Pavement Surface Properties Consortium: A Research Program - TPF-5(141)

Final Report

2007-2015

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Table of Contents

I. 2007 Annual Equipment Comparison Roundup at the Smart Road[1]

I.1. Introduction and Background

The Virginia Transportation Research Council (VTRC) and the Virginia Tech Transportation Institute (VTTI) formed a regional pooled-fund project known as the Pavement Surface Properties Consortium to establish a research program focused on enhancing the level of service provided by the roadway transportation system by optimizing pavement surface texture characteristics. The program was set up with support from the Federal Highway Administration (FHWA), and initially included four departments of transportation (DOTs) from the states of Georgia, Pennsylvania, South Carolina and Virginia. Established as a five year program, the consortium is part of the activities of the Virginia Sustainable Pavement Research Consortium (VA-SPRC) and is managed by VTRC and run by the Center for Sustainable Transportation Infrastructure at VTTI. The initial scope of work was geared towards establishing a comparison/verification facility for inertial and laser-based equipment for measuring pavement surface texture properties. Subsequently, this objective was revised to also include comprehensive research of those same pavement surface properties and to explore their relationships with pavement friction and noise. Complementing this effort, an additional research realm focuses on the review, testing, and evaluation of emerging technologies.

One of the main services of the consortium was to provide a venue to verify/ validate/ harmonize the measurements of the various pieces of equipment owned and operated by the participating agencies. All the agencies asked the same question: are our measurements being obtained correctly? Although it is difficult to define a "ground truth" that allows for an absolutely irrefutable answer to this question, the consortium is providing an annual event in which the participating agencies can determine how the results from the various pieces of equipment compare with each other. In order to do this, the research team organized the first consortium equipment comparison rodeo for the week of May 28, 2007. Each agency brought some of the equipment used in their respective states to measure profile and friction. Several new emerging technologies were also demonstrated to the members. This report is a summary of the activities and results from this first equipment roundup.

I.2. Objective

The objective of this comparison roundup was to evaluate some of the equipment utilized to measure smoothness and friction by the individual states participating in the consortium. All of the member states brought an inertial profiler, except for Virginia, which had two units, for a total of five inertial profilers. Georgia, Pennsylvania and Virginia each also brought a locked-wheel friction device. Additional slow-speed or "static" equipment included: a SURPRO manual profiler from Pennsylvania, a Circular Track Meter (macrotexture), a Dynamic Friction Tester (friction), and a hydrotimer, which were also tested and compared to the corresponding high-speed devices.

I.3. Data Collection

All of the testing was done at the Virginia Smart Road at the Virginia Tech Transportation Institute. This facility is particularly appropriate for this because it includes a variety of "real world" flexible and rigid surfaces and very convenient controlled conditions. The facility offers seven different types

[1] Prepared by Edgar de León Izeppi, Gerardo Flintsch, and Kevin K. McGhee

of asphalt pavement surfaces (five different Superpave™ mixtures, an open-graded friction course (OGFC), and a Stone Mastic Asphalt (SMA). The rigid pavement surfaces feature a continuously reinforced concrete pavement (CRCP) and a jointed reinforced concrete pavement (JRCP). The CRCP section is about 900 ft long and has recently been overlaid with two high-friction surfaces (HFS). These are Cargill SafeLane™ and the Virginia DOT's modified EP5 (epoxy concrete overlay). The complete set of pavement surfaces can be seen in Figure 1. Figure 2 depicts the layout of the HFS in the CRCP section.

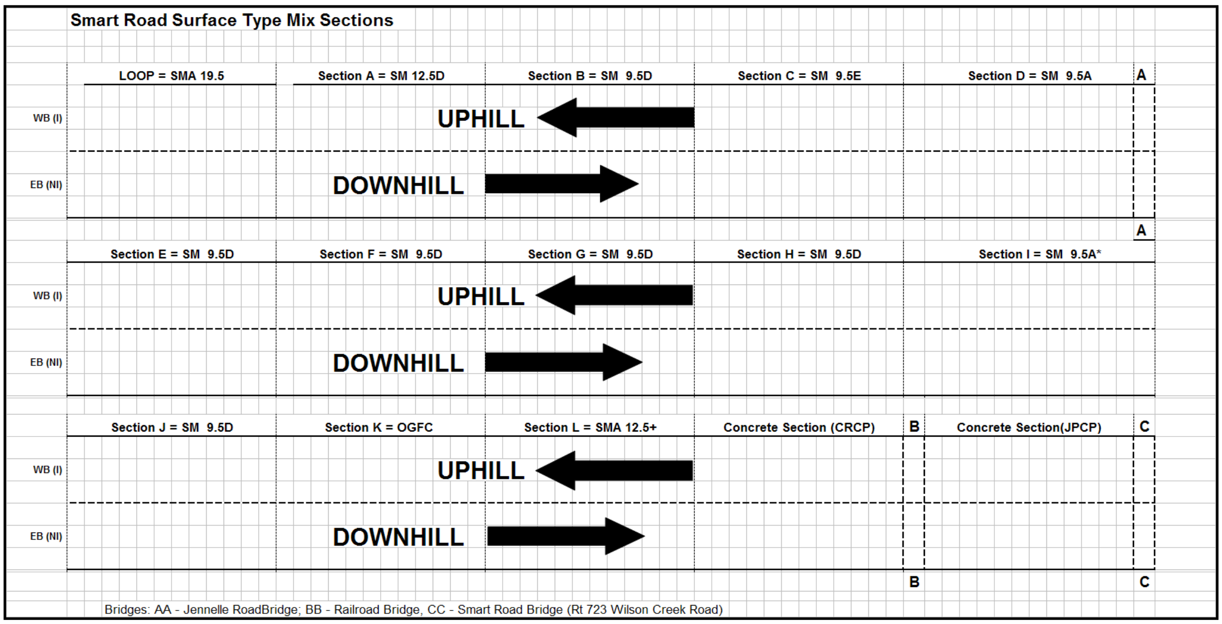


Figure 1. Smart Road Surface Sections

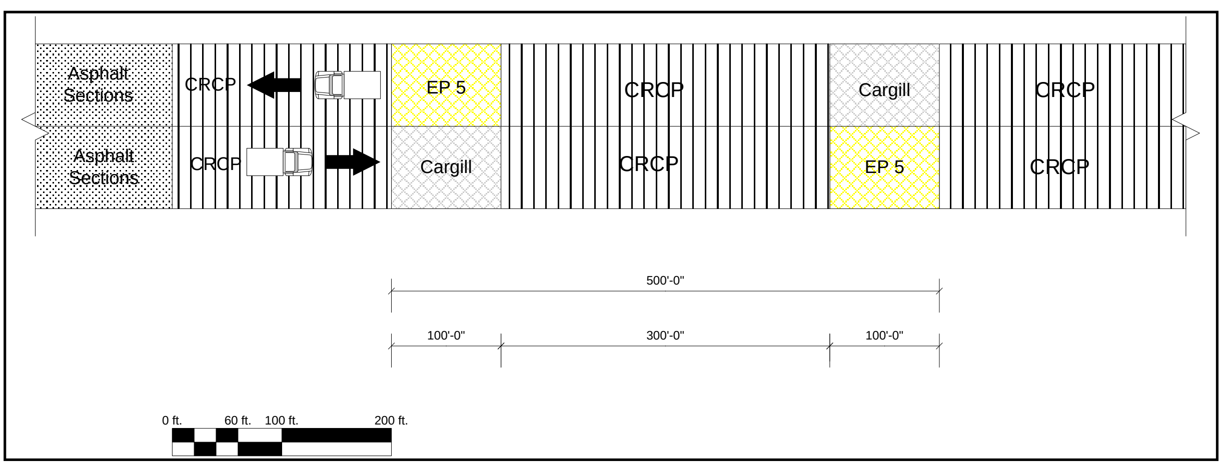


Figure 2. Smart Road CRCP section's HFS sections

The inertial profilers collected data ten times downhill starting at the beginning of section A and finished just before the Smart Road Bridge after the JRCP section. The operation was identical coming uphill but, because the slope is very steep, the run started at the end of the bridge in order to achieve the desired measuring speed when coming up the hill. Since several of the sections have similar surfaces, the friction data collection was limited to eight sections: Loop, B, D, K, L, Cargill, EP-5 and the CRCP, both for the downhill and the uphill runs.

Profile Data Collection

The five inertial data profilers plus the SURPRO unit can be seen in Figure 3.


(a) Georgia’s inertial profiler


(b) Pennsylvania’s inertial profiler


(c) South Carolina’s inertial profiler


(d) Virginia’s inertial profiler 1


(e) Virginia’s inertial profiler 2


(f) Pennsylvania’s SURPRO

Figure 3. Profilers that participated in the roundup

As explained, all units measured the road profile a total of ten times in both directions. Four of the profilers compared are ICC units; the fifth, from South Carolina, is a Dynatest unit. Because the raw profile measurements of this last unit could not be obtained previous to its processing, the profile could not be compared to the ones measured by the other four units that all used the same processing filters. Filters are used to remove the road grade and the long undulations in a profile measurement. The PROVAL software was used to compare the measured profiles and specifically the repeatability and reproducibility of the runs. Comparing processed profiles with different filters is not encouraged because there is uncertainty about what elements of the profile were removed and which were not. Therefore, for comparison purposes, the data from the South Carolina unit was only used when comparing the overall road indices, specifically the International Roughness Index or IRI.

Friction Data Collection

All the friction data was collected on May 30, with the three state-agency units collecting the skid data according to ASTM E-274[1]. Another unit that participated in the comparison was a fixed-slip device (Griptester) commonly used in airport friction testing, but at the time of preparing this report, the research team had yet to receive any data from this device. All four units can be seen in Figure 4.

(a) Georgia's Friction Trailer

(a) Pennsylvania's Friction Trailer

(a) Virginia's Friction Trailer

(d) AeroGroup's Griptester

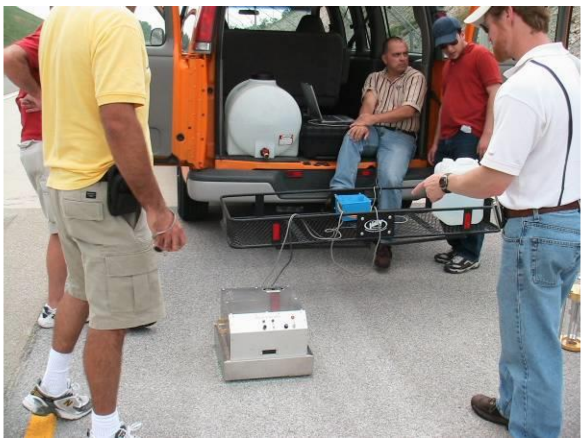
Figure 4. Friction measuring devices that participated in the roundup

The results from the data collection are included in Appendix 2: Friction Data. The skid tester from Georgia used only the ribbed tire (ASTM E 524[1]), the one from Pennsylvania only the smooth tire

(ASTM E 501[1]), as that is the standard practice in their respective states. The unit from Virginia had both tires available. This allowed for a comparison of two sets of measurements (tires).

CT Meter, Dynamic Friction Tester, Hydrotimer and DSRM

Static tests were conducted with several devices, as shown in Figure 5. The Circular Track Meter (CT Meter – ASTM E2157[1]) was used to obtain static macrotexture measurements at three different locations in each section in the left wheel path of each lane. The measurements were separated by approximately 75 ft. The Dynamic Friction Tester (DFT – ASTM E1911[1]) was used in the same location. These results were interpolated to match the speed used for the locked-wheel testers, i.e., 20, 40 and 50 mph. As an additional piece of data, the results of an outflow meter test with a Hydrotimer (ASTM E2380[1]) were also obtained in the same places in which the DFT and CT Meter measurements were taken.



(a) Circular Track Meter

(b) Dynamic Friction Tester

(c) Hydrotimer

(d) Digital Surface Roughness Meter

Figure 5. Additional devices used for reference comparison

An additional unit that was delivered late for testing texture was the Digital Surface Roughness Meter (DSRM). The measurements from the DSRM are made on a 4" by 4" area so, in order to get more representative measurements, four readings were obtained inside the area of the CT Meter box, as delimited by its casing.

I.4. Profile Comparisons

Figure 6 is the representation of one run from each of the profilers as it recorded the data in the downhill (east-bound) direction. The profiles are superimposed and it can be observed that the individual measurements do not differ significantly from the beginning of the run until the end of the measurements.

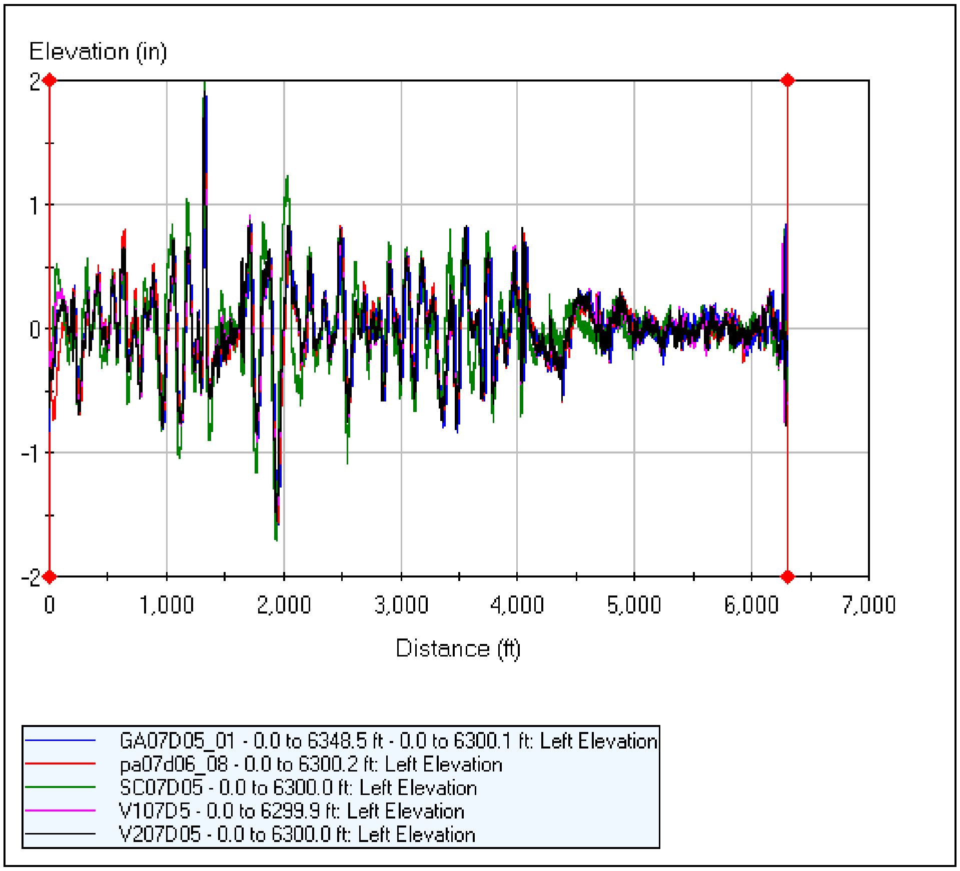
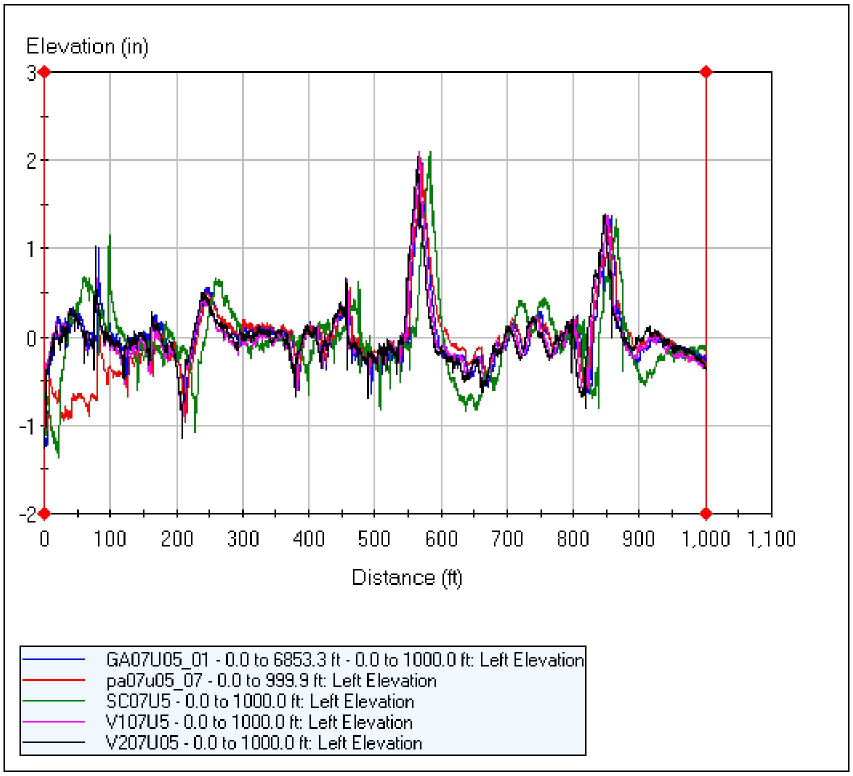
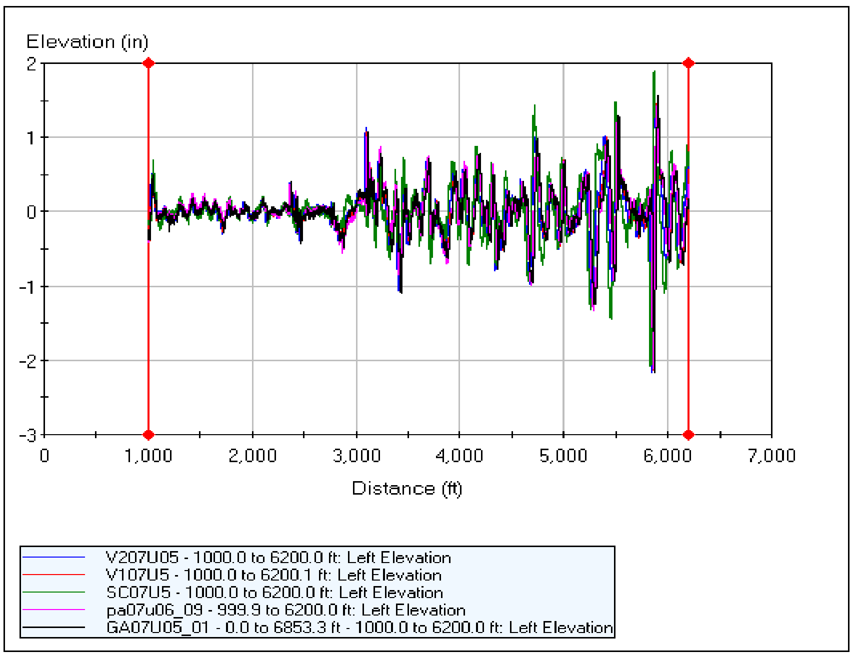


Figure 6. Profiler results for one downhill run for every profiler

In contrast, Figure 7a shows the results of the first 1,000 ft of profiler measurements on the uphill (west-bound) runs for all of the profilers, where considerable variation is evident. Ideally, as was observed in the downhill runs, the profiles for all the units should match substantially when superimposed over one another (i.e., good reproducibility). This was probably due to the difficulties experienced by some of the vehicles in achieving the desired uniform speed before reaching the beginning of the section. In Figure 7b, the results for the rest of the runs are shown, without including the first 1,000 ft of the section, and will be processed at a later date. These profile matching problems have also made difficult to compare the profiles with the "reference" SURPRO measurements. These comparisons will be made once the reference sections are properly delimited within the uphill profile traces.



(a) Initial 1,000 ft of uphill profiles



(b) Complete profile without the first 1,000 ft

Figure 7. Profiler results for one uphill run for every profiler

Profile Repeatability

According to the "Standard Practice for Certification of Inertial Profiling Systems" (AASHTO PP 49-03[2]), the calculation of repeatability is based on cross-correlating each of the ten profiles to each of the remaining nine. As an example, Table 1 provides an example of a correlation matrix for the Georgia profiler using all the downhill measurements with the left sensor. More correlation matrices are included in the Appendix I.

Table 1. Correlation Matrix for GA Profiler using the Downhill Left Wheelpath Measurements.

Run	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	97	98	98	97	97	97	87	97	97
2	-	98	98	97	97	98	94	97	97
3	-	-	99	99	99	99	95	99	99
4	-	-	-	99	98	99	83	99	96
5	-	-	-	-	99	98	94	99	99
6	-	-	-	-	-	98	96	99	99
7	-	-	-	-	-	-	91	98	98
8	-	-	-	-	-	-	-	94	98
9	-	-	-	-	-	-	-	-	99

Table 2 summarizes the repeatability obtained for each of the units tested, running downhill. The results for the uphill measurements are not shown because, as explained before with Figure 7a, it was difficult to match the starting of the various profile measurements. Consideration must be given to the fact that the starting speed, starting point and total length measured were different because of the grade conditions.

Table 2. Summary of the Repeatability Results for the Downhill Measurements.

Downhill	**GA**		**PA**		**VA1**		**VA2**		**SC**	
	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
Count	45	45	45	45	45	45	45	45	45	45
% Passing	93	93	89	31	100	100	100	80	100	100
Mean Cross-corr. (%)	97	97	96	86	98	98	98	97	99	99
Minimum CC (%)	83	84	86	65	96	95	94	90	98	99
Maximum CC (%)	99	100	99	97	99	99	100	99	100	100
Stand. Deviation (%)	3.1	3.1	2.7	8.3	0.7	1.1	1.7	3.6	0.3	0.3

The repeatability results show how efficient each unit was in obtaining the same profile measurements in each of its ten runs. The second row shows the percentage of the comparisons with a cross-correlation value of more than 92%. AASHTO PP49-03[2] requires a mean cross-correlation value of at least 92% to be considered a passing grade for repeatability (the third row). All the profilers achieved this requirement, except for the right sensor of the PA profiler. In all the other cases, the average cross-correlation values were higher than 96%. Even in the case of the right laser of the PA profiler, the average cross-correlation value is very reasonable (86%).

Profile Reproducibility

Reproducibility results were obtained by comparing a fixed "reference" run from each unit to all of the runs from each of the other units using cross-correlation analysis. A total of six comparisons were made, as can be seen in Table 3. Each of the comparisons consisted of the measurement obtained in the fifth run for the first unit to all of the ten runs of the second unit. This yields a relative comparison of the accuracy of the second unit with respect to the first. Ideally, this comparison would have to be made with a true reference profile measurement, but in lieu of this, all the units were compared to each other.

Table 3. Summary of Reproducibility Profiler Results in the Downhill Direction

	GAD5-PAD		**GAD5-VA2D**		**VA1D5-GAD**	
	Left	Right	Left	Right	Left	Right
Comparison Count	10	10	10	10	10	10
% Passing	10	0	100	90	80	30
Mean Cross-corr. (%)	88	81	96	94	90	87
Minimum CC (%)	83	70	92	89	73	70
Maximum CC (%)	92	90	98	96	95	93
Stand. Deviation (%)	2.2	6.4	1.4	2.1	6.4	6.4
	VA1D5-PAD		**VA1D5-VA2D**		**VA2D5-PAD**	
	Left	Right	Left	Right	Left	Right
Comparison Count	10	10	10	10	10	10
% Passing	60	20	100	90	50	10
Mean Cross-corr. (%)	91	79	97	93	90	83
Minimum CC (%)	85	65	94	88	86	72
Maximum CC (%)	95	93	98	94	94	92
Stand. Deviation (%)	2.7	9.4	1.4	1.7	2.3	6.2

(1) GAD5-PAD = cross-correlation comparison of the Georgia profiler's fifth downhill run (GAD5) with the 10 downhill runs with the profiler from Pennsylvania (PAD).

An individual comparison "passes" if the cross-correlation coefficient is higher than 90%. Two profilers pass the reproducibility test if the "percent passing" score is higher than 90%; this would mean that at least nine out of ten comparisons resulted in a cross-correlation value of more than 90%. In general, all the comparisons have a very high average coefficient of cross-correlation. The coefficient ranges from 87 to 97%, except for the comparisons that include the right measurements from the PA profilers, which ranged from 79 to 81%. The complete results are included in Appendix 1, Profiler data. There, it can be observed that the most significant differences come from the mismatch in the results of the right sensor measurements, whereas the left ones seem more comparable in all cases. This variation is unexpected and, considering that the difference in transversal grade is not excessive, an explanation should be sought to explain it.

International Roughness Index Comparisons

The final comparison contrasted the computed International Roughness Indices (IRI) that resulted from the measurements. Typically, IRI is a single value for a given segment of road for each of the sensors in the vehicles. All of the vehicles had at least a right and a left profiler, with South Carolina producing a third profile from a sensor in the middle of the vehicle. The following table 4 is a summary of the results of the mean of the right and the left IRI (MRI) calculated for all the vehicles, as calculated with the PROVAL software. It is interesting to note that all the values are very close and that the standard deviations are less than 1 in/mile in all cases. In spite of the differences noted earlier regarding prefiltering and the Dynatest/ICC comparison issue, note that the VA1, VA2, and SC profilers produced almost identical results.

Table 4. Summary MRI measurements for all profilers (in/mile)

Run	GA_MRI	PA_MRI	SC_MRI	VA1_MRI	VA2_MRI	Average
1	103.5	98.5	102.1	100.3	100.9	101.1
2	103.1	98.4	101.6	100.4	101.3	101.0
3	104.9	99.9	101.5	101.7	101.0	101.8
4	104.4	99.8	101.9	100.6	100.8	101.5
5	104.0	100.4	101.2	101.2	101.1	101.6
6	103.4	100.3	101.7	101.5	101.3	101.6
7	103.3	98.7	101.7	101.8	101.4	101.4
8	102.1	98.8	102.3	102.3	101.8	104.5
9	104.2	99.7	101.8	102.7	101.1	101.9
10	103.2	99.5	101.5	102.8	101.2	101.6
Average	103.61	99.4	101.73	101.53	101.19	101.49
Std Dev	0.79	0.74	0.32	0.91	0.28	0.61

I.5. Friction Comparisons

Previous research has indicated that the skid number is highly dependent upon the test speed and that to compare results with different equipment used at different speeds, the results need to be standardized using the exponential regression given in the following model (usually known as the SU Model[3]):

$SN=SN_0\, e^{(-0.01PNG*V)}$ (1)

where:

SN = calculated skid number

SN_0 = skid number at zero speed (indicator of microtexture)

PNG = percent normalized gradient (indicator of macrotexture) and

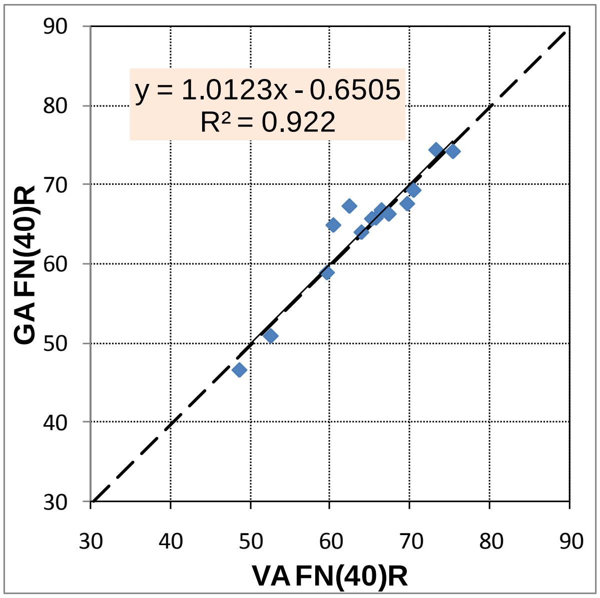
V = velocity in mph

Table 5 summarizes the normalized friction numbers for the two sets of measurements for the ribbed and smooth tires at target speeds of 20 and 40 mph. The measurements at 40 mph are presented in bold because this is the typical measurement speed for the participating devices.

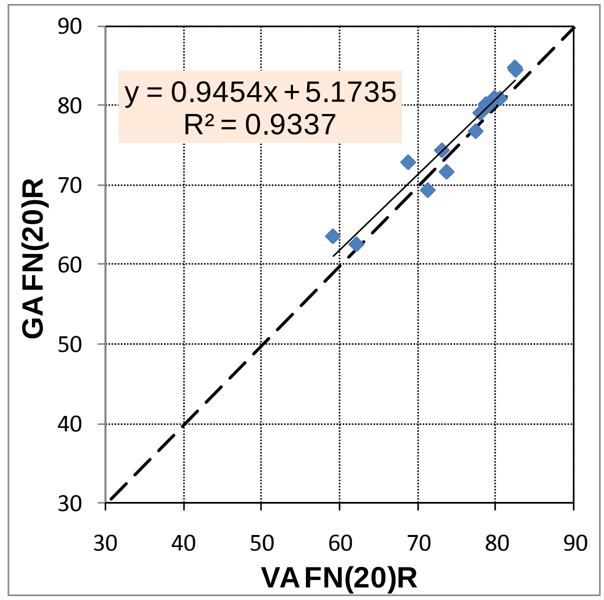
Table 5. Standardized Friction Numbers for Smooth (S) and Ribbed (R) tires at 20 & 40 mph.

Section		**Surface**	**Smooth Tire**				**Ribbed Tire**			
			PA FN(20)S	**VA** FN(20)S	**PA** FN(40)S	**VA** FN(40)S	**GA** FN(20)R	**VA** FN(20)R	**GA** FN(40)R	**VA** FN(40)R
1	Loop	SMA 19.0	78.0	77.0	**54.2**	**57.8**	80.2	78.7	**65.8**	**65.7**
2	B	SM 9.5A	74.2	72.9	**41.7**	**48.7**	84.5	82.5	**69.3**	**70.4**
3	D	SM 9.5A	68.2	66.3	**37.0**	**42.3**	80.9	80.5	**64.0**	**63.9**
4	K	OGFC	62.5	60.0	**49.5**	**49.8**	63.6	59.2	**46.6**	**48.7**
5	L	SMA 12.5	70.9	69.0	**50.7**	**51.8**	71.7	73.7	**58.9**	**59.6**
6	Cg	Cg	83.9	77.9	**56.8**	**66.0**	80.0	79.0	**74.4**	**73.2**
7	EP	EP-5	67.6	65.0	**48.6**	**55.8**	72.9	68.8	**66.8**	**66.4**
8	CRC	CRCP	69.2	72.8	**35.6**	**39.7**	N/A	75.9	**N/A**	**67.9**
9	CRC	CRCP	72.7	77.3	**53.3**	**56.9**	N/A	81.8	**N/A**	**73.7**
10	CG	Cg	85.5	82.8	**64.6**	**70.3**	84.8	82.4	**74.2**	**75.3**
11	EP	EP-5	71.4	68.5	**58.2**	**59.4**	69.4	71.3	**66.3**	**67.3**
12	L	SMA 12.5	72.9	69.6	**50.2**	**53.9**	74.4	73.1	**64.9**	**60.4**
13	K	OGFC	58.7	59.6	**46.8**	**49.7**	62.6	62.2	**50.9**	**52.6**
14	D	SM 9.5A	72.4	70.0	**46.6**	**50.5**	76.8	77.4	**65.7**	**65.2**
15	B	SM 9.5A	82.1	80.5	**59.6**	**60.2**	81.0	79.8	**67.6**	**69.6**
16	Loop	SMA 19.5	68.1	68.3	**45.0**	**47.7**	79.1	78.0	**67.3**	**62.4**

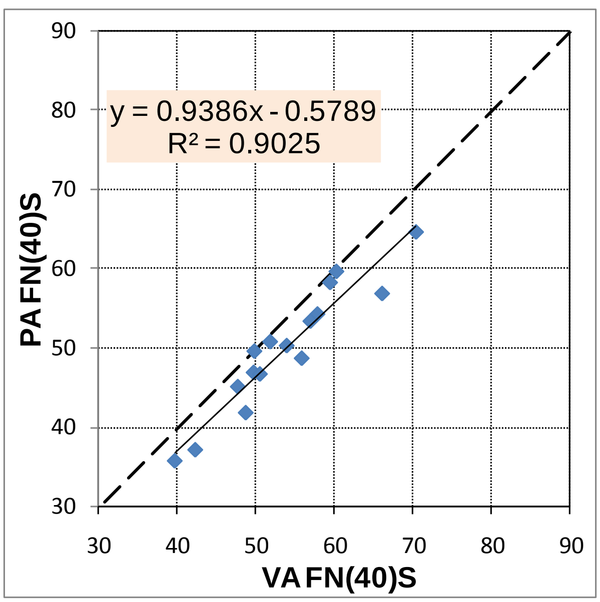
In order to calculate the PNG, a total of five runs were attempted at three speeds: 20 mph, 40 mph and 50 mph. It was difficult for some of the units to attain the 50 mph speed and, therefore, some of the measurements at this speed were not taken. The calculations for the friction gradient were then based on the best available data for the majority of the sections. Intuitively, it can be seen that this data looks comparable between both of the units with the smooth tire, as well as the ones with the ribbed tire, for both 20 and 40 mph, as is presented in Figure 8.



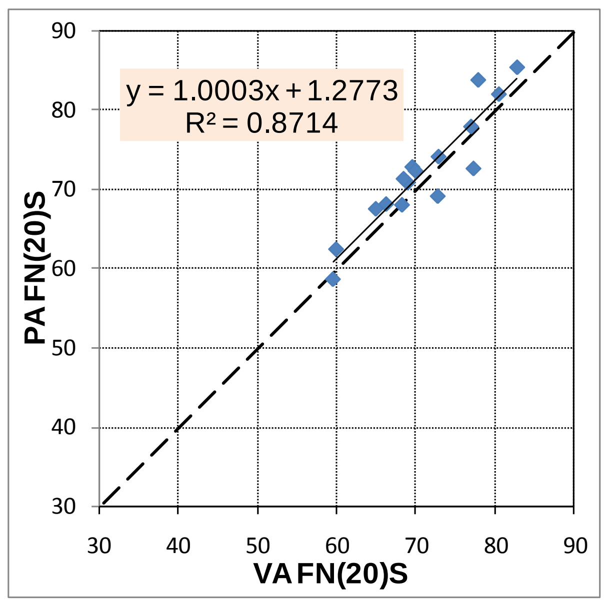
(a) Ribbed tire at 40 mph



(b) Ribbed tire at 20 mph



(c) Smooth tire at 40 mph



(c) Smooth tire at 20 mph

Figure 8. Pairwise Comparison of the Normalized Friction Measurements.

There are a couple of important factors that may be affecting the variability of the results. First, the unit from Georgia did not record the actual speed of the friction measurements; therefore, the calculated speed gradients assume that they were all measured at the target speeds. The normalized values obtained in this manner therefore have an error that is not quantifiable. Second, due to the fact that the trucks from Georgia and Pennsylvania did not have cruise control to set the measurement speeds, some of the measurements were taken at significantly different speeds, especially while going up the hill, which would explain some of the other apparent variations that can be seen in the data. This can only be seen in the data for the speed measurements of the Pennsylvania data, because the

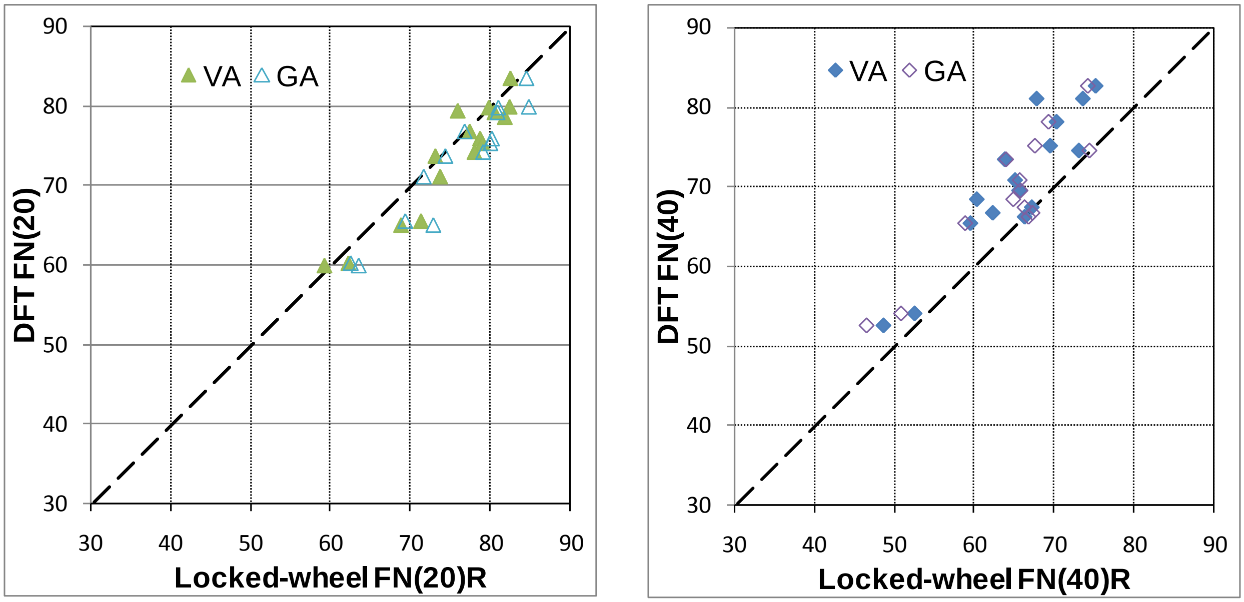
Georgia unit did not record the speed, as stated previously, but it would add another source of the variations. These two sources of variation may account for the differences. In general, however, there is not a significant difference between the measurements obtained with the same type of tire at 40 mph (in bold), which is the standard speed to perform friction measurements. It can therefore be concluded that measurements performed with the equipment are comparable.

Dynamic Friction Tester

The Dynamic Friction Tester was used in the sections that were tested with the skid testers. Table 6 shows the results obtained after the appropriate interpolations had been made to simulate the results, for comparison purposes, at 20, 40 and 50 mph. The results compare favorably to those obtained with the ribbed tires for the applicable sections. This is illustrated in Figure 9.

Table 6. DFT Measurements (Interpolated)

Section		FN20	FN40	FN50
1	Loop	75.9	69.5	64.8
2	B	83.5	78.1	70.3
3	D	79.2	73.4	67.1
4	K	59.9	52.6	50.8
5	L	71.1	65.4	60.6
6	Cg	75.3	74.5	71.4
7	EP	65.0	66.2	65.4
8	CRC	79.4	81.0	72.7
9	CRC	78.6	81.0	73.3
10	CG	79.9	82.6	74.1
11	EP	65.5	67.4	65.0
12	L	73.7	68.4	63.4
13	K	60.2	54.1	53.3
14	D	76.8	70.8	66.1
15	B	79.8	75.1	68.9
16	Loop	74.2	66.7	61.7



(a) Comparisons at 20 mph (b) Comparisons at 40 mph

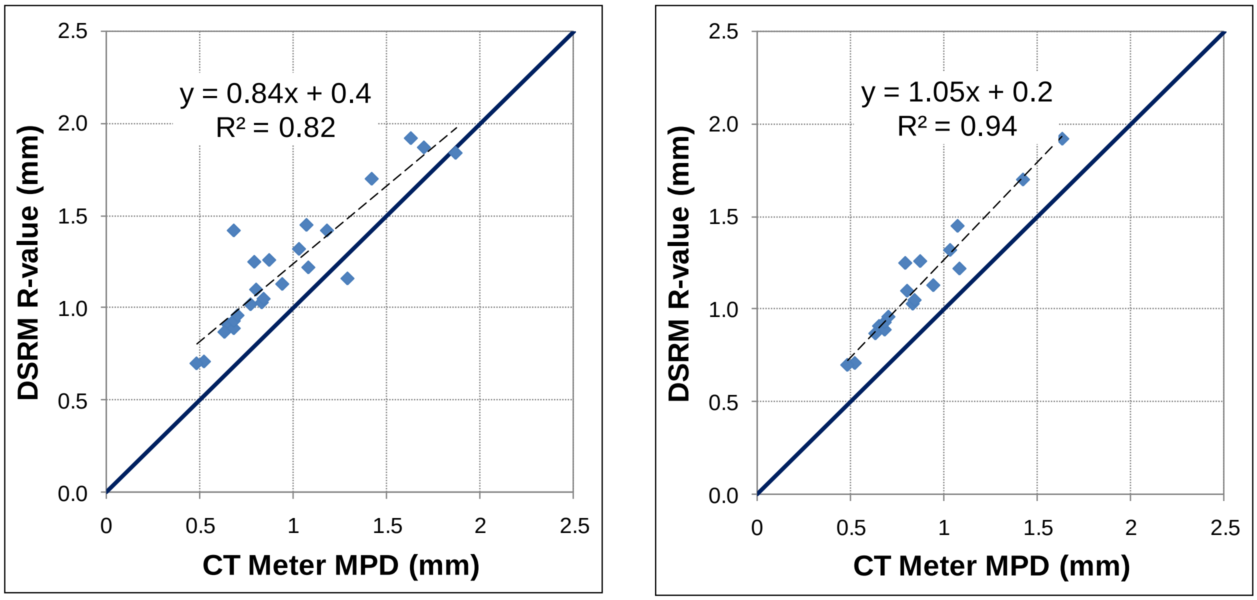
Figure 9. Comparison of DFT and Locked-wheel measurements at 20 and 40 mph.

I.6. Macrotexture Comparisons

The average of the various mean profile depth (MPD) macrotexture measurements taken on each section with the CT Meter and the comparable R-value with the DSRM are summarized in Table 7 and presented graphically in Figure 10.

