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PAVEMENT TECHNOLOGY

Measuring Pavement Profile at the Slip-Form Paver

May 2005

IOWA STATE UNIVERSITY

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16. Abstract

Pavement profile or smoothness has been identified nationally as a good measure of highway user satisfaction. This has led highway engineers to measure profiles of both operating and new highways. Operational highway profiles are often measured with high-speed inertial profilers. New highway profiles are usually measured with profilographs in order to establish incentives or disincentives for pavement construction. In most cases, these two processes do not measure the same value from the "cradle to grave" life of pavements. In an attempt to correct the inconsistency between measuring techniques, lightweight profilers intended to produce values to be used for construction acceptance are being made that measure the same profile as high-speed inertial profilers. Currently, two profiler systems have been identified that can measure pavement profile during construction.

This research has produced a field evaluation of the two systems. The profilers evaluated in this study are able to detect roughness in the final profile, including localized roughness and roughness at joints. Dowel basket ripple is a significant source of pavement surface roughness. The profilers evaluated in this study are able to detect dowel basket ripple with enough clarity to warn the paving crew. String-line disturbances degrade smoothness. The profilers evaluated in this study are able to detect some string-line disturbances during paving operations. The profilers evaluated in this study are not currently able to produce the same absolute International Roughness Index (IRI) values on the plastic concrete that can be measured by inertial profilers on the hardened concrete. Construction application guidelines are provided.

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MEASURING PAVEMENT PROFILE AT THE SLIP-FORM PAVER

Final Report
May 2005

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INTRODUCTION

Problem Statement

Pavement profile, or smoothness, has been identified nationally as a good measure of highway user satisfaction. This identification has led highway engineers to measure the profiles of both new and operational highways. The operational highways are measured on a frequent basis with high-speed inertial profilers. Incentives/disincentives for pavement construction are measured with profilographs. In most cases, these do not measure the same value from the “cradle to grave” life of the pavement.

In an attempt to correct the inconsistent measuring, lightweight profilers are being made for construction acceptance, measuring the same profile as the high-speed profilers. Problems currently exist in the correlation between profiler outputs and repeatability.

Another portion of the smoothness/profile problem is the understanding of what causes undulations in the pavement surface and how to prevent them from occurring. Currently, two types of equipment have been identified that measure profile at the slip-form paver and can be used to take corrective action prior to the setting of the concrete.

Research Objectives

This research evaluated equipment and methods to measure profile at the slip-form paver. The research was directed at evaluating the impact of various pieces of paving equipment and the processes used, from the deposit of the pavement concrete to the completion of the curing operation, on the resulting ride values. Construction application guidelines were also developed.

RESEARCH METHODOLOGY

Experimental Design

A layout for testing in different locations across the pavement surface and behind the slip-form paver, hand floating area, and the cure/texturing machine was developed prior to the field instrumentation. Two sensor configurations were selected for the field research. The first included the placement of four sensor devices across the pavement width with one sensor in each wheel path. The second configuration included four sensors in a single line in one wheel path between each operation in the paving train. Other variables included varying the type of surface texturing from floating only to variations in the use of burlap and Astroturf drags and tining.

Data Collection

Profile data from each of the two test configurations were collected at the designated locations in the paving train over a period of three days. Profile measuring equipment for the tests was supplied by the GOMACO Corporation and Ames Engineering, Inc. It was not considered feasible for this project to have both vendors operating on the same construction project. The GOMACO equipment was evaluated on a section of U.S. Highway 30 new construction near Le Grand, Iowa. The Ames Engineering Inc. equipment was evaluated on a section of U.S. Highway 34 new construction near Rockbridge, Iowa.

The Iowa DOT lightweight profiler was used to gather hardened concrete ride values on each of the pavement sections immediately after construction. This was done to provide a way of relating profile or ride between the values obtained on the plastic concrete and those obtained on the hardened concrete.

VENDOR RESEARCH PLAN AND EXECUTION

Both vendors were asked to provide a report on their approach to and execution and analysis of the test results. The following information was provided by the vendors directly to the research team.

GOMACO Smoothness Indicator (GSI) Evaluation

GSI Data Collection

Data were collected using the GOMACO Smoothness Indicator (GSI) on U.S. Highway 30. A total of six wheel path sensors and two computers were used to collect the data. One computer was mounted to Manatt's GOMACO Model 3000 slip-form paver along with four traces, one located in each wheel path. The other computer was mounted to a GSI vehicle along with two traces. See Figure 1.

Figure 1. GSI testing on U.S. Hwy 30 westbound from Tama to Le Grand, Iowa

The arrangement of sensors changed throughout the study. For the first three days, the four traces were located behind the paver pan, and two additional traces were tested after the cure/texture machine. For the final three days of testing, three traces were attached to the paver pan, and an additional trace was placed on the v-float in-line with a trace on the paver pan. The GSI vehicle was located behind hand finishers but in front of the cure/texture machine, which also had two traces, one that was in-line with the paver pan and the v-float traces. See Figure 2.

Figure 2. GSI arrangement over each wheel path (Arrangement 1)

After the concrete was cured (24–48 hours later) and scraped with a power broom blade, the GSI vehicle retested the concrete slab recording all four wheel paths of the two-lane concrete slab.

GSI Results

Arrangement 1

Four traces mounted to paver:
- Trace 1 Inside Lane – Outside Wheelpath
- Trace 2 Inside Lane – Inside Wheelpath
- Trace 3 Outside Lane – Inside Wheelpath
- Trace 8 Outside Lane – Outside Wheelpath

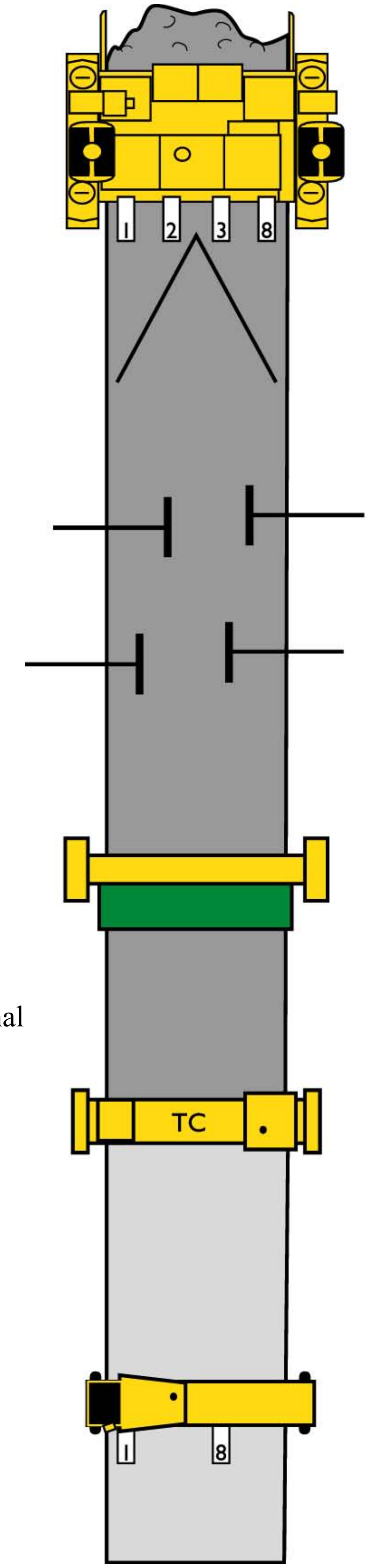
Two traces mounted to GSI vehicle,
located after cure/texture machine:
- Trace 1 Inside Lane – Outside Wheelpath
- Trace 8 Outside Lane – Inside Wheelpath

Day 1 Testing
Thursday 07/08/2004
Station 159+75 to Station 148+09
GSI Placement: Arrangement 1
Notes: Segment 8 is a partial segment of 203.83’

Day 2 Testing
Saturday 07/10/2004
Station 148+09 to Station 134+02
GSI Placement: Arrangement 1
Notes: Segment 9 is a partial segment of 290.17’

Day 3 Testing
Thursday 07/15/2004
Start Station 134+52
GSI Placement: Arrangement 1
Notes: Three segments were tested prior to the bridge and burlap drag was used instead of indoor/outdoor turf. The final five segments were obtained after crossing the bridge and the texturing was switched to indoor/outdoor turf again.

Arrangement 1



Arrangement 2

Four traces mounted to paver:

Trace 1 Inside Lane – Outside Wheelpath
Trace 2 Outside Lane – Inside Wheelpath
After V-Screed
Trace 3 Outside Lane – Inside Wheelpath
Trace 8 Outside Lane – Outside Wheelpath

Two traces mounted to GSI vehicle,
located before texture/cure machine:

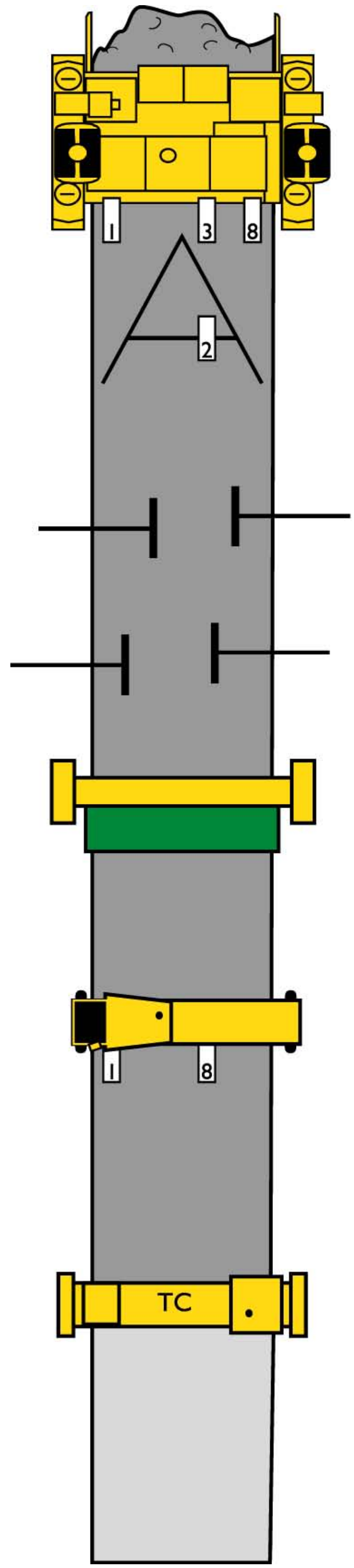
Trace 1 Inside Lane – Outside Wheelpath
Trace 8 Outside Lane – Inside Wheelpath

Day 8 Testing
Friday 07/23/2004
Station 101+63 to 87+62
GSI Placement: Arrangement 2
Notes: Segment 9 is a partial segment of 437.00 ft.
Trace 2 is located on V-Screed 30ft behind trace 3 on paver

Day 9 Testing
Saturday 07/24/2004
Start Station 87+62
GSI Placement: Arrangement 2
Notes: Segment 3 is a partial segment of 226.00 ft.
Trace 2 is located on V-Screed 30 ft behind trace 3 on slip-form paver.

Day 10 Testing
Monday 07/26/2004
Start Station 83+71
GSI Placement: Arrangement 2
Notes: Segment 9 is a partial segment of 477.67 ft.
Trace 2 is located on V-Screed 30 ft behind trace 3 on paver.

Arrangement 2



Arrangement 3

Four traces mounted to GSI vehicle:

Trace 1 Inside Lane – Outside Wheelpath
Trace 2 Inside Lane – Inside Wheelpath
Trace 3 Outside Lane – Inside Wheelpath
Trace 8 Outside Lane – Outside Wheelpath

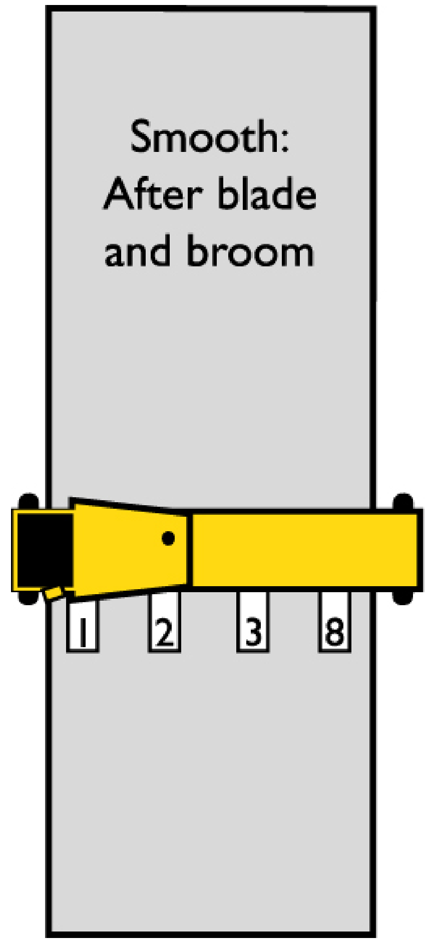
Testing was performed after the surface was cured.
A blade and broom cleaned the surface before testing

Day 8 Smooth Testing
Tuesday 07/27/2004
Station 101+63 to 87+62
GSI Placement: Arrangement 3
Notes: Segment 9 is a partial segment of 437.00 ft.

