A comparison between the four International Cybernetics Corporation profilers used by the LTPP Regional Support Contractors to collect profile data was performed from May 17 to 20, 2010 at the MnROAD facility in Albertville, Minnesota. This was the third comparison between the four LTPP ICC profilers after they went into operation in August 2002. The two previous profiler comparisons were also held at MnROAD, with the first held in July 2003 and the second in May 2007. Six test sections were used for profile testing and one test section was used to evaluate the accuracy of the Distance Measuring Instrument (DMI) in the profiler. The purpose of the profiler comparison was to: (1) evaluate the static accuracy of the height sensors in the profilers, (2) evaluate the results from the bounce test, (3) evaluate the accuracy of the DMI, (4) compare IRI values obtained by the profilers with those obtained from two reference devices (Dipstick and SurPRO), (5) compare the IRI values between the profilers, (6) compare the profiles obtained by the profilers, and (7) evaluate the repeatability and accuracy cross correlation values for each profiler.
### SI* (Modern Metric) Conversion Factors

#### Approximate Conversions to SI Units

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#### Illumination

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| tl | foot-Lamberts | 3.426 | candela/m² | cd/m² |

#### Force and Pressure or Stress

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#### Illumination

| lx | foot-candles | 0.0929 | foot-Lamberts | tl |
| cd/m² | candela/m² | 0.2819 | foot-Lamberts | tl |

#### Force and Pressure or Stress

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*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E188. (Revised March 2003)
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ACKNOWLEDGEMENTS

The LTPP profiler comparison was held at the MnROAD facility located in Albertville, Minnesota, which is maintained by the Minnesota Department of Transportation (Mn/DOT). The cooperation extended by the staff at MnROAD during the profiler comparison is acknowledged. In particular, the cooperation extended by Mr. Tim Clyne (Mn/DOT Office of Materials and Road Research) during the planning and scheduling phase is gratefully acknowledged.
CHAPTER 1 - INTRODUCTION

In the Long Term Pavement Performance (LTPP) Program, profile data at General Pavement Studies (GPS) and Specific Pavement Studies (SPS) sections are collected by four Regional Support Contractors. Each Regional Support Contractor (RSC) uses an International Cybernetics Corporation (ICC) MDR 4083 inertial profiler to collect profile data. These profilers are equipped with three laser sensors that collect data along the left and right wheelpaths, and along the center of the lane. Profile data are collected at 25-mm intervals along each of these paths.

After completion of data collection, the ProQual software is used to obtain profile data at 150-mm intervals along the left and right wheelpaths. This software applies a 300-mm moving average on the profile data collected at 25-mm intervals, and then saves the data at 150-mm intervals. This software also computes the left and right wheelpath International Roughness Index (IRI) of each section using the 150-mm interval data. After quality assurance checks, the 150-mm interval profile data as well as the computed IRI values are uploaded to the LTPP database. The profile data collected at 25-mm intervals are stored as part of the LTPP Ancillary Information Management System (AIMS).

A comparison between the four ICC profilers used by the LTPP RSCs was performed from May 17 to 20, 2010. This comparison was performed at the MnROAD facility in Albertville, Minnesota. This was the third comparison between the four LTPP ICC profilers after they went into operation in August 2002. The two previous profiler comparisons were also held at MnROAD, with the first held in July 2003 and the second in May 2007.

The profiler comparison was carried out using the procedures described in the LTPP Manual for Profile Measurements and Processing,\(^{(1)}\) hereafter referred to as the Profile Manual. Six test sections were used for profile testing and one test section was used to evaluate the accuracy of the Distance Measuring Instrument (DMI) in the profiler.

The purpose of the profiler comparison was to: (1) evaluate the static accuracy of the height sensors in the profilers, (2) evaluate the results from the bounce test, (3) evaluate the accuracy of the DMI, (4) compare IRI values obtained by the profilers with those obtained from two reference devices (Dipstick and SurPRO), (5) compare the IRI values between the profilers, (6) compare the profiles obtained by the profilers, and (7) evaluate the repeatability and accuracy cross correlation values for each profiler.

After completion of the profiler comparison, each RSC summarized the results obtained for their profiler, and forwarded a report and the collected data to the Federal Highway Administration (FHWA) and its Technical Support Services Contractor (TSSC). This report summarizes the activities that were conducted during the profiler comparison and presents the results of the inter-regional comparison between the LTPP profilers.
CHAPTER 2 - TEST PLAN AND TEST SECTIONS

2.1 Test Plan

The following tests were carried out during the profiler comparison:

1. Static Height Sensor Test: This test was performed to evaluate the precision and bias of the profiler height sensors in the static mode.

2. Bounce Test: This test was performed to see if the height sensors and the accelerometers in the profiler were functioning properly.

3. DMI Test: This test was performed to evaluate the precision and bias of the DMI.

4. Profiling of Test Sections: Six test sections were profiled by all profilers. Reference measurements at the test sections were obtained using the Dipstick and the SurPRO rolling profiler.

2.2 Test Sections

One test section was established for DMI testing, and six test sections were established for profile testing. The sections established for profile testing were: a smooth asphalt concrete (AC) sections, a rough AC section, two medium smooth portland cement concrete (PCC) sections, a rough PCC section, and a chip seal section.

The 300-m long DMI section was established on the mainline of MnROAD. All profile test sections were 152.4 m long, and were established on the MnROAD low-volume loop except for one section that was established on the mainline. Table 2.1 lists the test sections that were used as profile sections. All sections were profiled in the travel direction.

Table 2.1. Profile test sections.

<table>
<thead>
<tr>
<th>Test Section</th>
<th>Surface Type</th>
<th>Location</th>
<th>Roughness Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AC</td>
<td>Mainline</td>
<td>Smooth</td>
</tr>
<tr>
<td>2</td>
<td>AC</td>
<td>Low Volume Road</td>
<td>Rough</td>
</tr>
<tr>
<td>3</td>
<td>PCC</td>
<td>Low Volume Road</td>
<td>Medium Smooth</td>
</tr>
<tr>
<td>4</td>
<td>PCC</td>
<td>Low Volume Road</td>
<td>Medium Smooth</td>
</tr>
<tr>
<td>5</td>
<td>Chip Seal</td>
<td>Low Volume Road</td>
<td>Rough</td>
</tr>
<tr>
<td>6</td>
<td>PCC</td>
<td>Low Volume Road</td>
<td>Rough</td>
</tr>
</tbody>
</table>

Section 1 (Smooth AC): The outside lane of cell 20 was used as section 1. This section was profiled in the westbound direction. This section had no distress.

Section 2 (Rough AC): This section was profiled in the westbound direction and was located in the inside lane of the low-volume road. The beginning of the section was located at the beginning of Cell 77. Cell 77 is located within Cell 29. The established section encompassed
Cell 77, the transition area between Cells 29 and 28, and a portion of Cell 28. The first 107 m of this section had no distress. Surface raveling and distortions were observed along the last 45 m of this section. A 6.4-m long patch was located close to the end of the section with the beginning and the ending limits of the patch being 30.2 m and 23.8 m from the end of the section.

Section 3 (Medium Smooth PCC): This section was profiled in the eastbound direction and was located on the inside lane of the low volume road. The beginning of the section was approximately 6.5 m before the start of Cell 37. This section is transversely tined, and has skewed joints that are 4.6 m apart. This section had no distress.

Section 4 (Medium Smooth PCC): This section was profiled in the westbound direction and was located on the outside lane of the low volume road. The beginning of the section was approximately 61 m after the end of the grinding passes that were present in the outside lane. This section is transversely tined, and has skewed joints that are 4.6 m apart. This section had no distress.

Section 5 (Chip Seal): This section was profiled in the westbound direction and was located on the inside lane of the low volume road. The beginning of the section was approximately 9.5 m before the sign that indicated 27 (located on the fence). This section had no distress.

Section 6 (Rough PCC): This section was profiled in the westbound direction and was located on the inside lane of the low volume road. The beginning of the section was approximately 18 m after the sign that indicated 32 (located on the fence). The first 16.8 m of this section consist of slabs with a joint spacing of 4.6 m, with the start of the section located 1.5 m in front of a joint. The rest of the section had slabs with a joint spacing of 3 m. All slabs in the section had a broomed texture. There was no distress within the section. However, the slabs were curled upward resulting in a very rough ride.

Photographs of the test sections are included in Appendix A. Paint marks were placed along the left and right wheelpaths at 6-m intervals within all sections, as well as up to a distance of 61 m before the section. The paint marks were placed to aid the driver to align the profiler along the path to be tested and to maintain the path within the test section. In test sections 3 and 4, the wheelpaths were located such that they avoided metal plates and core holes that were located within the section.
CHAPTER 3 - STATIC HEIGHT SENSOR TEST

3.1 Overview

The purpose of performing the static height sensor test is to evaluate the precision and bias of the height sensors of the profiler in the static mode. The specified requirements outlined in the Profile Manual are that the bias be within 0.25 mm and the precision be less than 0.125 mm.

3.2 Test Procedure

The static height sensor test was performed on each height sensor using the following procedure.

1. Measure distance from the ground to the glass face of the height sensor, and record the reading for each height sensor.

2. Drive the vehicle onto support blocks so that all four tires rest on support blocks. The height of each support block is 76 mm.

3. Place a calibration base plate on the ground under each laser sensor. Place a calibration surface plate on top of each base plate. Let the computer take at least 500 readings.

4. Place a block on each base plate such that the 25 mm side of the block is vertical. Place a calibration surface plate on top of each block. Let computer take at least 500 readings and then record value shown for ‘Dif Ht’ on the computer screen for each sensor. This value represents the height of the block which is measured by the height sensor.

5. Repeat steps 3 and 4 four more times and record readings.

6. Repeat steps 3 through 6 for block heights of 50, 75, and 100 mm. For the 100-mm block height, place two blocks on top of each other such that the 50 mm sides are vertical to get a block height of 100 mm.

3.3 Test Results

The static height sensor test could not be performed on the center sensor of the North Atlantic and the North Central profilers, as the center accelerometer in these profilers was not working. Although the issue was with the accelerometer and not with the height sensor, because the way the electronics was configured, this test could not be performed. The data obtained from the static height sensor test for each profiler are included in Appendix B. The bias and precision of each height sensor for block heights of 25, 50, 75, and 100 mm were computed from the data included in Appendix B. For example, at the 25-mm block position, the bias of the height sensor is the difference between the average of the five block heights measured by the profiler for the five repeat tests and the actual height of the block. The precision of the height sensor is the standard deviation of the block heights measured by the profiler at this position for the five tests.

The defective center sensor accelerometer in the North Atlantic and the North Central profilers was replaced about a month after the profiler comparison. The static height sensor test was then
performed on the center sensor of these two profilers at the RSC facility. The data obtained from this test are included in appendix B.

Tables 3.1 and 3.2, respectively, present the bias and precision values for the three height sensors in each profiler corresponding to the 25, 50, 75, and 100 mm heights. The center sensor results shown for the North Atlantic and North Central profilers are the values obtained from the tests performed at the RSC facility. Cases that failed the criterion are shown in bold in these tables. These bias values are shown in figure 3.1, where the upper and lower limits of 0.25 mm and -0.25 mm are shown by a bold horizontal line. The precision values are shown in figure 3.2, with the limiting value of 0.125 mm shown by a bold horizontal line.

The LTPP specified criteria are that the bias of the sensors be within 0.25 mm and the precision of the sensors be less than 0.125 mm. All sensors in all profilers met the bias criterion at all four positions except for the center sensor in the North Atlantic and North Central profiler that failed the bias criterion for the following positions: (1) North Atlantic profiler at 50, 75 and 100 mm positions, and (2) North Central profiler at 75 and 100 mm positions. All sensors in all profilers met the precision criterion at all four positions except for the center sensor in the North Atlantic profiler that failed the criterion at the 25 and 100 mm positions.

Table 3.3 shows the measured distance from the ground to the sensor glass of the height sensors in each profiler. These distances for the North Atlantic, North Central, and Southern profilers were measured again at the RSC facility after the profiler comparison, as the distances were not within tolerance. Cases that failed the criterion are shown in bold in these tables. The slope of the surface on which the profiler is parked influences the measured distance from the ground to the sensor glass. As the measurements made at MnROAD may have been affected by the slope of the surface in which the profiler was parked, the measurements at the RSC facility were performed at a location in the garage where the surface was level. The values measured at the RSC facility are also shown in table 3.3. According to the Profile Manual, the distance from the ground to the glass face of the height sensor should be 325 ± 5 mm. The following is a summary of the results that were obtained:

- All sensors in the Western profiler met the specified criterion.
- All sensors in the North Central profiler had values that were slightly above the allowable upper value for the measurements obtained at MnROAD. However, the measurements obtained at the RSC facility met the specified criterion.
- The left and center sensor sensors of the North Atlantic profiler had values that were slightly above the allowable upper value for the measurements obtained at MnROAD. However, the measurements obtained at the RSC facility indicated that all sensors met the specified criterion.
- All sensors in the Southern profiler had values that were slightly below the allowable lower value for the measurements obtained at MnROAD. The center sensor met the specified criterion for the measurements obtained at the RSC facility. For the left and right sensor, the measurements obtained at the RSC facility were below the lower allowable value by 6 and 3 mm respectively; however, these values were slightly closer to the lower allowable value when compared to those obtained at MnROAD. A slight deviation outside the specified range (i.e., 3 to 6 mm) is not expected to have an effect on the quality of the data collected by the profiler.
Table 3.1. Bias values from the static height sensor test.

<table>
<thead>
<tr>
<th>Position</th>
<th>Sensor</th>
<th>Profiler North Atlantic</th>
<th>Profiler North Central</th>
<th>Profiler Southern</th>
<th>Profiler Western</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 mm</td>
<td>Left</td>
<td>-0.06</td>
<td>-0.06</td>
<td>0.06</td>
<td>-0.05</td>
</tr>
<tr>
<td></td>
<td>Center</td>
<td>-0.20</td>
<td>-0.12</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>-0.10</td>
<td>-0.12</td>
<td>-0.05</td>
<td>-0.05</td>
</tr>
<tr>
<td>50 mm</td>
<td>Left</td>
<td>0.09</td>
<td>-0.12</td>
<td>0.05</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>Center</td>
<td>-0.29</td>
<td>-0.16</td>
<td>0.13</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>-0.02</td>
<td>-0.01</td>
<td>0.09</td>
<td>0.05</td>
</tr>
<tr>
<td>75 mm</td>
<td>Left</td>
<td>-0.02</td>
<td>-0.05</td>
<td>0.03</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>Center</td>
<td>-0.38</td>
<td>-0.29</td>
<td>0.18</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>0.02</td>
<td>0.02</td>
<td>0.11</td>
<td>-0.03</td>
</tr>
<tr>
<td>100 mm</td>
<td>Left</td>
<td>-0.05</td>
<td>-0.05</td>
<td>-0.01</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>Center</td>
<td>-0.51</td>
<td>-0.42</td>
<td>0.05</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>0.02</td>
<td>-0.02</td>
<td>0.18</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 3.2. Precision values from the static height sensor test.

