Site 4 was on a new jointed plain concrete pavement with transverse tining of slightly variable spacing. The site appeared in the right lane of the return on the M-5 extension at Haggerty Road in Novi. It was 528 feet long, and terminated at station 265+57. The wheel path of interest was on the right side, 107 inches from the left slab edge. The slabs were 15 feet long throughout the site. Although the site was broom cleaned, the joints were filled with slurry so that the reservoir was rarely more than 1/4 inch deep. The site was smooth, and had an IRI value of about 60 in/mi.

Procedures

Only data from the right wheel path were requested. Participants were required to provide data before leaving each site. The start and end of each site was marked using a stake or cone. Obvious markings were already present on the surface of site 1. On sites 2 and 4, the starting and ending locations were also marked with orange paint. In addition, the right wheel path was marked with orange paint at every joint. No strict procedures were required for profiler operation. Ample lead-in distance was available at every site.

Participants were encouraged to use their recommended practices. Of course, the ratings assigned to repeatability and reproducibility in this report are assigned not only to the device, but to the combination of device, measurement conditions, and measurement procedures. Operators chose their measurement speed. Some operators elected to use devices to help them maintain the proper lateral positioning within a lane. Some operators also elected to use automated triggering to initiate and terminate data collection.[1] Participants were also allowed to calibrate their distance measurement instruments on any of the sites.

All of the measurements except for the rod and level surveys were performed over two days, as listed in table 2. Sites 2 and 4 were measured in the afternoon to avoid changes in roughness caused by temperature gradients that may have occurred as the sun warmed the pavement in the morning. No such changes were observed in the data. The ARRB Walking Profiler measured each site only once, because the measurement took over 30 minutes. The Walking Profiler measured the site by moving along the wheel path in the direction of travel, then returning along the same path for loop closure.[2] The SurPro 1000, the Cox Profilograph, and all of the inertial profilers were asked to measure the site at least three times.

Table 2. Timing of site coverage.

Site	Surface Type	Date	Timing
1	moderately rough asphalt, tight mix	July 9	Morning
2	new concrete, longitudinal tining	July 9	Afternoon
3	moderately rough concrete, broom finished	July 10	Morning
4	new concrete, transverse tining	July 10	Afternoon

Site 1 was visited on the morning of July 9th. Rain delayed the start of the experiment that morning. Some of the inertial profiler operators preferred to wait until the pavement surface was completely dry, so walking-speed devices and the profilograph measured the site while it was drying. Afterward, the high-speed and lightweight inertial profilers measured the site in no particular order.

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[1] None of the results depended on accurate representation of the starting location. All measurements were shifted to cover the same stretch of road, but the data were NOT corrected for distance measurement calibration errors.

[2] "Loop closure" is a procedure in which the measurement of grade is verified by making sure the change in elevation is recovered during the return measurement.

Site 2 was visited in the afternoon on July 9th. It was a 90-minute drive from the location of site 1. To save time, a small group of operators, their devices, and a small crew of experiment organizers moved on to site 2 before all of the rest of the devices had finished measuring site 1. A lightweight profiler measured the site first, followed by all of the slow-speed devices. Afterward, the rest of the lightweight profilers covered the site, followed by all of the high-speed profilers. One of the lightweight profilers was not able to obtain measurements on the first visit, and returned in the evening of July 10th.

Site 3 was visited on the morning of July 10th. All of the devices, their operators, their transport vehicles, and the experiment organizers passed through the security gate at the General Motors Proving Grounds as a group. The gate was crossed on the way in at about 8 AM and on the way out at about 12:30 PM. The site offered excellent traffic control and a convenient return lane. The devices that were not designed for use in mixed traffic were escorted in small groups to the site from a staging area. First, the lightweight profilers, the profilograph, and the SurPro measured the site one by one. Afterward, the three high-speed profilers measured the site in a group using the return lane to form a loop. The Walking Profiler measured the site last while the rest of the participants lined up to return to the security gate.

Site 4 was visited on the afternoon of July 10th. Lightweight and high-speed profilers measured the site as they arrived. Walking-speed devices were held off until the end. Appendix A provides a detailed listing of the timing of all of the measurements.

ANALYSIS

The primary concern of this project was comparison of profiles, rather than summary index values. Comparison of the summary index values provides little information about the source of profile measurement problems. When only a small number of repeat measurements are available on a small number of sites, index values may agree because of compensating error. Thus, statistical comparison of index values may not properly represent the variation that could be expected in a broader experiment or in practice. In contrast, direct comparison of profiles has the potential to reveal measurement problems using only a few repeat runs. Profile comparison can also expose cases in which index values agreed due to compensating error.

All of the profiles collected for this experiment were converted to a common file format. Although the segment starting and ending points were marked, the submitted profiles were not aligned perfectly. The longitudinal offsets between them were eliminated using an automated synchronization procedure. In this process, two profilers are pssed through the same filters, then the offset between them is adjusted until the correlation between them is highest. The procedure is described in Appendix B.

A few of the measurements excluded a short distance at the start or the end of the segment. To account for this only 500 feet of each site was considered in the analysis, excluding 14 feet at each end. On sites 1, 2, and 4, the Walking Profiler measurement was synchronized to the rod and level measurement first, then all of the other measurements were synchronized to it. Rod and level measurements were not performed on site 3, so all of the measurements were synchronized to the Walking Profiler.

Index Comparison

Too few measurements were made on too few sites to provide a useful statistical comparison of index values. Nevertheless, major variations in index values may provide a crude quantification of the kind of variations that may be expected in practice. Be careful when interpreting these results, however, since the pervasiveness of anecdotes has slowed technological improvement in the field of profile measurement and interpretation.

Tables 3 through 6 list the IRI values of all of the measurements included in this study. Measurements from the SSI LWP on site 1 were excluded at the request of the operator, because some filter settings were not correct.

Table 3. IRI Values, Site 1.

Device	**IRI (in/mi)**			
	Repeat 1	Repeat 2	Repeat 3	Ave
Rod and Level	165.2	—	—	165.2
SurPro1000	154.2	157.4	151.9	154.5
ARRB WP	149.9	—	—	149.9
LISA, Angelo	147.1	146.2	146.8	146.7
ICC LWP	146.9	147.9	152.4	149.0
LISA, Carlo	146.2	146.8	147.0	146.7
Dyn/KJL 6400	137.5	138.5	138.6	138.2
LISA, Ames	143.6	144.0	145.2	144.3
MDOT, HSP	147.0	144.3	148.6	146.7
Dynatest 5051	152.4	152.1	152.1	152.2
SSI, HSP	153.1	152.6	155.0	153.6

Table 4. IRI Values, Site 2.

Device	**IRI (in/mi)**			
	Repeat 1	Repeat 2	Repeat 3	Ave
Rod and Level	89.6	—	—	89.6
SurPro1000	96.0	99.8	100.0	98.6
ARRB WP	85.5	—	—	85.5
LISA, Angelo	82.5	82.6	83.0	82.7
ICC LWP	91.9	91.2	84.8	89.3
LISA, Carlo	95.5	86.0	86.0	89.2
Dyn/KJL 6400	78.4	83.5	82.9	81.6
LISA, Ames	87.4	91.8	91.6	90.2
SSI, LWP	92.9	84.6	89.2	88.9
MDOT, HSP	78.5	81.9	81.7	80.7
Dynatest 5051	89.2	89.0	87.6	88.6
SSI, HSP	82.4	93.7	84.5	86.8

The highest IRI value on sites 1 and 4 were measured by the rod and level. Several spikes with a duration of one to three samples appeared in the rod and level measurement of site 1 that did not appear in measurements from the ARRB WP and the SurPro 1000. A few of the spikes were obviously bad readings, but others could not be explained. Some of them contributed significantly to the IRI. On site 4, the rod and level simply had much higher short wavelength content than the ARRB WP and SurPro 1000. The SurPro 1000 always produced a higher IRI values than the ARRB WP, especially on site 2. This was because the ARRB WP was able to average out more of the short-wavelength content introduced by the longitudinal tining.

Table 5. IRI Values, Site 3.

Device	**IRI (in/mi)**			
	Repeat 1	Repeat 2	Repeat 3	Ave
SurPro 1000	138.0	138.9	140.8	139.2
ARRB WP	131.3	—	—	131.3
LISA, Angelo	134.7	131.9	135.0	133.9
ICC LWP	133.0	135.3	135.7	134.7
LISA, Carlo	135.9	137.3	136.0	136.4
Dyn/KJL 6400	133.1	132.6	132.2	132.6
LISA, Ames	136.6	—	137.2	136.9
SSI, LWP	119.2	120.2	131.2	123.6
MDOT, HSP	131.3	—	127.8	129.5
Dynatest 5051	134.5	131.0	132.9	132.8
SSI, HSP	134.0	133.0	134.1	133.7

Table 6. IRI Values, Site 4.

Device	**IRI (in/mi)**			
	Repeat 1	Repeat 2	Repeat 3	Ave
Rod and Level	76.3	—	—	76.3
SurPro1000	69.1	68.1	68.0	68.4
ARRB WP	65.6	—	—	65.6
LISA, Angelo	57.9	57.2	59.5	58.2
ICC LWP	59.7	58.9	56.4	58.3
LISA, Carlo	60.0	63.4	62.3	61.9
Dyn/KJL 6400	62.1	59.0	61.8	61.0
LISA, Ames	57.2	58.5	58.0	57.9
SSI, LWP	65.8	58.5	63.4	62.6
MDOT, HSP	57.6	60.9	58.7	59.1
Dynatest 5051	59.6	59.6	59.2	59.4
SSI, HSP	68.0	64.2	70.9	67.7

The overall group of inertial profilers did not reproduce each other's IRI measurements as well as might be expected. On a given site the total group of high-speed and lightweight profilers exhibited a standard deviation of 3-5 in/mi. In most cases, profilers reproduced measurements from the same manufacturer better than the rest of the group.

Measurement of overall IRI was generally less repeatable on sites 2 and 4 than on sites 1 and 3. Table 7 lists the standard deviation of the IRI measurements by each inertial profiler on each site, normalized by the average. The higher level of scatter on sites 2 and 4 exists for two reasons. First, they are smoother. Second, the coarse texture on sites 2 and 4 caused variability in short wavelength profile content. This added some variability to the overall IRI in each measurement. The principal effect of the texture was a lack of repeatability in the distribution of roughness within each measurement, which is not always reflected in the overall IRI values.

Table 7. Repeatability of IRI Measurement.

Device	**IRI, Standard Dev/Average (%)**			
	Site 1	Site 2	Site 3	Site 4
LISA, Angelo	0.29	0.32	1.28	2.03
ICC LWP	1.97	4.40	1.08	3.01
LISA, Carlo	0.26	6.17	0.58	2.76
Dyn/KJL 6400	0.45	3.41	0.32	2.79
LISA, Ames	0.60	2.75	—	1.11
SSI, LWP	—	4.66	5.40	5.94
MDOT, HSP	1.48	2.37	—	2.85
Dynatest 5051	0.12	0.97	1.31	0.37
SSI, HSP	0.81	6.93	0.46	4.95

Profile Comparison

Profile comparisons are often performed by looking at filtered plots, or using ASTM E-950. Inspection of filtered plots is a very useful diagnostic tool, but it does not provide objective ratings of agreement between profiles. ASTM E-950 is the established method of rating precision and bias in profile measurement. (*7*) Unfortunately, it has no direct relationship to the ability of a profiler to measure an index value, which is the most common use of a profile measurement.

An objective method of assessing agreement between profiles is needed that emphasizes only the aspects of the profile that are relevant to a given purpose. The method of cross correlation is used for this purpose in this project. (*8*) In this method the profiles are filtered to include only the wavelength range of interest, then compared using the discrete form of a convolution integral. A high rating using this method requires not only that the overall roughness level be equal between two profiles, but that the roughness occurs in the same locations within the profile. When the profiles are filtered using the IRI algorithm, the correlation level between the resulting signals is a direct rating of the agreement in the way roughness is spatially distributed throughout them.

The method of cross correlation described in Appendix B yields a -100 to 100 rating of agreement between two measurements. It can be used to rate repeatability or reproducibility between measurements. If one of the measurements is deemed correct, the agreement level could also be interpreted as profile accuracy. Regardless of the filters applied to the profiles or the type of rating, a correlation level of 90 or higher indicates good agreement and a level of 95 or higher indicates excellent agreement.

Five types of rating were calculated for each site: (1) agreement in IRI filter output, (2) agreement is RN filter output, (3) agreement in slope profile over the range of wavelengths from 26.2 to 131.2 feet (8 to 40 m), (4) agreement in slope profile over the range of wavelengths from 5.25 to 26.2 feet (1.6 to 8 m), and (5) agreement in slope profile over the range of wavelengths from 1.05 to 5.25 feet (0.32 to 1.6 m).

Repeatability

Ratings of profile repeatability are listed in tables 8 through 12. Ratings of 95 or better are shown in bold type. These were calculated by cross correlating all of the measurements of a given site by a given profiler to each other. In most cases, three repeat measurements were available, so the corresponding table entry is the average of three correlation values. In a few cases only two measurements were available, so the corresponding table entry is an individual correlation value.

Table 8. Repeatability Rating for IRI Filter Output.

