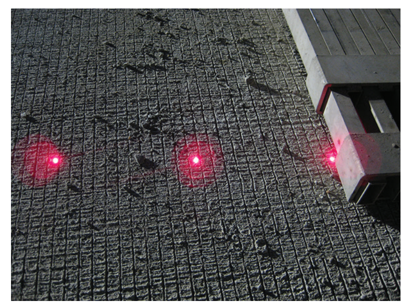
Implementation Support for Second Strategic Highway Research Program (SHRP2) Renewal R06E

Real-Time Smoothness Measurements on Portland Cement Concrete Pavements During Construction



Final Report
Updated February 2020

National Concrete Pavement Technology Center

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16. Abstract

The Second Strategic Highway Research Program (SHRP2) R06E project, Real-Time Smoothness Measurements on Portland Cement Concrete Pavements during Construction, advanced real-time smoothness measuring technologies through unbiased field evaluations and demonstrations and the development of a draft model specification and guidelines. Furthermore, the study validated technologies designed to improve quality control and the paving process and enhanced understanding of the construction artifacts that affect smoothness.

The Federal Highway Administration (FHWA), through the SHRP2 Solutions Implementation Assistance Program, funded additional work to continue development and implementation, with the goal to eventually achieve routine use of real-time smoothness measuring technologies by owner agencies and paving contractors.

This report summarizes the implementation tasks performed in support of R06E. Tasks included developing an equipment loan program involving real-time smoothness measuring technologies, holding a showcase and conducting workshops, conducting case studies of projects that took advantage of the equipment loan program, refining the specifications developed under R06E, and engaging in a wide array of marketing and outreach activities.

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The Appendix B: Draft Specification from the first publication of this report in September 2018 was revised and replaces the previous version in this February 2020 publication.

Implementation Support for Second Strategic Highway Research Program (SHRP2) Renewal R06E

REAL-TIME SMOOTHNESS MEASUREMENTS ON PORTLAND CEMENT CONCRETE PAVEMENTS DURING CONSTRUCTION

Final Report
Updated February 2020

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

The authors would like to thank the Federal Highway Administration (FHWA) and the Second Strategic Highway Research Program (SHRP2) Solutions Implementation Assistance Program for funding this work to continue development and implementation from the SHRP2 R06E project, Real-Time Smoothness Measurements on Portland Cement Concrete Pavements during Construction, with the goal to eventually achieve routine use of real-time smoothness measuring technologies by owner agencies and paving contractors.

Special thanks go to each of the 11 contractors that participated in the equipment loan program; GOMACO and Ames Engineering, which provided technical support throughout the project; the Utah Department of Transportation and Utah Concrete Paving Association, which hosted the national showcase; and the agencies and concrete paving industry associations that supported the workshops.

1. INTRODUCTION

The Second Strategic Highway Research Program (SHRP2) R06E project, Real-Time Smoothness Measurements on Portland Cement Concrete Pavements During Construction, did much to advance real-time smoothness measuring technologies through unbiased field evaluations and demonstrations and development of a draft model specification and guidelines (Rasmussen et al. 2013). Furthermore, the study provided validation of the technology for quality control and paving process improvements and improved understanding about which construction artifacts affect smoothness.

As such, the Federal Highway Administration (FHWA), through the SHRP2 Solutions Implementation Assistance Program, funded additional follow-up work to continue development and implementation, with the goal to eventually achieve routine use of real-time smoothness measuring technologies by owner agencies and paving contractors. This report summarizes implementation support for the project performed.

Summary of Task Order Activities

The following activities were performed and are described in this report:

- Equipment Loan Program
- Showcase and Workshops
- Case Studies/Results Documentation
- Specification Refinement
- Marketing and Outreach
- Performance Measures

2. EQUIPMENT LOAN PROGRAM

The FHWA purchased two commercially available real-time smoothness (RTS) systems, which were subsequently used for the equipment loan program. An Ames Engineering Real-Time Profiler (RTP) and a GOMACO Smoothness Indicator (GSI) were purchased, and each was used for about half of the equipment loans.

Eleven equipment loans were completed under this contract. Field reports documenting each equipment loan were prepared and distributed. These reports are available online at http://www.cptechcenter.org/real-time-smoothness/. A summary of the equipment loans is provided in Table 1.

Table 1. Summary of equipment loans

Agency	Route and Location	Date Range	Contractor	Real-Time System
Idaho DOT	I-84 Boise	April 7, 2015– April 24, 2015	Concrete Placing Corporation	Ames RTP
Nebraska DOT	I-80 Lincoln	May 5, 2015– May 13, 2015	Hawkins Construction Company	Ames RTP
Michigan DOT	I-69 Goodells	July 1, 2015– July 10, 2015	Ajax Construction Company	Ames RTP
Texas DOT	SH 99 Houston	August 4, 2015– August 15, 2015	Zachry-Odebrecht Parkway Builders	Gomaco GSI
Pennsylvania DOT	I-81 Pine Grove	September 15, 2015– October 1, 2015	Hi-Way Paving, Inc.	Gomaco GSI
Iowa DOT	L-26 Lyon County	April 12, 2016– April 21, 2016	Flynn Company, Inc.	Ames RTP
Illinois Tollway Authority	I-90 Chicago	June 15, 2016– June 27, 2016	K-Five Construction Corporation	Gomaco GSI
Utah DOT	I-215 Salt Lake City	July 13, 2016– August 9, 2016	Ralph L. Wadsworth Construction Company	Gomaco GSI
Utah DOT	I-15 Farr West	July 15, 2016– August 9, 2016	Geneva Rock Products, Inc.	Ames RTP
Caltrans	SR 46 Shandon	October 10, 2016– October 19, 2016	Brosamer and Wall, Inc.	Ames RTP
Iowa DOT	US 20 Correctionville	April 20, 2017– June 19, 2017	Cedar Valley Corp., LLC	Gomaco GSI

3. SHOWCASE AND WORKSHOPS

3.1 Showcase

A real-time smoothness showcase was held August 9, 2016 in conjunction with the two Utah equipment loans. A report documenting the showcase was prepared and is available online at http://www.cptechcenter.org/real-time-smoothness/).

3.2 Workshops

Materials for a half-day workshop were developed and made available in November 2015 and are available online at http://www.cptechcenter.org/real-time-smoothness/. Workshop modules include the following:

- Welcome and Introduction
- Fundamentals and Importance of Smoothness
- Real-Time Smoothness Measurement Technology and Practices
- Fundamentals of Ride Quality and Current Practices for International Roughness Index (IRI) Specifications
- Best Practices for Concrete Paving Operations
- Using Real-Time Smoothness Technology to Improve Concrete Pavement Smoothness

Eight workshops were delivered, as summarized in Table 2.

Table 2. Summary of real-time smoothness workshops

Location	Date	Number of Participants
Salt Lake City, Utah	January 20, 2016	120
Fontana, California	May 18, 2016	30
Fort Worth, Texas	January 17, 2017	38
Harrisburg, Pennsylvania	February 1, 2017	11
Houston, Texas	February 10, 2017	67
Cincinnati, Ohio	February 23, 2017	30
Greenville, South Carolina	March 21, 2017	16
Omaha, Nebraska	April 18, 2017	23

Evaluations were completed by participants at the conclusion of each workshop. Participants provided feedback in several areas on a scale of 1 to 5 (1 = needs improvement, 2 = fair, 3 = okay, 4 = good, and 5 = very good). The average results were as follows:

- Workshop topics = 4.4
- Organization of materials = 4.6

- Speakers’ knowledge = 4.8
- Meeting facilities = 4.5
- Expectations met = 4.4

4. CASE STUDIES/RESULTS DOCUMENTATION

A number of subtasks were performed as part of the Case Studies/Results Documentation task. The results are summarized in this chapter.

4.1 Synthesis of the Contractors' Experiences

A synthesis of current practice and contractors' experiences with RTS systems was completed in November 2015. This document is included in Appendix A. In summary, the synthesis revealed the following:

- Contractors use RTS to help adjust their paving operation until smoothness targets are met and then use it to monitor paving for bumps/defects and to optimize finishing processes. Contractors also use RTS to show paving crews the impacts of different events and actions on pavement smoothness.

- The use of RTS technology continues to increase as more and more contractors recognize it as a valuable quality control tool. As of 2014, about 75 RTS units were in service nationwide.

- As with any technology, RTS systems require care and regular maintenance. However, when properly cared for, RTS systems provide an essential tool for monitoring the paving process.

4.2 Real-Time Smoothness Comparison to Hardened IRI

It is already well known that real-time and hardened profiles are not identical to each other. RTS profiles are generally measured prior to any finishing, texturing, and joint sawing, while hardened profiles are measured after these processes and after the concrete itself has transitioned from a plastic to a rigid state. For this reason, the IRI values are also expected to be different, but how much different depends on many factors.

The wide variety of projects encountered during the equipment loans for this project made it difficult to establish fixed correlations or expectations regarding the differences between RTS and hardened profiles and smoothness values. However, the case studies discussed here present key findings that will help contractors and agencies better understand the relationship between real-time and hardened profile data.

Some of the key questions related to the comparison of real-time and hardened profile data that these equipment loans provided insight into include the following:

1. Is there any clear relationship or correlation between RTS and hardened profile data and smoothness indices?

2. Which features show up in real-time profiles but not in hardened profiles and vice versa?

3. Which artifacts of the pavement or paving process are picked up in the RTS data such that corrections/adjustments can be made?

Methods for Comparison

When comparing RTS to hardened profile data for the various equipment loan projects under this effort, the two primary methods that provided the most insight were as follows:

1. *Comparison of Smoothness (IRI) Values* – RTS and hardened profiles (typically from contractor quality control [QC] testing within a few days after paving) were analyzed to evaluate the IRI values for each. Overall IRI values for 0.1-mile segments were compared, as were continuous roughness reports (typically, IRI values for a 25 ft base length, which corresponds to what is used in most specifications to identify areas of localized roughness).

2. *Comparison of Spectral Content* – One of the key analysis modules within the Profile Viewing and Analysis (ProVAL) software is the Power Spectral Density (PSD) module. While an explanation of the specifics of this module are beyond the scope of this report, in short, the PSD module helps to identify repeating patterns in profile data that are caused by some aspect of the pavement or paving process.

Because paving is very repetitive by nature, with the same process repeated over and over throughout the day's operation, certain features of the pavement or processes in the operation can leave patterns in the pavement profile (both real-time and hardened). A PSD analysis helps to identify these patterns such that a determination can be made as to whether anything can be done to mitigate the cause in the pavement profile.

A common example for concrete pavements is joint spacing, which creates a pattern in the profile at the joint spacing interval (e.g., every 15 to 20 ft). Dowel bars in the paving slab, whether inserted by the paver or embedded through dowel baskets fastened to the subgrade in front of the paver, create a "disturbance" in the concrete slab that can leave a feature in the pavement profile at the joint spacing.

The PSD analysis can reveal which repeating features are unique to real-time or hardened profile data such that a determination can be made about adjustments to the paving process to minimize the effects. It is important to note, however, that these patterns in the profile data do not always adversely affect IRI values, as discussed in the case studies that follow.

Synchronization of Profile Data

Before RTS and hardened profile data can be compared, it is critical that the profiles are synchronized such that the beginning and ending point of a section of interest is the same. This can be very challenging because RTS and hardened profiles may look very different and distance measurement instrument (DMI) drift can result in less agreement farther into the profile. However, in most cases, the profiles can be lined up reasonably well by visual inspection of profiles that have been high-pass filtered at 50 to 100 ft. Figure 1 shows an example of good alignment between real-time and hardened profile data.

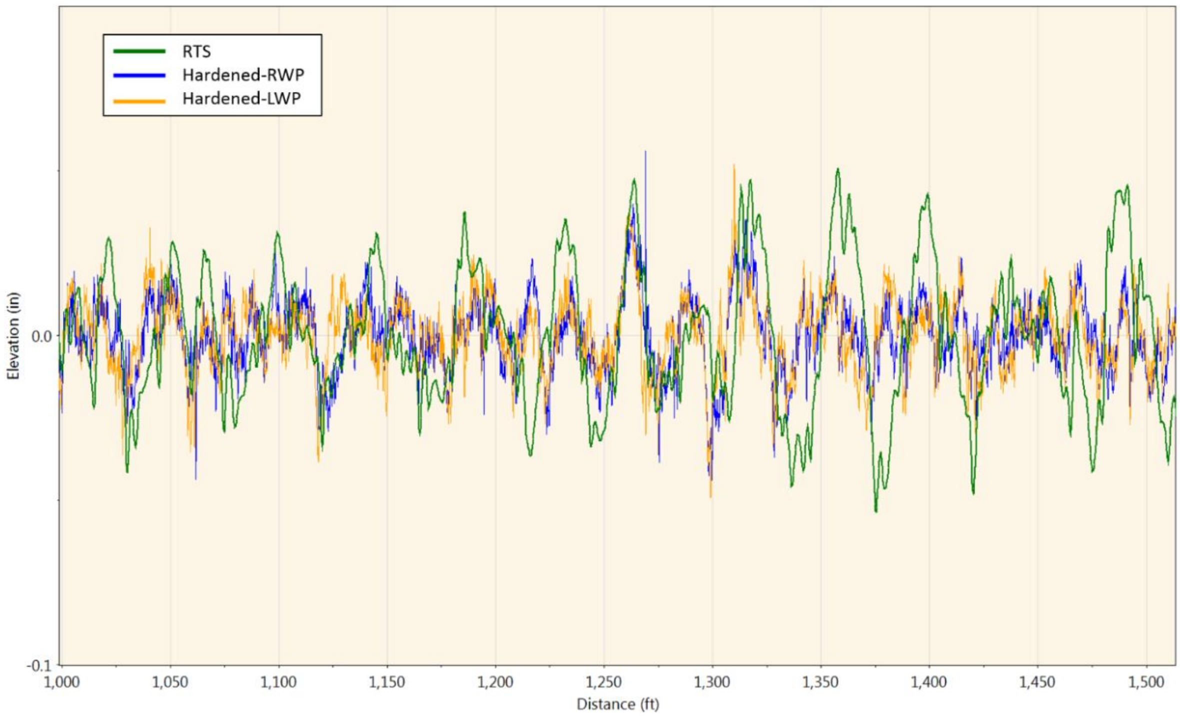


Figure 1. Example of RTS and hardened profile data alignment for analysis

Figure 1 shows that there are different characteristics in each profile, but the general trend is the same.

When comparing real-time and hardened profile data, it is also important that the profiles be from approximately the same location across the width of the slab (e.g., from the same lane and paver). In general, real-time data from the middle of a lane looks fairly similar to the hardened profile data from the wheelpaths of that same lane, as shown in Figure 1.

Iowa US Highway 20

The equipment loan in Iowa on US 20 provided a wealth of RTS and hardened profile data on a very stable, high-production paving project (see the Field Report online at http://www.cptechcenter.org/real-time-smoothness/). This project also provided an opportunity to evaluate RTS data on a project in a state currently in the process of transitioning from a zero-blanking band Profilograph Index (PrI) specification to the IRI.

RTS and hardened data from four days of paving during the equipment loan were evaluated in more detail with respect to the current PrI and proposed IRI specification limits. The Iowa Department of Transportation's (DOT's) profilograph specification for this particular highway (multi-lane divided highway with a speed limit greater than 45 mph) provides a positive pay adjustment for a PrI less than 26.1 in./mi and a negative pay adjustment or correction for a PrI greater than 40 in./mi, as shown in Table 3.