<table>
<thead>
<tr>
<th>Position</th>
<th>Sensor</th>
<th>Profiler North Atlantic</th>
<th>Profiler North Central</th>
<th>Profiler Southern</th>
<th>Profiler Western</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 mm</td>
<td>Left</td>
<td>0.060</td>
<td>0.102</td>
<td>0.103</td>
<td>0.059</td>
</tr>
<tr>
<td></td>
<td>Center</td>
<td>0.141</td>
<td>0.072</td>
<td>0.107</td>
<td>0.023</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>0.058</td>
<td>0.042</td>
<td>0.059</td>
<td>0.079</td>
</tr>
<tr>
<td>50 mm</td>
<td>Left</td>
<td>0.071</td>
<td>0.110</td>
<td>0.083</td>
<td>0.093</td>
</tr>
<tr>
<td></td>
<td>Center</td>
<td>0.093</td>
<td>0.027</td>
<td>0.068</td>
<td>0.068</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>0.055</td>
<td>0.079</td>
<td>0.049</td>
<td>0.025</td>
</tr>
<tr>
<td>75 mm</td>
<td>Left</td>
<td>0.106</td>
<td>0.062</td>
<td>0.055</td>
<td>0.024</td>
</tr>
<tr>
<td></td>
<td>Center</td>
<td>0.030</td>
<td>0.047</td>
<td>0.066</td>
<td>0.064</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>0.101</td>
<td>0.014</td>
<td>0.066</td>
<td>0.059</td>
</tr>
<tr>
<td>100 mm</td>
<td>Left</td>
<td>0.045</td>
<td>0.120</td>
<td>0.042</td>
<td>0.044</td>
</tr>
<tr>
<td></td>
<td>Center</td>
<td>0.220</td>
<td>0.058</td>
<td>0.014</td>
<td>0.044</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>0.044</td>
<td>0.069</td>
<td>0.026</td>
<td>0.060</td>
</tr>
</tbody>
</table>
Figure 3.1. Bias values from static height sensor test (NA- North Atlantic, NC – North Central, SO – Southern, WE – Western).
Figure 3.2. Precision values for height sensors from static height sensor test (NA- North Atlantic, NC – North Central, SO – Southern, WE – Western).
Table 3.3. Distance from ground to sensor glass.

<table>
<thead>
<tr>
<th>Profiler</th>
<th>Location of Test</th>
<th>Distance From Ground to Sensor Glass (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Left Sensor</td>
</tr>
<tr>
<td>North Atlantic</td>
<td>MnROAD</td>
<td>332</td>
</tr>
<tr>
<td></td>
<td>RSC Facility</td>
<td>320</td>
</tr>
<tr>
<td>North Central</td>
<td>MnROAD</td>
<td>332</td>
</tr>
<tr>
<td></td>
<td>RSC Facility</td>
<td>328</td>
</tr>
<tr>
<td>Southern</td>
<td>MnROAD</td>
<td>313</td>
</tr>
<tr>
<td></td>
<td>RSC Facility</td>
<td>314</td>
</tr>
<tr>
<td>Western</td>
<td>MnROAD</td>
<td>328</td>
</tr>
</tbody>
</table>
CHAPTER 4 - BOUNCE TEST RESULTS

A bounce test was performed on May 17, 2010 on all profilers after the static height sensor test was completed and the accelerometers were calibrated. The bounce test was performed according to the procedures outlined in the Profile Manual. All profilers performed another bounce test before collecting profile data on May 19, 2010. The bounce test consists of a static test and a dynamic bounce test. The static test is performed to evaluate the noise in the sensors. In this test, the profile is recorded while the vehicle is stationary. During the dynamic bounce test, a bouncing motion is induced on the profiler. The profile recorded during the static test and dynamic bounce test are used to compute an IRI value for each test.

Table 4.1 presents the IRI values from the static and dynamic bounce test, as well as the difference in IRI value between the dynamic and static test. Results from the bounce test were not available for the center sensor of the North Atlantic and North Central profilers as the center sensor accelerometer in both profilers was not working. According to the criteria presented in the Profile Manual, the static test IRI value should not exceed 0.08 m/km, while the difference in IRI from the dynamic bounce and static test should not exceed 0.10 m/km. All sensors in all profilers satisfied the required criteria.

<table>
<thead>
<tr>
<th>Profiler</th>
<th>Date</th>
<th>IRI Value (m/km)</th>
<th>Static Test</th>
<th>Dynamic Test</th>
<th>Dynamic Minus Static</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Left</td>
<td>Center</td>
<td>Right</td>
</tr>
<tr>
<td>North Atlantic</td>
<td>5/17/09</td>
<td>0.05</td>
<td>N/A</td>
<td>0.05</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>5/19/10</td>
<td>0.04</td>
<td>N/A</td>
<td>0.04</td>
<td>N/A</td>
</tr>
<tr>
<td>North Central</td>
<td>5/17/09</td>
<td>0.04</td>
<td>N/A</td>
<td>0.05</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>5/19/10</td>
<td>0.04</td>
<td>N/A</td>
<td>0.04</td>
<td>N/A</td>
</tr>
<tr>
<td>Southern</td>
<td>5/17/09</td>
<td>0.07</td>
<td>0.07</td>
<td>0.07</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>5/19/10</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>0.09</td>
</tr>
<tr>
<td>Western</td>
<td>5/17/09</td>
<td>0.04</td>
<td>0.05</td>
<td>0.05</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>5/19/10</td>
<td>0.04</td>
<td>0.04</td>
<td>0.05</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Note: Center sensor accelerometers in the North Atlantic and North Central profilers was not working.

A bounce test performed at the RSC facility after the profiler comparison test once the defective center sensor accelerometer was replaced in the North Central profiler indicated a static test IRI of 0.02 m/km and a dynamic bounce test IRI of 0.10 m/km. These values were within the LTPP required criteria. Shortly after the defective center sensor accelerometer was replaced in the North Atlantic profiler, there were some problems with the center height sensor, and hence center sensor bounce test results are not available for this profiler.
CHAPTER 5 - DMI TEST RESULTS

5.1 Overview

The purpose of the DMI test is to evaluate the bias and precision of the DMI in the profiler. The specified criteria are that the DMI bias should be within 0.05 percent of the distance and that the DMI precision be less than 0.025 percent of the distance (see Section 6 of the Profile Manual). A 300 m long section was laid out as the DMI section. For a 300 m long section, the bias and precision values are 0.15 and 0.075 m, respectively.

5.2 Test Procedure

Each profiler operator used the DMI section to calibrate the DMI of the profiler following the procedures outlined in the Profile Manual prior to obtaining profile measurements. Immediately after the DMI was calibrated, each operator performed six profiler runs on the DMI section and recorded the distance measured between the start and the end of the DMI section. After profiling all test sections, each profiler operator again performed six repeat runs at the DMI section and recorded the distance between the start and end of the section. The purpose of obtaining the second set of measurements was to evaluate the stability of the DMI over time.

5.3 Test Results

Table 5.1 shows the results obtained from the DMI tests that were conducted immediately after calibrating the DMI. Table 5.1 shows the following information: tire pressure before and after the test, the air temperature noted from the temperature probe in the profiler before and after the test, the DMI reading for each run, average of DMI readings, the standard deviation of DMI readings, and whether the profiler met the bias and the precision criterion. As seen from the results presented in this table, all profilers met the DMI bias as well as the DMI precision criterion.

Table 5.2 presents the results of the verification testing of the DMI that was performed after the profilers completed data collection at the six profile test sections. As seen from the results presented in this table, all profilers met the precision criterion. However, the North Atlantic and Western profilers failed the bias criterion.
Table 5.1. Results from the DMI test performed immediately after calibration.

<table>
<thead>
<tr>
<th>Description</th>
<th>Profiler</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>North Atlantic</td>
</tr>
<tr>
<td>DMI Reading - Run 1 (m)</td>
<td>299.965</td>
</tr>
<tr>
<td>DMI Reading - Run 2 (m)</td>
<td>300.024</td>
</tr>
<tr>
<td>DMI Reading - Run 3 (m)</td>
<td>300.004</td>
</tr>
<tr>
<td>DMI Reading - Run 4 (m)</td>
<td>300.024</td>
</tr>
<tr>
<td>DMI Reading - Run 5 (m)</td>
<td>299.946</td>
</tr>
<tr>
<td>DMI Reading - Run 6 (m)</td>
<td>300.004</td>
</tr>
<tr>
<td>Average (m)</td>
<td>299.99</td>
</tr>
<tr>
<td>Length of Section (m)</td>
<td>300.00</td>
</tr>
<tr>
<td>Bias (m)</td>
<td>-0.01</td>
</tr>
<tr>
<td>Standard Deviation (m)</td>
<td>0.032</td>
</tr>
<tr>
<td>Bias Criterion Satisfied?</td>
<td>Yes</td>
</tr>
<tr>
<td>Precision Criterion Satisfied?</td>
<td>Yes</td>
</tr>
</tbody>
</table>

| Left rear tire pressure before test (psi) | 80 | 80 | 80 | 80 |
| Left rear tire pressure after test (psi)  | 80 | 80 | 80 | 80 |
| Right rear tire pressure before test (psi)| 80 | 80 | 80 | 80 |
| Right rear tire pressure after test (psi)| 80 | 80 | 80 | 80 |
| Before Measurements - Air Temp. (°C)      | 21.4 | 24.5 | 26.4 | 23.2 |
| After Measurements - Air Temp. (°C)       | 20.6 | 25.3 | 25.7 | 23.8 |

Table 5.2. Results from the DMI test performed after profiling the test sections.

<table>
<thead>
<tr>
<th>Description</th>
<th>Profiler</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>North Atlantic</td>
</tr>
<tr>
<td>DMI Reading - Run 1 (m)</td>
<td>300.219</td>
</tr>
<tr>
<td>DMI Reading - Run 2 (m)</td>
<td>300.278</td>
</tr>
<tr>
<td>DMI Reading - Run 3 (m)</td>
<td>300.259</td>
</tr>
<tr>
<td>DMI Reading - Run 4 (m)</td>
<td>300.278</td>
</tr>
<tr>
<td>DMI Reading - Run 5 (m)</td>
<td>300.239</td>
</tr>
<tr>
<td>DMI Reading - Run 6 (m)</td>
<td>300.239</td>
</tr>
<tr>
<td>Average</td>
<td>300.252</td>
</tr>
<tr>
<td>Length of Section (m)</td>
<td>300.00</td>
</tr>
<tr>
<td>Bias (m)</td>
<td>0.25</td>
</tr>
<tr>
<td>Standard Deviation (m)</td>
<td>0.024</td>
</tr>
<tr>
<td>Bias Criterion Satisfied?</td>
<td>No</td>
</tr>
<tr>
<td>Precision Criterion Satisfied?</td>
<td>Yes</td>
</tr>
</tbody>
</table>

| Left rear tire pressure before test (psi) | 80 | 80 | 80 | 80 |
| Left rear tire pressure after test (psi)  | 80 | 80 | 80 | 80 |
| Right rear tire pressure before test (psi)| 80 | 80 | 80 | 80 |
| Right rear tire pressure after test (psi)| 80 | 80 | 80 | 80 |
| Before Measurements - Air Temp. (°C)      | 21.8 | 26 | 27.9 | 26.4 |
| After Measurements - Air Temp. (°C)       | 21.8 | 25.4 | 27.4 | 26.5 |
CHAPTER 6 - PROFILE DATA COLLECTION

6.1 Dipstick Data Collection

Dipstick data were collected along both wheelpaths at all six test sections on May 18, 2010. Data at all concrete sections were collected in the afternoon to minimize the effect of temperature related slab curling on the obtained measurements. Table 6.1 presents the following information for each test section: regional contractor who performed Dipstick measurements, Dipstick model used for testing, and the start and end time of testing.

Table 6.1. Dipstick testing at test sections.

<table>
<thead>
<tr>
<th>Section Number</th>
<th>Region Performing Measurements</th>
<th>Dipstick Used For Measurements</th>
<th>Start Time</th>
<th>End Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Northern</td>
<td>Model 2000, Serial No. 02130</td>
<td>14:10</td>
<td>15:44</td>
</tr>
<tr>
<td>2</td>
<td>Northern</td>
<td>Model 2000, Serial No. 32105</td>
<td>13:10</td>
<td>14:10</td>
</tr>
<tr>
<td>3</td>
<td>Southern</td>
<td>Model 1500, Serial No. 30023</td>
<td>12:38</td>
<td>14:00</td>
</tr>
<tr>
<td>4</td>
<td>Western</td>
<td>Model 2000, Serial No. 32108</td>
<td>13:48</td>
<td>14:56</td>
</tr>
<tr>
<td>5</td>
<td>Western</td>
<td>Model 2000, Serial No. 32108</td>
<td>10:24</td>
<td>11:36</td>
</tr>
<tr>
<td>6</td>
<td>Northern</td>
<td>Model 2000, Serial No. 32105</td>
<td>15:45</td>
<td>16:50</td>
</tr>
</tbody>
</table>

Table 6.2 shows the surface type and the Dipstick closure error for each test section. According to the Profile Manual, the closure error should be within 76 mm. This criterion was met at all sections except for Sections 2 and 5. However, the Dipstick passed the pre- and post-measurement checks at both of these sections.

Table 6.2. Dipstick closure error at the test sections.

<table>
<thead>
<tr>
<th>Section Number</th>
<th>Surface Type</th>
<th>Closure Error (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Asphalt</td>
<td>45.0</td>
</tr>
<tr>
<td>2</td>
<td>Asphalt</td>
<td>79.2</td>
</tr>
<tr>
<td>3</td>
<td>Concrete</td>
<td>13.5</td>
</tr>
<tr>
<td>4</td>
<td>Concrete</td>
<td>20.6</td>
</tr>
<tr>
<td>5</td>
<td>Concrete</td>
<td>95.3</td>
</tr>
<tr>
<td>6</td>
<td>Concrete</td>
<td>11.8</td>
</tr>
</tbody>
</table>

Section 2 is a rough asphalt section, and the high surface variability of this section is the possible reason why the closure error was not within the specified value. Section 5 is a chip seal section, and the surface texture of this section is the possible reason why the closure error was not within the specified value. For sections 2 and 5, high readings in the data file were compared with the data sheets to check for possible data entry errors, and no errors were detected. In the previous LTPP comparison performed in 2007 at MnROAD, the Dipstick closure error exceeded the
specified value at the rough AC section and was slightly below the specified limit at the chip seal section. (The rough AC and chip seal sections used in the 2007 comparison were different from the sections used for the 2010 comparison.)

6.2 SurPRO Data Collection

The SurPRO is a rolling profiler manufactured by ICC. A photograph of the SurPRO is shown in figure 6.1. This device is pushed along on the pavement surface at a speed between 1.6 and 2.4 km/h to collect elevation data of the pavement. The elevation data are recorded in a file. The data recording interval can be selected by the user, with the minimum data recording interval being 25 mm. For data collection at MnROAD, a data recording interval of 25 mm was selected. The diameter of the tire in the SurPRO is approximately 150 mm, while the average width of the tire determined using a caliper was 58 mm. The center to center distance between the wheels is 250 mm. The contact area of the tire was determined by spraying water on the tire and then placing the tire on the ground and measuring the length over which water was observed on the surface. This length was 17 mm.

![Figure 6.1. SurPRO rolling profiler.](image)

Data collection was performed at all six sections with three repeat runs being performed on each wheelpath. Data collection at the concrete sections was performed in the afternoon to minimize the effect of temperature related slab curling on the obtained measurements. Data collection on the right wheelpath was started at the beginning of the section and was terminated at the end of the section. Data collection on the left wheelpath was started at the end of the section and was terminated at the beginning of the section, with the data being collected against the travel direction.
6.3 Profiler Data Collection

The test sections were profiled according to the procedures described in the Profile Manual. Profile measurements on PCC sections were performed in the afternoon to minimize the effect of temperature related slab curling on the obtained measurements. Each RSC elected to make nine repeat runs at each test section. Each RSC processed the data collected by their profiler using the current version of the ProQual software. The ProQual software applies a 300-mm moving average on the 25-mm interval profile data collected by the profilers, and then extracts data at 150 mm intervals. The IRI values for the left and the right sensor data are then computed using this 150-mm interval data. Each region selected five most representative profile runs for each test section for the IRI comparison, and submitted the IRI values of the selected runs to the FHWA and the TSSC. Table 6.3 shows the profile runs that were selected by the RSC’s for the IRI comparison.

Table 6.3. Profile runs selected for analysis.

<table>
<thead>
<tr>
<th>Region</th>
<th>Runs Selected for Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test Section</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>North Atlantic</td>
<td>4, 6, 7, 8, 9</td>
</tr>
<tr>
<td>North Central</td>
<td>5, 6, 7, 8, 9</td>
</tr>
<tr>
<td>Southern</td>
<td>2, 3, 6, 7, 9</td>
</tr>
<tr>
<td>Western</td>
<td>3, 5, 7, 8, 9</td>
</tr>
</tbody>
</table>
CHAPTER 7 - COMPARISON OF IRI VALUES

7.1 Overview

This section describes the following: (1) IRI values obtained from the Dipstick and SurPRO measurements, (2) comparison of the IRI values obtained by the Dipstick and the SurPRO, (3) evaluation of repeatability of IRI values obtained by the profilers, (4) comparison of IRI values obtained by the profilers with IRI obtained from the Dipstick and SurPRO measurements, and (5) comparison of IRI values obtained by the profilers. In the tables and graphs presented in this section, the following notations are used for the profilers: NA – North Atlantic, NC – North Central, SO – Southern, and WE – Western.