Table 7. Average Macrotexture Results

Section	CT Meter MPD (mm)		DSRM R-value (mm)	
	Downhill	Uphill	Downhill	Uphill
Loop	1.03	0.79	1.32	1.25
A	0.52	0.94	0.71	1.13
B	0.65	1.08	0.91	1.22
C	0.63	0.7	0.87	0.96
D	0.48	0.68	0.70	0.93
I	0.83	0.68	1.03	0.89
J	0.84	0.8	1.05	1.10
K	1.42	1.63	1.70	1.92
L	0.87	1.07	1.26	1.45
Cargill	1.70	1.87	1.87	1.84
CRCP	0.77	0.68	1.02	1.42
EP-5	1.29	1.18	1.16	1.42



(a) Including All Surfaces (b) Including only HMA Surfaces

Figure 10. Comparison of DSRM and CTMeter Measurements

The downhill and uphill lanes within the same section have different textures because they were constructed on different dates. As can be observed, the texture measurements taken with the DSRM have a higher reading than the ones taken with the CT Meter, but the correlation is very reasonable, especially if only the hot-mix asphalt (HMA) surfaces are considered. It appears that the difference in the way the laser (CT Meter) and optical device (DSRM) “see” the grooves on the CRCP is responsible for some of the differences.

The correlation between the Hydrotimer and CT Meter results is also strong as can be seen in Table 8 and Figure 11. The results from all of the surfaces sampled correlated very highly ($R^2 = 0.90$). The formulas used to obtain the MTD values for each of the Hydrotimer (ASTM E-2380[1]) and CT Meter (ASTM E-2157[1]) are presented in equations (2) and (3), respectively.

MTD = 3.114/OFT + 0.636, (2)

where
OFT = out-flow test time.

MTD = 0.947 MPD + 0.069 (3)

where
MPD = mean profile depth reported by the CT Meter.

Table 8. Comparison of Hydrotimer MTD vs. CT Meter MTD (equation 2 & 3)

Section	**CTMeter MPD (mm)**		**Hydrotimer Time (sec)**		**CT Meter MTD (mm)**		**Hydrotimer MTD (mm)**	
	Downhill	Uphill	Downhill	Uphill	Downhill	Uphill	Downhill	Uphill
Loop	1.03	0.79	8.0	9.7	1.04	0.82	1.03	0.96
A	0.52	0.94	20.3	8.3	0.56	0.96	0.79	1.01
B	0.65	1.08	12.7	6.3	0.69	1.09	0.88	1.13
C	0.63	0.7	15.0	12.7	0.67	0.73	0.84	0.88
D	0.48	0.68	12.3	13.7	0.52	0.71	0.89	0.86
I	0.83	0.68	11.0	11.7	0.85	0.71	0.92	0.90
J	0.84	0.8	8.7	10.0	0.87	0.83	1.00	0.95
K	1.42	1.63	3.7	2.3	1.41	1.61	1.49	1.97
L	0.87	1.07	10.7	8.7	0.89	1.08	0.93	1.00
Cargill	1.7	1.87	2.7	2.7	1.68	1.84	1.80	1.80
CRCP	0.77	0.68	10.0	7.7	0.80	0.71	0.95	1.04
EP-5	1.29	1.18	4.3	5.0	1.29	1.19	1.35	1.26

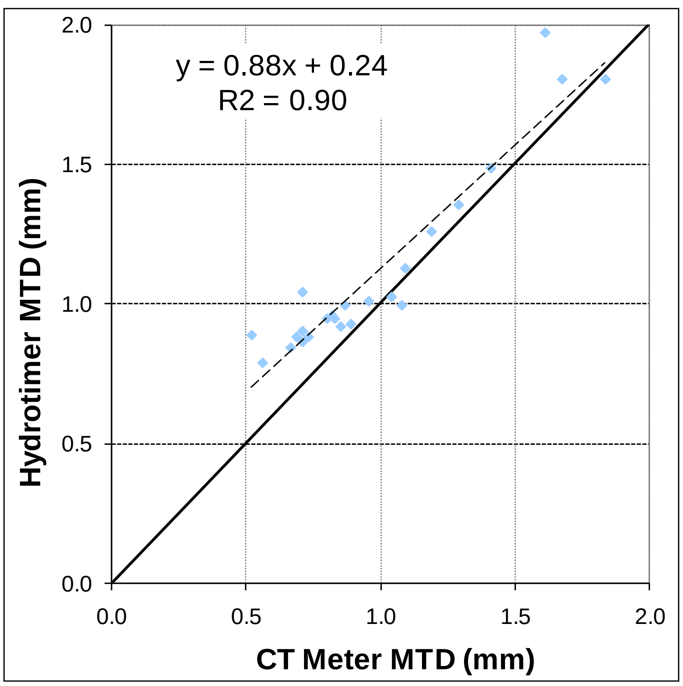


Figure 11. Comparison of CT Meter and Hydrotimer MTD macrotexture measurements

I.7. Final Remarks

Pavement surface property measurement equipment comparisons were performed at the first annual equipment roundup at the Smart Road. These test provided the Surface Properties consortium participants with an informal verification of their measurement equipment. The following are some of the most important findings:

Profile: Repeatability, reproducibility and accuracy were measured and reported for each of the participating profilers. Participants are encouraged to review the results to understand how the various participating units are performing. Repeatability seems to be an issue on the right sensors for two of the testing units.

Although the absolute accuracy of the measured profiles cannot be assessed at this moment, the measured MRI values were compared with each other. The results suggest that all of the profilers consistently obtained very similar MRI/IRI values. The repeatability standard deviation for each of the profilers was less than 1%.

It is recommended that next year's events feature an artificial bump at the beginning and end of each of the calibration segments to allow the exact pinpointing of the starting and ending points for the analysis of their profiles. Matching of these profiles will further facilitate the equipment comparisons that were initiated this year.

Friction: Comparable friction measurements results were obtained among the units that used the same type of tire. This represents a validation of the measurements obtained with the participating locked-wheel friction equipment. For those states that could be contemplating using the DFTester, the results were also highly correlated with the friction measurements using the ribbed tire.

Macrotexture: As the International Friction Index (IFI) finds more application in the USA, macrotexture measurements will become more important. DOT personnel should be aware that there are several devices that allow the measurement of this parameter. The test conducted showed that the results for the CTMeter, DSRM and Hydrotimer correlate reasonably well on the pavement surface evaluated. Further research with digital imaging and stereo vision technology is presently being evaluated and will be reported in the near future.

I.8. References

1. ASTM, Annual Book of ASTM Standards, vol. 04-03, ASTM International, (2007), West Conshohocken, PA.
2. AASHTO, Standard Practice for Certification of Inertial Profiling Systems, AASHTO Designation: PP 49-03, American Association of State Highway and Transportation Officials, Washington, D.C.
3. Wambold, James C., "Obtaining the Skid Number at Any Speed from a Test at Single Speed", Transportation Research Record, No. 1196 (1988), pp. 300-305.

II. 2008 Annual Equipment Comparison Roundup at the Smart Road[2]

II.1. Introduction and Background

The regional pooled-fund project known as the Pavement Surface Properties Consortium established a research program focused on enhancing the level of service provided by the roadway transportation system by optimizing pavement surface texture characteristics. The program was set up with support from the Federal Highway Administration (FHWA), and initially included four departments of transportation (DOTs) from the states of Georgia, Pennsylvania, South Carolina and Virginia. This year the number of member states grew to six when Connecticut and Mississippi joined the consortium. The consortium provides a practical mechanism to conduct research on pavement surface properties and explore their relationships with pavement ride quality, friction, and noise. Complementing this effort, an additional research domain focuses on the review, testing, and evaluation of emerging technologies.

One of the main services of the consortium is to provide a venue to verify/ validate/ harmonize the measurements of the various pieces of equipment owned and operated by the participating agencies. All the agencies ask the same questions: are our measurement systems working correctly and do they accurately characterize what we are trying to measure? Although it is difficult to define a "ground truth" that allows for an absolutely irrefutable answer to these questions, the consortium provides an annual event in which the participating agencies can determine how the results from the various pieces of equipment compare with each other. In order to do this, the research team organized the second consortium equipment comparison rodeo for the week of May 19, 2008. Agencies brought some of the equipment used in their respective states to measure profile, texture and friction. New emerging technologies were also demonstrated to the members.

II.2. Objective

The objective of this comparison roundup was to evaluate some of the equipment utilized to measure smoothness, texture and friction by the individual states participating in the consortium. Vehicles with high speed laser inertial profilers included one from Mississippi, Pennsylvania and South Carolina, and two from Virginia. Mississippi also brought a laser profiler with a single profiling sensor mounted on a "lightweight" all-terrain vehicle (ATV), for a total of six inertial profiler units. Connecticut, Mississippi, and Pennsylvania each also brought a locked-wheel friction device, whose measurements were compared this year with those of a Griptester, a continuous friction measuring instrument (CFMI) that belongs to the Federal Highway Administration (FHWA) and is on a loan program for demonstration.

Additional "static" equipment included: two Circular Track Meters, a Hydrotimer, and a stereo vision system (SVS) to measure macrotexture, and a Dynamic Friction Tester for friction. The SVS is being developed at Virginia Tech as a proof-of-concept project for the FHWA to measure three dimensional macrotexture.

[2] Prepared by Edgar de León Izeppi, Gerardo Flintsch, and Kevin K. McGhee

II.3. Data Collection

Test Surfaces

All of the testing was done at the Virginia Smart Road at the Virginia Tech Transportation Institute. This facility is particularly appropriate for this because it includes a variety of "real world" flexible and rigid surfaces and very convenient controlled conditions. The facility offers seven different types of asphalt pavement surfaces (five different Superpave™ mixtures, an open-graded friction course (OGFC), and a Stone Mastic Asphalt (SMA). The rigid pavement surfaces feature a continuously reinforced concrete pavement (CRCP) and a jointed plain concrete pavement (JPCP). The CRCP section is about 2,300 ft long and has recently been overlaid with two high-friction surfaces (HFS). These are Cargill SafeLane™ and the Virginia DOT's modified EP5 (epoxy concrete overlay). The complete set of experimental pavement sections and their respective surfaces can be seen in Figure 1. Figure 2 illustrates the layout of the HFS sections placed on the CRCP section.

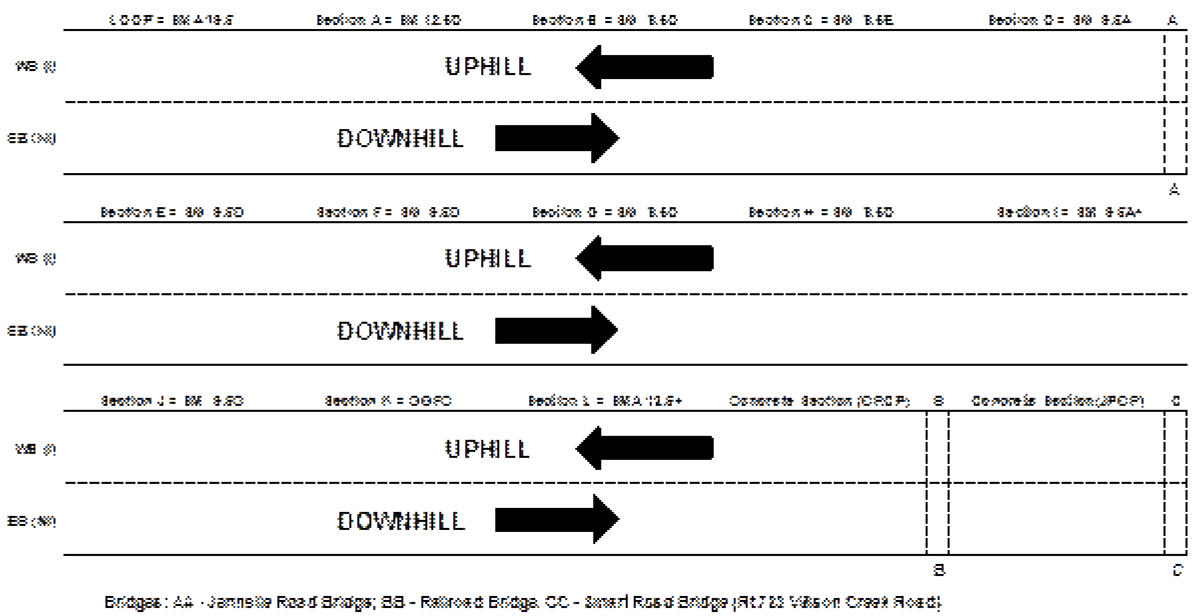


Figure 1. Smart Road sections layout

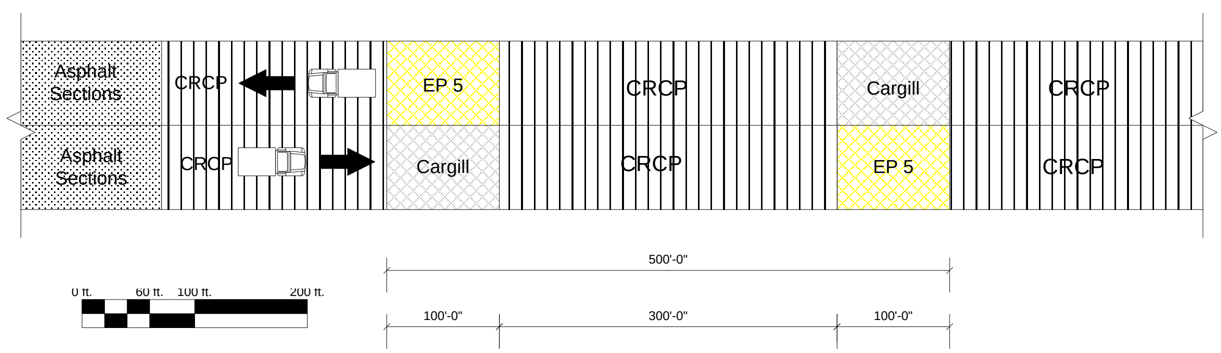


Figure 2. Detailed layout of the Smart Road HFS sections

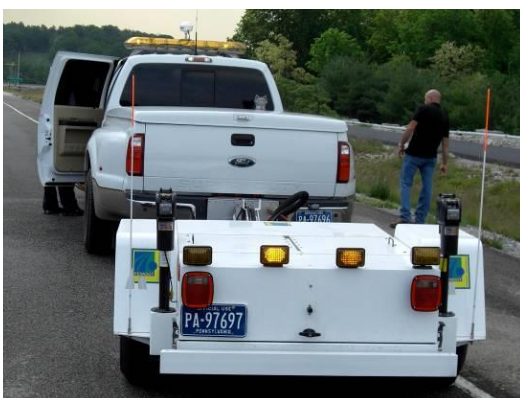
The inertial profilers collected data ten times downhill starting at the beginning of section A and finished just before the Smart Road Bridge after the JPCP section. The operation was identical coming uphill but, because the slope is very steep, the run started at the end of a bridge located several hundred feet below the first test section in order to achieve the desired measuring speed when coming up the hill.

Friction

All the friction data was collected on May 30, with the three state-agency units collecting the skid data according to ASTM E-274[1]. Another unit that participated in the comparison was a fixed-slip device (Griptester) commonly used in airport friction testing. Figure 3 shows the four units that participated in the comparison.

(a) Connecticut's Friction Trailer

(b) Mississippi's Friction Trailer



(c) Pennsylvania's Friction Trailer

(d) Griptester

Figure 3. Friction measuring devices that participated in the roundup

Since several of the sections have similar surfaces, friction data was collected in only twelve sections: Loop, A, B, C, D, I, J, K, L, Cargill, EP-5 and the CRCP, both for the downhill and the uphill runs. These sections are seen highlighted in Figure 4.

The results from the data collection are included in Appendix 1: Friction Data. The skid tester from Pennsylvania used only the smooth tire (ASTM E 501[1]), and the one from Mississippi used only the treaded tire (ASTM E 524[1]), as this is the standard practice in their respective states. The unit from Connecticut had both, a smooth and a ribbed tire, one on each side of the trailer. This allowed for a comparison of two sets of measurements (tires). All the measurements were taken on the left wheelpath, except for the measurements with the Connecticut unit using the ribbed tire, which were taken on the right wheelpath.

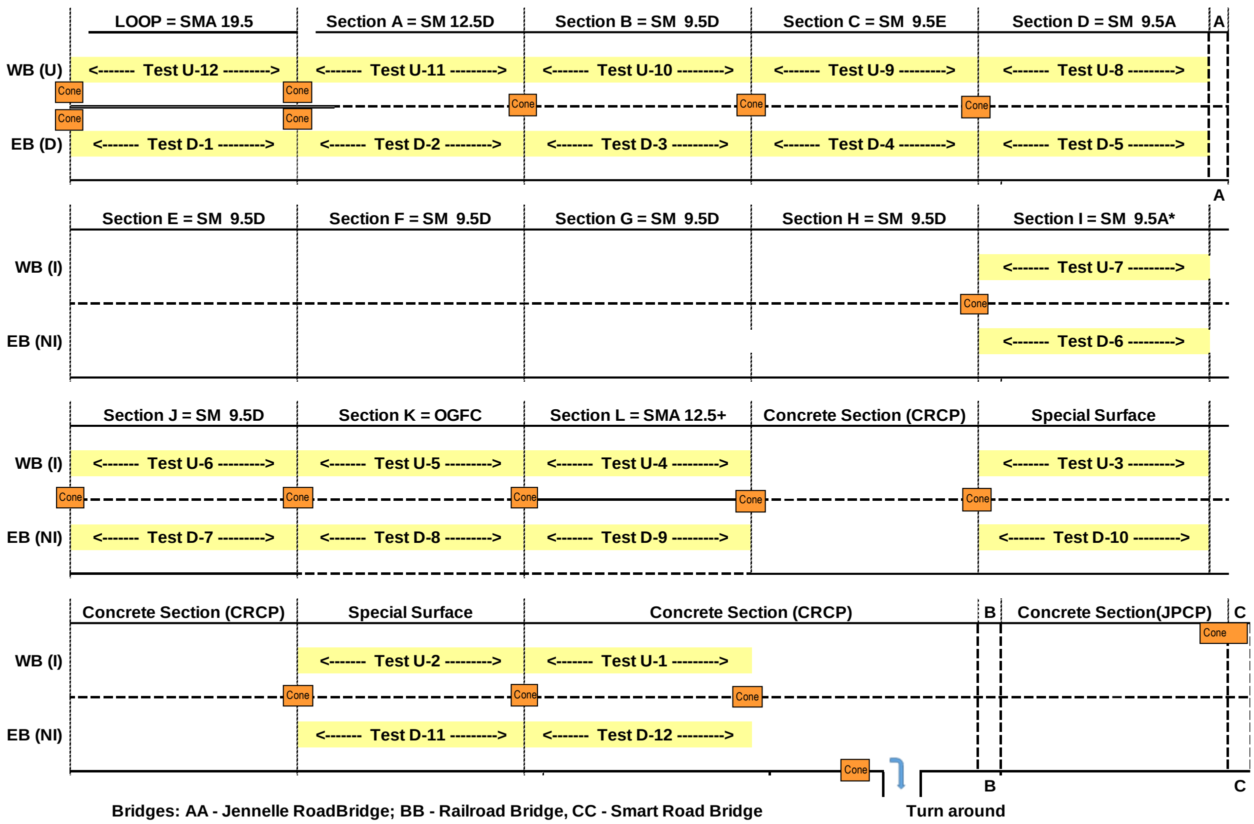


Figure 4. Layout of the sections selected for fiction and macrotexture tests.

Profile

In 2008, five inertial profilers mounted on vans plus a lightweight unit mounted on a four-wheel all-terrain vehicle, participated in the event. All units measured the road profile a total of ten times in both directions. Figure 5 shows pictures of these units.

Unfortunately, the raw profile measurements could not be obtained for all the units, because the profiles were filtered by each unit's proprietary programs. These filters are used to remove the road grade and the long undulations in a profile measurement. Comparing processed profiles with different filters is not encouraged because there is uncertainty about what elements of the profile were removed and which were not. Therefore, for comparison purposes, it should be noted that the results should only be evaluated for overall road indices, such as the results for the International Roughness Index (IRI).

(a) Mississippi's inertial profiler

(b) Pennsylvania's inertial profiler

(c) South Carolina's inertial profiler

(d) Virginia's inertial profiler 1

(e) Virginia's inertial profiler 2

(f) Mississippi's Lightweight profiler

Figure 5. Profilers that participated in the roundup

The section layout used for the profile testing is presented in Figure 6. The PROVAL software was used to compare the measured profiles and, specifically, the repeatability and reproducibility of the runs.

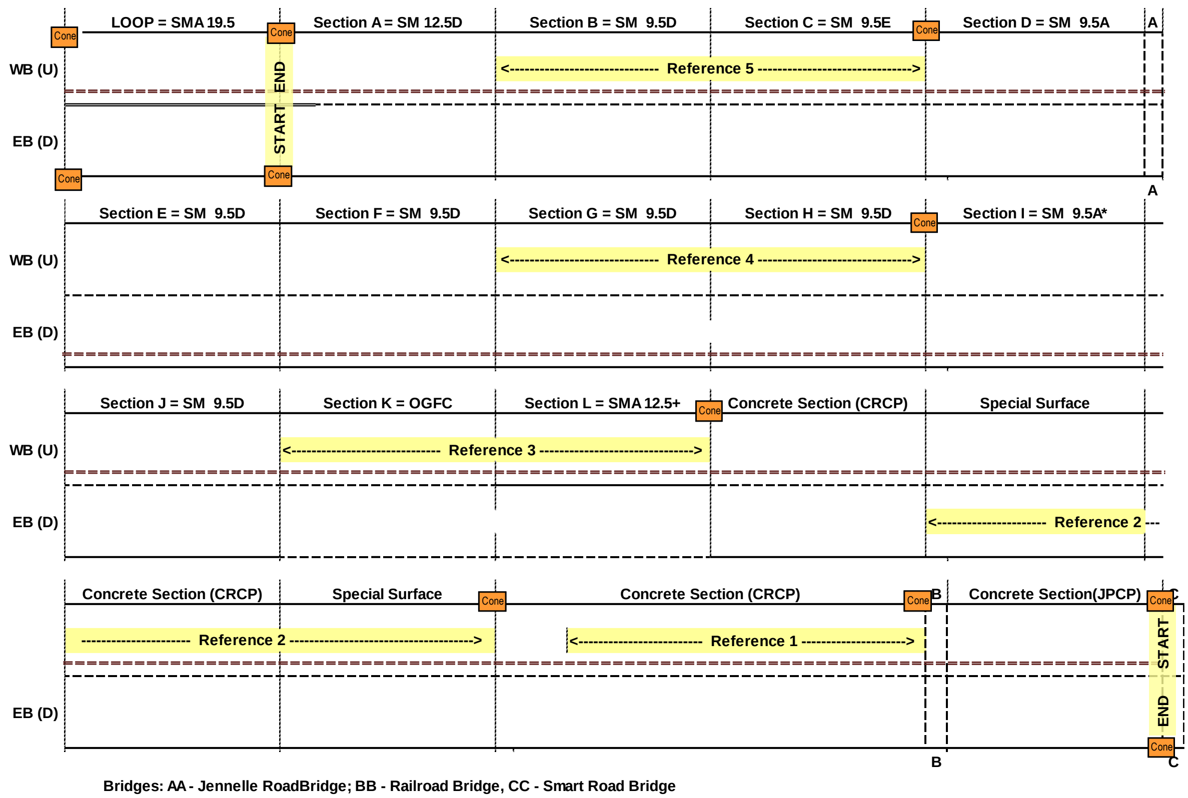


Figure 6. Layout of the sections selected for profile (texture) tests.

CT Meter, Dynamic Friction Tester, Hydrotimer and Stereo Vision System

Static tests were conducted with several devices, as shown in Figure 7. Two Circular Track Meter units (CT Meter – ASTM E2157[1]) were used to obtain static macrotexture measurements at three different locations in each section in the left wheel path of each lane. The measurements were separated by approximately 75 ft.

The Dynamic Friction Tester (DFT – ASTM E1911[1]) measurements were taken in the same location. An outflow meter test (Hydrotimer, ASTM E2380[1]) was also used in the same places in which the DFT and CT Meter measurements were taken. Finally, an experimental system (SVS) currently under development, that uses stereo vision technology to map true three-dimensional (3-D) surface maps, was also used. SVS results for the macrotexture mean texture depth (MTD) were obtained.

(a) Connecticut's CTMeter

(b) Virginia's CTMeter and SVS

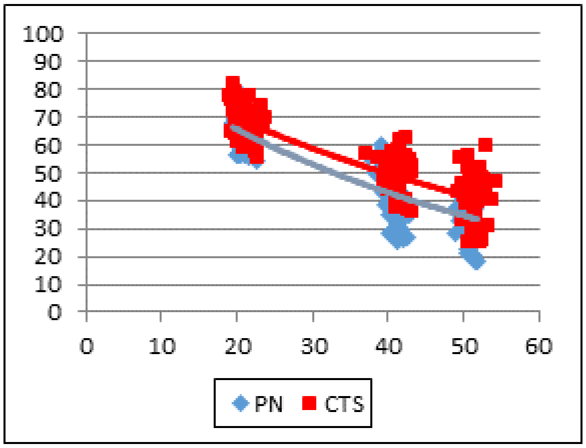
(c) Dynamic Friction Tester

(d) Hydrotimer

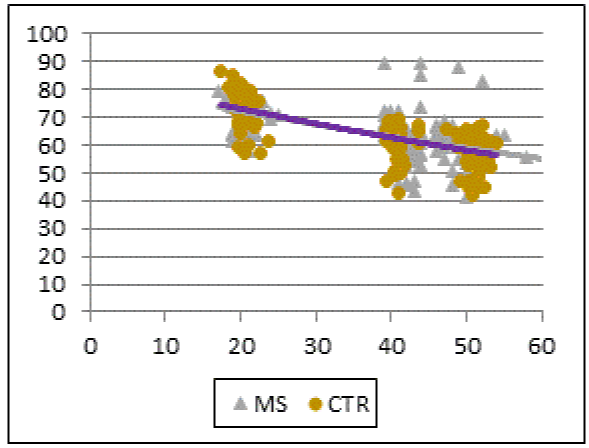
Figure 7. "Static" devices used for reference comparisons

II.4. Friction Comparisons

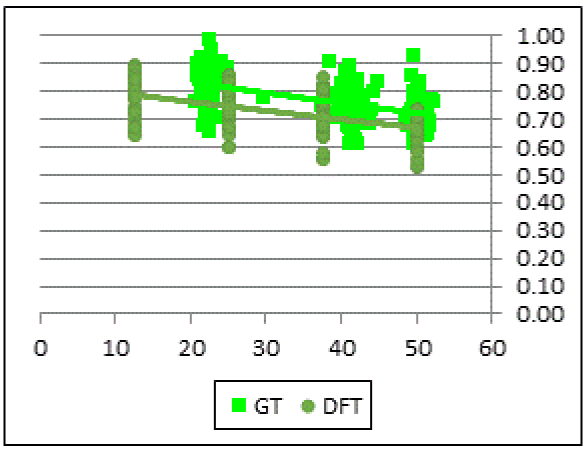
Raw friction measurements with different types of units and/or tires generally do not compare well. Figure 8a and 8b, however, shows plots for an overall view of the results of the similar types of tires. Figure 8c pairs the Griptester (GT) and the DFT results as these use a 0 to 1 scale, rather than the 0 to 100 scale used by the skid testers. The last plot (Figure 8d) has all the measurements, with a secondary axis for the GT and the DFT, to account for the difference in scales. All these plots represent the measurements obtained with the units going eastbound (downhill). The westbound results are included in the appendix. It must also be noted that the speeds shown for the Griptester are the test speeds and not the slip speeds at which the data is usually compared. The slip speed is 15.6% of the test speed.



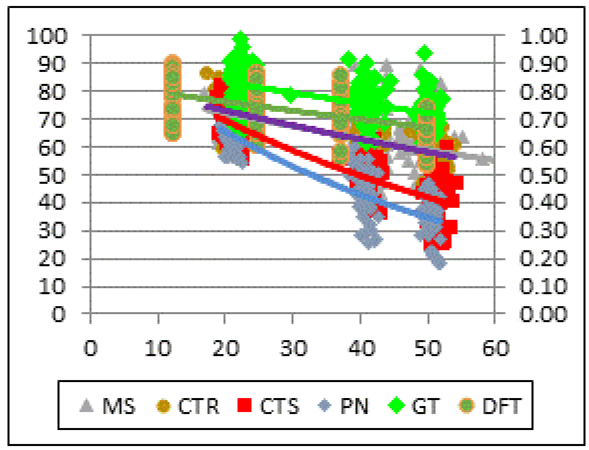
(a) Smooth tire results



(b) Ribbed tire results



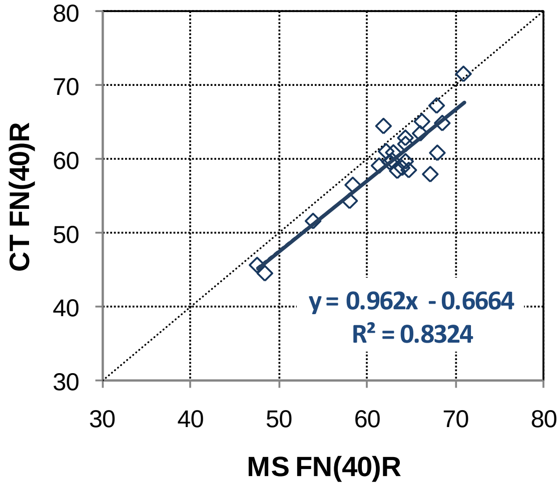
(c) Griptester and DFT results



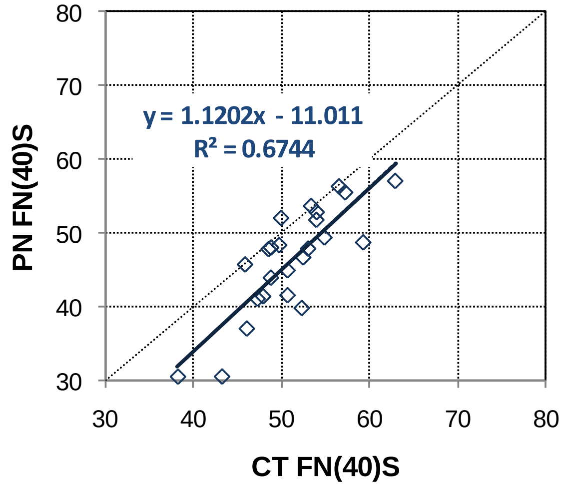
(d) All units results

Figure 8. Friction measurements for all units going eastbound (downhill)
PN = Pennsylvania (smooth tire), CTS = Connecticut (smooth tire), MS = Mississippi (ribbed), CTR = Connecticut (ribbed), GT = Griptester™, DFT = Dynamic Friction Tester

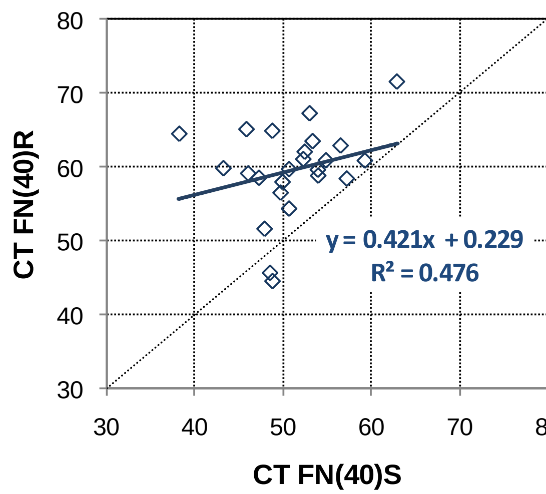
Figure 9a and 9b compares the average values measured with the two similar sets of locked-wheel trailers at the standard 40 mph speed. Both ribbed tire tests and both smooth tire tests gave very similar results as noted before, at 40 mph, which is the standard speed to perform friction measurements using skid trailers using ASTM E-274[1]. Figure 9c compares the results of the same unit that recorded both tires measurements.



(a) Ribbed tire at 40 mph



(b) Smooth tire at 40 mph

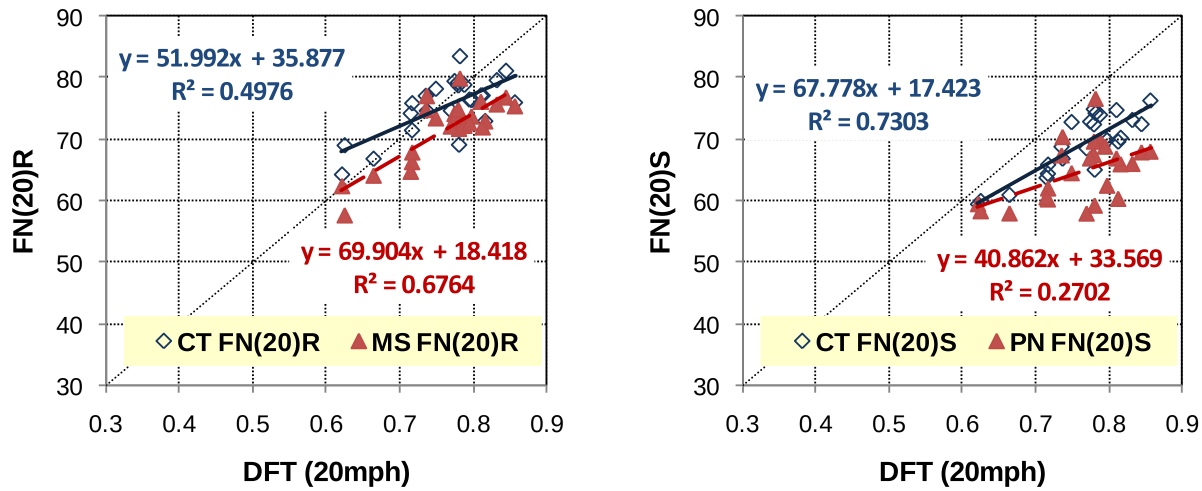


(c) Smooth vs. ribbed tire

Figure 9. Pairwise comparison of the locked-wheel trailer friction measurements.

In general, the plots in Figure 9 show that there is a reasonable correlation between the measurements taken with the same type of tire, but at the same time, the measurements with the same equipment using different tires does not show very good agreement. It should be emphasized that this could be due to the fact that these measurements where performed on different wheelpaths. Measurements with the ribbed tire are higher than those with the smooth tire.

Figure 10 shows the comparison between the average measurements taken with the locked-wheel trailers and the DFTester normalized at 20 mph. The values for the DFTester were interpolated from the measurements at 20 and 40 km/h. The results for the DFTester are closer to those measured with the ribbed tire than with the smooth tire.



(a) Ribbed tire comparisons at 20 mph (b) Smooth tire comparisons at 20 mph

Figure 10. Comparison of DFT and Locked-wheel measurements at 20 mph

II.5. Profile Comparisons

The six profilers measured the road ten times eastbound and ten times westbound. Analyses of all the profiles were obtained using PROVAL software. For illustration, Figure 11 shows the plot of one sensor from one run from each of the profilers as it recorded the data in the downhill (east-bound) direction. The profiles are superimposed and it can be observed that the individual measurements from each unit do not differ significantly. These profiles were all cropped for their comparison, to encompass a total length that includes all of the twelve asphalt sections labeled from A to L (4,045 feet) and all of the continuously reinforced concrete pavement (including the HFS sections, 2,287 feet) for a total of 6,332 feet.

Conversely, Figure 12 shows the plot for one sensor from one run from each of the profilers as it recorded the data in the uphill (west-bound) direction. The profiles are again superimposed and it can be observed that the individual measurements from each unit do not differ significantly, except for the one corresponding to the lightweight profiler (Mslwu1). This profile has a very high peak at about 2,290 feet which is the location of the joint between the concrete and the asphalt sections of the road. This unit is more sensitive to this disturbance than the others.

These profiles were again all cropped for their comparison. The length of all the uphill profiles include the continuously reinforced concrete pavement (including the HFS sections, 2,290 feet) plus eleven of the twelve asphalt sections labeled from L to B (3,715 feet) for a total of 6,005 feet. Section A was left out of the uphill comparison because it differs significantly at the end with the alignment of the downhill lane.

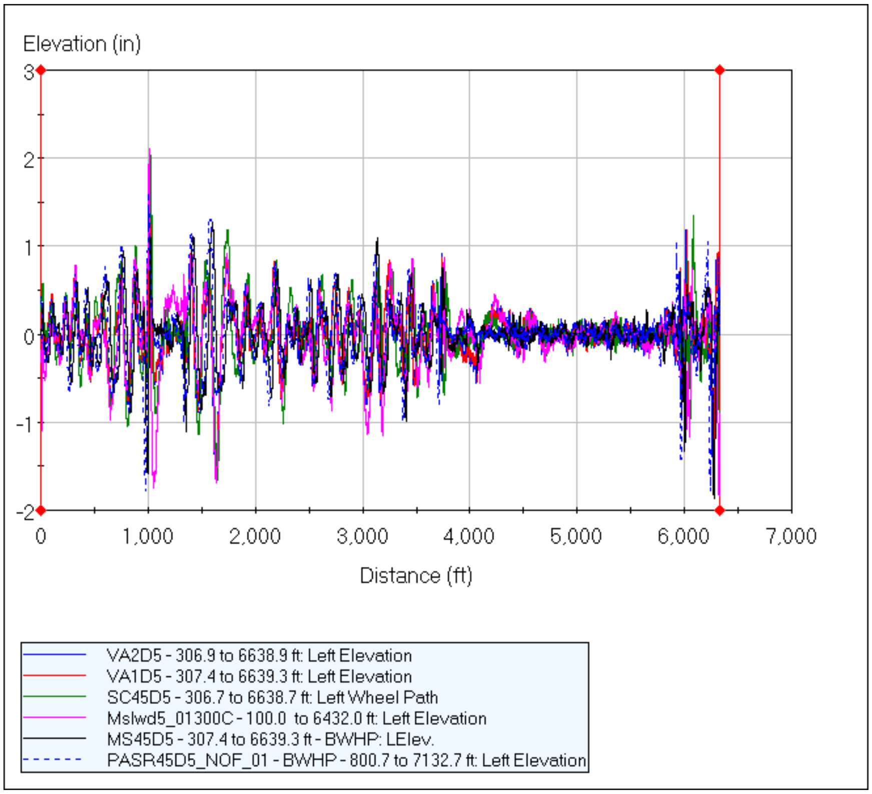


Figure 11. Profiler results for one downhill run for every profiler

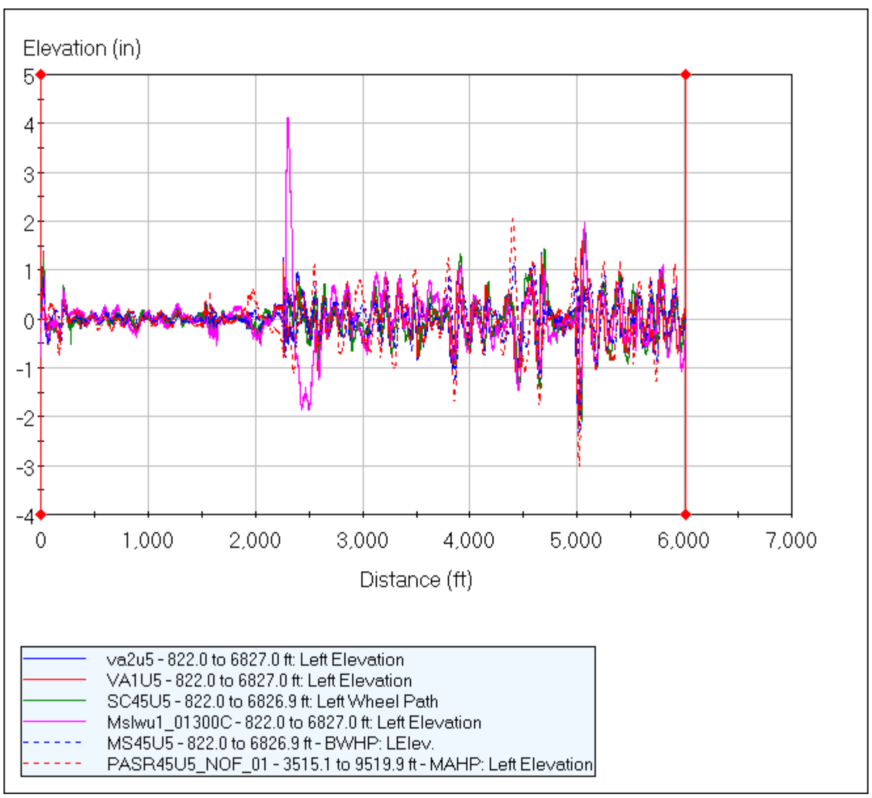


Figure 12. Profiler results for one uphill run for every profiler

A recurring problem when comparing inertial profile measurement systems is the lack of a true reference profile. Ideally the profiles for all the units should match substantially when superimposed over one another (i.e., good reproducibility). Steep grade conditions (6%) at the road affect the vehicles in achieving a desired uniform speed, especially on the downhill runs. Operators are forced to brake more often to try to maintain constant speed. Traveling uphill is easier using cruise control, if available (not all of the vehicles have cruise control). Marking the exact location of a reference on the road by means of a physical obstacle (bump) in the road to allow direct comparison of shorter sections was achieved partially on the downhill runs. It is intended that next year this will allow a comparison according to AASHTO Standard PP-49. A discussion of the repeatability, reproducibility and profile ride statistic comparisons is provided following.

Profile Repeatability

Repeatability according to the "Standard Practice for Certification of Inertial Profiling Systems" (AASHTO PP49 [2]) was made using PROVAL. Repeatability for each unit is based on cross-correlating each of the ten profiles to each of the remaining nine. The repeatability correlation matrices made for the six units are included in the Appendix II. Table 1 summarizes the repeatability obtained for each of the units tested, running downhill and uphill.