Table 3. Iowa DOT PrI pay adjustment schedule for portland cement concrete pavements

Profile Index Greater than 45 mph (inches per mile)	Profile Index 45 mph or Less and Ramps (inches per mile)	Interstate and Multi-Lane Divided Segments ($ per 0.1-mile segment per lane)	Other Primary Segments ($ per 0.1-mile segment per lane)
22.0 or less	25.0 or less	+950.00	+850.00
22.1 to 23.5		+800.00	+650.00
23.6 to 26.0	25.1 to 30.0	+600.00	+450.00
26.1 to 40.0	30.1 to 65.0	0.00	0.00
40.1 to 45.0	65.1 to 70.0	-600.00 or grind*	-450.00 or grind*
45.1 or more	70.1 or more	0.00*	0.00*

* These segments shall be corrected to the levels shown in Table 2317.04-1.
Source: Iowa DOT 2016

The current version of the IRI specification provides a positive pay adjustment for a mean roughness index (MRI) less than 63 in./mi and a negative pay adjustment (or correction) for an MRI greater than 75 in./mi, as shown in Table 4.

Table 4. Iowa DOT IRI pay adjustment schedule for portland cement concrete pavements

MRI (inches per mile)	$ per 0.1-mile segment per lane
Less than 55.0	1,500.00
55.0 to 63.0	11,812.5-187.5×MRI
63.0 to 75.0	0.00
75.0 to 90.0	7,500-100×MRI or grind*
Greater than 90.0	Grind*

* Correct these areas to below 75.0 in./mi.
Source: Iowa DOT 2017

RTS and hardened (QC) profile IRI values from four days of paving (early in the project) are summarized in Table 5 and Table 6, and PrI values are summarized in Table 7 and Table 8.

Table 5. RTS and QC IRI values for US 20 equipment loan, inside lane

Day	Segment	RTS IRI (in./mi)	QC MRI (in./mi)	Difference (in./mi)
1	1	63.1	49.9	13.1
1	2	57.6	53.1	4.5
1	3	49.8	46.5	3.4
2	1	61.6	53.0	8.7
2	2	58.2	50.1	8.1
2	3	61.4	48.0	13.4
2	4	55.8	46.3	9.5
3	1	58.1	47.3	10.8
3	2	66.7	59.6	7.2
3	3	68.6	48.5	20.1
3	4	76.2	57.1	19.0
4	1	60.5	53.6	6.9
4	2	81.5	56.0	25.5
4	3	70.3	49.5	20.8
4	4	83.6	58.0	25.6
Avg.		64.9	51.8	13.1

Table 6. RTS and QC IRI values for US 20 equipment loan, outside lane

Day	Segment	RTS IRI (in./mi)	QC MRI (in./mi)	Difference (in./mi)
1	1	66.2	61.1	5.1
1	2	65.7	62.2	3.5
1	3	58.0	48.8	9.2
2	1	59.3	51.6	7.7
2	2	59.4	47.7	11.7
2	3	62.5	45.1	17.4
2	4	54.3	48.2	6.2
3	1	54.7	44.1	10.6
3	2	65.6	57.8	7.8
3	3	69.6	57.6	12.0
3	4	70.9	61.1	9.8
4	1	58.1	53.0	5.1
4	2	91.8	66.3	25.4
4	3	71.2	54.3	17.0
4	4	86.5	66.5	20.1
Avg.		66.3	55.0	11.2

Table 7. RTS and QC PrI values for US 20 equipment loan, inside lane

Day	Segment	RTS PrI (in./mi)	QC PrI (in./mi)	Difference (in./mi)
1	**1**	22.6	18.5	4.1
1	**2**	22.3	22.1	0.2
1	**3**	17.3	18.4	-1.0
2	**1**	28.2	28.7	-0.6
2	**2**	24.4	21.0	3.4
2	**3**	22.1	18.5	3.6
2	**4**	21.0	18.0	2.9
3	**1**	22.9	24.1	-1.2
3	**2**	29.3	29.9	-0.5
3	**3**	19.6	17.1	2.5
3	**4**	25.3	23.1	2.2
4	**1**	31.2	30.8	0.4
4	**2**	33.3	26.4	6.9
4	**3**	24.4	16.7	7.7
4	**4**	28.6	22.1	6.5
Avg.		24.8	22.4	

Table 8. RTS and QC PrI values for US 20 equipment loan, outside lane

Day	Segment	RTS PrI (in./mi)	QC PrI (in./mi)	Difference (in./mi)
1	**1**	19.0	18.9	0.1
1	**2**	23.4	23.6	-0.2
1	**3**	20.2	16.3	4.0
2	**1**	25.3	26.0	-0.7
2	**2**	21.9	20.2	1.8
2	**3**	19.1	15.9	3.3
2	**4**	18.6	14.2	4.3
3	**1**	19.6	21.1	-1.4
3	**2**	24.7	27.7	-3.0
3	**3**	23.7	20.6	3.1
3	**4**	22.5	20.6	1.9
4	**1**	31.3	31.2	0.1
4	**2**	33.2	28.6	4.7
4	**3**	21.1	18.5	2.6
4	**4**	29.6	24.7	5.0
Avg.		23.5	21.8	

Hardened data are represented by the mean roughness index for 0.1-mile segments for each lane, while the RTS data are from a single trace from the real-time profiler in the middle of each lane. IRI values were computed using the Ride Quality module of ProVAL, and PrI values were computed using the Profilograph Simulation module in ProVAL for both the real-time and hardened profile data. The following was noted from the data presented in these tables:

- Although the QC MRI numbers were generally very good, the difference between the RTS and QC IRI values varied widely, from 3.4 in./mi to 25.6 in./mi, with an overall average of 12.2 in./mi. Certain segments, including the last three segments of Day 4 in particular, skewed this average significantly. Without those segments, the overall average was 9.6 in./mi.

- The higher differences between the RTS and QC IRI values were primarily from segments with higher real-time numbers. This confirms what has been observed from the various equipment loans, that the RTS profilers pick up roughness features (e.g., shorter wavelength content) that are typically removed by the finishing processes. Overall, the QC MRI values were about 82 percent of the RTS IRI values.

- The QC PrI numbers were also generally very good, but the difference between the RTS and QC PrI numbers was highly variable, with several segments where QC PrI was actually higher than RTS PrI. The overall average difference between QC PrI and RTS PrI for segments where RTS was higher than QC was 3.2 in./mi.

- Unlike IRI, segments with higher RTS PrI did not necessarily have a higher difference between the RTS and QC values. This highlights the fact that the IRI is more sensitive to different roughness features/roughness wavelengths than the PrI, which is why it is not possible to generate a good correlation between IRI and PrI. PrI is generally less sensitive to the shorter wavelength content (which is removed by the finishing processes) than IRI.

Figure 2 shows the continuous roughness report (IRI at a 25 ft base length) for the RTS and hardened profiles for a typical day.

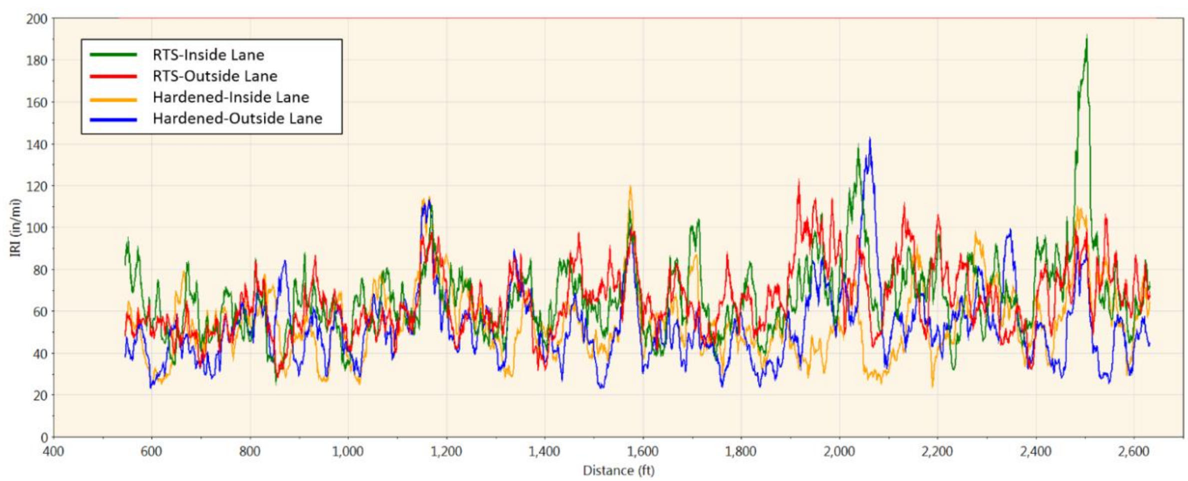


Figure 2. Typical continuous roughness report (25 ft base length) for Iowa US 20 project

Figure 2 shows RTS numbers that are only slightly higher than the hardened numbers, which is similar to the trend observed in the segment-by-segment analysis above. However, certain areas of the plot (e.g., at approximately 1,150 ft and 1,575 ft) show that some roughness features from the real-time profile are still present in the hardened profile. These locations would be areas for the contractor to review field logs to identify what occurred and to determine whether changes could be made to some process to minimize this roughness in the future.

Figure 3 shows a comparison of the spectral content from a PSD analysis of the RTS and hardened profile data from a typical day of paving (Day 3).

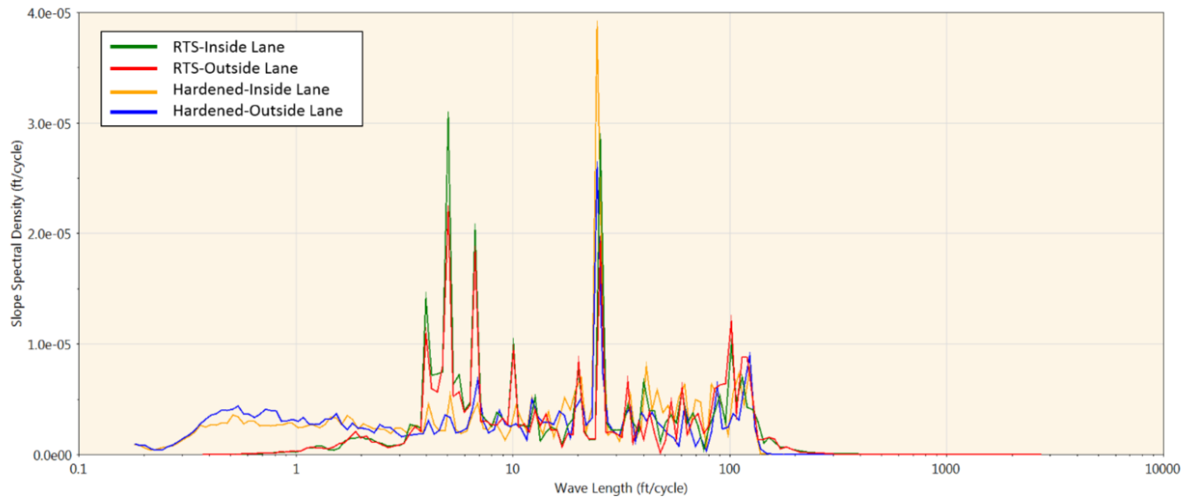


Figure 3. Typical RTS and hardened profile data spectral content for Iowa US 20 project

The dominant content in both the real-time and hardened profiles is the 25 ft spacing of the stringline pins. This content is more dominant than the joint-related (dowel basket) content at 20 ft. However, despite the prominence of this 25 ft content, it is important to view it in context of the overall smoothness numbers, which were very good (as shown in Table 5 and Table 6). If the smoothness numbers had been poor, the first place to look for adjustments might have been anything related to the stringline (e.g., stringline sag, chord effects). However, because the numbers were already very good, it is unlikely that much could be done relevant to the stringline pin spacing that would improve smoothness.

Idaho Interstate 84

This was the first of the equipment loan projects and provided many insights into real-time versus hardened profile data (see the Field Report online at http://www.cptechcenter.org/real-time-smoothness/). The project consisted of a 12 in. thick jointed concrete pavement placed over 3.5 in. of a dense-graded asphalt base. The project was constructed next to an existing pavement, with the tracks of one side of the paver on the existing pavement and tracks on the other side on the base. Paving was 24 ft wide and joint spacing was 15 ft, with dowel baskets pinned to the base. A belt placer was used to deposit concrete in front of the paver, and stringless guidance was utilized.

Table 9 and Table 10 summarize the IRI results for four days of paving during the equipment loan.

Table 9. RTS and QC IRI for Idaho I-84 equipment loan, Lane 3 (inside)

Day	Segment	RTS IRI (in./mi)	QC MRI (in./mi)	Difference (in./mi)
1	1	113.2	67.0	46.2
1	2	77.3	57.0	20.2
1	3	79.9	64.6	15.3
2	1	90.0	53.2	36.7
2	2	108.9	77.5	31.4
2	3	114.4	57.2	57.1
3	1	111.7	65.3	46.4
3	2	118.2	71.0	47.2
3	3	116.4	68.0	48.4
3	4	94.9	61.9	33.1
4	1	122.6	64.5	58.1
4	2	122.5	61.9	60.7
Avg.		105.8	64.1	41.7

Table 10. RTS and QC IRI for Idaho I-84 equipment loan, Lane 4 (outside)

Day	Segment	RTS IRI (in./mi)	QC MRI (in./mi)	Difference (in./mi)
1	1	89.5	63.2	26.2
1	2	79.1	59.1	20.0
1	3	85.9	63.1	22.9
2	1	68.1	47.6	20.5
2	2	104.3	71.9	32.3
2	3	92.3	59.6	32.7
3	1	94.4	61.5	33.0
3	2	93.0	61.9	31.1
3	3	74.3	59.1	15.2
3	4	74.1	55.3	18.8
4	1	90.0	64.0	26.0
4	2	73.5	58.9	14.6
Avg.		84.9	60.4	24.4

The RTS IRI values were consistently higher than the QC IRI values, ranging from approximately 15 to 61 in./mi higher, with an overall average of 33 in./mi. Overall, the QC IRI values were approximately 67 percent of the RTS IRI values. Note that RTS IRI for Lane 3 was consistently higher than that of Lane 4, but the QC IRI values for the two lanes were very similar. Similar to what was observed for the US 20 project in Iowa, the higher the RTS IRI values, the greater the difference between the RTS and QC IRI values (about 42 in./mi higher for Lane 3 and 24 in./mi higher for Lane 4).

Figure 4 shows the spectral content from a PSD analysis of the RTS and hardened profiles for Day 3, which is typical of all four days of paving.

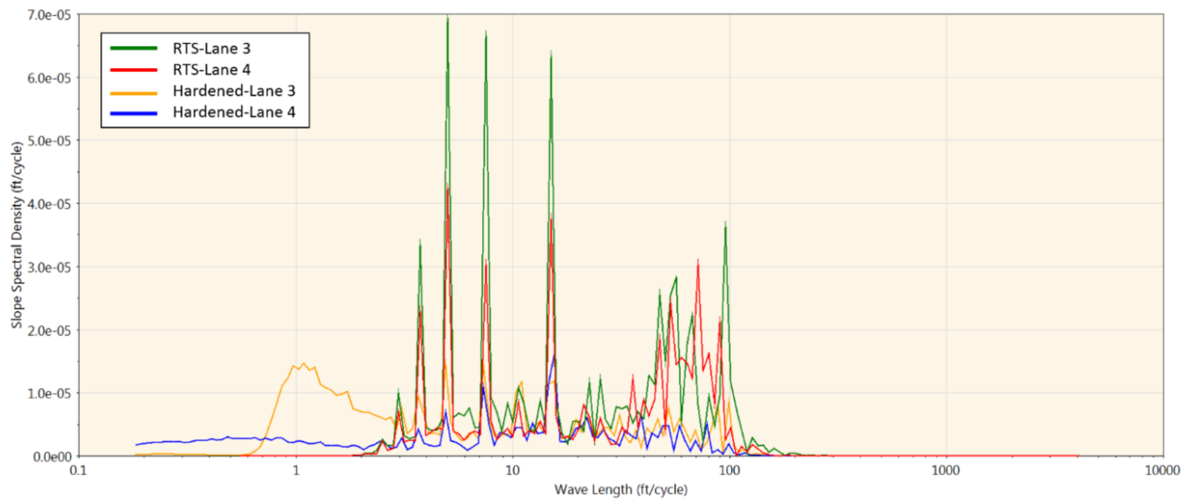


Figure 4. PSD analysis results for Day 3 of Idaho I-84 project

The dominant content in both the RTS and hardened profile data is the joint spacing at 15 ft, with related harmonics at 7.5 ft, 5 ft, 3.75 ft, and 3 ft, indicating that the joints had a significant impact on the profile. This pattern is believed to be indicative of dowel basket rebound, which is picked up by the RTS profilers that are collecting profile data just behind the finish pan when the down-pressure on the baskets is relieved.