Day 9 Smooth Testing
Tuesday 07/27/2004
Station 87+62
GSI Placement: Arrangement 3
Notes: Segment 3 is a partial segment of 226.00 ft.

Day 10 Smooth Testing
Wednesday 07/28/2004
Station 83+71
GSI Placement: Arrangement 3
Notes: Segment 9 is a partial segment of 477.67 ft.

Arrangement 3



Ames Engineering Real Time Profiler (RTP) Evaluation

RTP Data Collection

The paving operation took place on Highway 34 between Fairfield and Mount Pleasant, Iowa. All testing was performed between August 23 and September 9, 2004. The Real Time Profiler (RTP) was attached in two configurations during the paving operation.

The first configuration used four sensors attached across the concrete slab; sensor one was located in the outside wheel track of the passing lane and the three additional sensors were placed consecutively across the slab in each wheel track. See Figure 3.

Figure 3. RTP beams attached in each wheel track

The second configuration involved attaching two sensors to the paving machine in a train configuration. Sensor one remained attached to the float pan three feet off the centerline in the passing lane. Sensor two was placed about 18 feet behind sensor one at about 1 foot behind the auto-float. Sensors three and four were also placed in a train configuration further back in the paving operation connected to the curing and tining machine. Sensor three was placed in front of the tines, and sensor four was placed about nine feet behind sensor three after the tines. Data were collected for at least three days of paving in each configuration.

The Iowa DOT collected data with its LISA TriODS inertial laser profiler several days later. Because the concrete pavement was tined longitudinally, it was important that the TriODS laser system was used because it eliminates false roughness data picked up by single point laser systems. Reflective cones were placed at set intervals horizontally along the side of the road. These cones were used to trigger event markers that were recorded alongside the elevation data being collected. For most of the data collection, these cones were used to locate station pins at set intervals. For one full day, the cones were instead used to mark dowel bar basket locations.

RTP Results

Roughness Distribution Across the Four Wheel Tracks

To help understand how the roughness is distributed across all four wheel tracks, four sections of 300 meters each were examined from data collected from the RTP and data collected later from the LISA TriODS system. For each section, the data were broken into 100-meter segments and the average for the 3 sections was recorded. The LISA data were high-pass filtered with a third order Butterworth filter set to 15.24 meters, which is identical to the filter setting used on the RTP during data collection.

The three indexes compared were the international roughness index (IRI), the Profilograph index with a zero blanking band, and the Michigan ride quality index (RQI). Figure 4 shows bar plots of the RTP results of the three indexes compared for section one of the four sections tested. The 300-meter section was broken into 3 sections of 100 meters each. The average of the three sections is shown in the table and plots in Figure 4 below. The results in Figure 4 indicate that track four was the roughest wheel track. Wheel track one is slightly rougher than section three, and track two is the smoothest track. Figure 5 shows the results for the identical section tested by the LISA TriODS profiler. The results for each section tested followed this pattern. The index measurements for the RTP compared quite well to the LISA TriODS data. Both devices also show the same pattern of the inside wheel track data being smoother than the outside wheel track data. Wheel track two was almost always the smoothest of the four wheel tracks measured. Appendix A contains a table presenting the entire data set from RTP analysis, and Appendix B contains the entire data set for the LISA TriODS analysis.

8/30/2004	PASS OUT	PASS IN	DRIVE IN	DRIVE OUT
IRI(m/km)	1.27	1.03	1.28	1.34
PI(mm/km)	538.33	424.67	552	578.67
RQI	43.11	33.04	42.25	45.27

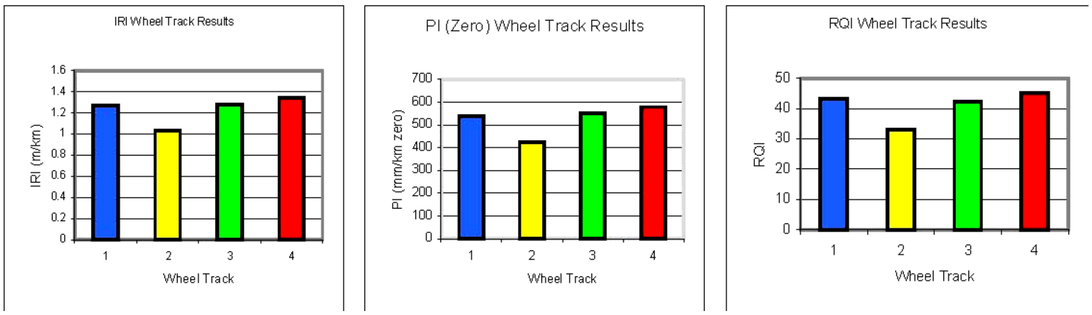


Figure 4. RTP section 1 index results

8/30/2004	PASS OUT	PASS IN	DRIVE IN	DRIVE OUT
IRI(m/km)	1.25	1.17	1.21	1.29
PI(mm/km)	555.67	485	535.33	678.33
RQI	39.07	33.44	36.71	43.77

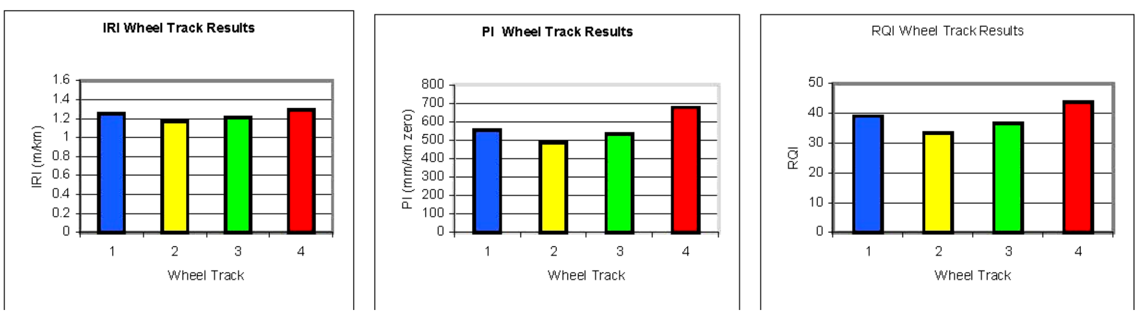


Figure 5. LISA TriODS section 1 index results

Figure 6 shows a low-resolution surface plot of roughness measured by the RTP across all four wheel tracks for nine contiguous 100-meter sections starting at station 172+30. Rougher sections are represented by darker colors, and smoother sections are represented by lighter colors. This plot gives a better representation of the roughness distribution across four pavement wheel tracks than Figure 4. Figure 7 shows the corresponding surface plot of the roughness measured by the LISA TriODS profiler.

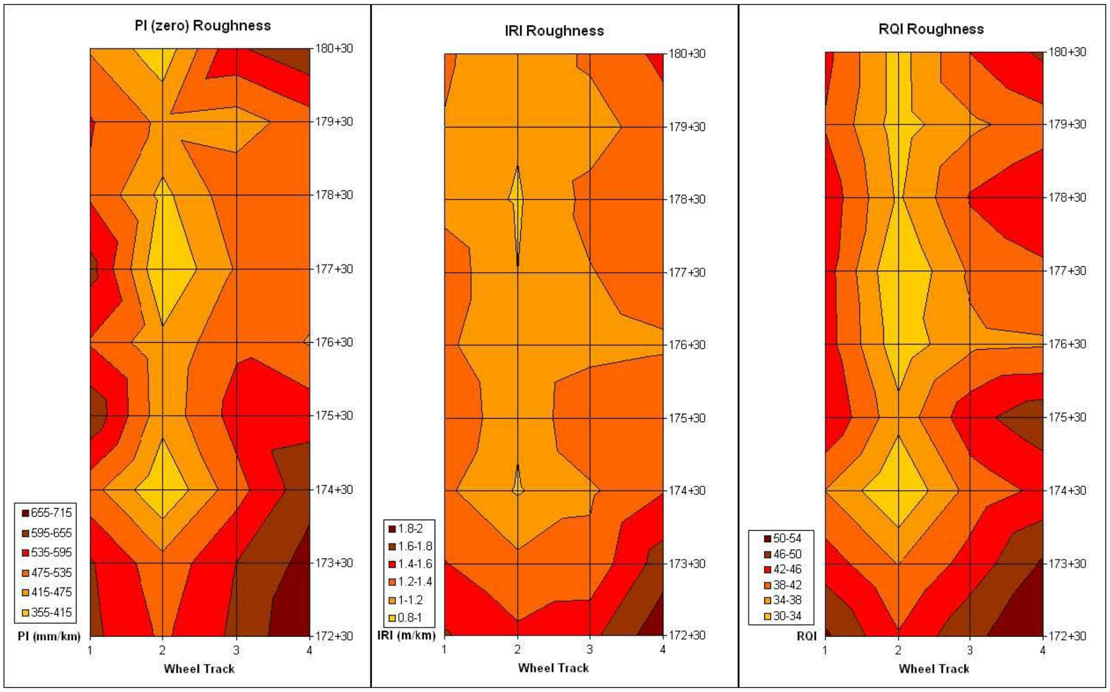


Figure 6. RTP surface roughness plots for nine 100-meter sections

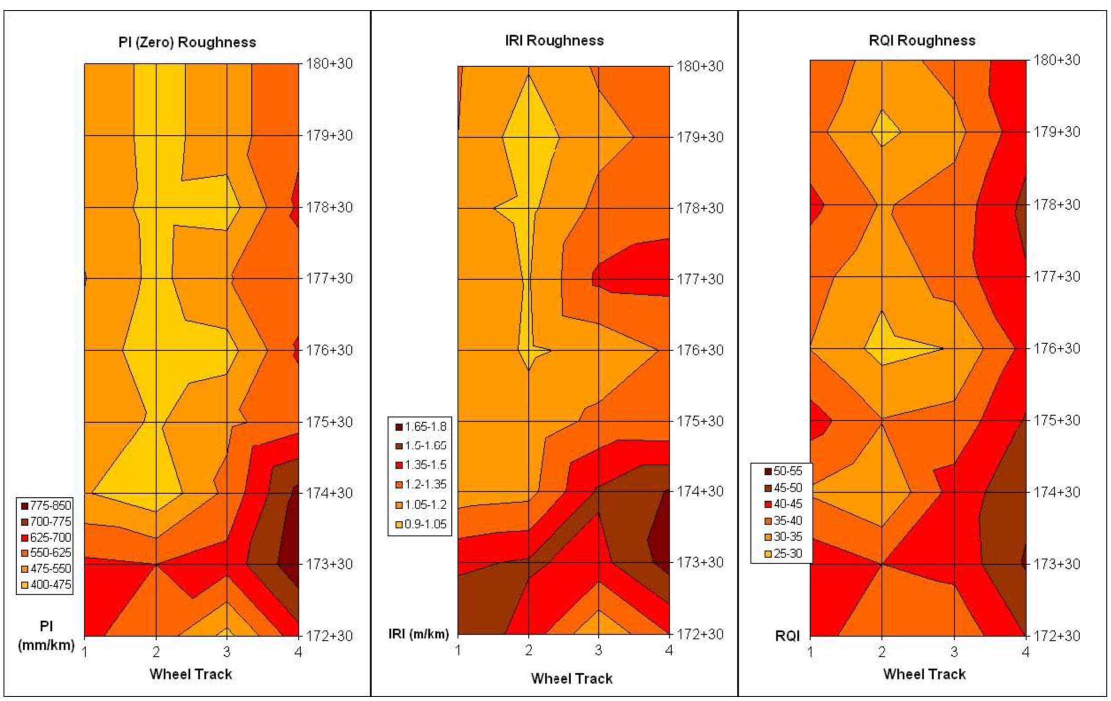


Figure 7. LISA surface roughness plots for nine 100-meter sections

Dowel Bar Ripple in RTP Wheel Track Profiles Compared

The plot in Figure 8 shows the profiles of four wheel tracks over a 100-meter section. These plots have been filtered to remove features longer than three meters to highlight the dowel bar ripple contribution to the surface roughness. The red line indicates the event marker cones that were typically placed in-line with the dowel bar baskets at an interval of every other basket, except in one case in this example where one cone was placed at an adjacent basket. The event marker cones were used to help locate the ripple in the profile caused by the dowel bar baskets. One would expect to see dowel bar ripple, if it existed, in-line with each event marker and halfway between each event marker. This effect is certainly evident in these profiles, and it could be argued that a majority of the roughness difference across the four wheel tracks is caused by the effects of the dowel bar ripple. When the ripple has a large amplitude in the outside wheel tracks one and four, the inside wheel tracks three and, to a greater extent, two usually show the same feature, but with less amplitude.