Table 1. Summary of the repeatability results for the profile measurements

Repeatability Correlations - Downhill											
	MS		PA		SC		VA-1		VA-2		LTW
Repeatability Statistics	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left
Repeatability Passing Score (%)	92	92	92	92	92	92	92	92	92	92	92
Comparison Count	45	45	45	45	45	45	45	45	45	45	45
% Passing	100	89	89	89	100	100	100	100	100	100	2
Mean	97	96	97	96	99	99	99	99	98	99	79
Minimum	94	88	91	89	98	99	99	98	97	98	66
Maximum	99	99	100	100	100	100	100	100	99	100	93
Standard Deviation	1.2	2.5	2.9	3.2	0.5	0.3	0.3	0.5	0.5	0.4	8.3
Grade	Passed	Passed	Passed	Passed	Passed	Passed	Passed	Passed	Passed	Passed	Failed

Repeatability Correlations - Uphill											
	MS		PA		SC		VA-1		VA-2		LTW
Repeatability Statistics	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left
Repeatability Passing Score (%)	92	92	92	92	92	92	92	92	92	92	92
Comparison Count	45	45	45	45	45	45	45	45	45	45	45
% Passing	100	100	100	100	100	100	100	100	100	100	2
Mean	97	98	99	98	99	99	99	99	98	99	47
Minimum	95	95	98	96	99	99	98	99	97	98	5
Maximum	100	100	100	100	100	100	100	100	99	100	93
Standard Deviation	1.2	1.2	0.5	0.8	0.3	0.3	0.5	0.2	0.5	0.4	25.8
Grade	Passed	Passed	Passed	Passed	Passed	Passed	Passed	Passed	Passed	Passed	Failed

The repeatability results show how efficient each unit was in obtaining the same profile measurements in each of its ten runs. All the profilers, except for the lightweight profiler, achieved a cross-correlation value of more than 92% required for a passing grade for repeatability for both the downhill and the uphill runs. The average cross-correlation values were higher than 96%, whereas the lightweight was only capable of getting 79% for the downhill and 47% for the uphill lanes. As explained before, this might have been the effect of the concrete-asphalt joint effect for this smaller unit.

Profile Reproducibility

Reproducibility results were obtained by comparing a fixed "reference" run (randomly chosen as the fifth run of each unit) to all of the runs from each of the other units again using a cross-correlation analysis with the PROVAL software for a total of six comparisons for five units each, as can be seen in Table 2. For example, MSD5-PAD denotes the cross-correlation comparison of the Mississippi profiler's fifth downhill run (MSD5) with the 10 downhill runs with the profiler from Pennsylvania (PAD). This yielded relative comparisons of the accuracy of the second unit with respect to the first. Ideally, this comparison would have to be made with a true reference profile measurement, but in lieu of this, all the units were compared to each other.

Table 2. Summary of reproducibility profiler results

Reporducibility Correlations - Downhill

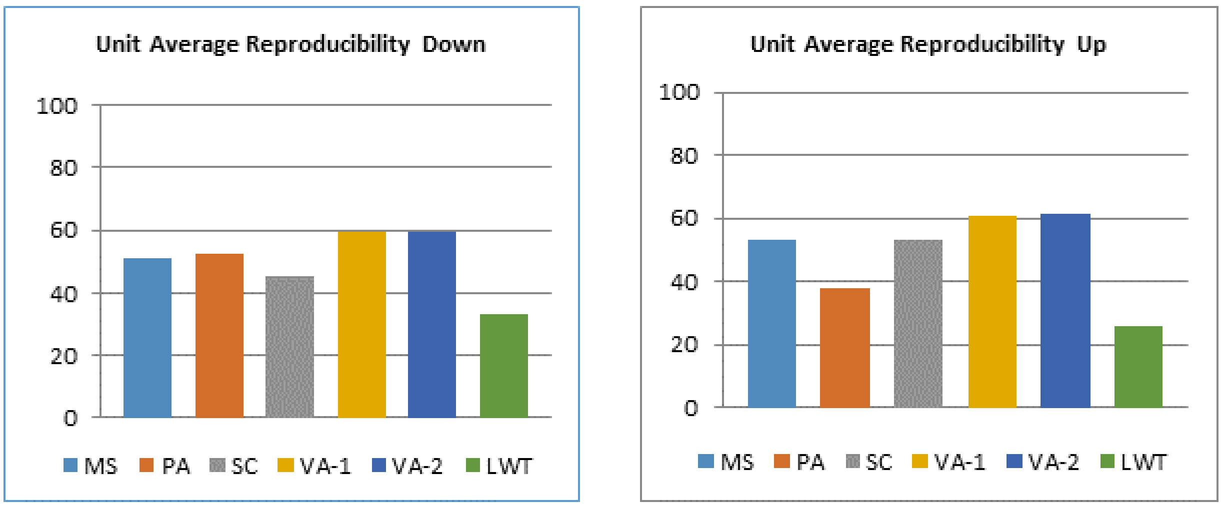
	MSD		PAD		SCD		VA-1D		VA-2D		LWTD
Reference:	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**
MSD5			88	83	37	37	54	51	56	52	8
PAD5	85	80			38	35	53	52	54	54	9
SCD5	37	36	38	35			61	60	59	59	22
VA-1D5	53	52	54	53	61	61			96	96	64
VA-2D5	55	53	55	55	58	59	96	96			62
LWTD5	6		7		21		5		5		
Sensor Average	47.2	55.3	48.4	56.5	43.0	48.0	53.8	64.8	54.0	65.3	33.0
Unit Average	51.2		52.5		45.5		59.3		59.6		33.0

Reporducibility Correlations - Uphill

	MSU		PAU		SCU		VA-1U		VA-2U		LWTU
Reference:	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**
MSU5			61	61	50	49	63	62	62	61	21
PAU5	63	62			36	35	35	34	37	35	15
SCU5	51	50	36	35			72	73	71	74	37
VA-1U5	61	60	34	34	72	72			96	97	31
VA-2U5	60	60	36	34	70	74	96	96			26
LWTU5	5		5		14		12		11		
Sensor Average	48.0	58.0	34.4	41.0	48.4	57.5	55.6	66.3	55.4	66.8	26.0
Unit Average	53.0		37.7		53.0		60.9		61.1		26.0

According to the standard, two profilers pass the reproducibility test if the "percent passing" score is higher than 90%. This would mean that at least nine out of the ten comparisons resulted in a cross-correlation value of more than 90%. In general, none of the comparisons have a very high average coefficient of cross-correlation, except for the comparisons that included the two units from Virginia (the complete results are for each run is included in Appendix II).

These variations are expected because these are the only two units that are manufactured by the same profiler manufacturer and apply the same processing filters to the collected profiles. The rest of the units use different filters and that makes it almost impossible to compare according to the guidelines. Only one profiler's data was submitted without any processing as "raw" files. It is intended for next year to try to do this for all the profilers to allow a more valid comparison. A graphical representation of these results can be seen in Figure 13.



(a) Downhill measurements (b) Uphill measurements

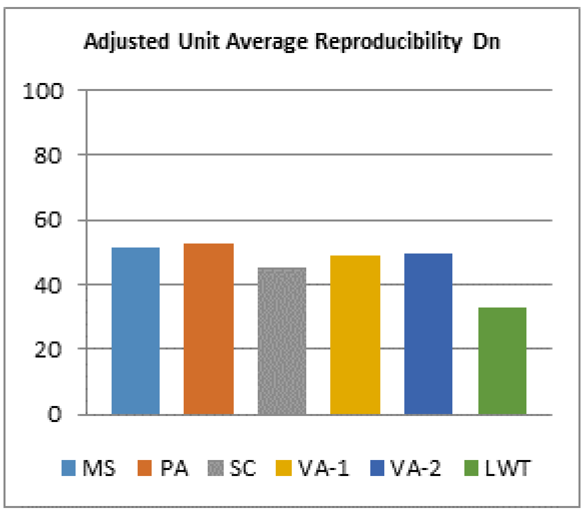
Figure 13. Profiler reproducibility average results

However, if the analysis is repeated but the results for the two units from Virginia are not taken into consideration for the average comparison, the overall results even out much more, giving most units around a 50% repeatability grade for the downhill and the uphill runs, respectively, as seen in Table 3. It must be noted that the profiler that resulted with the lowest grade does not have cruise control available, making it harder to control the speed and so a lot of braking is done while collecting the data. For the lightweight unit, this same condition probably has an inverse effect because it has to accelerate to maintain the speed, even downhill, but its sensor does not recover as easily on the pavement joints (rebound effect) when going uphill. Figure 14 presents graphically the adjusted results.

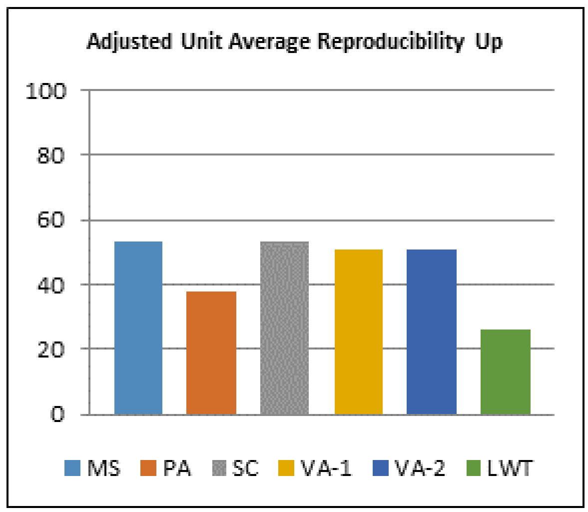
Table 3. Summary of reproducibility profiler adjusted results

Reproducibilility Correlations Adjusted - Downhill	MSD		PAD		SCD		VA-1D		VA-2D		LWTD
	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left
Sensor Average	47.2	55.3	48.4	56.5	43.0	48.0	53.8	64.8	54.0	65.3	33.0
Unit Average	51.2		52.5		45.5		59.3		59.6		33.0

Reproducibilility Correlations Adjusted - Uphill	MSU		PAU		SCU		VA-1U		VA-2U		LWTU
	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left
Sensor Average	48.0	58.0	34.4	41.0	48.4	57.5	45.5	56.3	45.3	56.7	26.0
Unit Average	53.0		37.7		53.0		50.9		51.0		26.0



(a) Downhill Measurements



(b) Uphill Measurements

Figure 14. Profiler reproducibility average “adjusted” results

Ride Statistics (International Roughness Index-IRI) Comparisons

The final, and of more practical significance comparison, analyzes the results of the computed International Roughness Indices (IRI) that resulted from the measurements. Typically, IRI is a single value for a given segment of road for each of the sensors in the vehicles. All of the vehicles, except the lightweight profiler, collected at least a right and a left profile, with South Carolina producing a third profile from a sensor in the middle of the vehicle. Table 4 summarizes the results for the IRI for each sensor and also the mean of the right and the left IRI (MRI), calculated by PROVAL.

Table 4. Summary of ride statistics (IRI and MRI)

Downhill

IRI Ride Statistics (in/mi)

Unit	MS		PA		SC		VA-1		VA-2		LWT
Channel	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left
Average	114.2	111.6	114.4	112.7	113.6	106.9	112.4	109.4	111.4	113.6	101.4
Std Dev	0.74	1.02	1.82	0.94	1.21	0.77	0.55	0.44	0.63	0.86	1.14

MRI Ride Statistics (in/mi)

Unit	MS	PA	SC	VA-1	VA-2	LWT
Average	112.9	113.6	110.3	110.9	112.5	N/A
Std Dev	0.27	0.57	0.43	0.19	0.32	N/A

Uphill

IRI Ride Statistics (in/mi)

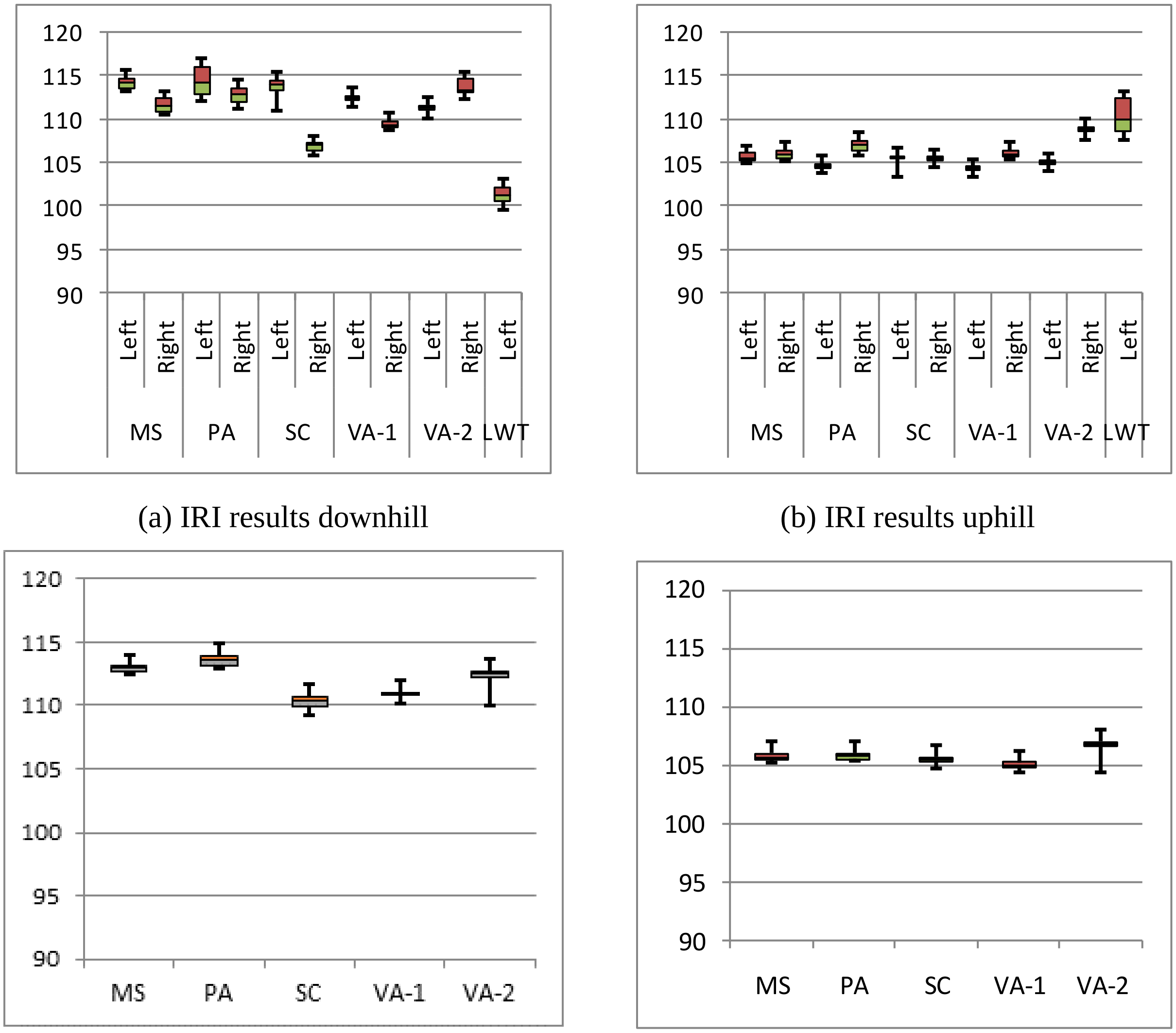
Unit	MS		PA		SC		VA-1		VA-2		LWT
Channel	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left
Average	105.4	106.1	104.7	107.0	105.7	105.4	104.3	106.0	105.0	108.7	110.9
Std Dev	0.67	0.82	0.34	0.74	0.39	0.46	0.41	0.67	0.28	0.93	4.21

MRI Ride Statistics (in/mi)

Unit	MS	PA	SC	VA-1	VA-2	LWT
Average	105.7	105.9	105.6	105.1	106.9	N/A
Std Dev	0.41	0.42	0.39	0.51	0.50	N/A

It is interesting to note that for all of the inertial profilers, except the lightweight, all the mean values are very close and the standard deviations are less than 1 in/mile in all cases. The individual sensors have larger values, probably pointing out some issues to be checked by those units, but in general they are also very acceptable. In spite of this, most results showed great correlation even after noting the differences regarding the filtering of the raw data and the difference in manufacturers' filtering issue.

These results are plotted with whisker bars in Figure 15, showing the maximum and minimum values and the three quartile data points for each. It is very evident that the ride statistics results are almost identical for all the profilers except for the lightweight in both directions.



(a) IRI results downhill

(b) IRI results uphill

(c) MRI results downhill

(d) MRI results uphill

Figure 15. Summary IRI and MRI measurements for all profilers (in/mile)

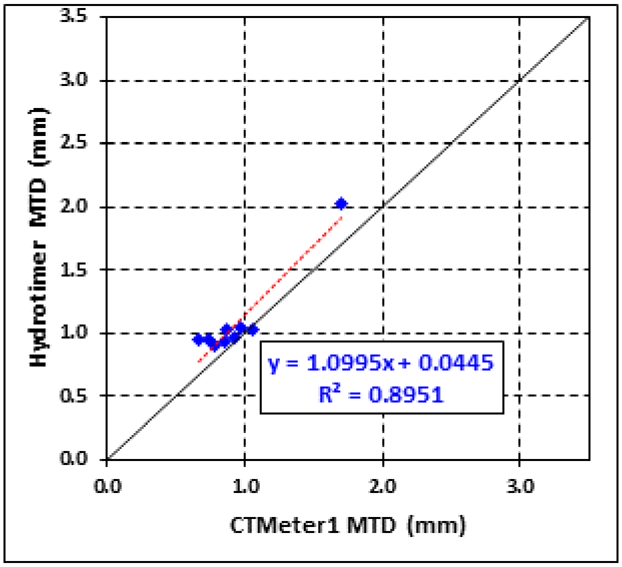
II.6. Macrotexture Comparisons

The testing of the all of the macrotexture instruments was conducted on all of the different pavement surfaces with very good results. Nine different variations of surface textures in the asphalt pavement sections and three in the continuously reinforced concrete sections with the HFS were measured. The asphalt surface types include five different SUPERPAVE mixtures, two stone mastic asphalt (SMA) mixes (Sections Loop and L), and a 12.5-mm open-graded friction course (OGFC) placed on section K. Table 5 summarizes the results of all the measurements. For each of the Smart Road pavement sections, there were two measurements because each lane was sampled separately, thus establishing directional differences in the sampled pavements. A textural difference exists between the travel lanes because the eastbound (downhill) lanes were not instrumented when the Smart Road was built, unlike the westbound (uphill) sections where all the instrumentation was placed. The instrumentation forced lower compaction efforts in the westbound lanes to avoid damaging the embedded instruments, resulting in coarser, less compacted surfaces with greater texture.

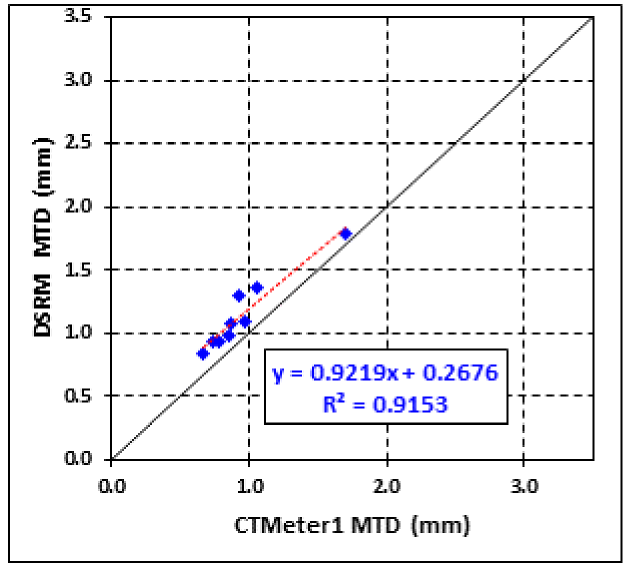
Table 5. Comparison of macrotexture measurements

Section		CTM1		CTM2		SVS	HT	SP	DSRM
		MPD	MTD	MPD	MTD	MTD	MTD	MTD	MTD
DOWNHILL	Loop	1.00	1.02	0.92	0.94	2.32	1.05	0.86	1.32
	A	0.53	0.57	0.52	0.56	1.19	0.89	0.38	0.74
	B	0.68	0.71	0.67	0.71	1.56	0.87		0.93
	C	0.71	0.74	0.69	0.73	1.67	0.83		0.89
	D	0.56	0.60	0.53	0.57	1.37	0.89		0.73
	I	0.92	0.94	0.93	0.95	2.02	0.97		1.04
	J	1.05	1.06	1.03	1.05	2.34	1.04	0.56	1.06
	K	1.63	1.61	1.60	1.58	3.18	1.85		1.68
	L	1.00	1.02	0.92	0.94	2.19	0.95	0.65	1.26
	Cargill	1.84	1.81	1.80	1.78	2.02	3.75	2.30	1.84
	EP5	1.20	1.20	1.19	1.19	1.62	1.50	1.55	1.41
	PCC	0.70	0.74	0.71	0.74	1.99	1.03	0.82	1.03
UPHILL	Loop	0.80	0.82	0.78	0.80	2.15	0.85		1.25
	A	0.89	0.91	0.90	0.92	1.81	1.01		1.14
	B	1.01	1.02	1.07	1.09	2.19	1.19		1.23
	C	0.79	0.81	0.79	0.81	1.86	0.98		0.98
	D	0.70	0.73	0.69	0.73	1.57	1.00		0.95
	I	0.73	0.76	0.70	0.74	1.72	0.89		0.91
	J	0.85	0.87	0.83	0.85	1.73	1.03		1.11
	K	1.80	1.78	1.64	1.62	3.33	2.19		1.89
	L	1.08	1.09	1.03	1.05	2.90	1.09		1.44
	Cargill	1.86	1.83	1.83	1.80	2.14	2.02	2.20	1.81
	EP5	1.17	1.18	1.17	1.18	1.38	1.20	1.52	1.17
	PCC	0.80	0.83	0.77	0.80	2.33	1.22	0.95	1.42

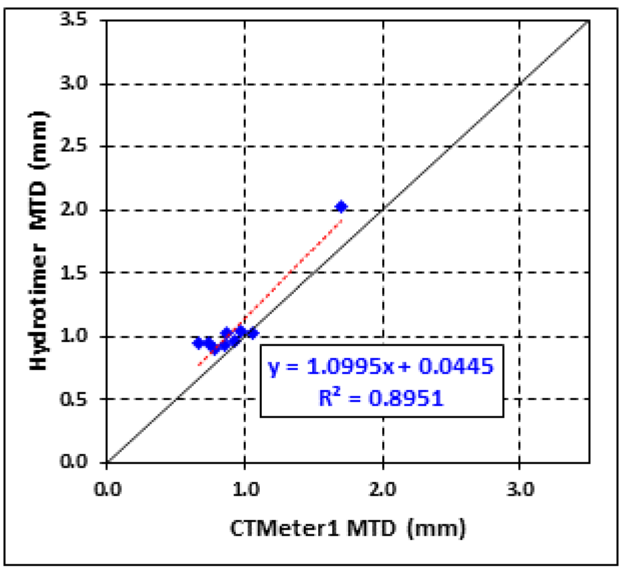
To establish comparisons to the other methods of macrotexture measurements, a Circular Track Meter ASTM E 2157[1], labeled CTMeter1, was used as the reference instrument. All mean profile depth (MPD) measurements were converted to mean texture depth (MTD) as indicated by the applicable standards, ASTM E 965[1] and E 2157[1]. Four other instruments were compared to this base measurement. Besides the prototype stereo vision system (SVS), the other three instruments included a Hydrotimer (HT) ASTM E 2380[1], a second Circular Track Meter labeled CTMeter2 and a Digital Surface Roughness Meter (DSRM)[4]. Figure 16 summarizes the results of all of these instruments on the asphalt surfaces tested.



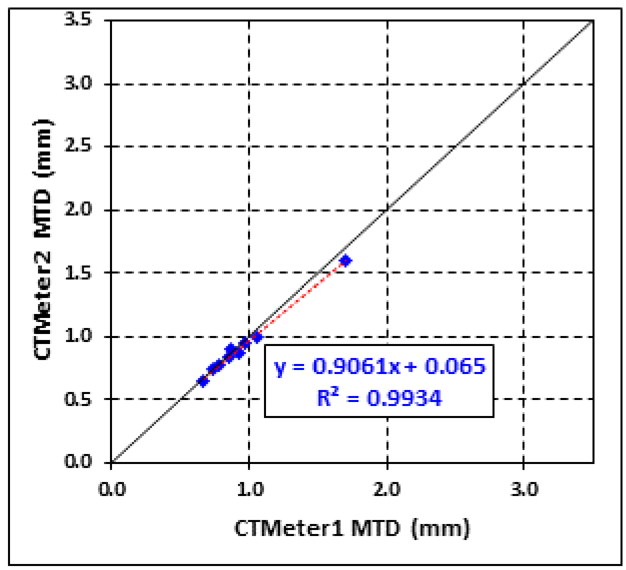
(a) SVS



(b) DSRM



(c) Hydrotimer



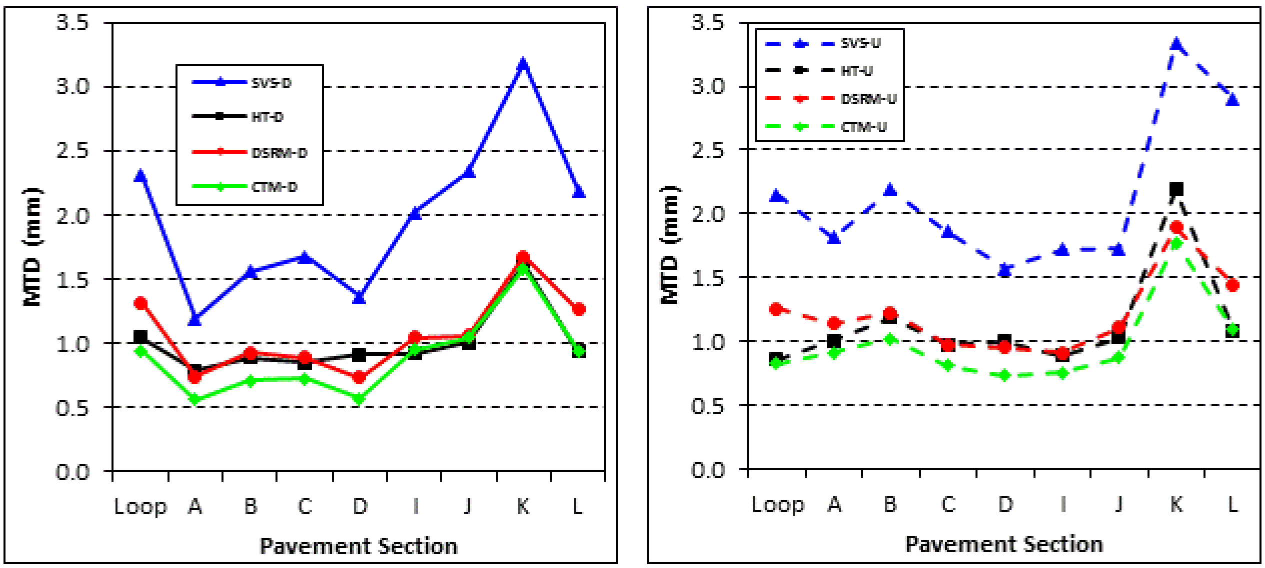
(d) CTMeter 2

Figure 16. Macrotexture measurements from different instruments at the Virginia Smart Road

The Hydrotimer is a technology that utilizes the permeability concept to correlate flow of water to the macrotexture of the pavement by relating the time it takes for a known volume of water to be emptied from a gauged container; the time is inversely proportional to the macrotexture of the surface being tested. The DSRM is a hybrid technology that uses a mix of laser and optical technologies to estimate the macrotexture parameters of the surfaces. Measurements with the DSRM were performed in 2007 during the first equipment comparison and are included in this report to evaluate and compare the SVS results.

Figure 16 shows that all of the technologies correlated very well with the CTMeter ($R^2 > 0.90$). However, it is interesting to point out that both the DSRM and the SVS tend to detect more texture than the other methods; which yield values of MTD consistently higher than the other methods. There are several possible reasons for this.

One of these reasons may be that the CTMeter uses only 1,024 points to scan a circular track where the measurements for a profile are made, which acts as a filter to eliminate many points that might increase the MTD. Compared to an area-based measurement such as the ones performed with the DSRM or the SVS, there can be anywhere from one to three more levels of magnitude in the number of sampling points in each measurement (pixels).



(a) Downhill (b) Uphill

Figure 17. Comparison of directional MPD measurements at the Virginia Smart Road

Another possible explanation for the difference in the measurements between the SVS and the CTMeter is seen in Figure 17. Figure 17a plots the macrotexture results for all these instruments in the downhill direction and figure 17b in the uphill direction. The high values in section K are due to the high porosity of the OGFC surface.

II.7. Final Remarks

Pavement surface property measurement equipment comparisons were performed at the second annual equipment roundup at the Smart Road. These tests provided the Surface Properties consortium participants with an informal verification of their measurement equipment. The following are some of the most important findings:

Friction: Comparable friction measurements results were obtained among the units that used the same type of tire. This represents a validation of the measurements obtained with the participating locked-wheel friction equipment.

Profile: Repeatability, reproducibility and accuracy were measured and reported for each of the participating profilers. Participants are encouraged to review the results to understand how the various participating units are performing. Although the absolute accuracy of the measured profiles cannot be assessed at this time, the measured MRI values were compared with each other. The results suggest that all of the profilers consistently obtained very similar MRI/IRI values. The repeatability standard deviation for each of the profilers was less than 1%.

It is recommended that next year's events feature an artificial bump at the beginning and end of each of the calibration segments to allow the exact pinpointing of the starting and ending points for the analysis of their profiles. Matching of these profiles will further facilitate the equipment comparisons that were initiated this year.

Macrotexture: As the International Friction Index (IFI) finds more application in the USA, macrotexture measurements will become more important. DOT personnel should be aware that there are several devices that allow the measurement of this parameter. The tests conducted showed that the results for the four technologies compared correlate reasonably well on the pavement surface evaluated.

II.8. References

1. ASTM, Annual Book of ASTM Standards, vol. 04-03, ASTM International, (2007), West Conshohocken, PA.
2. AASHTO, Standard Practice for Certification of Inertial Profiling Systems, AASHTO Designation: PP 49, American Association of State Highway and Transportation Officials, Washington, D.C.
3. Wambold, James C., "Obtaining the Skid Number at Any Speed from a Test at Single Speed", Transportation Research Record, No. 1196 (1988), pp. 300-305.
4. Mokarem, D. Use of the Digital Roughness Meter in Virginia. Technical Report VTRC 07-R4, Virginia Transportation Research Council and Federal Highway Administration, 2006.

III. 2009 Annual Equipment Comparison Roundup at the Smart Road[3]

III.1. Executive Summary

The regional pooled-fund project known as the Pavement Surface Properties Consortium is a research program focused on enhancing the level of service provided by the roadway transportation system by optimizing pavement surface texture characteristics. The program was set up in 2006 with support from the Federal Highway Administration (FHWA), and six departments of transportation (DOTs) from the states of Connecticut, Georgia, Mississippi, Pennsylvania, South Carolina and Virginia. The Consortium provides a practical mechanism to conduct research on pavement surface properties and explore their relationships with ride quality, friction, and noise. Complementing this effort, additional research focuses on the review, testing, and evaluation of emerging technologies.

To verify/ validate/ harmonize the measurements of the various pieces of equipment owned and operated by the participating agencies, the consortium organizes an equipment comparison rodeo, called the "Surface Properties Rodeo", at the Virginia Smart Road every year. The specific objectives for this year's event were:

- Develop speed adjustment factors for the skid locked-wheel trailers (ASTM E-274) using the smooth tire data collected in 2007 and 2008 and the ribbed tire data from the 2009 friction testing, and
- Follow the revised AASHTO PP–49 Standard Practice for Certification of Inertial Profiling Systems specification, to compare the eight profilers that participated in the 2009 comparison to the profile reference measurements made with an ICC SURPRO reference device to determine their repeatability and reproducibility compliance.

This year's profiler comparison had ample support from the FHWA. The rodeo had participation from one of the LTPP inertial profilers in the comparison. Additionally, FHWA hired a consultant to help provide technical assistance on profiler certifications procedures, evaluations and data analysis and any necessary recommendations regarding the set-up of the profiler certification site.

The following summarizes the activities, as well as the principal findings and recommendations from this year's rodeo:

Friction

- Adjustment factors to convert skid numbers from one speed to any desired speed were developed for the participating skid testers. The factors were computed for three different pavement surface types defined using principal component analysis. Linear relationships were used to model friction measurements as a function of test speed. The test speeds were typical of ordinary testing conditions (30-65 mph). Confidence intervals, which show the range in skid numbers over which the adjustment factors are valid for each group of mixes, were determined for each surface group for each tire tested.
- Confidence intervals for the smooth-tire friction testers were wider because the test results are more varied than those collected using the ribbed tire.

[3] Prepared by: Edgar de León Izeppi, Gerardo W. Flintsch, Kevin K. McGhee, Shahriar Najafi, and Sameer Shetty

- Adjustment factors derived from texture using ribbed-tire lock-wheeled friction testers had low coefficients of determination (R^2) probably because the measurements with this tire are not sensitive to macrotexture. This observation is in agreement with previous studies and additional research should be pursued to study the effects of tire thread depths on the determination of speed adjustment factors.

Profile

- Following AASHTO specifications, a profiler certification/ verification site was established at the Virginia Smart Road. The study focused on the comparison of profilers with a reference device (ICC SURPRO) and identified several different factors affecting this comparison.
- Good agreement of IRI values were found between the reference device (SURPRO) and each of the participant profilers IRI for all test sections. Repeatability of all of the profilers was in accordance with the specifications for most of the sections tested.
- Error in the distances recorded by the profilers DMIs were related to the procedures followed for their calibration. The grade of the test track likely affected DMI calibration, which resulted in relatively low cross-correlations for reproducibility with the reference profiler (SURPRO).

Recommendations

- It is recommended that each of the participating agencies try the linear relationships modeled (simple model) to convert friction measurements as a function of speed (30-65 mph) for each of the suggested surfaces groups. When possible, if texture data becomes available, it will be valuable to compare these conversions with those obtained if the second model developed is used to further investigate and validate this approach.
- In future skid testing equipment comparisons it is recommended to obtain a measurement of the tire thread depths of the ribbed tires of the participating skid testers to determine the effects of it in the determination of speed adjustment factors.
- It is also recommended to continue to make profiler comparisons such as the one implemented in the Virginia Smart Road for regional profiler verification. The reference device (SURPRO) was found to provide a reasonable basis for such comparisons and should be able to be used until a final reference device(s) can be identified by the TPF-5(063) and defined in a standard specification.
- It is strongly suggested that profiler DMIs be calibrated on flat grade test segments to avoid any possibility of DMI error which can impact cross-correlations, which profoundly affects repeatability and reproducibility.

III.2. Introduction

The regional pooled-fund project known as the Pavement Surface Properties Consortium established a research program focused on enhancing the level of service provided by the roadway transportation system by optimizing pavement surface texture characteristics. The program was set up with support from the Federal Highway Administration (FHWA), and six departments of transportation (DOTs) from the states of Connecticut, Georgia, Mississippi, Pennsylvania, South Carolina and Virginia. The Consortium provides a practical mechanism to conduct research on pavement surface properties and explore their relationships with ride quality, friction, and noise. Complementing this effort, additional research focuses on the review, testing, and evaluation of emerging technologies.

One of the main services of the consortium is to provide a venue to verify/ validate/ harmonize the measurements of the various pieces of equipment owned and operated by the participating agencies. In order to do this, the research team organized the third consortium equipment comparison rodeo, called the "Surface Properties Rodeo", at the Virginia Smart Road on the week of May 19, 2009. Participating agencies brought some of the equipment used in their respective states to measure profile, texture and friction. This report describes the results of this event.

III.3. Objectives

The general objective of every roundup is to evaluate and compare some of the equipment utilized to measure smoothness, texture and friction by the individual states participating in the consortium. The specific objectives for this year's event were:

- Friction: Develop speed adjustment factors for the skid locked-wheel trailers (ASTM E-274) using the smooth tire data collected in 2007 and 2008 and the ribbed tire data from the 2009 friction testing, for the different pavement types tested (six units participated in the 2009 comparison).
- Following revised AASHTO PP–49 Standard Practice for Certification of Inertial Profiling Systems specification, obtain profile measurements and compare them to the reference measurements made with an ICC SURPRO device to determine their repeatability and reproducibility correlations (eight profilers participated in the 2009 comparison).

III.4. Testing Facility

The Virginia Smart Road is a 2-mile facility particularly appropriate for this kind of testing because it includes a variety of real world flexible and rigid pavement surfaces and it is operated under controlled traffic conditions. In the first mile, the facility offers seven different types of asphalt concrete surfaces, including five different SUPERPAVE^{TM} mixtures, a 12.5mm stone mastic asphalt (SMA), and a 12.5mm open-graded friction course (OGFC).

In the second mile, two rigid concrete pavement surfaces complete the sections, featuring a continuously reinforced concrete pavement (CRCP) and a jointed reinforced concrete pavements (JRCP) section. The Continuously Reinforced Concrete Pavement (CRCP) has a transversely tined finish and it includes two 300-feet sections with epoxy overlays consisting of a double layer of aggregate bonded by epoxy coatings. The test road has a maximum longitudinal grade of 6 percent.

For the flexible pavement sections, the uphill (westbound) and the downhill (eastbound) lanes have slightly different micro- and macrotexture due to differences in construction compaction due to the sensors placed for the instrumentation located only on the uphill lane.

III.5. Friction Comparisons

The locked-wheel trailer is the friction measuring device currently used by the member state Departments of Transportation (DOTs) in the Consortium. It measures the steady-state friction force on a locked wheel on the wetted pavement surface as the wheel slides at a constant speed. The skid resistance of the paved surface is reported as skid number (SN), which is the force required to slide the locked test tire at a stated speed, divided by the effective wheel load and multiplied by 100 (ASTM E-274). Skid testing is conducted using a smooth tire (ASTM E-524) or a ribbed tire (ASTM E-501).

Although pavement friction measurements can be conducted at different speeds, the standard test speed is 40 mph. Speed on most rural interstate and primary roads is rarely lower than 65 mph, whereas on most urban environments, congestion, intersections, and high-traffic volumes, the prevailing speeds may be as low as 20 mph. These traffic conditions create problems for skid trailer operators who are trying to perform skid tests at the standard test speed. A solution would be to develop adjustment factors to convert those measurements obtained at higher (rural areas) or lower (urban areas) speeds to what might be obtained at a standard speed (e.g., 40 mph).

Data Collection

Skid trailer measurements were made in series of five runs for each device at different testing speeds. For the smooth tire, measurements were obtained with three skid testers in 2007 and 2008 at 20, 40 and 50 mph, while the ribbed tires the measurements in 2009 were obtained with three skid testers at 40, 50 and 60 mph. The macrotexture (Mean Profile Depth – MPD) data were collected with a Circular Texture Meter (CTMeter) in accordance with ASTM E-2157. Table 1 shows the average texture results and some basic material descriptors for the surfaces that were tested in 2007, 2008 and 2009. The texture measurements are listed as eastbound (downhill) and westbound (uphill) for the direction of the lanes.

Table 1 Section Texture and material properties of the pavement surfaces tested

Section	Mix Type	Asphalt Binder	NMS	Eastbound MPD (mm)	Westbound MPD(mm)
1	SMA 19.0	PG 70-22	19	1.00	0.80
2	SM-12.5D	PG 70-22	12.5	0.53	0.89
3	SM-9.5D	PG 70-22	9.5	0.68	1.01
4	SM-9.5E	PG 76-22	9.5	0.71	0.79
5	SM-9.5A	PG 64-22	9.5	0.56	0.70
6-9	SM-9.5D	PG 70-22	9.5	N/A	N/A
10	SM-9.5A(h)	PG 64-22	9.5	0.92	0.73
11	SM-9.5D	PG 70-22	9.5	1.05	0.85
12	OGFC	PG 76-22	12.5	1.63	1.80
13	SMA-12.5D	PG 70-22	12.5	1.00	1.08
14	Epoxy O/L	-	-	1.84	1.86
15	Epoxy O/L	-	-	1.20	1.17
16	CRCP	-	-	0.70	0.80

NMS = nominal maximum aggregate size, MPD = mean texture depth, O/L = overlay

The complete set of experimental pavement sections tested in 2009 with the ribbed tires can be seen in Figure 1. All the lock-wheeled friction data was collected on May 21. Continuous friction measurements were obtained with another unit that participated in the comparison, a fixed-slip device (GripTester) commonly used in airport friction testing. Future work and correlations will be obtained from the data collected with this instrument.