Device	**Repeatability Rating**			
	Site 1	Site 2	Site 3	Site 4
SurPro1000	**96**	86	**97**	89
LISA, Angelo	**98**	83	**97**	93
ICC LWP	**97**	78	**95**	91
LISA, Carlo	**98**	79	**98**	92
Dyn/KJL 6400	**98**	89	**98**	90
LISA, Ames	**96**	87	**97**	**98**
SSI, LWP	**95**	76	85	65
MDOT, HSP	**96**	83	93	90
Dynatest 5051	**100**	84	**97**	88
SSI, HSP	**97**	72	**96**	61

Repeatability was best on site 1. This site included a high level of long-wavelength content, a low level of short-wavelength content, and fine texture with no opened cracks. The ratings for IRI filter output, listed in table 8, were excellent for all devices. All of the devices also measured long-wavelength content with excellent repeatability. (See table 9.) A possible exception is the MDOT HSP, but it is not required to measure long wavelengths. This is because it is used to measure the Michigan RQI (rather than the IRI), which has a long-wavelength cutoff of 50 feet. Most of the devices exhibited good to excellent repeatability for medium wavelength content on site 1, but few of them measured short wavelength content sufficiently.

Repeatability was also very good on site 3. This site had fine texture, but included several opened joints. The ratings for IRI filter output and long-wavelength content were excellent for most devices, and ratings for medium-wavelength content were good or excellent for all devices. The exception was the SSI LWP. One of its measurements included tremendous long-wavelength drift compared to the others.

Site 4 was problematic because it was transversely tined. Only one of the devices, the Ames LISA, demonstrated excellent repeatability for IRI measurement on site 4. The rest were less repeatable over the entire range of wavelengths on site 4 than on sites 1 and 3. The SSI LWP and SSI HSP also picked up spikes at some of the joints. Since the same joints were not sensed in every measurement, the repeatability was reduced. This is not considered an error, because the joints are part of the surface shape, and no standard method exists for treating the downward spikes measured at joints.

Table 9. Repeatability Rating for Long Wavelength Content.

Device	**Repeatability Rating**			
	Site 1	Site 2	Site 3	Site 4
SurPro1000	**99**	69	**96**	89
LISA, Angelo	**98**	84	92	91
ICC LWP	**98**	72	**95**	84
LISA, Carlo	**98**	82	**97**	82
Dyn/KJL 6400	**99**	88	**97**	**97**
LISA, Ames	**99**	93	**98**	**98**
SSI, LWP	**95**	88	61	71
MDOT, HSP	93	75	**97**	**96**
Dynatest 5051	**100**	93	**97**	94
SSI, HSP	**99**	89	**98**	93

Table 10. Repeatability Rating for Medium Wavelength Content.

Device	**Repeatability Rating**			
	Site 1	Site 2	Site 3	Site 4
SurPro1000	88	84	**96**	87
LISA, Angelo	94	78	**97**	93
ICC LWP	93	74	**95**	89
LISA, Carlo	**97**	77	**98**	92
Dyn/KJL 6400	92	86	**98**	87
LISA, Ames	88	85	**97**	**96**
SSI, LWP	88	71	91	56
MDOT, HSP	91	79	90	88
Dynatest 5051	**98**	81	**97**	86
SSI, HSP	89	68	**96**	48

Table 11. Repeatability Rating for Short Wavelength Content.

Device	**Repeatability Rating**			
	Site 1	Site 2	Site 3	Site 4
SurPro1000	70	76	79	59
LISA, Angelo	61	53	88	71
ICC LWP	78	56	81	61
LISA, Carlo	87	59	88	68
Dyn/KJL 6400	69	67	87	59
LISA, Ames	82	70	84	82
SSI, LWP	69	47	74	28
MDOT, HSP	65	45	61	56
Dynatest 5051	88	65	85	50
SSI, HSP	47	37	71	13

Table 12. Repeatability Rating for RN Filter Output.

Device	**Repeatability Rating**			
	Site 1	Site 2	Site 3	Site 4
SurPro1000	75	77	87	67
LISA, Angelo	73	62	94	81
ICC LWP	84	61	90	74
LISA, Carlo	90	65	**95**	79
Dyn/KJL 6400	78	75	**95**	75
LISA, Ames	85	75	94	88
SSI, LWP	75	54	83	33
MDOT, HSP	74	56	80	70
Dynatest 5051	93	69	92	66
SSI, HSP	67	45	86	18

Site 2 was measured with the lowest level of repeatability overall. None of the profilers exhibited good repeatability in IRI measurement, and few performed well in any waveband. It is expected that the poor performance is caused by the longitudinal tining.

Overall, filtered RN output was not measured sufficiently on sites 1, 2, and 4. Some of the devices were able to measure overall RN values that were similar between repeat runs, but the spatial distribution of roughness that affected the RN was not repeated.

Reproducibility

Reproducibility is defined as the ability of one device to produce the same result as another. Thus, ratings of reproducibility can be calculated for any combination of two devices. Full matrices of repeatability ratings are provided in Appendix C. These cover comparison of measurements from a given device to measurements of each of the other devices. Each table in Appendix C lists the results of these comparisons for a given site using a given filter type. Individual entries in the tables are the average correlation coefficient for all measurements of a site by one device compared to all measurements of the same site by another. Usually, three measurements were made by each device, so an entry is really the average of nine coefficient values. In some cases, one or both device measured a site less than three times, so fewer coeffiecient values were calculated. Note that the diagonal entrees in each table actually compare a device to itself, and are the repeatability values listes in tables 8 through 12.

Reproducibility was poor overall, and worst on sites 2 and 4. This can be explained by (1) diversity in sensing technology and the treatment of narrow, downward profile features, (2) special difficulties posed by smooth concrete of coarse texture, (3) diversity in sampling interval, and (4) errors in the measurement of longitudinal distance.

Sensing Technology and Sample Interval

This experiment included profiling devices with a diverse range of sensing technology, covering several types of "footprint". Overall, the ARRB WP and SurPro 1000 reproduced each other's measurements better than either one of them reproduced the rod and level surveys. In addition, the ARRB WP and SurPro 1000 only reproduced each other's measurement of sites 1 and 3 with high quality, and only in the measurement of IRI and long-wavelength content.

The diversity in results between the slow-speed devices is a direct consequence of the diversity in sensing scheme. The ARRB WP moves along on several "feet" that establish a datum plane for measurements. In contrast, the SurPro 1000 rolls along on two small wheels. Each of these devices contacts the pavement surface in a manner that averages out texture somewhat and bridges over some narrow dips, but they are not equivalent. (See the photos in Appendix D.)

The rod and level contacted the road with a rigid plate at the bottom of the rod that is two inches wide and one inch deep. This scheme did possess some ability to bridge over narrow dips, but no averaging. The rod and level will read the elevation of the highest point under the level. Thus, it may assemble a collection of correct elevation values, but the meaning of them together in a complete profile is not clear. In particular, the potential for aliasing error on smooth pavement of coarse texture is enormous, because the rod and level reports individual readings, rather than averages over some interval. (*9*)

Most of the high-speed and lightweight inertial profilers use a laser height sensor with a footprint that is less than 2 mm long and less than 2 mm wide. This makes them very different from the slow-speed devices that contact the pavement surface in the way that they treat surface texture, particularly in the lateral direction. Note that only a few isolated cases exist in which non-contacting (inertial) profilers reproduced the measurements made by the slow-speed profilers. In fact, few ratings higher than 90 were achieved, which is evident in the tables.

The very narrow footprint of common laser height sensors makes them vulnerable to aliasing errors caused by coarse texture or narrow dips at joints. Slow drift of a height sensor with a narrow footprint into and out of the reservoirs on longitudinally tined concrete introduces significant content into the profile that would be misinterpreted as roughness that affects ride quality.

A narrow footprint can be an advantage on transversly tined concrete or over joints if the pavement surface is sampled at a very high rate. Most of these sensors are able to take readings at least 16,000 times per second, which is more than 10 times per inch at highway speed and up to 50 times per inch at the operating speed of lightweight profilers. These data can then be processed to eliminate the influence of tining and joints. Unfortunately, no standard exists for averaging these readings. Each brand of profiler applies a different set of analog and digital filters to the height sensor signals. In addition, no standard exists for removing narrow, downward spikes. Inspection of profile plots produced on sites 2 and 4 suggest that some profilers do throw out spikes, but it is unlikely that any two of them use the same criteria.

One of the lightweight profilers, the Dyn/KJL 6400, uses a height sensor with a footprint that is very different than the rest. Its height sensors covers an area that is 37 mm wide and 5 mm deep. This profiler computes elevation at a 25 mm interval, but only records profile data every 150 mm. Although it is very different than the others, it did not stand out as reproducing the measurements of the slow-speed devices any differently. It did produce lower IRI values on sites 2 and 4 than all of the lightweight profilers which used narrower height sensor footprints.

Figure 1 demonstrates the difference in the way various profilers will measure and report spikes at contraction joints. The figure shows a segment of profile from six different devices, covering three joints. The ICC LWP and SSI LWP recorded the profile at the shortest interval, and show spikes at each joint. The Angelo LISA records the profile at a longer interval. One of the spikes in its measurement is not as deep as those reported by the SSI LWP and ICC LWP, and one is not present at all. The Dyn/KJL 6400 measures the profile at a sample interval of 25 mm, but applies a 300-mm moving average to it and decimates the resulting signal to an interval of 150 mm. Although the influence of the spikes at the joints is present, they are not as visible because they have been smoothed. They do, however, still contribute to an index value determined from profile. The ARRB WP and SurPro 1000 both measure slab shapes that agree moderately well with the lightweight profilers, but do not detect any dips whatsoever at the joints. This is because they bridge over them. Overall, these measurements do not agree on the presence or magnitude of the dips at the joints. The best strategy for improving the agreement between these measurements is to standardize a method for eliminating narrow dips from profile.

Site Properties

Smooth pavement presents a challenge to most profilers. On smooth pavement, the level of body vibration of an inertial profiler will be very low. This decreases the signal level in the accelerometer and increases the relative influence of system noise. It also may cause only a small portion of the height sensor range to be used, which may require a higher level of resolution. These are a few of the reasons why the profilers were less repeatable and reproducible on sites 2 and 4. Another reason is the significance of texture and spikes at the joint compared to the rest of the profile. Tining often ranges from 1/8 to 3/16 inch deep, and even deeper spikes may appear in a profile at joints. Unfortunately, these levels are on the same order of magnitude as the amplitude of longer wavelength profile features that affect vehicle ride quality.

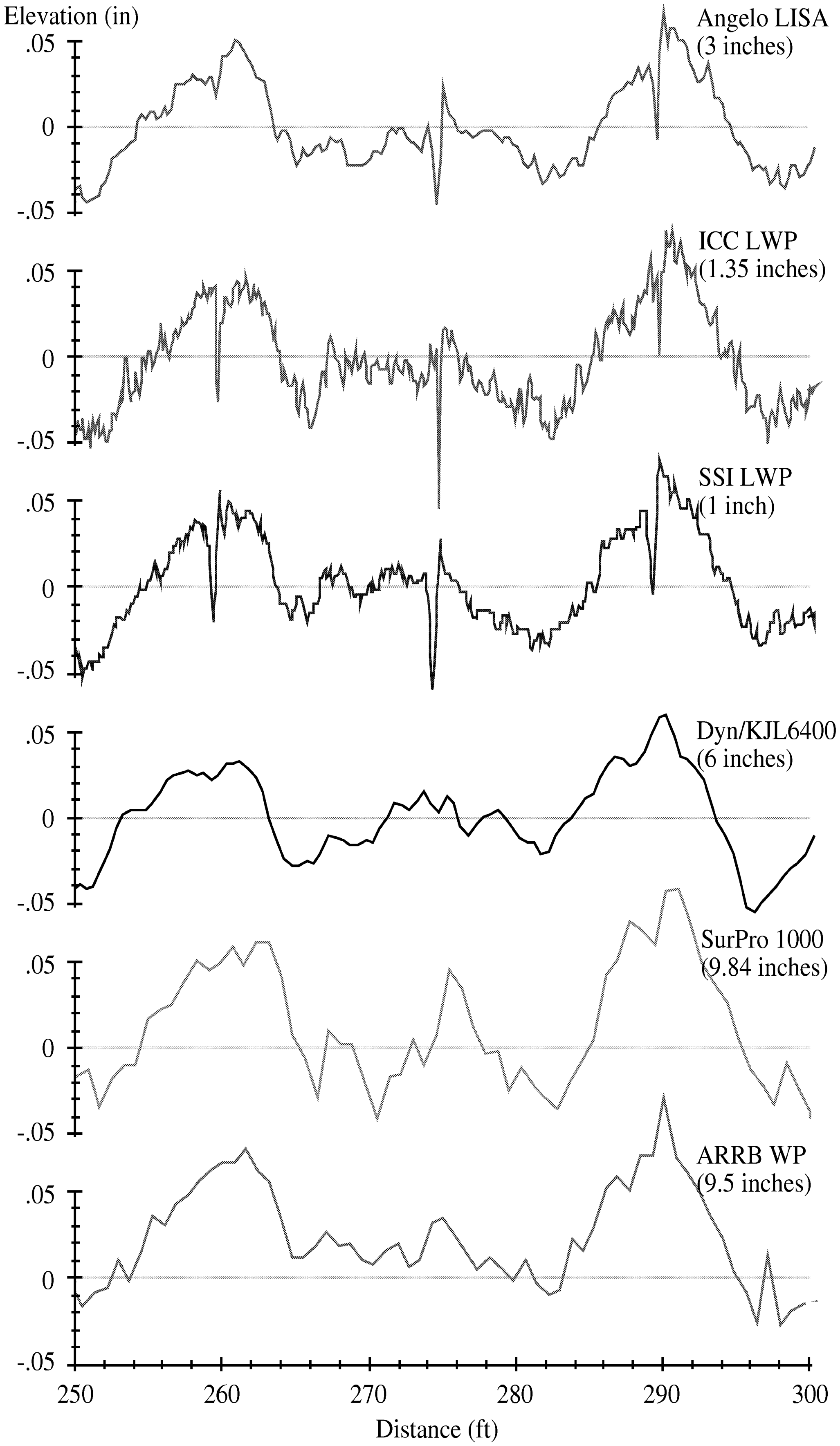

Figure 1. Detection of spikes at the joints.