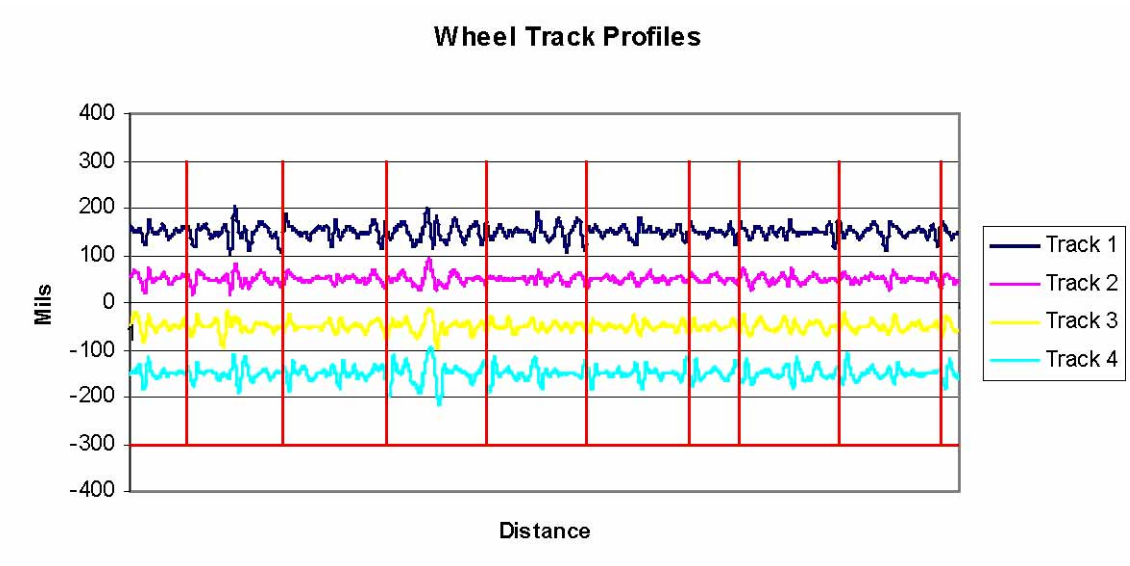


Figure 8. Dowel bar ripple plots across four wheel tracks

Comparing RTP Data Collected in the Train Configuration

The three pictures in Figure 9 show the data collected in the train configuration for the sensors mounted on the paving machine and on the curing and tining machines. Two sensors were placed on the paving machine in the passing lane inside wheel track. One sensor remained mounted to the float pan, and the other was mounted on a truss hanging out behind the paving machine to avoid the auto-float. The auto-float was not working for the first part of the testing, so burlap was attached and dragged behind the auto-float bridge. Later the auto-float was repaired and data were collected in this configuration as well. The two other sensors were mounted on the curing and tining machine in an attempt to see whether the hand finishers were making the surface any smoother.

Sensors before and after burlap drag **Sensors before and after auto-float**

Sensors mounted to texture and curing machine

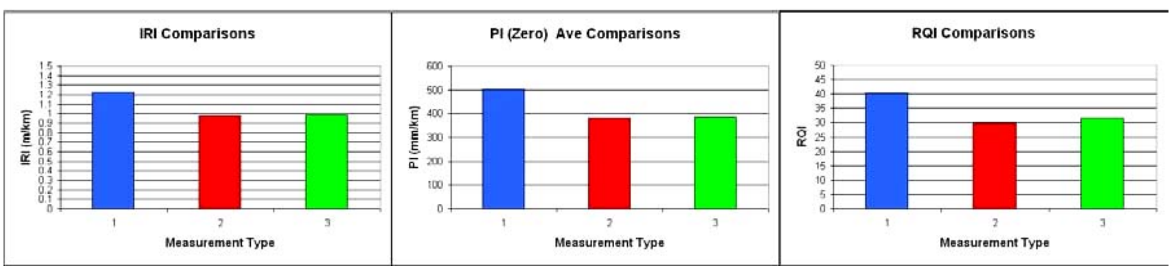
Figure 9. Train configuration for the sensors mounted on the paving machine and on the curing and tining machines

Collecting data on the curing and tining machine proved to be problematic. The first problem was that the machine would move forward and then back up before each new overlapping application. Continuous alignment of the beams is very important in a device measuring very small changes in slope, and the problem with the machine manifested itself in the appearance of false features in the profiles. An additional problem was encountered by sensor four, which was measuring the profile after the tining was applied. The tined concrete was creating a false feature due to the small footprint of the lasers used. The small footprint allowed the laser point to fall down into the one-eighth inch tine occasionally, which would cause a false feature to appear. We attempted several times to adjust the location of the laser sensor beam slightly to prevent it from falling into the tine but were unable to affect much of an improvement. Further analysis with additional filtering techniques may make some of the data gathered here useful, but no analysis of these data was done for this report. This problem could be eliminated in future studies by using a different laser with a wider footprint when collecting data in this location.

Improvement in the Index Results Due to the Auto-Float

Examining the data collected before and after the auto-float made it easy to see that the auto-float was improving the smoothness of the road. Four sections of 100 meters were analyzed. Data from the sensor before the auto-float was compared to data from the sensor after the auto-float and to the LISA TriODS data collected days later. Figure 10 shows the results of the average of the four sections. These results indicate not only that the sensor data collected after the auto-float matches very well with the LISA TriODS data, but also that the sensor data show similar improvement when compared to the float pan sensor in all three index calculations. In particular, it appears that the auto-float is removing some of the dowel bar basket ripple from the profile. This is apparent when the slope power spectral density (PSD) plots in Figures 11, 12, and 13 are examined. The dowel bar basket ripple is clearly shown by the sharp spikes that appear in the slope PSD plots at harmonics of the 20-foot spacing of the dowel bar baskets. The graph in Figure 11 shows a considerable reduction of the spikes after the auto-float is used. Figure 12 shows the PSD of the TriODS profile in red overlaid with the PSD of the auto-float sensor in blue.

Average Index	Float Pan (1)	Auto-Float (2)	LISA - TriODS (3)
IRI(m/km)	1.22	0.98	0.99
PI(mm/km)	500.75	381.75	384.5
RQI	40.32	29.73	31.58



% Improvement Compared to Float Pan Sensor			
Device	IRI	PI (Zero)	RQI
Auto-Float Sensor	19.67%	23.76%	26.26%
LISA – TriODS	18.85%	23.22%	21.68%