7.2 IRI from Dipstick Measurements

The RSC that collected the Dipstick data entered the data into ProQual, computed IRI values, and then submitted the IRI values to the TSSC. The raw Dipstick data recorded in the field were used to create the elevation profile for each wheelpath in an ERD file. Then these ERD files were loaded to the ProVAL software to compute the IRI values. The IRI values computed from ProVAL and ProQual agreed with each other. The IRI values for the Dipstick data are shown in table 7.1.

<table>
<thead>
<tr>
<th>Section Number</th>
<th>Dipstick IRI (m/km)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Left Wheel Path</td>
<td>Right Wheel Path</td>
</tr>
<tr>
<td>1</td>
<td>0.73</td>
<td>0.66</td>
</tr>
<tr>
<td>2</td>
<td>3.40</td>
<td>3.67</td>
</tr>
<tr>
<td>3</td>
<td>1.02</td>
<td>1.29</td>
</tr>
<tr>
<td>4</td>
<td>1.16</td>
<td>1.36</td>
</tr>
<tr>
<td>5</td>
<td>1.57</td>
<td>1.75</td>
</tr>
<tr>
<td>6</td>
<td>2.24</td>
<td>2.77</td>
</tr>
</tbody>
</table>

7.3 IRI from SurPRO Measurements

The ProVAL software was used to compute the IRI from the SurPRO ERD data files. As described previously, the SurPRO data collection on the left wheelpath was performed against the travel direction. When computing the IRI of the left wheelpath, the collected data were reversed to obtain the profile corresponding to the travel direction, and the IRI was computed using this reversed data. The IRI values for the three repeat SurPRO runs performed at each test section as well as the average of these values are shown in table 7.2.
Table 7.2. SurPRO IRI values.

<table>
<thead>
<tr>
<th>Section</th>
<th>Run</th>
<th>IRI (m/km)</th>
<th>Average IRI (m/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Left Wheelpath</td>
<td>Right Wheelpath</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0.77</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.81</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.81</td>
<td>0.69</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>3.52</td>
<td>3.87</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3.55</td>
<td>3.87</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3.53</td>
<td>3.87</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>1.07</td>
<td>1.28</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.05</td>
<td>1.29</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.05</td>
<td>1.30</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1.18</td>
<td>1.33</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.17</td>
<td>1.34</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.19</td>
<td>1.33</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>1.53</td>
<td>1.74</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.51</td>
<td>1.74</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1.50</td>
<td>1.72</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>2.49</td>
<td>2.99</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>2.42</td>
<td>2.91</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2.40</td>
<td>2.85</td>
</tr>
</tbody>
</table>

7.4 Comparison of IRI Values Obtained from the Dipstick and the SurPRO

Table 7.3 shows the IRI values obtained from the Dipstick data and the average IRI value computed from the three SurPRO runs for the left wheelpath at all sections. This table also shows the difference in IRI between the SurPRO IRI and the Dipstick IRI. Similar data for the right wheelpath are shown in table 7.4.

The SurPRO collects data at 25 mm intervals while the Dipstick collects data at 304.8 mm intervals. Therefore, the Dipstick can miss profile features that are recorded by the SurPRO. The data collection mechanisms of the two devices are also different. The footpad in the Dipstick will rest on a plane defined by the three highest contact points within the footpad area. The tires in the SurPRO will rest within an area enveloped by the tire contact area. These differences between the two devices will affect the recorded profile as well as the IRI computed from the data.

As seen in tables 7.3 and 7.4, the IRI computed from the SurPRO data was higher than that computed from the Dipstick data for all cases except for three (i.e., left wheel path of section 5 and right wheelpath of sections 4 and 5). A difference in IRI of over 0.1 m/km for the two devices occurred for both wheelpaths in sections 2 and 6. Section 2 is a rough asphalt section, while section 6 is a concrete section where the profile data indicated that the slabs were curled up. In both of these sections, the Dipstick because of its longer sampling interval missed features.
that were recorded by the SurPRO, which contributed to roughness. This resulted in a lower IRI value at these two sections for the Dipstick data when compared to the IRI computed from the SurPRO data.

Table 7.3. IRI values from the Dipstick and the SurPRO – left wheelpath.

<table>
<thead>
<tr>
<th>Section Number</th>
<th>Left Wheelpath IRI (m/km)</th>
<th>Difference in IRI(a) (m/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipstick</td>
<td>SurPRO</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.73</td>
<td>0.79</td>
</tr>
<tr>
<td>2</td>
<td>3.40</td>
<td>3.53</td>
</tr>
<tr>
<td>3</td>
<td>1.02</td>
<td>1.06</td>
</tr>
<tr>
<td>4</td>
<td>1.16</td>
<td>1.18</td>
</tr>
<tr>
<td>5</td>
<td>1.57</td>
<td>1.51</td>
</tr>
<tr>
<td>6</td>
<td>2.24</td>
<td>2.44</td>
</tr>
</tbody>
</table>

(a)SurPRO IRI – Dipstick IRI

Table 7.4. IRI values from the Dipstick and the SurPRO – right wheelpath.

<table>
<thead>
<tr>
<th>Section Number</th>
<th>Right Wheelpath IRI (m/km)</th>
<th>Difference in IRI(a) (m/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipstick</td>
<td>SurPRO</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.66</td>
<td>0.68</td>
</tr>
<tr>
<td>2</td>
<td>3.67</td>
<td>3.87</td>
</tr>
<tr>
<td>3</td>
<td>1.29</td>
<td>1.29</td>
</tr>
<tr>
<td>4</td>
<td>1.36</td>
<td>1.33</td>
</tr>
<tr>
<td>5</td>
<td>1.75</td>
<td>1.73</td>
</tr>
<tr>
<td>6</td>
<td>2.77</td>
<td>2.92</td>
</tr>
</tbody>
</table>

(a)SurPRO IRI – Dipstick IRI

7.5 IRI Repeatability of Profilers

The RSC’s computed the IRI values for the profilers using the ProQual software, which is the software used in the LTPP program to compute IRI values from profiler data. The left and right wheelpath IRI values for the five profile runs selected by the RSC’s for each test sections (see table 6.3) are shown in the table included in Appendix C.

These five IRI values were used to compute the standard deviation of IRI for the left and right wheelpaths, and the computed values are shown in table 7.5. These values are shown graphically in figures 7.1 and 7.2 for the left and right wheelpath, respectively. The IRI repeatability criterion presented in the Profile Manual is that the standard deviation of IRI for each wheelpath computed from five runs at a section should be less than 0.04 m/km. Cases that did not meet this
criterion are shown in bold in table 7.5. A bold horizontal line corresponding to 0.04 m/km is shown in figures 7.1 and 7.2 to show the LTPP specified criterion.

Table 7.5. Standard deviation of IRI.

<table>
<thead>
<tr>
<th>Wheel Path</th>
<th>Profiler</th>
<th>N. Atlantic</th>
<th>N. Central</th>
<th>Southern</th>
<th>Western</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left</td>
<td></td>
<td>0.005</td>
<td>0.008</td>
<td>0.007</td>
<td>0.004</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.019</td>
<td>0.021</td>
<td>0.007</td>
<td>0.006</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.011</td>
<td>0.010</td>
<td>0.011</td>
<td>0.013</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.011</td>
<td>0.019</td>
<td>0.013</td>
<td>0.010</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.023</td>
<td>0.014</td>
<td>0.016</td>
<td>0.019</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.009</td>
<td>0.012</td>
<td>0.024</td>
<td>0.017</td>
</tr>
<tr>
<td>Right</td>
<td>N. Atlantic</td>
<td>0.005</td>
<td>0.008</td>
<td>0.006</td>
<td>0.007</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.063</td>
<td>0.008</td>
<td>0.013</td>
<td>0.022</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.008</td>
<td>0.015</td>
<td>0.009</td>
<td>0.012</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.008</td>
<td>0.015</td>
<td>0.017</td>
<td>0.013</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.008</td>
<td>0.015</td>
<td>0.017</td>
<td>0.013</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.023</td>
<td>0.026</td>
<td>0.029</td>
<td>0.074</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.048</td>
<td>0.027</td>
<td>0.048</td>
<td>0.027</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.063</td>
<td></td>
<td>0.063</td>
<td></td>
</tr>
</tbody>
</table>

Note: NA – North Atlantic, NC – North Central, SO – Southern, WE – Western

All profilers met the repeatability criterion for the left wheelpath. The repeatability criterion was not met for the right wheelpath for the following four cases:

- North Atlantic profiler, section 2: The IRI values for the five runs were 3.73, 3.88, 3.74, 3.75, and 3.81 m/km.

- Southern profiler - section 5: The IRI values for the five runs were 1.62, 1.68, 1.72, 1.74, and 1.66 m/km.

- North Central profiler - section 6: The IRI values for the five runs were 2.76, 2.84, 2.91, 2.73, and 2.75 m/km.

- Western profiler - sections 6: The IRI values for the five runs were 2.84, 2.91, 2.90, 2.78, and 2.79 m/km.

Evaluation of the profile data for these cases did not show any problems with the profile data. It appears that the variations in the IRI values were due to lateral variability in the path followed during profile data collection.

7.6 Comparison of Profiler and Reference Device IRI

The Dipstick and the SurPRO are considered to be reference devices. This section presents the results from the comparison of IRI from these reference devices with the IRI obtained from the profilers. The IRI values of the five profiler runs that were selected for analysis at each section by the RSC’s are shown in the table included in Appendix C.
The average IRI value for each wheelpath at each section computed from this data for all profilers is shown in table 7.6. This table also includes the IRI computed from the Dipstick data and the average SurPRO IRI values. These IRI values are shown graphically in figures 7.3 and 7.4 for the left and the right wheelpath, respectively.

Figures 7.5 and 7.6 show the relationship between average profiler IRI and Dipstick IRI for left and right wheelpath respectively. Figures 7.7 and 7.8 respectively show the relationship between average profiler IRI and average SurPRO IRI for the left and right wheelpaths. A linear regression analysis was first performed between the Dipstick IRI and average profiler IRI by considering the IRI values from both wheelpaths. The Dipstick IRI was treated as the independent variable and the average profiler IRI was treated as the dependant variable. This regression yielded a coefficient of determination ($R^2$) of 0.992 and a standard error of estimate of 0.09 m/km. A similar analysis between average profiler IRI and average SurPRO IRI showed a $R^2$ of 0.996 and a standard error of estimate of 0.08 m/km.
Table 7.6. Average IRI values.

<table>
<thead>
<tr>
<th>Wheelpath</th>
<th>Profiler</th>
<th>Average IRI (m/km)</th>
<th>Test Section</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Left</td>
<td>Dipstick</td>
<td>0.73</td>
<td>3.40</td>
</tr>
<tr>
<td></td>
<td>SurPRO</td>
<td>0.79</td>
<td>3.53</td>
</tr>
<tr>
<td></td>
<td>N. Atlantic</td>
<td>0.78</td>
<td>3.44</td>
</tr>
<tr>
<td></td>
<td>N. Central</td>
<td>0.78</td>
<td>3.49</td>
</tr>
<tr>
<td></td>
<td>Southern</td>
<td>0.77</td>
<td>3.55</td>
</tr>
<tr>
<td></td>
<td>Western</td>
<td>0.77</td>
<td>3.51</td>
</tr>
<tr>
<td>Right</td>
<td>Dipstick</td>
<td>0.66</td>
<td>3.67</td>
</tr>
<tr>
<td></td>
<td>SurPRO</td>
<td>0.68</td>
<td>3.87</td>
</tr>
<tr>
<td></td>
<td>N. Atlantic</td>
<td>0.65</td>
<td>3.78</td>
</tr>
<tr>
<td></td>
<td>N. Central</td>
<td>0.63</td>
<td>3.85</td>
</tr>
<tr>
<td></td>
<td>Southern</td>
<td>0.64</td>
<td>3.92</td>
</tr>
<tr>
<td></td>
<td>Western</td>
<td>0.64</td>
<td>3.89</td>
</tr>
</tbody>
</table>

Note: Dipstick IRI obtained from a single run.

Figure 7.3. Left wheelpath IRI values.

Figure 7.4. Right wheelpath IRI values.
Figure 7.5. Relationship between profiler and Dipstick IRI, left wheelpath.

Figure 7.6. Relationship between profiler and Dipstick IRI, right wheelpath.
The relationship between Dipstick IRI and average SurPRO IRI for all test sections are shown in figure 7.9. The SurPRO IRI was higher than the Dipstick IRI for all cases except for three (see table 7.3 and 7.4).
The difference between the average profiler IRI value and the Dipstick IRI value (i.e., average profiler IRI – Dipstick IRI) as well as the difference between average profiler IRI value and the average SurPRO IRI value (i.e., average profiler IRI – average SurPRO IRI) for both wheelpaths at all sections are shown in table 7.7. These values for the Dipstick are shown graphically in figures 7.10 and 7.11 for the left and the right wheelpath, respectively. The values for the SurPRO are shown graphically in figures 7.12 and 7.13 for the left and the right wheelpath, respectively.

Table 7.7. Difference between profiler and reference device IRI.

<table>
<thead>
<tr>
<th>Wheelpath</th>
<th>Profiler</th>
<th>Test Section</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Difference in IRI (m/km)</td>
<td>Difference in IRI (m/km)</td>
<td>Difference in IRI (m/km)</td>
<td>Difference in IRI (m/km)</td>
<td>Difference in IRI (m/km)</td>
<td>Difference in IRI (m/km)</td>
<td></td>
</tr>
<tr>
<td>Left</td>
<td>NA</td>
<td>0.05</td>
<td>-0.01</td>
<td>0.04</td>
<td>-0.09</td>
<td>0.10</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>NC</td>
<td>0.05</td>
<td>-0.01</td>
<td>0.09</td>
<td>-0.04</td>
<td>0.12</td>
<td>0.07</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>SO</td>
<td>-0.03</td>
<td>-0.03</td>
<td>0.15</td>
<td>0.02</td>
<td>0.10</td>
<td>0.06</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>WE</td>
<td>0.04</td>
<td>-0.03</td>
<td>0.11</td>
<td>-0.02</td>
<td>0.09</td>
<td>0.04</td>
<td>0.01</td>
</tr>
<tr>
<td>Right</td>
<td>NA</td>
<td>-0.01</td>
<td>-0.04</td>
<td>0.11</td>
<td>-0.09</td>
<td>0.04</td>
<td>0.05</td>
<td>-0.05</td>
</tr>
<tr>
<td></td>
<td>NC</td>
<td>-0.03</td>
<td>-0.05</td>
<td><strong>0.18</strong></td>
<td>-0.02</td>
<td>0.05</td>
<td>0.06</td>
<td>-0.05</td>
</tr>
<tr>
<td></td>
<td>SO</td>
<td>-0.02</td>
<td>-0.04</td>
<td><strong>0.25</strong></td>
<td>0.05</td>
<td>0.05</td>
<td>0.06</td>
<td>-0.07</td>
</tr>
<tr>
<td></td>
<td>WE</td>
<td>-0.02</td>
<td>-0.04</td>
<td>0.22</td>
<td>0.02</td>
<td>0.03</td>
<td>0.04</td>
<td>-0.05</td>
</tr>
</tbody>
</table>

Dip - Dipstick, Sur - SurPRO, NA – North Atlantic, NC – North Central, SO – Southern, WE – Western
Figure 7.10. Difference between profiler and Dipstick IRI, left wheelpath.

Figure 7.11. Difference between profiler and Dipstick IRI, right wheelpath.

Figure 7.12. Difference between profiler and SurPRO IRI, left wheelpath.