While the 15 ft content and associated harmonics are still present in the hardened profile data, they are much less pronounced, indicating that the finishing processes behind the RTS profilers removed some of this effect of dowel basket rebound. Note that there is also content at about 10.5 ft in both the real-time and hardened data, which was determined to be related to concrete load spacing. As with the joint content (dowel basket rebound), the 10.5 ft content is more prominent in the RTS data than the hardened profile, indicating that the finishing processes likely removed much of this effect. Also note the longer wavelength content in the RTS profiles, which is not present in the hardened profile data.

Figure 5 shows a typical continuous roughness report (IRI at a 25 ft base length) from the same day of paving as the PSD plot.

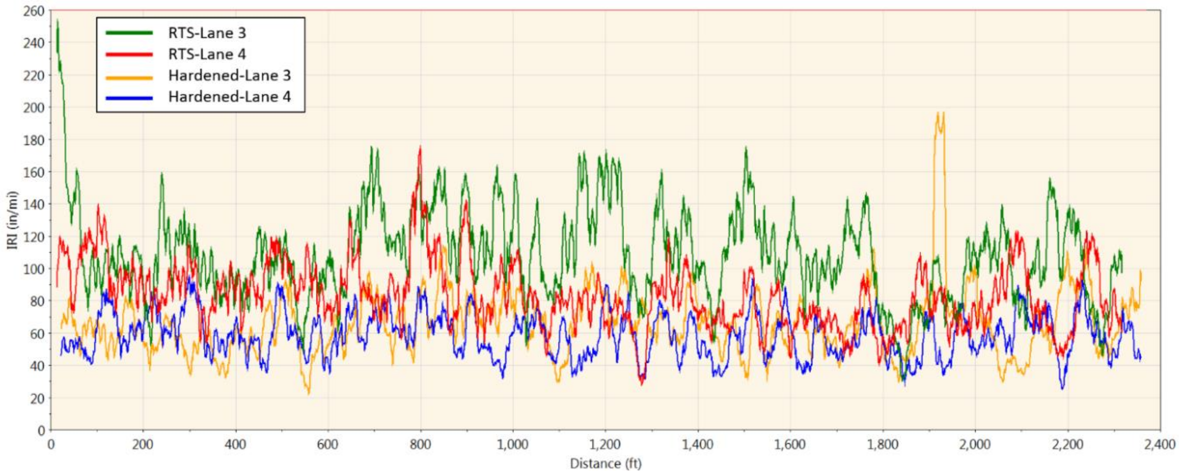


Figure 5. Localized roughness plot for Day 3 of Idaho I-84 project

Note the higher levels of roughness for the RTS profiles, with Lane 3 generally rougher than Lane 4, as shown in Table 9 and Table 10. Note also the peaks present in the roughness plot, particularly for RTS Lane 3, spaced approximately at the 15 ft joint spacing. These peaks are not nearly as prominent in the hardened data, confirming what was discussed previously related to spectral content.

Illinois Tollway Interstate 90

This project was very similar to the Idaho I-84 project with one key exception: a dowel bar inserter was used in lieu of dowel baskets (see the Field Report online at http://www.cptechcenter.org/real-time-smoothness/). The slab thickness was 13 in., placed over a 3 in. dense-graded asphalt base. Paving width was 26 ft, and joint spacing was 15 ft. Similar to the Idaho I-84 project, the pavement was placed next to existing pavement, with the paver tracks on one side of the paver up on the existing pavement and the paver tracks on the other side on the base. For this project, however, concrete was dumped in front of the paver rather than deposited with a placer.

Table 11 and Table 12 summarize the IRI results for two full segments from four days of paving during the equipment loan.

Table 11. RTS and QC IRI for Illinois Tollway I-90 equipment loan, Lane 1 (inside)

Day	Segment	RTS IRI (in./mi)	QC MRI (in./mi)	Difference (in./mi)
1	**1**	131.9	75.2	56.7
1	**2**	179.8	83.9	95.9
2	**1**	121.7	72.8	48.9
2	**2**	100.0	67.0	33.1
3	**1**	124.4	73.0	51.5
3	**2**	85.9	68.5	17.5
4	**1**	111.3	85.4	26.0
4	**2**	111.1	103.9	7.2
Avg.		120.8	78.7	42.1

Table 12. RTS and QC IRI for Illinois Tollway I-90 equipment loan, Lane 2 (outside)

Day	Segment	RTS IRI (in./mi)	QC MRI (in./mi)	Difference (in./mi)
1	**1**	155.4	79.9	75.5
1	**2**	177.2	81.9	95.4
2	**1**	135.1	69.7	65.3
2	**2**	106.9	65.8	41.1
3	**1**	136.4	69.9	66.5
3	**2**	101.1	57.8	43.3
4	**1**	135.5	93.4	42.2
4	**2**	131.9	102.2	29.7
Avg.		134.9	77.6	57.4

The RTS IRI values were consistently higher than the QC IRI values and had a very wide range from about 7 in./mi to more than 95 in./mi, with an overall average of 49.7 in./mi. Although both the RTS and QC IRI values were significantly higher for this project than for the I-84 project in Idaho, the QC IRI values were very similar at about 63 percent of the RTS IRI values. Similar to the I-84 project, the RTS values for one lane (Lane 2) were consistently higher than for the other lane (Lane 1), even though the QC IRI values were very similar for both lanes. It is interesting to note that for both this project and the Idaho I-84 project, the higher RTS numbers were for the side of the paver positioned on the existing pavement. And similar to both the US 20 project in Iowa and the I-84 project in Idaho, the higher the RTS IRI values, the greater the difference between the RTS and QC IRI values.

Figure 6 shows a typical continuous roughness report (IRI at a 25 ft base length) from one day of paving (Day 3).

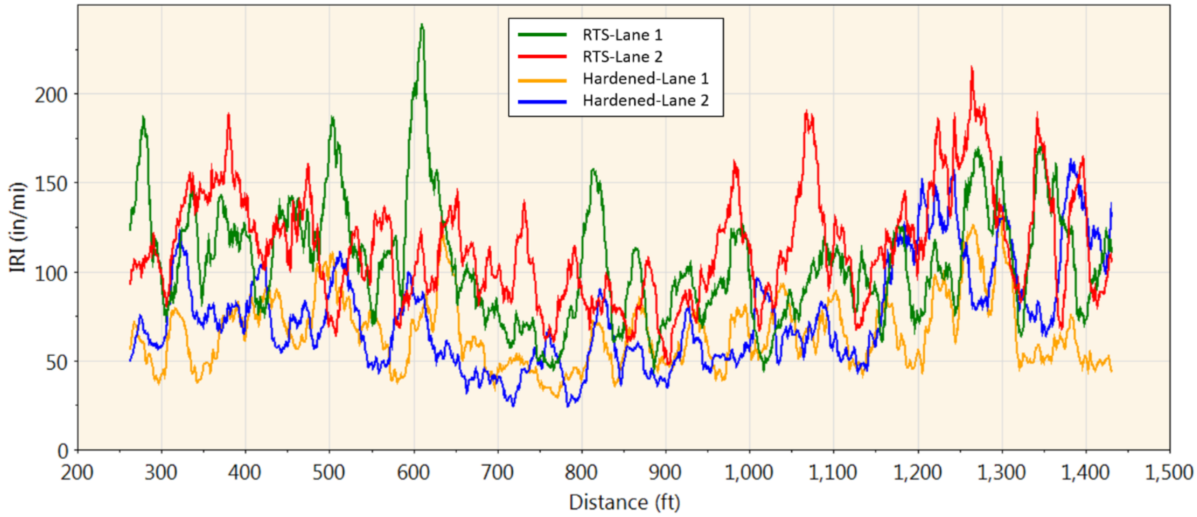


Figure 6. Localized roughness plot for Day 3 of Illinois Tollway I-90 project

Consistent with what has been discussed previously in this report, the levels of roughness for the RTS profiles were higher, with Lane 2 generally rougher than Lane 1, as shown in Table 11 and Table 12. In contrast with the Idaho I-84 project, however, there were no distinct peaks at the joint spacing, likely because a dowel bar inserter was used in lieu of dowel baskets.

Figure 7 shows the spectral content from a PSD analysis of the RTS and hardened profile data from Day 3, which is typical of all four days of paving.

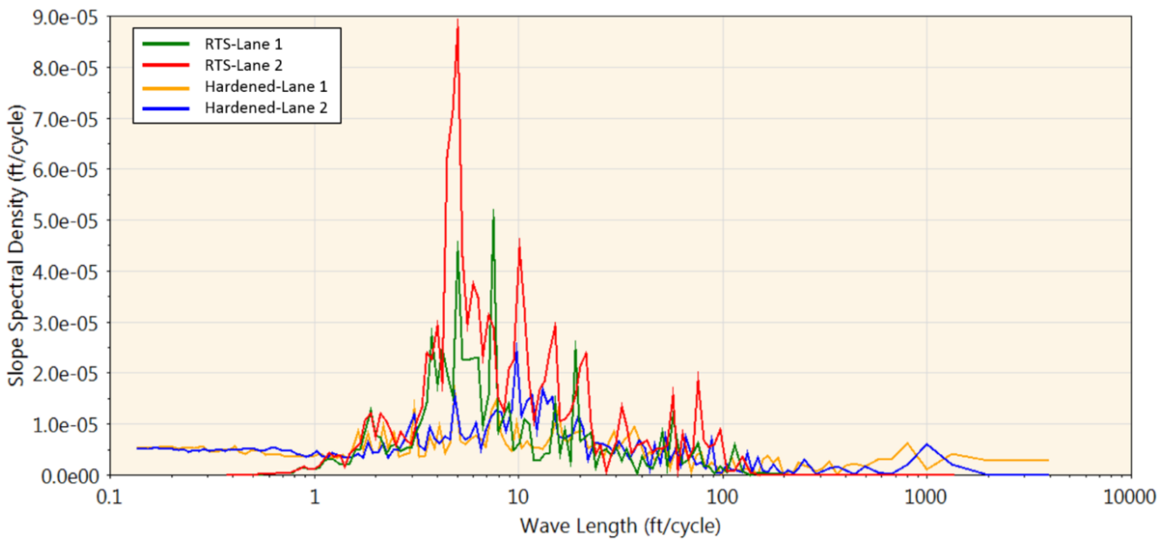


Figure 7. PSD analysis results for Day 3 of Illinois Tollway I-90 project

Note that, in contrast to the Idaho I-84 project, the dominant content for the RTS and hardened profiles was not at the joint spacing, but rather at shorter wavelength content (about 3 to 12 ft).

This result is possibly related to the dowel bar inserter and oscillating correcting beam or some other process. Similar to what was observed on the I-84 project, shorter wavelength content was dramatically reduced in the hardened data, most likely due to the finishing processes behind the RTS profiler. The source of the dominant content in the RTS data at 4 to 5 ft is not known but may be a harmonic of content at 10 ft, which may be related to concrete load spacing, or, again, the dowel bar inserter. It should be noted that the PSD data for Day 2 (not shown here) did show distinct content at the joint spacing of 15 ft, but it was still not as dominant at the shorter wavelength content.

This equipment loan also provided an example for comparing real-time and hardened data for an isolated area of localized roughness. During paving on Day 3, a malfunction of the dowel bar inserter left an area of localized roughness that was picked up by the RTS system. The finishing processes, however, were able to correct the surface profile, resulting in smoothness very similar to (if not slightly better than) that of the surrounding pavement. Figure 8 shows a localized roughness plot (IRI at a 25 ft base length) of this area that illustrates the contrast between IRI as measured by the RTS profiler and on the hardened surface after finishing.

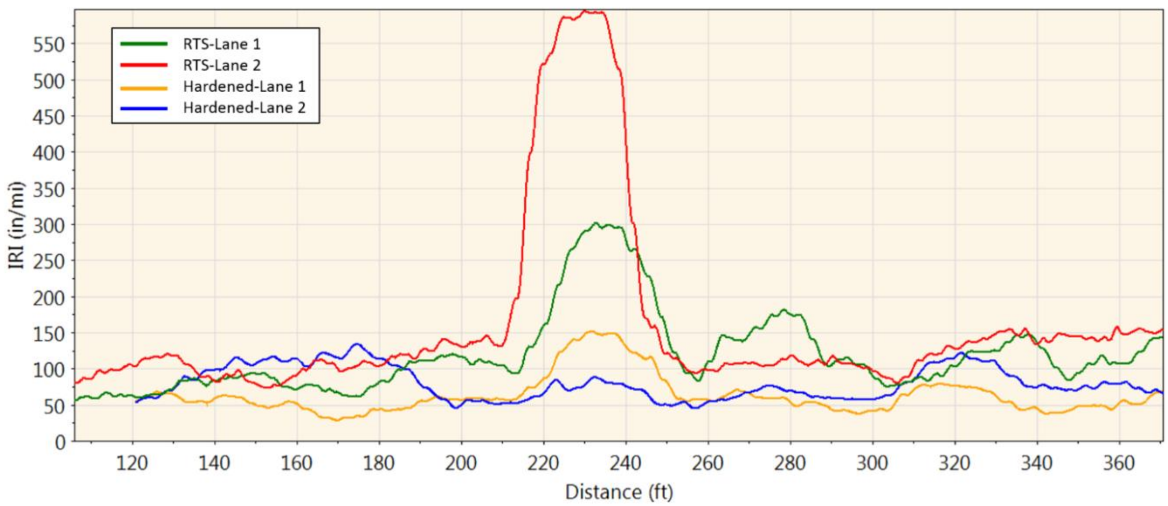


Figure 8. Example of localized roughness in RTS removed by finishing processes

North Dakota Highway 2

This project was not an official equipment loan project because the contractor was already using an RTS system (Ames RTP). However, data were still collected from one day of paving on this project because the data represented some of the smoothest concrete paving documented by the project team. The project was rural mainline paving of an 8 in. thick jointed concrete pavement over a compacted subgrade. The paver was set up for a paving width of 30 ft, and joint spacing was 15 ft with dowel baskets. Two placer spreaders were used in front of the paver for concrete placement.

As the results in Table 13 show, the average RTS IRI was below 44 in./mi, with no segments above 55 in./mi.

Table 13. RTS and QC IRI summary for North Dakota Highway 2, driving lane

Segment	RTS IRI (in./mi)	QC MRI (in./mi)	Difference (in./mi)
1	43.7	27.8	15.9
2	42.8	28.9	13.9
3	47.5	34.2	13.3
4	41.2	30.3	10.8
5	38.7	27.4	11.2
6	41.6	30.1	11.5
7	34.1	25.1	9.1
8	54.9	27.6	27.3
Avg.	43.1	28.9	14.1

As the results in Table 14 show, the average QC IRI values were all below 30 in./mi, with no segments over 35 in./mi.

Table 14. RTS and QC IRI summary for North Dakota Highway 2, passing lane

Segment	RTS IRI (in./mi)	QC MRI (in./mi)	Difference (in./mi)
1	28.3	26.5	1.8
2	33.1	27.1	6.0
3	33.5	33.2	0.3
4	29.7	28.0	1.6
5	25.6	24.3	1.3
6	35.0	28.9	6.1
7	34.4	22.4	12.0
8	38.1	24.4	13.7
Avg.	32.2	26.9	5.3

Differences between RTS and QC IRI ranged from just over 1 in./mi to just over 27 in./mi, with an overall average of 9.7 in./mi. As observed with other equipment loan data, the higher the RTS values, the higher the difference between the RTS and QC values.

Figure 9 shows the spectral content from a PSD analysis of the real-time and hardened profile data for the same day of paving.