Figure 10. Auto-float improvements to smoothness

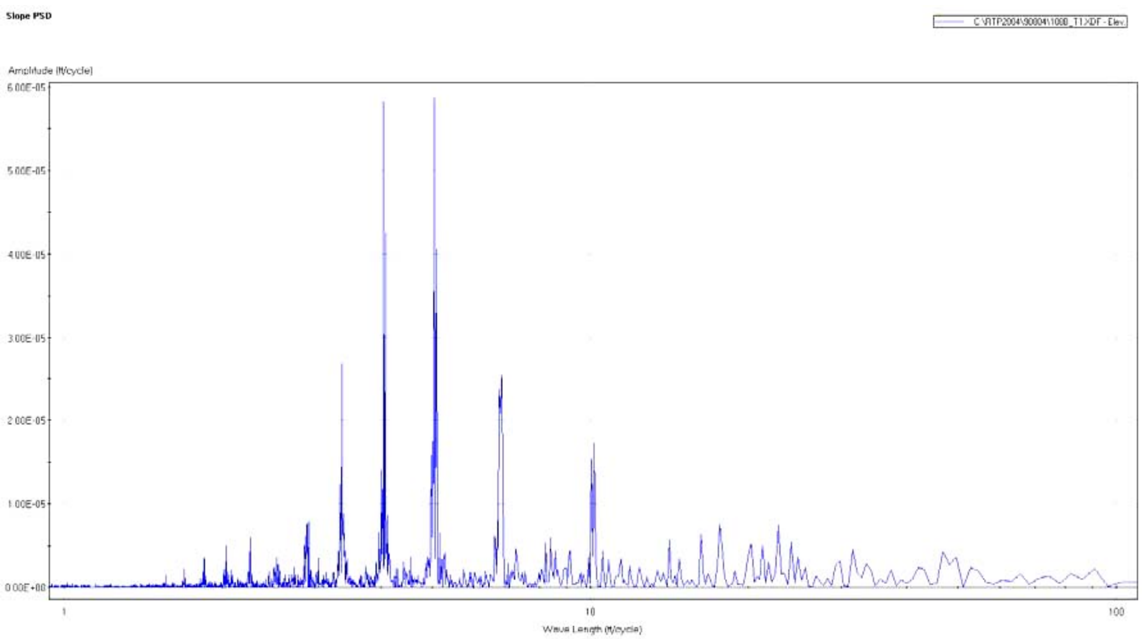


Figure 11. Slope PSD plot from float pan sensor

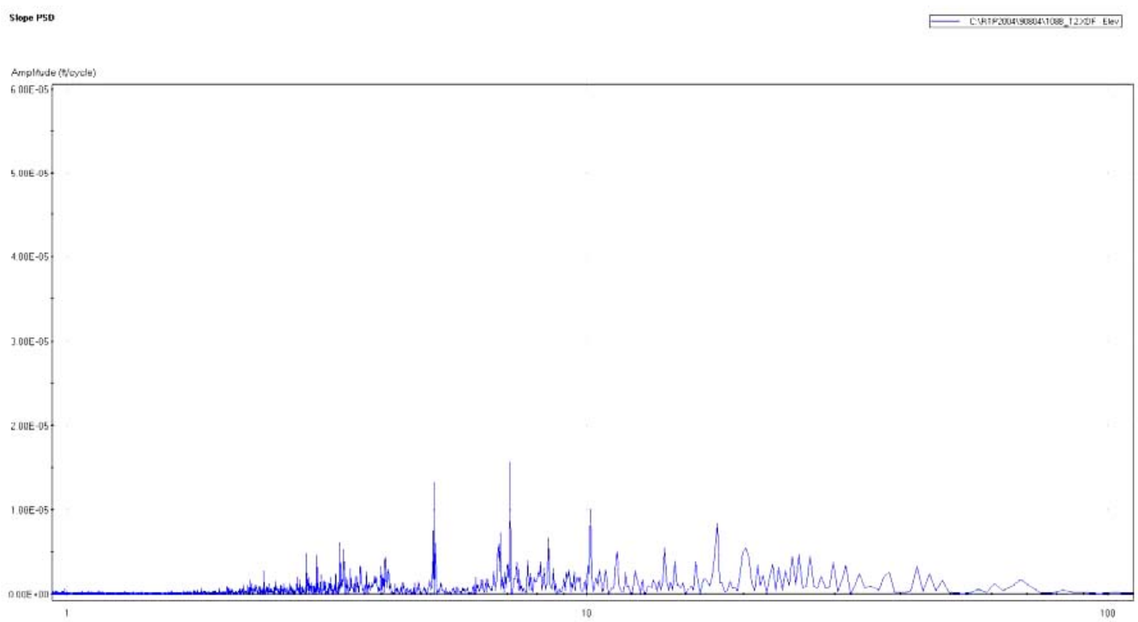


Figure 12. Slope PSD plot from auto-float sensor

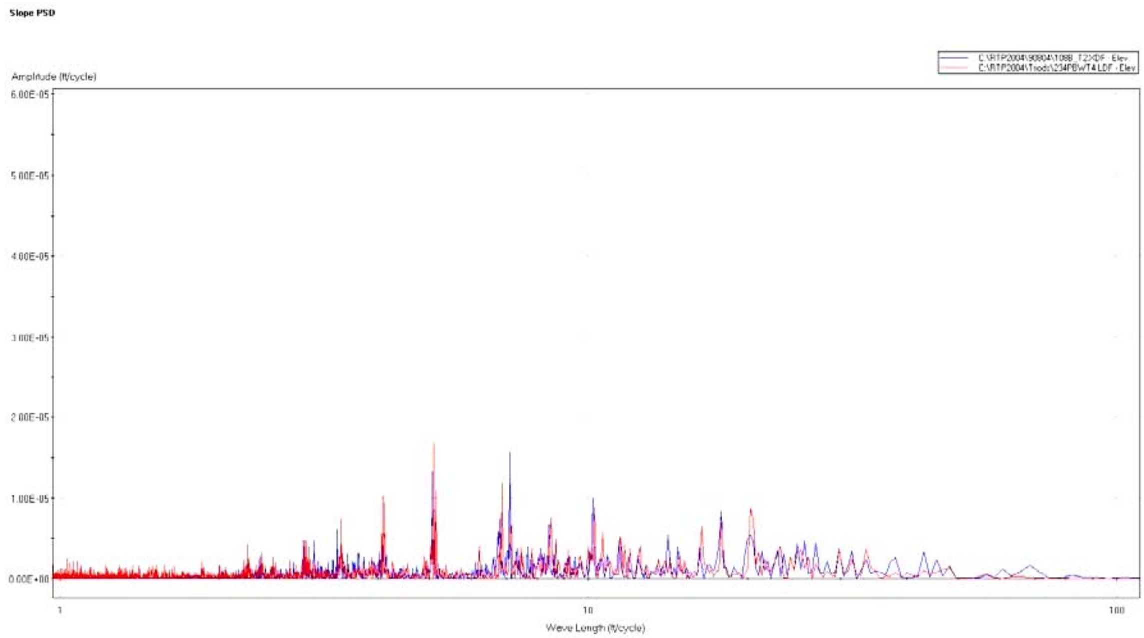
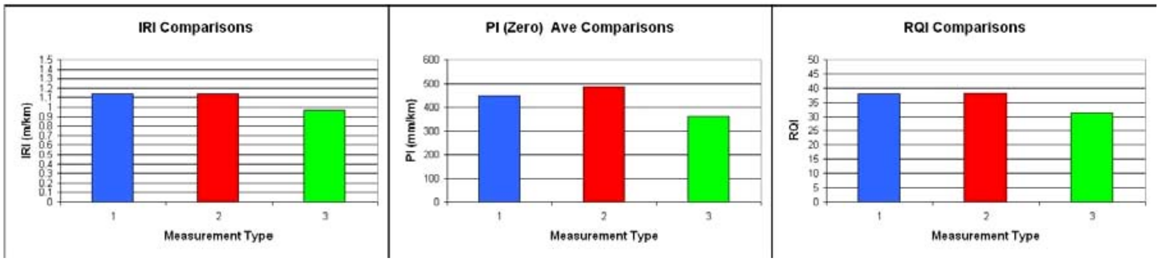


Figure 13. LISA TriODS PSD and RTP auto-float sensor PSD overlaid

Improvement in the Index Results Due to Manual Floating

The auto-float was not used during the first day of profiling performed in the train configuration, and this proved to be advantageous for reasons of comparison. By looking at the data collected while the auto-float was not in use and comparing these data to the results from the LISA TriODS data collected days later, we can conclude that any improvement in the smoothness measured by the LISA TriODS is the result of the manual float operators. Instead of the auto-float, the paving machine operators had attached a burlap drag to the auto-float structure. Figure 14 shows the results of the average of the four sections. When the data after the burlap drag is examined, a slight increase is apparent in the penetration index (PI) and RQI indexes and no change in the IRI index is noted. In comparing these data to the LISA TriODS data for this same section, a considerable increase in the smoothness is evident, but not as much as was found by the use of the auto-float. On examining all the individual sections as listed in Appendices C and D, the auto-float seems to improve results more consistently over all the sections tested.

Average Index	Float Pan (1)	Burlap (2)	LISA - TriODS (3)
IRI(m/km)	1.14	1.14	0.97
PI(mm/km)	447.75	486	360.5
RQI	38.16	38.3	31.24



% Improvement Compared to Float Pan Sensor			
Device	IRI	PI (Zero)	RQI
Burlap Sensor	0.00%	-8.54%	-0.37%
LISA - TriODS	14.91%	19.49%	18.13%

Figure 14. Average of index calculations without auto-float

RTP Conclusions

- It was shown by this testing that roughness distribution across the concrete slab is not consistent. The inside wheel tracks were significantly smoother than their corresponding outside wheel tracks. The passing lane inside wheel track was the smoothest of all the wheel tracks tested. In examining the profiles and the slope PDS plots, it appears that most of this additional roughness is the result of the dowel bar basket ripple. The outside wheel tracks have a ripple amplitude larger than that of the inside wheel tracks.
- The results of this testing conclusively showed that applying an auto-float after the float pan significantly reduces the dowel bar ripple, which is a major contributor to the roughness found in these sections of concrete pavement. It was also shown that any manual floating also improved the smoothness in the surface if an auto-float was not used. However, the improvements from manual floating were not as consistent as those shown by use of the auto-float.
- It would seem reasonable to take the conclusions of this testing a step further and assume that the design of the auto-float has never been optimized by the use of a profiling device like the RTP, and improvements could be made by trying different auto-float designs in the attempt to eliminate the roughness caused by the dowel bar basket ripple. The RTP can provide a real time method by which to test modifications to the existing auto-float design.

INDEPENDENT DATA ANALYSIS

Statistical analysis of the profiles developed at each location and with each data collection device to determine how pavement profile changes are formed and how they can be controlled is discussed later in this report. This analysis can also be used to select the optimum location and number of profile sensors to be added to the paving equipment.

U.S. Highway 30 Using GSI

U.S. Highway 30 Testing Configuration

Data were collected using GSIs during an active paving job on Highway 30 westbound from Tama to Le Grand, Iowa. The testing covered the driving and passing lanes from station 159+75 through 70+86. Data, summarized in Table 1, were collected on six days of paving. Note that the station layout is described in meters, while the length of pavement tested is expressed in feet. Two testing configurations were used.

Table 1. GSI measurement log

Date	Starting Station	Length Measured (ft)	Sensor Configuration
July 8	159+75	3,920	1
July 10	148+09	4,540	1
July 15	134+52	1,655	1
July 23	101+63	4,560	2
July 24	87+62	1,310	2
July 26	83+71	4,770	2

In configuration 1, traces were collected in all four wheel paths from sensors mounted directly to the paver just behind the pan: (1) the inside lane, outside wheel path; (2) the inside lane, inside wheel path; (3) the outside lane, inside wheel path; and (4) the outside lane, outside wheel path. Configuration 1 also included another set of sensors mounted to a special vehicle that followed the tining and curing machine. These sensors appeared in the inside lane outside, wheel path and the outside lane, inside wheel path.

In configuration 2, traces were collected in three wheel paths from sensors mounted directly to the paver just behind the pan: (1) the inside lane, outside wheel path; (2) the outside lane, inside wheel path; and (3) the outside lane, outside wheel path. Another trace was collected in the outside lane, inside wheel path, after the V-screed. Configuration 2 also included another set of sensors mounted to a special vehicle that followed the hand finishers but which preceded the tining and curing machine. These sensors appeared in the inside lane, outside wheel path and the outside lane, inside wheel path. Configuration 2 also included measurements taken a few days later (July 27 and 28) of the pavement in all four wheel paths that represent the roughness remaining after the blade and broom operation.

A lightweight inertial profiler also passed over the pavement in the outside wheel path of both lanes on July 29 before sunrise and at about noon. Thus, profile data were collected over the job at seven different stages, listed in Table 2. Table 2 assigns numbers to the stages that will appear in the summary roughness table to follow.

Table 2. Measurement stages

Stage	Description	Device
1	Behind the pan	GSI
2	After the V-screed	GSI
3	After the hand finishers	GSI
4	After the tining and curing machine	GSI
5	After the blade and broom	GSI
6	Days after the blade and broom, before sunrise	Inertial
7	Days after the blade and broom, noon	Inertial

IRI values by 528-foot lot are listed in Tables E1 through E6 in Appendix E. Note that values are only provided for complete lots, so some length at the end of each day of paving is ignored. The tables identify the lane, wheel path, paving stage, and lot for each roughness value. The most interesting data are those that correspond to several paving stages along the same wheel path of the same lane. For example, days one and two include data from the pan, after the tining and curing machine, and the hardened concrete profiles from two thermal gradient conditions for the inside lane, outside wheel path. Days eight through ten also include data from the pan, after the V-screed, after the hand finishers, and after the blade and broom operation for the outside lane, inside wheel path. Drawing from these data, the observations below cover some aspects of data quality and some aspects of pavement behavior.

U.S. Highway 30 Comparison to Inertial Profiler Data

The profiles collected with an inertial profiler on the hardened concrete did not have a strong relationship to the profiles collected during paving operations. It is possible that the dissimilar profiles reflect genuine changes in the pavement surface during each paving stage. However, it was expected that the medium and longer wavelength content (10–125 feet) would not change radically after the material was placed. The lack of a strong relationship was more likely caused by differences in the wavebands of the two types of profilers and differences in their validity.

Data from the paving operation could not be synchronized, either visually or through automated correlation, to the hardened concrete data. Therefore, roughness values from the hardened concrete profiles were associated with roughness values from the paving operation using the starting station of the measurement and travel distance.

Unfortunately, the longitudinal distance measurements made by the inertial profiler appeared to underestimate distance by more than 3% when compared to the profiles from the paving operation. (This was estimated based on the shift in the location of peaks within the PSD plot caused by periodic roughness associated with dowel basket spacing.) The error is attributed to operator calibration in this case. When properly calibrated for tire pressure and ambient air temperature, the LISA distance-measuring instrument is typically accurate to less than 1%. As such, roughness data from the inertial profiler were only compared to data from the paving operation for the first two days of paving, where the absolute longitudinal shift between the devices was small. Further data were excluded from the inertial profiler if a leave-out was found within a given lot. A leave-out is a sudden change in elevation found within a profile when the profiler was not operating over some distance. (This is often requested by the operator over a bridge.)

This particular study did not compare IRIs from the GSI or RTP on plastic concrete behind the paving train to the hardened concrete IRI.

U.S. Highway 30 Short Wavelength Profile Measurement

All of the profile data from the GSI units contain elevated content in the wavelength range near three feet. This was sometimes evident when viewing filtered profiles, but was always obvious in the PSD plots. The IRI is somewhat sensitive to roughness with a wavelength near three feet, so it is expected that the IRI values in Tables E1 through E6 in Appendix E are influenced by this extraneous profile content. Note that the hardened concrete profiles showed no evidence of this type of roughness.

U.S. Highway 30 Dowel Bar Ripple

During the first three days of paving, the trace from the inside lane, inside wheel path that was collected at the paver appeared to be much rougher than the traces in the other three wheel paths. Tables E1 through E3 in Appendix E show that the IRI values were much higher in the inside lane, inside wheel path than in the other wheel paths and were often significantly higher than 100 in./mi. (Values much higher than 100 in./mi often prompt a requirement of corrective action or a penalty to the contractor.) The elevated roughness is caused by disturbances covering about 5 feet of pavement that appear every 20 feet. The peak-to-trough elevation difference across these disturbances is typically about 0.25 inches. Figure 15 shows an example of three of these bumps. The same features appear in the traces from the other three wheel paths, but with less than half the severity.

Data collected on the hardened concrete by an inertial profiler also include disturbances at a regular spacing of 20 feet. Figure 16 shows an example from the inside lane, outside wheel path. It is suspected that these dips actually appear at the joints as a result of dowel basket ripple.