25
Figure 7.13. Difference between profiler and SurPRO IRI, right wheelpath.

The Profiler Manual specifies that the difference between the profiler IRI and the Dipstick IRI should be within ± 0.16 m/km for each wheelpath. Cases that failed this criterion when applied to Dipstick IRI as well as SurPRO IRI are shown in bold in Table 7.7. Figures 7.5 through 7.8 include a bold horizontal lines corresponding to IRI values of -0.16 and 0.16 m/km, which are the LTPP specified limits.

The following observations were noted for the difference between profiler IRI and reference device (i.e., Dipstick and SurPRO) IRI:

- Section 1: All profilers satisfied the specified criterion for both wheelpaths with the Dipstick as well as the SurPRO IRI.

- Section 2: All profilers satisfied the specified criterion with the SurPRO IRI for the left and the right wheelpaths, and with the Dipstick IRI for the left wheelpath. In the right wheelpath, the North Central, Southern, and Western profilers obtained IRI values that were outside the specified criterion when compared with the Dipstick IRI.

- Section 3: All profilers satisfied the specified criterion for both wheelpaths with the Dipstick as well as the SurPRO IRI.

- Section 4: All profilers satisfied the specified criterion for both wheelpaths with the Dipstick as well as the SurPRO IRI.

- Section 5: All profilers satisfied the specified criterion in the left wheelpath with the SurPRO IRI. All profilers except for the North Atlantic profiler satisfied the specified criterion for the left wheelpath with the Dipstick IRI. The North Atlantic and North Central profilers failed the specified criterion with the SurPRO as well as the Dipstick IRI for the right wheelpath, while the other two profilers met the specified criterion with the Dipstick as well as the SurPRO IRI.

- Section 6: All profilers satisfied the specified criterion for the left wheelpath with both the SurPRO and Dipstick IRI. For the right wheelpath, all profilers satisfied the criterion with the...
SurPRO IRI and the Dipstick IRI, except for the North Atlantic profiler that failed the criterion with the SurPRO IRI.

Evaluation of the profile data for the cases that failed the criterion did not show any problems with the profile data. For some cases, features appeared in the profile data at some localized areas that did not appear in the reference device data. This was probably caused by lateral variation in the path measured by the profiler from the path where the reference device collected data, which caused the profiler IRI to not meet the specified criterion.

### 7.7 Comparison of IRI Values between the Profilers

Table 7.8 shows the range of the average IRI values obtained for each wheelpath at each test section by the four profilers. This table also shows the difference in IRI between the average maximum and average minimum IRI values for both wheelpaths at all sections.

<table>
<thead>
<tr>
<th>Section No</th>
<th>Range in IRI Values (m/km)</th>
<th>Difference Between Maximum and Minimum IRI (m/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wheelpath</td>
<td>Left</td>
</tr>
<tr>
<td></td>
<td>Left</td>
<td>Right</td>
</tr>
<tr>
<td>1</td>
<td>0.77 - 0.78</td>
<td>0.63 - 0.65</td>
</tr>
<tr>
<td>2</td>
<td>3.44 - 3.55</td>
<td>3.78 - 3.92</td>
</tr>
<tr>
<td>3</td>
<td>1.10 - 1.13</td>
<td>1.33 - 1.35</td>
</tr>
<tr>
<td>4</td>
<td>1.17 - 1.20</td>
<td>1.29 - 1.31</td>
</tr>
<tr>
<td>5</td>
<td>1.37 - 1.49</td>
<td>1.48 - 1.73</td>
</tr>
<tr>
<td>6</td>
<td>2.34 - 2.36</td>
<td>2.75 - 2.85</td>
</tr>
</tbody>
</table>

The difference between the maximum and minimum IRI was less than 0.05 m/km except for the following cases:

- **Left and right wheelpath of Section 2:** This is a very rough section. Some differences in the features collected by the profilers were noted in the last 30 m of this section that has a high level of roughness. It appears that the differences in IRI values were due to lateral variations in the profiled paths.

- **Left and right wheelpath of Section 5:** In the right wheelpath, the North Atlantic and North Central profilers had average IRI values of 1.48 and 1.50 m/km, respectively while the Southern and Western profilers had average IRI values of 1.69 and 1.73 m/km, respectively. Evaluation of the right wheelpath data from the Southern and Western profilers indicated major dips at approximately 88, 117, and 119 m that were not observed in the data collected by the other two profilers. This resulted in the Southern and Western profilers obtaining higher IRI values for the right wheelpath when compared to those obtained by the other two profilers. It appears that the differences in IRI values among the profilers for both wheelpaths at this section were due to lateral variations in the profiled path.
Right wheelpath of Section 6: This is a rough section. The average IRI for the right wheelpath for the North Central, North Atlantic, Southern, and Western profilers were 2.75, 2.80, 2.85, and 2.84 m/km, respectively. Evaluation of the profile data showed that the Southern and Western profiler data had a major downward feature at about 114 m, which was not observed in the data collected by the other two profilers. The inclusion of this feature in the profile resulted in the Southern and Western profilers to have a higher IRI than the other two profilers, which resulted in a high difference between the maximum and minimum IRI for the right wheelpath.

The effect of lateral variability in the profiled paths is illustrated by the following example. Figures 7.14 and 7.15, respectively, show the right wheelpath profile data collected for a profile run by the North Atlantic and Southern profilers at section 5. The Southern profiler data shows three downward features at distances of 88, 117, and 119 m, while the North Atlantic profiler data does not show these three features. As the data from the North Atlantic profiler did not have these features, the IRI corresponding to the right wheelpath data for the North Atlantic profiler was less than that for the Southern profiler. The Western profiler data also shows the three downward features picked up by the Southern profiler at 88, 117, and 119 m. However, the North Central profiler as was the case for North Atlantic profiler does not show these three features.

![Figure 7.14](image)

Figure 7.14. Data collected by the North Atlantic profiler along the right wheelpath of section 5.
Figure 7.15. Data collected by the Southern profiler along the right wheelpath of section 5.
CHAPTER 8 - EVALUATION OF PROFILER PROFILE PLOTS

8.1 Overview

Three types of evaluations were performed using profile data plots. In the first evaluation, the overlaid profile plots that showed the replicate profile runs collected by a profiler at each section were reviewed to visually evaluate the repeatability of the profilers. In the second evaluation, a representative profile was selected for each profiler at each test section, and the profiles for the left and right wheelpaths were compared among the profilers. In the third evaluation, the power spectral density (PSD) plots generated from the representative profile runs selected for the previous analysis were reviewed.

8.2 Evaluation of Replicate Profile Runs Collected by the Profilers

A visual evaluation was performed on the replicate profile runs collected by each profiler at each test section to evaluate the repeatability of profile data. This evaluation was performed separately for the left, right, and center sensor data using the five profile runs that were selected for the IRI analysis.

Figure 8.1 shows an example of a typical plot generated by ProQual, which shows the profile plots for five runs of the North Atlantic profiler along the left wheelpath at section 1. (The legend in the figure shows three notations, the second notation is the profiler run number and the third notation is the sensor. For example, 1-4-L indicates the data corresponds to left sensor data for run 4.)

Figure 8.1. Profile plots for repeat runs of North Atlantic profiler along the left wheelpath at section 1.
Appendix D contains the overlaid profile plots for all profilers along the left and right wheelpaths at all test sections. Appendix E contains the overlaid profile plots for the center sensor. Overall, a review of these plots did not show any obvious problems with the profile data, with reasonable repeatability being observed for all profilers, except for three cases. These three cases are: (1) North Atlantic profiler, section 3, left wheelpath; (2) North Central profiler, section 6, right wheelpath, and (3) Western profiler, section 6, left wheelpath. Figure 8.2 shows profile plots of the five repeat runs collected by the North Atlantic profiler along the left wheelpath of section 3, where some differences among the profiles are seen. (The legend in this plot follows the same format that was described earlier.)

![Figure 8.2. Profile plots for repeat runs of North Atlantic profiler along the left wheelpath at section 3.](image)

A mathematical evaluation of profile repeatability using the cross correlation method is presented in Section 10.

### 8.3 Comparison of Profiles between Profilers

A representative profile run for each profiler was selected at each test section by evaluating the five replicate profile runs. Thereafter, the selected profiles for each test section were overlaid separately for the left and the right wheelpaths. Figure 8.3 shows an example of a plot that was generated, with the data shown in this plot being those for the right wheelpath at section 3. The legend in this figure shows the region, section number, and the profiler run. For example, NA 3-1 means run number 1 of the North Atlantic profiler at section 3.
As seen in figure 8.3, the profile plots for the four profilers overlay each other, and therefore it is difficult to see differences between profiles. Another plot was generated by offsetting the profiles from each other so that differences between profiles, if any, could be seen. Figure 8.4 shows an example of an offset plot that was generated, with the data shown in this plot being the same data shown in figure 8.3.
Appendix F contains the overlaid profile plots as well as the offset profile plots for both wheelpaths at all sections. An evaluation of the overlaid profile plots indicates reasonable agreement in profiles among the four profilers, except for the left wheelpath of section 5 and the right wheelpath of section 6.

For the left wheelpath of section 5, the profile for the North Atlantic profiler had a slight vertical shift when compared to the data collected by the other three profilers. However, the offset profile plot shows that the North Atlantic profiler was collecting similar profile features as the other three profilers.

There was some variability in the data collected by the four profilers along the right wheelpath of section 6, with the profiles being offset from each other in the vertical direction. However, the offset profile plot shows that all profilers were collecting similar data. Section 6 has a high roughness with a high degree of upward slab curling, with the magnitude of curling being greater along the right wheel path than the left wheelpath. It is unclear if the slab curling contributed the variability that was seen in the profile data.

Overall, the evaluation of the profile plots showed that all four profilers appear to be capturing similar profile features with no profiler showing a profile shape that was not in agreement with the other profilers.

8.4 Power Spectral Density Plots

A road profile encompasses a spectrum of sinusoidal wavelengths. The PSD function is a statistical representation of the importance of the various wavelengths contained in the profile. A PSD plot shows how the content in the profile is distributed over the various wavebands. A Fourier transform is used to generate a PSD plot from profile data.

The representative profile runs selected for each profiler for the previous analysis were used to generate overlaid PSD plot for each wheelpath at all test sections. Figure 8.5 shows an example of a PSD plot that was generated from the left wheelpath data of the four profilers at section 1. The legend in this figure shows the region, the section number, and the profiler run number (e.g., WE 1-3 indicate Western profiler, section 1, and run 3).

![Figure 8.5. PSD plots of four profilers (left wheelpath of section 1).](image-url)
The generated PSD plots for both wheelpaths at all sections are included in appendix G. The PSD plots were examined to detect differences among the profilers. A noticeable difference among the profilers was seen for the right wheelpath of section 5 for wavelengths less than about 3 m. In this wavelength range, the Southern and Western profilers showed reasonable agreement with each other, while the North Atlantic and North Central profilers showed reasonable agreement with each other. However the two sets of profilers showed significant differences with each other. This difference is attributed to differences in the features that were picked up by the two sets of profilers. The cause of the difference between the two sets of profilers was described in Section 7.7.

Overall, there was good agreement in the PSD plots for all four profilers indicating that all four profilers appear to be collecting similar data.
CHAPTER 9 - COMPARISON OF PROFILE DATA COLLECTED BY THE DIPSTICK AND THE SURPRO

9.1 Elevation Profiles

As described previously, three SurPRO runs were performed on each wheelpath at each test section, while only one Dipstick run was performed on each wheelpath of each test section. Table 9.1 shows the absolute difference in elevation between the start and the end of the test section that was determined from the data collected by the Dipstick and the SurPRO.

Table 9.1. Difference in elevation between start and end of section.

<table>
<thead>
<tr>
<th>Section</th>
<th>Run Number</th>
<th>Difference in Elevation Between Start and End of Section (mm)</th>
<th>Left Wheelpath</th>
<th>Right Wheelpath</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>SurPRO</td>
<td>Dipstick</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>293.1</td>
<td>221.9</td>
<td>274.4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>311.0</td>
<td></td>
<td>284.2</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>301.9</td>
<td></td>
<td>289.8</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>323.0</td>
<td>336.1</td>
<td>313.9</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>321.5</td>
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<td>301.5</td>
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<tr>
<td></td>
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<td></td>
<td>313.8</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>492.7</td>
<td>451.0</td>
<td>468.1</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>486.6</td>
<td></td>
<td>492.0</td>
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<td>484.4</td>
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<td>491.6</td>
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<td>4</td>
<td>1</td>
<td>683.9</td>
<td>666.9</td>
<td>682.4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>690.4</td>
<td></td>
<td>685.1</td>
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<tr>
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<td>3</td>
<td>679.1</td>
<td></td>
<td>686.3</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>884.0</td>
<td>880.7</td>
<td>853.8</td>
</tr>
<tr>
<td></td>
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<tr>
<td></td>
<td>3</td>
<td>880.7</td>
<td></td>
<td>844.4</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>242.0</td>
<td>225.8</td>
<td>233.5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>238.8</td>
<td></td>
<td>246.5</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>240.0</td>
<td></td>
<td>243.9</td>
</tr>
</tbody>
</table>

As seen in table 9.1, there were differences in the elevation change for a section obtained by the three repeat SurPRO runs along a wheelpath. For a specific wheelpath at a specific section, the difference between the maximum and minimum elevation change obtained from the three SurPRO runs was less than 15 mm, except for three cases (i.e., left and right wheelpath of section 1 and right wheelpath of section 3). The maximum difference of 23.9 mm occurred for the right wheelpath of section 3. It is unclear what factors caused these elevation differences to occur.

Figure 9.1 shows plots of the data obtained by three runs of the SurPRO for the left wheelpath of section 6, which had the least difference in elevation change between the maximum and minimum elevations (i.e., 3.2 mm). Figure 9.2 shows plots of the data obtained by three runs of
the SurPRO for the right wheelpath of section 3, which had the highest difference in elevation between the maximum and minimum elevation (23.9 mm).

Figure 9.1. Elevation profiles collected by three SurPRO runs along left wheelpath of section 6.

Figure 9.2. Elevation profiles collected by three SurPRO runs along right wheelpath of section 3.

Figure 9.3 shows the PSD plots for the three SurPRO runs along the right wheelpath of section 3, which had the highest difference in elevation between the maximum and minimum elevation (23.9 mm). The three PSD plots overlay well with each other except that run 1 has lower spectral content at a wavelength of about 7.5 m/cycle when compared to the other runs. Although there
were some differences in the end elevation for the three repeat SurPRO runs along a wheelpath at a test section, these differences seem to have had little effect on the IRI (see table 7.2).

Figure 9.3 PSD plots of data collected by the three SurPRO runs along the right wheelpath of section 3.

Table 9.2 shows the average elevation change at a section obtained by the SurPRO, which was computed by averaging the elevation change for the three runs. This table also shows the elevation change corresponding to the Dipstick measurements, and the difference between average SurPRO and Dipstick elevations.

Table 9.2. Average SurPRO elevations and difference between SurPRO and Dipstick elevations.

<table>
<thead>
<tr>
<th>Section</th>
<th>Difference in Elevation Between Start and End of Section (mm)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Left Wheelpath</th>
<th>Right Wheelpath</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SurPRO</td>
<td>Dipstick</td>
<td>Difference(1)</td>
<td>SurPRO</td>
<td>Dipstick</td>
<td>Difference(1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>301.97</td>
<td>221.93</td>
<td>80.0</td>
<td>282.79</td>
<td>267.67</td>
<td>15.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>325.02</td>
<td>336.10</td>
<td>-11.1</td>
<td>309.74</td>
<td>256.74</td>
<td>53.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>487.88</td>
<td>451.00</td>
<td>36.9</td>
<td>483.87</td>
<td>464.70</td>
<td>19.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>684.47</td>
<td>666.92</td>
<td>17.6</td>
<td>684.62</td>
<td>639.50</td>
<td>45.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>881.17</td>
<td>880.65</td>
<td>0.5</td>
<td>849.54</td>
<td>788.90</td>
<td>60.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>240.29</td>
<td>225.80</td>
<td>14.5</td>
<td>241.31</td>
<td>236.50</td>
<td>4.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) Difference = SuPRO Elevation - Dipstick Elevation

The difference in the change in elevation for a section determined from the average SurPRO elevation and the Dipstick elevation ranged from 0.5 mm (left wheelpath of section 5) to 80 mm (left wheelpath of section 1). Figure 9.4 shows plots of a SurPRO run and the Dipstick run along the left wheelpath of section 1, which had the maximum difference for the change in elevation. Figure 9.5 shows plots of a SurPRO run (run 3) and the Dipstick run along the right wheelpath of section 3, where the difference in elevation at the end of the section between the SurPRO run and the Dipstick run was 3.4 mm.
9.2 PSD Plots of SurPRO and Dipstick Data

Figure 9.6 shows the PSD plots of the data collected by a SurPRO run and the Dipstick run along the left wheelpath of section 4. Figure 9.7 shows a similar plot for the data collected along the left wheelpath of section 2.