Note that site 1 contrasts with sites 2 and 4 in texture and overall roughness. A better assessment of the effect of texture on profiler performance could be made if the experiment included a site as smooth as site 4 without coarse texture.

Longitudinal Distance Measurement

In most cases, the longitudinal distance measurement was consistent between profilers. This was investigated by adjusting the sample interval of each profile in small steps (of 0.01 percent) over a range from ±2 percent. The sample interval that produced the highest correlation to the rod and level measurement for filtered IRI output was considered the "correct" value. On site 3, the ARRB WP was used as the reference, since no rod and level survey was performed. This procedure was used to search for errors in longitudinal distance measurement greater than 0.40 percent. Usually, all of the repeat measurements by a given device on a given site either violated the limit, or all of them did not. The Dynatest 5051 underestimated distance compared to the reference measurements by 1.2 to 1.5 percent in all of its measurements. Although it was very repeatable on each, it did not agree with the other devices. The Angelo LISA underestimated distance by about 1.4 percent on site 2, and the Dyn/KJL6400 overestimated distance on site 1 by about 0.7 percent.

These errors in longitudinal distance measurement reduced the ability of the corresponding profilers to reproduce the measurements of other profilers, particularly the short wavelength content. When the sample interval of these measurements were adjusted to correct for distance measurement error, their agreement with other measurements (and their reproducibility ratings) improved significantly.

Accuracy

As described above, the rod and level did not turn out to be a proper reference measurement on coarse-textured concrete. As such, comparison to it is treated as another case of reproducibility, rather than accuracy.

CONCLUSIONS AND RECOMMENDATIONS

This study demonstrated that high-speed and lightweight inertial profilers were sufficiently repeatable for the measurement of IRI on a moderately rough asphalt site of typical surface texture and a moderately rough concrete site of unusually smooth surface texture. Repeatability was compromised on a smooth concrete site with transverse tining, and was inadequate on a smooth concrete site with longitudinal tining.

This study also demonstrated that high-speed and lightweight profilers are not able to reproduce profiles sufficiently when the spatial distribution of roughness is of interest. (Spatial distribution of roughness is important in the location of isolated rough spots, and diagnosis of problems in the paving process.) The level of reproducibility between inertial profilers demonstrated on smooth concrete with coarse texture needs improvement if they are to find acceptance for use in construction quality control.

Poor reproducibility and reduced repeatability on new concrete with coarse texture is attributed to the high relative amplitude of very short-wavelength features compared to long-wavelength features. For example, tining is often 1/8 to 3/16 inch deep, and reserviors that may exist at joints up to 1/2 inch deep. On a new concrete pavement, the height of longer wavelength features that are relevant to vehicle response is often smaller than the depth of tining and joints. This causes a situation where tining and joints, which are common features of a new concrete pavement, introduce a critical level of noise into a profile measurement. With this in mind, great care must be taken to develop and standardize a combination of profile measurement hardware and processing algorithms that are sensitive only to those pavement features that affect vehicle vibration response.

The three slow-speed measurement devices used in this project as candidate reference devices did not agree with each other well enough to use any pair of them interchangeably. This is because they each used a unique scheme for contacting the pavement surface, which gave measurements from each of them a separate meaning. The end use of a profile must be defined more completely before a reference device can be deemed adequate for measurement of coarse-textured concrete. For example, the IRI and RN use a moving average to represent the envelopment of short-duration surface features by a vehicle tire. Most slow-speed profiling devices "average" out short duration surface features by virtue of their footprint (wheels, feet, etc.). Some of them bridge over narrow dips and others do not. None of them has clearly demonstrated envelopment behavior that is equivalent to a common vehicle tire.

At present, no reference measurement device can be deemed the most legitimate for verification of profilers on coarse-textured concrete. A standard is needed that defines the most relevant method of filtering, averaging, or ignoring profile features with a duration equal to or shorter than the contact patch of a vehicle tire. A standard is recommended that best emulates tire bridging and envelopment. Existing and potential new reference profiling devices should then be tested to select those which satisfy the standard. Inertial profiler manufacturers can then apply sensing technology and processing algorithms that all strive to measure the same thing. In the absence of this standard, the most pervasive technology will guide the interpretation of profile measurements, rather than letting the preferred interpretation guide the technology.

Reproducibility of profile measurements on coarse-textured jointed concrete and their relevance to vehicle response could be improved using two strategies. First, the sensor footprint of inertial profilers could be altered to better represent the enveloping and bridging behavior of vehicle tires. These sensors will require logic that carefully interprets the variations in surface shape within the footprint. This has the potential to improve the relevance of profile measurements over joints, transverse tining, and longitudinal tining. Second, a "tire bridging filter" could be used in conjunction with a very small sensor footprint. If this filter is customized to ignore narrow downward features that do not affect vehicle ride vibrations it could replace the moving average in the IRI and RN calculation procedures. This could improve the reproducibility and relevance of profile measurement over joints and transverse tining, but not over longitudinal tining.

A formal profiler qualification experiment is recommended in which profilers that qualify in the second phase will be endorsed by the ACPA for use by their members to evaluate the smoothness of newly constructed concrete pavements. The experiment should not commence until manufacturers of lightweight profilers have new technology to demonstrate that has the potential to improve performance on new concrete. The testing and data processing procedures should be defined and communicated to potential participants well in advance. This way, manufacturers seeking this assessment can verify their performance before the official tests. Potential participants will also have the opportunity to review the procedures and provide feedback to the experiment organizers.

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Appendix A: Measurement Timing

This appendix lists the timing of the measurements taken for this study by each device.

Table A.1. Timing of Measurements on Site 1 (Lansing).

Device	Type	Time	Date
LISA, Tony Angelo Cement Construction	LW	08:53 – 09:11	July 9
SurPro 1000	WS	09:15 – 09:55	July 9
LISA, John Carlo Construction	LW	09:40 – 09:49	July 9
ARRB Walking Profiler	WS	09:59 – 10:30	July 9
Cox Profilograph	PG	10:35 – 11:07	July 9
Surface Systems Instruments	LW	11:06 – 11:15	July 9
LISA, Ames	LW	11:15 – 11:18	July 9
International Cybernetics Corporation	LW	11:21 – 11:25	July 9
Dynatest/KJL 6400	LW	11:29 – 11:32	July 9
Dynatest 5051	HS	11:42 – 11:47	July 9
Surface Systems Instruments	HS	11:59 – 12:07	July 9
Michigan DOT	HS	12:18 – 12:32	July 9
Rod and Level	ST	Evening	July 11-14

HS - High-Speed LW - Lightweight PG - Profilograph ST - Static WS - Walking Speed

Table A.2. Timing of Measurements on Site 2 (Bay City).

Device	Type	Time	Date
LISA, Tony Angelo Cement Construction	LW	13:50 – 13:55	July 9
ARRB Walking Profiler	WS	13:56 – 14:30	July 9
SurPro 1000	WS	14:45 – 15:15	July 9
Cox Profilograph	PG	15:15 – 15:34	July 9
LISA, John Carlo Construction	LW	15:35 – 15:40	July 9
Dynatest/KJL 6400	LW	15:38 – 15:45	July 9
LISA, Ames	LW	15:55 – 16:03	July 9
Surface Systems Instruments	LW	16:04 – 16:13	July 9
Dynatest 5051	HS	16:16 – 16:20	July 9
Michigan DOT	HS	16:29 – 16:35	July 9
Surface Systems Instruments	HS	16:41 – 16:55	July 9
International Cybernetics Corporation	LW	19:41 – 19:46	July 10
Rod and Level	ST	All Day	July 23

HS - High-Speed LW - Lightweight PG - Profilograph ST - Static WS - Walking Speed

Table A.3. Timing of Measurements on Site 3 (Milford).

Device	Type	Time	Date
LISA, Tony Angelo Cement Construction	LW	09:15 – 09:22	July 10
Dynatest/KJL 6400	LW	09:24 – 09:28	July 10
LISA, John Carlo Construction	LW	09:34 – 09:39	July 10
LISA, Ames	LW	09:43 – 09:48	July 10
Surface Systems Instruments	LW	09:57 – 10:04	July 10
Cox Profilograph	PG	10:10 – 10:26	July 10
International Cybernetics Corporation	LW	10:39 – 10:44	July 10
SurPro 1000	WS	10:44 – 11:06	July 10
Surface Systems Instruments	HS	11:14 – 11:35	July 10
Michigan DOT	HS	11:18 – 11:26	July 10
Dynatest 5051	HS	11:20 – 11:27	July 10
ARRB Walking Profiler	WS	11:35 – 12:10	July 10

HS - High-Speed LW - Lightweight PG - Profilograph WS - Walking Speed

Table A.4. Timing of Measurements on Site 4 (Novi).

Device	Type	Time	Date
Michigan DOT	HS	14:51 – 14:58	July 10
Surface Systems Instruments	LW	14:56 – 15:02	July 10
Dynatest/KJL 6400	LW	15:03 – 15:10	July 10
LISA, Ames	LW	15:04 – 15:13	July 10
LISA, John Carlo Construction	LW	15:20 – 15:26	July 10
International Cybernetics Corporation	LW	15:26 – 15:32	July 10
Surface Systems Instruments	HS	15:33 – 15:59	July 10
Dynatest 5051	HS	15:40 – 15:52	July 10
LISA, Tony Angelo Cement Construction	LW	15:46 – 15:49	July 10
Cox Profilograph	PG	15:57 – 16:16	July 10
SurPro 1000	WS	16:18 – 16:40	July 10
ARRB Walking Profiler	WS	17:15 – 17:50	July 10
Rod and Level	ST	All Day	July 25

HS - High-Speed LW - Lightweight PG - Profilograph ST - Static WS - Walking Speed

Appendix B: Cross Correlation

This appendix describes the use of cross correlation for synchronizing profiles to each other and rating the agreement between them. Some of this material is adapted from a recent FHWA report. (*1*)

INTRODUCTION

Cross correlation functions are a statistical measure of the dependence of one variable on another. (*2*) The cross correlation function of repeat measurements of road profiles provides a way to synchronize them and rate their agreement. For two measures of road profile, the cross-correlation function is defined as:

$$Rpq(\delta) = \lim_{L \to \infty} \frac{1}{L} \int_0^L p(x)q(x+\delta)dx \qquad \text{(B–1)}$$

where p and q are each measurements of road profile as a function of distance x. The correlation function, R, exists as a continuous function of the offset distance d between the profiles, and has length L. Since actual measures of road profile are finite in length and sampled at discrete intervals, the integral is replaced with a summation. A correlation coefficient also exists and is defined as the correlation function normalized by the standard deviations of p and q. The definition for sampled variables p and q is:

$$\rho_{pq}(\delta) = \frac{1}{\sigma_p \sigma_q} \sum_{i=1}^{N} p(x_i)q(x_i+\delta) \qquad \text{(B–2)}$$

where N is the number of points common to both profiles at an offset distance d (equal to an integer multiple of the sample interval), and s represents the standard deviation of each profile. If the profiles are in exact agreement, r will have a value of 1. If they are exactly opposites, r will be -1. If they are uncorrelated, r is zero.

It is essential that the same filters be applied to both profiles before using this analysis. If the profiles are not filtered similarly the results will be clouded by the differences in wavelength content. It is also helpful to convert the profiles from elevation to slope before computing the correlation coefficient. If elevation is used, the agreement for the longest wavelength range included in the analysis has a disproportionate influence on the results.

SYNCHRONIZATION

For research studies that involve several measurements of the same road section by a single device or a collection of devices, it is often desirable to "synchronize" the profiles by adjusting their longitudinal offset to make sure they all cover exactly the same stretch of road. A common way to synchronize a set of profile measurements is to simply plot them and read a distance offset from the plots. Since cross correlation provides a rating of agreement between profiles at a given offset, it can be used to automate this process. The procedure is based on matching two measurements of a section of road and finding the offset associated with the highest level of correlation. If the profile measurements are properly filtered and normalized, the output of the algorithm is a number between -1.0 and 1.0 that describes the agreement of the two measurements at each offset.

Figure B-1 shows the cross-correlation between a measurement by a lightweight profiler and a measurement from the SurPro 1000 as a function of offset. Both were converted to slope profile and band-pass filtered to include only content in the wavelength range from about 5 to 25 feet. Because the shape of roads changes so randomly with distance, the level of agreement is very poor except where the measurements are synchronized. The function has a value less than 0.2 everywhere except when the offset is about 1 foot, where the segments are synchronized. The analysis shows the correct offset to be 1.15 feet, where the correlation coefficient reaches a peak at 0.898.