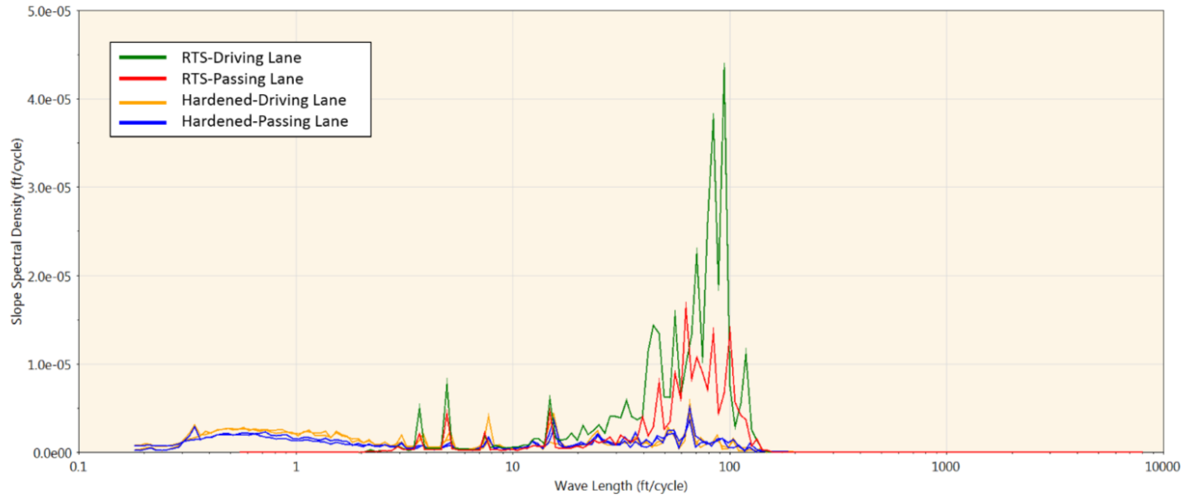


Figure 9. PSD analysis results for North Dakota Highway 2

Aside from the longer wavelength (80 to 100 ft) content common to RTS profiles, the dominant content is at the joint spacing of 15 ft (and associated harmonics) in both the real-time and hardened profiles. This again affirms the effects of dowel basket rebound on the profile data. Note, however, that the magnitude (slope spectral density on the y-axis) of this joint-related content is significantly lower than that of the other projects discussed above. This is an indication that even though the joint-related content is dominant, it has very minimal impact on the overall smoothness because the overall smoothness numbers are so low to begin with.

Summary of Key Findings

In summary, the case studies discussed above, along with analysis of data from the rest of the equipment loans, have revealed some key findings pertinent to the relationship between real-time and hardened profile data. Using the questions from the beginning of this section as a guide, the following can be concluded:

1. Is there any clear relationship or correlation between RTS and hardened profile data and smoothness indices?

- With regard to IRI, there is no definitive relationship between real-time versus hardened smoothness values that can be applied to all projects.

- In general, real-time IRI will be higher (rougher) than hardened data, but not by a fixed amount. And the higher the real-time IRI values, the greater the difference between the real-time and hardened IRI values. For the projects discussed herein, real-time numbers ranged from less than 2 in./mi to over 95 in./mi higher than the hardened numbers.

- The relationship will be project-specific and will need to be established during the first few days of a paving project in order for the contractor to use the real-time data to adjust paving processes.

2. Which features show up in real-time profiles but not in hardened profiles and vice versa?

- Very good agreement exists between the real-time and hardened profiles, assuming the DMIs are properly calibrated. Similar trends in the profile can be observed when comparing real-time and hardened profiles after high-pass filtering of the profile data.

- Real-time profiles will generally contain a greater amount of shorter wavelength content than hardened profiles. This is due to the finishing processes (straightedge and float) applied to the pavement slab behind the RTS profilers, which remove much of this shorter wavelength content.

- Real-time profilers generally pick up long wavelength content (greater than 80 ft) that is not necessarily relevant to ride quality and not likely caused by any processes related to the paving operation. Further investigation of the source of this long wavelength content, and what relevance it may have to paving processes, is needed.

3. Which artifacts of the pavement or paving process are picked up in the RTS data such that corrections/adjustments can be made?

- Real-time profilers pick up the effects from dowel basket rebound, which show up as dominant spectral content at the joint (dowel basket) spacing. This joint-related spectral content was not as dominant and, in most cases, was not observed in projects that utilized dowel bar inserters. In most cases, dowel basket effects are less dominant in the hardened profiles, likely due to the finishing processes that remove many of these disturbances at the dowel baskets.

- Stringline effects (stringline sag or chord effects) are picked up in both the real-time and hardened profile data. This is likely due to the inability of the finishing processes to remove this longer (25 to 50 ft) wavelength content.

- Although dowel basket rebound and stringline sag effects may be dominant content in a spectral analysis, this does not mean that these factors adversely affect smoothness numbers. Dominant spectral content should always be evaluated in context of the overall smoothness numbers.

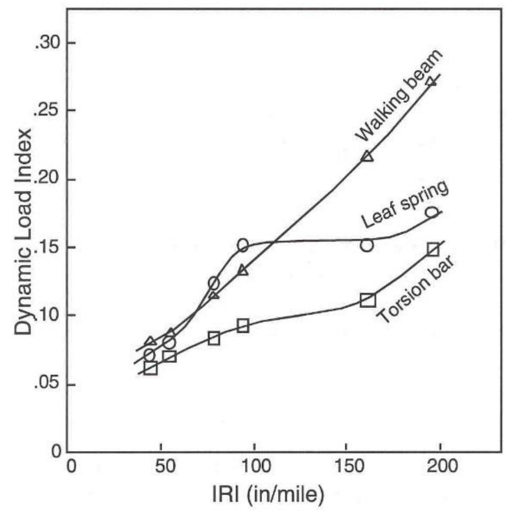
- Spacing of concrete loads can also be picked up in real-time and hardened profile data. Load spacing content may be due to slight variations in the concrete mixture, which cause the paver to respond in such a manner as to leave a feature in the pavement profile, or this content may simply be due to the paver’s response to varying heads of fresh concrete in front of the paver. Similar to stringline effects, PSD content at the load spacing interval should always be evaluated in context of the overall smoothness numbers.

4.3 Long-Term Performance of Real-Time Technology

One of the goals of this research was to study the long-term performance of concrete pavement projects that utilized real-time technology. Unfortunately, due to the difficulty in locating exact test sections where RTS technology was utilized for some of the original SHRP2 R06E pilot projects, it was not possible for the project team to evaluate performance and smoothness numbers from those sections for the purpose of comparison to the original real-time smoothness results. What follows, however, is a brief discussion of the importance of initial pavement smoothness as it relates to long-term pavement performance and the importance of tools such as RTS technology in helping to achieve long-term performance.

RTS is a tool to improve initial (as-constructed) smoothness. As far back as the original American Association of State Highway Officials (AASHO) Road Test, it has been recognized that users judge the quality of a roadway primarily by its ride quality (Carey and Irick 1960). Therefore, the primary motivation behind specifications for initial smoothness (construction acceptance) is generally user (driver) satisfaction, or functional performance. However, there is evidence that smoother pavements also lead to improved structural performance and remain smoother longer. In performance terms, smoother pavements last longer, and smoother pavements stay smoother longer.

With respect to structural performance (the assertion that smoother pavements last longer), there have been very few studies of this particular issue for concrete pavements. Studies that have analyzed Long-Term Pavement Performance (LTPP) program data do indicate, however, that, all other factors being equal, there is evidence that smoother pavements last longer (Smith et al. 1997). One of the potential causes of roughness-related structural deterioration is dynamic loading on pavements, particularly from heavy trucks, which can accelerate fatigue. Figure 10 shows the relationship between IRI and a so-called dynamic load index (standard deviation of dynamic load divided by static load) for common truck suspensions.



Ma and Caprez 1995

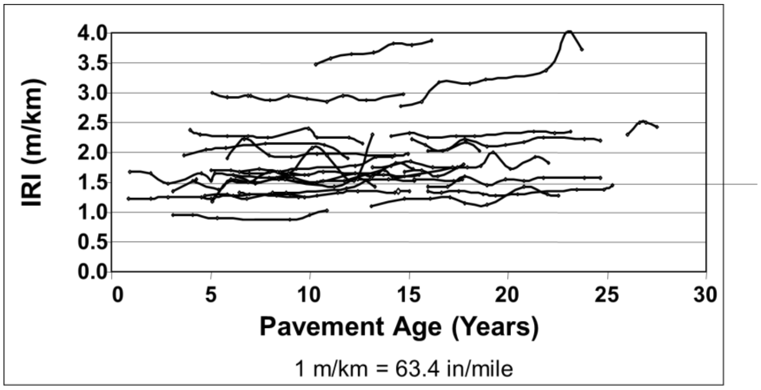
Figure 10. Effect of roughness (IRI) on dynamic load index for various truck suspensions

Note that moderate increases in roughness (IRI) can lead to significant increases in dynamic loading.

It is also well known that certain phenomena, such as curling and warping of jointed concrete pavement slabs (which effectively leads to rougher pavement), contributes directly to structural distresses such as mid-panel and corner cracking. While slab curling and warping is not evident in real-time profile data because it occurs after the concrete has reached final set, it is still an early-age phenomenon that can significantly affect pavement performance, and it can effectively be identified using profile data from the hardened pavement.

This understanding of the effects of pavement smoothness on structural performance still does not answer the questions of "how smooth is smooth enough," "how low should initial smoothness specification thresholds be set," or "how much incentive should an agency pay for superior initial smoothness," and no known studies have answered these questions from a structural performance standpoint. It is safe to say, however, that the smoother a pavement is after construction, within reason, the better chance that roughness-related distresses can be mitigated over the life of the pavement.

With respect to functional performance (the assertion that smoother pavements stay smoother longer), there have also been very few studies of this issue, and, again, existing studies have primarily used LTPP data. Like structural performance, however, the available evidence indicates that pavements that are smoother initially tend to stay smoother longer. Figure 11 shows the results from one such analysis of LTPP data from a jointed dowelled concrete pavement in a wet-freeze environment.



Perera and Kohn 2001

Figure 11. IRI progression with age for LTPP GPS-3 sections with dowels in wet-freeze climate

As Figure 11 shows, the roughness of dowelled jointed concrete pavements tends to remain fairly stable over time, but there are indications that slightly higher initial roughness leads to more roughness progression over time.

The AASHTOWare Pavement ME Design Guide (AASHTO 2015), recognizes the impact of initial smoothness on long-term roughness progression and includes it as the first term of the following expression for jointed concrete pavement (using global calibration coefficients):

$$IRI = \boldsymbol{IRI_I} + 0.8203 \times CRK + 0.4417 \times SPALL + 1.4929 \times TFAULT + 25.24 \times SF$$

where:

IRI = Predicted IRI, in./mi

IRI_I = Initial smoothness measured as IRI, in./mi

CRK = Percent slabs with transverse cracks (all severities)

SPALL = Percentage of joints with spalling (medium and high severities)

TFAULT = Total joint faulting cumulated per mile, in.

SF = Site factor related to pavement age, freezing index, and subgrade fines

Note that while the effects of pavement distress are included in the IRI progression over time, IRI is not included as a factor in the progression of pavement distress (equations not shown here) due to the difficulty in predicting the exact effects of higher roughness on structural performance.

To examine the sensitivity of initial smoothness on long-term (terminal) smoothness, the AASHTOWare Pavement ME software was used to predict the terminal IRI (30-year design life) for one of the equipment loan projects on US 20 in Iowa. Initial IRI was varied from 55 in./mi (upper limit for maximum incentive) to 90 in./mi (threshold for correction) for the Iowa DOT's proposed IRI specification. Table 15 summarizes the terminal IRI prediction for the various initial IRIs.

Table 15. AASHTOWare Pavement ME prediction of terminal IRI based on initial IRI

Limit	Initial IRI (in./mi)	Terminal IRI at 30 years (in./mi)	Difference (in./mi)
Maximum incentive upper limit	55	169	114
Full pay lower limit	63	180	117
Full pay upper limit	75	195	120
Threshold for correction	90	213	123

Although the AASHTOWare Pavement ME global calibration constants were used in the example, and therefore the predictions may not be completely accurate for the local conditions of this particular project, the example illustrates the effect that initial IRI can have on long-term IRI. An increase in initial IRI of 35 in./mi (from 55 to 90 in./mi) leads to an increase in terminal IRI of approximately 44 in./mi.

Once again, this does not explicitly answer the questions of "how smooth is smooth enough" and "how low should initial smoothness specification thresholds be set," but the models used for the AASHTOWare Pavement ME design equation above indicate that the average range for full pay of 56.5 to 71.5 in./mi, which is based on a 2015 synthesis of concrete pavement ride quality specifications in the US (Merritt et al. 2015), is reasonable for helping to ensure long-term pavement performance. From a user-satisfaction perspective, a recent study by the North Carolina Department of Transportation (NCDOT) found that users generally rate a pavement with an IRI less than 103 in./mi as "acceptable" and pavements over 151 in./mi as "unacceptable," and therefore a target IRI for initial construction of 60 to 70 in./mi is recommended to help ensure that this "acceptable" ride quality is maintained over the life of the pavement (Chen et al. 2014).

Again, it is safe to say that the smoother a pavement is after construction, within reasonable and achievable limits, the better chance that the pavement will stay smoother over time and provide satisfactory functional performance. But it must be recognized that there are a multitude of factors that affect smoothness that are completely independent of initial smoothness, as discussed above, and there is also a cost associated with achieving very low initial smoothness numbers. RTS technology, however, provides a relatively low-cost method for helping contractors achieve the best possible smoothness numbers behind the paver.

4.4 Documentation of Field Trials/Lessons Learned

As previously noted, the field reports from the 11 equipment loans can be found online at http://www.cptechcenter.org/real-time-smoothness/. These reports document many unique observations from the various projects and some key lessons learned. Summarized below are some of the lessons learned that were common to many of the equipment loans or that stood out as significant.

Load Transfer Dowels and Bar Supports are Typically the Dominant Influence on Real-Time Profiles

In most cases, the dominant spectral content wavelengths associated with real-time and hardened pavement roughness were related to load transfer dowels (jointed pavements) and transverse bar supports (continuously reinforced concrete pavement [CRCP]). Figure 3 and Figure 4, presented above for the Iowa US 20 and Idaho I-84 equipment loans, show the impact of dowel baskets on initial smoothness as the dominant content in the spectral analysis. Recall that the impact of load transfer dowels is present in the hardened profiles as well but is significantly lower than in the real-time profiles. This difference is attributable to improvements made by hand finishing behind the real-time profilers. The spectral content at 25 ft (Figure 3) is related to the spacing of the stringline pins, which results in a subtler profile deviation than the load transfer dowels (discrete bump and dip features). These subtle profile impacts are not as easily removed by hand finishing techniques, which is why there is not much difference between the real-time and hardened spectral content at this wavelength.

Figure 12 shows the spectral content from a PSD analysis for a CRCP from the SH 99 equipment loan in Texas.