The PSD plots show differences between Dipstick and SurPRO data for wavelengths less than about 0.7 m. This is because the Dipstick cannot measure wavelengths that are shorter than 0.61
According to Nyquist theorem, the highest frequency that can be accurately represented from discretely sampled data is less than one-half of the sampling rate. When this theorem is applied to the Dipstick that has a sampling interval of 0.305 m, it means the Dipstick cannot accurately measure wavelengths less than twice its sampling interval, which is 0.61 m. The SurPRO can measure wavelengths as small as 0.050 m according to this theorem.

![Figure 9.6. PSD plots of Dipstick and SurPRO data for left wheelpath of section 4.](image)

![Figure 9.7. PSD plots of Dipstick and SurPRO data for left wheelpath of section 2.](image)

Figure 9.6 shows some differences in the PSD plots for the two devices for other wavelengths, and this was the pattern seen for the majority of the wheelpaths. The PSD plots in figure 9.7 show better agreement for the two devices, but this level of agreement was seen only for a few cases.

The American Association of State Highway and Transportation Officials (AASHTO) Standard R 56-10(2) that describes procedures for certifying profilers indicate the reference device that is used to collect the reference data should have a data recording interval of at least 70 mm. The SurPRO that has a recording interval of 25 mm satisfies this criterion, while the Dipstick that has a data recording interval of 304.8 mm does not satisfy this requirement.

Figures 9.8 and 9.9, respectively, show the same data shown in figures 9.6 and 9.7, except that the PSD plot of the data collected by a profiler is also included in the figures. The profile data included in these plots are the 25-mm interval data collected by the North Central profiler. Differences between the SurPRO and the profiler data are seen in both plots for wavelengths shorter than about 0.8 m/cycle. The geometric configuration of the SurPRO results in a 250-mm moving average being applied to the data, which attenuates wavelengths shorter than about 0.8
m. No short wavelength filtering is performed on the profiler data, and this is the reason for the difference between SurPRO and profiler data for the short wavelengths. If ProQual processed data that has a 300-mm moving average applied to the profile data were used to generate the PSD plot, no differences between the SurPRO data and profile data will be seen for the short wavelengths. This is because the application of the moving average on the profile data by ProQual will attenuate the short wavelengths. Further details about this issue are presented by Perera.\(^{(3)}\) The profiler data has been subjected to an upper wavelength cut-off filter having a cut-off value of 100 m. This is the reason for the difference in the longer wavelengths seen between the profiler and the SurPRO data as well as between the profiler and Dipstick data.

Figure 9.8. PSD plots of Dipstick, SurPRO, and profiler data (section 4, left wheelpath).

Figure 9.9. PSD plots of Dipstick, SurPRO and profiler data (section 2, left wheelpath)
CHAPTER 10 - CROSS CORRELATION ANALYSIS

10.1 Overview

Karamihas developed a procedure to apply the cross correlation method for objective comparison of profiles.\(^4,5\) This procedure is based on the cross correlation function described by Bendant and Piersol.\(^6\) This method has been used to evaluate profile data on several recent projects.\(^7,8\) The cross correlation method can be used to rate agreement between profiles in a given waveband or to rate agreement between devices for any given roughness index including the IRI. This procedure provides a rating agreement ranging from 0 and 1 that describes how well two profiles correlate with each other, with 1 indicating perfect agreement.

Although the IRI algorithm is often thought of as an analysis procedure that takes a profile as input and produces an index value as output, it is actually a linear filter that takes a profile as input (in units of elevation) and produces a modified signal in units of slope as output.\(^9\) The modified signal is produced by simulating the motion of a quarter-car on the profile, with a slope value being outputted at an interval corresponding to the profile data recording interval. The profile obtained by this procedure is referred to as the IRI-filtered profile. Figure 10.1 shows an example of an IRI filtered profile obtained from profile data collected at 25-mm intervals. This figure contains slope values outputted by the simulation of the quarter car in the IRI algorithm at 25-mm intervals.

![Figure 10.1](image)

Figure 10.1. Example of an IRI filtered profile.

The IRI reported for a segment is the average rectified value of the output signal (i.e., average of the absolute values). For example, the IRI value for the 161-m long segment shown in figure 10.1 is obtained by computing the average of the absolute slope values shown in this figure.
When the cross correlation method is used to compare the IRI for two profiles, the IRI algorithm is first applied to both profiles to obtain the IRI-filtered profiles corresponding to each profile. Thereafter, the cross correlation method is applied to the two IRI filtered profiles to find a rating agreement between 0 and 1.

The rating agreement provided by this procedure represents repeatability when it is applied to two measurements of the same section by the same device, reproducibility when it is applied to two measurements of the same section by different devices and accuracy when a measurement from one of the devices is deemed correct.

The AASHTO standard R56-10, Standard Practice for Certification of Inertial Profiling Systems describes procedures for certifying inertial profilers. The standard indicates the minimum requirements described in the standard are aimed at equipment that collects smoothness data on new construction. However, the standard states the certification procedures described in the standard is also applicable to profilers that collect data at network level. In this standard, the repeatability and the accuracy of a profiler is determined by applying the cross correlation technique to IRI filtered profiles. The repeatability and the accuracy are evaluated separately for each sensor of the profiler.

In AASHTO standard R56-10, the repeatability of a profiler is evaluated by computing an average repeatability score for a profiler. The repeatability score is computed using the following steps: (1) the repeat runs performed by a profiler at a test section is filtered with the IRI-filter, (2) each IRI-filtered profile is cross correlated with all other IRI-filtered profiles to obtain cross correlation values (i.e., cross-correlation values are computed for all possible profile pairs), (3) the obtained cross correlation values are averaged to obtain the average repeatability cross correlation, which is the repeatability score for the profiler. According to R56-10, a profiler must obtain a repeatability score of at least 0.92 to pass the repeatability criterion.

The accuracy of a profiler is evaluated in AASHTO R56-10 by comparing the data collected by the profiler with the data collected by a reference device. In this method, one run from a reference device is selected, and the IRI-filtered cross-correlation between this device and each of the repeat runs performed by the profiler at that section is computed. Thereafter, the average of these cross correlation values is computed. According to R56-10, a profiler must obtain an accuracy cross-correlation value of at least 0.90 to pass the accuracy criterion.

The ProVAL software developed by the FHWA has a module for determining the repeatability and accuracy of a profiler that uses the procedures described in AASHTO standard R56-10. The cross correlation method for comparing IRI is a better method than comparing the overall IRI values obtained at a section as the cross correlation method compares the distribution of the IRI within the section as well as the IRI magnitude when computing the cross correlation value. When the procedures in R56-10 are used to certify profilers that collect data on newly constructed pavements, the test sections that are used for certifying profilers are typically distress free, to avoid any effects related to pavement distress from influencing the cross correlation value.
The following five analyses involving cross correlation were performed on the data collected at the profiler comparison:

- Evaluate the repeatability of the profile data collected by the profilers by computing the repeatability cross correlation of the profile elevation data.

- Evaluate each profiler’s ability to collect repeatable IRI data by computing the IRI-filtered repeatability cross correlation values at each section.

- Evaluate the ability of the SurPRO to collect repeatable IRI data by computing the IRI-filtered repeatability cross correlation values at each section.

- Evaluate each profiler’s ability to collect accurate IRI data by computing the IRI-filtered cross correlation between profiler data and the data collected by the two reference devices (i.e., Dipstick and SurPRO).

- Evaluate the reproducibility of IRI data collected by profilers by comparing IRI-filtered cross correlation values among the profilers.

The ProVAL software was used in all of these analyses to compute cross-correlation values. For profilers, the 25-mm interval profile data files in ERD format that were created using the LTPP ProXport software were used for all cross-correlation analyses. None of these cross correlation analyses were performed when data from previous LTPP profiler comparisons were analyzed. This was because of two reasons: (1) the first research report that demonstrated the application of the cross correlation method to evaluate profile data was published in 2002, and (2) software to perform the cross correlation analysis was not available in the public domain.

10.2 Repeatability Cross Correlation of Profile Data

The five repeat profile runs that were selected for analysis for a profiler (see table 6.3) were cross correlated with each other, and the average of these cross correlation values was computed. (The data used for this analysis is the profile data that were obtained by the profiler. This profile data has been subjected to an upper wavelength cut-off filter having a cut-off value of 100 m. No additional filtering was performed on the data before computing the cross correlation values.) The computed cross-correlation values are shown in table 10.1, and indicate the repeatability of the profile data collected by the profiler. Values less than 0.95 are shown in bold in table 10.1. Overall, the profile data collected by all profilers showed excellent profile repeatability, with the average cross correlation values being 0.95 or higher except for a few cases (i.e., left wheelpath of section 3 for the North Atlantic profiler, the right wheelpath at section 6 for the North Central profiler and the left wheelpath at section 6 for the Western profiler).

10.3 Repeatability Cross Correlation of IRI-Filtered Profile Data

The ability of the profiler and the SurPRO to collect repeatable IRI data along the section was evaluated by computing the IRI-filtered repeatability cross correlation values for each device at each section. The five repeat profile runs that were selected for analysis for a profiler (see table
6.3) were first subjected to the IRI filter and then cross correlated with each other, and the average of these cross correlation values was computed. A similar analysis was performed on the three repeat SurPRO runs that were collected along each wheelpath at each section. The computed IRI-filtered cross correlation values are shown in Table 10.2. All profilers obtained IRI filtered repeatability cross correlation values greater than 0.92 at all sections, which is the criterion specified in AASHTO R56-10 to pass the repeatability criterion. The overall average IRI-filtered repeatability of the profilers when all test sections were considered ranged from 0.96 to 0.98. The SurPRO also obtained IRI-filtered repeatability cross correlation values of 0.94 or higher except along the left wheelpath of section 1.

### Table 10.1. Profile elevation cross correlation values.

<table>
<thead>
<tr>
<th>Wheelpath</th>
<th>Profiler</th>
<th>Profile Repeatability Cross-Correlation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N. Atlantic</td>
<td>0.83, 0.96, 0.95, 0.97, 0.97, 0.96</td>
</tr>
<tr>
<td></td>
<td>N. Central</td>
<td>0.98, 0.97, 0.97, 0.97, 0.98, 0.98</td>
</tr>
<tr>
<td></td>
<td>Southern</td>
<td>0.98, 0.98, 0.95, 0.97, 0.98, 0.98</td>
</tr>
<tr>
<td></td>
<td>Western</td>
<td>0.99, 0.99, 0.98, 0.98, 0.98, 0.98</td>
</tr>
<tr>
<td>Right</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N. Atlantic</td>
<td>0.97, 0.98, 0.95, 0.98, 0.98, 0.96</td>
</tr>
<tr>
<td></td>
<td>N. Central</td>
<td>0.98, 0.98, 0.96, 0.97, 0.98, 0.98</td>
</tr>
<tr>
<td></td>
<td>Southern</td>
<td>0.98, 0.98, 0.97, 0.98, 0.99, 0.98</td>
</tr>
<tr>
<td></td>
<td>Western</td>
<td>0.99, 0.99, 0.98, 0.98, 0.99, 0.98</td>
</tr>
</tbody>
</table>

### Table 10.2. IRI-filtered repeatability cross correlation values.

<table>
<thead>
<tr>
<th>Wheelpath</th>
<th>Profiler</th>
<th>IRI-Filtered Profile Repeatability Cross-Correlation</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SurPRO</td>
<td>0.88, 1.00, 0.96, 0.95, 0.95, 0.97</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>N. Atlantic</td>
<td>0.97, 0.97, 0.96, 0.93, 0.95, 0.93</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>N. Central</td>
<td>0.96, 0.99, 0.95, 0.92, 0.95, 0.98</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>Southern</td>
<td>0.97, 0.98, 0.96, 0.95, 0.97, 0.97</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>Western</td>
<td>0.98, 0.98, 0.96, 0.95, 0.97, 0.97</td>
<td>0.97</td>
</tr>
<tr>
<td>Right</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SurPRO</td>
<td>0.94, 1.00, 0.98, 0.97, 0.94, 0.97</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>N. Atlantic</td>
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<tr>
<td></td>
<td>N. Central</td>
<td>0.95, 0.98, 0.94, 0.96, 0.92, 0.93</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>Southern</td>
<td>0.96, 0.99, 0.96, 0.95, 0.92, 0.97</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>Western</td>
<td>0.96, 0.99, 0.97, 0.97, 0.94, 0.95</td>
<td>0.96</td>
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</table>
10.4 Accuracy Cross-Correlation of IRI-Filtered Profile Data

The ability of a profiler to obtain accurate IRI data on a section was evaluated by computing the IRI-filtered cross correlation between the profiler data and the reference device data. First, one SurPRO run was selected for a wheelpath at a section and IRI-filtered cross correlation between this run and each of the repeat profiler runs performed at this section was computed. Next, an average cross correlation value was computed by averaging the cross correlation values, which is referred to as the accuracy cross correlation value. Only one Dipstick run is available for each wheelpath at each section. A similar analysis as performed on the SurPRO data was performed using the Dipstick data. The computed IRI-filtered accuracy cross correlation values for the left and right wheelpaths are shown in table 10.3 and 10.4, respectively.

Table 10.3. IRI-filtered accuracy cross-correlation values, left wheelpath.

<table>
<thead>
<tr>
<th>Section</th>
<th>Average Profiler IRI (m/km)</th>
<th>Accuracy Cross-Correlation, Left Wheelpath</th>
<th>With Dipstick</th>
<th>Average</th>
<th>With SurPRO</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Profiler</td>
<td></td>
<td>Profiler</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NA</td>
<td>NC</td>
<td>SO</td>
<td>WE</td>
</tr>
<tr>
<td>1</td>
<td>0.78</td>
<td></td>
<td>0.76</td>
<td>0.78</td>
<td>0.78</td>
<td>0.80</td>
</tr>
<tr>
<td>2</td>
<td>3.50</td>
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<td>0.86</td>
<td>0.87</td>
<td>0.86</td>
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</tr>
<tr>
<td>3</td>
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<td>0.74</td>
<td>0.72</td>
<td>0.72</td>
<td>0.74</td>
</tr>
<tr>
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<td>0.75</td>
<td>0.78</td>
<td>0.79</td>
<td>0.79</td>
</tr>
<tr>
<td>5</td>
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<td>0.65</td>
<td>0.72</td>
<td>0.77</td>
<td>0.77</td>
</tr>
<tr>
<td>6</td>
<td>2.35</td>
<td></td>
<td>0.84</td>
<td>0.86</td>
<td>0.83</td>
<td>0.85</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>0.77</td>
<td>0.79</td>
<td>0.79</td>
<td>0.81</td>
</tr>
</tbody>
</table>

NA - North Atlantic, NC - North Central, SO - Southern, WE - Western

Table 10.4. IRI-filtered accuracy cross-correlation values, right wheelpath.