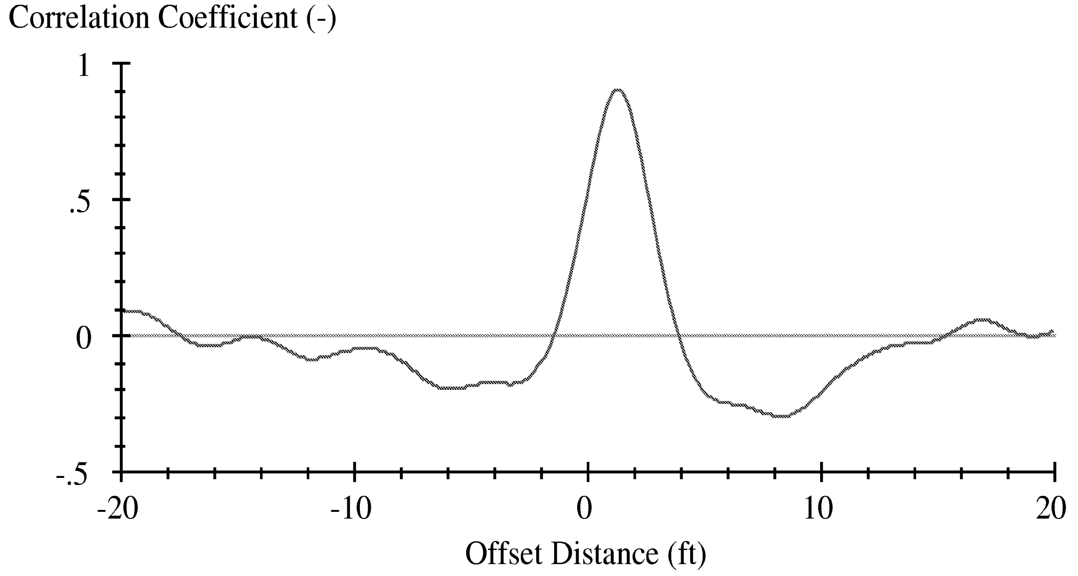

Figure B-1. Cross-correlation of two measurements for synchronization.

In the 1993 and 1994 RPUG calibration studies, an artificial bump was placed before and after each road section to help isolate the segment of interest. (*3*) A simple bump finder was used to synchronize the sections. The profiles were then synchronized a second time using cross correlation to verify its use for this purpose. (*4*)

RATING OF AGREEMENT

If the measurements compared in figure B-1 agreed perfectly, the maximum correlation coefficient would be unity. However, differences between the measurements, even when they are lined up properly, still exist. This lowers the maximum correlation level. Once two measurements are synchronized, the result of the algorithm provides a quantitative rating of the agreement between the them. This can be used to rate the agreement between two measurements from the same instrument (repeatability) or measurements from unlike instruments (reproducibility). The process is to (1) filter the profiles identically; and (2) cross-correlate them to see how well they agree in the waveband of interest.

Using cross-correlation to evaluate agreement between profile measurements is much more rigorous than comparison of summary roughness indices. Two profilers might produce the same index value even though the profiles are not the same. In contrast, cross correlation of filtered profiles requires the same level of roughness and that rough features appear in the same location in each. Thus, it does not reward compensating error. This reduces the number of repeat measurements needed to reveal profile measurement problems. This method also offers the ability to diagnose measurement errors by considering a variety of wavebands. For example, bad agreement for short wavelengths but good agreement for long wavelengths suggests a problem with the height sensors and the opposite often suggests a problem with the accelerometer signal.

A powerful adaptation of this method is to pass two profiles through the IRI algorithm, then cross-correlate the filtered output. This has the advantage of comparing only those aspects of the profile that are important to the IRI and applying appropriate weighting to them. (Of course, if another index is of interest, filter the profile using its algorithm.) High correlation using this procedure requires not only that the overall IRI values match, but that the roughness is spatially distributed the same way in both measurements. This may be important if the profiles are intended for location of isolated rough spots, or if they are to be used for feedback to a paving crew in construction quality control.

Figure B-2 provides an example of very high correlation. The figure shows three repeat measurements by a device after they have passed through the filters in the IRI algorithm. These signals compare to each other with an average correlation higher then 0.995. Note that the traces overlay so well that they are barely distinguishable from each other. Figure B-3 provides an example of moderate correlation. It shows three repeat measurements from the same device on a different pavement section after they have passed through the filters in the IRI algorithm. These compare with an average correlation of about 0.84. The traces do not overlay nearly as well, and do not agree on the severity of roughness in locations of elevated IRI. At few locations, such as 245 and 250 feet, concentrated roughness appears in only one or two of the measurements.

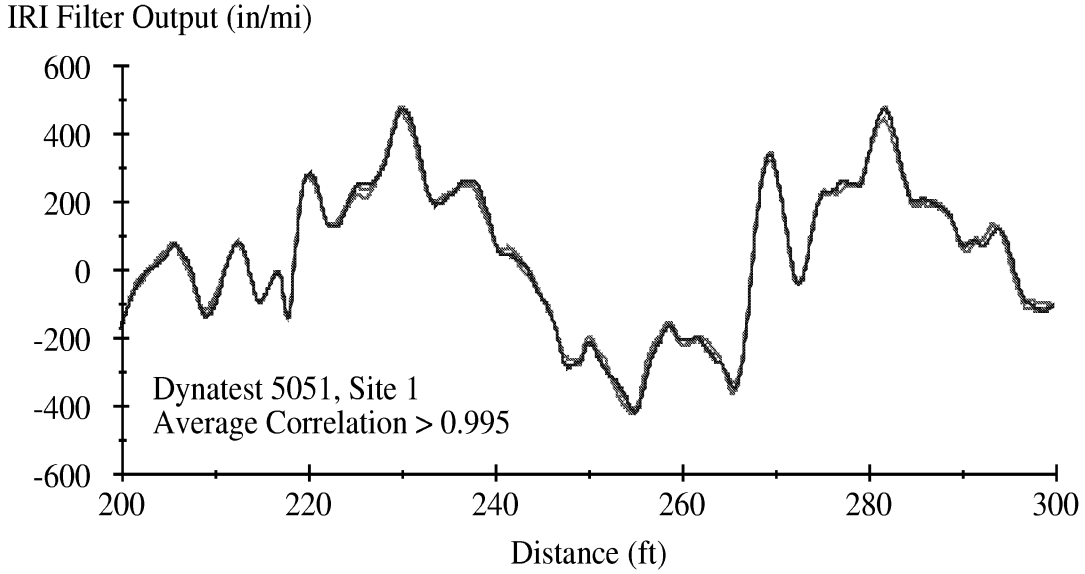

Figure B-2. Three highly correlated repeat measurements.

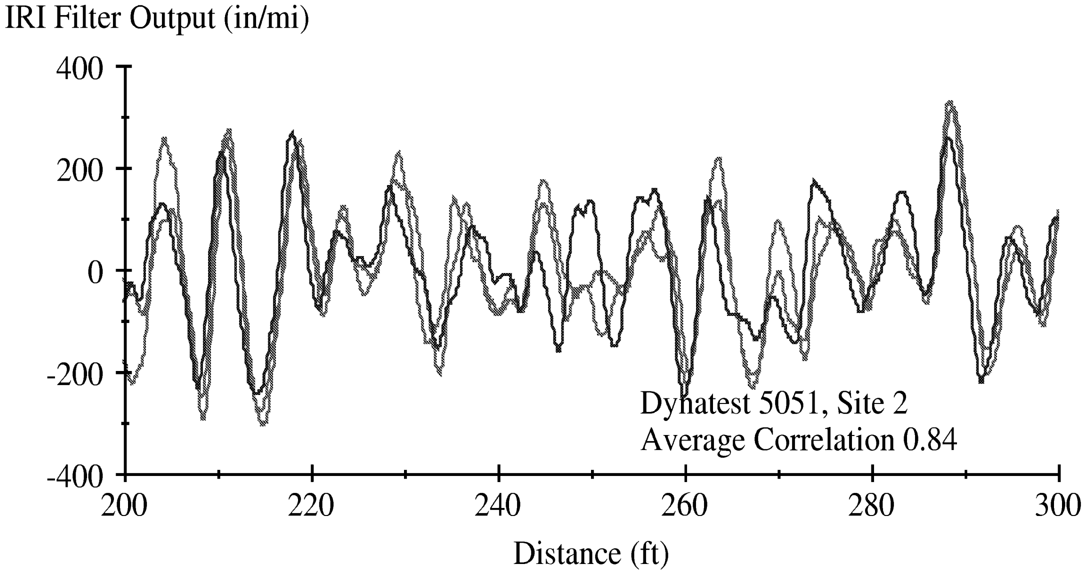

Figure B-3. Three moderately correlated repeat measurements.

PROCESSING STEPS

Synchronization

Synchronization of profiles using cross correlation is performed with the following steps:

Step 1: Identify a fixed profile. It will be considered the location reference. The profile will have a sample interval D, a total length L_p, and a total number if samples Np (=L_p/D).

Step 2: Cut a segment out of the correlated, or shifted, profile of shorter length than the reference profile, L_q. Preprocess it as follows.

- Step 2a: Filter it.
- Step 2b: Interpolate the filtered profile to the sample interval of the reference profile. The result is q_i. It will have N_q samples ($=L_q/D$).
- Step 2c: Offset the profile vertically so that the mean is zero.
- Step 2d: Calculate the variance of the filtered, interpolated, and shifted profile (s_q).

Step 3: Apply a negative offset (d_0) to the correlated profile so that the first point in it is also the first point in the reference profile. This value of offset is equal to X_{sP} - X_{sq}, where X_{sP} is the longitudinal position of the start of the broader reference profile (P_i), and X_{sq} is the longitudinal position of the start of the correlated profile.

Step 4: Extract the portion of the reference profile that is covered by the correlated profile. The extracted segment will cover N_q samples.

- Step 4a: Filter it.
- Step 4b: Offset the result vertically so that the mean is zero. The result is $p^m{}_i$. Note that this signal must be conditioned *after* it has been extracted from the broader reference profile. This ensures equal application of end conditions in the two signals that will be correlated in eq. B-3.
- Step 4c: Calculate the variance of the filtered and shifted profile over the range of interest (s_p).

Step 5: Cross-correlate the signals. In this application, the variance must be calculated over the segment of interest only to account for the common situation in which the broader profile is not stationary.

$$\begin{aligned}\rho_m &= \frac{1}{\sigma_p \sigma_q} \sum_{i=1}^{N_q} p^m{}_i q_i \\ \delta_m &= X_{sP} - X_{sq} + m \bullet \Delta\end{aligned} \tag{B-3}$$

Step 6: Shift the offset of the correlated signal by a distance equal to the sample interval of the reference profile. This amounts to shifting ahead one sample on the reference profile. (Each time this is done, increment the value of "m".)

Step 7: If the end of the reference profile has not been reached, return to step 4.

The offset that corresponds to the highest value of r is the proper offset for synchronization. Note that the choice of a reference profile in this process does not necessarily mean that it is correct. Often, this process is simply a way to make the location referencing consistent between measurements.

For this study, all of the synchronization was done using the output of the filters from the IRI algorithm. These filters produce a slope profile that covers a wavelength range from about 4 to 100 feet. Distance offsets were also examined in narrower wavebands to study the phase shift produced by each type of profiler.

The process outlined above provides a rating of agreement between profiles as a function of offset distance. Often, measurements differ in their distance measurement accuracy as well as their longitudinal referencing. Even small errors in measurement of longitudinal distance may compromise the correlation level. This occurs when the ratio of the smallest wavelength of interest to the overall length of the profile is on the same order of magnitude as the longitudinal distance measurement error level.

Cross correlation can also be used to quantify linear distance measurement error. This requires that correlation level is expressed as a function of both offset distance and distance measurement error level. The combination offset distance and sample interval correction factor that produce the highest correlation to the reference are then considered “correct”.

Rating of Agreement

The same process listed above can be used for rating of agreement between profiles. When it is used to rate repeatability, it does not matter which of the measurements is considered the “reference”. This is because the sample intervals will be equal, and the process has reciprocity. (That is, the same result is obtained if the reference and correlated profiles are switched.) When profiles of unlike sample interval are compared, the choice of a reference can be important. In particular, the method used to measure a road datum plane (i.e. the height sensor footprint) are deemed correct in the reference measurement.

The method of cross correlation described above was altered slightly for rating of profile agreement. Eq. B-1 through B-3 require that two profiles have the same shape for a high rating. They do not penalize a measurement for having the same shape as the reference, but a different roughness level. To account of this, the following scale factor is applied to the correlation levels listed in this report:

$$f = \frac{\min(\sigma_p, \sigma_q)}{\max(\sigma_p, \sigma_q)} \tag{B-4}$$

This penalizes the correlation level by the ratio of the variance of each signal. (It is equivalent to requiring a line of equality, instead of a best-fit line.)

Rating of agreement were calculated using cross correlation for five filtering options:

1. The output of the IRI algorithm. This is a slope profile with frequency weighting determined by the quarter car filter using the Golden Car parameters.
2. The output of the RN algorithm. This is a slope profile with frequency weighting optimized to predict user panel ratings from experiments in Ohio and Minnesota.
3. The slope profile, passed through a four-pole Butterworth filter with cutoff wavelengths of 26.2 and 131.2 feet (8 and 40 m).
4. The slope profile, passed through a four-pole Butterworth filter with cutoff wavelengths of 5.25 and 26.2 feet (1.6 and 8 m).