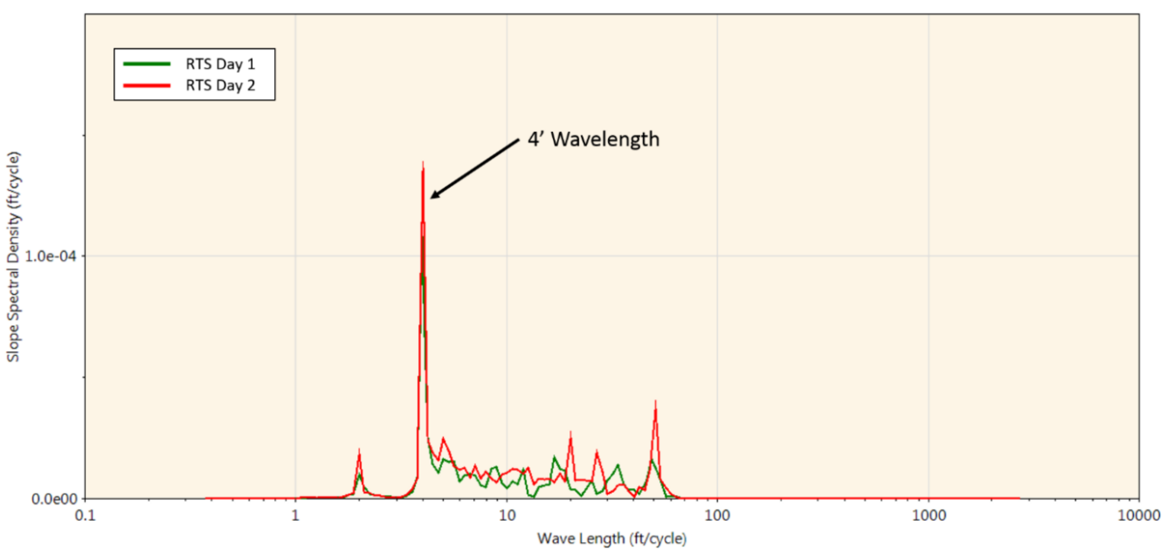


Figure 12. Spectral content for RTS data from Texas SH 99 CRCP

This plot shows the impact of transverse bar supports every 4 ft on the overall spectral content, which is similar to the impact of dowel baskets for jointed concrete pavement.

Further supporting this lesson learned is the lack of any dominant shorter wavelength spectral content for the Iowa Lyon County L-26 project, shown in Figure 13.

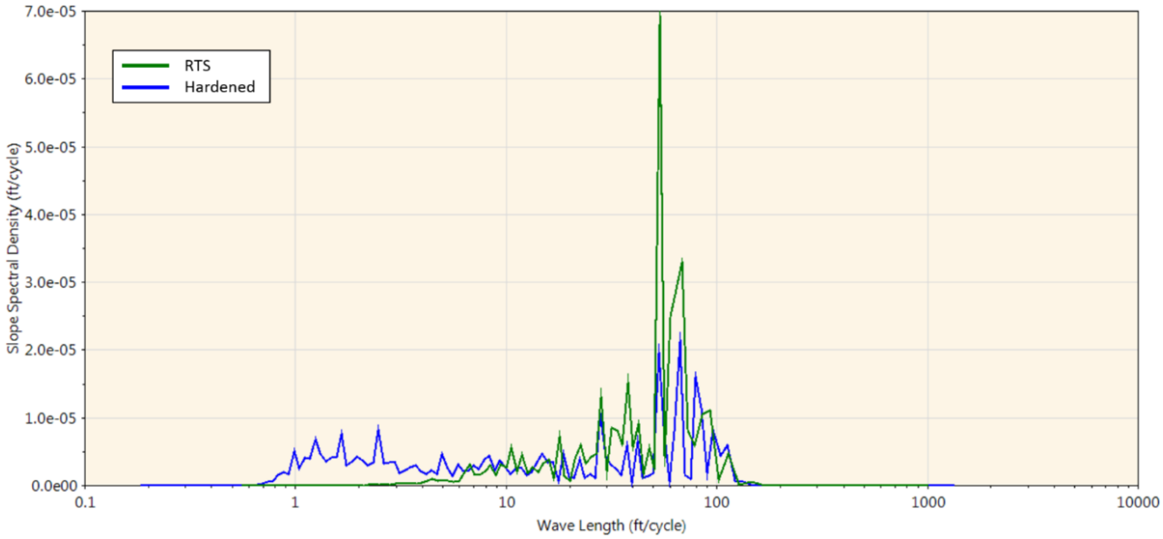


Figure 13. Spectral content for Iowa Lyon County L-26 RTS and hardened profile data

This project was a 5 in. concrete overlay with no embedded steel (dowels or tie-bars). The dominant spectral content for this project was at a longer wavelength, which is in contrast to all of the other dowelled jointed concrete pavement projects, which showed dominant content at wavelengths related to the joint spacing.

It should be noted that completely eliminating the roughness contributed by load transfer dowels or transverse bar supports is difficult. There are no adjustments or modifications that have proven effective at mitigating their effects on initial smoothness. However, proper use of a real-time smoothness system can aid in eliminating other sources contributing to initial pavement roughness, resulting in a "baseline" real-time IRI that can serve as the gauge for how the paving process is proceeding with respect to initial IRI.

Hand Finishing Typically Improves the Initial Hardened IRI

As discussed in the case studies above, in nearly all instances the real-time IRI is higher than the hardened profile IRI. Only two exceptions to this were observed during the equipment loans:

- The first day of paving on I-215 in Salt Lake City, where the auto-float behind the RTS system was improperly adjusted, resulting in a higher IRI for the hardened pavement (see the Field Report online at http://www.cptechcenter.org/real-time-smoothness/).

- Lyon County, Iowa L-26 paving, which was a 5 in. overlay having no embedded steel (see the Field Report online at http://www.cptechcenter.org/real-time-smoothness/)

The most likely explanation for this difference is hand finishing and/or the use of a properly adjusted auto-float, both of which take place behind the real-time smoothness profilers. If one accepts that real-time profilers accurately measure the profile directly behind the paver and then considers all of the potential changes to the early-age pavement profile that could occur between the real-time IRI measurement and the hardened IRI measurement, finishing (whether by hand finishing or auto-float) is the only item that could potentially lower the IRI. Table 16 summarizes the potential impacts of the various items on hardened profile IRI.

Table 16. Potential impacts of various processes on hardened IRI

Items Affecting Early-Age Profile that Occur after RTS Measurement	Potential Impact on IRI
Hand finishing	↑ or ↓
Auto-float	↑ or ↓
Burlap/Turf drag	↓
Longitudinal/Transverse tining	↓
Application of curing compound	Neutral
Sawing joints	Neutral
Curling and warping	↓

It has already been noted that in at least one case (Utah I-215) the auto-float was detrimental to the hardened IRI. The effect of an auto-float on the hardened IRI was also checked on the Idaho I-84 equipment loan project, where the auto-float was removed from use for approximately 300 ft of paving. There was no discernable difference in the hardened IRI where the auto-float was removed as compared to where it was in use.

There are numerous examples where hand finishing was effective at removing roughness due to shorter wavelength content (less than 20 ft). One of these is the example shown previously in Figure 5 from the Idaho I-84 project, which indicates that hand finishing was effective at mitigating the roughness from load transfer dowels. Figure 8, from the Illinois I-90 equipment loan project, shows another example where an equipment breakdown resulted in a significant increase in the real-time IRI. The localized profile feature was removed by hand finishing, as indicated by the relative constant hardened IRI through this area.

Based on the observations and analyses performed throughout the equipment loans, proper hand finishing can improve the initial smoothness of concrete paving. Contractors can compare real-time and hardened profile data to confirm that the hand finishing techniques being used by their crews are effective. However, because there are so many factors that have the potential to increase the hardened IRI, the same comparison cannot be used to determine whether the finishing techniques are introducing roughness into the profile.

Increase in IRI Related to Stringless Paver Controls

During the equipment loan on I-15 in Utah, it was observed during one night of paving that the IRI values fluctuated regularly (see the Field Report online at http://www.cptechcenter.org/real-time-smoothness/). A pattern of increasing, and then decreasing, IRI was apparent at intervals of approximately 350 ft, and particularly on the right side of the paver, as shown in Figure 14.

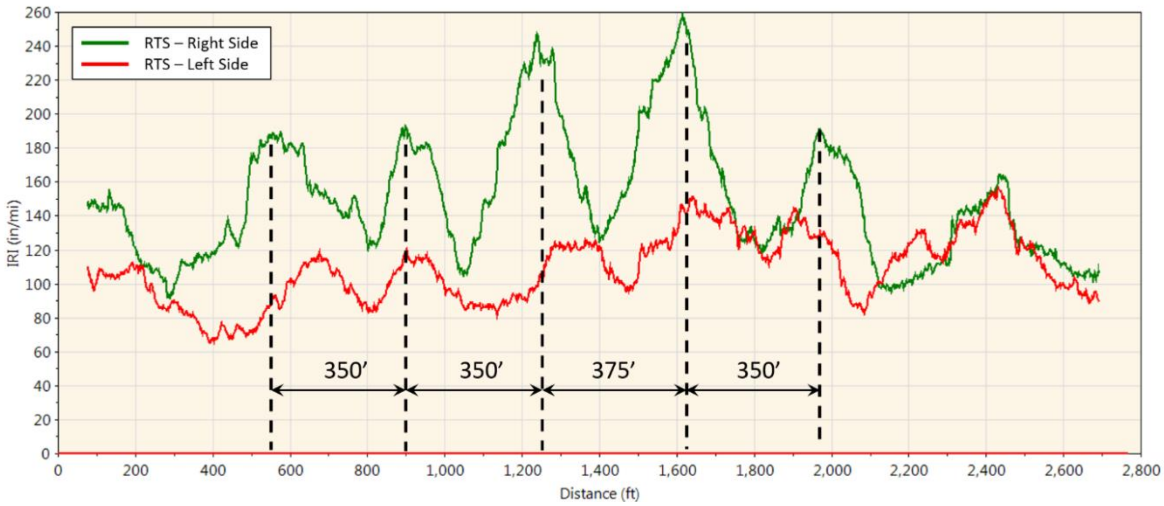


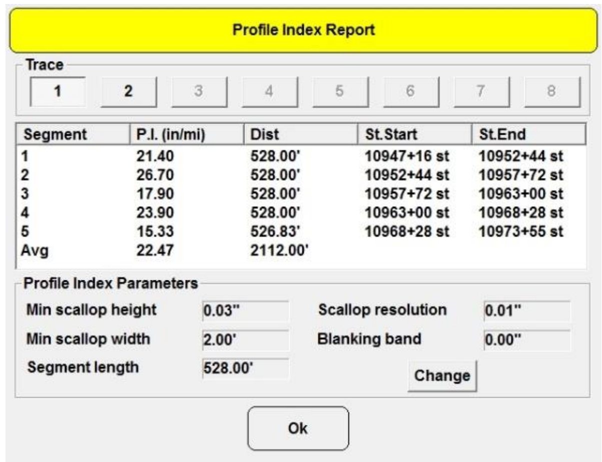
Figure 14. Real-time profile data illustrating fluctuation of IRI corresponding to stringless system total station swaps

This pattern matched the spacing between the stringless robotic total stations controlling the paver's elevation and steering, with the right side of the paver being further from the stringless total stations than the left side. The pattern indicated that this was likely the source of the roughness variation.

Once this relationship was observed, the contractor reduced the distance between robotic total stations to improve the IRI results. Without an RTS system in operation, however, this effect would not have been observed until the hardened profile data were collected and analyzed, and it may still not have been as apparent as when looking at the RTS data.

Using an RTS System to Prepare for a Change in Smoothness Acceptance Criteria

The equipment loan in Iowa on US 20 allowed the contractor, Cedar Valley Corp., LLC (CVC), to evaluate how an RTS system could be used to improve the initial smoothness of concrete pavements with respect to a proposed IRI specification (see the Field Report online at http://www.cptechcenter.org/real-time-smoothness/). CVC is accustomed to paving under the Iowa DOT's current zero-blanking band PrI specification but realizes that the proposed switch to IRI for acceptance could significantly affect the smoothness levels that the company is used to achieving because IRI is sensitive to different profile features than PrI. This switch could also potentially impact costs by altering pay adjustments for smoothness and potentially requiring additional corrective actions. As discussed in the case study above, the current Iowa DOT specification (2016) provides positive pay adjustment for PrI less than 26.1 in./mi and negative pay adjustment or correction for PrI greater than 40 in./mi, as shown in Table 3. The proposed IRI specification provides positive pay adjustment for MRI less than 63 in./mi and negative pay adjustment (or correction) for MRI greater than 75 in./mi, as shown in Table 4. Using the RTS system during paving, CVC's crews were able to see in real-time the potential impact of the switch to IRI for acceptance. Figure 15 through Figure 18 show screenshots from the RTS display for one day of paving during the equipment loan.

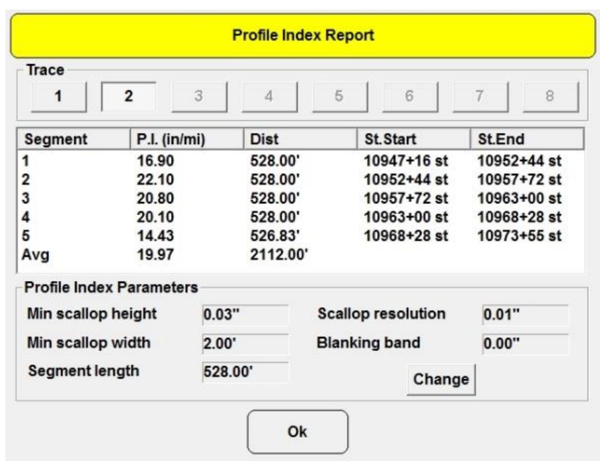

Profile Index Report

Trace: 1 2 3 4 5 6 7 8

Segment	P.I. (in/mi)	Dist	St.Start	St.End
1	21.40	528.00'	10947+16 st	10952+44 st
2	26.70	528.00'	10952+44 st	10957+72 st
3	17.90	528.00'	10957+72 st	10963+00 st
4	23.90	528.00'	10963+00 st	10968+28 st
5	15.33	526.83'	10968+28 st	10973+55 st
Avg	22.47	2112.00'		

Profile Index Parameters
Min scallop height 0.03"
Min scallop width 2.00'
Segment length 528.00'
Scallop resolution 0.01"
Blanking band 0.00"
Change
Ok

Figure 15. GSI of PrI report for passing lane during one day of paving on Iowa US 20


Profile Index Report

Trace: 1 2 3 4 5 6 7 8

Segment	P.I. (in/mi)	Dist	St.Start	St.End
1	16.90	528.00'	10947+16 st	10952+44 st
2	22.10	528.00'	10952+44 st	10957+72 st
3	20.80	528.00'	10957+72 st	10963+00 st
4	20.10	528.00'	10963+00 st	10968+28 st
5	14.43	526.83'	10968+28 st	10973+55 st
Avg	19.97	2112.00'		

Profile Index Parameters
Min scallop height 0.03"
Min scallop width 2.00'
Segment length 528.00'
Scallop resolution 0.01"
Blanking band 0.00"
Change
Ok

Figure 16. GSI of PrI report for truck lane during one day of paving on Iowa US 20

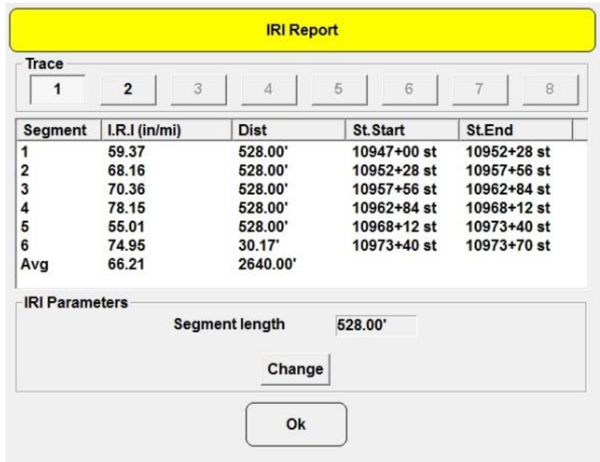


Figure 17. GSI of IRI report for passing lane during one day of paving on Iowa US 20

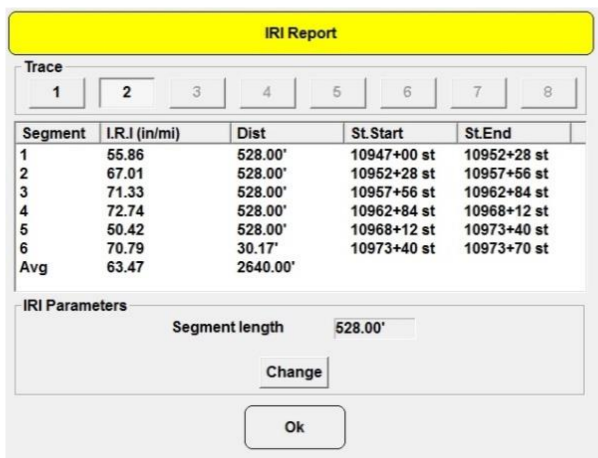


Figure 18. GSI of IRI report for truck lane during one day of paving on Iowa US 20

Looking at Figure 15 and Figure 16 in real-time, CVC's crews could see that nine of ten 0.1-mile segments had a PrI of less than 26 in./mi, while only four of ten 0.1-mile segments had an IRI of less than 63 in./mi (Figure 17 and Figure 18). Keeping in mind that these are real-time measurements and that the hardened results for IRI for this project should be approximately 10 to 15 in./mi lower than the real-time numbers, it is safe to assume that at least nine of ten segments would meet the proposed IRI criteria of 63 in./mi. Using the real-time feedback from the RTS allowed CVC to make adjustments to its processes (mixture, paver setup, and stringline tension), monitor the effect of those adjustments, and further evaluate the potential impacts of IRI acceptance criteria.