<table>
<thead>
<tr>
<th>Section</th>
<th>Average Profiler IRI (m/km)</th>
<th>Accuracy Cross-Correlation, Right Wheelpath</th>
<th>With Dipstick</th>
<th>Average</th>
<th>With SurPRO</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Profiler</td>
<td></td>
<td>Profiler</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NA</td>
<td>NC</td>
<td>SO</td>
<td>WE</td>
</tr>
<tr>
<td>1</td>
<td>0.64</td>
<td></td>
<td>0.79</td>
<td>0.80</td>
<td>0.81</td>
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<tr>
<td>2</td>
<td>3.86</td>
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<td>0.91</td>
<td>0.88</td>
<td>0.90</td>
</tr>
<tr>
<td>3</td>
<td>1.34</td>
<td></td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
<td>0.81</td>
</tr>
<tr>
<td>4</td>
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<td></td>
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<td>0.86</td>
<td>0.84</td>
</tr>
<tr>
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<tr>
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<td></td>
<td>0.91</td>
<td>0.87</td>
<td>0.80</td>
<td>0.83</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>0.80</td>
<td>0.81</td>
<td>0.82</td>
<td>0.83</td>
</tr>
</tbody>
</table>

NA - North Atlantic, NC - North Central, SO - Southern, WE - Western
Tables 10.3 and 10.4 also show the average accuracy cross correlation value computed for each wheelpath of each section by averaging the cross correlation values obtained by the four profilers with the Dipstick as well as with the SurPRO. When evaluating these average values it can be seen that the profilers had a higher cross correlation with the SurPRO data than with the Dipstick data for all but two cases (i.e., left wheelpath of section 5 (chip seal) and right wheelpath of section 1 (smooth AC)). The Dipstick and the SurPRO both had similar cross correlation values for the right wheelpath of section 5 (chip seal).

Accuracy cross correlation comparisons were made with each reference device for 48 cases in this analysis (6 sections x 2 wheelpaths x 4 profilers). The SurPRO had a higher cross-correlation with a profiler than the Dipstick for 38 cases, the cross correlation between a profiler with the Dipstick and SurPRO was similar for 4 cases, while the Dipstick had a higher cross correlation with a profiler for 6 cases. When all accuracy cross correlations were considered, the overall average cross correlation between SurPRO and profilers was 0.85, and between Dipstick and profilers was 0.80.

According to AASHTO R56-10, the accuracy cross correlation between a profiler and a reference device must be 0.90 or higher for a profiler to pass certification. As pointed out earlier, R56-10 indicates this criterion applies when certifying profilers that collect data on new pavements. According to R56-10, the IRI level of the two test sections used for certification of profilers used to measure smoothness of new pavements should be between 0.47 and 1.18 m/km (smooth section) and 1.50 and 2.12 m/km (medium smooth section). In addition, the sites used for certification are typically distress free and a coarse textured surface such as chip seal is not used as a certification site. Therefore, the requirements described in AASHTO R56-10 do not apply to all test sections that were used for the profiler comparison.

There were only three cases out of 48 cases where the accuracy cross correlation between the Dipstick and a profiler was 0.90 or higher. There were 13 cases where the accuracy cross correlation between a profiler and the SurPRO was 0.90 or higher. (The left and right wheelpath of section 2 and right wheelpath of section 6 accounted for 12 of these cases.)

The data collected along the right wheelpath of section 1 by the SurPRO and the North Atlantic profiler were used to investigate the cause of the low cross correlation between the SurPRO and profiler data. The data from both the profiler and the SurPRO were subjected to Butterworth band pass filters that had the following wavelength ranges: 0.3 to 1.5 m, 1.5 to 6 m, and 6 to 30 m. (A band pass filter keeps the wavelengths within a desired range and eliminates the wavelengths outside the range. For example, a band pass filter with lower and upper wavelength cut-off values of 0.3 and 1.5 m, respectively, will keep wavelengths between 0.3 and 1.5 m and eliminate the wavelengths outside this range.) Thereafter the IRI-filtered cross correlation values were computed between the SurPRO and profiler data for each waveband range. The following results were obtained:

- Band pass filtered profiles, 0.3 to 1.5 m: IRI filtered cross correlation = 0.87.
- Band pass filtered profiles, 1.5 to 6 m: IRI filtered cross correlation = 0.86.
- Band pass filtered profiles, 6 to 30 m: IRI filtered cross correlation = 0.82.
Overlaid IRI filtered plots for the SurPRO and the profiler for the three wavebands are shown in figures 10.2 through 10.4. For the waveband between 0.3 and 1.5 m, the cross correlation values between the SurPRO and profiler will be influenced by the differences in data collection methodology used by the two devices (i.e., single-point laser for profiler and tire-pavement contact area of SurPRO).

![Figure 10.2. Overlaid IRI filtered plots, waveband 0.3 to 1.5 m.](image)

![Figure 10.3. Overlaid IRI filtered plots, waveband 1.5 to 6 m.](image)
Differences in IRI-filtered profiles for the two devices are clearly seen for the waveband between 6 and 20 m, and would have certainly had a major effect in contributing to the degradation of the accuracy cross correlation between the two devices. A recent in-depth investigation of the same phenomenon for an ICC profiler owned by the Florida DOT showed that the differences between SurPRO and profiler data for the waveband from 6 to 20 m was due to the upper wavelength cut-off filter that was applied on the profiler data.

The profile data obtained from LTPP profilers have been subjected to an upper wavelength cut-off filter with a cut-off wavelength of 100 m. ICC refers to this upper wavelength cut-off filter that is applied on the data as a cotangent filter. The reason for the LTPP profilers not being able to meet the accuracy requirements indicated in AASHTO R56-10 needs further investigation, and is beyond the scope of this study. One interesting point is that all LTPP profilers met the AASHTO R 56-10 criterion for three wheelpaths, all of which were extremely rough (i.e., left wheelpath of section 2, SurPRO IRI = 3.53 m/km; right wheelpath of section 2, SurPRO IRI = 3.87 m/km; and right wheelpath of section 6, IRI = 2.92 m/km).

10.5 Reproducibility Cross Correlation of IRI-Filtered Profile Data

One representative profiler run was selected for each profiler at each section. The IRI-filtered reproducibility among the profilers as well as between the profilers and the reference devices were then computed using these runs. The results from these analyses for the six sections are shown in tables 10.5 through 10.10. (The following notations are used in these tables: Dip – Dipstick, Sur-SurPRO, NA – North Atlantic profiler, NC – North Central profiler, SO – Southern profiler, WE – Western profiler). Cases where the reproducibility cross correlation was less than 0.90 are shown in bold in these tables. The profilers showed good reproducibility (i.e., values of 0.90 or higher) with each other except for a few cases. Evaluation of the profile data for the cases that showed low reproducibility cross correlations indicated lateral variations in the profiled paths appeared to be the reason for the low cross correlation (see section 7.7 for an example).
The cross-correlation values between the Dipstick and the SurPRO ranged from 0.81 to 0.95 and averaged 0.87.

### Table 10.5. Reproducibility cross correlation – section 1.

<table>
<thead>
<tr>
<th>Cross Correlation, Section 1</th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Left Wheelpath</td>
<td>Right Wheelpath</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dip</td>
<td>Sur</td>
<td>NA</td>
<td>NC</td>
<td>SO</td>
<td>WE</td>
<td>Dip</td>
<td>Sur</td>
<td>NA</td>
<td>NC</td>
<td>SO</td>
</tr>
<tr>
<td>Dip</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Sur</td>
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Table 10.9. Reproducibility cross correlation – section 5.

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Table 10.10 Reproducibility cross correlation – section 6.

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CHAPTER 11 - SUMMARY AND CONCLUSIONS

A summary of the results obtained for each of the analysis performed on the data are presented separately in this section.

Data could not be collected by the center sensor in the North Atlantic and North Central profilers as the center sensor accelerometer in both profilers was not working. About a month after the profiler comparison, the defective accelerometers in both profilers were replaced. Shortly after that, the center height sensor in the North Atlantic profiler had problems, and is currently in an inoperable condition.

Static Height Sensor Test

The LTPP specified criteria are that the bias of the sensors be within 0.25 mm and the precision of the sensors be less than 0.125 mm. The static height sensor test could not be performed on the center sensor of the North Atlantic and North Central profiler during the profiler comparison as this sensor was not working in both profilers. However, after receiving the new accelerometers, this test was performed on the center sensor of these two profilers at the RSC facility.

All sensors in all profilers met the bias criterion at all four block positions (i.e., 25, 50, 75, and 100 mm) except for the center sensor in the North Atlantic and North Central profiler that failed the bias criterion for the following positions: (1) North Atlantic profiler at 50, 75 and 100 mm positions, and (2) North Central profiler at 75 and 100 mm positions. All sensors in all profilers met the precision criterion at all four positions except for the center sensor in the North Atlantic profiler that failed the criterion at the 25 and 100 mm positions.

Distance from Ground to Sensor Glass

According to the Profile Manual, the distance from the ground to the glass face of the height sensor should be 325 ± 5 mm. All three sensors in the North Atlantic, North Central, and Western profilers met this criterion. In the Southern profiler, the center sensor met this criterion; but the left and the right sensor were lower than the lower allowable value of 320 mm by 6 and 3 mm, respectively. Deviation from the lower allowable value by a small amount (e.g., 3 to 6 mm) is not expected to have an effect on the data quality.

Bounce Test

According to the criteria presented in the Profile Manual, the static test IRI value should not exceed 0.08 m/km, while the difference in IRI from the dynamic bounce and static test should not exceed 0.10 m/km. All sensors in all profilers satisfied the required criteria. (The bounce test could not be performed on the center sensor of the North Atlantic and North Central profiler as this sensor in both profilers was not working.) The bounce test performed at the RSC facility after the defective center accelerometer in the North Central profiler was replaced indicated that the sensor met the required static test and dynamic test criterion. After the defective center sensor accelerometer was replaced in the North Atlantic profiler, there were problems with the center height sensor, and hence the bounce test results are not available for this sensor.
DMI Test Results

Results from the DMI test that was performed immediately after calibration of the DMI showed that the DMI in all four profilers met the specified bias criterion (bias within ±0.15 m) and the precision criterion (precision less than 0.075 m). All profilers passed the precision criterion for the DMI verification test that was performed after data collection was completed at the profile test sections. The North Central and Southern profilers met the DMI bias criterion for the verification test, but the North Atlantic and Western profilers failed to meet the criterion for the DMI verification test. A review of the DMI calibration results obtained after the profiler comparison for the North Atlantic and Western profilers did not show any DMI issues in these two profilers.

Comparison of IRI Obtained from the SurPRO and the Dipstick

The difference in IRI between the SurPRO and the Dipstick was within ± 0.10 m/km for both wheelpaths at four sections (i.e., Section 1 – smooth AC, Sections 3 and 4 – medium smooth PCC, and Section 5 – Chip Seal). At the other two sections (i.e., Section 2 – rough AC and Section 6 – rough PCC), the IRI from SurPRO was higher than that from the Dipstick by amounts ranging from 0.13 to 0.20 m/km. The SurPRO collects data at 25 mm intervals while the Dipstick collects data at 304.8 mm intervals. Therefore, the Dipstick can miss profile features that are recorded by the SurPRO. Section 2 is a rough asphalt section, while section 6 is a concrete section where the profile data indicated that the slabs were curled up. It appears in both of these sections, the Dipstick because of its longer sampling interval missed features that were recorded by the SurPRO. This resulted in a lower IRI being obtained for the Dipstick data.

IRI Repeatability of Profilers

The Profile Manual indicates the standard deviation of IRI obtained for each wheelpath from five profiler runs at a section must be less than 0.04 m/km. All profilers met this criterion for the left wheelpath. However, this criterion was not met for the right wheelpath for the following four cases: (1) North Atlantic profiler, section 2, (2) Southern profiler, section 5, (3) North Central profiler, section 6, and (4) Western profiler, sections 6. Evaluation of the profile data for these cases did not show any problems with the profile data. It appears that the variations in the IRI values were due to lateral variability in the path followed during data collection. Overall, all profilers appear to be obtaining repeatable IRI values. The standard deviation of IRI values did not indicate that a particular profiler was behaving differently when compared to the other profilers.

Comparison of Profiler and Reference Device IRI

The Profiler Manual specifies that the difference between the profiler IRI and the Dipstick IRI should be within ± 0.16 m/km for each wheelpath. This criterion was also applied to the IRI obtained from the SurPRO. The profilers satisfied the specified IRI criterion for all cases except for the following: (1) Section 2, right wheelpath: North Central, Southern, and Western profilers obtained IRI values that were outside the specified criterion when compared with the Dipstick.
IRI, (2) Section 5, left wheelpath: North Atlantic profiler obtained IRI values that were outside the specified criterion when compared to the Dipstick IRI, (3) Section 5, right wheelpath: North Atlantic and North Central profilers obtained IRI values that were outside the specified criterion when compared to both SurPRO and Dipstick IRI, and (4) Section 6, right wheelpath: North Atlantic profiler obtained IRI values that were outside the specified criterion when compared to the SurPRO IRI. Evaluation of the profile data for the cases that failed the criterion did not show any problems with the profile data. For some cases, features appeared in the profile data at some localized areas that did not appear in the reference device data. This was probably caused by lateral variation in the path profiled by the profiler from the path where the reference device collected data, which caused the profiler IRI to not meet the specified criterion.

Comparison of IRI Values Obtained by Profilers

The average IRI values obtained by the profilers along a wheelpath for all sections were compared. For each wheelpath in each section, the difference between the maximum IRI and the minimum IRI were computed and evaluated. This difference in IRI was 0.10 m/km or less for both wheelpaths at section 1, 3, 4, and 6. These results indicate that the four profilers are obtaining IRI values that are close to each other at these sections. The difference was 0.11 and 0.14 m/km respectively for the left and right wheelpaths at section 2, 0.12 m/km for the left wheelpath at section 5, and 0.25 m/km for the right wheelpath of section 5. Evaluation of the profile data for the cases where the difference was higher than 0.10 m/km indicated the difference appeared to be related to the lateral variability in the path profiled by the profilers.

Evaluation of Profile Plots

A review of overlaid profile plots of the replicate profile runs obtained by a profiler for the left and the right wheelpath at a test section did not show any obvious problems in any profiler, with reasonable repeatability being observed for all profilers for the left, right, and center sensor data. (Center sensor data were not available for North Central and North Atlantic profilers.) The only cases where somewhat variable profiles were observed were for the left wheelpath of section 3 for the North Atlantic profiler, right wheelpath at section 6 for the North Central profiler, and the left wheelpath at section 6 for the Western profiler. The cause for this variability could not be determined.

Overall, the evaluation of the profile plots showed that all four profilers appear to be capturing similar profile features. Overall, there was good agreement in the PSD plots for the data collected by the four profilers, which indicated that all four profilers were collecting similar data.

Cross Correlation Analysis

Repeatability of Profile Data Obtained by the Profilers: Overall, the profile data collected by all profilers showed excellent repeatability, with the average cross correlation values being 95 percent or higher except for three cases (i.e., left wheelpath of section 3 for the North Atlantic profiler, the right wheelpath at section 6 for the North Central profiler, and the left wheelpath at section 6 for the Western profiler).
Repeatability of IRI Values Obtained by the Profilers: All profilers obtained IRI filtered repeatability cross correlation values greater than 0.92 for both wheelpaths at all sections, and met the repeatability criterion specified in AASHTO R56-10 (i.e., IRI filtered cross correlation of at least 0.92).

Accuracy of IRI Values Obtained by the Profilers: Evaluation of accuracy cross correlations were made with each reference device for 48 cases (6 sections x 2 wheelpaths x 4 profilers). AASHTO R56-10 specifies an accuracy cross correlation of at least 0.90 between a profiler and a reference device in order for the profiler to pass certification. There were only 3 cases out of 48 cases where the accuracy cross correlation between the Dipstick and a profiler was 0.90 or higher. There were 14 cases where the accuracy cross correlation between a profiler and the SurPRO was 0.90 or higher. (The left and right wheelpath of section 2 and right wheelpath of section 6 accounted for 12 of these cases). The required criterion could not be achieved on the smooth AC or the two medium-smooth PCC sections. However, all profilers met the accuracy criterion with the SurPRO data for both wheelpaths of the rough AC section (section 2) and the right wheelpath of the rough PCC section (section 6). A recent investigation to study why a Florida DOT ICC profiler failed to achieve the AASHTO specified accuracy cross correlation criterion found that the reason for not achieving the criterion was due to profile distortion caused by the upper wavelength cut-off filter that was applied on the profile data. Further investigation is needed to study why the LTPP profilers were not able to achieve the AASHTO specified accuracy cross correlation value; investigating this issue was outside the scope of work of this study.