5. The slope profile, passed through a four-pole Butterworth filter with cutoff wavelengths of 1.05 and 5.25 feet (0.32 and 1.6 m).

The first two options are meant to amphasize content in the profiles that is relevant to the accumulation of each index. The other three filters were included to help diagnose the source of disagreement between profiles by isolating each waveband. All of these filters are described in detail elsewhere. (*1*) Conversion to slope is a prominent feature of all five filtering options used in the analysis. This is because most profiles exhibit much less variation in slope amplitude than elevation amplitude over the wavelength range of interest. Thus, using slope prevents the long-wavelength portion of the filtered profile from dominating the results.

Note also that correlation level is expressed on a -100 to 100 scale, rather than -1 to 1. This is done for ease of interpretation.

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3. Perera, R.W. and S.D. Kohn, *Road Profiler User Group Fifth Annual Meeting. Road Profiler Data Analysis and Correlation.* Soil and Materials Engineers, Inc. Research Report No. 92-30, (1994) 87 p.

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Appendix C: Cross Correlation Results

This appendix lists the results of cross correlation analysis performed on all of the profiles measured for this study. Twenty tables are provided, covering five types of filter and four sites. Each filter type provides unique diagnostic information about profile content.

For each combination of filter and site, all of the measurements from a given device are compared to all of the measurements from the rest of the devices. Measurements from the device listed as the correlation reference are assumed to be correct, and measurements from the correlated device are compared to them. Measurements from the profiler listed as the "correlated" device are always interpolated to the sample interval of the correlation reference. Each entry in the table is the average of up to nine correlation levels (if each device made three measurements of the site). The individual entrees provide a rating of the ability of one device to reproduce the measurements of another. The diagonal entrees in the tables provide a rating of repeatability, because they are the average of the correlation levels that result for all combinations of repeat measurements by the same device.

Ratings of repeatability of 95 or greater and ratings of reproducibility of 90 or greater are considered excellent. These ratings indicate that two measurements agree sufficiently well to report the same overall roughness level and spatial distribution for roughness within a given waveband.

Tables C-1 through C-20 provide comparisons of the profiles with no distance measurement correction. Errors in distance measurement as small as 1 percent reduce correlation, particularly in the short wavelength range. As such, a second set of profile comparisons were performed in which a linear distance measurement correction was applied to the correlated measurements to optimize their agreement to the reference. This is done by searching for the combination of distance offset and sampling interval scale factor that result in the highest correlation. Of course, a unique correction is usually needed for every combination of two profiles. Tables C-21 through C-24 list the results for IRI filter output. Note that many of the worst correlation levels listed in tables C-1 though C-4 improve tremendously.

Table C-1. International Roughness Filter, Site 1 (Lansing Airport).

Correlation Reference		Correlated Device											
		0	1	2	3	4	5	6	7	8	9	10	11
0	Rod and Level	—	86	85	76	75	77	69	81	69	63	66	83
1	SurPro 1000	87	**96**	**93**	82	83	83	75	88	75	67	71	**90**
2	ARRB WP	85	**95**	—	85	84	86	77	**90**	77	69	74	**90**
3	LISA, Angelo	76	83	87	**98**	**93**	**98**	74	88	82	86	82	80
4	ICC LWP	76	85	85	**93**	**97**	**95**	75	87	80	88	81	81
5	LISA, Carlo	77	85	88	**98**	**95**	**98**	73	89	83	87	82	81
6	Dyn/KJL 6400	69	76	78	75	75	74	**98**	80	67	70	67	78
7	LISA, Ames	82	89	**91**	88	87	89	79	**96**	80	71	70	86
8	SSI, LWP	69	76	79	83	80	83	67	80	**95**	69	64	73
9	MDOT, HSP	62	68	70	86	89	88	70	71	68	**96**	82	79
10	Dynatest 5051	65	72	75	82	81	81	67	70	64	82	**100**	81
11	SSI, HSP	83	**91**	**90**	80	81	81	78	86	73	80	80	**97**

Table C-2. International Roughness Filter, Site 2 (Bay City).

Correlation Reference		Correlated Device											
		0	1	2	3	4	5	6	7	8	9	10	11
0	Rod and Level	—	71	77	23	70	73	68	81	70	70	22	69
1	SurPro 1000	68	86	67	12	65	69	57	73	69	64	14	66
2	ARRB WP	76	72	—	21	63	75	74	77	69	74	22	65
3	LISA, Angelo	23	13	22	83	20	24	27	17	18	24	69	18
4	ICC LWP	70	68	67	20	78	67	62	72	66	66	24	64
5	LISA, Carlo	73	73	76	24	67	79	76	80	76	77	23	73
6	Dyn/KJL 6400	67	63	79	27	61	77	89	74	69	78	28	66
7	LISA, Ames	81	78	80	17	72	80	74	87	78	74	19	75
8	SSI, LWP	71	71	74	19	66	76	73	78	76	72	16	71
9	MDOT, HSP	70	67	80	24	66	77	79	74	71	83	20	73
10	Dynatest 5051	23	14	21	70	24	24	28	19	16	21	84	16
11	SSI, HSP	70	69	73	18	64	74	69	75	71	74	16	72

Table C-3. International Roughness Filter, Site 3 (General Motors).

Correlation Reference	Correlated Device										
	1	2	3	4	5	6	7	8	9	10	11
1 SurPro 1000	**97**	87	86	86	80	81	**90**	77	85	35	87
2 ARRB WP	**92**	—	**92**	87	69	87	**93**	84	89	47	**94**
3 LISA, Angelo	**91**	**92**	**97**	**94**	80	**93**	88	85	**93**	38	**92**
4 ICC LWP	**92**	87	**94**	**95**	86	**91**	86	82	**91**	35	89
5 LISA, Carlo	83	68	79	86	**98**	74	71	65	79	31	73
6 Dyn/KJL 6400	87	87	**92**	89	75	**98**	85	79	87	44	88
7 LISA, Ames	**92**	**92**	89	85	71	87	**97**	81	86	46	**92**
8 SSI, LWP	82	87	85	82	65	81	81	85	86	34	84
9 MDOT, HSP	89	**91**	**93**	**91**	79	89	85	85	93	38	**91**
10 Dynatest 5051	34	48	38	35	31	43	46	34	38	**97**	48
11 SSI, HSP	**91**	**95**	**92**	89	73	**91**	**92**	84	**91**	48	**96**

Table C-4. International Roughness Filter, Site 4 (Novi).

Correlation Reference	Correlated Device											
	0	1	2	3	4	5	6	7	8	9	10	11
0 Rod and Level	—	54	52	45	49	50	39	48	41	45	30	46
1 SurPro 1000	47	89	79	69	76	76	63	76	49	68	39	66
2 ARRB WP	45	83	—	68	75	73	60	76	63	66	43	57
3 LISA, Angelo	45	72	72	93	84	87	82	**90**	63	**90**	50	64
4 ICC LWP	50	78	79	84	91	88	77	88	68	83	50	61
5 LISA, Carlo	50	79	79	87	88	92	81	88	66	85	49	67
6 Dyn/KJL 6400	37	66	64	80	75	81	90	77	62	82	54	53
7 LISA, Ames	48	79	78	**90**	88	89	79	**98**	73	87	50	67
8 SSI, LWP	42	68	65	70	69	73	63	72	65	68	36	54
9 MDOT, HSP	45	70	70	**90**	83	85	84	87	61	90	53	62
10 Dynatest 5051	30	39	45	50	50	49	55	50	35	53	88	37
11 SSI, HSP	46	65	63	62	61	65	57	67	54	60	37	61

Table C-5. Ride Number Filter, Site 1 (Lansing Airport).

Correlation Reference		Correlated Device											
		0	1	2	3	4	5	6	7	8	9	10	11
0	Rod and Level	—	32	32	29	27	37	9	26	34	32	12	18
1	SurPro 1000	38	75	36	32	51	44	9	28	38	46	19	24
2	ARRB WP	32	40	—	60	30	70	11	43	45	38	25	38
3	LISA, Angelo	27	50	66	73	41	72	12	54	50	51	26	43
4	ICC LWP	31	69	46	44	84	51	15	43	34	58	28	30
5	LISA, Carlo	36	63	74	72	47	90	11	60	65	72	27	48
6	Dyn/KJL 6400	9	15	18	13	14	13	78	17	11	11	13	15
7	LISA, Ames	29	48	60	58	44	64	17	85	44	48	30	43
8	SSI, LWP	39	48	58	55	35	68	10	44	75	57	19	37
9	MDOT, HSP	31	63	59	54	57	73	11	45	52	74	23	38
10	Dynatest 5051	14	25	30	29	27	29	14	27	19	24	93	23
11	SSI, HSP	20	38	53	46	31	50	16	44	37	40	25	67

Table C-6. Ride Number Filter, Site 2 (Bay City).

Correlation Reference		Correlated Device											
		0	1	2	3	4	5	6	7	8	9	10	11
0	Rod and Level	—	35	36	9	26	36	31	41	37	29	10	30
1	SurPro 1000	25	77	28	5	40	31	20	40	35	36	8	30
2	ARRB WP	42	45	—	8	23	42	35	44	23	32	7	23
3	LISA, Angelo	9	8	11	62	7	11	12	8	7	10	33	6
4	ICC LWP	29	47	30	6	61	33	23	41	31	37	9	34
5	LISA, Carlo	36	51	52	11	33	65	50	64	47	52	9	36
6	Dyn/KJL 6400	35	42	63	14	27	58	75	57	37	48	11	27
7	LISA, Ames	46	61	58	8	42	66	51	75	54	55	9	40
8	SSI, LWP	41	47	44	8	32	54	45	54	54	42	9	39
9	MDOT, HSP	29	50	51	9	38	52	43	55	36	56	7	34
10	Dynatest 5051	11	8	8	35	10	10	10	9	8	7	69	10
11	SSI, HSP	34	42	34	7	35	39	29	41	39	37	10	45

Table C-7. Ride Number Filter, Site 3 (General Motors).

Correlation	Correlated Device										
Reference	1	2	3	4	5	6	7	8	9	10	11
1 SurPro 1000	87	58	58	59	45	56	57	55	56	33	57
2 ARRB WP	74	—	69	60	43	64	85	60	64	40	67
3 LISA, Angelo	83	78	94	87	58	86	79	79	88	31	68
4 ICC LWP	83	67	86	90	66	77	70	70	81	30	67
5 LISA, Carlo	60	48	56	66	**95**	55	50	46	56	26	44
6 Dyn/KJL 6400	84	80	89	82	59	**95**	83	81	84	33	75
7 LISA, Ames	78	85	80	71	52	82	94	79	76	38	77
8 SSI, LWP	76	78	82	71	48	84	79	83	77	28	74
9 MDOT, HSP	82	77	88	82	58	85	75	74	80	32	66
10 Dynatest 5051	24	33	30	30	27	33	38	28	31	92	36
11 SSI, HSP	73	74	75	68	47	75	77	74	72	35	86

Table C-8. Ride Number Filter, Site 4 (Novi).

Correlation	Correlated Device											
Reference	0	1	2	3	4	5	6	7	8	9	10	11
0 Rod and Level	—	15	13	14	14	14	12	15	13	12	10	12
1 SurPro 1000	14	67	33	32	41	41	26	37	10	30	16	19
2 ARRB WP	15	49	—	40	36	38	35	44	22	32	18	13
3 LISA, Angelo	14	48	51	81	51	68	61	75	18	70	24	16
4 ICC LWP	16	58	55	52	74	67	45	59	17	51	27	15
5 LISA, Carlo	14	55	45	68	63	79	49	74	19	66	25	17
6 Dyn/KJL 6400	11	50	51	64	44	55	75	62	22	67	32	13
7 LISA, Ames	18	55	53	75	60	78	55	88	25	66	30	21
8 SSI, LWP	17	17	13	24	18	25	16	25	33	21	8	15
9 MDOT, HSP	12	46	45	70	51	66	61	66	15	70	25	16
10 Dynatest 5051	11	28	27	27	27	27	34	30	7	28	66	8
11 SSI, HSP	13	16	14	18	15	19	14	22	15	17	8	18

Table C-9. Long Wavelength Content, Site 1 (Lansing Airport).

Correlation Reference		Correlated Device											
		0	1	2	3	4	5	6	7	8	9	10	11
0	Rod and Level	—	**96**	**98**	82	78	85	66	**96**	71	39	63	73
1	SurPro 1000	**96**	**99**	**98**	79	75	81	63	**93**	68	36	62	70
2	ARRB WP	**98**	**98**	—	80	76	83	64	**95**	70	37	64	71
3	LISA, Angelo	81	78	80	**98**	**96**	**95**	68	81	74	61	85	73
4	ICC LWP	77	74	75	**96**	**98**	**94**	67	74	70	64	87	71
5	LISA, Carlo	84	81	83	**95**	**94**	**98**	63	80	69	55	88	67
6	Dyn/KJL 6400	68	65	66	72	72	67	**99**	68	87	70	58	**93**
7	LISA, Ames	**96**	**93**	**95**	82	77	83	65	**99**	72	37	58	74
8	SSI, LWP	71	68	69	75	72	70	85	72	**95**	61	57	86
9	MDOT, HSP	38	35	35	62	65	56	66	36	60	93	68	69
10	Dynatest 5051	61	61	62	85	87	88	55	56	57	68	**100**	57
11	SSI, HSP	74	70	71	76	74	70	**91**	75	86	70	58	**99**

Table C-10. Long Wavelength Content, Site 2 (Bay City).