Making Adjustments to the Paving Process

Exit interviews were conducted with the contractors after each equipment loan. The consensus among the contractors was that RTS systems are beneficial in identifying factors in the paving process that contribute to initial pavement roughness. The RTS system reduces the risk of making adjustments to the paving process because the real-time feedback gives an indication of the impact of any adjustments on IRI (positive or negative) within an hour or two instead of on the following day, which is the case for hardened profile results.

Making the proper adjustments to the paving processes requires knowledge and experience of the paving mixture and the paving equipment. Using an RTS system can shorten the learning curve for inexperienced crews because it is easier to see the impacts of process changes on initial smoothness in real-time rather than on the following day when hardened profiles are available.

Step-by-Step Implementation of Real-Time Smoothness

Based on the experience gained through the equipment loans, the project team developed a step-by-step process recommended for contractors implementing an RTS system in their projects. This implementation strategy is summarized as follows:

(1) Purchase an RTS system.

Factors that should be considered when choosing the system include the following:

- Ease of mounting and switching between multiple pavers
- Field ruggedness
- Familiarity with operating software
- Cost

The project team's experience with the Ames RTP and GOMACO GSI through the 11 equipment loans revealed that both of these systems are rugged and perform well under highly variable conditions. While there are differences between the user interface and sensor technology (laser or acoustic), both systems were equally capable of accurately measuring the real-time profile and providing the contractor with the feedback necessary for confidently making adjustments to the paving process.

(2) Install and operate the RTS system with the sensor(s) near the middle of each lane.

One sensor per lane is adequate for monitoring real-time smoothness. It is not necessary and many times impractical to mount the sensors directly in line where hardened profiles will be measured. It is desirable to compare the real-time profiles to the hardened profiles. However, the data obtained from the equipment loans has shown that even when these profiles are taken at points across the pavement, they often show very close agreement with respect to profile features (bumps and dips). Figure 1 shows real-time and hardened data from the North Dakota Highway 2 project, where the real-time profile was collected in the middle of the lane, approximately 3 ft from the hardened profiles in the wheelpaths. In this case, both the real-time and hardened data are very similar.

In situations where the real-time and hardened profiles are not similar, the following actions are recommended:

- Check to make sure that the start and end stations of both profiles are the same.

- Eliminate the first 100 to 200 ft of paving from the profile comparison because this is normally where adjustments are still being made to the paver coming off the header.

If the profile features still do not match, this may be indicative of the effects of hand finishing or that the paver is in need of adjustment. The lateral location of the RTS sensors can be adjusted to assist in troubleshooting specific areas across the width of the paver that are consistently rougher (e.g., at tie-bar insertion points or breaks in the cross-slope). After troubleshooting has been performed, return the RTS sensors to the center of each lane.

The amount of data generated by real-time and hardened profile collection can be overwhelming. Therefore, it is important to develop a filename structure for both data sets that will ease the identification of and comparison between both sets of data.

(3) For each new installation and for first time use on each project, begin by passively using the RTS system to establish a baseline of smoothness results.

- Monitor real-time and hardened profile results for one to two days.
- Make ordinary paving process adjustments such as the following:
  - Mixture
  - Vibrators
  - Speed
  - Head
  - Paver stops
- Observe typical responses to the ordinary adjustments and make notes or add event markers in the RTS.
- Real-time and hardened IRI values will not be the same. This is typical; by focusing on reducing the real-time IRI, the hardened IRI values will also be reduced.

(4) After establishing a baseline real-time IRI and a general relationship between the real-time and hardened IRI, begin actively using the real-time smoothness feedback.

- Reduce or eliminate large profile events, such as the following:
  - Stringline or stringless system interference
  - Paver stops
  - Padline issues
  - Fluctuation of paver head
  - Non-uniformity of concrete mixture

Eliminating large profile events yields a new baseline IRI and a new relationship between real-time and hardened IRI.

(5) As necessary, make systematic and incremental adjustments the paving process to improve overall smoothness.

Monitor the real-time feedback for approximately 0.1 miles of consistent paving (i.e., during an absence of any of the large profile events described above). Determine whether the adjustment had an impact on IRI and continue making small incremental adjustments. These adjustments include, but are not limited to the following:

- Maintain a consistent head of concrete in the paver (e.g., between the metering gates and main pan)
- Minimize lead/draft to get the paver as flat as possible
- Adjust the hydraulic and/or stringless sensitivities that control the rate of reaction of the elevation controls of the paver relative to the stringline or 3D model input
- Adjust the vibrator height and frequency
- Adjust the concrete mixture workability and uniformity
- Match the paving speed to the concrete delivery rate or to the improved IRI results if paver stops are not introducing localized roughness

(6) Identify repeating features in the real-time profiles using a PSD analysis.

Use a software tool such as ProVAL to perform a PSD analysis of real-time and hardened profile data. Look for repeating features but focus particularly on features that show up in both the real-time and hardened profiles. These profile features may prove difficult to mitigate, but if they consistently dominate the spectral content in the PSD analysis, this indicates that most of the other impacts on initial pavement roughness have been mitigated to some degree. The most common repeating features include the following:

- Load transfer dowels (joint spacing) for jointed concrete pavement
- Transverse bar supports for continuously reinforced concrete pavement
- Load spacing

5. SPECIFICATION REFINEMENT

Under the original R06E project, a model specification was developed for use by an agency in implementing RTS technology (Rasmussen et al. 2013). Based on observations from the various equipment loans conducted under this effort, several modifications were made to the original model specification. The revised draft specification is included in Appendix B.

It is important to note that RTS is a tool primarily for contractor quality control. As such, this model specification provides general requirements for the capabilities of RTS systems and general best practices for use on a project, but it does not define requirements that an agency could use to include RTS as part of acceptance testing. As discussed previously, the data and resulting smoothness indices from RTS systems will differ, sometimes significantly, from the hardened profile data used for project acceptance and pay adjustment. The difference will be project (and contractor) specific, and therefore an agency should not attempt to establish acceptance protocols for RTS systems.

6. MARKETING AND OUTREACH

A number of marketing and outreach subtasks were undertaken as a part of this effort.

Outreach Materials

Thirty-minute briefings (see section 6.3 below) were deemed to be most effective at reaching potential users of RTS systems. Therefore, four additional briefings were provided in addition to the outreach materials described in the original proposal.

Quick Field References

Two products were developed under this task and are included in Appendix C:

- Pocket Reference
- Quick Reference Index

The pocket reference is also available as a standalone portable document format (PDF) file at http://www.cptechcenter.org/real-time-smoothness/ and can be downloaded and viewed on a smartphone, tablet, or computer. The pocket reference provides key information about RTS installation, daily startup and shutdown, and recommendations for maximizing the benefits of the technology.

As a companion to this pocket reference, an index was developed and designed to be printed as a magnet that can be affixed to the frame of a slipform paver. (The index is also available as a standalone PDF file online at http://www.cptechcenter.org/real-time-smoothness/.)

Thirty-Minute Briefings

This task order required the delivery of 10 briefings, each 30 minutes long. The project team was able to combine many of these briefings with other speaking engagements at concrete pavement-focused venues. Travel costs and delivery costs were reduced by coupling the RTS briefings with these other technology transfer activities. These cost savings allowed the project team to provide four additional briefings, resulting in a total of 14 briefings. A summary of the 30-minute briefings delivered is provided in Table 17.

Table 17. Summary of real-time smoothness briefings

Meeting	Location	Date	Approx. Number of Participants
ACPA 2014 Annual Meeting, Smoothness Task Force	Scottsdale, Arizona	December 2, 2014	60
ASCE 2015 Airfield and Highway Pavement Conference	Miami, Florida	June 8, 2014	30
ACPA 2015 Annual Meeting, Main Session	Bonita Springs, Florida	December 4, 2015	220
2016 TRB Annual Meeting, AFH50 Committee Meeting	Washington, DC	January 12, 2016	40
Pennsylvania Concrete Pavement Association, Main Session	Harrisburg, Pennsylvania	January 16, 2016	200
Nebraska Concrete Pavement Association, Main Session	Lincoln, Nebraska	January 19, 2016	250
Iowa Concrete Paving Association, Two Breakout Sessions	Altoona, Iowa	January 28, 2016	300
Illinois Concrete Pavement Association, Main Session	Lincoln, Illinois	February 2, 2016	200
South Dakota Concrete Pavement Association, Breakout Session	Deadwood, South Dakota	February 10, 2016	150
Concrete Paving Association of Minnesota, Main Session	Duluth, Minnesota	March 10, 2016	250
Colorado-Wyoming Concrete Pavement Association, Main Session and Breakout Session	Denver, Colorado	March 17, 2016	400
Ninth TxDOT-Cement Council of Texas Conference, Breakout Session	Austin, Texas	April 5, 2016	80
Eleventh International Conference on Concrete Pavements, Poster Session	San Antonio, Texas	August 31, 2016	60
Road Profiler Users' Group 2016 Annual Meeting, Main Session	San Diego, California	November 2, 2016	120

Development of Brochures

Four brochures and one technical brief were developed under this task to help promote the equipment loans, workshops, showcase, and RTS technology in general. The technical brief and the following brochures are available online at http://www.cptechcenter.org/real-time-smoothness/:

- Real-Time Smoothness Implementation
- Real-Time Smoothness Equipment Loans
- Real-Time Smoothness Workshop
- Real-Time Smoothness Showcase

7. PERFORMANCE MEASURES

After award of the task order, a number of performance measures were identified by the FHWA and SHRP2. A summary of the status of these performance measures and their outputs, outcomes, and impacts is provided in Tables 18 through 21.

Table 18. Performance measures

Goal	Performance Measure	Potential Target/Date	Progress Through August 2017
National exposure of industry/contractors and state agencies to real-time smoothness technology	Number of states that have been involved in either outreach webinars, showcases, workshops and/or the equipment loan program as part of this deployment effort	15 to 20 state agencies; by September 2016	States Reached ≈ 41 (21 from local venues and 20 estimated from national venues) People exposed to the technology through implementation activities ≈ 2,750 **Equipment Loans:** • Idaho (lead adopt state) • Nebraska • Michigan • Texas • Pennsylvania (lead adopt state) • Iowa (2) • Illinois • Utah (2) • California **Briefings:** • 2014 ACPA Annual Meeting (national venue, audience ≈ 60) • 2015 ASCE Conference (national venue, audience ≈ 30) • 2016 ACPA Annual Meeting (national venue, audience ≈ 220) • 2016 TRB Annual Meeting, AFH50 Committee Meeting (national venue, audience ≈ 40) • Pennsylvania 2016 Paving Conference (audience ≈ 200) • Nebraska 2016 Paving Conference (audience ≈ 250) • Iowa 2016 Paving Conference (audience ≈ 300) • Illinois 2016 Paving Conference (audience ≈ 200)

Goal	Performance Measure	Potential Target/Date	Progress Through August 2017
			• South Dakota 2016 Paving Conference (audience ≈ 150) • Concrete Paving Association of Minnesota (audience ≈ 250) • Colorado-Wyoming Concrete Pavement Association (audience ≈ 400) • 9th TXDOT-Cement Council of Texas Conference (audience ≈ 80) • 11th International Conference on Concrete Pavements (audience ≈ 60) • Road Profiler Users' Group 2016 Annual Meeting (audience ≈ 120) **Workshops:** • Salt Lake City, Utah (audience ≈ 120) • Fontana, California (audience ≈ 30) • Fort Worth, Texas (audience ≈ 38) • Harrisburg, Pennsylvania (audience ≈ 11) • Houston, Texas (audience ≈ 67) • Cincinnati, Ohio (audience ≈ 30) • Greenville, South Carolina (audience ≈ 16) • Omaha, Nebraska (audience ≈ 23) **Showcase:** • Salt Lake City, Utah (national venue, 9 state DOTs represented, audience ≈ 58)
Contractors routinely use the real-time technology on PCC pavement projects	Number of new projects using real-time technology on PCC pavement projects	At least 25 projects by September 2016	Equipment loans = 11 Additional projects by contractors that purchased a system—Iowa (2), Idaho, Michigan, and Utah (2)—after the equipment loans ≈ 18

Goal	Performance Measure	Potential Target/Date	Progress Through August 2017
Owner/agencies support adoption of real-time smoothness technology on PCC pavement projects	Number of state agencies that have encouraged piloting and adoption of real-time technology on PCC projects	At least 10 state agencies by September 2016	Equipment loans = 11 Workshops, showcases, and briefings in non-lead adopt states = 4

Table 19. Output performance measures checklist

Output Measures	Supporting Data (Information that can be provided to assess pilot performance)	Data Collection Deliverable Date	Progress Through August 2017
Number of successful workshops and people trained; success defined by overall positive feedback provided at conclusion of individual workshops	Class surveys distributed at each workshop and workshop attendance, updated on a quarterly basis	March 2017	8 workshops, estimated attendance for all workshops was approximately 335 individuals Average workshop ratings for all workshops (1 = needs improvement, 2 = fair, 3 = okay, 4 = good, and 5 = very good): • Workshop topics = 4.4 • Organization of the materials = 4.6 • Speakers' knowledge of the subject(s) = 4.8 • Comfort of the meeting facilities = 4.5 • Expectations of the workshop were met = 4.4
Produce quarterly reports summarizing the quarterly activities, findings, and planned short term activities of the following quarter provided within 30 days after end of quarter	Quarterly reports	Quarterly report due 30 days after end of the quarter	All quarterly reports were submitted on time

Table 20. Outcome performance measures checklist

Outcome Measures	Supporting Data (Information that can be provided to assess pilot performance)	Data Collection Deliverable Date	Progress Through August 2017
Number of successful field trials performed by December 2016	Documentation of field trials Case study on deployment	February 2017	Equipment loans completed = 11 Field reports documenting the equipment loan activities and lessons learned completed = 11 Case studies and best practices for implementation of real-time smoothness measurements provided in the final report
Number of equipment purchases		February 2017	By the National Concrete Pavement Technology Center = 2 By contractors who participated in equipment loans = 6
Number of successful showcases held; success defined by overall positive feedback provided at conclusion of showcase	Showcase conclusion report, which includes comments by attendees	August 2016	August 2016 in Salt Lake City, Utah = 1
Specification refinement recommendations provided	Specification recommendations	March 2016	Included in the final report = 1
Documentation of field trials and lessons learned	Documentation of field trials and lessons learned	March 2017	Field trials documented = 11

Outcome Measures	Supporting Data (Information that can be provided to assess pilot performance)	Data Collection Deliverable Date	Progress Through August 2017
Number of marketing materials generated; number of outreach activities supported	Quarterly updates	Quarterly Final report March 2017	Outreach activities completed = 21 • 30-minute briefings = 14 • Brochures = 4 • MAP Brief = 1 • Digital pocket reference = 1 • Magnetic placard = 1
Adoption of technology by contractors	Potential survey of manufacturers	March 2017	Contractors who participated in equipment loans purchased real-time smoothness systems = 6
Sustainability and ability for long-term use of technology	Field trial lessons learned	March 2017	Based on state agencies transition from PrI specifications to IRI specifications, the need for this technology will continue to grow Alternative technologies are currently cost prohibitive
Reduced construction zone exposure	Field trial lessons learned	March 2017	None documented to date
Improved IRI using this technology over existing methods	Potentially from field trial lessons		Equipment loans have shown the potential to reduce IRI values
Reduction of bump grinds to achieve IRI compared to existing methods	Potentially from field trial lessons		Equipment loans have shown the potential to reduce localized roughness

Outcome Measures	Supporting Data (Information that can be provided to assess pilot performance)	Data Collection Deliverable Date	Progress Through August 2017
Better understanding of pavement designs, materials selection, climate, and construction techniques needed to improve specification	Field trial lessons learned	March 2017	The following factors and their impact on smoothness have been documented: • Non-uniformity of the concrete mixture • Paver adjustments—lead/draft, vibrator frequency, and hydraulic sensitivity • Concrete spreading techniques • Effect of joints on smoothness • Effect of transverse bar supports on smoothness • The impact of stringline and stringless controls
Real-time identification of objectionable profile characteristics, their root causes, and appropriate corrective measures, minimizing more costly corrections later	Field trial lessons learned	March 2017	Equipment loans have shown the potential to reduce overall IRI and localized roughness
Fewer penalties associated with pavement smoothness imposed on contractor	Case study IRI comparison	March 2016	Contractors have reported that the real-time systems pay for themselves through reduced penalties and/or corrective action
Other			N/A

Table 21. Impact performance measures checklist

Impact Measures	Supporting Data (Information that can be provided to assess the pilot performance)	Data Collection Deliverable Date	Progress Through August 2017
Conduct a synthesis on contractor's experience		Completed, November 2014	Complete
Conduct a case study—Real-time smoothness numbers compared to IRI		June 2016	Complete
Conduct a case study—Long-term performance of real-time technology		September 2016	Complete
Save Time—Reduced average construction duration across all PCC projects	Field report may show the number of localized roughness areas that could be addressed during the construction process instead of grinding after project completion.	March 2017	Fewer corrective actions through the use of real-time smoothness measurement may reduce the overall construction duration.
Save Time—Less road user delay associated with shorter construction duration	Field trial lessons learned	March 2017	Fewer corrective actions through the use of real-time smoothness measurement may reduce the overall construction duration.