The SurPRO had a higher cross correlation with the profilers than the Dipstick for 38 of the 48 cases that were evaluated. The Dipstick had a higher cross correlation for 6 cases, while similar cross correlation values were obtained for the Dipstick and the SurPRO for 4 cases. When all accuracy cross correlations were considered, the overall average cross correlation between SurPRO and profilers was 0.85, and between Dipstick and profilers was 0.80.

Reproducibility of IRI Values of the Profilers: The profilers showed good reproducibility with each other, obtaining IRI-filtered cross correlation values of 0.90 or higher except for a few cases. Evaluation of the profile data for the cases where the reproducibility cross correlation was less than 0.90 indicated lateral variations in the profiled paths as the cause for the low value, where one profiler measured features that were not measured by the other profiler.

Operational Capability of Profilers

The RSC’s took delivery of the ICC profilers in July 2002, and they have now been in operation for approximately 8 years. All RSC’s indicated that they have had intermittent problems with their profiler. During the profiler comparison, all profilers were able to successfully collect data at all six test sections. Midway during data collection, the vertical photocell of the North Atlantic profiler failed to trigger at the start of the section. However, this issue was resolved, and the profiler was able to resume data collection.
Two profilers (Western and North Atlantic) failed to meet the bias criterion (± 0.15 m) during the DMI verification test, obtaining bias values of -0.19 and 0.25, respectively. There were a few cases where the profilers did not satisfy the LTPP criterion of obtaining a standard deviation of IRI that was less than 0.04 m/km for a wheelpath (North Atlantic profiler: right wheelpath of section 2, Southern profiler: right wheelpath of section 5, North Central profiler: right wheelpath of section 6, and Western profiler: right wheelpath of section 6). There also were some cases where the difference between the profiler IRI and the reference device IRI was not within the LTPP specified criterion of ± 0.16 m/km for each wheelpath (i.e., section 2 – right wheelpath: North Central, Southern, and Western profilers with the Dipstick; section 5, left wheelpath: North Atlantic profiler with the Dipstick; section 5, right wheelpath: North Atlantic and North Central profilers with SurPRO and Dipstick; and section 6, right wheelpath: North Atlantic profiler with SurPRO. Evaluation of the profile data for the cases that failed the previously described two criterion did not show any problems with the profile data. The failure to achieve the specified criterion appeared to be related to lateral variation in the path profiled by the profiler.

One profiler failed the DMI verification test during the 2003 profiler comparison. For the 2003 and 2007 comparisons, there were cases similar to this comparison where some profilers at some sections failed to meet the IRI standard deviation criterion or the IRI accuracy criterion.

Overall, in spite of their age, the four LTPP profilers appear to be collecting satisfactory data.
CHAPTER 12 - RECOMMENDATIONS

The center sensor in the North Atlantic profiler failed the bias criterion at 50, 75, and 100 mm positions, while the center sensor in the North Central profiler failed the bias criterion at the 75 and 100 mm positions. The center sensor in the North Atlantic profiler also failed the precision criterion at 25 and 100 mm positions. Subsequently there were problems with the center height sensor in the North Atlantic profiler, and this sensor is currently in an inoperable condition. We recommend ICC be contacted to address the center height sensor problems in North Central and North Atlantic profilers.

Traditionally, the Dipstick has been used in the LTPP program to collect reference profile data. The profilers collect profile data at 25 mm intervals, while the Dipstick collects data at 304.8 mm intervals. The longer sampling interval of the Dipstick can miss features that are recorded by profilers. This can affect the computed IRI values. The recently released AASHTO standard R 56-10 indicates a reference device that is used to collect data to certify profilers should have a data recording interval of less than 70 mm. The Dipstick does not meet this criterion. This shortcoming can be overcome by using a reference device such as the SurPRO, which has a data recording interval of 25 mm, which is similar to the profiler data recording interval. Another advantage of acquiring such a device is that it can also be used to collect transverse profile data at 25 mm intervals, which will give a more complete picture of the transverse profile when compared to the current transverse profiles obtained from the Dipstick.

It is recommended in future LTPP comparisons, reference measurements be obtained along an additional longitudinal path that coincides with the path traversed by the center sensor of the profiler so that the data collected by the center sensor can be compared with data collected by a reference device. Currently, data from the center sensor is not used for computing IRI values and this data is not uploaded to the LTPP database. However, this data is available in the AIMS.

It is recommended that the cross correlation method described in this report be employed in future LTPP profiler comparisons to evaluate the repeatability of profile data as well as the repeatability of IRI data. The cross correlation method for evaluating the repeatability of IRI is a better method than evaluating the standard deviation of IRI obtained from repeat runs as the cross correlation method compares the distribution of the IRI within the section as well as the IRI magnitude when computing the repeatability cross correlation value. However, further investigation is needed before using the cross correlation method to evaluate the accuracy of the IRI computed from profiler data. The LTPP profilers did not meet the accuracy cross correlation indicated in AASHTO R 56-10 at most sections. The reason why the profilers did not meet the criterion needs further investigation. Investigating this issue was outside the scope of work for this study.
APPENDIX A - PHOTOGRAPHS OF TEST SECTIONS
Figure A1. Section 1 – Smooth Asphalt Concrete.
Figure A2. Section 2 – Rough Asphalt Concrete.
Figure A3. Section 2 – Rough Asphalt Concrete.
Figure A4. Section 3 – Medium Smooth Concrete.
Figure A5. Section 4 – Medium Smooth Concrete.
Figure A6. Section 5 – Chip Seal.
Figure A7. Section 6 – Rough Concrete.
# Static Height Sensor Measurements

**Position** | **Value Shown on Monitor for Diff Ht (Note 1)** | **Avg. of Heights (mm)** | **Actual Block Height (Note 2) (mm)** | **Actual Minus Average (mm)** | **Std Dev of Heights (mm) (Note 3)**
--- | --- | --- | --- | --- | ---
Base Plate + 25 mm Block + Calibration Plate | Test 1: 25.065  Test 2: 24.992  Test 3: 25.130  Test 4: 25.065  Test 5: 25.142 | 25.076 | 25.024 | -0.052 | 0.060
Base Plate + 50 mm Block + Calibration Plate | Test 1: 49.983  Test 2: 49.950  Test 3: 49.989  Test 4: 49.976  Test 5: 49.997 | 49.973 | 50.005 | 0.032 | 0.071
Base Plate + 75 mm Block + Calibration Plate | Test 1: 75.183  Test 2: 75.064  Test 3: 74.938  Test 4: 74.978  Test 5: 74.932 | 75.019 | 75.001 | -0.018 | 0.105
Base Plate + 100 mm Block + Calibration Plate | Test 1: 100.043  Test 2: 100.066  Test 3: 100.013  Test 4: 100.132  Test 5: 100.040 | 100.068 | 100.01 | -0.049 | 0.045

**Position** | **Value Shown on Monitor for Diff Ht (Note 1)** | **Avg. of Heights (mm)** | **Actual Block Height (Note 2) (mm)** | **Actual Minus Average (mm)** | **Standard Dev. of Heights (mm) (Note 3)**
--- | --- | --- | --- | --- | ---
Base Plate + 25 mm Block + Calibration Plate | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0!
Base Plate + 50 mm Block + Calibration Plate | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0!
Base Plate + 75 mm Block + Calibration Plate | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0!
Base Plate + 100 mm Block + Calibration Plate | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0! | #DIV/0!

**Position** | **Value Shown on Monitor for Diff Ht (Note 1)** | **Avg. of Heights (mm)** | **Actual Block Height (Note 2) (mm)** | **Actual Minus Average (mm)** | **Standard Dev. of Heights (mm) (Note 3)**
--- | --- | --- | --- | --- | ---
Base Plate + 25 mm Block + Calibration Plate | Test 1: 25.172  Test 2: 25.189  Test 3: 25.062  Test 4: 25.068  Test 5: 25.114 | 25.121 | 25.024 | -0.097 | 0.058
Base Plate + 50 mm Block + Calibration Plate | Test 1: 50.119  Test 2: 49.991  Test 3: 50.003  Test 4: 49.996  Test 5: 49.996 | 50.021 | 50.005 | -0.016 | 0.055
Base Plate + 75 mm Block + Calibration Plate | Test 1: 75.129  Test 2: 74.860  Test 3: 74.921  Test 4: 74.978  Test 5: 75.038 | 74.972 | 75.001 | 0.022 | 0.101
Base Plate + 100 mm Block + Calibration Plate | Test 1: 100.025  Test 2: 100.025  Test 3: 99.940  Test 4: 99.950  Test 5: 100.023 | 99.992 | 100.01 | 0.017 | 0.044
## STATIC HEIGHT SENSOR MEASUREMENTS

**RSC:** North Central  
**Date:** 5/17/2010

Distance from Ground to Sensor Glass (mm):  
Left: 332  Center: 336  Right: 335

### Left Sensor

<table>
<thead>
<tr>
<th>Position</th>
<th>Value Shown on Monitor for Diff Ht (Note 1)</th>
<th>Avg. of Heights (mm)</th>
<th>Actual Block Height (Note 2) (mm)</th>
<th>Actual Minus Average (mm)</th>
<th>Std Dev. of Heights (mm) (Note 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test 1</td>
<td>Test 2</td>
<td>Test 3</td>
<td>Test 4</td>
<td>Test 5</td>
</tr>
<tr>
<td>Base Plate + 25 mm Block + Calibration Plate</td>
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<td>Base Plate + 75 mm Block + Calibration Plate</td>
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<td>75.074</td>
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<td>75.088</td>
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<td>Base Plate + 100 mm Block + Calibration Plate</td>
<td>99.978</td>
<td>99.947</td>
<td>100.142</td>
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### Center Sensor

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<th>Avg. of Heights (mm)</th>
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### Right Sensor

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<tr>
<th>Position</th>
<th>Value Shown on Monitor for Diff Ht (Note 1)</th>
<th>Avg. of Heights (mm)</th>
<th>Actual Block Height (Note 2) (mm)</th>
<th>Actual Minus Average (mm)</th>
<th>Std Dev. of Heights (mm) (Note 3)</th>
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</thead>
<tbody>
<tr>
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<td>Test 1</td>
<td>Test 2</td>
<td>Test 3</td>
<td>Test 4</td>
<td>Test 5</td>
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<td>Base Plate + 25 mm Block + Calibration Plate</td>
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<td>25.195</td>
<td>25.128</td>
<td>25.169</td>
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<tr>
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<td>49.987</td>
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<td>Base Plate + 75 mm Block + Calibration Plate</td>
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<td>74.989</td>
<td>74.966</td>
<td>74.968</td>
<td>74.977</td>
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<td>99.956</td>
<td>100.002</td>
<td>100.133</td>
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<td>100.064</td>
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## STATIC HEIGHT SENSOR MEASUREMENTS

RSC: Southern  
Date: 17-May-10

Distance from Ground to Sensor Glass (mm):  
Left: 313 Center 317 Right 314

### Left Sensor

<table>
<thead>
<tr>
<th>Position</th>
<th>Value Shown on Monitor for Dif Ht (Note 1)</th>
<th>Avg. of Heights (mm)</th>
<th>Actual Block Height (Note 2) (mm)</th>
<th>Actual Minus Average (mm)</th>
<th>Std Dev. of Heights (mm) (Note 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Plate + 25 mm Block + Calibration Plate</td>
<td>24.988, 25.026, 25.052, 24.963, 24.791</td>
<td>24.964, 25.024</td>
<td>0.06</td>
<td>0.102584112</td>
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<tr>
<td>Base Plate + 50 mm Block + Calibration Plate</td>
<td>50.032, 49.539, 49.844, 50.051, 49.949</td>
<td>49.963, 50.012</td>
<td>0.049</td>
<td>0.082822099</td>
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</tr>
<tr>
<td>Base Plate + 75 mm Block + Calibration Plate</td>
<td>74.98, 74.552, 74.924, 75.003, 75.069</td>
<td>74.9856, 75.019</td>
<td>0.0334</td>
<td>0.055256674</td>
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<tr>
<td>Base Plate + 100 mm Block + Calibration Plate</td>
<td>99.993, 100.1, 100.041, 100.003, 100.044</td>
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<td>0.042193841</td>
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### Center Sensor

<table>
<thead>
<tr>
<th>Position</th>
<th>Value Shown on Monitor for Dif Ht (Note 1)</th>
<th>Avg. of Heights (mm)</th>
<th>Actual Block Height (Note 2) (mm)</th>
<th>Actual Minus Average (mm)</th>
<th>Standard Dev. of Heights (mm) (Note 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Plate + 25 mm Block + Calibration Plate</td>
<td>25.069, 24.864, 25.021, 24.865, 25.078</td>
<td>24.9794, 25.024</td>
<td>0.0446</td>
<td>0.107184155</td>
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<tr>
<td>Base Plate + 50 mm Block + Calibration Plate</td>
<td>49.833, 49.876, 49.861, 49.831, 49.957</td>
<td>49.8796, 50.012</td>
<td>0.1324</td>
<td>0.063328618</td>
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<tr>
<td>Base Plate + 75 mm Block + Calibration Plate</td>
<td>74.92, 74.778, 74.983, 74.813, 74.778</td>
<td>74.8364, 75.014</td>
<td>0.1776</td>
<td>0.066259339</td>
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</tr>
<tr>
<td>Base Plate + 100 mm Block + Calibration Plate</td>
<td>99.97, 99.968, 99.993, 99.98, 99.956</td>
<td>99.9731, 100.022</td>
<td>0.0486</td>
<td>0.013886524</td>
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### Right Sensor

<table>
<thead>
<tr>
<th>Position</th>
<th>Value Shown on Monitor for Dif Ht (Note 1)</th>
<th>Avg. of Heights (mm)</th>
<th>Actual Block Height (Note 2) (mm)</th>
<th>Actual Minus Average (mm)</th>
<th>Standard Dev. of Heights (mm) (Note 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Plate + 25 mm Block + Calibration Plate</td>
<td>25.006, 25.07, 25.037, 25.164, 25.057</td>
<td>25.0663, 25.022</td>
<td>-0.0448</td>
<td>0.059453343</td>
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<tr>
<td>Base Plate + 50 mm Block + Calibration Plate</td>
<td>49.85, 49.915, 49.956, 49.911, 49.979</td>
<td>49.9222, 50.012</td>
<td>0.0898</td>
<td>0.043933319</td>
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<tr>
<td>Base Plate + 75 mm Block + Calibration Plate</td>
<td>74.963, 74.876, 74.9, 74.785, 74.914</td>
<td>74.8876, 75.001</td>
<td>0.1134</td>
<td>0.065569048</td>
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</tr>
<tr>
<td>Base Plate + 100 mm Block + Calibration Plate</td>
<td>99.831, 99.88, 99.852, 99.818, 99.871</td>
<td>99.8504, 100.029</td>
<td>0.1786</td>
<td>0.025120873</td>
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# STATIC HEIGHT SENSOR MEASUREMENTS