Correlation Reference		Correlated Device											
		0	1	2	3	4	5	6	7	8	9	10	11
0	Rod and Level	—	72	77	67	62	48	35	79	62	56	61	74
1	SurPro 1000	70	69	73	55	50	43	28	63	49	43	53	59
2	ARRB WP	75	74	—	66	55	44	31	69	54	48	57	66
3	LISA, Angelo	67	56	67	84	60	51	45	57	49	63	73	61
4	ICC LWP	61	50	55	60	72	58	45	56	50	62	70	60
5	LISA, Carlo	48	43	44	51	59	82	43	53	51	55	60	59
6	Dyn/KJL 6400	32	28	30	46	46	44	88	42	49	64	62	49
7	LISA, Ames	79	64	69	58	56	53	42	93	77	63	61	89
8	SSI, LWP	62	49	54	51	50	52	48	77	88	60	55	77
9	MDOT, HSP	56	43	49	64	62	55	64	63	59	75	66	70
10	Dynatest 5051	59	50	55	73	69	60	60	60	54	67	93	67
11	SSI, HSP	75	60	67	63	60	60	49	89	77	71	67	89

Table C-11. Long Wavelength Content, Site 3 (General Motors).

Correlation	Correlated Device										
Reference	1	2	3	4	5	6	7	8	9	10	11
1 SurPro 1000	**96**	**94**	89	**92**	**93**	78	**97**	71	**92**	76	**95**
2 ARRB WP	**94**	—	88	**93**	**91**	81	**94**	73	**96**	82	**97**
3 LISA, Angelo	89	88	92	**91**	89	85	**90**	71	89	80	**91**
4 ICC LWP	**93**	**93**	**91**	**95**	**94**	89	**93**	72	**95**	82	**95**
5 LISA, Carlo	**93**	**91**	89	**94**	**97**	83	**92**	70	**93**	73	**94**
6 Dyn/KJL 6400	79	80	85	89	83	**97**	81	62	86	84	84
7 LISA, Ames	**97**	**95**	**90**	**93**	**92**	81	**98**	72	**92**	81	**96**
8 SSI, LWP	72	74	71	72	70	63	72	61	74	63	73
9 MDOT, HSP	**92**	**97**	89	**95**	**93**	86	**92**	74	**97**	83	**95**
10 Dynatest 5051	75	81	79	82	73	84	81	63	82	**97**	83
11 SSI, HSP	**96**	**97**	**91**	**95**	**94**	85	**96**	73	**95**	83	**98**

Table C-12. Long Wavelength Content, Site 4 (Novi).

Correlation	Correlated Device											
Reference	0	1	2	3	4	5	6	7	8	9	10	11
0 Rod and Level	—	85	87	53	66	57	30	87	64	59	43	76
1 SurPro 1000	85	89	**90**	56	67	62	30	86	64	60	45	75
2 ARRB WP	86	**90**	—	58	67	63	32	86	66	61	46	76
3 LISA, Angelo	54	57	59	91	81	83	48	65	59	88	68	66
4 ICC LWP	67	67	68	81	84	78	60	77	69	88	78	81
5 LISA, Carlo	58	62	63	83	78	82	47	67	58	82	64	66
6 Dyn/KJL 6400	31	31	33	49	60	47	**97**	39	47	60	73	51
7 LISA, Ames	87	86	87	65	78	67	39	**98**	74	73	58	88
8 SSI, LWP	64	64	66	59	69	58	47	74	71	67	63	76
9 MDOT, HSP	59	60	61	88	88	82	60	73	67	**96**	79	76
10 Dynatest 5051	44	45	47	69	78	64	73	59	63	79	94	73
11 SSI, HSP	76	75	76	66	81	67	51	88	77	76	73	93

Table C-13. Medium Wavelength Content, Site 1 (Lansing Airport).

Correlation Reference	Correlated Device											
	0	1	2	3	4	5	6	7	8	9	10	11
0 Rod and Level	—	55	55	53	50	57	22	51	51	52	28	41
1 SurPro 1000	57	88	75	68	76	75	29	70	67	72	44	55
2 ARRB WP	57	83	—	84	72	88	31	71	71	72	47	62
3 LISA, Angelo	53	74	88	94	76	**92**	29	76	82	81	53	64
4 ICC LWP	50	81	76	76	93	82	32	75	73	84	52	59
5 LISA, Carlo	57	82	**90**	**92**	81	**97**	31	79	87	88	51	64
6 Dyn/KJL 6400	22	32	34	30	32	31	92	31	28	28	29	33
7 LISA, Ames	52	74	76	76	75	79	31	88	70	71	50	59
8 SSI, LWP	53	76	83	83	73	88	29	70	88	78	41	59
9 MDOT, HSP	51	77	79	83	85	88	28	70	77	91	51	54
10 Dynatest 5051	28	46	50	54	52	51	28	50	41	51	**98**	45
11 SSI, HSP	41	60	66	64	60	64	33	59	59	54	44	89

Table C-14. Medium Wavelength Content, Site 2 (Bay City).

Correlation Reference	Correlated Device											
	0	1	2	3	4	5	6	7	8	9	10	11
0 Rod and Level	—	68	69	17	60	67	64	75	64	61	17	60
1 SurPro 1000	62	84	61	9	59	63	53	68	62	61	11	61
2 ARRB WP	68	69	—	18	54	70	71	73	60	69	17	55
3 LISA, Angelo	17	10	20	78	14	21	23	14	16	19	60	14
4 ICC LWP	61	63	60	13	74	61	55	67	58	60	19	58
5 LISA, Carlo	67	69	73	21	61	77	73	78	72	72	19	69
6 Dyn/KJL 6400	64	62	81	24	55	75	86	74	64	74	23	60
7 LISA, Ames	77	75	76	14	67	78	73	85	74	71	16	71
8 SSI, LWP	65	67	69	16	58	73	70	74	71	67	14	65
9 MDOT, HSP	61	64	77	19	60	72	75	71	65	79	15	65
10 Dynatest 5051	18	11	18	61	19	20	23	16	14	16	81	13
11 SSI, HSP	63	67	66	14	58	70	63	71	65	66	13	68

Table C-15. Medium Wavelength Content, Site 3 (General Motors).

Correlation Reference	Correlated Device										
	1	2	3	4	5	6	7	8	9	10	11
1 SurPro 1000	**96**	84	84	83	75	81	86	75	83	33	85
2 ARRB WP	**91**	—	**91**	85	65	89	**93**	82	87	44	**92**
3 LISA, Angelo	**91**	**91**	**97**	**94**	77	**95**	89	85	**93**	36	**90**
4 ICC LWP	**91**	86	**94**	**95**	84	**91**	85	81	**91**	33	87
5 LISA, Carlo	80	64	77	84	**98**	74	68	62	76	24	69
6 Dyn/KJL 6400	**90**	89	**93**	89	76	**98**	89	81	89	42	**91**
7 LISA, Ames	**91**	**92**	89	85	68	**90**	**97**	81	85	44	**92**
8 SSI, LWP	81	87	85	81	62	84	81	91	85	32	83
9 MDOT, HSP	89	**90**	**93**	**91**	77	**91**	85	85	90	36	88
10 Dynatest 5051	32	44	35	32	24	41	43	31	35	**97**	44
11 SSI, HSP	**90**	**93**	**91**	87	70	**92**	**92**	83	89	44	**96**

Table C-16. Medium Wavelength Content, Site 4 (Novi).

Correlation Reference	Correlated Device											
	0	1	2	3	4	5	6	7	8	9	10	11
0 Rod and Level	—	44	41	35	39	38	33	38	32	33	24	37
1 SurPro 1000	38	87	73	63	71	70	62	69	37	61	36	56
2 ARRB WP	34	79	—	62	70	66	60	69	57	59	39	46
3 LISA, Angelo	35	67	67	93	81	86	82	89	50	88	44	51
4 ICC LWP	39	74	76	81	89	87	76	86	55	78	43	49
5 LISA, Carlo	38	73	73	87	86	92	83	89	52	83	45	53
6 Dyn/KJL 6400	30	67	66	80	73	82	87	79	58	81	50	45
7 LISA, Ames	39	73	73	89	86	89	81	**96**	60	84	47	54
8 SSI, LWP	33	59	53	59	56	61	55	60	56	55	28	43
9 MDOT, HSP	33	64	64	88	78	83	84	84	47	88	45	48
10 Dynatest 5051	24	37	41	45	43	45	51	47	28	46	86	30
11 SSI, HSP	36	54	50	50	49	53	49	55	43	47	30	48

Table C-17. Short Wavelength Content, Site 1 (Lansing Airport).

Correlation	Correlated Device											
Reference	0	1	2	3	4	5	6	7	8	9	10	11
0 Rod and Level	—	19	18	16	17	26	4	12	24	23	7	9
1 SurPro 1000	30	70	23	20	44	34	4	13	29	40	13	16
2 ARRB WP	22	25	—	53	19	65	6	32	39	29	17	32
3 LISA, Angelo	15	30	52	61	23	60	6	38	38	38	17	34
4 ICC LWP	21	62	25	26	78	31	8	20	19	42	19	15
5 LISA, Carlo	26	46	63	60	28	87	5	46	55	64	19	41
6 Dyn/KJL 6400	4	7	9	6	7	5	69	8	6	7	7	5
7 LISA, Ames	15	24	43	42	21	51	9	82	31	36	12	33
8 SSI, LWP	31	33	46	42	20	59	4	31	69	48	13	29
9 MDOT, HSP	23	53	48	41	41	65	6	31	42	65	14	33
10 Dynatest 5051	9	15	20	19	19	21	8	11	13	13	88	10
11 SSI, HSP	10	24	47	38	16	44	6	34	29	36	10	47

Table C-18. Short Wavelength Content, Site 2 (Bay City).

Correlation	Correlated Device											
Reference	0	1	2	3	4	5	6	7	8	9	10	11
0 Rod and Level	—	23	25	7	15	26	20	30	29	18	10	20
1 SurPro 1000	17	76	20	5	36	24	12	34	29	31	8	23
2 ARRB WP	36	36	—	6	14	32	24	33	15	22	7	16
3 LISA, Angelo	7	7	6	53	5	8	7	6	6	7	24	5
4 ICC LWP	18	37	18	5	56	21	11	30	21	28	9	26
5 LISA, Carlo	26	41	42	8	21	59	39	56	38	41	6	25
6 Dyn/KJL 6400	24	28	50	8	14	47	67	45	27	30	6	15
7 LISA, Ames	35	54	48	6	31	59	40	70	44	46	7	29
8 SSI, LWP	32	35	34	6	22	44	34	44	47	32	8	29
9 MDOT, HSP	18	42	37	7	29	41	27	46	27	45	5	24
10 Dynatest 5051	10	7	5	26	9	6	5	7	7	5	65	8
11 SSI, HSP	24	30	22	5	27	28	17	29	29	26	9	37

Table C-19. Short Wavelength Content, Site 3 (General Motors).

Correlation Reference	Correlated Device										
	1	2	3	4	5	6	7	8	9	10	11
1 SurPro 1000	79	34	34	37	20	35	30	40	32	25	31
2 ARRB WP	49	—	43	33	24	41	66	35	35	28	44
3 LISA, Angelo	65	52	88	72	21	70	49	58	76	20	43
4 ICC LWP	64	35	70	81	31	53	34	49	64	22	40
5 LISA, Carlo	27	27	20	31	88	22	16	20	22	27	19
6 Dyn/KJL 6400	70	64	80	62	25	87	60	59	73	20	51
7 LISA, Ames	50	71	53	35	17	68	84	55	49	15	50
8 SSI, LWP	57	53	63	49	21	64	55	74	56	19	65
9 MDOT, HSP	65	49	76	66	22	66	46	51	61	21	40
10 Dynatest 5051	14	20	18	21	27	20	15	19	20	85	20
11 SSI, HSP	44	48	51	40	20	53	50	65	48	19	71

Table C-20. Short Wavelength Content, Site 4 (Novi).

Correlation Reference	Correlated Device											
	0	1	2	3	4	5	6	7	8	9	10	11
0 Rod and Level	—	6	5	8	6	6	5	8	9	5	6	7
1 SurPro 1000	8	59	15	18	28	28	11	22	6	17	9	11
2 ARRB WP	9	26	—	24	16	16	18	25	10	13	10	5
3 LISA, Angelo	8	28	23	71	26	55	37	64	12	56	11	9
4 ICC LWP	7	41	25	26	61	49	18	37	9	27	15	7
5 LISA, Carlo	6	32	17	55	45	68	24	62	13	52	12	9
6 Dyn/KJL 6400	5	29	23	42	16	28	59	39	10	46	15	5
7 LISA, Ames	10	34	25	63	37	67	32	82	17	50	17	13
8 SSI, LWP	11	7	4	16	9	16	7	16	28	12	4	9
9 MDOT, HSP	5	27	16	56	27	52	36	51	10	56	11	9
10 Dynatest 5051	6	18	13	14	15	14	17	17	4	13	50	3
11 SSI, HSP	7	6	4	10	7	10	5	13	9	9	3	13

Table C-21. International Roughness Filter, Site 1, With Distance Correction.