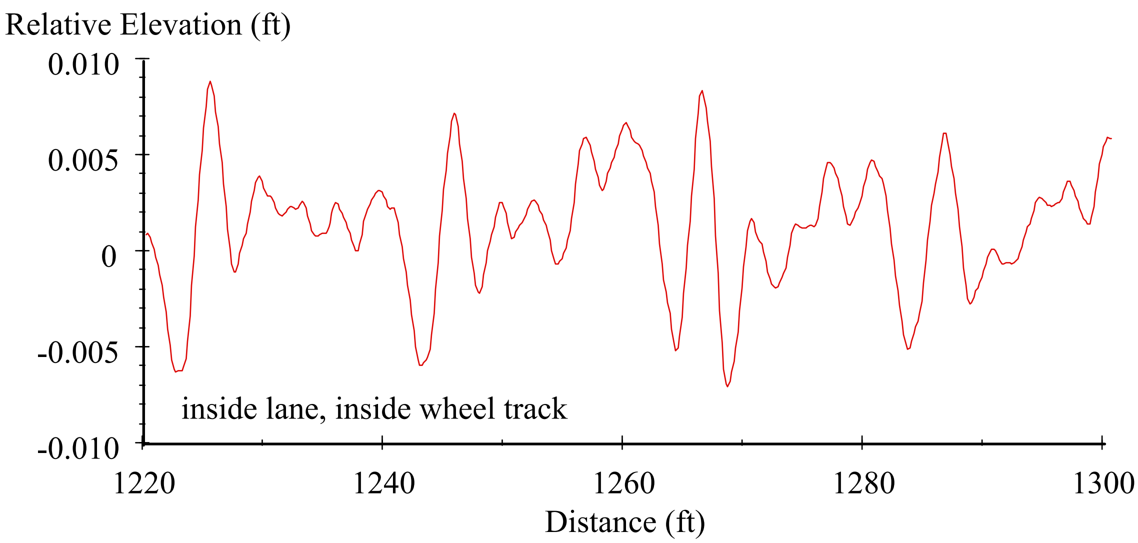


Figure 15. Disturbances spaced 20 feet apart

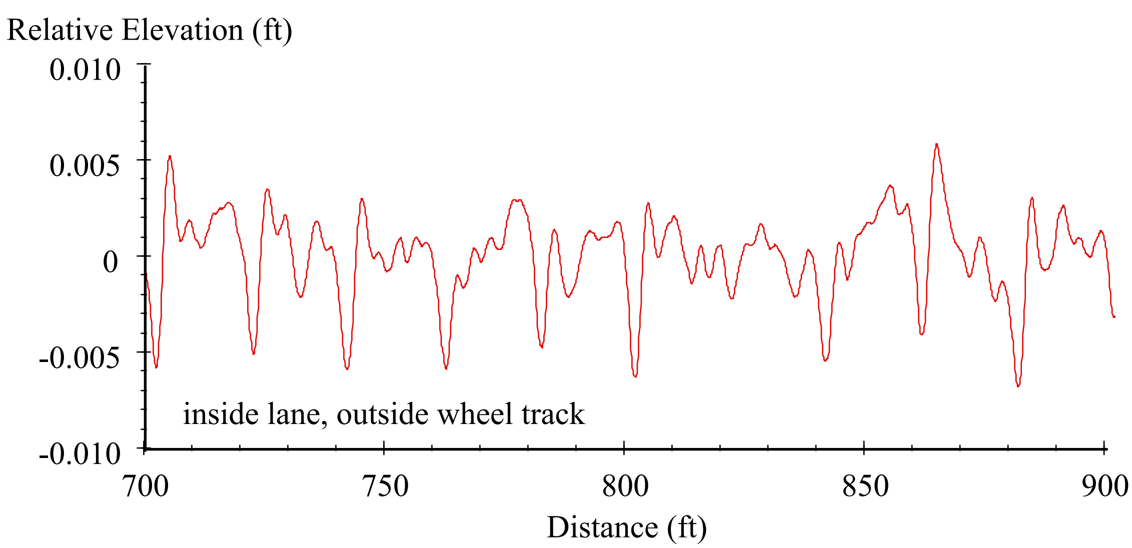


Figure 16. Dowel basket ripple

U.S. Highway 30 Roughness Trends

Data were collected on the hardened concrete before sunrise and at about noon on the same day. The roughness values from these data, listed in Tables E1 and E2 in Appendix E, did not exhibit changes that could be attributed to diurnal changes in profile. The roughness values were very similar in most of the lots listed. An exception was lot five of day two, measured in the outside lane, outside wheel path. On this segment, localized roughness that was more severe before sunrise than at noon appeared every 20 feet. This change in roughness caused a difference in IRI of about 15 in./mi. Note that lot six from these traces was rough at both times of day during which roughness was measured. This roughness was caused by two bumps that stood out as much rougher than the rest of the profile.

To characterize the first three days of paving, pairs of profiles were available from behind the pan (stage one) and after the tining and curing machine (stage four) for the inside lane, outside wheel path and the outside lane, inside wheel path. On day one and day three of paving, the roughness at stage four was lower than the roughness at stage one in a great majority of the lots tested. (See Tables E1 and E3 in Appendix E.) Inspection of filtered profile plots and continuous roughness plots showed that the improvement on day one came almost exclusively from the elimination of localized rough features that appeared with a regular spacing of 20 feet. Figure 17 shows a continuous report of roughness with a base length of 5.28 feet. In the plot, each point represents the portion of the IRI that was accumulated within a 5.28-foot-long segment of road, centered at that location. The trace for stage one includes concentrated roughness every 20 feet, but the trace for stage four does not. If the source of the roughness was dowel bar ripple, it was eliminated between these two stages. Note that the hand finishing operation was performed between stage one and stage four.

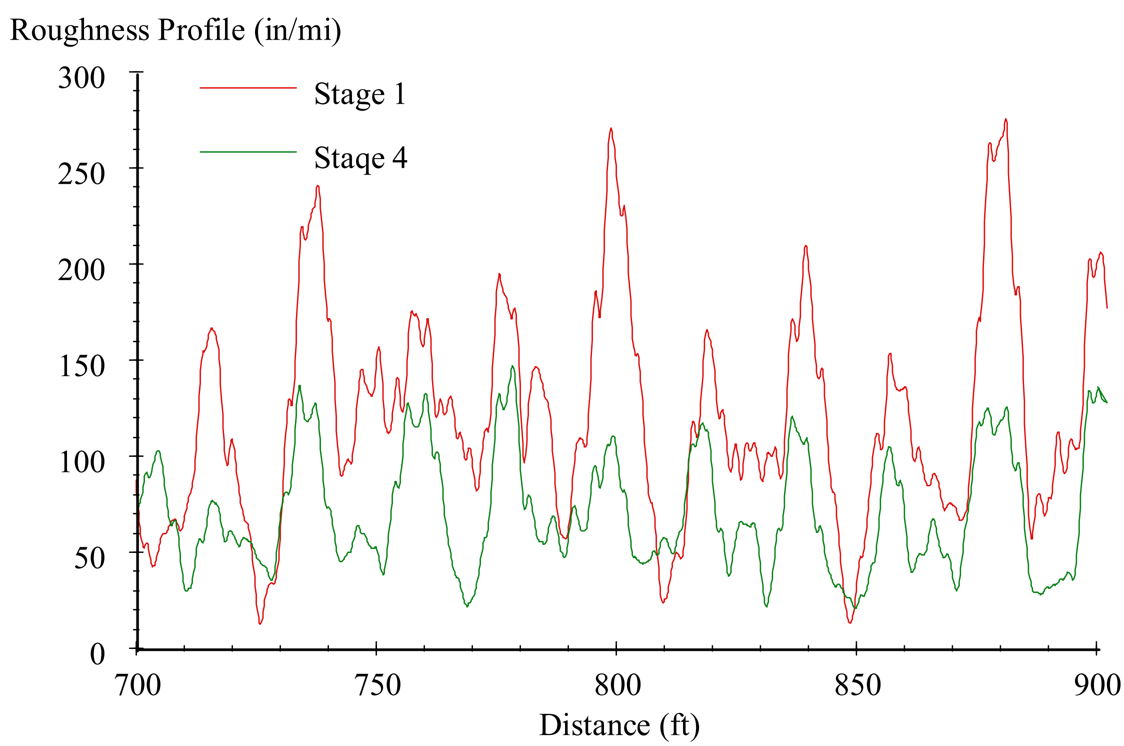


Figure 17. Reduction in roughness by hand finishing

Day two presents a contrasting case, in which many of the lots became rougher between stage one and stage four. Although the roughness with a characteristic wavelength was improved significantly between stage one and stage four on day two as well as on day one, the extraneous content with a wavelength of three feet became much worse. This extraneous content overwhelmed the improvement of the IRI.

On days eight through ten, one of the profile measurement devices was placed behind the V-screed (stage two) in the outside lane, inside wheel path. On days nine and ten, the IRI after the V-screed was always lower than the IRI measured at the pan. This could not be linked to any systematic changes in the profile.

On days eight through ten, profile was also measured behind the hand finishing operation in the outside lane, inside wheel path and the inside lane, outside wheel path. For the outside lane, inside wheel path, the IRI values were frequently lower after the hand finishing than at the pan. For the inside lane, outside wheel path, the IRI values were frequently higher after the hand finishing than at the pan. Note also that the roughness of the outside lane, inside wheel path was nearly always reduced between stages two and three, which included only the hand finishing operation. (See Tables E4 through E6 in Appendix E.) Most of this effect is due to a reduction in localized roughness that appeared with a regular spacing over 20 feet, which may have been dowel bar ripple. Although this effect could only be observed in one wheel path, the difference in roughness was significant in many of the lots.

Days eight through ten also included measurements of all four wheel paths after the blade and broom operation (stage five). No significant trend in roughness was found when the profiles of stage five were compared to those of stage three. (The roughness decreased, increased, and changed very little in nearly the same number of cases.)

U.S. Highway 34 Using Ames Engineering RTP

U.S. Highway 34 at Lockridge

Data were collected using Ames Engineering RTPs during an active paving job on U.S. 34 Eastbound at Lockridge. The testing covered the driving and passing lanes from station 164+70 through 235+50. Data, summarized in Table 3, were collected on seven days of paving. Note that the station layout is described in meters, while the length of pavement tested is expressed in feet. Two testing configurations were used. First, in the *side-by-side* configuration, four sets of RTP sensors were attached to the float pan. One set was placed in each of four wheel paths. Second, all sets of RTP sensors were placed in the inside wheel path of the passing lane, each at a different stage of the paving process. For example, starting on September 7 sensors were attached (1) to the float pan, (2) to the paving machine, but on a truss extended behind the automated float, (3) to the leading side of the curing and tining machine, and (4) to the trailing side of the curing and tining machine. This is called the *train* configuration.

Table 3. RTP measurement log

Date	Starting station	Length measured (ft)	Sensor configuration
August 23	164+70	800	Side-by-side
August 30	168+30	1,200	Side-by-side
August 31	172+30	3,220	Side-by-side
September 1	183+60	2,320	Side-by-side
September 7	208+10	2,350	Train
September 8	216+00	3,330	Train
September 9	226+50	2,980	Train

The profile of the hardened pavement was measured using an Ames LISA with TriODS height sensors less than a week after the completion of the paving. The LISA is a lightweight inertial profiler operated by the Iowa DOT. These profile measurements covered all four wheel paths in the range of pavement from 160+07 through 191+00 and from 194+91 though 230+09.

The side-by-side configuration provided a means of detecting rough features built directly into the pavement at the time of placement. Further, it was possible to provide examples of the shapes of these features as well as an estimate of the penalty to the overall smoothness. In turn, the hardened concrete profiles provided a way of verifying that these rough features actually appeared on the finished pavement. Two important sources of roughness that were found are dowel bar ripple and a broken string line.

The train configuration provided a way of studying the impact of various stages of the paving process. The measurements performed on September 8 and 9 provided examples of the as-placed smoothness of the pavement, as well as the effect of the auto-float and the tining and curing operation. On September 7, the auto-float was not working, so a burlap drag was attached to the auto-float truss.

US Highway 34 Dowel Bar Ripple

When a paving machine passes over a dowel basket, the machine exerts significant downward pressure on it. Often, this compresses the basket into the foundation that supports it. When the paving machine moves beyond the basket and the pressure is relieved, the basket will rebound. If the rebound is significant, the concrete above the basket will protrude above the intended surface level. The result is a bump in the pavement that occurs near each joint. This is called *dowel bar ripple*.

The RTP detected dowel bar ripple consistently over the entire paving job. Figure 18 shows the effect that dowel bar ripple has on the surface profile. The figure shows profiles from both wheel tracks of the driving lane, measured on August 23. The traces were conditioned with a moving average anti-smoothing filter with a base length of ten feet to help make short deviations more visible. Note that the distance axis simply provides the distance from the start of the measurement. Roughly, the plot covers station 165+26 though 165+87.

Every 20 feet, a disturbance appears in both profiles. Since this pavement includes joints that are skewed by a ratio of 6:1, the bumps from the outside wheel path lag those of the inside wheel path by about one foot. In fact, the bumps from the driving lane outside wheel path consistently lag those of the passing lane outside wheel path by about three feet as well. On September 7, the measurements included event markers placed at the longitudinal location of every other dowel basket beside the passing lane. These markers helped verify that the bumps were indeed near the dowel baskets.