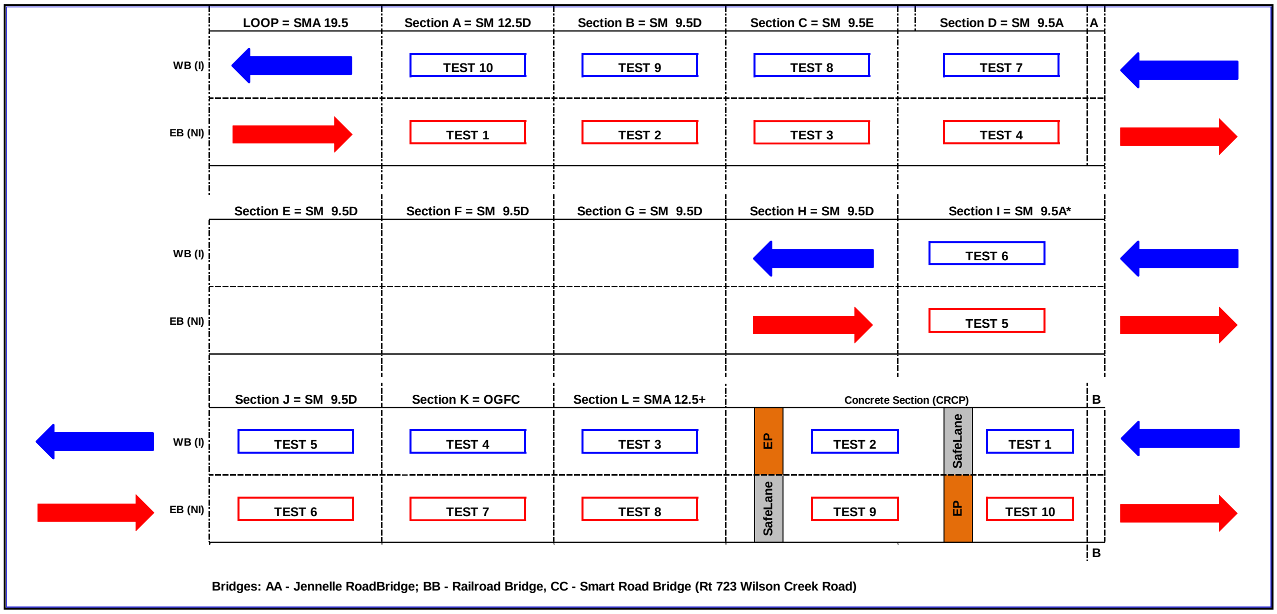
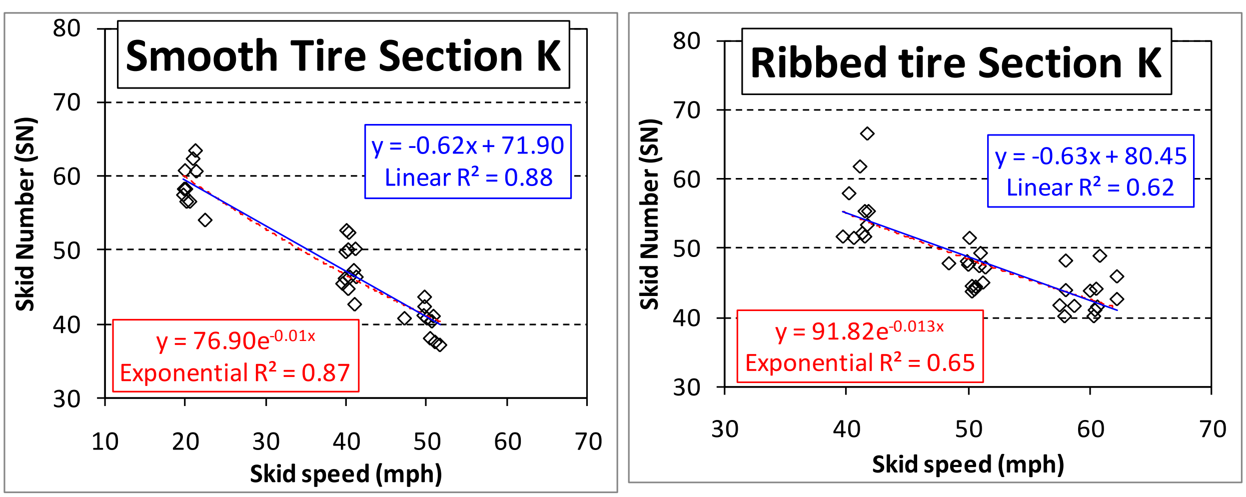


Figure 1 Smart Road sections layout

Results and Analysis

The skid testing data from all of the different surfaces at the Smart Road were used to make individual plots of skid versus speed and fitted with linear and exponential models (Figure 2).



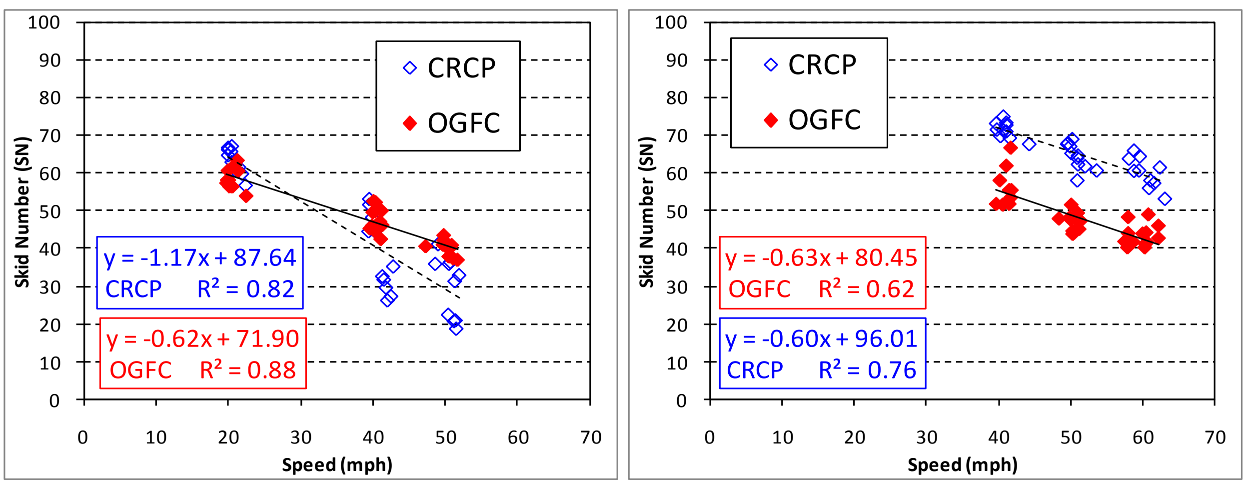
(a) Ribbed tire skid results section J

(b) Ribbed tire skid results section K

Figure 2 Sample results for skid data in two different sections

Figure 3 shows sample results for two sections with each of the test tires. Important differences can be observed between the test results for each of the test tires. For smooth tires, the magnitudes of the skid measurements are very similar for both pavement surfaces whereas the results for the ribbed tire have approximately a 25% difference between the surfaces shown. Overall, as expected, smooth tire results are lower than ribbed tire results at similar speeds. Although it has been documented that skid measurements vary with speed through an exponential trend (*1*), simpler linear correlations exhibited almost identical R^2 values to the exponential models over the range of the speeds tested (20-60 mph) in the study.

For the example shown in Figure 3a, it can be observed that the trend lines corresponding to each surface for the smooth tire have very different slopes, appearing to cross at approximately 30 mph. The OGFC pavements tested have higher macrotexture than the CRCP. When tested with the smooth tire, the loss of friction with speed (indicative by the slope of the line) was significantly less. This clearly demonstrates the sensitivity of the smooth tire to macrotexture. The results for the ribbed tire suggest that they may not be as sensitive to macrotexture, as is shown in figure 3b. Ribbed tire results lead to best-fit lines with slopes that have a more parallel trend between the two surfaces shown, very different than the results obtained for the smooth tires.



(a) Smooth tire skid test results (b) Ribbed tire skid results

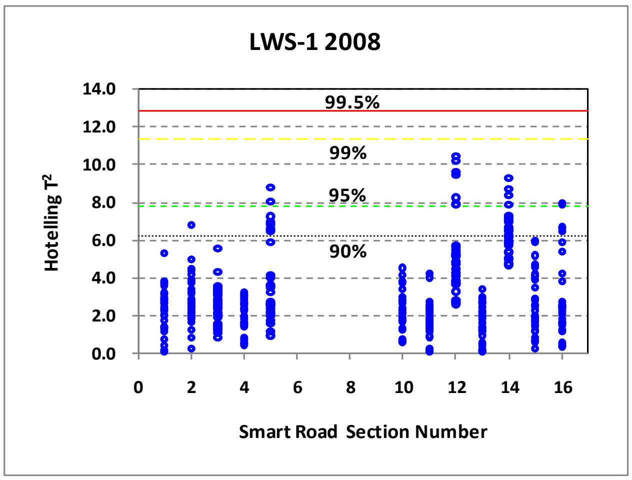
Figure 3 Sample skid testing results for two sections of the Smart Road

In order to simplify the development of the speed adjustment factors, it was important to group types of pavement surfaces with similar behavior. Due to the large amount of data, visualizing all of it together in skid number-speed plots was not practical or useful. Data collected included several variables for each friction measurement, so the pavements were grouped into similar categories by using a multiple variable approach that analyzed texture, speed, and skid number concurrently. For this purpose, the Principal Component Analysis (PCA) method was used, as is explained below.

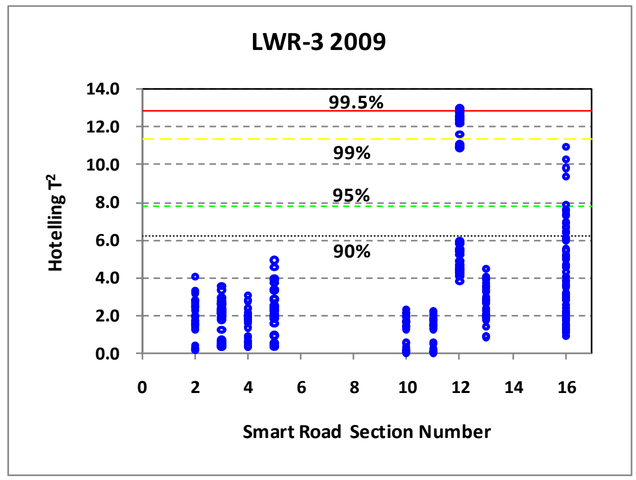
Principal Component Analysis to Group Similar Surfaces

Hotelling's T^2 statistic is used to differentiate individual data points where multiple variables or properties are measured by converting them with PCA into a new single objective score that can identify the different behavior of the pavement surfaces. Hotelling's T^2 is a statistical measure of the multivariate distance of each observation from the center of the data set. It is an analytical method to find the most extreme points in the data set. Using T^2 after the PCA allows the incorporation of all of the variability into one statistic (*2*).

Figure 4 shows an example of these analyses for the results of a smooth tire and a ribbed tire skid test for five repetitions on each surface measured at three speeds. Because the multivariate analysis using PCA was done with three different variables, the critical values using a chi-square distribution are 6.25, 7.81, 11.34, and 12.84 for the corresponding 90, 95, 99, and 99.5 % level of confidence that the data is significantly different than the rest.



(a) Smooth tire PCA analysis



(b) Ribbed tire PCA analysis

Figure 4 Sample principal component analysis results for smooth and ribbed tires

Not all of the surfaces were tested with both tires. The epoxy overlaid sections were tested in 2008, but were not included during the 2009 testing. Knowing this and using a 90% confidence level, results indicated that differences were detected for the smooth tire on sections 5, 12, 14, and 16, which correspond to an SM 9.5 D, the OGFC, concrete O/L and CRCP sections, respectively. Ribbed tire results were also sensitive to the OCFG and the CRCP, but not to any of the more conventional asphalt sections. After these considerations, it was decided to separate the surfaces into three groups and obtain individual adjustment factors for them as follows: a) dense and gap-grade asphalt surfaces (SM and SMA); b) open-graded mixes (OGFC); and c) all CRCP surfaces.

Correlation between Skid Number and Speed

Linear models have been used in this study in order to correlate the skid number to the speed. To evaluate their significance, tests of the hypotheses on slope and intercept were done. This test shows if the regression variable (Speed) truly influences the response (Skid Number) and if the model adequately predicts the expected responses. To do this, the null hypothesis (H_0) is that the slope is zero (H_0: $\beta_1 = 0$) and if H_0 is true, then it can be concluded that speed does not affect skid number. Rejection of H_0 would show that speed has influence on the skid number.

To determine the level of confidence in this assumption it is necessary to evaluate the quality of the fit of the line using a simple F-test, where large values of F would favor H_1 (*3*). Figure 5 shows all of the plots made with the data measured for each unit in each of the three groups of surfaces tested.

Adjustment Factors – Surface Type/Group

All of the regression slopes of the lines that were tested had statistically significant linear trends between the speeds and the skid numbers (p-values less than 0.0001). Table 2 summarizes the slopes (change in friction per unit of speed) for each surface type for both types of tires.

Table 2 Slopes of the regression models SN vs. Speed

Surface	**SM and SMA**			**OGFC**			**CRCP**		
Smooth tire	LWS-1	LWS-2	LWS-3	LWS-1	LWS-2	LWS-3	LWS-1	LWS-2	LWS-3
	-0.96	-0.94	-1.19	-0.62	-0.60	-0.61	-1.17	-1.16	-1.29
Ribbed tire	LWR-1	LWR-2	LWR-3	LWR-1	LWR-2	LWR-3	LWR-1	LWR-2	LWR-3
	-0.66	-0.50	-0.34	-0.63	-0.40	-0.33	-0.65	-0.50	-0.47

Note: LWS-1 = PN, LWS-2 = CT, LWS-3 = VA-S, LWR-1 = SC, LWR-2 = MS and LWR-3 = VA.

The slopes of the lines show the changes of skid number per one mile per hour change of speed, which are the proposed adjustment factors requested for each type of test tire. As can be seen from the plots in Figure 5, smooth tire results show better correlations than the ribbed tire results. However, it can also be seen that the data for the smooth tire is more scattered than the data for the ribbed tires. This is likely due to the smooth tire's heightened sensitivity to macrotexture (*1*). From Table 2 it can be seen that the correction factors for different smooth tire skid testers are almost identical for similar sections. However, for the ribbed tires, they seem to be equipment dependent which could be due to the different tire tread depths.

In order to obtain statistically significant calculations, confidence intervals have to be determined for the mean and predicted observations for both the smooth and the ribbed tire results. The confidence intervals show the range of values with a certain probability that can be predicted with the linear equation for any friction measurements taken. Confidence intervals can be obtained from the following equations (*3*):

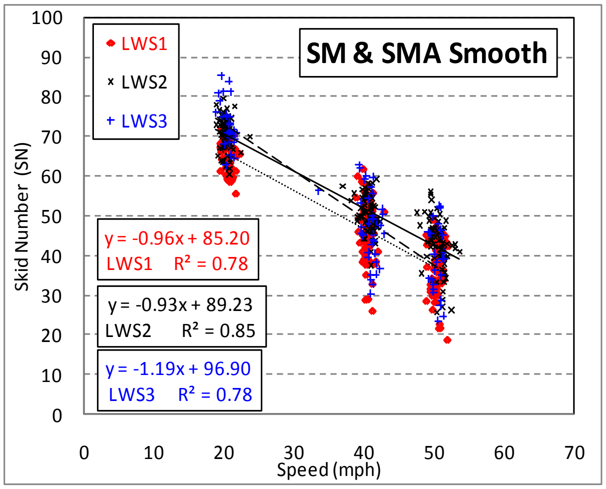
Confidence interval on observations

$$\hat{Y}(x_o) \pm t_{\alpha/2,n-2} s \sqrt{1 + \frac{1}{n} + \frac{(x_o - \bar{x})^2}{S_{xx}}} \quad (1)$$

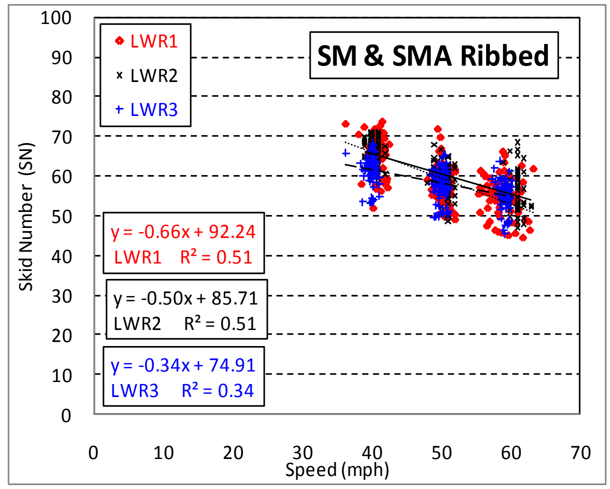
Confidence interval on mean

$$\hat{Y}(x_o) \pm t_{\alpha/2,n-2} s \sqrt{\frac{1}{n} + \frac{(x_o - \bar{x})^2}{S_{xx}}} \quad (2)$$

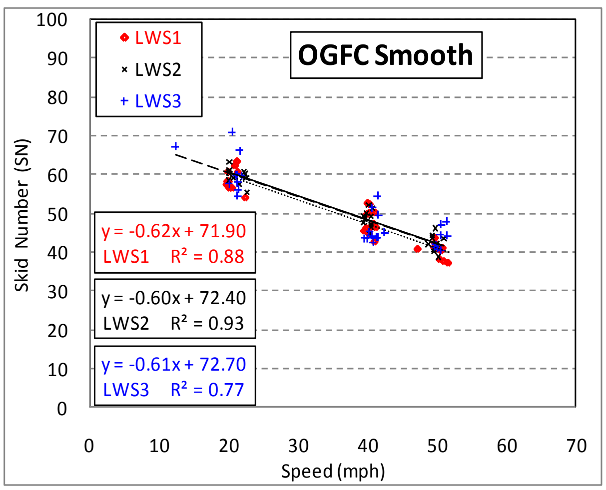
where,
$\hat{Y}$ = estimated response
t = t-distribution probability
α = chosen probability
n = number of observations for the model
s = square root of error mean square
s xx = sum of squares



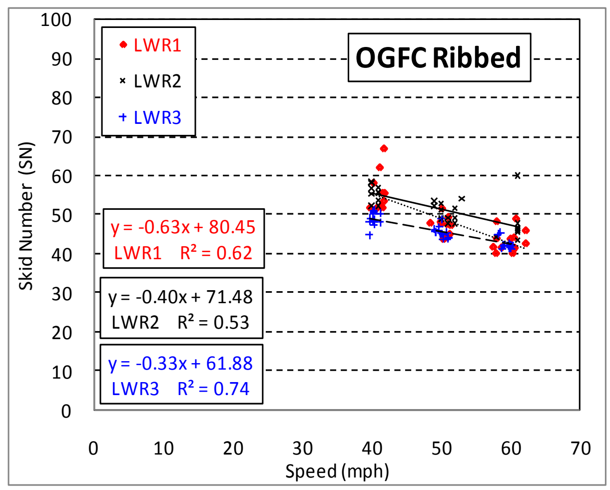
(a) Smooth tire results for SM and SMA



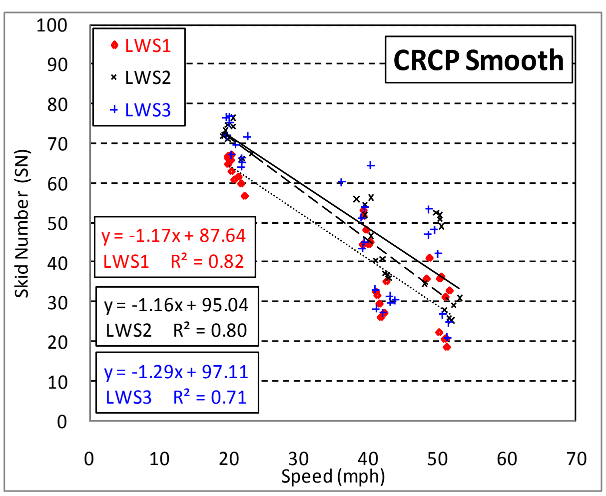
(b) Ribbed tire results for SM and SMA



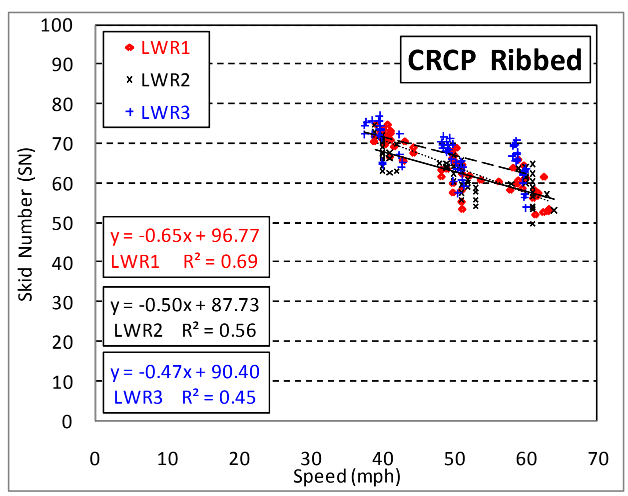
(c) Smooth tire results for OGFC



(d) Ribbed tire results for OGFC



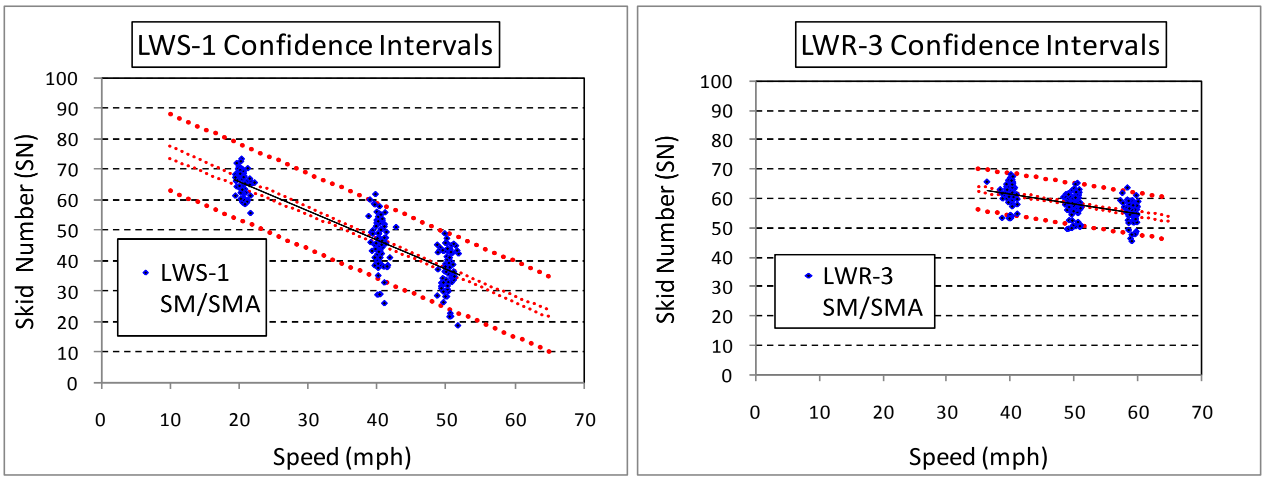
(e) Smooth tire results for CRCP



(f) Ribbed tire results for CRCP

Figure 5 Linear regressions for the three surfaces types for both skid tester types

Based on these formulas, confidence intervals have been determined for all tires in each group of surfaces. Figure 6 shows an example of the confidence interval on mean and observed values for a skid tester equipped with a smooth tire (LSW-1) and another equipped with a ribbed tire (LWR-3) for the first group of surface types (SM and SMA), and a 95% probability. The amplitude of the confidence intervals was approximately SN ± 12 for this smooth tire tester and SN ± 8 for the ribbed tire. The confidence intervals show the range of the skid number of the skid data where the adjustment factors can be used for each group of mixes.



a) Smooth tire confidence intervals b) Ribbed tire confidence intervals

Figure 6 Confidence intervals for smooth and ribbed tire skid testers for SM and SMA

Adjustment Factors – Texture

Another approach for estimating the adjustment factors is to make them dependent on the pavement surface macrotexture. This has been the approach used in other studies that have tried to make speed and instrument correlations (*4*, *5*). The advantage of this approach is that the validity of the correlations could extend beyond the pavement surfaces available for these tests.

Table 3 shows the slopes for each SN-speed plot for each of the smooth tire units and their averaged value for SM and SMA mixes. Correlations of the average coefficients were made with the macrotexture values for each section. These correlations represent the change of skid values for different pavement surface textures for one mile per hour changes in speed. By plotting the different speed adjustment factor averages ($C_{average}$) with MPD values as seen in Figure 7, the following relationship for speed adjustment for smooth tire measurements can be obtained:

$$C = 0.85MPD - 1.64 \quad (3)$$

where,
C = speed adjustment factor for all smooth tire units
MPD = Mean Profile Depth (mm)

To convert measured friction at any speed to the desired speed, the model would be the following:

$$SN_{V_2} = SN_{V_1} + \Delta SN \quad (4)$$

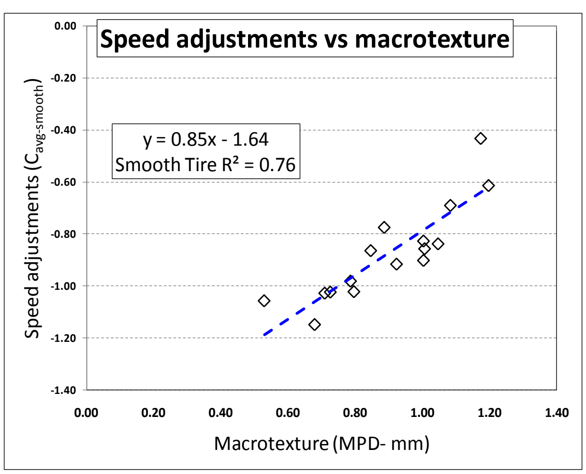
where,

Table 3 Skid number adjustment factors for different surfaces derived from texture

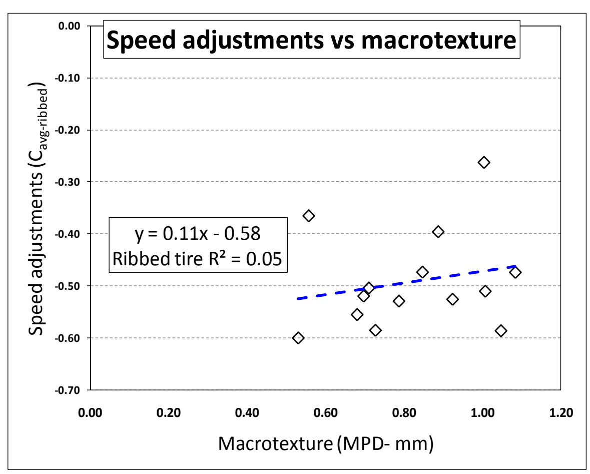
Section	Direction	MPD (mm)	LSW-1	LSW-2	LWS-3	C average
1	Eastbound	1.00	-0.95	-0.83	-0.92	-0.90
2	Eastbound	0.53	-1.02	-1.09		-1.06
3	Eastbound	0.68	-1.13	-1.15	-1.16	-1.15
4	Eastbound	0.71	-1.17	-0.89		-1.03
10	Eastbound	0.92	-0.80	-1.03		-0.92
11	Eastbound	1.05	-0.98	-0.70		-0.84
13	Eastbound	1.00	-0.87	-0.77	-0.83	-0.83
1	Westbound	0.80	-0.95	-1.11	-1.00	-1.02
2	Westbound	0.89	-0.82	-0.73		-0.77
3	Westbound	1.01	-0.76	-0.82	-0.98	-0.86
4	Westbound	0.79	-0.97	-0.99		-0.98
10	Westbound	0.73	-1.12	-0.93		-1.02
11	Westbound	0.85	-0.79	-0.94		-0.86
13	Westbound	1.08	-0.70	-0.66	-0.71	-0.69

SN_{V2} = skid number at desired speed (V_2)
SN_{V1} = skid number at measured speed (V_1)
$\Delta SN = (0.85 * MPD – 1.64) * \Delta V$ where $\Delta V = V_2 - V_1$

Figure 7 shows that this method works better for the smooth tire measurements than for the ribbed tire ones (R^2 = 0.76 vs. R^2= 0.05), likely again due to the insensitivity of the ribbed tire to macrotexture.



(a) Smooth Tire Adjustment Factors



(b) Ribbed Tire Adjustment Factors

Figure 7 Correlation between speed adjustment factors with macrotexture

III.6. Profile Comparisons

When state agencies program maintenance, repair and rehabilitation work of their road networks, they do it by measuring road roughness, since it has significant influence on the performance of the pavements and is also a major determinant of road user costs (*6*). Many techniques have evolved since the 1960's when roughness (or smoothness) of a road was first computed by measuring the vertical deviations of the road surface along a longitudinal line of travel in a wheel path - a longitudinal profile (*7*). Since then, many different profilers have been developed with an aim to capture those aspects of a longitudinal profile that affect ride quality, vehicle dynamic loading and safety (*6*, *7*).

Most of the longitudinal road profile measurements are summarized using an index known as the International Roughness Index (IRI) which was developed by the National Cooperative Highway Research Program (NCHRP) and the World Bank (*8*). The International Roughness Index (IRI) represents the accumulation all of the vertical movements of a "standard" vehicle over a given length of road, usually expressed in inches/mile (mm/km). If the sum of these movements is large, the surfaces are usually rough (not smooth or even) because travel over them is uncomfortable. If the sum is small, travel is more comfortable.

All of the agencies participating in the Consortium use laser-based inertial profilers for measuring longitudinal profiles at highway speeds and from which compute the IRI at project and network levels. The major problem associated with inertial profilers is the accuracy of the road profile measurements, because the verification of these measurements can only be done when compared to a stable, consistent reference. To verify the correct operation of the member-state profilers, the Consortium established a profiler verification site for 2009, following available guidelines and specifications that test the compliance of profilers in terms of accuracy and precision.

Background

AASHTO has developed provisional standards to help state highway departments implement standard equipment specifications for inertial profilers, including their certification. Since 2006, pooled fund study TPF-5(063), Improving the Quality of Profiler Measurement, has been helping establish the criteria to implement verification centers and assist in their development (*6*). AASHTO specification PP–49 (*9*) sets guidelines for the comparison of road profiles taken with a reference device, referred to as a Class-1 instrument, to verify the IRI bias in the measurements and also the repeatability and reproducibility of inertial profilers (*10*).

Test Sections

All of the Virginia Smart Road section characteristics are summarized in Table 4. Based on the general requirements set forth by AASHTO PP-49 specifications, a decision was made to design five test sections on the uphill (westbound) lane of the facility. AASHTO PP-49 requires the sections for the test comparisons to be at least one-tenth of a mile long or 528 feet. The first two test sections were established in the JRCP and the CRCP pavements. The rest of the test sections then had to be placed over the asphalt concrete pavements. From Table 4, it is apparent that it would be easy to assign another test section to the coarse asphalt pavements (SMA and OGFC) as section 3. The two remaining sections were chosen based on their roughness, choosing one with a low and one with a high IRI. Although sections E and F would probably have made a better match for the low IRI criterion, sections F and G were chosen for test section 4 because section E lies on a horizontal curve. Finally, sections A and B were chosen as test section 5 as the combination had a relatively high IRI.

Table 4 Virginia Smart Road section pavement surfaces

Section.	Name	Surface mix type	Length (feet)	MPD uphill (mm)	Last IRI meas. (in/mi)	Test Section No.	Length (feet)
1	Loop	SMA 19.0	N/A	0.80	N/A		
2	A	SM-12.5D	347	0.89	**123**	**5**	**528**
3	B	SM-9.5D	289	1.01	**164**		
4	C	SM-9.5E	292	0.79	77		
5	D	SM-9.5A	407	0.70	195		
6	E	SM-9.5D	268	N/A	90		
7	F	SM-9.5D	302	N/A	**99**	**4**	**528**
8	G	SM-9.5D	304	N/A	**108**		
9	H	SM-9.5D	292	N/A	112		
10	I	SM-9.5A(h)	338	0.73	93		
11	J	SM-9.5D	280	0.85	105		
12	K	OGFC	302	1.80	**134**	**3**	**528**
13	L	SMA-12.5D	326	1.08	**113**		
14	CRCP	Tined	2,290	0.80	**69**	**2**	**528**
15	JRCP	Grooved	591	N/A	N/A	**1**	**528**

Note: MPD = mean profile depth, Past IRI measured on 05/13/2009

Each of the test section wheel-paths were marked every 10 feet with paint so that operators could align the profilers when traveling at the required speed of 50 mph. The paintings would also help to reduce possible wandering errors (*12*). The left wheel-path was marked 34.5 inches from the center line and the right one was separated from the left by 69 inches. Each test section also had paint-marked lead-in distances of 150 feet starting over a one-inch high electrical rubber cable cord protector that was placed as an artificial bump to indicate the start of each of the lead-in sections. These bumps were intended to produce a spike in the profiles, which make it possible to determine the exact location of the test sections during subsequent analysis (*13*).

Reflective material trigger markers were also placed 50 feet before the first artificial bump and 50 feet after the end of the last test section, to activate the start and end of the data collection. Traffic cones with reflective material were also placed next to each of the bumps before the lead-in sections of each test section to help the profiler operators become aware of the beginning location and try to align properly in the marked wheel paths.

Data Collection

Reference Profiler

An ICC SURPRO walking profiler was chosen as the reference instrument used to measure each of the five test section profiles along the left and right wheel paths. Five passes were made on both wheel-paths to assure good repeatability and to compute the IRI of each wheel path in each section. This reference profiler is used by many state agencies (*14*). Figure 8 shows two different angles of the SURPRO during reference measurements of test section 5.

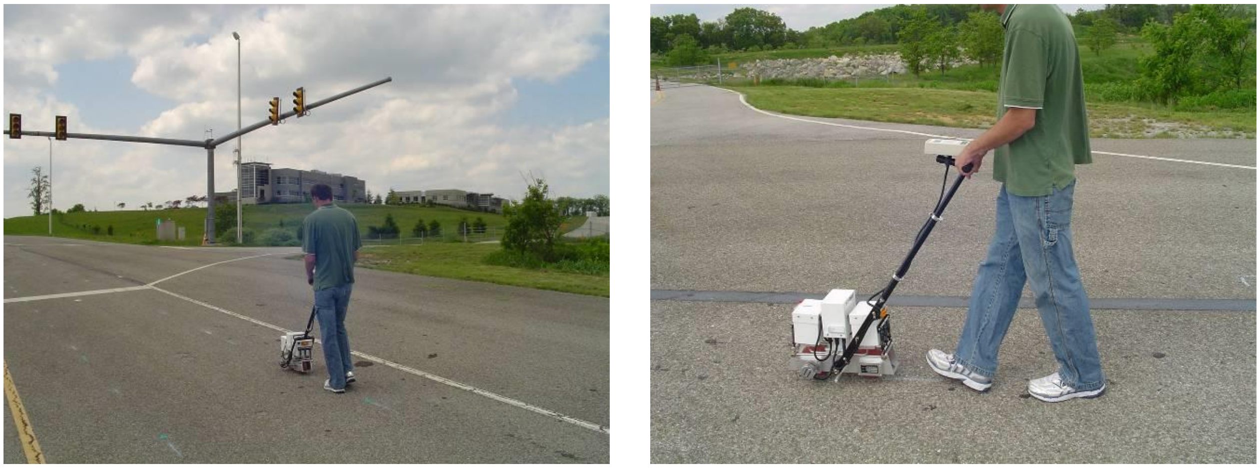


Figure 8 Reference measurements being taken with the ICC SURPRO reference profiler

High Speed Profilers

Profiles from eight high-speed devices were compared to the reference measurements made with the SURPRO device. Data was collected in accordance with the procedures mentioned in AASHTO PP-49. Pre-test system calibration, including block, bounce and distance calibrations were also performed. The block tests were done with blocks provided by each profiler manufacturer and with a standard set of calibration blocks purchased by VTTI. Bounce tests were carried out for each unit as recommended by each manufacturer (ICC, DYNATEST, etc.). These tests are made to detect any serious malfunctions outside the permissible limits in the normal operation of the height and accelerometer sensors.

A distance measuring instrument (DMI) calibration section with a length of 1,000 feet was also marked on the downhill portion of the CRCP section where the road is straight, but has a maximum slope of about 6%. Each profiler made at least 5 runs to calibrate their DMI as per normal operating recommendations by their manufacturers. All profilers then collected profile data ten times at a constant speed of 50 mph, trying to avoid sudden speed changes throughout the sections. Table 5 lists the profilers' manufacturers, the sampling interval used by each, and the result of the static and dynamic calibration bounce tests for all of the profilers that participated in this study.

Table 5 Profiler Units, Manufacturer, Sample Interval and Bounce Test Results

Profiler	Manufacturer	Sampling Interval (inches)	Bounce Test IRI values (in/mile)					
			Static Test		Dynamic Test		Dynamic - Static	
			Left	Right	Left	Right	Left	Right
1-SC1	DYNATEST	1.00	N/A	N/A	N/A	N/A	N/A	N/A
2-SC2	DYNATEST	1.00	1.7	1.6	12.4	10.9	10.7	9.3
3-LTPP	ICC	0.98	1.4	2.6	7.0	6.2	5.5	3.6
4-MS	ICC	1.21	2.8	2.9	6.0	5.0	3.2	2.1
5-VA1	ICC	3.06	2.8	3.9	18.3	13.6	15.5	9.6
6-VA2	ICC	3.06	2.5	2.6	10.8	19.3	8.3	16.7
7-VA3	ICC	0.77	5.1	3.8	17.3	26.9	12.2	23.1
8-CT	ARAN	0.93	3.2	3.2	7.6	7.6	4.4	4.4
Reference	ICC	1.00	N/A	N/A	N/A	N/A	N/A	N/A

Note: The results of the bounce test should not be compared among profilers as these were made by different operators and run at different times. They are only included here as a reference.

Results and analysis

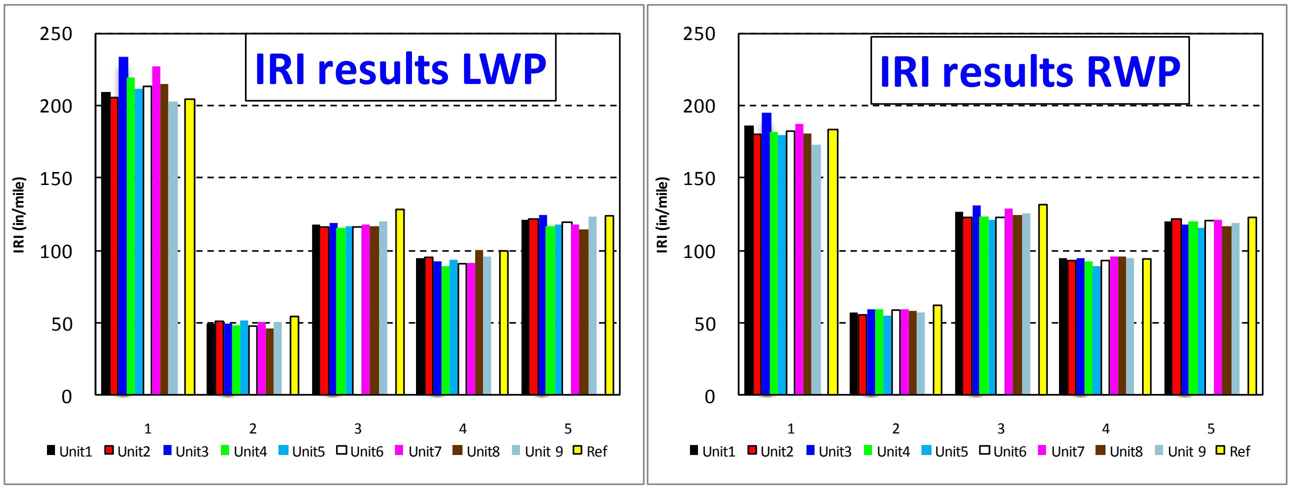
The ride statistics, repeatability and reproducibility assessment for all of the data collected was calculated using the analysis methods that are included in the Profile Viewing and Analysis (ProVAL) software developed under the sponsorship of the FHWA (*15, 16*). The following is a brief description of the results.

Ride Statistics

IRI values of the all profile runs for all test sections were also computed using ProVAL. All IRI computations in ProVAL apply a 250 mm moving average filter (*14*). The IRI results from all the profilers for all sections are shown in Figure 9.

The left wheel path IRI values are higher than the right ones in the first section (JRCP). These results are also the highest of all five sections, probably consistent with all the vertical movements caused by the concrete pavement joints. The lowest IRI results were obtained in the second (CRCP) section where the lack of joints may have contributed to the better ride. Right wheel-paths in the CRCP section have higher results, again in contrast with the first section. The relative coarseness (high texture) of the wearing course from test section 3 does not result in the highest flexible pavement IRI. This is found in section 5, which exhibits the highest cracking damage of all the asphalt sections. Section 4 has lower IRI than both of the aforementioned asphalt sections.

The repeatability of all the profilers' IRI was evaluated by calculating the coefficient of variation (COV) of the IRI-values for all repeat runs of each profiler. It was found that the profilers were very repeatable in IRI-measurement with a COV less than 3% for both wheel paths. No significant variation was observed when the IRI values from the high-speed profilers were compared with the SURPRO IRI-values.



(a) Left wheel path IRI ride statistics (b) Right wheel path IRI ride statistics

Figure 9 IRI ride statistics for the test sections for all units and the reference profilers

Repeatability

Repeatability results show how well each unit obtains the same profile measurements in each of its ten runs. For this study, cross-correlation was performed on the profile data after the output IRI filter was applied, to evaluate both profiler repeatability and reproducibility. For repeatability, AASHTO PP-49 requires an average cross-correlation of at least 92% when each profile is compared with the remaining nine (90 comparisons).

Table 6 Average Repeatability Cross-Correlations for all Profiler Units

Profiler	Average Repeatability Cross Correlation									
	Section 1		Section 2		Section 3		Section 4		Section 5	
	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
Unit 1	*88*	*86*	*88*	92	94	93	95	94	92	*88*
Unit 2	97	96	94	94	94	96	97	96	93	*90*
Unit 3	96	92	*89*	92	93	93	95	95	89	*90*
Unit 4	95	92	93	94	95	95	95	95	93	*91*
Unit 5	96	92	*90*	92	95	96	96	95	*89*	*87*
Unit 6	95	92	94	95	94	95	95	95	93	*90*
Unit 7	96	92	93	91	95	94	95	93	94	*87*
Unit 8	95	*88*	93	96	96	96	95	95	93	*88*

The repeatability results for each of the laser sensors, left and right, as computed with ProVAL are shown in Table 6 for each test section. Bold italicized numbers show those that ***did not*** pass the repeatability criteria. None of the profilers passed all the repeatability tests with values of more than 92% for all of the sections. Only for sections 3 and 4, did all the profilers pass the repeatability test for both wheel paths. However, the computed IRI values were very close, as presented in the previous section.

Reproducibility

The reproducibility results were obtained by comparing the profile run with the highest cross correlation repeatability for each wheel path from the SURPRO profiles to the ten runs from each participant profiler. Power Spectrum Density (PSD) plots of the data collected with the SURPRO indicated that a moving average filter had already been applied to the data. Hence, no separate moving average was required for the SURPRO runs, and the IRI-filtered cross correlation was only applied to the profilers' data (*14*). The results from the profiler certification (reproducibility) module are shown in Table 7.

Table 7 Average Reproducibility Cross-Correlations for all Profiler Units

Profiler	**Average Reproducibility Cross Correlation**									
	Section 1		**Section 2**		**Section 3**		**Section 4**		**Section 5**	
	Left	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
Unit 1	73	66	67	70	74	76	71	72	75	73
Unit 2	*93*	*90*	86	82	75	76	77	76	84	*93*
Unit 3	49	52	33	35	64	63	61	51	43	49
Unit 4	62	51	49	53	69	68	66	62	67	62
Unit 5	86	77	75	72	75	75	74	74	76	86
Unit 6	73	63	53	65	72	73	68	68	74	73
Unit 7	62	52	43	50	71	72	65	63	63	62
Unit 8	62	48	49	53	78	79	86	80	69	62

According to AASHTO PP-49, a profiler passes the reproducibility test if it has a cross-correlation value of more than 90% when compared with the respective reference profile. As can be seen in Table 7, the reproducibility cross-correlations (IRI-filtered) between the SURPRO and all of the profilers are relatively low; only one profiler scored satisfactorily in only one section. These results are discussed and possible reasons for this are explored in the following sections.