Correlation	Correlated Device											
Reference	0	1	2	3	4	5	6	7	8	9	10	11
0 Rod and Level	—	87	85	77	76	77	69	82	69	63	67	83
1 SurPro 1000	88	**96**	**94**	83	84	84	75	89	76	68	75	**91**
2 ARRB WP	86	**95**	—	86	86	87	78	**91**	79	70	77	**91**
3 LISA, Angelo	77	84	87	**98**	**96**	**98**	76	89	84	86	89	80
4 ICC LWP	76	85	87	**96**	**97**	**96**	76	87	80	89	89	81
5 LISA, Carlo	78	85	88	**98**	**96**	**99**	75	**90**	83	88	88	81
6 Dyn/KJL 6400	69	76	79	76	76	76	**99**	81	69	73	76	79
7 LISA, Ames	82	89	**91**	89	87	**90**	80	**97**	80	72	76	86
8 SSI, LWP	69	76	79	84	80	83	68	80	**95**	69	70	73
9 MDOT, HSP	63	69	70	87	**90**	88	73	73	69	**96**	**94**	80
10 Dynatest 5051	69	78	80	89	**90**	89	75	76	70	**95**	**100**	84
11 SSI, HSP	83	**91**	**91**	80	82	81	79	86	73	80	83	**97**

Table C-22. International Roughness Filter, Site 2, With Distance Correction.

Correlation	Correlated Device											
Reference	0	1	2	3	4	5	6	7	8	9	10	11
0 Rod and Level	—	73	78	70	74	73	70	81	71	70	73	71
1 SurPro 1000	70	87	71	67	68	74	65	76	72	65	69	68
2 ARRB WP	76	77	—	82	71	80	77	83	74	78	69	72
3 LISA, Angelo	72	71	83	84	71	78	82	77	76	83	70	76
4 ICC LWP	74	69	72	69	78	73	71	76	71	68	77	66
5 LISA, Carlo	74	76	76	77	73	79	76	81	77	78	72	76
6 Dyn/KJL 6400	71	69	81	83	72	77	89	76	73	83	70	71
7 LISA, Ames	81	80	80	76	76	80	75	87	78	74	74	76
8 SSI, LWP	71	73	75	75	70	76	74	78	76	73	67	71
9 MDOT, HSP	71	68	80	83	68	78	83	75	73	83	70	74
10 Dynatest 5051	72	67	72	70	77	72	70	74	67	69	84	67
11 SSI, HSP	70	70	74	74	66	75	71	76	71	74	67	72

Table C-23. International Roughness Filter, Site 3, With Distance Correction.

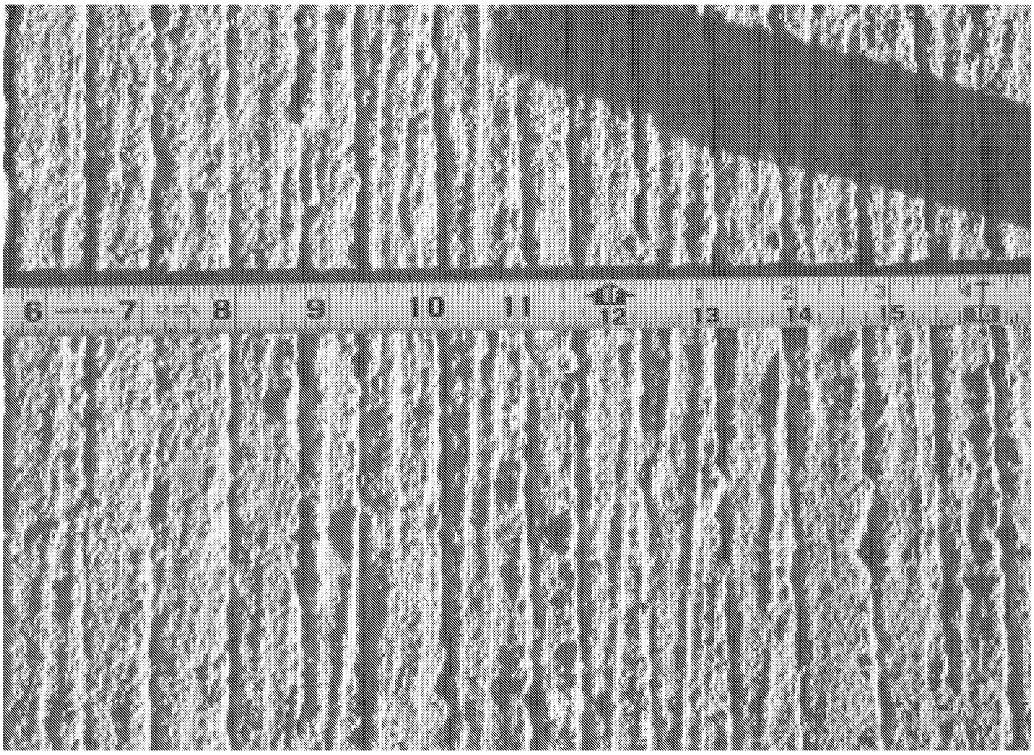
Correlation Reference	Correlated Device										
	1	2	3	4	5	6	7	8	9	10	11
1 SurPro 1000	**97**	**91**	89	**90**	**92**	84	**94**	81	87	88	**91**
2 ARRB WP	**95**	—	**94**	**95**	**95**	89	**94**	86	**92**	**92**	**95**
3 LISA, Angelo	**92**	**95**	**98**	**96**	**93**	**94**	**92**	86	**93**	**91**	**94**
4 ICC LWP	**92**	**94**	**96**	**95**	**93**	**93**	**92**	85	**92**	**91**	**94**
5 LISA, Carlo	**95**	**92**	**92**	**93**	**98**	**90**	**95**	83	**91**	**94**	**95**
6 Dyn/KJL 6400	87	**90**	**94**	**93**	**91**	**98**	88	82	**90**	**93**	**90**
7 LISA, Ames	**95**	**92**	**91**	**92**	**95**	87	**97**	82	88	87	**92**
8 SSI, LWP	83	88	86	85	83	82	82	85	86	82	85
9 MDOT, HSP	**90**	**95**	**94**	**92**	**91**	**91**	88	87	**93**	**92**	**93**
10 Dynatest 5051	89	**92**	**91**	**91**	**93**	**93**	87	82	**92**	**97**	**94**
11 SSI, HSP	**93**	**95**	**94**	**94**	**95**	**90**	**92**	84	**93**	**94**	**96**

Table C-24. International Roughness Filter, Site 4, With Distance Correction.

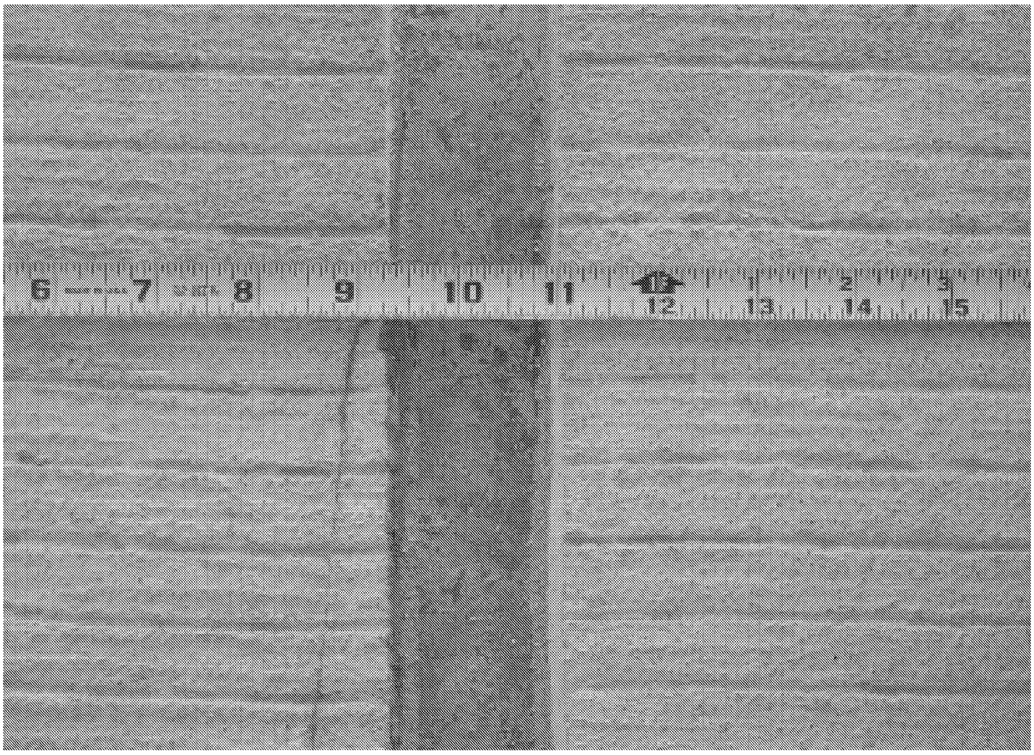
Correlation Reference	Correlated Device											
	0	1	2	3	4	5	6	7	8	9	10	11
0 Rod and Level	—	54	53	47	50	50	41	49	43	45	46	50
1 SurPro 1000	53	89	80	73	77	78	65	78	72	70	68	73
2 ARRB WP	52	85	—	74	79	79	67	79	71	72	71	72
3 LISA, Angelo	47	74	76	94	89	89	83	**91**	75	**90**	81	68
4 ICC LWP	50	78	80	89	91	89	83	**92**	73	87	84	66
5 LISA, Carlo	50	79	80	88	89	92	82	89	75	86	78	73
6 Dyn/KJL 6400	42	68	69	82	83	83	91	79	69	85	79	64
7 LISA, Ames	49	80	81	**90**	**92**	89	80	**98**	73	87	82	68
8 SSI, LWP	42	69	68	71	71	73	63	72	66	68	60	55
9 MDOT, HSP	46	72	74	**90**	87	86	85	88	72	90	80	66
10 Dynatest 5051	46	70	71	81	84	78	79	82	60	81	88	62
11 SSI, HSP	49	68	66	62	66	67	57	67	55	61	61	61

Appendix D: Photos

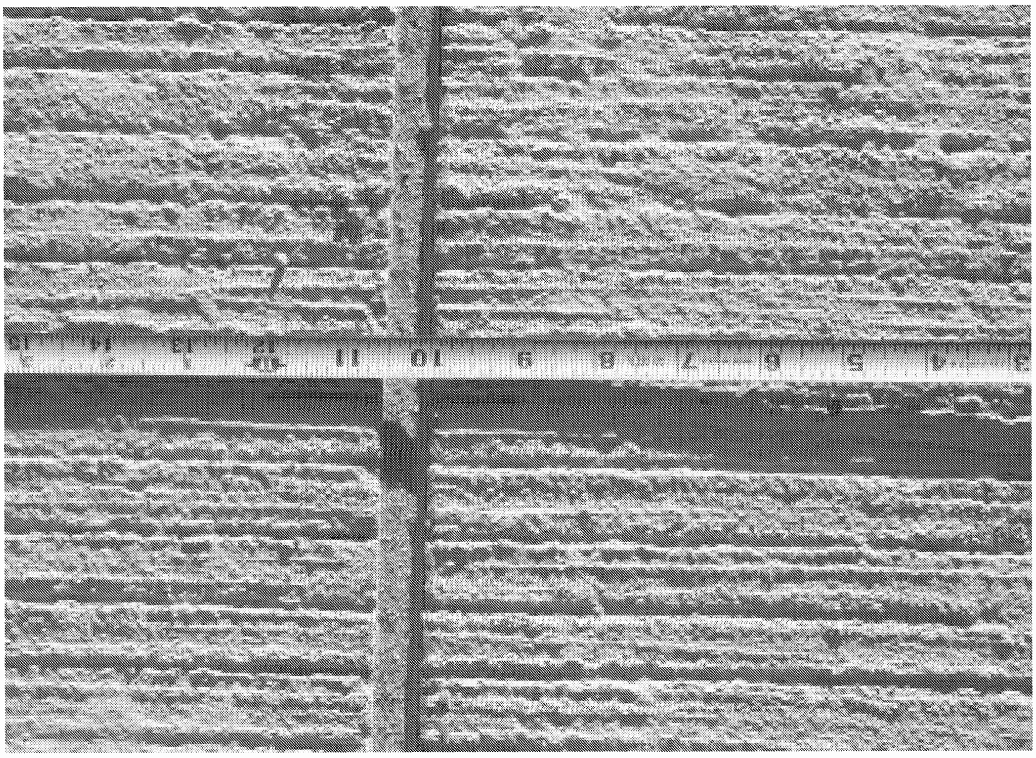
This appendix displays some photos that were taken during the experiment. Some of the sites and devices were not photographed. (No photographs were taken at the General Motors site.)