**RSC:** Western  
**Date:** 17-May-10

Distance from Ground to Sensor Glass (mm):  
Left: 328  Center: 330  Right: 330

## Left Sensor

<table>
<thead>
<tr>
<th>Position</th>
<th>Value Shown on Monitor for Dif Ht (Note 1)</th>
<th>Avg. of Heights (mm)</th>
<th>Actual Block Height (Note 2) (mm)</th>
<th>Actual Minus Average (mm)</th>
<th>Std Dev. of Heights (mm) (Note 3)</th>
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<tbody>
<tr>
<td></td>
<td>Test 1  Test 2  Test 3  Test 4  Test 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base Plate + 25 mm Block + Calibration Plate</td>
<td>25.116  24.973  25.088  25.118  25.074</td>
<td>25.0738</td>
<td>25.023</td>
<td>-0.051</td>
<td>0.059</td>
</tr>
<tr>
<td>Base Plate + 50 mm Block + Calibration Plate</td>
<td>49.858  50  49.873  49.85  50.052</td>
<td>49.9266</td>
<td>50.015</td>
<td>0.088</td>
<td>0.093</td>
</tr>
<tr>
<td>Base Plate + 75 mm Block + Calibration Plate</td>
<td>74.966  74.906  74.92  74.934  74.912</td>
<td>74.9276</td>
<td>74.993</td>
<td>0.065</td>
<td>0.024</td>
</tr>
<tr>
<td>Base Plate + 100 mm Block + Calibration Plate</td>
<td>99.888  99.866  99.914  99.923  99.983</td>
<td>99.9143</td>
<td>100.025</td>
<td>0.110</td>
<td>0.044</td>
</tr>
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</table>

## Center Sensor

<table>
<thead>
<tr>
<th>Position</th>
<th>Value Shown on Monitor for Dif Ht (Note 1)</th>
<th>Avg. of Heights (mm)</th>
<th>Actual Block Height (Note 2) (mm)</th>
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<tr>
<td></td>
<td>Test 1  Test 2  Test 3  Test 4  Test 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base Plate + 25 mm Block + Calibration Plate</td>
<td>24.987  25.003  24.978  24.961  24.944</td>
<td>24.9745</td>
<td>25.019</td>
<td>0.044</td>
<td>0.023</td>
</tr>
<tr>
<td>Base Plate + 50 mm Block + Calibration Plate</td>
<td>50.039  49.904  49.92  49.938  49.853</td>
<td>49.9308</td>
<td>50.015</td>
<td>0.084</td>
<td>0.068</td>
</tr>
<tr>
<td>Base Plate + 75 mm Block + Calibration Plate</td>
<td>74.816  74.951  74.93  74.941  74.924</td>
<td>74.923</td>
<td>74.993</td>
<td>0.070</td>
<td>0.064</td>
</tr>
<tr>
<td>Base Plate + 100 mm Block + Calibration Plate</td>
<td>99.732  99.858  99.902  99.852  99.824</td>
<td>99.8436</td>
<td>100.022</td>
<td>0.178</td>
<td>0.044</td>
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</table>

## Right Sensor

<table>
<thead>
<tr>
<th>Position</th>
<th>Value Shown on Monitor for Dif Ht (Note 1)</th>
<th>Avg. of Heights (mm)</th>
<th>Actual Block Height (Note 2) (mm)</th>
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<th>Standard Dev. of Heights (mm) (Note 3)</th>
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<td></td>
<td>Test 1  Test 2  Test 3  Test 4  Test 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Base Plate + 25 mm Block + Calibration Plate</td>
<td>25.05  25.054  25.013  25.213  25.039</td>
<td>25.0738</td>
<td>25.021</td>
<td>-0.053</td>
<td>0.079</td>
</tr>
<tr>
<td>Base Plate + 50 mm Block + Calibration Plate</td>
<td>49.928  49.966  49.996  49.949  49.964</td>
<td>49.9606</td>
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<td>Base Plate + 75 mm Block + Calibration Plate</td>
<td>75.112  74.975  75.045  74.969  75.004</td>
<td>75.021</td>
<td>74.933</td>
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<td>0.059</td>
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<td>Base Plate + 100 mm Block + Calibration Plate</td>
<td>100.034  99.931  99.955  100.012  100.081</td>
<td>100.025</td>
<td>100.025</td>
<td>0.022</td>
<td>0.060</td>
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</table>
**STATIC HEIGHT SENSOR MEASUREMENTS**

| Distance from Ground to Sensor Glass (mm):  | Left: 328 | Center: 330 | Right: 323 |

### Left Sensor

<table>
<thead>
<tr>
<th>Position</th>
<th>Value Shown on Monitor for Dif Ht (Note 1)</th>
<th>Avg. of Heights (mm)</th>
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<td>Base Plate + 25 mm Block + Calibration Plate</td>
<td>Test 1: 25.097 Test 2: 25.086 Test 3: 25.265 Test 4: 25.158 Test 5: 25.124</td>
<td>25.146</td>
<td>25.028</td>
<td>-0.118</td>
<td>0.072</td>
</tr>
<tr>
<td>Base Plate + 50 mm Block + Calibration Plate</td>
<td>Test 1: 50.169 Test 2: 50.194 Test 3: 50.202 Test 4: 50.136 Test 5: 50.195</td>
<td>50.1792</td>
<td>50.015</td>
<td>-0.164</td>
<td>0.027</td>
</tr>
<tr>
<td>Base Plate + 75 mm Block + Calibration Plate</td>
<td>Test 1: 75.312 Test 2: 75.320 Test 3: 75.277 Test 4: 75.336 Test 5: 75.217</td>
<td>75.2924</td>
<td>74.998</td>
<td>-0.294</td>
<td>0.047</td>
</tr>
<tr>
<td>Base Plate + 100 mm Block + Calibration Plate</td>
<td>Test 1: 100.472 Test 2: 100.526 Test 3: 100.384 Test 4: 100.400 Test 5: 100.421</td>
<td>100.4406</td>
<td>100.026</td>
<td>-0.415</td>
<td>0.058</td>
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### Center Sensor

<table>
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<tr>
<th>Position</th>
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### Right Sensor

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<tr>
<th>Position</th>
<th>Value Shown on Monitor for Dif Ht (Note 1)</th>
<th>Avg. of Heights (mm)</th>
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<td>0.072</td>
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<td>100.026</td>
<td>-0.415</td>
<td>0.058</td>
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## STATIC HEIGHT SENSOR MEASUREMENTS

**RSC:**  NARO  
**Date:**  7/16/2010  

Distance from Ground to Sensor Glass (mm):  Left:  320  Center:  322  Right:  320

<table>
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<th>Left Sensor</th>
<th>Position</th>
<th>Value Shown on Monitor for Dif Ht (Note 1)</th>
<th>Avg. of Heights (mm)</th>
<th>Actual Block Height (Note 2) (mm)</th>
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<td>Test 3</td>
<td>Test 4</td>
<td>Test 5</td>
<td>Test 1</td>
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<tr>
<td>Base Plate + 25 mm Block + Calibration Plate</td>
<td>25.377</td>
<td>25.288</td>
<td>25.082</td>
<td>25.075</td>
<td>25.324</td>
<td>25.2288</td>
</tr>
<tr>
<td>Base Plate + 50 mm Block + Calibration Plate</td>
<td>50.418</td>
<td>50.355</td>
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<th>Standard Dev. of Heights (mm) (Note 3)</th>
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<th>Standard Dev. of Heights (mm) (Note 3)</th>
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<td>Test 4</td>
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APPENDIX C - IRI VALUES
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Note: SD - Standard Deviation, Avg - Average, NA - North Atlantic, NC - North Central, SO - Southern, WE - Western
APPENDIX D - PLOTS OF LEFT AND RIGHT SENSOR PROFILE DATA OBTAINED FROM REPEAT PROFILER RUNS
Each figure in this appendix contains the overlaid profile plots of the profile data collected by a profiler at each test section, with separate plots showing the left and the right sensor data. The plots shown in each figure correspond to the five profiler runs that were selected by the RSC’s for computing the IRI values from the nine profile runs that were made at each test section.

The first graph in this appendix shows the left sensor profile data for the five profiler runs collected by the North Atlantic profiler at section 1. This graph was created using the ProQual software. The legend for this graph includes notations such as 1-4-L, 1-6-L, 1-7-L etc., where the first digit refers to the set number, second digit is the profiler run number, and the third digit refers to the sensor. For example, in 1-4-L, 1 is the set number, 4 is the profiler run number, and L refers to the left sensor. All graphs have 1 as the set number. The legends in other plots have similar notations. The section numbers range from 1 to 6, while the profiler run numbers range from 1 to 9. The sensor is either L for the left sensor or R for the right sensor.
Figure D1. Section 1 – North Atlantic – Left Wheelpath.

Figure D2. Section 1 – North Atlantic – Right Wheelpath.
Figure D3. Section 1 – North Central – Left Wheelpath.

Figure D4. Section 1 – North Central – Right Wheelpath.
Figure D5. Section 1 – Southern – Left Wheelpath.

Figure D6. Section 1 – Southern – Right Wheelpath.
Figure D7. Section 1 – Western – Left Wheelpath.

Figure D8. Section 1 – Western - Right Wheelpath.
Figure D9. Section 2 – North Atlantic – Left Wheelpath.

Figure D10. Section 2 – North Atlantic – Right Wheelpath.
Figure D11. Section 2 – North Central – Left Wheelpath.

Figure D12. Section 2 – North Central – Right Wheelpath.
Figure D13. Section 2 – Southern – Left Wheelpath.

Figure D14. Section 2 – Southern – Right Wheelpath.
Figure D15. Section 2 – Western – Left Wheelpath.

Figure D16. Section 2 – Western – Right Wheelpath.
Figure D17. Section 3 – North Atlantic – Left Wheelpath.

Figure D18. Section 3 – North Atlantic – Right Wheelpath.
Figure D19. Section 3 – North Central – Left Wheelpath.

Figure D20. Section 3 – North Central – Right Wheelpath.
Figure D21. Section 3 – Southern – Left Wheelpath.

Figure D22. Section 3 – Southern – Right Wheelpath.
Figure D23. Section 3 – Western – Left Wheelpath.

Figure D24. Section 3 – Western – Right Wheelpath.
Figure D25. Section 4 – North Atlantic – Left Wheelpath.

Figure D26. Section 4 – North Atlantic – Right Wheelpath.
Figure D27. Section 4 – North Central – Left Wheelpath.

Figure D28. Section 4 – North Central – Right Wheelpath.
Figure D29. Section 4 – Southern – Left Wheelpath.

Figure D30. Section 4 – Southern – Right Wheelpath.
Figure D31. Section 4 – Western – Left Wheelpath.

Figure D32. Section 4 – Western – Right Wheelpath.
Figure D33. Section 5 – North Atlantic – Left Wheelpath.

Figure D34. Section 5 – North Atlantic – Right Wheelpath.
Figure D35. Section 5 – North Central – Left Wheelpath.

Figure D36. Section 5 – North Central – Right Wheelpath.
Figure D37. Section 5 – Southern – Left Wheelpath.

Figure D38. Section 5 – Southern – Right Wheelpath.
Figure D39. Section 5 – Western – Left Wheelpath.

Figure D40. Section 5 – Western – Right Wheelpath.
Figure D41. Section 6 – North Atlantic – Left Wheelpath.

Figure D42. Section 6 - North Atlantic – Right Wheelpath.
Figure D43. Section 6 – North Central – Left Wheelpath.

Figure D44. Section 6 – North Central – Right Wheelpath.
Figure D45. Section 6 – Southern – Left Wheelpath.

Figure D46. Section 6 – Southern – Right Wheelpath.
Figure D47. Section 6 – Western – Left Wheelpath.

Figure D48. Section 6 – Western - Right Wheelpath.
APPENDIX E - PLOTS OF CENTER SENSOR PROFILE DATA OBTAINED FROM REPEAT PROFILER RUNS
This appendix contains the overlaid profile plots of the data collected by the center sensor in a profiler at each test section. The plots shown in each figure correspond to the five profile runs that were selected by the RSC’s for computing the IRI values of the left and the right wheelpaths from the nine profile runs that were made at each test section. The center sensor in the North Atlantic and North Central profilers was not working, and hence center sensor data could not be collected by these two profilers.

The first graph in this appendix shows the profile data for five profiler runs collected at section 1 by the center sensor of the Southern profiler. This graph was generated by the ProQual software. The legend for this graph includes notations such as 1-3-C, 1-7-C, 1-9-C etc., where the first digit refers to the set number (all graphs have 1 as the set number), the second digit refers to the profiler run number, and the third digit refers to the path along where data were collected, which is C for all data shown in this appendix. For example, in 1-3-C, 1 is the set number, 3 is the profiler run number, and C refers to the center sensor. The section numbers range from 1 to 6, while the profiler run numbers range from 1 to 9.
Figure E1. Section 1 – Southern.

Figure E2. Section 1 – Western.
Figure E3. Section 2 – Southern.

Figure E4. Section 2 – Western.
Figure E5. Section 3 – Southern.

Figure E6. Section 3 – Western.
Figure E7. Section 4 – Southern.

Figure E8. Section 4 – Western.
Figure E9. Section 5 – Southern.

Figure E10. Section 5 – Western.
Figure E11. Section 6 – Southern.

Site 270006: Set 1 (19/May/2010)

Figure E12. Section 6 – Western.

Site 270006: Set 1 (19/May/2010)
APPENDIX F - COMPARISON OF LEFT AND RIGHT SENSOR PROFILE PLOTS FOR THE FOUR PROFILERS
This appendix includes plots of profile data collected by the four profilers at each test section shown in one graph, with separate graphs being provided for the left and right sensor data. A representative profile run was selected for each profiler at each test section for generating the graphs. This appendix includes overlaid profile plots as well as offset profile plots for each section and wheelpath.

The first graph in this appendix shows profile plots for the left sensor data at section 1, with one run from each profiler shown in this graph. The legend for this graph contains the notations NA-1-4, NC-1-9, SO-1-2, and WE-1-3. In the notation, the first digit refers to the section number, the second digit refers to the region (NA – North Atlantic, NC – North Central, SO – Southern, and WE – Western), and the third digit refers to the profiler run number. Legends shown in other graphs follow the same procedure. The section numbers range from 1 to 6, while the profiler run numbers range from 1 to 9.

As seen from the first figure, as the plots for the four profilers overlay with each other, it is hard to see if there are differences between the profiles. Therefore, offset profile plots were created by offsetting the profile plots from each other. The second graph in this appendix shows an offset profile plot for the left wheelpath of section 1. The legend used for this plot is similar to that used for the first graph.

Each page in this appendix contains two graphs. The first graph shows the overlaid profile plots for the four profilers for a specific section and wheelpath. The second graph shows the same data shown in the first graph, with the data for the profilers being offset from each other.
Figure F1. Section 1 – Left Wheelpath.
Figure F2. Section 1 – Right Wheelpath.
Figure F3. Section 2 – Left Wheelpath.
Figure F4. Section 2 – Right Wheelpath.
Figure F5. Section 3 – Left Wheelpath.
Figure F6. Section 3 – Right Wheelpath.
Figure F7. Section 4 – Left Wheelpath.
Figure F8. Section 4 – Right Wheelpath.
Figure F9. Section 5 – Left Wheelpath.
Figure F10. Section 5 – Right Wheelpath.
Figure F11. Section 6 – Left Wheelpath.
Figure F12. Section 6 – Right Wheelpath.
APPENDIX G - POWER SPECTRAL DENSITY PLOTS OF PROFILE DATA
This appendix contains power spectral density (PSD) plots generated from the profile data collected by the four profilers. Each figure is for a specific sensor (either left or right) at a test section, and contains PSD plots for all four profilers. A representative profile run was selected for each profiler at each section to generate these PSD plots.

The legend in each figure indicates the profiler, the test section, and the profiler run number. The first digit indicates the region (NA – North Atlantic, NC – North Central, SO – Southern and WE-Western), the second digit indicates the test section number (test sections number ranges from 1 to 6), and the third digit indicates the profiler run number (ranges from 1 to 9).

For example, the first item in the legend in the first figure is WE-1-3. This means the data corresponds to run number 3 of the Western profiler at test section 1.
Figure G1. Section1. Left wheelpath.

Figure G2. Section1. Right wheelpath.
Figure G3. Section 2. Left wheelpath.

Figure G4. Section 2. Right wheelpath.
Figure G5. Section 3. Left wheelpath.

Figure G6. Section 3. Right wheelpath.
Figure G7. Section 4. Left wheelpath.

Figure G8. Section 4. Right wheelpath.
Figure G9. Section 5. Left wheelpath.

Figure G10. Section 5. Right wheelpath.
Figure G11. Section 6. Left wheelpath.

Figure G12. Section 6. Right wheelpath.
REFERENCES