Inter-Profiler Reproducibility

Since the reproducibility results with the SURPRO used as the reference device were found to be low, another cross-correlation comparison was made between all of the participant profiler units with each other to check inter-profiler reproducibility correlations. This approach was used because if cross-correlations among the high-speed profilers were good, fundamental differences between their profiles and those collected with the SURPRO could be the reason for the low results. Those profilers' runs that had the highest cross-correlation results with the SURPRO, also referred to as the "best runs" from each profiler for each section, were selected and used to compare all the profilers among themselves.

An example of this analysis is shown in Tables 8, where the results obtained for the right wheel paths for test sections 1 can be seen. The large majority of these results are also lower than 90%, so it was concluded that the reference profiler was not the reason that none of the profilers showed good reproducibility. Another explanation, related with the distance measurements, is explored in the next section.

Table 8 Inter-Profiler Reproducibility for Section 1 for Right Wheel Path (RWP)

Reference Unit	Compared Profiler Unit							
	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8
Unit 2	70							
Unit 3	49	51						
Unit 4	83	47	64					
Unit 5	90	79	44	78				
Unit 6	89	66	45	88	90			
Unit 7	82	51	62	95	79	88		
Unit 8	78	46	59	88	74	82	85	

Reproducibility issues and DMI Calibration

When the distances between the artificial bumps before the first test section and after the last test section were obtained from the profiler data for several runs from each profiler, it resulted in distances between the bumps that were very close to each other for each profiler, with differences being on the order of 1 to 2 feet. However, when compared with each other, significant differences were observed as can be seen in the fourth column of Table 9.

Table 9 Comparative differences in distance between bumps for all profiler units

Profiler	Bump 1	Bump 6	Difference	%	Bump 1	Bump 2	Difference	%
Unit 1	50	7280	7230	0.42%	50.0	1775.4	1724.8	0.48%
Unit 2	50	7250	7200	N/A	49.8	1766.7	1716.7	0.01%
Unit 3	50	7332	7282	1.14%	50.2	1788.7	1738.4	1.27%
Unit 4	51	7299	7248	0.66%	51.1	1780.9	1729.7	0.76%
Unit 5	51	7270	7219	0.27%	51.0	1774.0	1723.0	0.37%
Unit 6	52	7286	7235	0.48%	51.6	1778.1	1726.1	0.55%
Unit 7	51	7297	7246	0.63%	51.4	1780.1	1728.7	0.71%
Unit 8	51	7299	7248	0.66%	51.2	1780.8	1729.5	0.75%

Field measurement with a metal tape were used to confirmed the actual distance between bumps 1 and 2 (1,716.6 ft.), which was again compared to the data collected by each profiler (column eight). Only unit 2 was within the acceptable range of error of 0.15% as stipulated by PP-49. After this was done, the conclusion was that the actual distance between bumps 1 and 6 was very close to the 7,200 feet as measured by unit 2. Notice how the margins of error for all of the other profilers are very similar for both of these comparisons.

Since AASHTO PP-49 guidelines require that all DMI measurements have to be within 0.15 % accuracy, it can reasonably be concluded that this is the probable cause for the low reproducibility cross-correlations with the reference SURPRO profiler.

As noted previously, the DMI calibration section was located on a downhill section and all the vehicles calibrated their DMIs going downhill, but then proceeded to measure the profiles going uphill. The DMI calibration depends on the rolling radius of the tire at the time of testing, and this rolling radius might have changed while going downhill which resulted in incorrect distances recorded by the profilers. This change in rolling radius is a direct result of tire-pavement interaction which depends on many factors, one of them being the properties or characteristics of each tire.

Repositioning and "Squeezing" Profiles

The IRI-filtered plots of the participating profiler units and SURPRO were compared again to adjust possible shifts in the profile which caused the errors in the DMI. In Figure 10 it is obvious that there is a displacement in the profiles of Unit-3 (which showed maximum % difference in distances recorded) and the SURPRO, which increases with distance in the measured profiles.

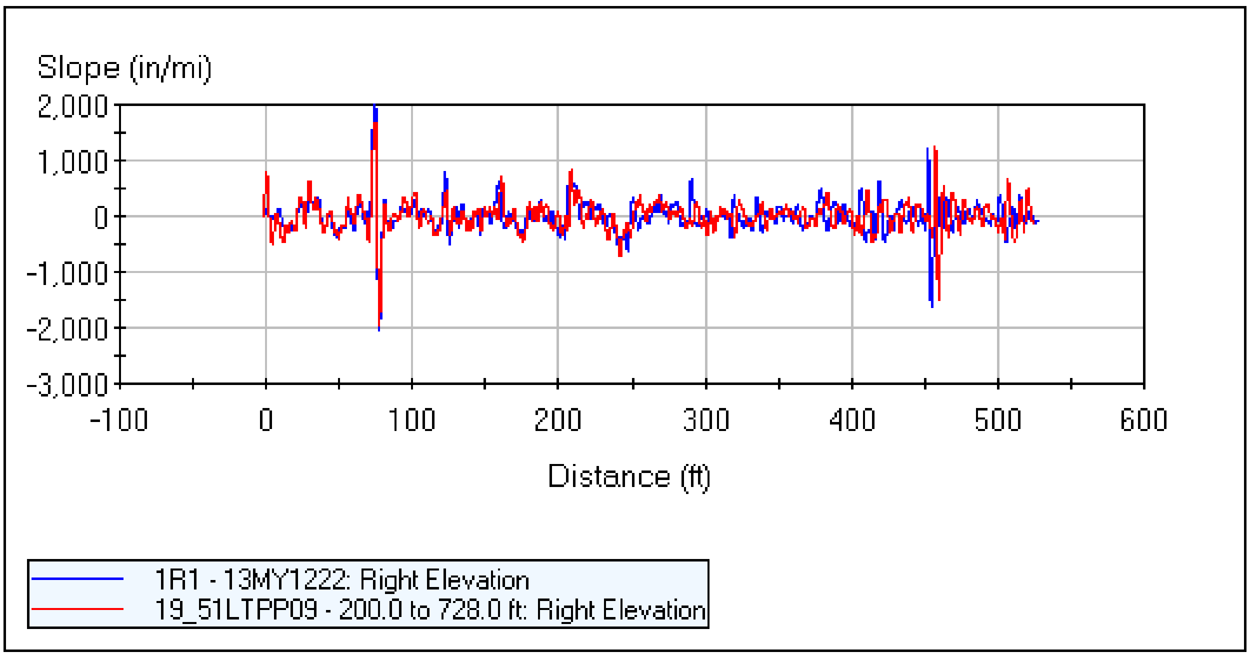


Figure 10 Section 1 profile results before squeezing (unit 3 and reference RWP)

The amount of shift was calculated for the best run of the each profiler unit with SURPRO for all sections and the profiles were repositioned by squeezing them with respect to the SURPRO profiles. This squeezing of the profiles was done by changing the original sample interval by an amount adjusted to the total shift discussed above. As a result of squeezing of the profiles, the lengths of the best-run profiles for all sections changed and allowed the profiles to synchronize better with the SURPRO profiles as shown in Figure 11.

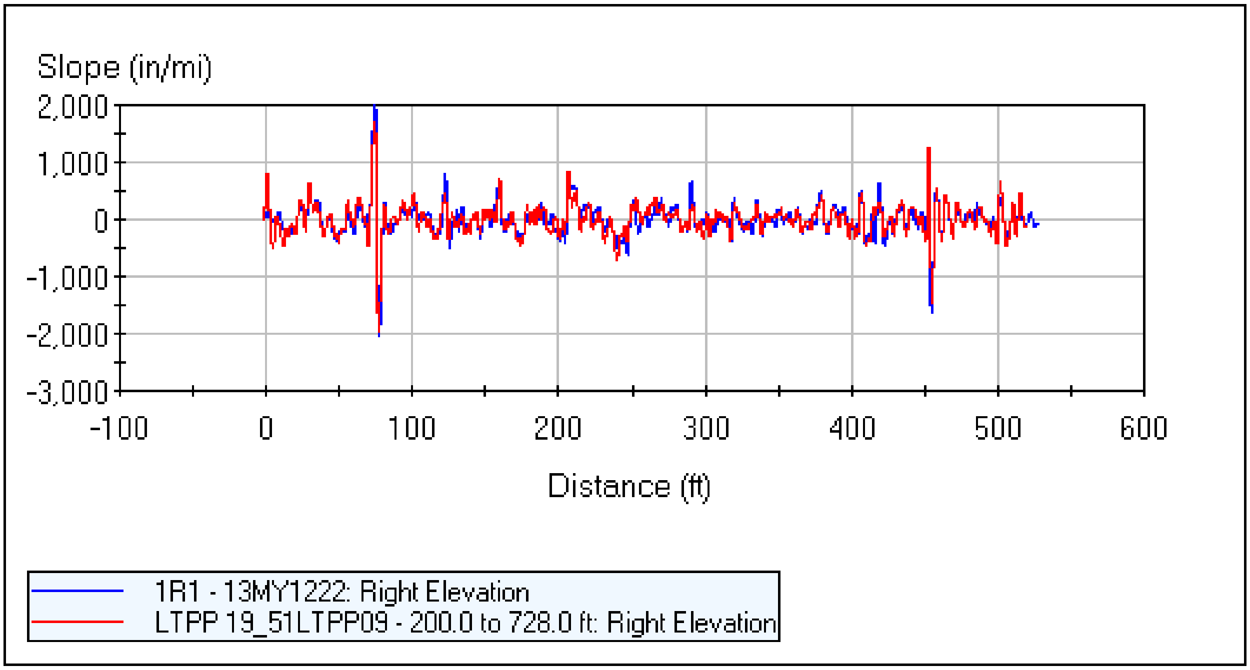
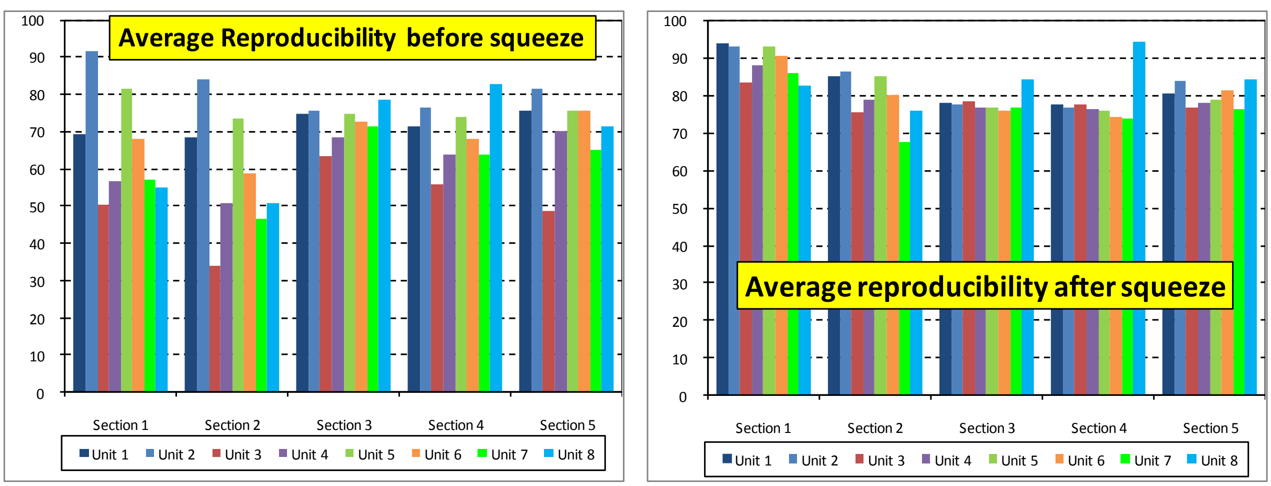


Figure 11 Section 1 profile results after squeezing (unit 3 and reference RWP)

Reproducibility Results after Squeezing

The profiler reproducibility test was repeated after squeezing of the profiles, this time only using the best-runs of the profiler units and SURPRO as the reference profiler. The results obtained from the test, as shown in Figure 12, showed significant improvement in the IRI-filtered cross-correlations for all sections. The effect of squeezing on the profiles for section 1 and 2 was much more prominent when compared to other sections. One reason for this was assumed to be that these sections have the higher climbing slopes (± 6%) of all five. Section 3, which has a coarser texture (OGFC), showed little improvement. Similarly, sections 4 and 5 had relatively small improvements when compared to section 1 and 2.



(a) Profiler reproducibility before squeezing (b) Profiler reproducibility after squeezing

Figure 12 Reproducibility Cross-Correlations before and after Squeezing

Ride Statistics after Squeezing (IRI-results)

As summarized in Table 10, the increase in IRI values after squeezing the profiles was very low, almost negligible, with the unit with the largest change in sampling interval being affected the most (Unit-3), showing an increase of 1.83%.

Table 10 Percent increase in IRI after squeezing

Profiler	% Increase in IRI									
	Section 1		Section 2		Section 3		Section 4		Section 5	
	LWP	RWP	LWP	RWP	LWP	RWP	LWP	RWP	LWP	RWP
Unit 1	0.38	0.33	0.20	0.17	0.17	0.24	0.32	0.21	0.24	0.25
Unit 2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Unit 3	0.78	0.68	1.00	0.33	1.34	1.30	1.83	1.38	1.16	1.09
Unit 4	0.50	0.50	0.41	0.16	1.14	1.14	1.24	0.98	0.17	0.17
Unit 5	0.23	0.22	0.19	0.18	0.00	0.00	0.32	0.23	0.09	0.09
Unit 6	0.37	0.33	0.41	0.17	0.43	0.49	0.66	0.54	0.16	0.17
Unit 7	0.35	0.38	0.60	0.34	0.17	1.08	1.20	0.74	0.25	0.17
Unit 8	0.48	0.45	0.43	0.34	1.39	1.36	0.89	0.73	0.43	0.42

III.7. Findings and Recommendations

Pavement surface property measurement equipment comparisons were performed at the Third annual equipment roundup at the Smart Road. These tests provided the Surface Properties Consortium participants with an informal verification of their measurement equipment. The following are some of the most important findings of these comparisons:

Friction

This report proposes adjustment factors to convert skid numbers from one speed to any desired speed. The factors were computed for three different groups of pavement surface types - groups that were identified using principal component analysis.

- Linear relationships were used to model friction measurements as a function of the speed at which they were obtained, which is in the range of speeds typically used during regular testing conditions (30-65 mph).
- The friction measurements performed with the skid testers presented different responses to the different pavement surface types considered in the study. The surfaces were grouped using principal component analysis.
- Adjustment factors were computed for each group of pavements and confidence intervals were determined for each group for each tire tested. Confidence intervals show the range (in terms of skid number) over which the adjustment factors can be used for each group of mixes. The confidence intervals for the smooth tire friction testers were wider because the data are more scattered than those collected using the ribbed tire. This is consistent with previous findings that showed that measurements with the smooth tire are more sensitive to pavement texture and testing conditions.

- Statistically significant correlations between speed gradient and macrotexture were obtained for measurements with the smooth tire. The authors believe that the model developed will probably be valid for pavement surfaces beyond those tested in this study, but this should be further investigated and validated.
- Adjustment factors derived from texture using ribbed tire skid testers had low coefficients of determination (R^2) probably because the measurements with this tire are not sensitive to macrotexture. This observation is also in agreement with previous studies. Additional research should be pursued to study the effects of tire thread depths on the determination of speed adjustment factors.

Profile

The report also discussed the establishment of a profiler certification/ verification site at Virginia Smart Road. This part of the study focused on the comparison of profilers with a reference device (ICC SURPRO) and identified several different factors affecting this comparison.

- Good agreement of IRI values were found between the reference device (SURPRO) and each of the participant profilers IRI for all test sections.
- Repeatability of all of the profilers was in accordance with the specifications for most of the sections tested.
- Error in the distances recorded by the profilers DMIs were related to the procedures followed for their calibration. The grade of the test track likely affected DMI calibration, which resulted in relatively low cross-correlations for reproducibility with the reference profiler (SURPRO).
- An artificial adjustment of the profiles by "squeezing" them to match actual length of the test sections, significantly improve the reproducibility results. Furthermore, the increase in IRI values after squeezing the profiles was very low.

Recommendations

- It is recommended that each of the participating agencies try the linear relationships modeled (simple model) to convert friction measurements as a function of speed (30-65 mph) for each of the suggested surfaces groups. When possible, if texture data becomes available, it will be valuable to compare these conversions with those obtained if the second model developed is used to further investigate and validate this approach.
- In future skid testing equipment comparisons it is recommended to obtain a measurement of the tire thread depths of the ribbed tires of the participating skid testers to determine the effects of it in the determination of speed adjustment factors.
- It is also recommended to continue to make profiler comparisons such as the one implemented in the Virginia Smart Road for regional profiler verification. The reference device (SURPRO) and was found to provide a reasonable basis for such comparisons and should be able to be used until the Profiler Pooled Fund (TPF-5[063]) standardizes the requirements of a final reference device and incorporates them into the appropriate protocols.
- It is strongly suggested that profilers DMIs be calibrated on flat grade test segments to avoid any possibility of DMI error which can impact low cross-correlations repeatability and reproducibility.

III.8. References

1. Henry J.J., Evaluation of Pavement Friction Characteristics: A Synthesis of Highway Practice, *NCHRP Synthesis 291*, Transportation Research Board, National Research Council, Washington, D.C., 2000.
2. de León, E. and Flintsch, G.W., "High-speed Non-Contact Digital Imaging for Inspection of Hot-Mix Asphalt Pavements," ASCE *Journal of Transportation Engineering*, 2008, Vol. 134(6), pp. 246-254.
3. Myers, R., *Classical and Modern Regression with Applications*, Duxbury Press, Belmont, CA, 1990.
4. Wambold, J. C., C. E. Antle, J. J. Henry, and Z. Rado, International *PIARC Experiment to Compare and Harmonize Texture and Skid Resistance Measurements*, Final Report submitted to the Permanent International Association of Road Congresses (PIARC), State College, PA, 1995.
5. Flintsch, G.W., de León Izeppi, E., McGhee, K.K., and Roa, J.A., "Evaluation of the International Friction Index coefficients for various devices", *Transportation Research Record 2094*, Transportation Research Board, National Research Council, Washington, DC, 2009, pp 136-143.
6. Karamihas, S.M., Gillespie, T.D., Kohn, S.D., Perera, R.W., Guidelines for Longitudinal Pavement Profile Measurement, NCHRP Project 10-47, 1999
7. Sayers, M.W., and Karamihas, S.M., The Little Book of Profiling, University of Michigan Transportation Research Institute, 1998
8. Sayers, M.W., et al., Guidelines for Conducting and Calibrating Road Roughness Measurements, World Bank Technical Paper Number 46, 1986
9. AASHTO, *Standard Practice for Certification of Inertial Profiling Systems (PP49)*, The American Association of State Highway and Transportation Officials, Washington, D.C., 2007.
10. *Improving the Quality of Pavement Profiler Performance*, Federal Highway Administration (FHWA) Pooled Fund Study TPF-5(063), www.pooledfund.org/documents/TPF-5_063, Accesed June 1, 2009.
11. Karamihas, S.M., Critical Profiler Accuracy Requirements, Final Report, Federal Highway Administration (FHWA) Pooled Fund study TPF-5(063), 2005.
12. Perera, R.W., Kohn, S.D., and Wiser, L.J., Factors Contributing to Differences Between Profiler and the International Roughness Index, In Transportation Research Record: Journal of the Transportation Research Board, No. 1974, Transportation Research Board of the National Academies, 2006
13. Perera, R.W., Kohn, S.D., and Bemanian, S., Comparison of Road Profilers, In Transportation Research Record: Journal of the Transportation Research Board, No. 1536, Transportation Research Board of the National Academies, 1993
14. Perera, R.W and Kohn, S.D., Evaluation of Wisconsin DOT Walking Profiler, Federal Highway Administration (FHWA), 2007
15. Karamihas, S.M., *Development of Cross Correlation for Objective Comparison of Profiles*, University of Michigan Transportation Research Institute, 2002
16. Chang, George, PROVAL Users Guide: Profile Viewing and Analysis Software, TRANSTEC, Austin, Texas, 2007.

IV. 2010 Annual Equipment Comparison Roundup at the Smart Road [4]

IV.1. Executive Summary

The regional pooled-fund project known as the Pavement Surface Properties Consortium is a research program focused on enhancing the level of service provided by the roadway transportation system by optimizing pavement surface texture characteristics. The program was set up in 2006 with support from the Federal Highway Administration (FHWA), and six departments of transportation (DOTs) from the states of Connecticut, Georgia, Mississippi, Pennsylvania, South Carolina and Virginia. The Consortium provides a practical mechanism to conduct research on pavement surface properties and explore their relationships with ride quality, friction, and noise. Complementing this effort, additional research focuses on the review, testing, and evaluation of emerging technologies.

To verify/ validate/ harmonize the measurements of the various pieces of equipment owned and operated by the participating agencies, the consortium organizes an equipment comparison rodeo, called the "Surface Properties Rodeo", at the Virginia Smart Road every year. The specific objectives for this year's event were:

- Compare and verify the results obtained in 2009 of the speed adjustment factors for the skid locked-wheel trailers (ASTM E-274) using only the smooth tire, for the different pavement types tested (three units participated in the 2010 comparison).
- Following AASHTO PP–49 Standard Practice for Certification of Inertial Profiling Systems specification, obtain profile measurements and compare them to the reference measurements made with an ICC SURPRO device to determine their repeatability and reproducibility correlations (four profilers participated in the 2010 comparison).

The following summarizes the activities, as well as the principal findings and recommendations from this year's rodeo:

Friction

- Adjustment factors to convert skid numbers from one speed to any desired speed were developed for the participating skid testers with only the smooth tire. The factors were computed for four different pavement surface types. Linear relationships were used to model friction measurements as a function of test speed. The test speeds were typical of ordinary testing conditions (30-50 mph).
- The adjustment factors obtained in 2010 differ from the ones obtained in this exercise the previous year, but in direct comparisons it can be said that all the units were measuring the same trend and magnitude of friction.

Profile

- Following AASHTO specifications, a profiler certification/ verification site was revisited in 2010 at the Virginia Smart Road. The study focused on the comparison of profilers with a reference device (ICC SURPRO) and identified several different factors affecting this comparison.

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[4] Prepared by: Edgar de León Izeppi, Gerardo Flintsch, and Kevin K. McGhee,

- Good agreement of IRI values were found between the reference device (SURPRO) and each of the participant profilers IRI for all test sections. Repeatability of all of the profilers was in accordance with the specifications for most of the sections tested.

Recommendations

- It is recommended that each of the participating agencies try the linear relationships modeled (simple model) to convert friction measurements as a function of speed (30-50 mph) for each of the suggested surfaces groups.
- If in the future skid testing equipment comparisons are to be made with ribbed tires, it is recommended to obtain a measurement of the tire thread depths tires of the participating skid testers to determine the effects of it in the determination of speed adjustment factors.
- It is also recommended to continue to make profiler comparisons such as the one implemented in the Virginia Smart Road for regional profiler verification. The reference device (SURPRO) and was found to provide a reasonable basis for such comparisons and should be able to be used until the Profiler Pooled Fund (TPF-5[063]) standardizes the requirements of a final reference device and incorporates them into the appropriate protocols.
- Modifications in both the reference profiler and the grinding and grooving of the test track will allow for other types of verifications next year. It is recommended to verify the measurements of the reference profiler used with the measurement of the UMTRI reference profiler developed under TPF-5(063).

IV.2. Introduction

The regional pooled-fund project known as the Pavement Surface Properties Consortium [TPF-5(141)] has been over the past four years carrying research focused on optimizing pavement surface texture characteristics. The program was set up with support from the Federal Highway Administration (FHWA) and six departments of transportation from the states of Connecticut, Georgia, Mississippi, Pennsylvania, South Carolina and Virginia. The Consortium has provided its members with a practical mechanism to research ride quality, friction, and texture, along with emerging technologies.

One of the services that the consortium provides is the opportunity for its members to meet once a year to compare the measurements of the various pieces of equipment owned and operated by them. The fourth comparison rodeo, called the "Surface Properties Rodeo", was held at the Virginia Smart Road on the week of May 19, 2009. Participating agencies brought some of the equipment used in their respective states to measure profile, texture and friction. This report describes the results of this event.

IV.3. Objectives

The general objective of every roundup is to evaluate and compare some of the equipment utilized to measure smoothness, texture and friction by the individual states participating in the consortium. The specific objectives for this year's event were:

- Friction: Compare and verify the results obtained in 2009 of the speed adjustment factors for the skid locked-wheel trailers (ASTM E-274) using only the smooth tire, for the different pavement types tested (three units participated in the 2010 comparison).

- Following AASHTO PP–49 Standard Practice for Certification of Inertial Profiling Systems specification, obtain profile measurements and compare them to the reference measurements made with an ICC SURPRO device to determine their repeatability and reproducibility correlations (four profilers participated in the 2010 comparison).

IV.4. Testing Facility

The Virginia Smart Road is a 2-mile facility particularly appropriate for this kind of testing because it includes a variety of real world flexible and rigid pavement surfaces and it is operated under controlled traffic conditions. In the first mile, the facility offers seven different types of asphalt concrete surfaces, including five different SUPERPAVE ™ mixtures, a 12.5mm stone mastic asphalt (SMA), and a 12.5mm open-graded friction course (OGFC).

In the second mile, two rigid concrete pavement surfaces complete the sections, featuring a continuously reinforced concrete pavement (CRCP) and a jointed reinforced concrete pavements (JRCP) section. The Continuously Reinforced Concrete Pavement (CRCP) has a transversely tined finish. The test road has a maximum longitudinal grade of 6 percent.

For the flexible pavement sections, the downhill (eastbound) and the uphill (westbound) lanes have slightly different micro- and macrotexture due to differences in construction compaction due to the sensors placed for the instrumentation located only on the uphill lane. A complete list of the mix type, material properties and texture measurements for both lanes for all of the sections available in the Smart Road is presented in Table 1.

Table 1 Section Material Properties and Texture of the pavement surfaces

Section	Mix Type	Asphalt Binder	NMS	Eastbound MPD (mm)	Westbound MPD(mm)
1	SMA 19.0	PG 70-22	19	1.00	0.80
2	SM-12.5D	PG 70-22	12.5	0.53	0.89
3	SM-9.5D	PG 70-22	9.5	0.68	1.01
4	SM-9.5E	PG 76-22	9.5	0.71	0.79
5	SM-9.5A	PG 64-22	9.5	0.56	0.70
6-9	SM-9.5D	PG 70-22	9.5	N/A	N/A
10	SM-9.5A(h)	PG 64-22	9.5	0.92	0.73
11	SM-9.5D	PG 70-22	9.5	1.05	0.85
12	OGFC	PG 76-22	12.5	1.63	1.80
13	SMA-12.5D	PG 70-22	12.5	1.00	1.08
14	Epoxy O/L	-	-	1.84	1.86
15	Epoxy O/L	-	-	1.20	1.17
16	CRCP	-	-	0.70	0.80

NMS = nominal maximum aggregate size, MPD = mean texture depth, O/L = overlay

IV.5. Friction Comparisons

All of the states participating in the Consortium own a locked-wheel trailer, which is the friction measuring device currently used by most state Departments of Transportation (DOTs) in the U.S. These devices measure the steady-state friction force on a locked wheel on the wetted pavement surface as the wheel slides at a constant speed. The skid resistance of the paved surface is reported as skid number (SN), which is the force required to slide the locked test tire at a stated speed, divided by the effective wheel load and multiplied by 100 (ASTM E-274). Skid testing can be conducted using a smooth tire (ASTM E-524) or a ribbed tire (ASTM E-501).

The 2009 Rodeo presented preliminary speed adjustment factors for pavement friction measurements conducted at different speeds other than the standard test speed of 40 mph. These adjustment factors were developed using data from 2007 to 2009 for both tires. The intent of the 2010 Rodeo was to verify the adjustment factors derived for the smooth tire in 2009 by repeating the tests at 30, 40 and 50 mph in 2010. In conjunction with these tests a continuous friction fixed slip device, known as the GripTester, was also used and the results of this unit will also be compared with those obtained for the locked-wheel skid units.

Data Collection

All of the friction measurements were made in series of six runs for each device at the three different testing speeds in both directions. The complete set of the experimental friction test pavement sections tested in 2010 can be seen in Figure 1. All the lock-wheel and GripTester friction data was collected on May 19-20. The results averaged for each of the test sections is included in the appendix. Preliminary correlations were obtained from the data collected as will be discussed following

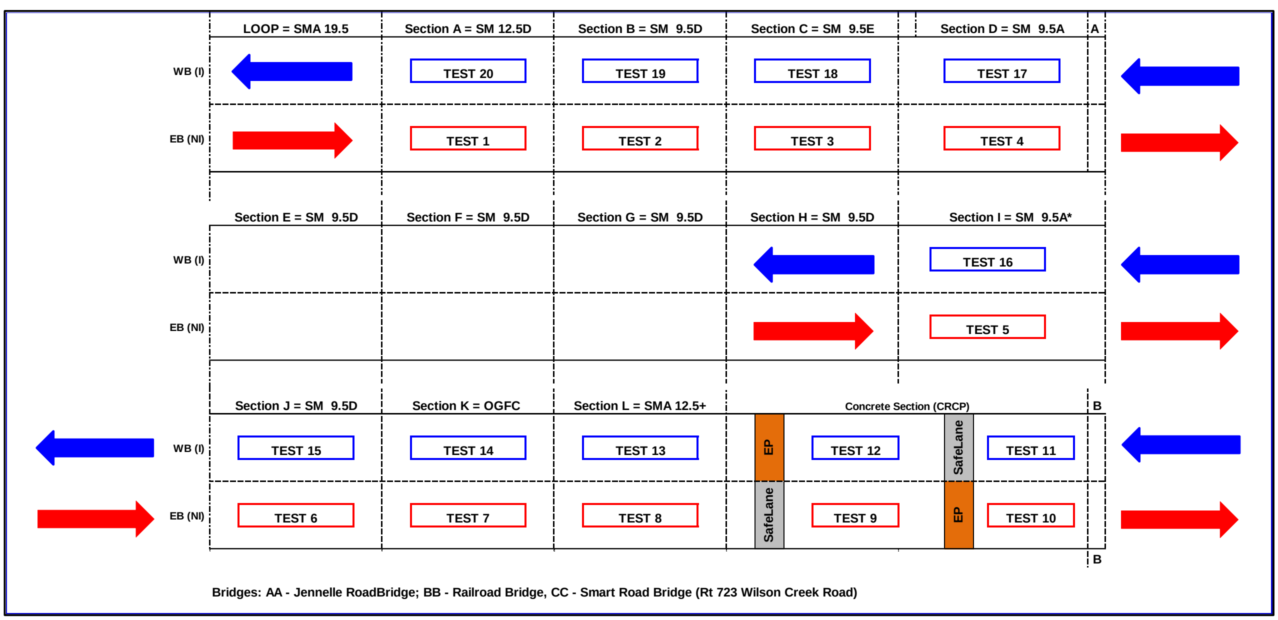
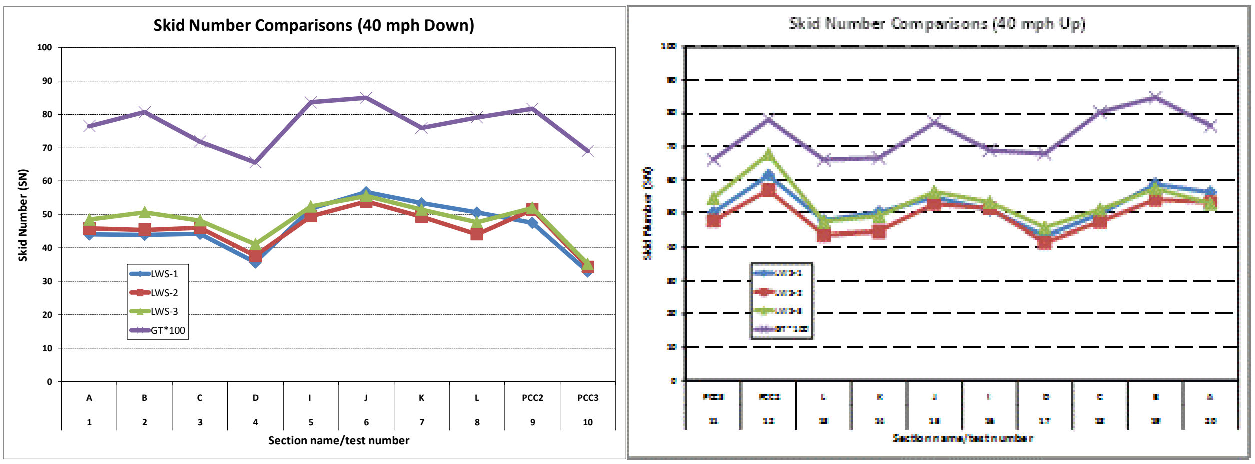


Figure 1 Smart Road Friction Test Sections Layout for 2010

Results and Analysis

The results of the friction measurements show that in general the friction numbers for all three units behave in similar trend and the GripTester is always measuring a higher number than all of the other three units. Two examples of this can be seen in Figure 2 which shows the average of the downhill (eastbound) and the uphill (westbound) lane measurements for all four devices made at 40 mph. These differences can be explained by observing that fixed slip devices are always measuring at a higher level of friction due to the behavior of the relationship between slip and friction (*Henry, 2000*).



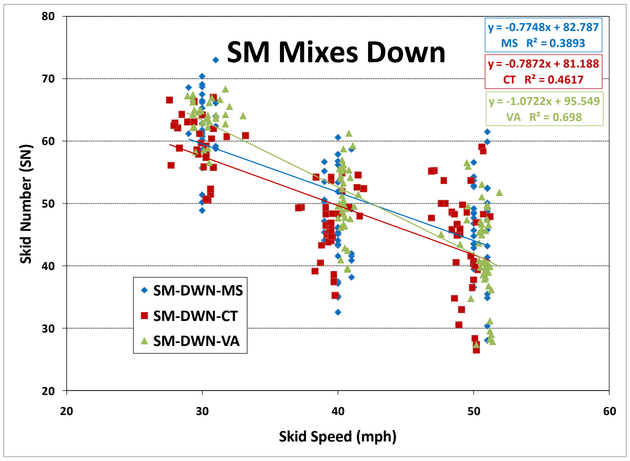
a) Friction number results east 40 mph

b) Friction number results west 40 mph

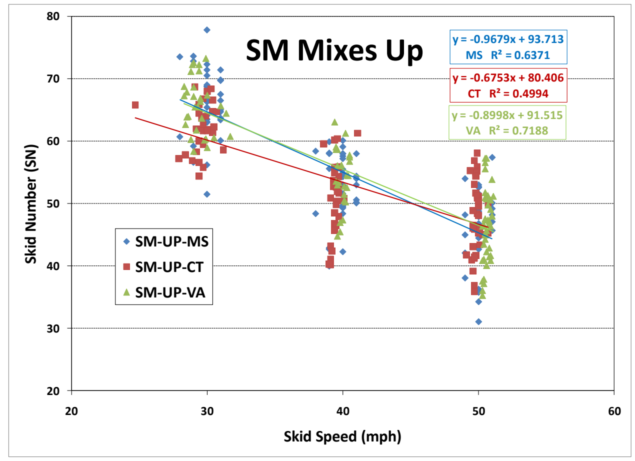
Figure 2 Average Skid Number results for all sections at 40 mph, both directions

Similarly the same behavior can be observed at the other two speeds for all of the devices tested. Taking this into consideration the same procedure used to obtain the speed adjustment factors in 2009 was followed with the 2010 tests. This procedure was explained in last year's report and was also published as a paper in the Journal of the Transportation Research Board (*Flintsch et. al., 2010*). Figure 3 below shows two examples of the results plotted for the three locked wheel skid testers for all of those sections with a SUPERPAVE Surface Mix (SM).

Similarly, all the results for all of the locked wheel skid testers were also plotted for the Open Graded Friction Course (OGFC), the Stone Mastic Asphalt (SMA) and the Continuously Reinforced Concrete Pavement (CRCP). The results of the relationships to find the speed correction factors by mix type are discussed below.



(a) SM mixes skid results eastbound (down)



(b) SM mixes skid results westbound (up)

Figure 3 Sample results for all locked wheel skid testers for SM mixes

Speed Adjustment Factors – Surface Type/Group

Table 2 summarizes the slopes (change in friction per unit of speed) for each surface type for the smooth tires as resulted in 2009 and 2010. It must be pointed out that there is one unit that did not participate but was replaced with another one, so the comparison is not completely one to one. The other observation is that for the factors obtained in 2009 the SM and SMA factors were considered in the same category and in 2010 they are considered separate and they are also reported depending on the lane tested (downhill and uphill).

Table 2 Slopes of the regression models SN vs. Speed

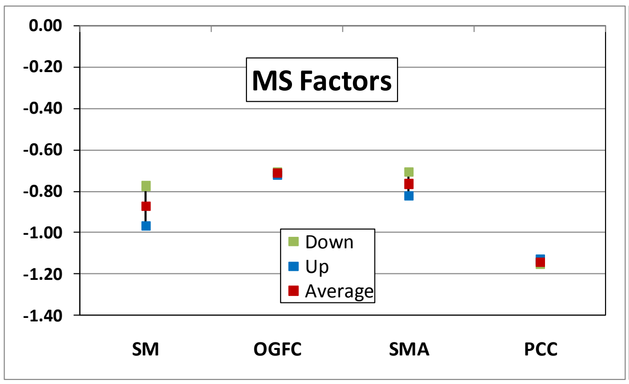
Surface	**SM / SMA**						**OGFC**			**CRCP**		
Unit	**PN**	**CT**	**VA**				**PN**	**CT**	**VA**	**PN**	**CT**	**VA**
2009 Fact.	-0.96	-0.94	-1.19				-0.62	-0.60	-0.61	-1.17	-1.16	-1.29
Surface	**SM**			**SMA**			**OGFC**			**CRCP**		
Unit	MS	CT	VA	MS	CT	VA	MS	CT	VA	MS	CT	VA
DOWN	-0.77	-0.79	-1.07	-0.71	-0.76	-0.69	-0.71	-0.53	-0.38	-1.15	-0.90	-1.11
UP	-0.97	-0.68	-0.90	-0.82	-0.49	-0.66	-0.72	-0.28	-0.33	-1.13	-0.66	-0.92
2010 Factors*	-0.87	-0.73	-0.99	-0.76	-0.63	-0.67	-0.71	-0.40	-0.36	-1.14	-0.78	-1.01

* Note: the factors shown for 2010 represent the average of the downhill and the uphill results.

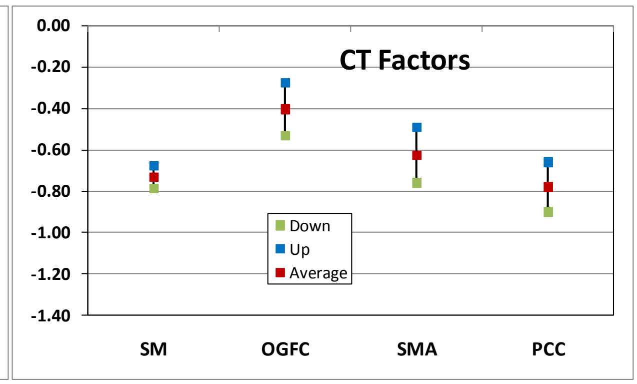
The slopes of the trend lines obtained for each tester for every type of mix is the changes of skid number per one mile per hour change of speed, which are the proposed adjustment factors suggested for each unit with a smooth tire. From Table 2 it can be seen that the correction factors for different smooth tire skid testers were almost identical for similar surface types in 2009 but that is not the case for the four types of surfaces considered in 2010. It is also important to point out that no single unit seems to have consistent measures in all types of pavements and are also affected by the direction of travel.

Range of speed correction factors

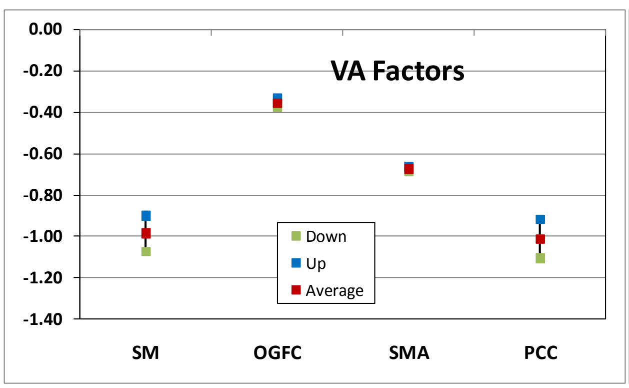
To better understand the difference in speed correction factors that were obtained with the tests for each unit, a plot showing the range for each coefficients for each unit was made. In this plot the uphill, downhill, and the average coefficient are plotted as reported in Table 2. This allows visualizing that if the range is large, the difference in direction is affecting the unit more than those which have a smaller range (see figure 4). The results for the GripTester have been included for comparison on the effect of the grade on this device.