Impact Measures	Supporting Data (Information that can be provided to assess the pilot performance)	Data Collection Deliverable Date	Progress Through August 2017
Save Time—Refined specification for materials, equipment, and process needed to produce desired quality and smoothness helps reduce time needed for putting together job-specific provisions for future contracts	Number of states that have adopted the refined specification	March 2017	Complete Real-time systems are a quality control tool that is beneficial for the contractor to use. There are two approaches for implementation: require their use by specification or encourage their use through appropriate incentives for initial smoothness. The project team feels that the latter should be the strategy employed by agencies.
Save Money—Better adherence to quality specifications	Field trial lessons learned	March 2017	Fewer corrective actions through the use of real-time smoothness measurement may reduce the overall cost of PCC pavement projects.
Save Money—Longer PCC pavement life leads to fewer repairs and reconstruction cycles	Long-term performance case study	September 2016	Complete
Save Money—Fewer recouping of penalties by passing costs on through future pavement projects, driving down costs associated with transportation improvement program	Data may not be available for any or all trial sites		Fewer corrective actions through the use of real-time smoothness measurement may reduce the overall cost of PCC pavement projects.
Save Money—Reduced instances of hand finishing (need to determine how real time smoothness values correlate to the hardened IRI values)	Data may not be available for any or all trial sites		In the majority of cases, hand finishing has been shown to improve the initial IRI.
Other			N/A

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APPENDIX A. SYNTHESIS OF CONTRACTORS' EXPERIENCE

Helga Torres, Gary Fick, David K. Merritt, and Robert O. Rasmussen (from original December 2014)

This synthesis presents the findings of five phone interviews conducted with paving contractors that have utilized the real-time smoothness (RTS) measuring technology since the conclusion of the SHRP2 R06E effort in 2011. Interviewees explained how they are using the technology on their paving projects, including to monitor smoothness and make paver/mechanical adjustments, optimize finishing, etc. In addition, contractors use the technology to train paving crews (particularly finishers) and show them the impact of different events and actions on smoothness. Contractors shared their opinion regarding outstanding challenges, including RTS equipment mounting to pavers with an oscillating correcting beam (OCB), the relationship between real-time and final smoothness numbers, equipment maintenance, and software.

Acknowledgments

The authors would like to thank the contractors that participated in the phone interviews for this synthesis: Jeff Borden with Cold Spring Construction Co., Cal Thomas with Interstate Highway Construction, Inc., Jim Peace with GLF Construction Corporation, Matt Parlow with Milestone Contractors, L.P., and Tim Tometich with Manatt's, Inc. Their interest and willingness to share their hands-on experiences with the real-time smoothness measuring technologies are greatly appreciated.

Cold Spring Construction Co.

Cold Spring Construction Co. was the contractor for the last SHRP2 R06E demonstration in August 2011 along I-90 near Weedsport, New York. Cold Spring Construction had previously purchased an Ames Engineering Real-Time Profiler (RTP) unit, and during the demonstration Ames Engineering provided a second RTP system, which allowed for measurements with both units for comparison purposes. Since the SHRP2 demonstration, Cold Spring Construction has used the Ames RTP on a limited basis (on two or three additional projects in 2012 and 2013) because there has been limited concrete paving in the company's area.

Jeff Borden with Cold Spring Construction explained that the company purchased an Ames Engineering RTP based on its satisfaction with other Ames Engineering products, including lightweight profilers, and customer service. As for the RTS technology operation, Jeff explained that there is a learning curve with this technology, but it provides a very valuable tool that helps contractors meet smoothness specifications.

Cold Spring Construction uses the RTS technology to train finishing crews and show them how the smoothness numbers are affected in real-time, typically by monitoring the 100 ft (30 m) average International Roughness Index (IRI) number during paving. Jeff explained that the RTS technology helps finishing crews take ownership in relationship to smoothness and improve the overall quality of the pavement. In addition, Jeff explained that Cold Spring Construction has found good agreement (for paving adjustments and finishing purposes) between the real-time (wet) and the final (hardened) IRI numbers, as shown in Figure 19. The figure shows the quality control (QC) profiler measurements (yellow line) along with the RTP measurements in real-time (blue line) and the RTP measurements of the hardened pavement surface (green line).

Figure 19. Measurements with QC profiler and RTP (wet and hardened surface)

Challenges and Lessons Learned

Oscillating Correcting Beam

As reported in the final report for SHRP2 R06E (Rasmussen et al. 2013), Cold Spring Construction uses pavers with an OCB, and the resulting vibrations heavily influence the readings of the RTP mounted to the back of the paver. Jeff Borden explained that the IRI numbers appear to be "inflated" as a result. Since this contractor is already aware of this issue, when mounting the RTP to the back of pavers with an OCB, Cold Spring Construction assumes a "skew" on the RTP IRI numbers but still finds the RTP feedback to be useful for its operations.

Another solution to address this issue, also reported in the SHRP2 R06E report, is that Cold Spring Construction mounts the RTP equipment on a separate motorized bridge that the finishing foreman also uses to carry tools (Figure 20). Since the work bridge is not directly attached to the paver, this setup also allows the contactor to take measurements before and after the hand finishers and optimize their operation.

Figure 20. RTP equipment mounted to a work bridge during the SHRP2 New York demonstration

Software and Analysis Tools

Cold Spring Construction reported some software issues for the RTP; however, Ames Engineering may have addressed some of them and Cold Spring Construction needs to check with Ames Engineering for an update. Cold Spring Construction works in New York state, where projects still use metric units, and the RTP only allowed for stationing in feet. Jeff would like to see an option to log events during paving in the RTP screen. As a temporary solution, Jeff has used a GPS rover and data collector to log issues (e.g., wet concrete load and stationing) and later prints the log to compare it against the RTP trace to determine if the event affected smoothness.

Jeff noted that more analysis tools in the RTP software would be useful, such as the power spectral density (PSD) module in the Profile Viewing and Analysis (ProVAL) software. Jeff explained that he exports the morning measurements from the RTP and analyzes them during his lunch break using ProVAL on a laptop.

Interstate Highway Construction, Inc.

Interstate Highway Construction, Inc. (IHC) was the contractor for the SHRP2 R06E demonstrations near Vilonia, Arkansas, in May 2011 and Jackson, Michigan, in July 2011. During the demonstration in Arkansas, IHC was able to become familiar with the GOMACO Smoothness Indicator (GSI) system that attaches to the back of a paver as well as the standalone

GSI machine. During the demonstration in Michigan, both the GOMACO GSI and Ames Engineering RTP were used. Since the SHRP2 demonstration, IHC has purchased three GOMACO GSI units for its operations in Michigan, Colorado, and the southwest (Texas and Arkansas), and it has used the RTS technology on several projects. Cal Thomas with IHC explained that even though IHC uses GSI units, it is familiar with the Ames Engineering RTP from discussions with other contractors using it.

Cal Thomas explained that IHC uses RTS technology to monitor for mechanical problems, determine the effect of events (e.g., paver stops, paver adjustments) on the overall smoothness, find bumps/deficiencies and address them during finishing, etc. IHC feels that the RTS profilers are most beneficial when set up behind the paver; in contrast, the GSI machine is typically placed behind the finishers, making it harder to correct deficiencies. In addition, the GSI machine represents another piece of equipment in the paving train, which adds expense.

Challenges and Lessons Learned

Training

Cal Thomas explained that the first challenge with the RTS technology is training paving crews to use it. He explained that it takes changing the current mindset, especially with finishing crews (typically a lead finisher and three other finishers). In the past, the crews would actively be finishing to meet smoothness; now, with the RTS technology, they are told to monitor the RTS device (GSI screen) for indications of bumps/deficiencies, check with a straightedge, and then try to correct it. It takes training for the lead finisher to find the station where the GSI indicates that there is an issue and determine if there is a bump/deficiency.

Cal noted that paving crews' typical reaction to the RTS devices is that an extra person is needed to monitor the screen, but over time the lead finisher understands the technology and assumes the role to monitor it. Also, in addition to monitoring smoothness in real-time, IHC trains the lead finisher or someone else to download data from GSI at the end of the day and use ProVAL to compare real-time (wet) IRI and QC (hardened) IRI measurements. IHC also uses ProVAL to analyze the day's operations and make adjustments for the following day (e.g., if there were too many stops to wait for concrete loads, then slow down paving speed the following day).

When asked about possible tools to assist with the training, Cal said that webinars with videos (similar to ACPA's) are possibly the most effective way to train contractors.

Oscillating Correcting Beam

Cal Thomas recalled the SHRP2 research and the Arkansas demonstration where the RTS devices were mounted to a Guntert & Zimmerman paver with an OCB that was inducing a lot of movement/vibrations (Figure 21). However, he recalled the Michigan demonstration, where the contractor was using an identical paver; in that project, the contractor replaced the bearings that drive the OCB and thereby eliminated most of the movement/vibrations.

Figure 21. Paver-mounted GSI setup on paver with OCB

Similar to Cold Spring Construction, IHC also tried mounting the RTS equipment to a work bridge during the Michigan demonstration (Figure 22).

Figure 22. GOMACO GSI and Ames RTP mounted to a work bridge towed by the paver

Real-Time IRI and Final IRI Relationship

Cal Thomas explained that it is understood that there is not a “tight” correlation between real-time (wet) and QC (hardened) IRI measurements. However, IHC has observed an improvement (reduction) from 20 to 50 percent between real-time and QC numbers. He attributes this difference to the fact that IHC is conducting RTS measurements right behind the paver and then correcting any identified issues with finishing. IHC has also observed that the higher the RTS numbers, the greater the percent improvement, and that the lower the RTS measurements, the tighter the correlation with the hardened measurements, which can be attributed to less finishing.

Maintenance

Cal Thomas noted that maintenance of RTS equipment is important. As with other paving equipment that involves a lot of electronic parts, there are issues with the paving environment, such as rain and humidity getting into the control boxes and affecting plugs/connections. One example was a project where the water system used to keep the burlap drag moist was affecting the GSI readings. IHC carries spare parts and cables for its GSI units and send its GSI units to GOMACO for annual maintenance.

GLF Construction Corporation

Jim Peace with GLF Construction Corporation (previously with Hinkle Contracting, LLC) is familiar with the GOMACO GSI, which he used during the paving of I-65 in Alabama. He is also familiar with the Ames Engineering RTP, which he observed during a demonstration in Iowa. His first impression was that the laser technology on the Ames Engineering RTP would make it more expensive.

Jim finds the feedback of the paver-mounted units to be more valuable because it allows adjustments to the finishing operation. Jim also finds the GSI machine (standalone unit after finishers) to be valuable but not as useful for making adjustments to hand-finishing operations.

Challenges and Lessons Learned

Training, Real-Time and Final IRI Relationship, and Paver Adjustments

Jim believes that the RTS technology is a great tool to monitor smoothness, grade control, and equipment mechanical issues. Similar to Cold Spring Construction and IHC, he notes that it is also a great training tool for paving crews, where they can learn the effect of events, such as a dry versus wet concrete load, by watching the RTS device feedback. Jim also believes that the feedback from the RTS devices is a very good indicator of smoothness, even though it is understood that there is not a good correlation between wet and hardened concrete IRI numbers.

Jim recalled some issues when using misters on a project to moisten the burlap drag, which affected the GSI readings. He also noted that when adjustments are made to the paver, the GSI readings show a bump/defect, and therefore an event marker is needed to identify those spots for future reference.

Milestone Contractors, L.P.

Matt Partlow with Milestone Contractors, L.P. in Indiana explained that the company purchased a GOMACO GSI three years ago and has been using it since on every project. The Indiana DOT uses the Profilograph Index (PrI), so Milestone Contractors monitors the sine wave plot in the GSI screen and adjusts the paver until the PrI number is constant and below the target. Once paving is going smoothly, the company monitors the PrI number and has finishers use it to optimize the finishing operation.

Matt explained that Milestone Contractors puts a lot of faith in the GSI feedback and has made adjustments to its paving operation accordingly. The company monitors the GSI feedback for sensitivity tuning and to evaluate the impact of dry/wet concrete loads, trackline adjustments, stringless system issues, etc.

Matt reported very minor issues/challenges with the GSI, noting that the software could be updated to improve stationing/event markers.

Manatt’s, Inc.

Tim Tometich with Manatt’s, Inc. in Iowa explained that the company owns two GOMACO GSI units and that two of the company’s paving crews use them on a daily basis. Manatt’s sees the benefit of making adjustments in real-time instead of waiting one day for QC smoothness measurements when the concrete hardens.

Tim reported very minor issues with the GSI equipment and operation. One issue previously noted by other contractors is related to moisture getting into the GSI sensors and affecting the readings. Tim also mentioned that the company’s GSI units are slightly different, with one of them being more difficult to calibrate in terms of the distance measurement instrument (DMI). Tim explained that the initial setup of the GSI units and training take more effort, but once the equipment is running and the crews are trained, the company sees a lot of benefit in the technology.

Conclusions and Recommendations

The use of RTS technology is increasing. Based on information provided by GOMACO and Ames Engineering in November of 2014, there are approximately 75 units in service nationwide.

Paving contractors are using the RTS technology mainly for the following purposes:

- To monitor smoothness and adjust their operation until a target smoothness is met. Once paving is going smoothly, they monitor the RTS feedback for indications of bumps/deficiencies and optimize their finishing operation.
- To train paving crews, particularly finishers, and show them the impact of different events and actions on smoothness.