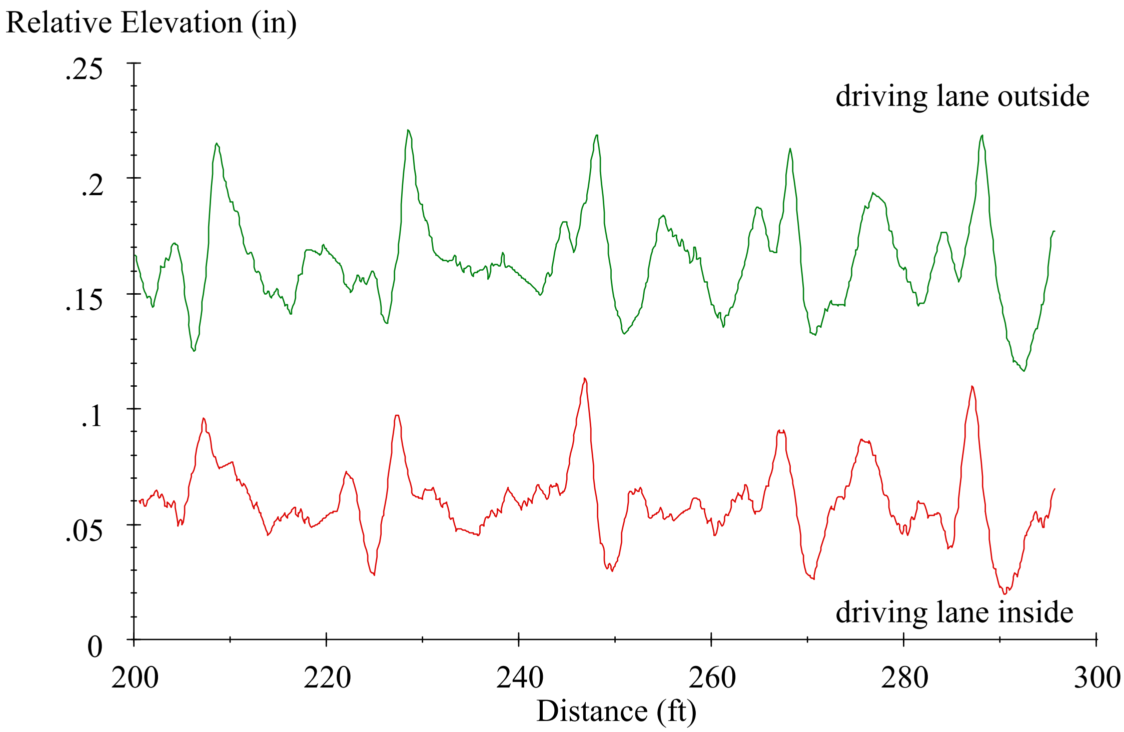


Figure 18. Dowel bar ripple

These ripples certainly increase the PI significantly when no blanking band is applied. Figure 19 shows a simulated profilograph trace in the passing lane, outside wheel path over three of the joints with clear dowel basket ripple. The approximate dowel basket locations are marked. Under a zero blanking band, the ripple causes an upward scallop at the dowel basket, and exacerbates downward scallops on either side. (Keep in mind that some of these downward scallops will not increase the PI, because typical counting schemes require scallops to be at least two feet wide before they are counted.) The upward scallops at the first two dowel baskets in Figure 19 are 0.050 inches and 0.067 inches high. These alone penalize the overall PI for a one-tenth of a mile lot by 0.50 and 0.67 inches/mile, respectively. The overall PI for this wheel path, under a zero blanking band, was about 38 inches/mile. More than a third of this can be attributed directly to the ripple.

Alone, dowel bar ripple does not cause bumps or dips high enough to penalize the PI with a 0.2-inch blanking band. For example, none of the simulated profilograph traces in Figure 19 exceeds an absolute value of 0.1 inches. However, when the bumps are superimposed on other sources of roughness, they increase the size of scallops.

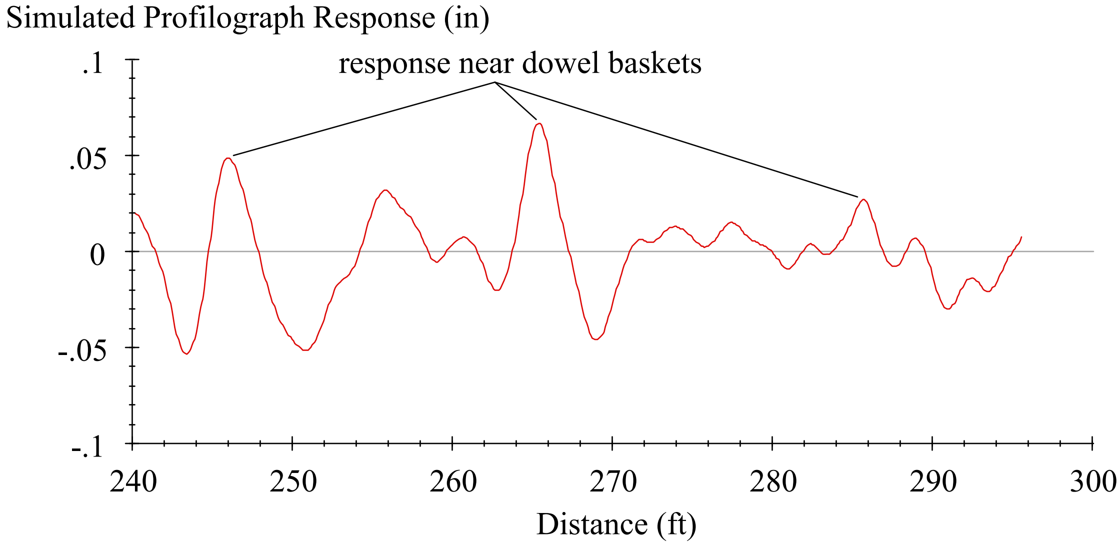


Figure 19. Simulated profilograph trace, passing lane outside trace

Dowel bar ripple also increases the IRI of the pavement. Figure 20 shows a continuous report of roughness for the driving lane outside wheel path with a base length of 5.28 feet (Michael W. Sayers, 1990). In the plot, each point represents the portion of the IRI that was accumulated within a 5.28-foot long segment of road, centered at that location. The plot is scaled so that the average of all of the values is the IRI for the overall length of the plot. This technique is used to search the pavement for hot spots and to help get an idea of the contribution of a given disturbance to the overall IRI. Figure 20 shows a local peak in roughness near each joint. This indicates that the IRI judges the bumps caused by dowel bar ripple to be concentrated roughness. The continuous report of roughness shows peak values from 106 to 158 inches/mile at the dowel baskets. The values are the average over 1% of a one-tenth of a mile-long segment. That means that the roughness in the vicinity of the dowel baskets contributed from 1.06 to 1.58 inches/mile per joint.

The penalty to smoothness caused by dowel basket ripple is only important if it appears on the finished pavement. Figure 21 compares the profile of the driving lane outside wheel path measured by the RTP to a profile measurement taken on the hardened surface with a lightweight inertial profiler. Again, the traces have been filtered to show only short wavelength roughness. The traces are very similar. This similarity verifies that dowel basket ripple does indeed appear on the finished pavement. Further, it confirms the credibility of the RTP's measurement of this type of feature. (Note that the RTP does not measure wavelengths greater than 50 feet. As a result, the raw output from the RTP and the lightweight inertial profiler would not have the same visual agreement as the traces in Figure 21.)

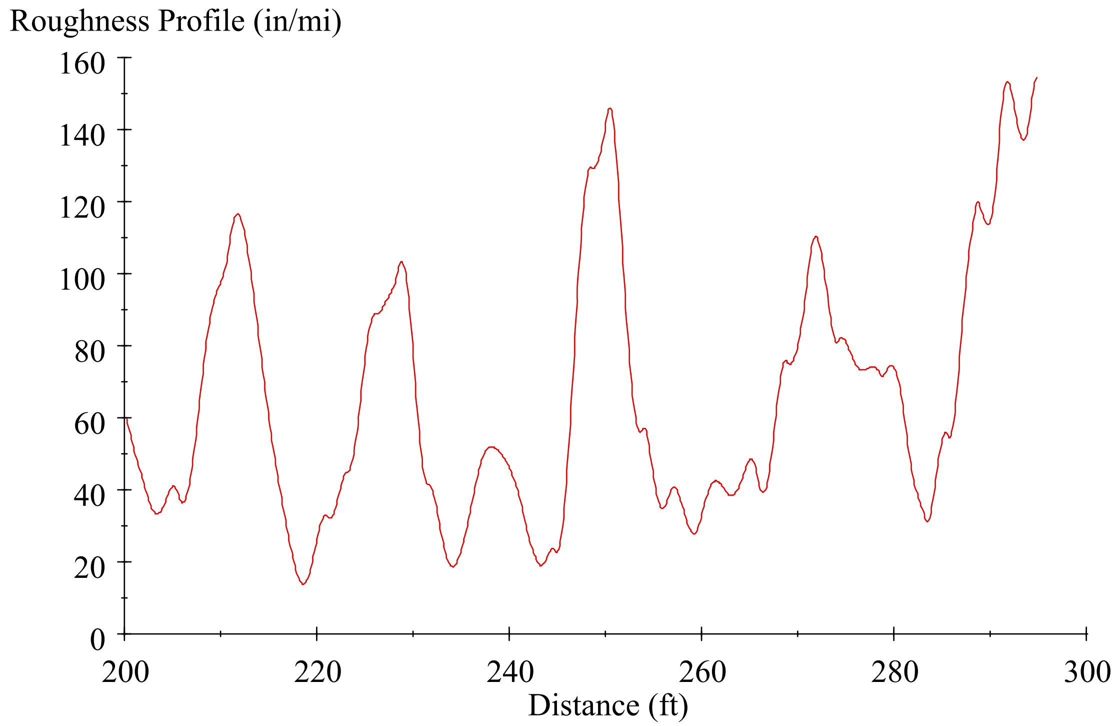


Figure 20. Continuous roughness report, driving lane inside track

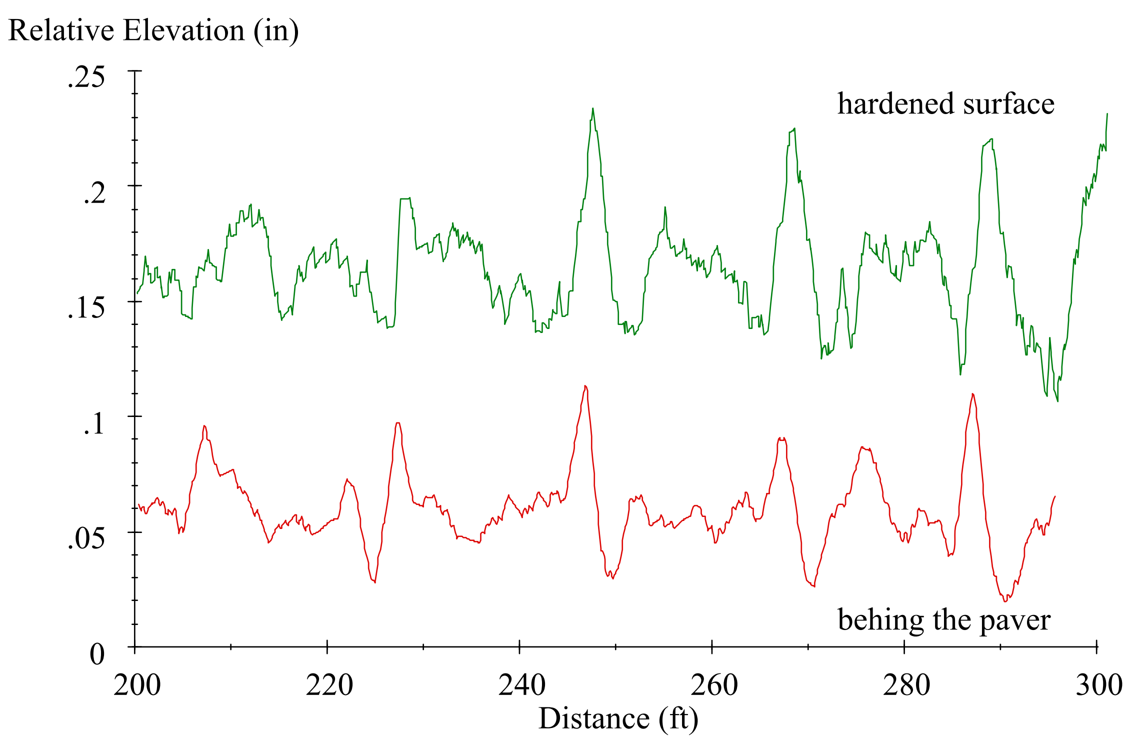


Figure 21. Change in the profile with time

U.S. Highway 34 Broken String Line

The field notes from August 31 reported that about 200 feet into the run, the string line broke on the passing lane side. Figure 22 shows the profile from all four wheel paths around this location. The traces were conditioned with a moving average anti-smoothing filter with a base length of 25 feet to remove the trend. They were also offset vertically from each other to help make a clearer comparison among them. Near the 200-foot mark, a deep narrow dip appears. Since the string line was broken on the passing lane side, the dip is most severe in the passing lane outside wheel path. In all of the wheel paths, the dip is followed by a broad area of pavement that is elevated above the overall trend. The field notes did not describe what method was used to deal with the broken line, or how quickly it was addressed.

The roughness added to the pavement by the broken string line is sure to degrade the ride quality. Ironically, however, the dip is so narrow that it may be ignored by a profilograph if a 0.2-inch blanking band is applied. This is because scallops in a profilograph trace are typically not counted unless they violate the blanking band limits for a distance of more than two feet. Figure 22 shows that the dips are narrower than two feet through about half of their depth.