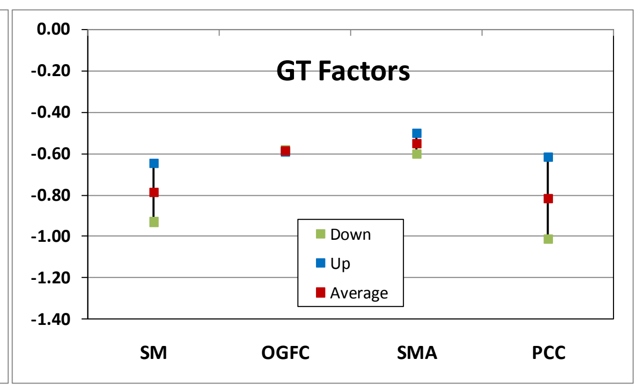
(a) Smooth tire results for MS



(b) Smooth tire results for CT



(c) Smooth tire results for VA



(d) Smooth tire results for GT

Figure 4 Range of speed corrections factors for all devices by direction of travel

IV.6. Profile Comparisons

All of the agencies participating in the Consortium use laser-based inertial profilers for measuring longitudinal profiles at highway speeds and from which they can obtain the IRI at project and network levels. The major problem associated with inertial profilers is the accuracy of the road profile measurements, because the verification of these measurements can only be done when compared to a stable, consistent reference. To verify the correct operation of the member-state profilers, the Consortium established a profiler verification site in 2009, following available guidelines and specifications that test the compliance of profilers in terms of accuracy and precision. This exercise was repeated in 2010 to correct the Distance Measurement Instrument calibration flaw that was discovered in 2009 by calibrating the DMI on an inclined part of the Smart Road. Following are the results obtained in 2010.

Background

AASHTO has developed provisional standards to help state highway departments implement standard equipment specifications for inertial profilers, including their certification. Since 2006, pooled fund study TPF-5(063), Improving the Quality of Profiler Measurement, has been helping establish the criteria to implement verification centers and assist in their development (*3*). AASHTO specification PP–49 (*4*) sets guidelines for the comparison of road profiles taken with a reference device, referred to as a Class-1 instrument, to verify the IRI bias in the measurements and also the repeatability and reproducibility of inertial profilers (*5*).

Test Sections

Based on the general requirements set forth by AASHTO PP-49 specifications, a decision was made in 2009 to design five test sections on the uphill (westbound) lane of the facility. This specification requires the sections to be one-tenth of a mile long (528 feet). Table 3 presents the characteristics of Virginia Smart Road sections used for the profiler comparison. The first two test sections are JRCP and CRCP pavements. The rest of the test sections are asphalt concrete pavements.

Table 3 Virginia Smart Road section pavement surfaces

Section.	**Name**	**Surface mix type**	**Length (feet)**	**MPD uphill (mm)**	**SURPRO 2009 IRI (in/mi)**		**Length (feet)**
	Loop	SMA 19.0	N/A	0.80			
	A	SM-12.5D	347	0.89	**Left**	**Right**	**528**
	B	SM-9.5D	289	1.01	**204**	**183**	
	C	SM-9.5E	292	0.79			
	D	SM-9.5A	407	0.70			
	E	SM-9.5D	268	N/A			
	F	SM-9.5D	302	N/A	**Left**	**Right**	**528**
	G	SM-9.5D	304	N/A	**55**	**62**	
	H	SM-9.5D	292	N/A			
	I	SM-9.5A(h)	338	0.73			
	J	SM-9.5D	280	0.85			
3	K	OGFC	302	1.80	**Left**	**Right**	**528**
	L	SMA-12.5D	326	1.08	**128**	**132**	
2	CRCP	Tined	2,290	0.80	**Left**	**Right**	**528**
					99	**94**	
1	JRCP	Tined & Grooved	591	N/A	**Left**	**Right**	**528**
					124	**122**	

Note: MPD = mean profile depth

Again each of the test section wheel-paths was marked every 10 feet with paint so that operators could align the profilers when traveling at the required speed of 50 mph. The paintings help to reduce possible wandering errors (*6*). Each test section also had paint-marked lead-in distances of 150 feet starting over a one-inch high electrical rubber cable cord protector that was placed as an artificial bump to indicate the start of each of the lead-in sections. These bumps were intended to produce a spike in the profiles, which make it possible to determine the exact location of the test sections during subsequent analysis.

Reflective material trigger markers were also placed 50 feet before the first artificial bump and 50 feet after the end of the last test section, to activate the start and end of the data collection. Traffic cones with reflective material were also placed next to each of the bumps before the lead-in sections of each test section to help the profiler operators become aware of the beginning location and try to align properly in the marked wheel paths.

Data Collection

Reference Profiler

An ICC SURPRO walking profiler was again chosen as the reference instrument used to measure each of the five test section profiles along the left and right wheel paths. At least five passes were made on both wheel-paths to assure good repeatability and to compute the IRI of each wheel path in each section. Figure 5 shows two different angles of the SURPRO during reference measurements of test sections 1 and 5.

a) Reference measurements in Section 1 b) Reference measurements in Section 5

Figure 5 Reference measurements being taken with the ICC SURPRO reference profiler

High Speed Profilers

Profiles from four high-speed devices were compared to the reference measurements made with the SURPRO device. Data was collected in accordance with the procedures mentioned in AASHTO PP-49. Pre-test system calibration, including block, bounce and distance calibrations were also performed. The block tests were done with blocks provided by each profiler manufacturer and with a standard set of calibration blocks purchased by VTTI. Bounce tests were carried out for each unit as recommended by each manufacturer (ICC, DYNATEST, etc). These tests are made to detect any serious malfunctions outside the permissible limits in the normal operation of the height and accelerometer sensors.

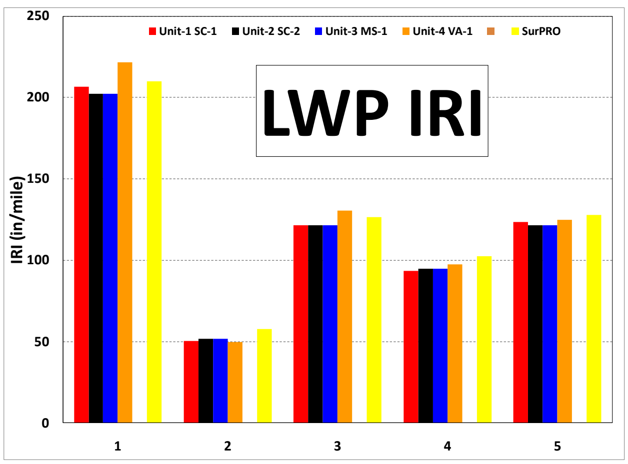
Distance measuring instrument (DMI) calibration where made on straight road and verified in the inclined segment that has a maximum slope of about 6%. All profilers then collected profile data ten times at a constant speed of 50 mph, trying to avoid sudden speed changes throughout the sections. The profilers' manufacturers that participated in 2010 in this study were two Dynatest units from South Carolina, and two International Cybernetics Corporation (ICC) units, one from Mississippi and the other one from Virginia. Their sampling interval is 1.00, 1.00, 1.21 and 3.06 inches for each of these units respectively.

Results and analysis

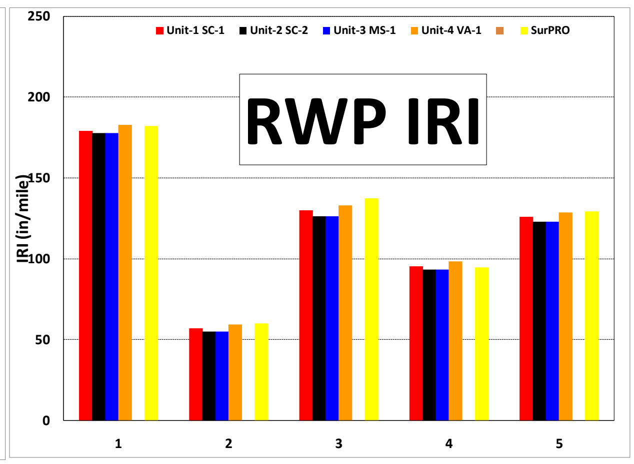
The ride statistics, repeatability and reproducibility assessment for all of the data collected was calculated using the analysis methods that are included in the Profile Viewing and Analysis (ProVAL) software developed under the sponsorship of the FHWA (*7*, *8*). The following is a brief description of the results.

Ride Statistics

IRI values of the all profile runs for all test sections were also computed using ProVAL. All IRI computations in ProVAL apply a 250 mm moving average filter (*8*). The IRI results from all the profilers for all sections are shown in Figure 6.



(a) Left wheel path IRI ride statistics



(b) Right wheel path IRI ride statistics

Figure 6 IRI ride statistics for the test sections for all units and the reference profiler

The left wheel path IRI values are higher than the right ones in the first section (JRCP). These results are also the highest of all five sections, probably consistent with all the vertical movements caused by the concrete pavement joints. The lowest IRI results were obtained in the second (CRCP) section where the lack of joints may have contributed to the better ride. Right wheel-paths in the CRCP section have higher results, again in contrast with the first section.

This year, the relative coarseness (high texture) of the wearing course from test section 3 did not result in the highest flexible pavement IRI, but it was very close to that found on in section 5, which exhibits the highest cracking damage of all the asphalt sections. Section 4 has lower IRI than both of the aforementioned asphalt sections.

The repeatability of all the profilers' IRI was evaluated by calculating the coefficient of variation (COV) of the IRI-values for all repeat runs of each profiler. It was found that the profilers were very repeatable in IRI-measurement with a COV less than 3% for both wheel paths. No significant variation was observed when the IRI values from the high-speed profilers were compared with the SURPRO IRI-values.

Repeatability

Repeatability results show how well each unit obtains the same profile measurements in each of its ten runs. For this study, cross-correlation was performed on the profile data after the output IRI filter was applied, to evaluate both profiler repeatability and reproducibility. For repeatability, AASHTO PP-49 requires an average cross-correlation of at least 92% when each profile is compared with the remaining nine (90 comparisons).

Table 4 Average Repeatability Cross-Correlations for all Profiler Units

Profiler	Average Repeatability Cross Correlation									
	Section 1		Section 2		Section 3		Section 4		Section 5	
	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
SC 1	94	92	*89*	93	94	96	94	95	*90*	*84*
SC 2	96	96	94	94	92	95	96	95	93	*87*
MS	97	92	*90*	93	95	95	95	94	*91*	*90*
VA 1	94	*90*	*89*	93	*90*	95	94	93	93	*87*

The repeatability results for each of the laser sensors, left and right, as computed with ProVAL are shown in Table 4 for each test section. Bold italicized numbers show those that ***did not*** pass the repeatability criteria. None of the profilers passed all the repeatability tests with values of more than 92% for all of the sections. Only for section 4, did all the profilers pass the repeatability test for both wheel paths. However, the computed IRI values were very close, as presented in the previous section.

Reproducibility

The reproducibility results were obtained by comparing the profile run with the highest cross correlation repeatability for each wheel path from the SURPRO profiles to the ten runs from each participant profiler. The results from the profiler certification (reproducibility) module are shown in Table 5.

Table 5 Average Reproducibility Cross-Correlations for all Profiler Units

Profiler	Average Reproducibility Cross Correlation									
	Section 1		Section 2		Section 3		Section 4		Section 5	
	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
Unit 1	92	89	82	86	74	80	73	77	81	73
Unit 2	79	74	71	65	72	71	71	70	74	73
Unit 3	87	76	77	80	75	76	73	77	82	69
Unit 4	79	72	60	73	79	80	78	74	80	77

According to AASHTO PP-49, a profiler passes the reproducibility test if it has a cross-correlation value of more than 90% when compared with the respective reference profile. As can be seen in Table 5, the reproducibility cross-correlations (IRI-filtered) between the SURPRO and all of the profilers are relatively low; only one profiler scored satisfactorily in only one section wheel-path sensor.

IV.7. Findings and Recommendations

Pavement surface property measurement equipment comparisons were performed at the Fourth annual equipment roundup at the Smart Road. These tests provided the Surface Properties Consortium participants with an informal verification of their measurement equipment. The following are some of the most important findings of these comparisons:

Friction

This report verified the speed adjustment factors to convert skid numbers from one speed to any desired speed with smooth tires as developed in 2009. The factors were computed for four different groups of pavement surface types.

- Linear relationships were used to model friction measurements as a function of the speed at which they were obtained, which is in the range of speeds typically used during regular testing conditions (30-50 mph).
- The friction measurements performed with the skid testers presented different responses to the different pavement surface types considered in the study.
- Adjustment factors were computed for each group of pavements.
- Some of the adjustment factors derived using smooth tire skid testers had low coefficients of determination (R^2) for certain units.

Profile

The report also discussed the results of a simulated profiler certification/ verification at the Virginia Smart Road. This part of the study focused on the comparison of profilers with a reference device (ICC SURPRO) and identified several different factors affecting this comparison.

- Good agreement of IRI values were found between the reference device (SURPRO) and each of the participant profilers IRI for all test sections.
- Repeatability of all of the profilers was in accordance with the specifications for most of the sections tested.

Recommendations

- It is recommended that each of the participating agencies try the linear relationships modeled (simple model) to convert friction measurements as a function of speed (30-50 mph) for each of the suggested surfaces groups.
- If in the future skid testing equipment comparisons are to be made with ribbed tires, it is recommended to obtain a measurement of the tire thread depths tires of the participating skid testers to determine the effects of it in the determination of speed adjustment factors.

It is also recommended to continue to make profiler comparisons such as the one implemented in the Virginia Smart Road for regional profiler verification. The reference device (SURPRO) and was found to provide a reasonable basis for such comparisons and should be able to be used until the Profiler Pooled Fund (TPF-5[063]) standardizes the requirements of a final reference device and incorporates them into the appropriate protocols.

Modifications in both the reference profiler and the grinding and grooving of the test track will allow for other types of verifications next year. It is recommended to verify the measurements of the reference profiler used with the measurement of the UMTRI reference profiler developed under TPF-5(063).

IV.8. References

1. Henry J.J., Evaluation of Pavement Friction Characteristics: A Synthesis of Highway Practice, *NCHRP Synthesis 291*, Transportation Research Board, National Research Council, Washington, D.C., 2000.
2. Flintsch, G. W., de León Izeppi, E., McGhee, K. K. and Najafi, S., Speed Adjustment Factors for Locked-Wheel Skid Trailer Measurements, *Transportation Research Record: Journal of the Transportation Research Board, No. 2155*, Transportation Research Board of the National Academies, Washington, D.C., 2010, pp. 117–123.
3. *Improving the Quality of Pavement Profiler Performance*, Federal Highway Administration (FHWA) Pooled Fund Study TPF-5(063), www.pooledfund.org/documents/TPF-5_063, accessed October 22, 2010.
4. AASHTO, *Standard Practice for Certification of Inertial Profiling Systems (PP49)*, The American Association of State Highway and Transportation Officials, Washington, D.C., 2007.
5. Karamihas, S.M., Gillespie, T.D., Kohn, S.D., Perera, R.W., Guidelines for Longitudinal Pavement Profile Measurement, NCHRP Project 10-47, 1999.
6. Perera, R.W., Kohn, S.D., and Wiser, L.J., Factors Contributing to Differences Between Profiler and the International Roughness Index, In Transportation Research Record: Journal of the Transportation Research Board, No. 1974, Transportation Research Board of the National Academies, 2006
7. Karamihas, S.M., *Development of Cross Correlation for Objective Comparison of Profiles*, University of Michigan Transportation Research Institute, 2002
8. Chang, George, PROVAL Users Guide: Profile Viewing and Analysis Software, TRANSTEC, Austin, Texas, 2007.

V. 2011 Annual Equipment Comparison Roundup at the Smart Road[5]

V.1. Overview

The regional pooled-fund project known as the Pavement Surface Properties Consortium is a research program focused on enhancing the level of service provided by the roadway transportation system through the optimization of pavement surface texture characteristics. The program was established in 2006 with support from the Federal Highway Administration (FHWA) and six state departments of transportation (DOTs): Connecticut, Georgia, Mississippi, Pennsylvania, South Carolina, and Virginia. The Consortium provides a practical mechanism to conduct research about pavement surface properties and explore their relationships with ride quality, friction, and noise. Complementing this effort is research focused on the review, testing, and evaluation of emerging technologies.

Several friction and profiler measuring devices were included in the 2011 equipment roundup. The main objective of the study this year was to compare and harmonize various friction tester and profiler measurements. The effects of grinding and grooving on the surface properties of concrete pavements were also investigated.

A Limits of Agreement (LOA) method was used to compare the friction measurements. It was found that this methodology can offer an objective procedure for friction tester users to evaluate the repeatability and reproducibility of the equipment. Additionally, high-speed laser profilers were used to evaluate the pavement profile. All measurements were analyzed using the Profile Viewing and Analysis (ProVAL) software and compared to a SURPRO reference profiler. Introducing longitudinal grooves on concrete pavement surface increased the macrotexture, which resulted in friction improvement. The grinding and grooving of the concrete pavements also enhanced their smoothness. Although this improvement was evident in the SURPRO measurement, single-spot laser profilers could not detect it. It was concluded that longitudinal grooving can introduce an artificial wavelength to profiler measurements. For future studies a multi-footprint profiler is recommended for use on pavement surfaces with longitudinal grooving.

V.2. Introduction

To harmonize the measurements of the various pieces of equipment owned and operated by participating agencies, the Consortium annually organizes an equipment comparison rodeo (the "Surface Properties Rodeo") at the Virginia Smart Road located in Blacksburg, VA.

Four friction testers and four profilers (plus one reference profiler) were used in the 2011 event. Mississippi and South Carolina DOTs brought their locked-wheel friction testers. Measurements from these testers were compared with the GripTester and Dynatest Highway Friction Tester (HFT), which are Continuous Friction Measuring Equipment (CFME) owned by the FHWA. High-speed laser profilers included two from South Carolina, one from Georgia, and one from Virginia. Mississippi also brought a SURPRO reference profiler.

[5] Prepared by Edgar de León Izeppi, Gerardo Flintsch, Kevin K. McGhee, Shahriar Najafi, and Steve Valeri

V.3. Purpose and Scope

The objective of the 2011 annul equipment roundup was to harmonize various friction and profile measuring equipment. The main objectives for the rodeo this year were:

- Friction: Compare the measurements of various friction testers using new statistical techniques; evaluate the effects of tires on harmonizing locked-wheel friction measurements.
- Profiler: Compare measurements of high-speed laser profilers and a reference profiler using ProVAL; evaluate the International Roughness Index (IRI) of test sections.
- Evaluate the effects of grinding and grooving on the surface properties of concrete pavements.

V.4. Methods

Several friction, texture, and profile measurements were collected at the Smart Road. The following sections explain the data collection procedures for each of these measurements. Discussions of the results are provided in each section. Using the friction and profile data, the effects of grinding and grooving of concrete pavements were evaluated.

V.5. Friction

Friction Data Collection

Friction data were collected on May 26, 2011, at the Smart Road. Two locked-wheel skid trailers and two fixed-slip friction testers (Grip Tester and Dynatest 6875H) were used during the experiment. The measurements were collected on 10 test sections: A, B, C, D, I, J, K, L, PCC1, and PCC2. The layout of the test surfaces is illustrated in Figure 3.

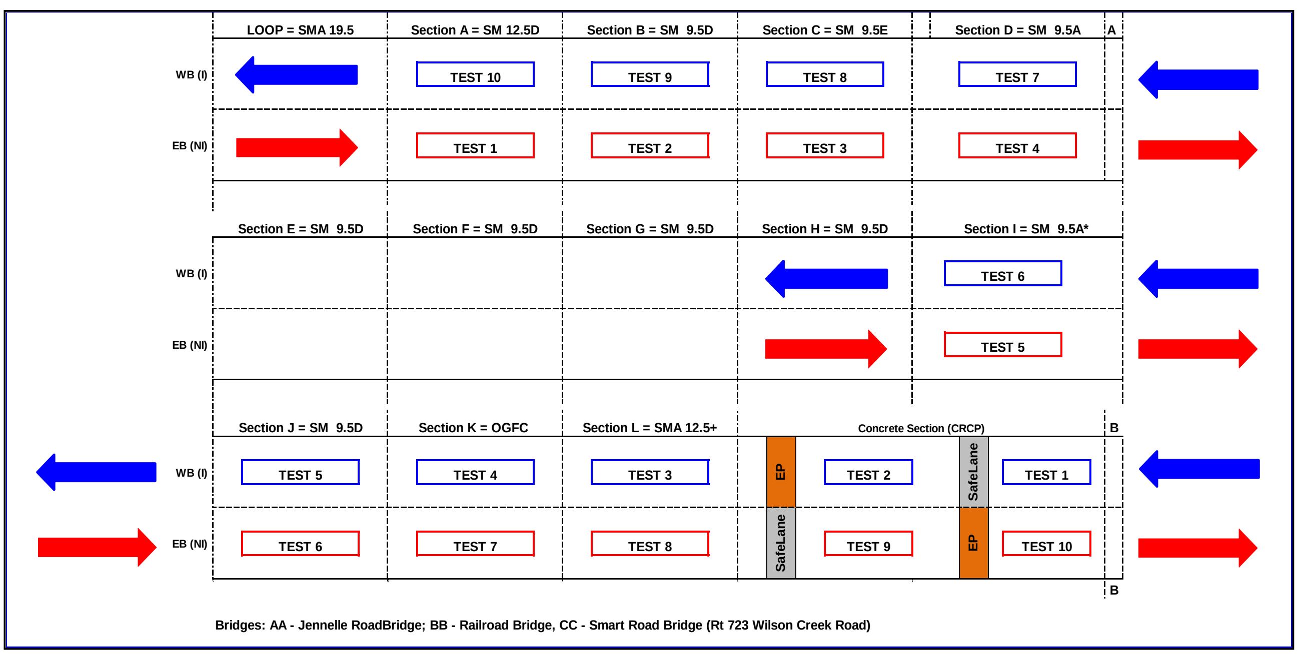


Figure 3. Layout of the sections for friction tests.

Measurements were collected at three speeds (25 mph, 40 mph, and 55 mph) from both eastbound and westbound directions. Skid trailer measurements were collected in accordance with ASTM E-274 using both a smooth tire (ASTM E-524) and ribbed tire (ASTM E-501). To eliminate the effects of tire characteristics (especially for the ribbed tire of the skid testers, as the measurement can be sensitive to thread depth), tires were switched between the units. There is no ribbed tire available for the fixed-slip devices. A summary of the tests conducted is provided in Table 6.

Table 6. Summary of the friction tests.

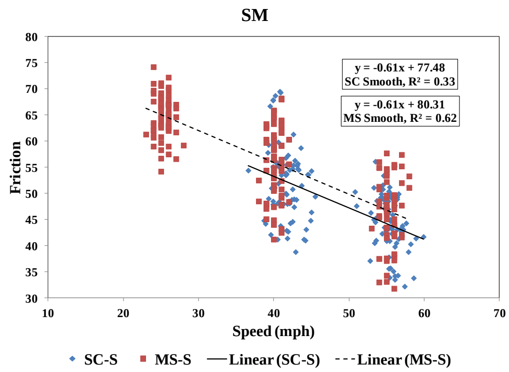
Unit	**Type**	**Tire**	**# Test Sections**	**Test Speed (mph)**
Mississippi (MS) skid trailer	Locked wheel	Smooth & ribbed	10	25, 40, 55
South Carolina (SC) skid trailer	Locked wheel	Smooth & ribbed	10	25, 40, 55
GripTester	Fixed slip	Smooth	10	25, 40, 55
Dynatest 6875H	Fixed slip	Smooth	10	25, 40, 55

Friction Results and Discussion

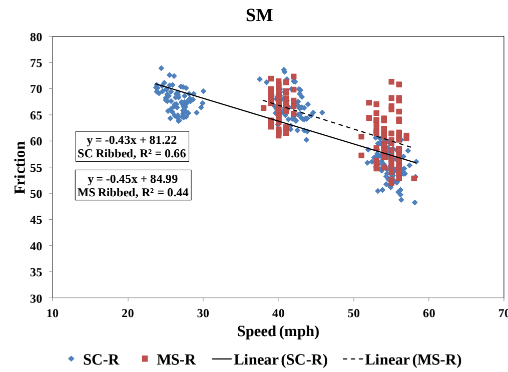
It is widely accepted that speed has a pronounced effect on skid trailer measurements. To visualize this effect, locked-wheel measurements are plotted against the test speeds in Figure 4. Measurements are divided into four groups based on the surface type: SUPERPAVE (SM), Stone Matrix Asphalt (SMA), Open Graded Friction Course (OGFC), and Portland Cement Concrete (PCC). A previous experiment (Surface Properties Rodeo 2010) revealed that grouping the surfaces is not only beneficial for data visualization but also improves the friction-speed correlations.

From the figure it can be observed that both unit measurements are comparable and, in most cases, overlap. Linear correlations also have similar slopes, in most cases. Contrary to the results obtained in the Rodeo 2010 for ribbed tires, it can be observed that the changes of friction due to speed are similar for compared units (parallel lines). It is believed that these results may be due to switching the same ribbed tire between units.

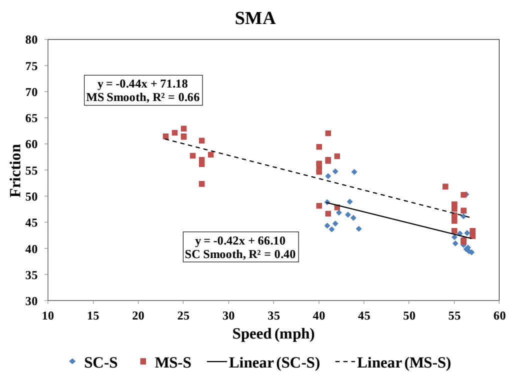
A more complete comparison showing correlations between various friction tester measurements made is shown in Figure 5. For this comparison, only the data collected at the standard 40 mph test speed were used to perform these correlations. These comparisons show also only the most significant comparisons found.



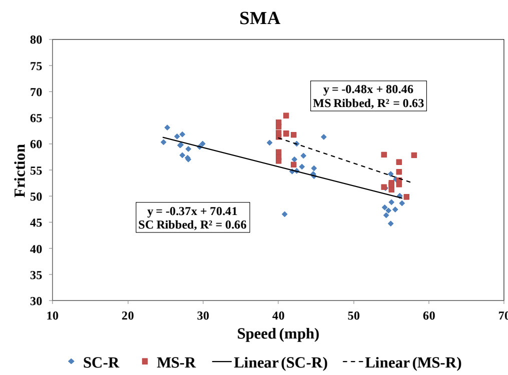
a) SUPERPAVE (SM) – Smooth tires



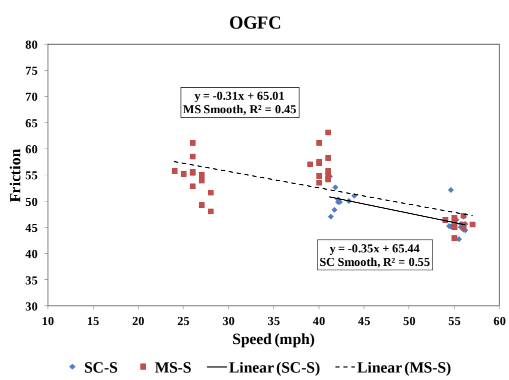
b)SUPERPAVE (SM) - Ribbed tires



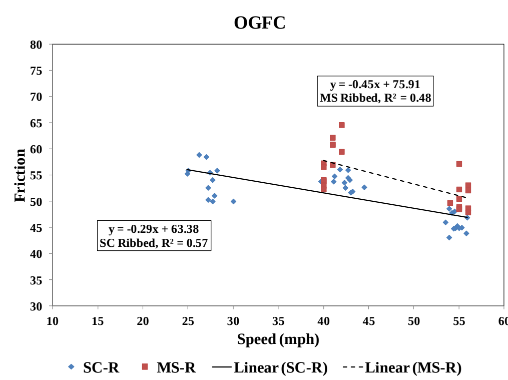
c) Stone Matrix Asphalt - Smooth tires



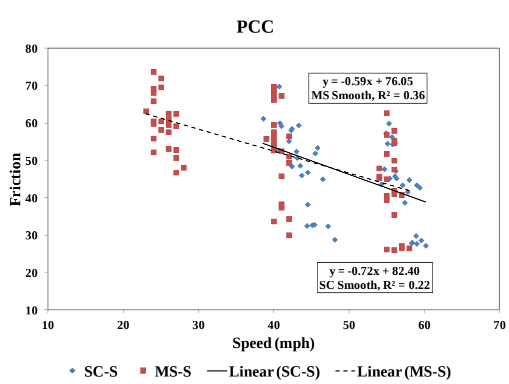
d) Stone Matrix Asphalt - Ribbed tires



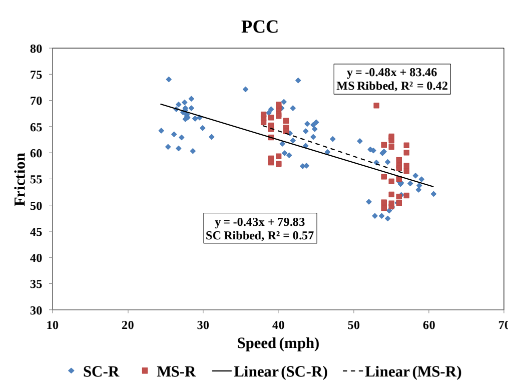
e) Open Graded Friction Course-Smooth tires



f) Open Graded Friction Course- Ribbed tires



g) Portland Cement Concrete - Smooth tires



h) Portland Cement Concrete - Ribbed tires

Figure 4. Friction versus speed for locked-wheel measurements.

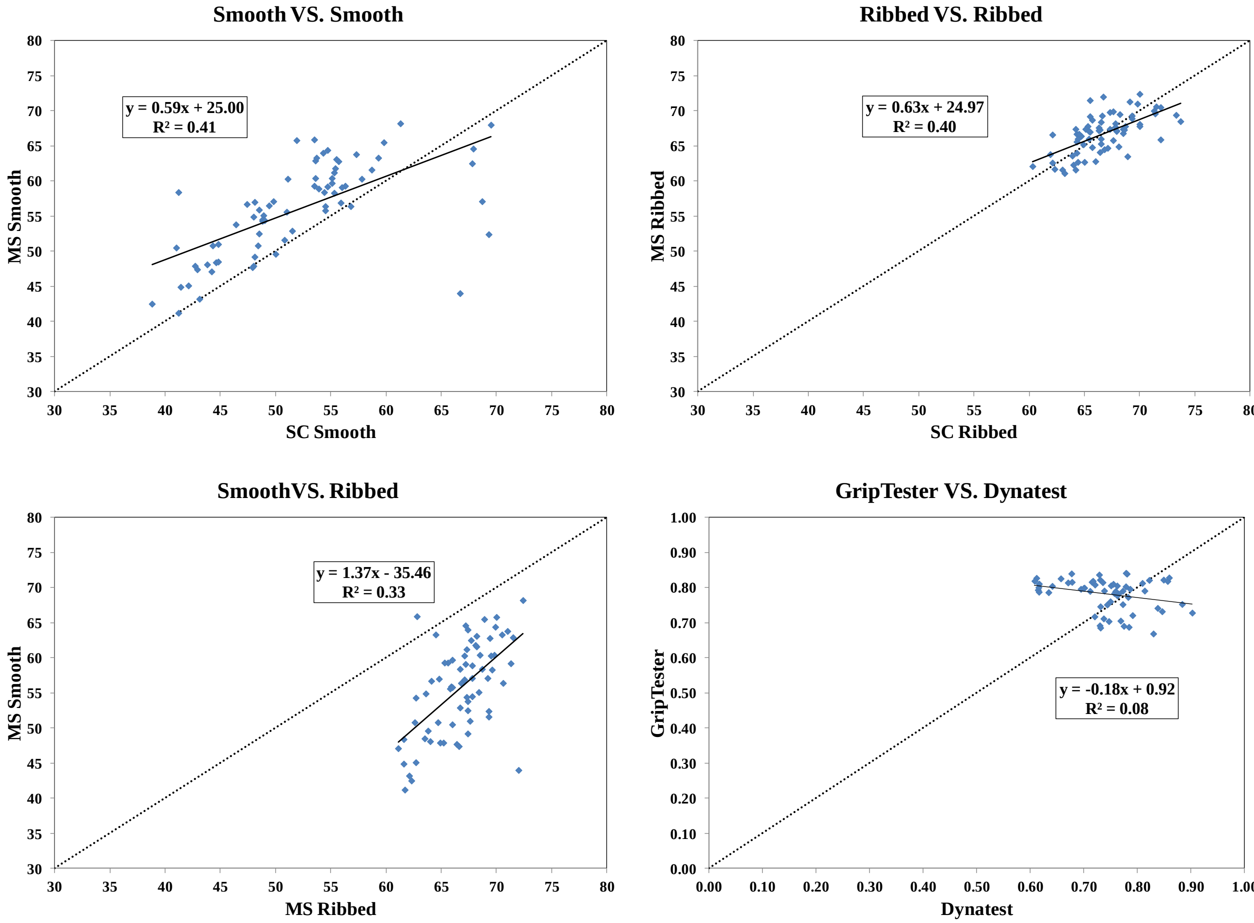


Figure 5. Correlation between various friction tester measurements.

Overall, the correlation is reasonable if the same type of tire is used for the test. As shown by the correlation found between the Grip Tester and Dynatest, a comparison between these two units is inadequate. This may be due to the way the data are averaged.

Although correlations between two measurements of the same property (e.g., friction) offer a practical approach for comparison, it is not statistically appropriate. This is because both measurements are collected with error. In general, the correlation coefficient shows the association and not the agreement between measurements (*1*). Developed by Altman and Bland, Limits of Agreement (LOA), is one method widely used for comparing the agreement between the measurements of the same property. LOA is calculated based on the Mean Square Error (MSE) of the measurement of each unit and the variance of the difference between the measurements of two units. More information regarding the calculation of LOA can be found in references (*1*, *2*) of the report.

All possible comparisons, made with the results of the LOA analysis between all the units, were found. The limits with 95% reliability between different measurements with the same unit (repeatability, Table 7) and the limits with 95% reliability between different equipment measurements (reproducibility, Table 8) are provided below for this comparison.

Table 7. Repeatability of friction tester measurements.

Repeatability (r)						
	SC					
	25 smooth	25 ribbed	40 smooth	40 ribbed	55 smooth	55 ribbed
Downhill	-	5.2	7.8	6.8	3.4	5.5
Uphill	-	4.9	5.9	5.6	4.9	4.5
	MS					
	25 smooth	25 ribbed	40 smooth	40 ribbed	55 smooth	55 ribbed
Downhill	5.2	-	13.2	6.5	13.1	7.8
Uphill	8.3	-	6.9	4.8	10.8	5.9
	GripTester					
	25 mph		40 mph		55 mph	
Downhill	6.8		7.3		8.7	
Uphill	5.3		4.7		9.3	
	Dynatest					
	25 mph		40 mph		55 mph	
Downhill	7.8		5.4		7.5	
Uphill	8.4		7.7		4.5	

Table 8. Reproducibility of friction tester measurements.

LOA (Reproducibility)						
	SC vs. MS					
	25 smooth	25 ribbed	40 smooth	40 ribbed	55 smooth	55 ribbed
Downhill	-	-	10.0	6.7	10.1	6.7
Uphill	-	-	7.3	7.5	8.3	5.7
	SC vs. GripTester					
	25 smooth	25 ribbed	40 smooth	40 ribbed	55 smooth	55 ribbed
Downhill	-	7.9	11.1	13.7	7.9	14.7
Uphill	-	6.8	8.2	10.2	13.6	11.3
	SC vs. Dynatest					
	25 smooth	25 ribbed	40 smooth	40 ribbed	55 smooth	55 ribbed
Downhill	-	11.5	10.4	10.7	9.0	11.3
Uphill	-	8.5	12.4	12.4	8.2	13.7
	MS vs. GripTester					
	25 smooth	25 ribbed	40 smooth	40 ribbed	55 smooth	55 ribbed
Downhill	7.9	-	13.2	13.3	11.8	14.0
Uphill	8.7	-	11.4	10.7	14.8	12.7
	GripTester vs. Dynatest					
	25 mph		40 mph		55 mph	
Downhill	12.1		7.7		10.5	
Uphill	11.0		15.9		15.3	

This means, for example, that a measurement with the SC skid tester, with 95% reliability, is between plus or minus 7.8 SN with smooth tire at 40 mph and between 6.8 SN with the ribbed tire, if it is to be measured again by the same skid tester, when traveling downhill. For comparison, the MS skid tester, will vary between 13.2 SN for the smooth and 6.5 for the ribbed tires, respectively. From these results, it is apparent that the MS tester has a greater variability with a smooth tire than the SC tester. Notice also that the difference in direction of the measurements tends to affect the MS tester more as it is significantly less repeatable downhill than uphill, which is not the case with the MS tester. Most of the testers do, however, have a different range of values for their repeatability when measuring in these two directions, which means that the grade is affecting, somehow, their performance, in different magnitude.

Conversely, when comparing measurements made in the same sections between different testers (reproducibility), the range for the same reliability is increased more because of the lack of agreement between the devices. For example, a measurement with the SC skid tester compared to the MS tester, with 95% reliability, is between plus or minus 10.0 SN with smooth tire at 40 mph and between 6.7 SN with the ribbed tire, when traveling downhill. When traveling uphill, the difference between tires is nullified making the limit between both measurements almost equally around 7.5 SN. This reinforces the previous statement about the problem of the MS tester dealing with the downhill measurements. Between the other units, the agreement gets worse, some being affected by the slope and others between specific types of testers. It is apparent that the results between the HFT and the GT are the most unreliable to compare as their measurements can have a range of difference of more than 30 points in some cases.

V.6. Texture

Macrotexture data were collected using the ASTM E-2157 CT-Meter. This static device has a displacement sensor mounted on an arm at a radius of 142 mm (5.6 inches), which rotates at a fixed elevation from the surface. Three sets of measurements were collected on each surface of the left lane of the road. The average MPDs for each surface are provided in Table 9.

Table 9. Macrotexture measurement (MPD).

Section	Eastbound	Westbound
A	0.70	1.12
B	0.82	1.18
C	0.87	0.87
D	0.58	0.73
I	1.08	0.87
J	-	-
K	1.43	1.68
L	1.02	1.23
PCC1	0.64	0.95
PCC2	0.38	2.14

V.7. Profiler

Profiler Data Collection

When state agencies schedule maintenance, repair, and rehabilitation work on their road networks, they accomplish such by measuring road roughness since it has significant influence on the performance of pavements and is a major determinant of road user costs (*3*). Techniques have evolved since the 1960s when roughness (or smoothness) of a road was first computed by measuring the vertical deviations of the road surface along a longitudinal line of travel in a wheel path (i.e., a longitudinal profile [*4*]). Since then, profilers have been developed with an aim to capture those aspects of a longitudinal profile that affect ride quality, vehicle dynamic loading, and safety (*3, 4*).

Most of the longitudinal road profile measurements are summarized using the IRI, which was developed by the National Cooperative Highway Research Program (NCHRP) and the World Bank (*5*). The IRI represents the accumulation of all vertical movements of a "standard" vehicle across a given length of road, usually expressed in inches/mile (mm/km). If the sum of these movements is large, the surfaces are usually rough (not smooth or even), and travel over them is uncomfortable. If the sum is small, travel is more comfortable.

All agencies participating in the Consortium use single-spot laser-based inertial profilers for measuring longitudinal profiles at highway speeds and then computing the IRI values at project and network levels. The major problem associated with inertial profilers is the accuracy of the collected road profile measurements. The verification of these measurements can only be accomplished when compared to a stable, consistent scale. To verify the profilers' correct operations, the Consortium decided to implement a profiler verification site following available guidelines and specifications that test the compliance of the accuracy of the profilers of its members.

The American Association of State Highway and Transportation Officials (AASHTO) has developed provisional standards, including AASHTO certification, to help state highway departments implement equipment specifications for inertial profilers. Since 2006 the pooled-fund study TPF-5(063), Improving the Quality of Profiler Measurement, has helped establish the criteria to implement verification centers and assist in their development (*6*). AASHTO specification PP–49 (*7*) sets guidelines for the comparison of road profiles taken with a reference device (i.e., a Class-1 instrument) to verify the IRI biases in the measurements and the repeatability and reproducibility of inertial profilers (*8-13*).

Test Sections

All Smart Road section characteristics are summarized in Table 10. Based on the general requirements set forth by AASHTO PP-49 specifications, a decision was made to design five test sections on the uphill (westbound) lane of the facility. AASHTO PP-49 requires the sections for the test comparisons to be at least one-tenth of a mile long, or 528 feet. The first two test sections were established in the JRCP (jointed reinforced concrete pavement) and the CRCP (continuously reinforced concrete pavement) pavements. It must be noted that both of these sections were grounded, and the CRCP section was grooved in January 2011. The remainder of the test sections then had to be placed over the asphalt concrete pavements. From Table 10, test section 3 was chosen from the coarse asphalt pavements (SMA and OGFC). The two remaining sections were chosen based on their roughness: one with a low IRI value and one with a high IRI value. Although sections E and F would have made a better match for the low IRI criterion, sections F and G were chosen for test section 4 because section E lies on a horizontal curve. Finally, sections A and B were chosen as test section 5 since the two had relatively high IRI values.

Table 10. Smart Road section pavement surfaces.

Section	Name	Surface Mix Type	Length (feet)	MPD Uphill (mm)	Last IRI Meas. (in/mi)	Test Section No.	Length (feet)
1	Loop	SMA 19.0	N/A	0.80	N/A		
2	A	SM-12.5D	347	0.89	**123**	**5**	**528**
3	B	SM-9.5D	289	1.01	**164**		
4	C	SM-9.5E	292	0.79	77		
5	D	SM-9.5A	407	0.70	195		
6	E	SM-9.5D	268	N/A	90		
7	F	SM-9.5D	302	N/A	**99**	**4**	**528**
8	G	SM-9.5D	304	N/A	**108**		
9	H	SM-9.5D	292	N/A	112		
10	I	SM-9.5A(h)	338	0.73	93		
11	J	SM-9.5D	280	0.85	105		
12	K	OGFC	302	1.80	**134**	**3**	**528**
13	L	SMA-12.5D	326	1.08	**113**		
14	CRCP*	Tined	2,290	0.80	**69**	**2**	**528**
15	JRCP*	Grooved	591	N/A	N/A	**1**	**528**

Note: Past IRI measured on 05/13/2009.

* Both JRCP and CRCP sections were grounded, and the CRCP was grooved. These values do not represent the texture (MPD) or smoothness (IRI) values, which will be reported below for the first time.