Some of the issues and challenges with the RTS equipment include the following:

- Mounting to pavers with an OCB
- Equipment maintenance
- DMI setup and calibration
- Software improvements
- Moisture affecting the electronics and possibly interfering with the sensors

Based on the uses and challenges listed above, the team proposed the following items for the workshops and equipment loan program:

- Add a module on how to train paving crews, with photos and videos of specific examples (e.g., RTS equipment screenshots of bumps/deficiencies and the causes)
- Add a training module on RTS equipment maintenance and troubleshooting
- Work with equipment vendors (GOMACO and Ames Engineering) to check on the status of software issues cited by contractors
- Investigate the issues with OCBs and the relationship between the real-time and final IRI during the equipment loan program
- Investigate potential issues with mister systems used to moisten the burlap drag

APPENDIX B. DRAFT SPECIFICATION

Recommended Practice for

Real-Time Smoothness Measurements on Concrete Pavements During Construction

XX-## (2020)

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1. SCOPE

1.1. This document provides language that can be used by an Owner-Agency to develop equipment and construction specifications with the objective of conducting real-time smoothness measurements on concrete pavements during construction. These measurements involve conducting pavement profile measurements as pavement is being constructed in order to provide smoothness-related feedback and the corresponding displays to the paving crew. This information is intended for quality control and process improvement purposes and not as a replacement for quality acceptance tests. Nevertheless, the practices presented herein have been demonstrated to increase the likelihood of constructing durable, smoother concrete pavements.

1.2. If any part of this practice is in conflict with references made, such as ASTM or AASHTO standards, this practice takes precedence for its purposes.

1.3. The values stated are in U.S. customary units and are to be regarded as the standard.

1.4. This practice should only be adopted after an evaluation of existing smoothness measurement standards. Smoothness standards should be modified as necessary to minimize or eliminate prescriptive language that may conflict with the end-result practices described herein.

1.5. *This specification does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this specification to establish appropriate safety and health practices and determine the applicability of regulatory limitations related to and prior to its use*.

2. REFERENCED DOCUMENTS

2.1. *AASHTO Standards*:

- M 328-14, Standard Specification for Inertial Profiler
- R 54-14, Standard Practice for Accepting Pavement Ride Quality When Measured Using Inertial Profiling Systems
- R 56-14, Standard Practice for Certification of Inertial Profiling Systems
- R 57-17, Standard Practice for Operating Inertial Profiling Systems

2.2. *ASTM Standards*:

- E1926-08(2015), Standard Practice for Computing International Roughness Index of Roads from Longitudinal Profile Measurements
- E2560-17, Standard Specification for Data Format for Pavement Profile

3. TERMINOLOGY

3.1. *International Roughness Index (IRI)*—according to AASHTO R 56-14, a statistic used to determine the amount of roughness in a measured longitudinal profile. The IRI is computed from a single longitudinal profile using a quarter-car simulation as described in the paper "On the Calculation of International Roughness Index from Longitudinal Road Profile" (Sayers 1995). Computer programs to calculate the IRI statistic from a longitudinal profile are referenced in ASTM E1926-08(2015).

3.2. *Area of Localized Roughness (ALR)*—any segment of roadway where the roughness contributes disproportionately to the overall roughness index value. The most common method for identifying ALR within an IRI-based specification is using a report of continuous IRI with a base length of 25 feet. This yields the IRI of every possible 25-foot segment. Any segment of pavement that causes the continuous report to exceed a threshold IRI value is considered a defective segment requiring correction.

3.3. *Longitudinal Profile*—according to AASHTO M 328-14, a two-dimensional slice of the roadway surface taken along an imaginary line, such as the wheel path, in the longitudinal or travel direction. This measure yields a set of relative elevation values recorded at a constant distance interval along a designated path or trace in the direction of travel.

3.4. *Profilograph Index (PrI)*—a smoothness index that is computed from a profilograph trace. This is sometimes called profile index (PI) but is more specifically called PrI.

3.5. *Real-Time Smoothness*—the process of conducting pavement profile measurements as pavement is being constructed.

3.6. *Continuous Roughness Report*—a plot that shows the variation in roughness (e.g., IRI or PrI) over a section of pavement.

3.7. *Smoothness Statistic*—a statistic that summarizes the roughness, as measured by an index such as IRI or PrI, of a profile measured over a section of pavement with a defined length.

3.8. *Trace*—the path along a pavement's surface where the longitudinal profile is measured.

4. SIGNIFICANCE AND USE

4.1. This example provides specification language for conducting real-time smoothness measurements on concrete pavements during construction. Smoothness statistics for profiles measured in real time differ from smoothness statistics for profiles measured on the final surface due to subsequent effects such as those caused by finishing operations (straightedge and float), texturing, joint sawing, curling, warping, etc.

5. EQUIPMENT

5.1. *General Requirements*—Provide a qualified real-time smoothness measuring system. Provide the Owner-Agency with documentation of the system's qualifications.

5.1.1. *Profiler*—The profiler shall be equipped with various sensors, interface hardware, computer hardware, and software that, working together, perform the measurement and recording of the longitudinal profile. The data shall be stored internally during the test and transferable onto suitable high-density removable storage media after the test.

5.1.1.1. The profiler shall have the capability to process the collected data, to display the derived profile(s), and to report industry standard smoothness statistics including IRI and simulated PrI in real time.

5.1.1.2. The profiler shall function independently from motion and vibration of the hardware to which it is mounted.

5.1.2. *Mounting*—The equipment shall mount to a host machine used in the paving operation, such as on a paving machine behind the pan or on an independent work bridge. The system shall cause minimal disturbance to the paving operation and operate without contacting the fresh pavement surface. The sensors shall be free from interference from burlap/turf drag and auto-float apparatus behind the paver, if used.

5.1.3. *Data Display*—The system shall include a live readout display accessible by the project supervisor or the paver operator. Such display needs to be visible in daylight.

5.1.4. *Software*—The system's operational software shall provide a means to trigger the start of data collection manually at a given location and terminate data collection manually at a given location.

5.1.5. *Calibration*—The equipment shall have built-in provisions to facilitate the calibration of each transducer signal. Any external devices required for calibration shall be included with the equipment. In addition, the equipment shall alert the operator if transducer signals are out of range or fail to vary. The calibration system, in conjunction with a calibration protocol specified by the supplier, shall ensure the accuracy of the data.

5.2. *Functional Capabilities*—The system shall meet the following specifications:

5.2.1. The system shall measure distance data in feet, meters, kilometers, or miles in an incrementing or decrementing mode from a selected starting point and relate the distance to station at any point.

5.2.2. The system shall be capable of obtaining and storing longitudinal profile at a distance interval of 3 inches or less.

5.2.3. The system shall be capable of calculating, displaying, and storing the smoothness statistic values obtained from the stored data at user-specified intervals. The system shall be capable of collecting and storing internally at least 25 lane miles of longitudinal profile.

5.2.4. A distance transducer shall be provided to produce a pulse for each increment of distance traveled by the profile host machine along the track line. The data acquisition system (DAS) shall accept these pulses and, in combination with the DAS software, shall determine distance traveled and vehicle speed. The system shall process the signals and record the data from the distance transducer. The calibration procedure shall record the data to allow the recorded distance pulses to be interpreted into the desired measurement units selected by the operator. The measured distance shall be accurate to 0.1 percent per mile for typical test speeds.

5.2.5. The DAS shall be capable of recording profile in at least four tracks simultaneously.

5.2.6. The system shall demonstrate both repeatability and agreement relative to a reference profile via cross-correlation, on smooth-textured hardened concrete, of 0.8 or better, with 0.94 preferred.

5.3. *Software*—The profiler shall be capable of producing profile files in the format described by ASTM E2560-17.

5.3.1. The system shall provide a plot of elevation versus distance in real time.

5.3.2. The roughness of each profile trace shall be produced in real time using any user-selected report interval chosen for the calculation.

5.3.3. The system shall be capable of calculating a continuous report of IRI or PrI with a relatively short running base length (25 to 528 feet) and displaying the value and location of continuous IRI values above a user-settable threshold.

5.3.4. The system shall be capable of warning the user of ALR, determined either by values in the continuous report of IRI above a user-entered threshold value or by failure of a simulated profilograph bump template.

5.3.5. The system shall record user-entered event markers that include the event type and the location in the designated distance units.

5.3.6. The system shall reset the station value in real time at a known landmark.

6. EQUIPMENT VERIFICATION

6.1. *Accuracy and Repeatability*—The system shall demonstrate both repeatability and agreement relative to a reference profile via cross-correlation on smooth-textured hardened concrete. The following steps are recommended to accomplish equipment verification if there is concern regarding the reliability of the results or as a system initiation process at the beginning of a project. Verification testing should be performed following equipment manufacturer recommendations. The following steps provide a general procedure in lieu of a manufacturer-specific process:

6.1.1. Designate a 1,000-foot-long section of completed pavement to conduct profile measurements. Before testing, the concrete surface should be thoroughly cleaned using a motorized broom or other means approved by the Owner-Agency.

6.1.2. *Repeatability*—Conduct a set of three repeated longitudinal profile measurements along the track of interest (e.g., the wheel path or center of the lane) with the real-time profiler mounted to a stable host vehicle. The equipment manufacturer is to provide detailed specifications, including equipment operation procedures, to complete this exercise.

6.1.2.1. Evaluate repeatability by conducting cross-correlation analysis of the three repeated measurements using Profile Viewer and Analysis (ProVAL) software (or another software package capable of interpreting the measurements obtained from the technology). This analysis procedure is thoroughly described in AASHTO R 56-14, Standard Practice for Certification of Inertial Profiling Systems.

6.1.2.2. An average repeatability score of 0.8 or better is required, with 0.94 preferred.

6.1.3. *Accuracy*—Conduct a set of three repeated longitudinal profile measurements with a reference profiler in accordance with the requirements in AASHTO R 56-14, Standard Practice for Certification of Inertial Profiling Systems.

6.1.3.1. Evaluate accuracy by conducting cross-correlation analysis of the profile measurements obtained by the real-time profiler and the reference profiler using ProVAL (or another software package capable of interpreting the measurements obtained from the technology) in accordance with AASHTO R 56-14, Standard Practice for Certification of Inertial Profiling Systems.

6.1.3.2. An average agreement score of 0.8 or better is required, with 0.94 preferred.

7. WORK METHODS

7.1. *Pre-paving Activities*—Set up the real-time system in accordance with the manufacturer's instructions. Prior to commencement of paving, inspect all real-time system components to ensure the integrity of the connections and that the sensors are securely mounted, and perform the recommended sensor checks.

7.1.1. Determine the location of the longitudinal traces to be profiled based on project considerations and the number of sensors that the system includes.

7.1.1.1. Typical profile traces follow the wheel paths or the center of the lane(s). It is recommended that the locations designated for measurement on the final hardened concrete be considered.

7.1.1.2. If the system configuration allows, and if feasible given the specifics of the paving project, profile measurements may be taken along the same longitudinal trace at different stages in the paving train. For example, measurements may be taken behind the paver followed by measurements taken behind the hand-finishing operation in order to assess the latter's effects on smoothness.

7.1.2. Inspect the area to be paved and make note of any locations with features that may potentially affect real-time smoothness measurements, such as leave-outs, changes in the subbase or paver track line, changes in pavement slab thickness, grade changes, cross-slope/superelevation transitions, etc.

7.2. *Testing*—Perform continuous real-time profile measurements on a daily basis throughout the duration of the project. Monitor real-time feedback and adjust the paving materials and processes to improve real-time smoothness results.

7.2.1. Operate the real-time smoothness measuring system in accordance with the manufacturer's instructions in order to provide real-time feedback to the project supervisor or the paver operator throughout the day.

7.2.1.1. Use the event marker tool to record relevant events (e.g., concrete mixture changes, paver stops, track line roughness, leave-outs, or stringline/stringless system issues) that are expected to have an impact on smoothness.

7.2.2. Use the real-time system display to monitor the profile, continuous roughness reports (i.e., continuous IRI or PrI plots), and smoothness statistics (in terms of IRI or PrI values and section summaries) in real time.

7.2.3. Provide the project supervisor or project engineer with the test data in a file format readable by ProVAL (e.g., in .erd or .ppf format per ASTM E2560-17) at the end of the day, at minimum, and as requested throughout the day. Note that real-time systems generally require the user to stop logging data in order to export a data file.

7.2.3.1. Provide a clear description identifying the location of the profile traces with respect to the paving lanes and location within the paving train.

Note 1—The ProVAL software program, originally developed for the Federal Highway Administration, can be used to import, display, and analyze the characteristics of pavement profiles from many different sources and is available for free at www.RoadProfile.com.

7.2.4. Periodically check sensor functionality, including the distance measurement transducer calibration factors, in accordance with the manufacturer's instructions throughout the day.

7.3. *Detailed Analysis*—The project supervisor or project engineer shall use software capable of interpreting the data from the pavement profiler, such as ProVAL, to conduct detailed analyses of the profiles measured in real time, as required throughout the day. The specifics about how these analyses can be performed in ProVAL are not included here but can be found in the supporting documentation for the ProVAL software package (Transtec 2016).

7.3.1. Inspect the profiles using the ProVAL Viewer tool or an equivalent analysis tool. Plot elevation versus distance to seek trends in the profile, and identify sources of roughness such as rapid changes in elevation. To facilitate diagnosis, compare several traces from the same road segment if they are available. As needed, apply high-pass filtering. Most applications related to detection of roughness sources require high-pass filtering with a cut-off wavelength of 300 feet or less, where a value of 100 feet often makes important details more visible. For highly localized disturbances, a value of 25 feet may be needed.

7.3.2. For work performed under an acceptance specification that is based on PrI, inspect the simulated profilograph traces using the ProVAL Profilograph

Simulation tool or an equivalent analysis tool. Identify scallops and PrI values using the settings corresponding to the acceptance specification criteria.

7.3.3. For work performed under an IRI acceptance specification, use the ProVAL Ride Quality module or an equivalent analysis tool. Compute the IRI (or other required index) for the specified section length. Use the continuous report of IRI to further inspect the profile data for specific areas exceeding the required threshold. Shorter segment lengths in the range of 25 to 100 feet in the continuous report will yield helpful results for identifying areas of localized roughness.

7.3.4. Use the Power Spectral Density (PSD) module in ProVAL or an equivalent analysis tool to inspect the profile data for systematic elements within the profile. Many construction artifacts occur on a repeated basis throughout the paving process, and PSD analysis allows these artifacts to be efficiently identified.

7.3.5. Use the Automated Profile Synchronization module in ProVAL or an equivalent analysis tool to assist with synchronizing repeat profiles from the same equipment or to synchronize profile data obtained from different profilers (e.g., real-time and hardened profile data).

7.3.6. Use the ProVAL Smoothness Assurance Module or an equivalent analysis tool to compare, side-by-side, roughness values to the longitudinal profile in order to examine the effects of various features in the profile on roughness.

7.3.7. The project supervisor or the project engineer shall use the results of the detailed analysis to evaluate the paving methods and equipment. If the source of localized roughness or objectionable profile characteristics is identified during the analysis, adjustments may be made.

8. MEASUREMENT AND PAYMENT

8.1. *Measurement and Payment*—The work performed; materials furnished; equipment, labor, and tools required to perform the work; and incidentals shall not be measured or paid for directly but shall be subsidiary to bid items in the contract. No positive or negative pay adjustments are associated with real-time smoothness measurements.

9. REFERENCES

9.1. Sayers, M. W. 1995. On the Calculation of International Roughness Index from Longitudinal Road Profile. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1501, pp. 1–12.

9.2. Transtec. 2016. *ProVAL User's Guide, Version 3.6*. The Transtec Group, Inc., Austin, TX.

APPENDIX C. QUICK REFERENCE INDEX AND POCKET REFERENCE

This appendix includes copies of the two quick field references developed for this project:

- Quick Reference Index—An index to the Pocket Reference, designed and developed to be printed as a magnet that can be affixed to the frame of a slipform paver

- Pocket Reference—Key information about RTS installation, daily startup and shutdown, and recommendations for maximizing the benefits of the technology, designed and developed as a standalone PDF file that can be downloaded and viewed on a smartphone, tablet, or computer (with the version in this appendix adapted to an 8.5-by-11-inch page size/format)

Both of these are also available as standalone PDF files at http://www.cptechcenter.org/real-time-smoothness/.

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