Figure 23 shows a continuous roughness report for the vicinity of the rough area in the passing lane outside wheel path. The plot was developed with a base length of 5.28 feet. The peak roughness near the broken string line is about 400 inches/mile higher than the prevailing trend. This suggests that the broken string line increased the roughness of a one-tenth of a mile lot by four in./mi. Inspection of the profile measured after the concrete hardened also included elevated roughness at this location, but not as severe.

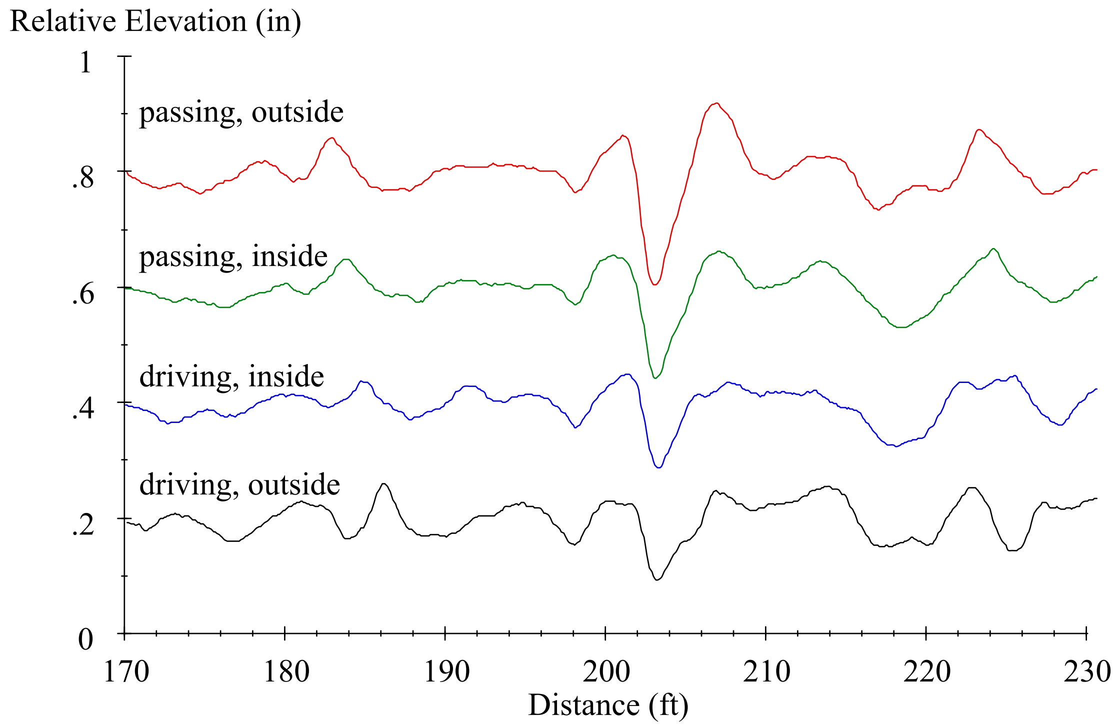


Figure 22. Dips caused by a broken string line

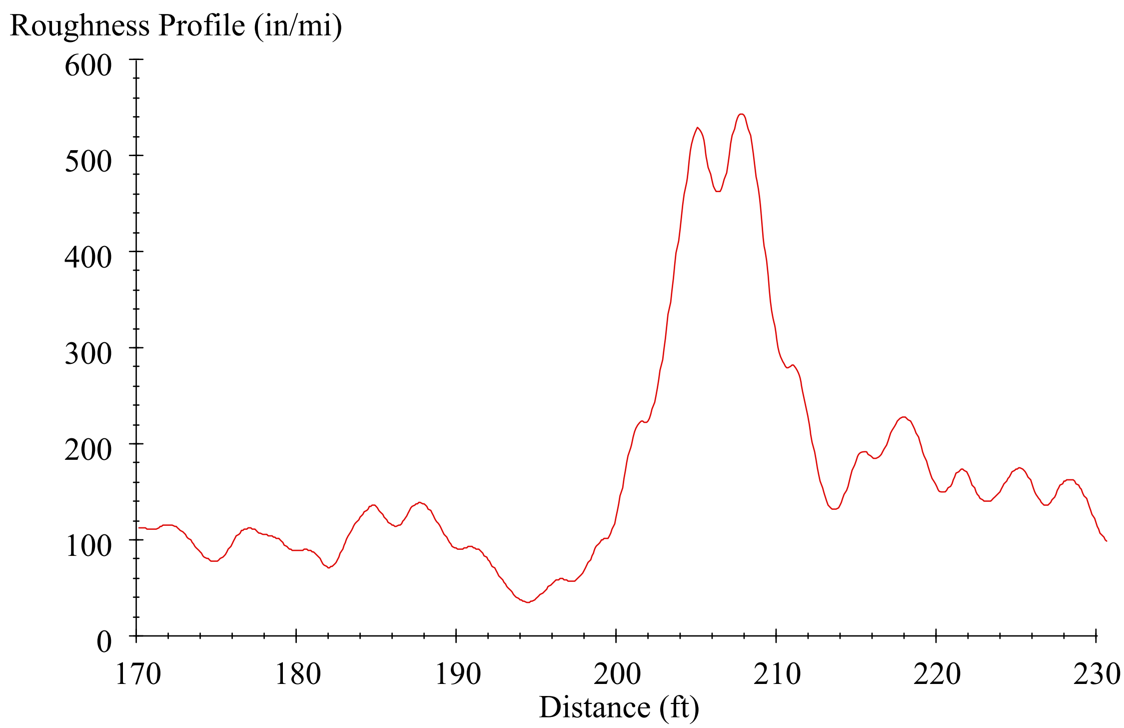


Figure 23. Roughness caused by a broken string line

U.S. Highway 34 Burlap Drag and Tining

On September 7, profile data were collected in a train configuration along the inside wheel path of the passing lane. This included a measurement of a profile directly behind the paving machine and another measurement just after a burlap drag. Two other profiles were measured along the same train, one just before the tining and curing machine and one just after. An inspection of filtered profile plots and power spectral density plots showed that all four measurements were very similar in the wavelength range below 20 feet. The profiles did not agree well for wavelengths above 20 feet, but this discrepancy is attributed to the waveband of the profiler, rather than to the effect of paving operations.

The burlap drag and tining operations are intended to add macrotexture to the pavement surface. It is possible that either of these operations also added megatexture and very short wavelength roughness to the pavement. However, the RTP does not detect roughness below a wavelength of 0.5 feet. As such, the impact of these paving operations on megatexture could not be quantified.

Some portions of the measurements from the RTP on September 7 were contaminated by false readings, which the operators reported in the field notes. When these sections were removed, profiles from each stage of the paving train agreed exceptionally well with the profiles measured by the inertial profiler (several days after paving) in the wavelength range from 4 to 20 feet. (Most of the roughness in this wavelength range was caused by dowel bar ripple.) Below a wavelength of four feet, the RTP sensed less roughness than the inertial profiler. It is likely that this is caused by the filtering properties inherent in the sensor arrangement of the RTP. Wavelengths below 0.5 feet are also removed by filters within the instrumentation of the RTP.

U.S. Highway 34 Auto-float

On September 9, profile data were collected in a train configuration along the inside wheel path of the passing lane. These data included a measurement of the profile directly behind the paving machine and another measurement just after application of an auto-float. The auto-float diminished the roughness caused by dowel bar ripple significantly. Figure 24 shows a portion of the profile before and after the auto-float. Before application of the auto-float, severe instances of dowel bar ripple appear in a regular pattern (every 20 feet). Afterward, the roughness near most of the dowel baskets is reduced or eliminated. Over the 2,980 feet of pavement measured on that day, the auto-float reduced the IRI by 11 inches/mile. The PI, with no blanking band applied, was reduced by 6.5 inches/mile.

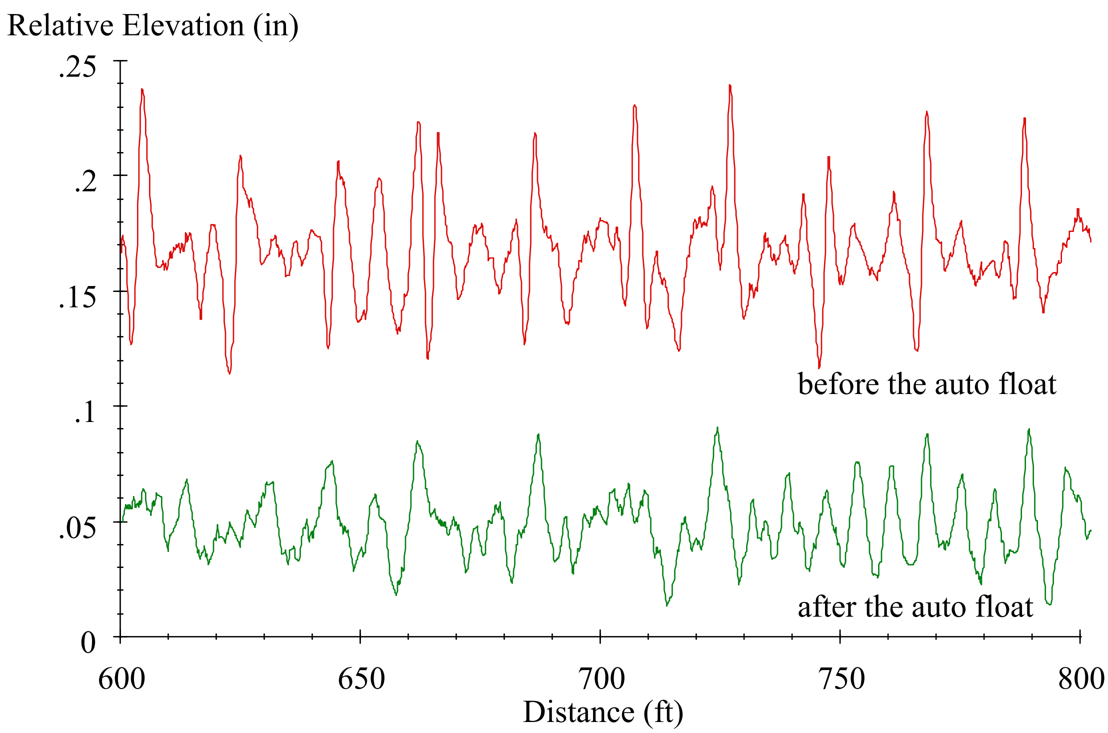


Figure 24. Change in profile caused by the auto-float

CONSTRUCTION APPLICATION GUIDELINES

The goal of using devices such as the Ames Engineering RTP and the GOMACO GSI profile measuring equipment is to improve the profile of the finished portland cement concrete surface.

The following construction guidelines are provided:

1. Due to the number of operations in the slip-form paving train and the concrete hydration/curing process, it is not possible at this time to accurately estimate the hardened concrete profile values in the plastic concrete.
2. The devices evaluated in this research can accurately measure profile on the plastic concrete surface to isolate problems created by the various operations in the paving train.
   a. Placement of the sensors over the wheel paths or quarter points of the pavement can assist the user in developing a profile in the same location that will be measured in the hardened concrete. It can also point out the impact of adjacent haul road conditions, string-line tension, dowel baskets, and mechanical problems in the slip-form paver operation.
   b. Placement of the sensors in a chain throughout the paving train in either a wheel path or quarter point can be used to identify the sources and reduce pavement roughness caused by various pieces of equipment or humans in the paving train operations. This includes the slip-form paving machine, mechanical floats, human floating operations, and the cure/tining machine.
   c. This equipment can be used at the slip-form paver and behind the cure/tining machine to determine the need for an additional operation to remove surface irregularities created by the aggregates and surface texturing that increase profile values.
3. Both devices tested can be used to measure the top of the base materials in front of the slip-form paver and the top of the finished concrete surface behind the paving operation to evaluate pavement thickness. This can reduce or eliminate the need for quality assurance coring for pavement depth.
4. Each device can be referenced to longitudinal stationing for referencing surface imperfections for modification of the profile in the plastic or hardened concrete state.
5. Follow manufacturer guidelines on height of each sensor above the pavement surface during measurements:
   a. The RTP has a defined focal length range that affects the results accuracy.
   b. The GSI device has an operating range distance from the pavement surface that aids in eliminating wind effects on the output.
6. When either of the devices is employed in the slip-form paving train, shrouds should be placed around the sensors to prevent concrete and curing material splatter from damaging the sensors or adversely impacting the profile measurements.
7. The RTP and GSI sensors can be mounted on any portion of the paving train (slip-form paver, mechanical floats, cure carts, or bridges) to assist in profile measurement and evaluation.

8. Specialized knowledge in electronics and profile interpretation is recommended for those operating these devices.
9. Both devices can be operated in conjunction with all brands of equipment employed in the paving train.