Each of the test section wheel paths were marked every 10 feet with paint so that operators could align the profilers when traveling at the required speed of 50 mph. The paint markings also helped reduce possible wandering errors (*14*). The left wheel path was marked 34.5 inches from the center line, and the right one was separated from the left by 69 inches. Each test section also had paint-marked, lead-in distances of 150 feet starting across a one-inch high electrical rubber cable cord protector that was placed as an artificial bump to indicate the start of each of the lead-in sections. These bumps were intended to produce a spike in the profiles, which made it possible to determine the exact location of the test sections during subsequent analysis (*14*). The paint markings for the 150-foot lead-in areas were colored yellow, while the 528-foot test sections were colored green.

Reflective material trigger markers were also placed 50 feet before the first artificial bump and 50 feet after the end of the last test section to activate the start and end times of the data collection. Traffic cones with reflective material were also placed next to each bump before the lead-in areas of each test section to help the profiler operators become aware of the beginning location and to align properly in the marked wheel paths. A diagram of the profiler testing setup for each test section is shown in Figure 6.

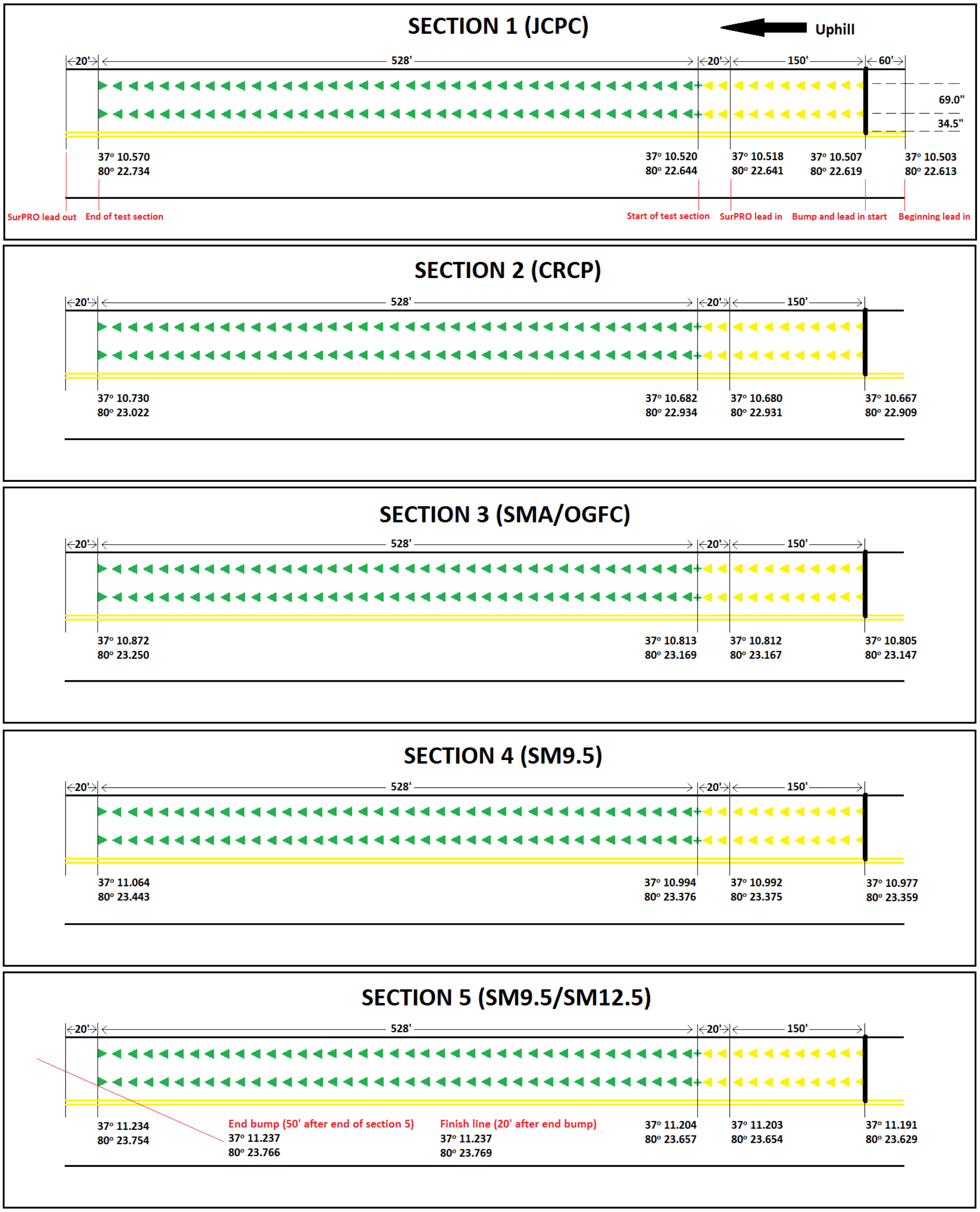


Figure 6. Smart Road profiler test section setup for 2011 Rodeo.

Data Collection

Reference Profiler

An ICC (International Cybernetics Corporation) SURPRO walking profiler was chosen as the reference instrument used to measure each of the five test section profiles along the left and right wheel paths. Five passes were made on both wheel paths to assure ideal repeatability and to compute the IRI value of each wheel path in each section. In some cases, preliminary analysis of the SURPRO output suggested that more passes were needed. Therefore, some of the sections have results for seven or eight runs. This reference profiler is used by many state agencies (*15*). Figure 7 shows the SURPRO during reference measurements.

Figure 7. Reference profile measurements being taken with the SURPRO.

High-speed Profilers

Four profilers were used to obtain measurements for comparison to the reference measurements made with the SURPRO device. Data were collected following the procedures mentioned in AASHTO PP-49. Pre-test system calibration, including block, bounce, and distance calibrations, were also performed. The block tests were conducted with blocks provided by each profiler manufacturer and with a standard set of calibration blocks purchased by the Virginia Tech Transportation Institute (VTTI). Bounce tests were performed for each unit as recommended by each manufacturer (e.g., ICC, Dynatest, etc.). These tests are designed to detect any serious malfunctions outside the permissible limits during the normal operation of the height and accelerometer sensors.

A distance measuring instrument (DMI) calibration section with a length of 1,000 feet was also marked on the downhill portion of the CRCP section where the road is straight but has a maximum slope of approximately 6%. Each profiler made at least five runs to calibrate the DMI as per normal operating recommendations by manufacturers. All profilers then collected profile data 10 times at a constant speed of 50 mph, trying to avoid sudden speed changes throughout the sections.

Profiler Results and Discussion

The ride statistics, repeatability, and reproducibility assessments for all data collected were calculated using the analysis methods that are included in the Profile Viewing and Analysis (ProVAL) software developed under the sponsorship of FHWA (*16*, *17*). The following is a brief description of the results.

Ride Statistics

IRI values of all profile runs for all test sections were computed using ProVAL. The averages of the 10 runs from each profiler were computed. All IRI computations made in ProVAL applied a 250 mm moving average filter (*17*). The IRI results from all profilers for all sections are shown in Figure 8 and Figure 9.

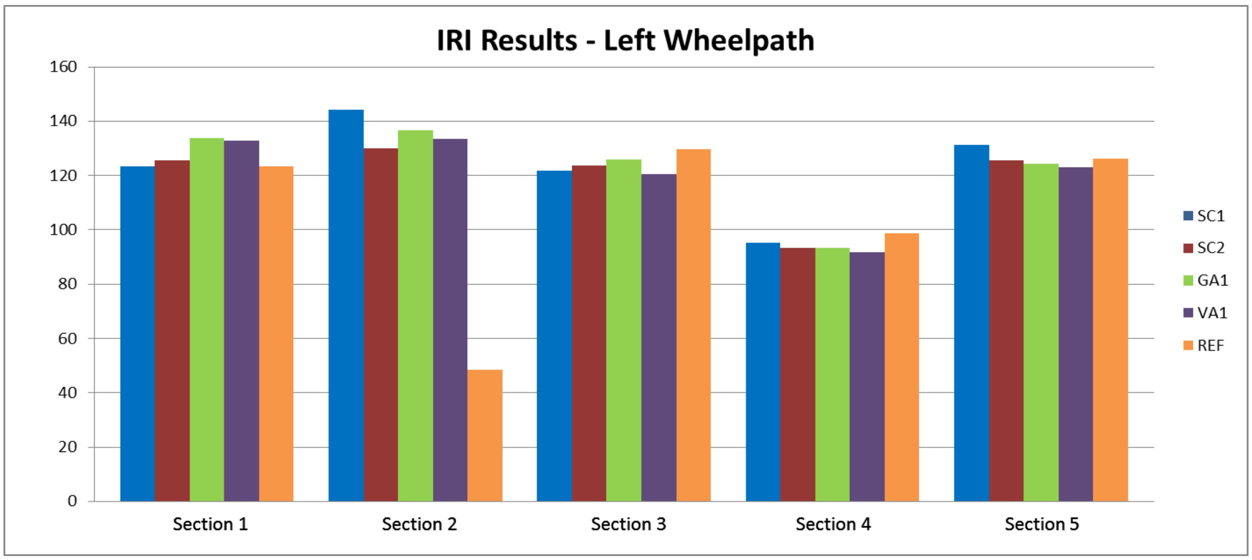


Figure 8. Left wheel path ride statistics.

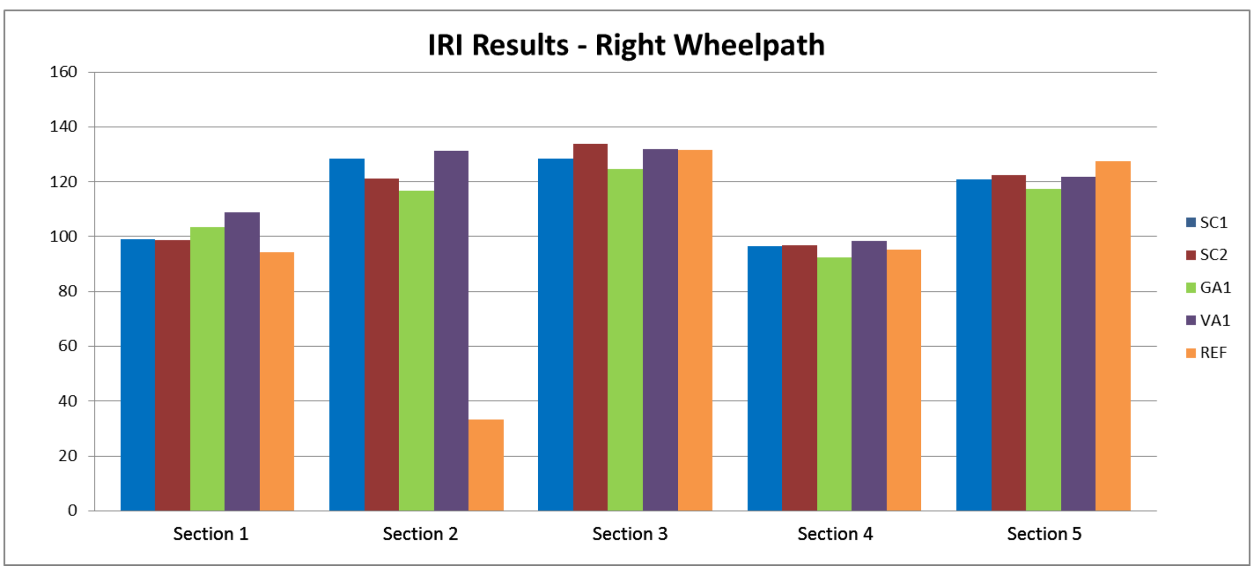


Figure 9. Right wheel path ride statistics.

The left wheel-path IRI values are greater than the right ones in the first section (JRCP). The highest IRI values are found in the second section, most likely due to the vertical deviations caused by recent grinding and grooving. It should be noted that the results from the Rodeo 2010 showed that the second section yielded the lowest IRI results prior to grinding and grooving. The coarser textured pavement found in test section 3 and the high cracking damage of test section 5 caused the IRI values for these areas to be relatively high. Section 4 has a lower IRI value than the aforementioned asphalt sections and the overall lowest IRI value of all test sections, although it is section 2 that has the lowest IRI as demonstrated by the reference profiler measurements. This will be further explained below when the grooved section is analyzed independently.

The repeatability of the IRI values of all profilers was evaluated by calculating the coefficient of variation (COV) of the IRI values for all repeat runs of each profiler. It was found that the profilers were repeatable in IRI measurements with a COV less than 3% for both wheel paths. No significant variations were observed when the IRI values from the high-speed profilers were compared with the SURPRO IRI values, except for section as explained before.

Repeatability

Repeatability results illustrate how well each unit obtains the same profile measurements during each of the 10 runs. For this study, cross-correlation was performed on the profile data to evaluate both profiler repeatability and reproducibility. For repeatability, AASHTO PP-49 requires an average cross-correlation of at least 92% when each profile is compared with the remaining nine runs (90 comparisons). Higher repeatability results were achieved without applying any comparison output filter. The repeatability results for each of the laser sensors (i.e., left and right) as computed with ProVAL are shown in Table 11 for each test section. Bold, italicized red numbers indicate those that did not pass the repeatability criteria.

Table 11. Average repeatability cross-correlations for all profiler units.

Profiler	Average Repeatability Cross-correlations									
	Section 1		Section 2		Section 3		Section 4		Section 5	
	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
SC1	*82*	94	*68*	*60*	*86*	92	99	98	98	97
SC2	97	96	*71*	*63*	98	98	99	98	99	98
GA1	*91*	93	*59*	*51*	95	95	98	97	98	98
VA1	97	97	*58*	*53*	99	98	99	99	99	99

The profilers that were present at the rodeo included two from South Carolina Department of Transportation (SC1 and SC2), one from Georgia DOT (GA1), and one from Virginia DOT (VA1). The majority of the repeatability results showed ideal correlation between the various runs in all sections, with the exception of test section 2. None of the profilers passed all the repeatability tests with values of more than 92% for all sections. Only for sections 4 and 5 did the entire group of profilers pass the repeatability test for both wheel paths. However, the computed IRI values were close, as explained in the previous section.

Reproducibility

Reproducibility results were obtained by comparing the highest cross-correlation repeatability for each wheel path based on the SURPRO profiles to the 10 runs from each participant profiler. Power

Spectrum Density (PSD) plots of the data collected with the SURPRO indicated that a moving average filter had already been applied to the data. Hence, no separate moving average was required for the SURPRO runs, and the IRI-filtered cross-correlation was only applied to the data of the profilers (*17*). The results from the profiler certification (reproducibility) module are shown in Table 12.

Table 12. Average reproducibility cross-correlations for all profiler units.

Profiler	Average Reproducibility Cross-correlations									
	Section 1		Section 2		Section 3		Section 4		Section 5	
	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
SC1	32	39	7	5	74	78	74	76	59	66
SC2	31	40	11	5	77	79	75	77	77	72
GA1	57	58	12	7	66	70	69	65	59	63
VA1	49	57	8	5	74	78	72	72	81	77

According to AASHTO PP-49, a profiler passes the reproducibility test if it has a cross-correlation value of more than 90% when compared with the respective reference profile. As can be seen in Table 12, the reproducibility cross-correlations (IRI filtered) between the SURPRO and all profilers are relatively low; no profilers scored satisfactorily. Section 2, which displayed poor repeatability results in the previous section, also displays the lowest reproducibility.

Inter-profiler Reproducibility

Since the reproducibility results with the SURPRO used as the reference device were found to be low, another cross-correlation comparison was made between all participant profiler units to verify inter-profiler reproducibility correlations. This approach was used because, if cross-correlations among the high-speed profilers were ideal, the fundamental differences between their profiles and those collected with the SURPRO could be the reason for the low results. Those runs of profilers that showed the highest cross-correlation results with the SURPRO (i.e., the "best runs" from each profiler for each section) were selected and used to compare all profilers among themselves.

An example of this analysis is shown in Table 13 in which the results obtained for the right wheel path for test section 1 can be seen. These results are lower than 90%, so it was concluded that the reference profiler was not the reason that the profilers did not show ideal reproducibility.

Table 13. Inter-profiler reproducibility for section 1 of right wheel path.

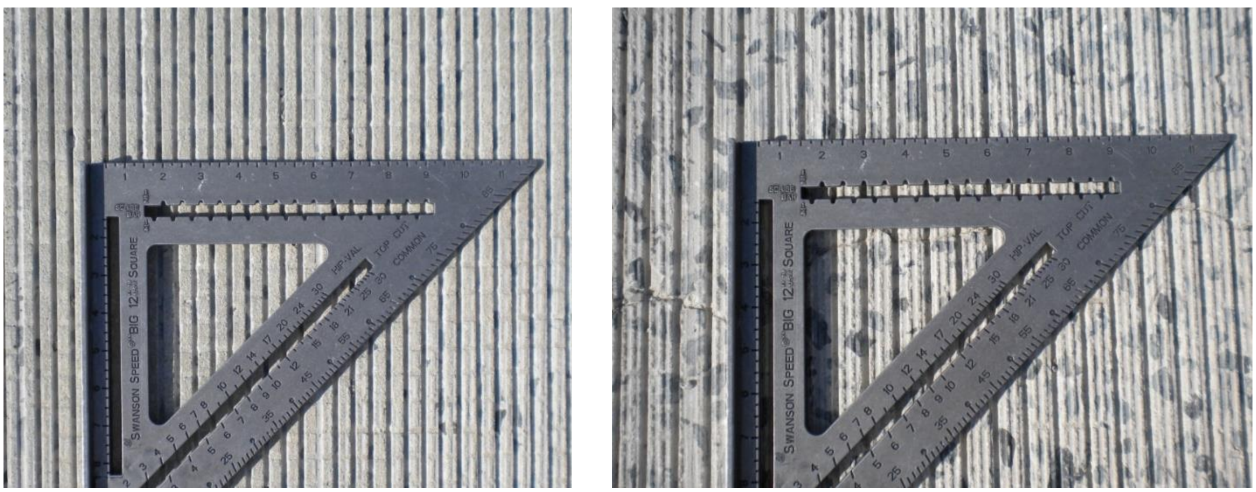
Reference Unit	Compared Profiler Unit			
	SC1	SC2	GA1	VA1
SC2	69			
GA1	42	40		
VA1	47	49	58	

V.8. Evaluation of the effect of diamond grinding and grooving on surface characteristics of concrete pavements

In January 2011, one of the PCC and JRCP concrete sections at the Smart Road was diamond grounded and longitudinally grooved by the International Grooving and Grinding Association (IGGA). To evaluate the effect of this practice on surface characteristics of concrete pavements, several measurements were collected on concrete sections as part of the Rodeo 2010 and 2011. Following are results received from the PCC section subjected to diamond grinding and grooving.

Grooving Pattern

Two different groove spacing were used for each half of the PCC section lane: 1) ½-inch along the left wheel path, and 2) ¾-inch along the right wheel path. Figure 10 illustrates grooving on the PCC section.



- PCC left wheel path, ½-inch groove spacing.
- PCC right wheel path, ¾-inch groove spacing.

Figure 10. Grooving on PCC section.

Texture

Texture measurements were obtained using the ASTM E-2157 CTMeter. To determine the effect of diamond grinding and grooving on surface macrotexture, measurements were collected on both tinned and grooved PCC. The tinned PCC section is located along the eastbound lane of the Smart Road, while the grooved section is located along the westbound lane. All measurements for both sections were collected in the left wheel path. Overall, three sets of measurements were obtained for each section. Table 14 shows the macrotexture data for each test section.

Table 14. Macrotexture measurements using CTMeter.

Section Type	# of Measurements	Average MPD (mm)
Original tinned PCC	3	0.38
Diamond ground and grooved PCC	3	2.14

From the results of Table 14, it can be seen that diamond grinding and grooving have significantly increased the macrotexture of the PCC pavement (i.e., higher MPD). This high macrotexture can improve the skid resistance of the surface by significantly reducing the effect of hydroplaning.

Friction

Friction measurements were obtained using two locked-wheel skid trailers. One of the locked wheels used the ASTM E-524 smooth test tire while the other used the ASTM E-501 ribbed tire. Five sets of measurements were obtained on both original tinned and grooved PCC sections at three speeds: 25 mph, 40 mph, and 55 mph. All measurements were collected during Rodeo 2011. Figure 11 shows the layout of the test sections. A summary of the locked-wheel measurements is presented in Table 15.

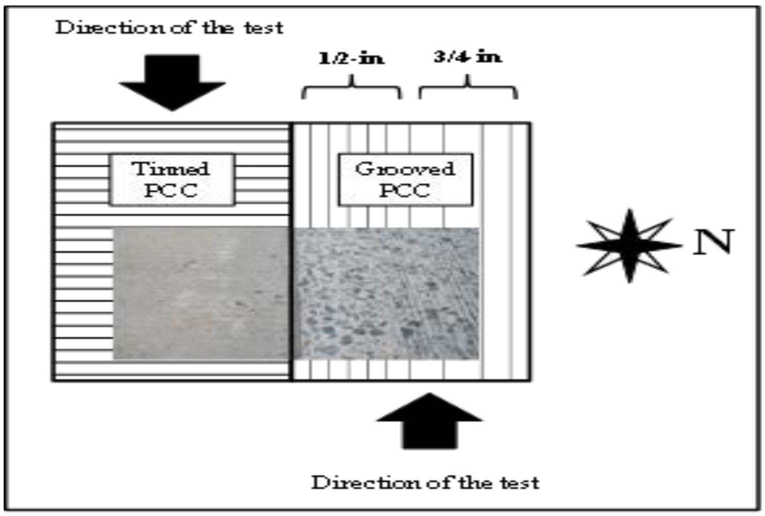


Figure 11. Test sections layout.

Table 15. Summary of locked-wheel skid trailer measurements.

Unit #	Test Tire	Test Section	Test Speed (mph)	# Measurements	Average Skid Number
1	Smooth	Original Tinned PCC	25	5	51.23
			40	5	36.60
			55	5	28.65
		Grooved PCC	25	5	58.90
			40	5	56.07
			55	5	44.97
2	Ribbed	Original Tinned PCC	25	5	67.77
			40	5	64.07
			55	5	53.10
		Grooved PCC	25	5	62.23
			40	5	59.65
			55	5	48.82

To evaluate the frictional properties of the tested surfaces, linear correlations were made for all measurements (Figure 12). Several observations can be made. Smooth tire results show a significant increase in the skid numbers of the concrete section subjected to diamond grinding and grooving. This agrees with the higher measured macrotexture achieved on concrete after grinding and grooving.

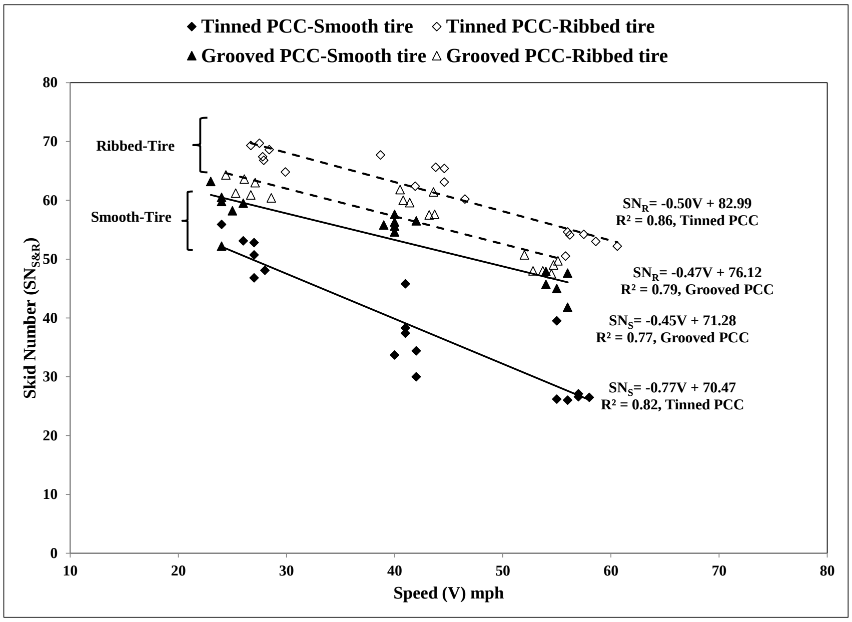


Figure 12. Correlation between skid number and speed.

Another interesting observation for smooth tires is the slope of the correlation line between skid numbers and speed for the sections. This slope is less for ground and grooved PCC than it is for tinned PCC, which suggests that friction is less sensitive to the changes of speed for this section. At lower speeds (25 mph) smooth tire measurements for both sections seem to be relatively close. However, at high speeds (40 and 55 mph) the difference is more evident. In general, the effect of hydroplaning is more pronounced at greater speeds. Since the grooved section has greater macrotexture, it is less sensitive to hydroplaning and consequently provides increased friction during tests made at higher speed.

Ribbed tire results, on the other hand, do not show a significant difference in the skid values collected on the two test surfaces. The sensitivity of friction to speed is similar for both tinned and grooved test sections (parallel slopes). It is surprising that the ribbed tire skid numbers are slightly higher for tinned PCC than the grooved PCC. This seeming paradox between smooth tire and ribbed tire results may be explained by sensitivity of the test tire to the pavement surface texture and surface condition. Smooth tires are more sensitive to macrotexture while ribbed tires are more sensitive to microtexture.

It can therefore be postulated that tinned PCC has a greater microtexture while grooved concrete has a greater macrotexture. Since the difference between ribbed tire measurements for the two types of PCC surfaces is not significant, constructing grooved concrete surfaces would be a preferred choice for preventing hydroplaning at high speeds (i.e., it increases macrotexture). The lack of sensitivity of ribbed tires to the effect of macrotexture has been cited by other researchers. There is evidence that pavement grooving significantly decreases the rate of wet-weather accidents; however, ribbed tires fail to show this effect. For this reason some researchers believe that smooth tires are a better choice for predicting skidding potentials (*18*).

Smoothness

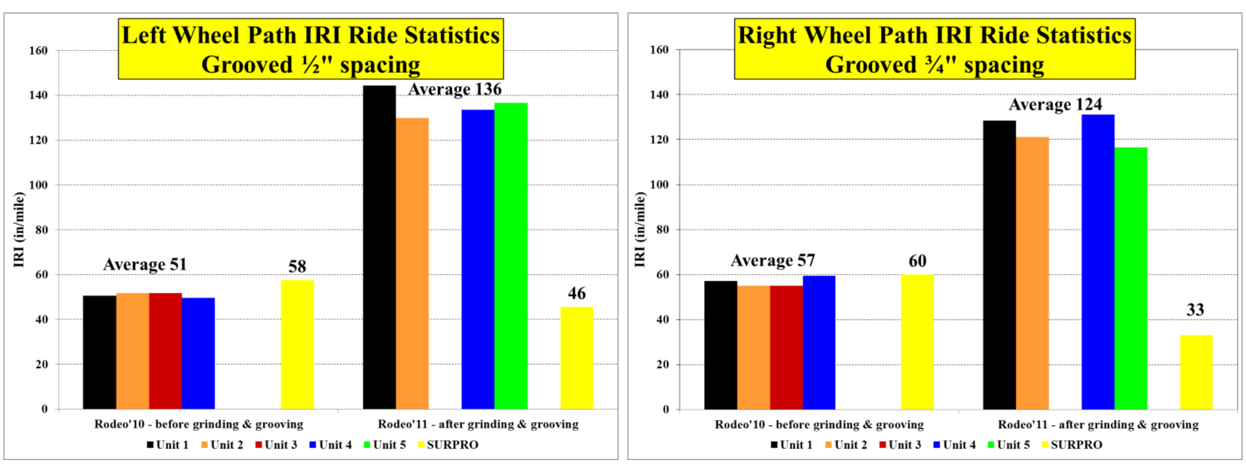
For smoothness assessment, longitudinal profile measurements made before and after diamond grinding and longitudinal grooving were evaluated. Several high-speed inertial profilers were included in this comparison from two years rodeos. Table 16 includes a list of the profiler manufacturers, sensor types, and the sampling intervals of all profilers that were included in the comparative study conducted as part of the rodeos in 2010 and 2011.

Table 16. Summary of the profiler tests.

Profiler Unit	Manufacturer	Sensor Type	Data Recording Interval	
			Rodeo 2010	Rodeo 2011
Unit 1	Dynatest	Single-spot laser	1.00"	1.00"
Unit 2	Dynatest		0.998"	1.00"
Unit 3	ICC		1.248"	1.21"
Unit 4	ICC		3.1"	3.06"
SURPRO	ICC	Inclinometer	1.00"	1.00"

To evaluate the effect of the diamond grinding and longitudinal grooving on the smoothness of the PCC section, the IRI values of the profiles were computed using ProVAL. All IRI computations made in ProVAL applied a 250 mm moving average filter. Figure 13 shows the IRI results from all profilers used before and after diamond grounding and longitudinal grooving were performed on the PCC section.

As expected, the SURPRO IRI measurements made on a ground and grooved PCC section were found to be less than the transversely tinned PCC section. On the other hand, a significant increase in the average IRI values was observed for profiles collected by single-spot laser profilers on the PCC section after it was subjected to diamond grinding and longitudinal grooving. This is mainly caused by the wander of the single spot laser as it moves in the grooves.



(a) Left wheel-path IRI ride statistics. (b)Right wheel-path IRI ride statistics.

Figure 13. IRI ride statistics for PCC before and after diamond grinding and grooving.

Conclusions and Recommendations

Friction

- Measurements of various friction testers were compared using LOA. This methodology is an objective approach designed to evaluate the repeatability and reproducibility of friction testers.
- Switching the tires between friction testers improved the agreement between their measurements. It is recommended to use the same tire when assessing the reproducibility of two friction testers. This is critical for ribbed tires since the rib depth can significantly affect the measurement.

Profiler

- Four high-speed laser profilers and a single reference profiler measured the profile of the road. With the exception of section 2, a grooved PCC pavement, the profilers exhibited acceptable repeatability, while the reproducibility between profilers and the reference profiler was relatively low.

Effects of Diamond Grinding and Grooving

- Diamond grinding and grooving significantly increased the macrotexture of the PCC surface. High macrotexture can aid in removing water from the pavement surface, which can cause hydroplaning and skidding problems during wet-weather conditions.
- Friction measurements revealed that friction increased after applying diamond grinding and grooving to the PCC surface, especially when using the smooth tire. This effect was found to be significant during increased speeds.
- Ribbed tire skid trailer results did not show a significant difference in friction measurements made on the ground and grooved PCC compared to the tinned PCC. This was expected as ribbed tire measurements are not very sensitive to changes in pavement macrotexture. This finding is in agreement with other studies that have cited that pavement grooving can help reduce the rate of wet crashes, but ribbed tire skid trailers are incapable of showing this effect.
- SURPRO reference profiler results showed a decrease in IRI values on the PCC surface after grooving. The improvement in smoothness was greater on the right wheel path with ¾-inch grooving compared to the left wheel path with ½-inch grooves.
- Compared to the reference profiler, single-spot laser profilers over-predicted the IRI values on the ground and grooved PCC. This disagreement is due to grooves on the section, which render the single-spot profilers incapable of measuring the correct profile. Multi-footprint profiling systems should be used during future research conducted on pavement with longitudinal grooves, and system performance should be compared to single-spot laser profilers.

Acknowledgments

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Hobbs, James Bryce, Shahriar Najafi, Mohamed Saleh, Sameer Shetty, Chris Tomlinson, and Steve Valeri (from CSTI) collaborated with the data collection and processing.

References

1. Altman, D. G., and Bland, J. M. (1983) Measurement in medicine: the analysis of method comparison studies, *The statistician*, 307-317.

2. de León, E., Flintsch, G., and McGhee, K., (2012), Limits of Agreeement (LOA) Method for Comparing Pavement Friction Measurements, *Presented at the 91st Transportation Research Board Annual Meeting, Washington DC*.

3. Perera, R. W., Kohn, S. D., and Wiser, L. J. (2006) Factors contributing to differences between profiler and the international roughness index, *Transportation Research Record: Journal of the Transportation Research Board 1974*, 81-88.

4. Perera, R. W., Kohn, S. D., and Bemanian, S. (1996) Comparison of road profilers, *Transportation Research Record: Journal of the Transportation Research Board 1536*, 117-124.

5. Sayers, M.W., et al., Guidelines for Conducting and Calibrating Road Roughness Measurements, World Bank Technical Paper Number 46, 1986

6. Improving the Quality of Pavement Profiler Performance, Federal Highway Administration (FHWA) Pooled Fund Study TPF-5(063), www.pooledfund.org/documents/TPF-5_063, Accesed June 1, 2009.

7. AASHTO, Standard Practice for Certification of Inertial Profiling Systems (PP49), The American Association of State Highway and Transportation Officials, Washington, D.C., 2007.

8. Karamihas, S.M., Gillespie, T.D., Kohn, S.D., Perera, R.W., Guidelines for Longitudinal Pavement Profile Measurement, NCHRP Project 10-47, 1999

9. Sayers, M.W., and Karamihas, S.M., The Little Book of Profiling, University of Michigan Transportation Research Institute, 1998

10. Karamihas, S.M., Critical Profiler Accuracy Requirements, Final Report, Federal Highway Administration (FHWA) Pooled Fund study TPF-5(063), 2005.

12. Perera, R.W., Kohn, S.D., and Wiser, L.J., Factors Contributing to Differences Between Profiler and the International Roughness Index, In Transportation Research Record: Journal of the Transportation Research Board, No. 1974, Transportation Research Board of the National Academies, 2006

13. Perera, R.W., Kohn, S.D., and Bemanian, S., Comparison of Road Profilers, In Transportation Research Record: Journal of the Transportation Research Board, No. 1536, Transportation Research Board of the National Academies, 1993

14. Flintsch, G., de León Izeppi, E. D., McGhee, K. K., and Shetty, S. S. (2010) Profiler Certification Process at the Virginia Smart Road, *Presented at the 89th Transportation Research Board Annual Meeting, Washington DC*.

15. Perera, R.W and Kohn, S.D., Evaluation of Wisconsin DOT Walking Profiler, Federal Highway Administration (FHWA), 2007

16. Karamihas, S.M., Development of Cross Correlation for Objective Comparison of Profiles, University of Michigan Transportation Research Institute, 2002

17. Chang, George, PROVAL Users Guide: Profile Viewing and Analysis Software, TRANSTEC, Austin, Texas, 2007.

18. Wambold, J. C., Henry, J. J., and Hegmon, R. R. (1986) Skid resistance of wet-weather accident sites, p 47, ASTM International.

VI. 2012 Annual Equipment Comparison Roundup at the Smart Road[6]

VI.1. Overview

“The regional pooled-fund project known as the Pavement Surface Properties Consortium is a research program focused on enhancing the level of service provided by the roadway transportation system through the optimization of pavement surface texture characteristics. The program was established in 2006 with support from the Federal Highway Administration (FHWA) and six state departments of transportation (DOTs): Connecticut, Georgia, Mississippi, Pennsylvania, South Carolina, and Virginia. The Consortium provides a practical mechanism to conduct research about pavement surface properties and explore their relationships with ride quality, friction, and noise. Complementing this effort is research focused on the review, testing, and evaluation of emerging technologies.”

Various friction testers and profilers were assessed during 2012 equipment roundup. The objective of this year rodeo was to harmonize the participant friction tester’s and profiler’s measurements.

VI.2. Introduction

The Pavement Surface Properties Consortium hosts an annual event every year in May at the Virginia Smart Road in order to evaluate and compare various types of highway friction and profile measuring equipment. This event is called “the Surface Properties Rodeo”. Seven friction testers and seven high-speed profilers (plus a reference profiler) participated in the 2012 Rodeo equipment roundup. The Departments of Transportation (DOTs) of Virginia (VA), Mississippi (MS), South Carolina (SC), Georgia (GA), and the International Grinding and Grooving Association (IGGA) brought locked-wheel skid trailers. The University of Costa Rica Materials Laboratory (LANAMME) and the Virginia Tech Transportation Institute (VTTI) brought Grip Testers, which is a Continuous Friction Measuring Equipment (CFME). The High-speed laser profilers included one from Georgia, one from Mississippi, two from South Carolina, and three from Virginia (Figure 1).

Figure 1 High-speed Profilers participants in the 2012 Rodeo

[6] Prepared by Edgar de León Izeppi, Gerardo Flintsch, Kevin K. McGhee, Shahriar Najafi, and Daniel Mogrovejo

VI.3. Purpose and Scope

The main objectives of the 2012 rodeo were as follow:

- Friction: Compare and evaluate the various friction testers' measurements, assessing the repeatability and reproducibility of the measurements.
- Profiler: Compare the measurements of the seven high-speed laser profilers and the reference profiler using ProVAL and the International Roughness Index (IRI) of the test sections, also assessing the repeatability and reproducibility of the measurements.

VI.4. Methods

Measurements for friction and profile were collected at the Virginia Smart Road. The procedure of data collection is explained in detail for each of these measurements. The summary of the results and analysis is also provided in each section.

VI.5. Friction

Friction Data Collection

Friction measurements were collected on May 23, 2012, at the Virginia Smart Road. Five locked-wheel skid trailers and two Grip Tester units participated in the comparison. Measurements were collected at 40 mph (standard speed for friction tests). To assess the effect of slope on the measurement, data were collected in both uphill and downhill directions on the same wheel-path. Locked-wheel tests were performed in accordance with ASTM E-274. Virginia, Mississippi, and South Carolina tested both smooth (ASTM E-524) and ribbed (ASTM E-501) test tires. Georgia and IGGA only used ribbed tires. Both GripTester units used ASTM E-1844 smooth tires. Measurements were collected over 11 tests sections: A, B, C, D, I, J, K, L, PCC1, PCC2, and JRCP, as shown in Figure 2 below (except JRCP). It is believed that the sharp fins of the recently diamond ground JRCP section cut through the locked-wheel tires, which made the data inconsistent for this section. A summary of the tests is provided in Table 17.

Table 17 Summary of the friction tests.

Unit	Type	Tire	# test sections	Test Speed (mph)
VA skid trailer	Locked wheel	Smooth & ribbed	11	40
MS skid trailer	Locked wheel	Smooth & ribbed	11	40
SC skid trailer	Locked wheel	Smooth & ribbed	11	40
GA skid trailer	Locked wheel	Ribbed	11	40
IGGA skid trailer	Locked wheel	Ribbed	11	40
VTTI Grip Tester	Fixed slip	Smooth	11	40
Costa Rica Grip Tester	Fixed slip	Smooth	11	40

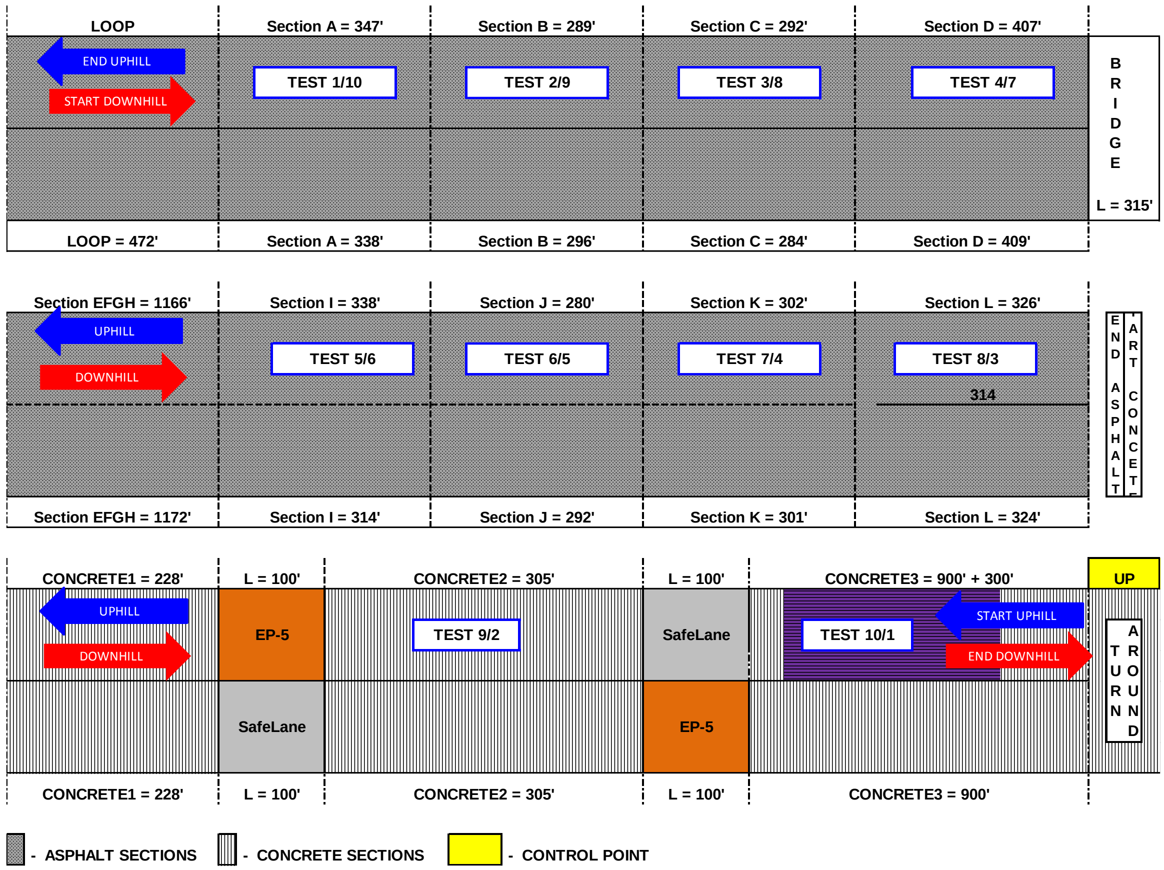
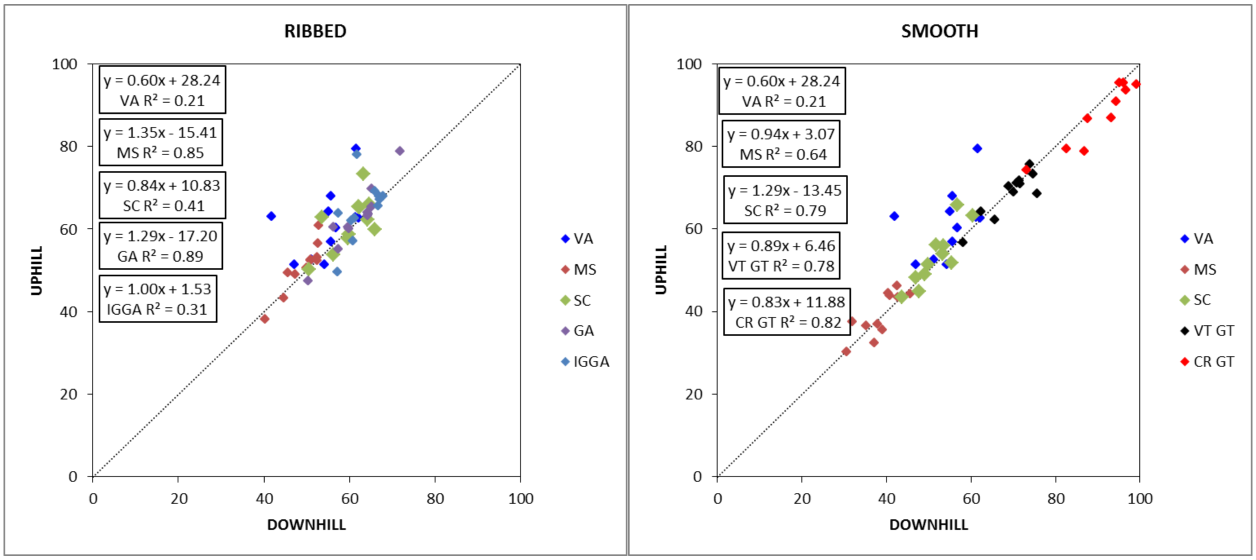


Figure 2. Section Layout

Friction Results and Discussion

To compare the friction measurements made going downhill and uphill, and better visualize the data, plots with correlations for each unit and each tire were made and can be seen as Appendix A.1. A summary of these results for all the friction testers' measurements is shown in Figure 3a and 3b for the Ribbed and Smooth Tires. Some correlations have a reasonably high coefficient of determination (R-square) and the measurements seem to be comparable in each direction, but some correlations don't.