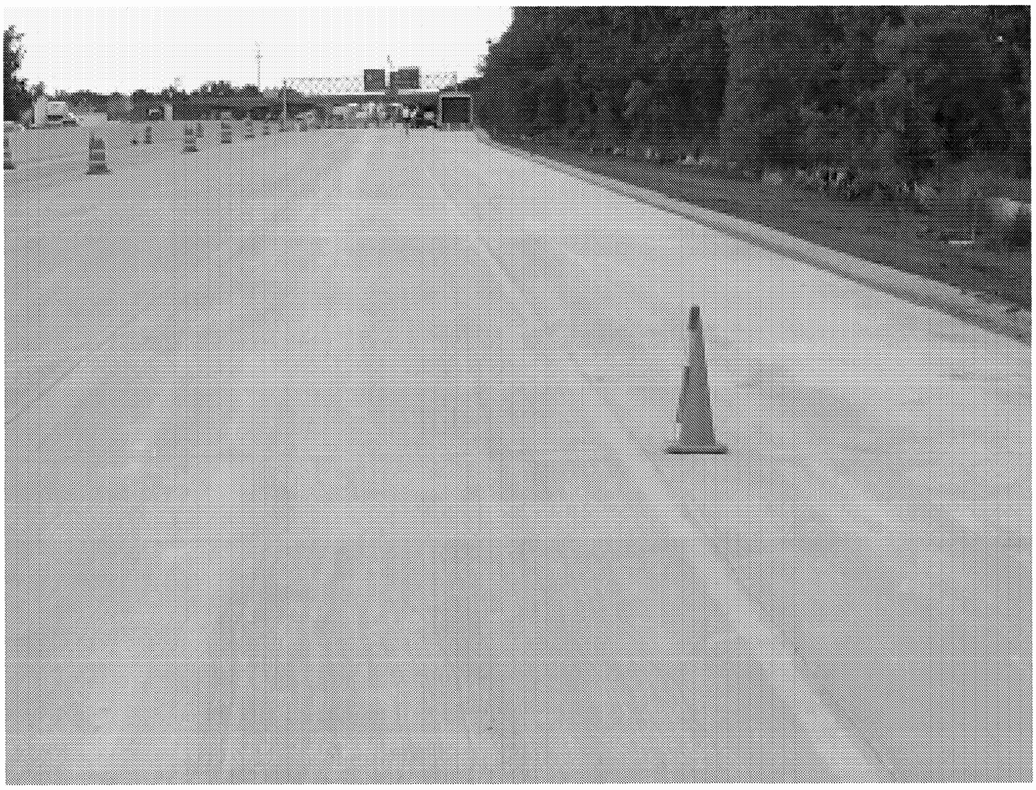
Site 2 (Bay City) Texture, Directon of Travel Bottom to Top.



Site 2 (Bay City) Expansion Joint, Direction of Travel Left to Right.



Site 2 (Bay City) Contraction Joint, Direction of Travel Left to Right.

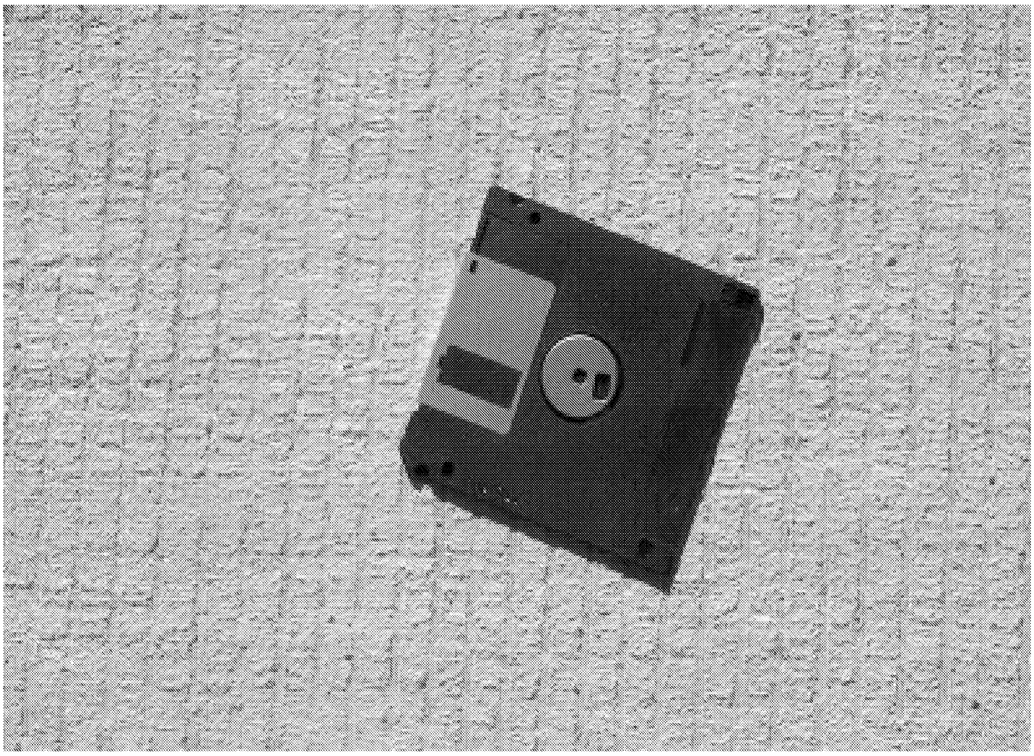


Site 2 (Bay City) Long View, Looking Downstream.

Site 2 (Bay City) Long View, Looking Upstream.

Site 4 (Novi) Long View, Looking Downstream.

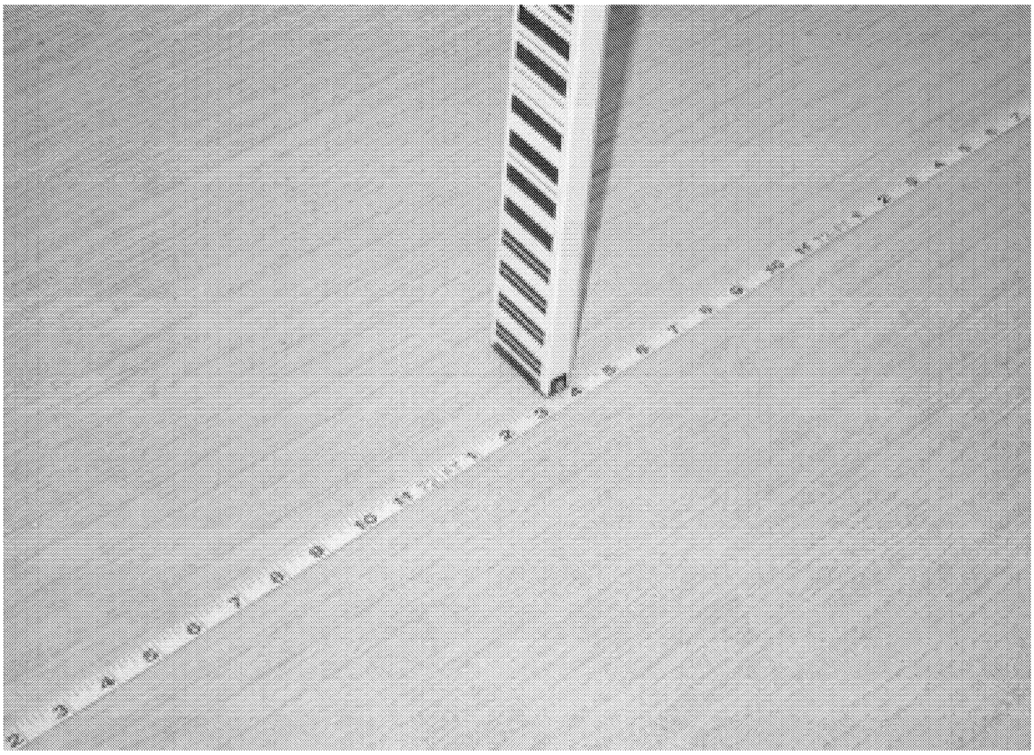
Site 4 (Novi) Long View, Looking Upstream



Site 4 (Novi) Texture, Direction of Travel Left to Right.

Optical Level at Site 2

Rod and Operator at Site 2



Rod and Tape at Site 2

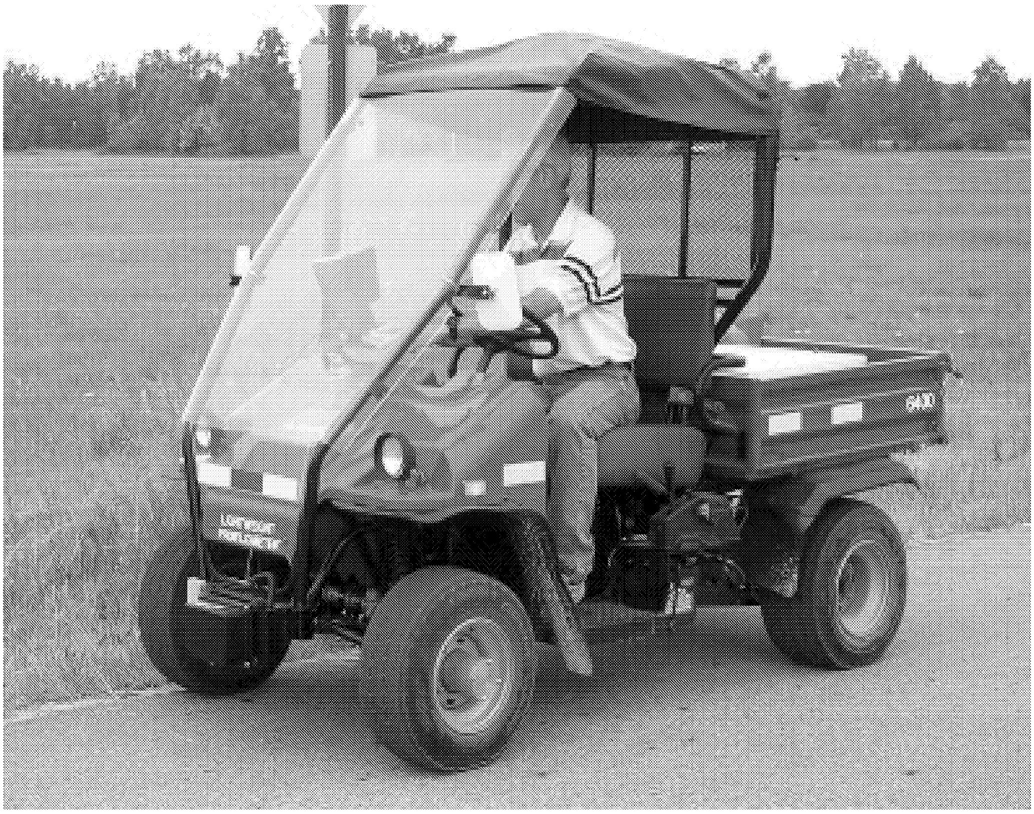
Rod Footprint

Site 1 (Lansing) Long View, Looking Downstream, Walking Devices

Cox Profilograph at Site 1

SurPro 1000 at Site 4

Walking Profiler at Site 4



Dynatest/KJL 6400 Lightweight Profiler at Site 1

International Cybernetics Corporation Lightweight Profiler at Site 1

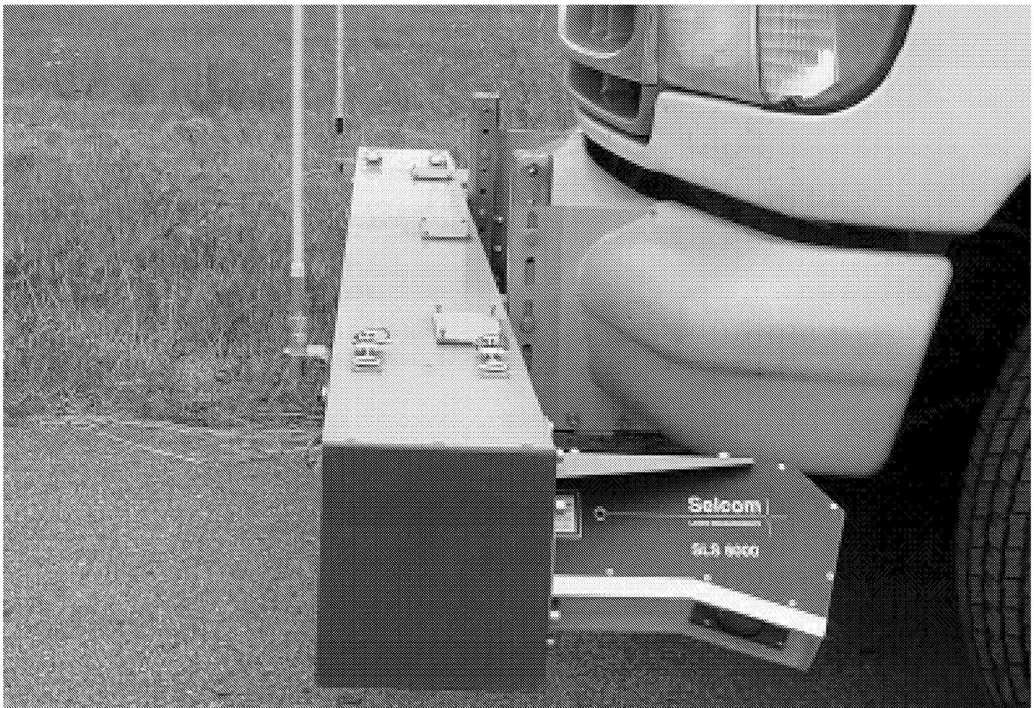
Surface System Instruments Lightweight Profiler at Site 1

AMES LISA at Site 1, Operated by AMES Engineering.

AMES LISA at Site 1, Operated by John Carlo Construction.

AMES LISA at Site 1, Operated by Tony Angelo Cement Construction.

Dynatest 5051 High-Speed Profiler at Site 1



Dynatest 5051 Sensor Bar

Surface Systems Instruments High-Speed Profiler at Site 4.

ZF Industries High-Speed Profiler at Site 2.