CONCLUSIONS

- The profilers used in this study were not able to produce the same absolute IRI in the plastic concrete as values measured by inertial profilers after paving. As such, they are not able to predict the roughness values that will be measured in a smoothness incentive program. However, both profilers demonstrated the ability to detect roughness that appears in the final profile, such as localized roughness and roughness at joints.
- Both paving jobs covered by this study exhibited clear evidence of dowel basket ripple. At both jobs, the profiler was able to detect dowel basket ripple with enough clarity to justify a warning to the paving crew. Dowel basket ripple was also found to be a significant source of pavement surface roughness.
- String line disturbances were found to degrade smoothness. An example of a string line disturbance was successfully detected by a profiler during paving operations.
- Either of the profiling devices examined in this project demonstrated potential as a real-time warning system for surface roughness problems.
- Both devices demonstrated erroneous content in some instances. An automated warning system is recommended to help detect obvious measurement problems.
- The GSI was found to include extraneous content in its measurements with a wavelength near three feet. (This has been corrected since this evaluation, by way of a software change.)
- The RTP showed a clear relationship to the measurements of an inertial profiler taken after paving was completed. Although the inertial profiler is a different type than the RTP, it should be noted that the inertial profiler was built by the same manufacturer.

APPENDIX A: RPT ROUGHNESS ACROSS FOUR WHEEL TRACKS—U.S. HIGHWAY 34

Section 1

8/30/2004	PASS OUT	PASS IN	DRIVE IN	DRIVE OUT
IRI (m/km)	1.27	1.03	1.28	1.34
PI (mm/km)	538.33	424.67	552	578.67
RQI	43.11	33.04	42.25	45.27

Section 2

8/31/2004	PASS OUT	PASS IN	DRIVE IN	DRIVE OUT
IRI (m/km)	1.43	1.22	1.33	1.68
PI (mm/km)	570	460.33	572.33	676
RQI	44.25	35.47	44.12	48.72

Section 3

8/31/2004	PASS OUT	PASS IN	DRIVE IN	DRIVE OUT
IRI (m/km)	1.31	1.01	1.23	1.29
PI (mm/km)	595.67	408.67	522	518.33
RQI	44.59	31.83	40.15	42.43

Section 4

8/31/2004	PASS OUT	PASS IN	DRIVE IN	DRIVE OUT
IRI (m/km)	1.18	1.01	1.21	1.37
PI (mm/km)	512	412	516	556.67
RQI	43.23	32.61	40.54	44.25

APPENDIX B: LISA TRIODS ROUGHNESS ACROSS FOUR WHEEL TRACKS—U.S. HIGHWAY 34

Section 1

8/30/2004	PASS OUT	PASS IN	DRIVE IN	DRIVE OUT
IRI (m/km)	1.25	1.17	1.21	1.29
PI (mm/km)	555.67	485	535.33	678.33
RQI	39.07	33.44	36.71	43.77

Section 2

8/31/2004	PASS OUT	PASS IN	DRIVE IN	DRIVE OUT
IRI (m/km)	1.41	1.37	1.35	1.57
PI (mm/km)	586.33	546	558	765
RQI	40.14	35.19	39.92	48.13

Section 3

8/31/2004	PASS OUT	PASS IN	DRIVE IN	DRIVE OUT
IRI (m/km)	1.16	1.06	1.24	1.28
PI (mm/km)	534.33	448.67	508	607.33
RQI	37.97	31.65	34.92	43.92

Section 4

8/31/2004	PASS OUT	PASS IN	DRIVE IN	DRIVE OUT
IRI (m/km)	1.16	1.01	1.2	1.28
PI (mm/km)	527	443.33	495.33	672.67
RQI	39.11	31.98	35.87	44.11

APPENDIX C: ROUGHNESS MEASUREMENTS WITH AUTO-FLOAT OPERATIONAL—U.S. HIGHWAY 34

Section 1			
Index	Float Pan (1)	Auto-Float (2)	LISA - TriODS (3)
IRI(m/km)	1.23	0.98	0.95
PI(mm/km)	526	344	349
RQI	40.56	28.42	33.63

% Improvement Compared to Float Pan Sensor			
Device	IRI	PI (Zero)	RQI
Auto-Float Sensor	20.33%	34.60%	29.93%
LISA - TriODS	22.76%	33.65%	17.09%

Section 2			
Index	Float Pan (1)	Auto-Float (2)	LISA - TriODS (3)
IRI(m/km)	1.32	0.98	0.94
PI(mm/km)	519	384	400
RQI	42.35	30.15	30.05

% Improvement Compared to Float Pan Sensor			
Device	IRI	PI (Zero)	RQI
Auto-Float Sensor	25.76%	26.01%	28.81%
LISA - TriODS	28.79%	22.93%	29.04%

Section 3			
Index	Float Pan (1)	Auto-Float (2)	LISA - TriODS (3)
IRI(m/km)	1.18	1.05	1.06
PI(mm/km)	525	450	438
RQI	40.5	33.31	33.68

% Improvement Compared to Float Pan Sensor			
Device	IRI	PI (Zero)	RQI
Auto-Float Sensor	11.02%	14.29%	17.75%
LISA - TriODS	10.17%	16.57%	16.84%

Section 4			
Index	Float Pan (1)	Auto-Float (2)	LISA - TriODS (3)
IRI(m/km)	1.16	0.92	1.02
PI(mm/km)	433	349	351
RQI	37.85	27.05	28.96

% Improvement Compared to Float Pan Sensor			
Device	IRI	PI (Zero)	RQI
Auto-Float Sensor	20.69%	19.40%	28.53%
LISA - TriODS	12.07%	18.94%	23.49%

APPENDIX D: ROUGHNESS MEASUREMENTS WITH BURLAP DRAG INSTEAD OF AUTO-FLOAT—U.S. HIGHWAY 34

Section 1			
Index	Float Pan (1)	Burlap (2)	LISA - TriODS (3)
IRI(m/km)	1.03	1.04	1.00
PI(mm/km)	349	350	291
RQI	32.28	34.26	32.42

% Improvement Compared to Float Pan Sensor			
Device	IRI	PI (Zero)	RQI
Burlap Sensor	-0.97%	-0.29%	-6.13%
LISA - TriODS	2.91%	16.62%	-0.43%

Section 2			
Index	Float Pan (1)	Burlap (2)	LISA - TriODS (3)
IRI(m/km)	1.09	1.09	1.05
PI(mm/km)	400	465	425
RQI	34.65	34.85	29.53

% Improvement Compared to Float Pan Sensor			
Device	IRI	PI (Zero)	RQI
Burlap Sensor	0.00%	-16.25%	-0.58%
LISA - TriODS	3.67%	-6.25%	14.78%

Section 3			
Index	Float Pan (1)	Burlap (2)	LISA - TriODS (3)
IRI(m/km)	1.22	1.25	0.87
PI(mm/km)	545	659	349
RQI	43.38	41.6	27.65

% Improvement Compared to Float Pan Sensor			
Device	IRI	PI (Zero)	RQI
Burlap Sensor	-2.46%	-20.92%	4.10%
LISA - TriODS	28.69%	35.96%	36.26%

Section 4			
Index	Float Pan (1)	Burlap (2)	LISA - TriODS (3)
IRI(m/km)	1.21	1.17	0.98
PI(mm/km)	497	470	377
RQI	42.35	42.48	35.38

% Improvement Compared to Float Pan Sensor			
Device	IRI	PI (Zero)	RQI
Burlap Sensor	3.31%	5.43%	-0.31%
LISA - TriODS	19.01%	24.14%	16.46%

APPENDIX E: GSI IRI VALUES—U.S. HIGHWAY 30

Table E.1. Day 1 IRI values (in./mi)

Lane	Inside					Outside				
Track	Outside				Inside	Inside		Outside		
Stage	1	4	6	7	1	1	4	1	6	7
Lot 1	90.9	76.5	96.0	91.2	141.1	76.7	58.3	65.7	69.3	—
Lot 2	98.4	75.9	121.2	121.8	159.8	112.1	74.9	61.9	69.5	—
Lot 3	83.8	91.0	122.5	123.6	162.0	96.0	69.5	57.7	72.0	65.5
Lot 4	86.7	76.4	126.7	123.0	175.7	90.3	74.7	63.0	71.8	74.1
Lot 5	69.6	64.3	107.9	109.0	163.7	79.4	64.8	51.2	61.1	64.4
Lot 6	56.1	80.4	84.4	85.2	118.8	64.5	50.5	52.5	69.9	71.0
Lot 7	55.3	68.0	80.9	77.6	130.8	65.5	59.6	55.6	57.1	55.5

Table E.2. Day 2 IRI values (in./mi)

Lane	Inside					Outside				
Track	Outside				Inside	Inside		Outside		
Stage	1	4	6	7	1	1	4	1	6	7
Lot 1	88.1	88.2	67.8	67.8	103.4	82.4	56.9	60.2	55.2	63.0
Lot 2	45.8	94.5	65.0	64.5	100.3	60.5	55.7	45.5	63.0	60.8
Lot 3	38.0	70.3	60.8	62.5	82.7	51.0	55.3	51.0	65.4	61.2
Lot 4	39.6	81.1	75.2	77.1	95.8	66.4	65.8	57.7	68.4	66.8
Lot 5	48.3	102.0	64.6	63.3	100.4	56.7	69.9	61.8	80.2	64.8
Lot 6	49.3	112.1	74.2	77.2	81.8	61.6	69.3	73.1	91.6	91.8
Lot 7	41.5	96.3	77.4	80.6	146.3	72.1	56.6	34.1	52.6	57.1
Lot 8	37.7	80.0	71.3	71.4	111.1	37.7	53.7	37.2	64.6	56.0

Table E.3. Day 3 IRI values (in./mi)

Lane	Inside			Outside		
Track	Outside		Inside	Inside		Outside
Stage	1	4	1	1	4	1
Lot 1	93.6	69.7	163.4	148.7	49.5	109.4
Lot 2	55.8	55.4	116.1	65.6	42.2	58.9
Lot 3	61.6	50.1	117.3	66.6	40.7	62.9

Table E.4. Day 8 IRI values (in./mi)

Lane	Inside				Outside					
Track	Outside			Inside	Inside				Outside	
Stage	1	3	5	5	1	2	3	5	1	5
Lot 1	61.2	72.5	63.9	58.6	86.7	70.5	63.7	60.5	64.2	53.9
Lot 2	41.6	57.7	50.1	59.6	61.7	62.4	56.4	50.6	53.8	54.6
Lot 3	41.6	56.1	49.5	63.2	69.6	67.1	52.4	49.2	63.2	58.1
Lot 4	31.2	50.6	46.2	50.3	54.1	61.9	49.3	50.0	52.4	50.3
Lot 5	28.7	52.0	49.2	52.1	41.4	61.8	58.9	59.4	49.8	54.5
Lot 6	32.5	58.9	80.8	58.4	45.6	65.8	77.3	78.3	52.7	63.4
Lot 7	33.0	53.9	63.3	53.4	43.4	64.6	67.8	58.6	52.0	56.0
Lot 8	40.4	52.1	48.9	55.0	61.4	59.3	51.4	50.8	63.1	56.9

Table E.5. Day 9 IRI values (in./mi)

Lane	Inside				Outside					
Track	Outside			Inside	Inside				Outside	
Stage	1	3	5	5	1	2	3	5	1	5
Lot 1	59.5	71.1	54.7	78.0	78.9	75.5	53.3	59.0	96.0	67.4
Lot 2	60.1	75.9	66.3	100.0	82.0	75.0	71.6	66.6	74.5	77.0

Table E.6. Day 10 IRI values (in./mi)

Lane	Inside				Outside					
Track	Outside			Inside	Inside				Outside	
Stage	1	3	5	5	1	2	3	5	1	5
Lot 1	157.5	68.8	73.7	115.2	140.5	94.9	75.9	68.1	95.5	63.8
Lot 2	76.2	76.2	70.6	86.6	90.8	82.2	61.1	60.7	71.5	60.2
Lot 3	41.5	58.8	63.9	64.9	72.8	71.9	57.5	56.4	58.3	55.7
Lot 4	60.2	64.0	65.7	118.8	119.8	91.1	78.9	81.6	64.7	63.0
Lot 5	55.3	60.6	64.1	71.6	85.8	76.5	58.1	67.6	60.1	50.6
Lot 6	55.3	66.1	65.5	74.6	91.7	80.6	66.8	69.7	56.2	48.0
Lot 7	51.2	56.1	48.0	55.8	88.5	83.0	49.8	50.5	52.4	47.6
Lot 8	51.6	75.0	57.2	59.2	85.4	51.7	53.3	57.5	43.6	56.1