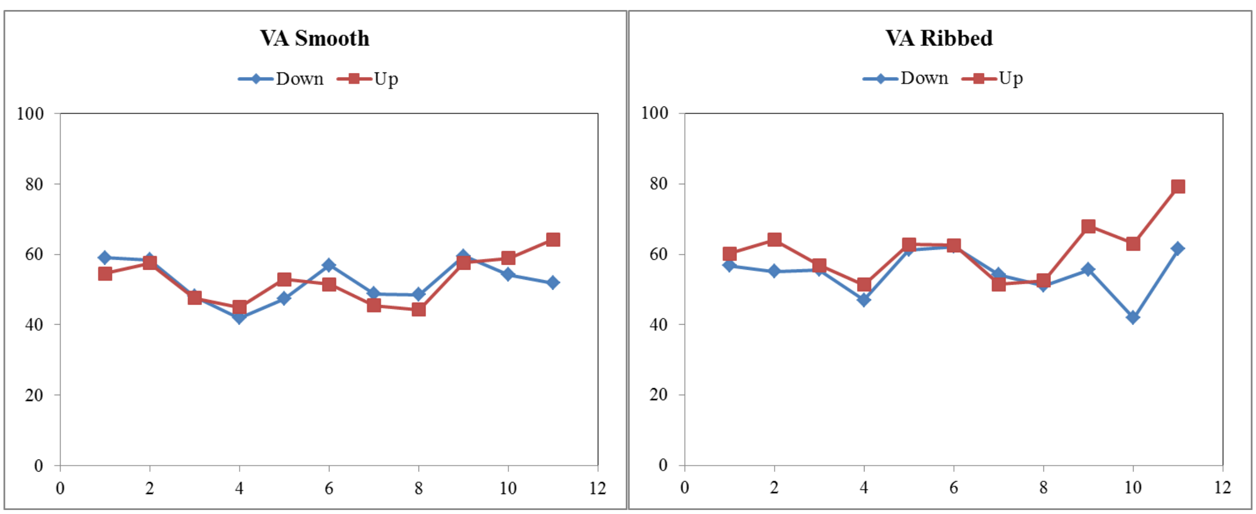
Overall, the correlations between ribbed tires seem to be better than those for smooth tires (higher R-square). This can be due to the higher sensitivity of smooth tires to the test condition and pavement macrotexture which can introduce noise in the measurements. Notice also the wide range in the measurements between each of the units, again being much wider for those units using a smooth tire than for those that use the ribbed tire. However, smooth tire devices seem to have a smaller overall difference in their directional measurements, as evidenced by the data points being closer to the line of equality.



(a) Ribbed Tires (b) Smooth Tires

Figure 3 Correlation between friction tester measurements downhill and uphill

A more helpful plot to gauge the difference between downhill and uphill measurements for each device is shown in Figure 4a and 4b for the locked-wheel skid tester from Virginia for both of the tires tested. In this figure it is obvious that the measurements made going downhill are not the same ones as the ones going uphill; thus it can be concluded that this unit is susceptible to the effect of the grade. It is also important to notice that this susceptibility is increased especially in the last sections which are the concrete pavement sections, probably because this are located in the section of the road with the highest grade (6%). A complete set of similar plots is included as Appendix A.2 for all of the devices. It is noteworthy that this last observation is relatively valid for all of them, varying the difference for each device.



(a) Smooth tire (b) Ribbed tire

Figure 4 Virginia locked-wheel friction tester measurements downhill and uphill

Another way of comparing the data is to plot the measurements against each of the surface types for all the devices. These plots are practical to compare the difference in the measurements from all the devices for an overall comparison. A plot of all of the devices can be seen in Figure 5. It is very hard to notice a lot of details except that MS Smooth is the lowest and CR GT is the highest, with a big concentration in the middle without a discernible pattern.

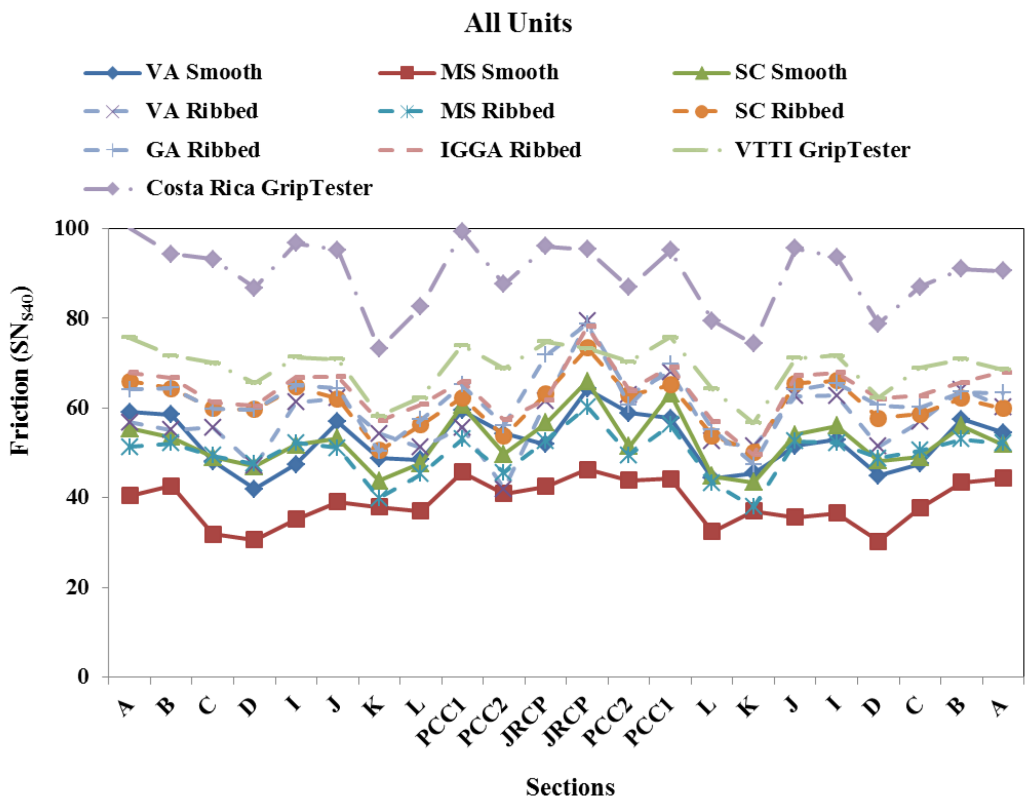


Figure 5 Virginia locked-wheel friction tester measurements downhill and uphill

If this analysis gets separated by tire type, a more significant pattern can be examined. In Figure 6a and 6b, a more clear comparison can be made between the different devices (the Grip Tester measurements were multiplied by 100 to be comparable with locked wheel trailer measurements).

General observations that can be made from Figure 6:

- Most measurements seem to be following a similar trend; however, there is a difference between the magnitudes of the measurements.
- For locked-wheel skid testers with smooth tires, MS unit's measurements are extremely lower than those for VA and SC. VA and SC measurements are reasonably close.
- For locked-wheel skid testers with ribbed tires, again MS unit's measurements are extremely lower than those for all the rest and the VA unit data seems to be very different in about half of the sections. However, the SC, GA, and IGGA are very similar.
- The Costa Rica Grip Tester has significantly higher values than the one from VTTI.

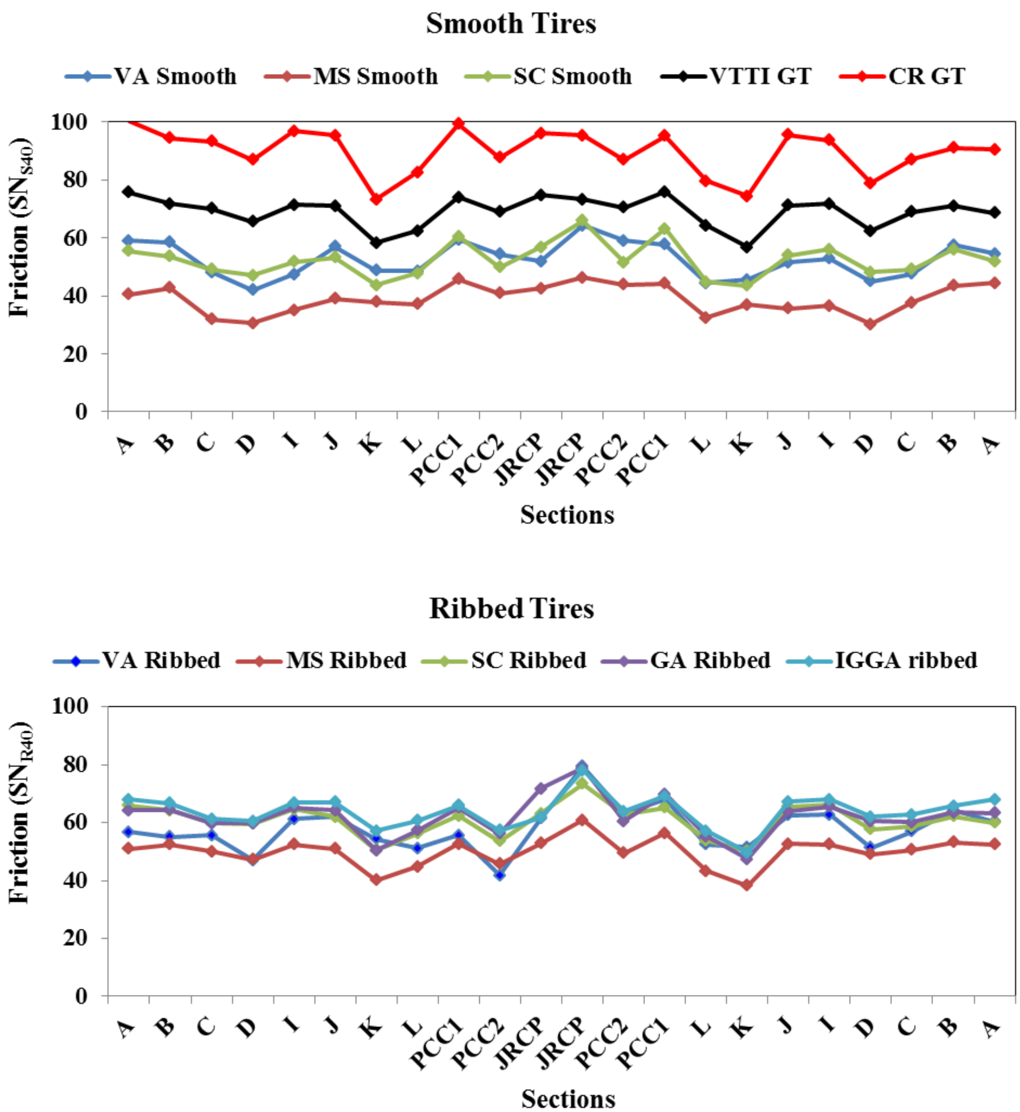
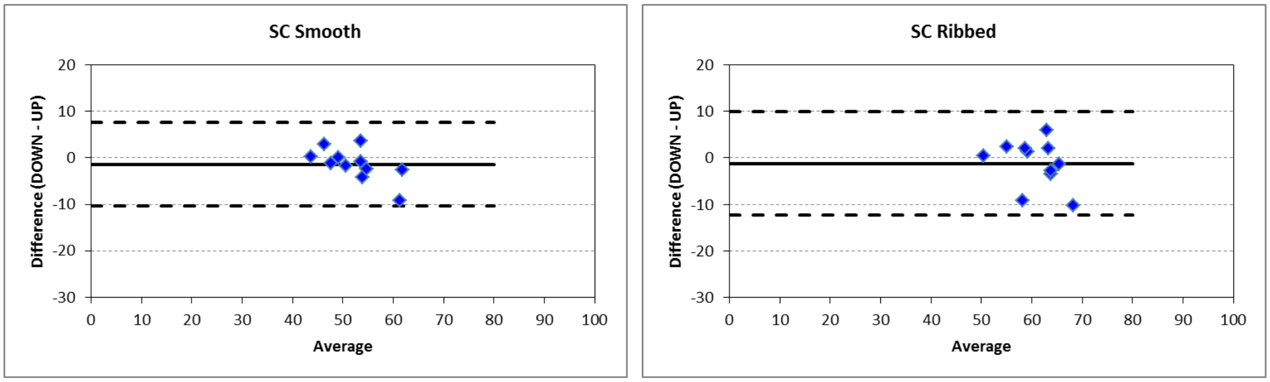


Figure 6 Friction measurements vs. sections

As was discussed in the 2011 Rodeo report, correlation analysis is a method to compare measurements of the same property but it cannot be used to make any statistical inferences since both measurements are collected with errors. To account for the errors in measurement, a comparison of the repeatability and reproducibility of each unit is needed. The Limits of Agreement (LOA) method is used because LOA takes into consideration the error in each device by incorporating the signal to noise ratio (Mean Square Error) into the analysis.

Effect of Grade for each device

An example of the effect of the grade in an individual device is shown by plotting the average values for each section and the difference measured in each direction as shown in Figure 7. This example is made with the SC smooth tire (figure 7a) and the SC ribbed tire (figure 7b) results.



(a) Smooth Tire (b) Ribbed Tire

Figure 7 Friction measurements vs. sections

From figure 6, on average, the SC unit using the smooth tire measures 1.4 SN lower going downhill than uphill (-1.4) and 95% of the measurements are within plus or minus 9.0 SN from this average. Notice also that the whole range of measurements is included between 43 and 62. Using the ribbed tire, measures 1.2 SN lower going downhill than uphill (-1.2) and 95% of the measurements are within plus or minus 11.1 SN from this average, in a range between 50 and 68. The variability of the measurements is more affected, on average, using the ribbed tire, and the ranges of the smooth tire are about 7 SN lower than the ribbed tire. The results for all the units with all of the tires tested for both directions are summarized in Table 2.

Table 2 Reproducibility of friction measurements for each direction for each unit

Reproducibility uphill and downhill				
Friction Tester Units	**Smooth**		**Ribbed**	
	Bias	**+ or -**	**Bias**	**+ or -**
VA	-0.5	13.3	-6.4	20.9
MS	-0.7	8.4	-1.7	7.6
SC	-1.4	9.0	-1.2	11.1
GA	-	-	-0.9	9.3
IGGA	-	-	-1.5	13.5
VTTI Grip Tester	0.9	7.5		-
Costa Rica Grip Tester	3.4	8.5		-

The results of a similar comparison for all the units with all of the tires tested among themselves is also included in tabular form, in the two tables shown as Table 3 and Table 4 below. These tables show the repeatability coefficients and the reproducibility coefficients or + or – bands that were explained for the SC unit between downhill and uphill measurements.

Table 3 Repeatability explains the variability that each unit has, in each direction, with each tire. For example, using SC smooth and SC ribbed again, their repeated runs going downhill vary by 6.8 SN going downhill and 6.8 going uphill with the smooth tire, whereas with the ribbed tire these values are 5.8 and 6.1 respectably. In order for a pair of units to have good agreement in their measurements, their repeatability has to be low.

Table 3 Repeatability of friction measurements

Repeatability				
	Smooth		Ribbed	
Friction Tester Units	**Downhill**	**Uphill**	**Downhill**	**Uphill**
VA	9.5	8.2	18.9	12.0
MS	6.2	5.8	5.9	5.8
SC	6.8	6.8	5.8	6.1
GA	-	-	6.8	8.0
IGGA	-	-	5.5	8.5
VTTI Grip Tester	7.1	4.4	-	-
Costa Rica Grip Tester	5.8	5.8	-	-

Repeatability numbers from SC, MS, and the CR GT are significantly low. However, VA only shows good repeatability using the smooth tire, but the results for the ribbed tire are almost twice, showing that the repeatability is not very good with this tire. Good repeatability is necessary when trying to reproduce measurements, so it is concluded that any comparison made to the VA ribbed tire measurements is not going to be positive.

The reproducibility between all the combinations of devices, direction of measurements and type of tires used is shown in Table 4. Because these numbers shown are the limits of the comparisons, a plus or minus (+ or –) range is the comparison between the pair of units chosen.

Table 4 Reproducibility of friction measurements

Reproducibility				
	Smooth		Ribbed	
Friction Tester Units	**Downhill**	**Uphill**	**Downhill**	Uphill
VA vs. MS	9.4	8.7	16.2	11.8
VA vs. SC	10.9	9.6	16.1	10.9
VA vs. GA	-	-	16.5	11.6
VA vs. IGGA	-	-	15.7	12.1
VA vs. VTTI Grip Tester	12.5	10.1	-	-
VA vs. Costa Rica Grip Tester	15.5	11.7	-	-
MS vs. SC	9.3	11.5	6.4	7.1
MS vs. GA	-	-	7.6	8.1
MS vs. IGGA	-	-	7.2	7.5
MS vs. VTTI Grip Tester	12.1	10.5	-	-
MS vs. Costa Rica Grip Tester	16.4	13.1	-	-
SC vs. GA	-	-	8.0	8.6
SC vs. IGGA	-	-	6.7	8.1
SC vs. VTTI Grip Tester	8.0	8.6	-	-
SC vs. Costa Rica Grip Tester	10.7	9.3	-	-
GA vs. IGGA	-	-	10.0	8.3
VTTI Grip Tester vs. Costa Rica Grip Tester	8.5	7.4	-	-

For example, regardless of the difference between the measurements any two units (bias), 95% of any comparable measurements will be between + or – of these numbers. In particular, measurements between the VA and SC units, on average will be around 10 SN plus or minus of each other if both units use a smooth tire. However, when using a ribbed tire, the range of agreement between measurements is greater than 16 SN going downhill and almost 11 SN uphill. Acceptable ranges of measurements have to be decided before comparing measurements. A difference of more than 10 SN would seem to be greater than what is practical when making a friction comparison because this would mean a range of values greater than 20 SN which would not allow for any practical standard regarding an acceptable lower limit friction regarding any action from a state road maintenance department. When repair maintenance can take more than a year to be done, 20 SN can very easily become a difference maker between investigation and intervention due to accident probabilities.

Texture

Macrotexture data were collected using ASTME E 2157 CT Meter. The CT Meter has a displacement sensor which rotates at a fixed elevation from the surface and the software reports the processed data as Mean Profile Depth (MPD). Three sets of measurements were collected on each section tested for friction. All the measurements were collected on the left wheel path of west bound lane. The MPD values for each surface are provided in Table 5.

Table 5 Macrotexture measurements (MPD)

Section	**Run**			**Average**	**Std. Dev.**
	1	**2**	**3**		
A	1.04	1.07	1.15	1.09	0.06
B	1.39	1.29	1.62	1.43	0.17
C	1.04	0.88	0.77	0.89	0.14
D	0.73	0.78	0.83	0.78	0.05
I	1.08	0.81	0.87	0.92	0.14
J	0.97	1.10	1.30	1.12	0.17
K	1.67	1.86	1.79	1.77	0.10
L	1.13	1.34	1.11	1.19	0.13
PCC1	0.52	0.76	1.11	0.80	0.29
PCC2	2.36	1.84	1.89	2.03	0.29
JRCP	1.36	2.00	1.69	1.69	0.32

VI.6. Profiler

Profiler Data Collection

Longitudinal road profile measurements are summarized using the International Roughness Index (IRI). The IRI represents the accumulation of all vertical movements of a "standard" vehicle across a given length of road, usually expressed in inches/mile (mm/km). If the sum of these movements is large, the surfaces are usually rough (not smooth or even), and travel over them is uncomfortable. If the sum is small, travel is more comfortable.

All agencies participating in the Consortium use single-spot laser-based inertial profilers for measuring longitudinal profiles at highway speeds and then computing the IRI values at project and network levels. The major problem associated with inertial profilers is the accuracy of the collected road profile measurements. The verification of these measurements can only be accomplished when compared to a stable, consistent scale. To verify the profilers' correct operations, the Consortium decided to implement a profiler verification site following available guidelines and specifications that test the compliance of the accuracy of the profilers of its members.

Test Sections

All Smart Road section characteristics are summarized in Table 10. Based on the general requirements set forth by AASHTO PP-49 specifications (1), a decision was made to design five test sections on the uphill (westbound) lane of the facility. AASHTO PP-49 (1) requires the sections for the test comparisons to be at least one-tenth of a mile long, or 528 feet. The first two test sections were established in the JRCP (jointed reinforced concrete pavement) and the CRCP (continuously reinforced concrete pavement) pavements. It must be noted that both of these sections were grounded, and the CRCP section was grooved in January 2011. The remainder of the test sections then had to be placed over the asphalt concrete pavements. From Table 6, test section 3 was chosen from the coarse asphalt pavements (SMA and OGFC). The two remaining sections were chosen based on their roughness: one with a low IRI value and one with a high IRI value. Although sections E and F would have made a better match for the low IRI criterion, sections F and G were chosen for test section 4 because section E lies on a horizontal curve. Finally, sections A and B were chosen as test section 5 since the two had relatively high IRI values.

Each of the test section wheel paths were marked every 10 feet with paint so that operators could align the profilers when traveling at the required speed of 50 mph. The paint markings also helped reduce possible wandering errors. The left wheel path was marked 34.5 inches from the center line, and the right one was separated from the left by 69 inches. Each test section also had paint-marked, lead-in distances of 150 feet starting across a one-inch high electrical rubber cable cord protector that was placed as an artificial bump to indicate the start of each of the lead-in sections. These bumps were intended to produce a spike in the profiles, which made it possible to determine the exact location of the test sections during subsequent analysis. The paint markings for the 150-foot lead-in areas were colored yellow, while the 528-foot test sections were colored green.

Reflective material trigger markers were also placed 50 feet before the first artificial bump and 50 feet after the end of the last test section to activate the start and end times of the data collection. Traffic cones with reflective material were also placed next to each bump before the lead-in areas of each test section to help the profiler operators become aware of the beginning location and to align properly in the marked wheel paths. A diagram of the profiler testing setup for each test section is shown in Figure 8.

Table 6 Smart Road section pavement surfaces

Section	**Name**	**Surface Type**	**Length** (feet)	**MPD Uphill** (mm)	**Test Section No.**	**Length** (feet)
1	Loop	SMA 19.0	N/A	0.80		
2	A	SM-12.5D	347	0.89	**5**	**528**
3	B	SM-9.5D	289	1.01		
4	C	SM-9.5E	292	0.79		
5	D	SM-9.5A	407	0.70		
6	E	SM-9.5D	268	N/A		
7	F	SM-9.5D	302	N/A	**4**	**528**
8	G	SM-9.5D	304	N/A		
9	H	SM-9.5D	292	N/A		
10	I	SM-9.5A(h)	338	0.73		
11	J	SM-9.5D	280	0.85		
12	K	OGFC	302	1.80	**3**	**528**
13	L	SMA-12.5D	326	1.08		
14	CRCP*	Tined	2,290	0.80	**2**	**528**
15	JRCP*	Grooved	591	N/A	**1**	**528**

* Both JRCP and CRCP sections were grounded, and the CRCP was grooved.

Reference Data Collection

Reference Profiler

An ICC (International Cybernetics Corporation) SURPRO walking profiler was used to measure the reference profile of each of the five test section along the left and right wheel paths. Three passes were made on both wheel paths to assure ideal repeatability and to compute the IRI value of each wheel path in each section. Figure 9 shows the SURPRO during reference measurements.

High-speed Profilers

Seven profilers were used to obtain measurements for comparison to the reference measurements made with the SURPRO device. Data were collected following the procedures mentioned in AASHTO PP-49 (*1*). Pre-test system calibration, including block, bounce, and distance calibrations, were also performed. The block tests were conducted with blocks provided by each profiler manufacturer and with a standard set of calibration blocks purchased by the Virginia Tech Transportation Institute (VTTI). Bounce tests were performed for each unit as recommended by each manufacturer (e.g., ICC, Dynatest, etc.). These tests are designed to detect any serious malfunctions outside the permissible limits during the normal operation of the height and accelerometer sensors.

A distance measuring instrument (DMI) calibration section with a length of 1,000 feet was also marked on the downhill portion of the CRCP section where the road is straight but has a maximum slope of approximately 6%. Each profiler made at least five runs to calibrate the DMI as per normal operating recommendations by manufacturers. All profilers then collected profile data 10 times at a constant speed of 50 mph, trying to avoid sudden speed changes throughout the sections.

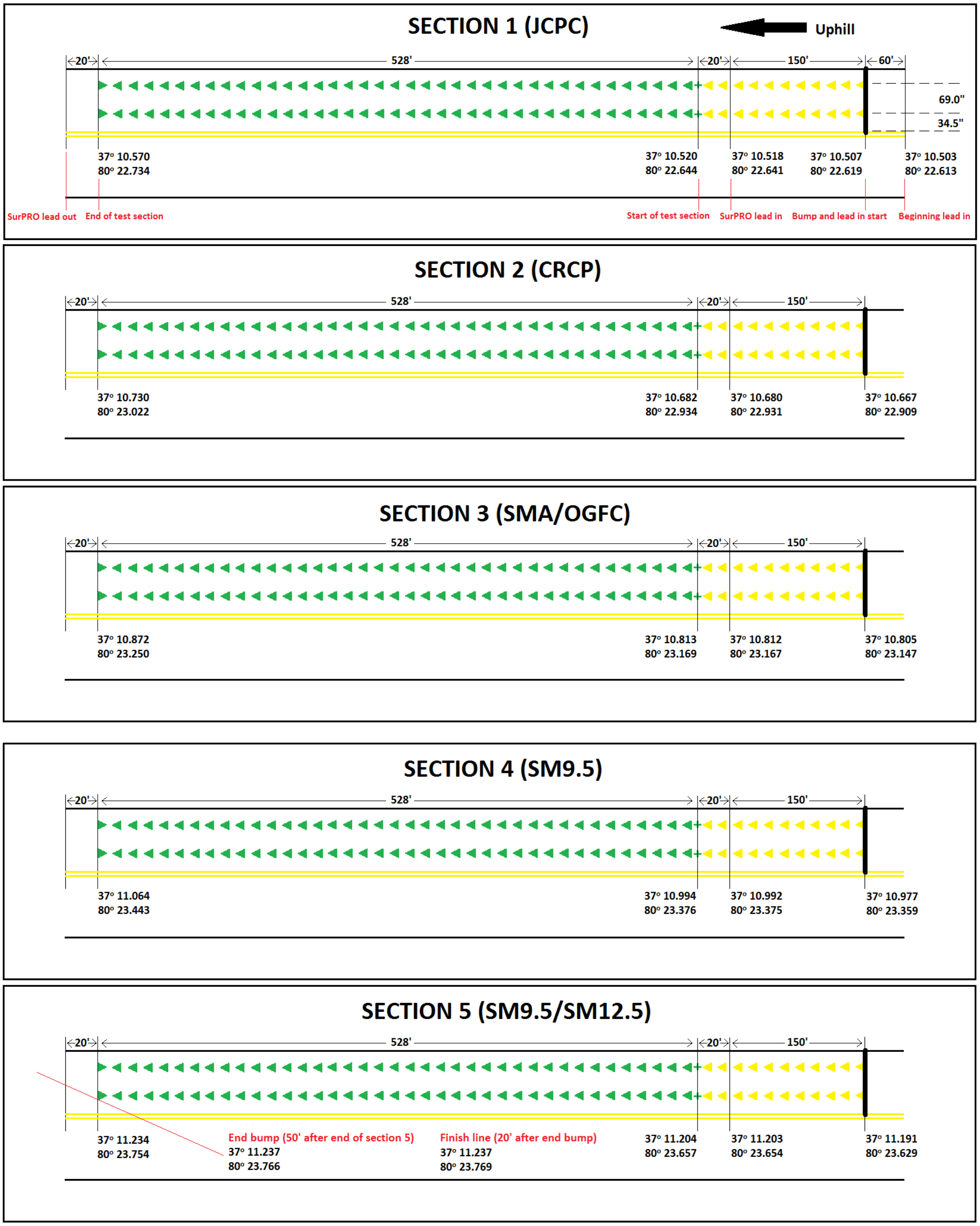


Figure 8 Smart Road profiler test section setup for 2012 Rodeo

Figure 9 Reference profile measurements using the SURPRO.

Profiler Results and Discussion

The analysis methods included in the Profile Viewing and Analysis (ProVAL) software were used to determine the ride statistics, repeatability, and reproducibility assessments for all data collected were calculated, ProVAL software were developed under the sponsorship of FHWA (*2*). The following is a brief description of the results.

Ride Statistics

IRI values of all profile runs for all test sections were computed using ProVAL. The averages of the 10 runs from each profiler were computed. All IRI computations made in ProVAL applied a 250 mm moving average filter (2). The IRI results from all profilers for all sections are shown in Figures 10 and 11, and individually for each section in Appendix B.1.

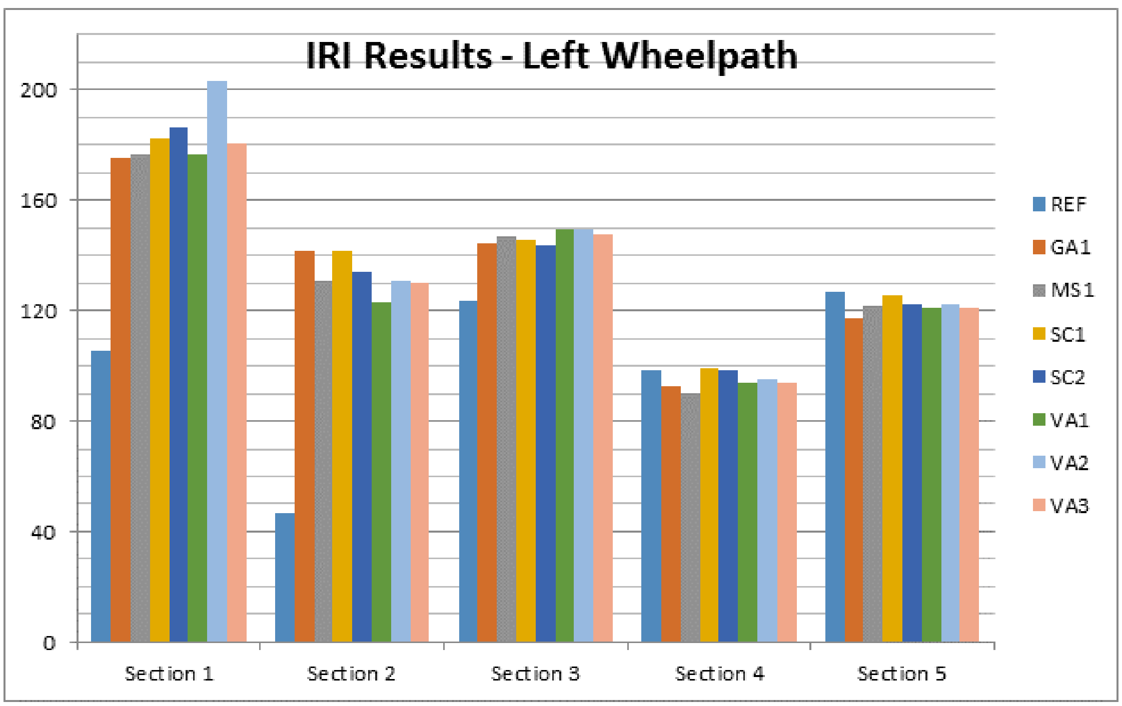


Figure 10 Left wheel path ride statistics.

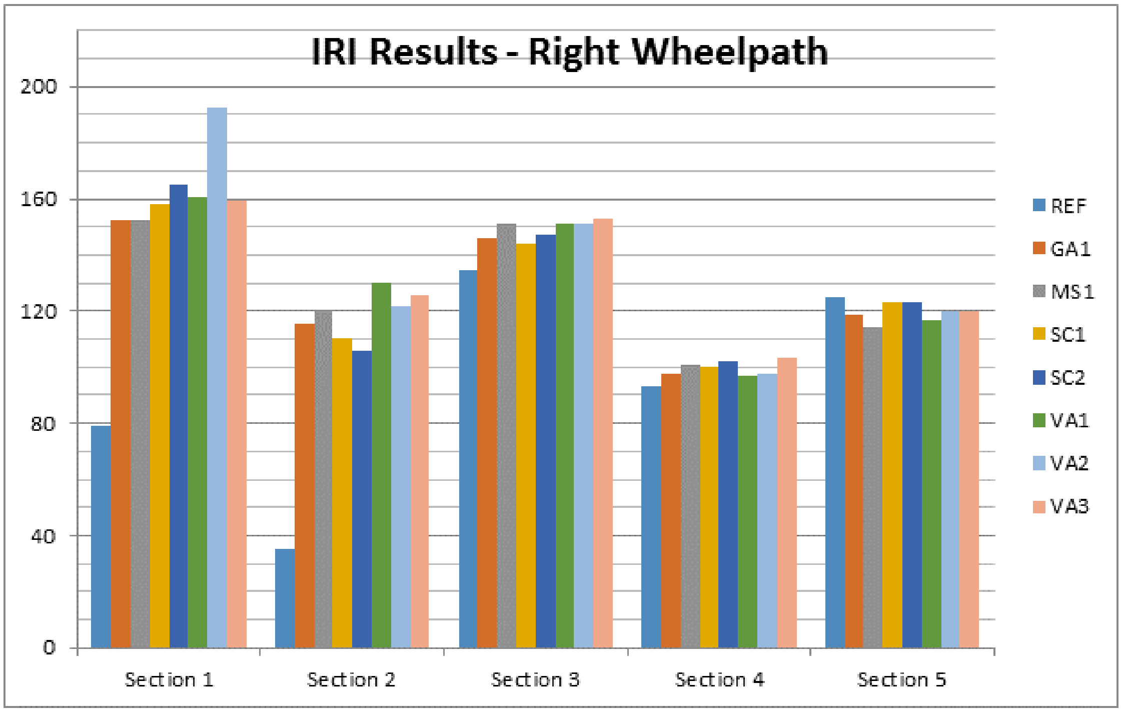


Figure 11 Right wheel path ride statistics.

Section 1 shows the highest IRI values for both wheel paths and among the five sections, the left wheel-path IRI values are greater than the right ones in the first section (JRCP). Notice that for the rodeo 2011, the highest IRI values were found in the second section. The coarser textured pavement found in test section 3 and the high cracking damage of test section 5 caused the IRI values for these areas to be relatively high. Section 4 has a lower IRI value than the aforementioned asphalt sections and the overall lowest IRI value of all test sections, although it is section 2 that has the lowest IRI as demonstrated by the reference profiler measurements.

The result of high IRI values for section 2 (according to the single-spot laser profilers) was explained on the rodeo 2011 when the grooved section were analyzed independently, it was demonstrated that a significant increase in the average IRI values was observed for profiles collected by single-spot laser profilers on the PCC section after it was subjected to diamond grinding and longitudinal grooving. This is mainly caused by the wander of the single spot laser as it moves in the grooves (*3*).

Repeatability

Repeatability results illustrate how well each unit obtains the same profile measurements during each of the 10 runs. For this study, cross-correlation was performed on the profile data to evaluate both profiler repeatability and reproducibility. For repeatability, AASHTO PP-49 (1) requires an average cross-correlation of at least 92% when each profile is compared with the remaining nine runs (90 comparisons). The repeatability results for each of the laser sensors (i.e., left and right) as computed with ProVAL are shown in Table 8 for each test section. Bold, italicized numbers indicate those that did not pass the repeatability criteria.

The profilers that were present at the rodeo included one from Georgia DOT (GA1), one from Mississippi DOT (MS1), two from South Carolina Department of Transportation (SC1 and SC2), and three from Virginia DOT (VA1, VA2, and VA3). The repeatability results for Section 3 and Section

4 show ideal correlation between the various runs in all sections. None of the profilers passed all the repeatability tests with values of more than 92% for sections 1 and section 2 for both wheel paths and Section 5 left wheel path, only both of the South Carolina profilers passed the repeatability test for section 5 right wheel path.

Table 8 Average repeatability cross-correlations for all profiler units.

Profiler	Average Repeatability Cross-correlations									
	Section 1		Section 2		Section 3		Section 4		Section 5	
	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
GA1	*87*	*80*	*18*	*16*	95	91	92	*91*	*90*	*87*
MS1	*87*	*89*	*18*	*16*	93	*89*	92	90	*89*	*89*
SC1	*87*	*91*	*19*	*18*	95	93	95	93	*86*	92
SC2	*86*	*83*	*21*	*18*	94	96	94	95	*91*	92
VA1	*89*	*78*	*18*	*17*	95	95	92	93	*89*	*88*
VA2	*58*	*49*	*19*	*17*	93	93	92	92	*91*	*88*
VA3	*87*	*83*	*19*	*18*	96	96	93	92	*91*	*89*

Reproducibility

Reproducibility results were obtained by comparing the highest cross-correlation repeatability for each wheel path based on the SURPRO profiles to the 10 runs from each participant profiler. Power Spectrum Density (PSD) plots of the data collected with the SURPRO indicated that a moving average filter had already been applied to the data. Hence, no separate moving average was required for the SURPRO runs, and the IRI-filtered cross-correlation was only applied to the data of the profilers (*2*). The results from the profiler certification (reproducibility) module are shown in Table 9.

Table 9 Average reproducibility cross-correlations for all profiler units.

Profiler	Average Reproducibility Cross-correlations									
	Section 1		Section 2		Section 3		Section 4		Section 5	
	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
GA1	27	25	6	5	62	56	58	52	39	51
MS1	42	36	9	4	76	75	69	72	72	74
SC1	42	28	7	7	83	80	74	70	74	72
SC2	17	18	8	5	71	66	53	48	35	44
VA1	48	32	11	4	77	78	72	78	76	75
VA2	43	29	8	5	79	81	72	77	73	76
VA3	43	30	8	5	79	83	68	71	76	76

According to AASHTO PP-49, a profiler passes the reproducibility test if it has a cross-correlation value of more than 90% when compared with the respective reference profile. As can be seen in Table 9, the reproducibility cross-correlations (IRI filtered) between the SURPRO and all profilers are relatively low; no profilers scored satisfactorily. Section 2, which displayed poor repeatability results in the previous section, also displays the lowest reproducibility.

VI.7. Conclusions and Recommendations

Friction

- Correlation analysis showed that there is a general agreement between various friction testers' measurements; however, the magnitudes of the measurements are variable. Equipment need to be calibrated in order to bring the measurements to the same scale.
- LOA was used to evaluate the repeatability and reproducibility of the measurements. This methodology provides an objective approach to compare the various friction testers' measurements.
- Equipment comparisons should be performed on periodic basis to harmonize various equipment measurements and as a diagnostic method to identify any possible anomalies with the data collection system.

Profiler

- Seven high-speed laser profilers and a single reference profiler were used to measure the profile of five sections established on the Smart Road. For section 3 and section 4, the profilers exhibited acceptable repeatability, Section 1 and section 5 showed almost acceptable values of repeatability but all the values were under the limit, although the values measured on section 5 right wheel path showed acceptable repeatability for both South Carolina profilers. Section 2 Shows the lowest values for repeatability
- The reproducibility between profilers and the reference profiler was relatively low. As well as repeatability, the lowest reproducibility values are shown for section 2.
- Recalling the analysis presented on the previous rodeo report (2011) about the grooved sections which is valid for the 2012 experiments as well, the single-spot laser profilers over-predicted the IRI values (compared with the reference values) on the ground and grooved PCC due to grooves on the section because the single-spot profilers are incapable of measuring the correct profile.

VI.8. Acknowledgments

The Consortium for Pavement Surface Properties has been made possible thanks to the contributions of the Virginia Transportation Research Council (VTRC), the Federal Highway Administration (FHWA), the Connecticut, Georgia, Mississippi, Pennsylvania, South Carolina, and Virginia Departments of transportation (DOT) and the Virginia Tech Transportation Institute (VTTI). William Hobbs, James Bryce, Shahriar Najafi, Chris Tomlinson, Akyiaa Hosten, and Daniel Mogrovejo (from CSTI) collaborated with the data collection and processing.

VI.9. References:

1. AASHTO, Standard Practice for Certification of Inertial Profiling Systems (PP49), The American Association of State Highway and Transportation Officials, Washington, D.C., 2007.
2. Chang, George, PROVAL Users Guide: Profile Viewing and Analysis Software, TRANSTEC, Austin, Texas, 2007.
3. Flintsch, G., de León Izeppi, E. D., Valeri, S., and Najafi, Sh. (2011) 2011 Annual Equipment Comparison Roundup at the Smart Road, Blacksburg, Virginia, 2011

VII. 2013 Annual Equipment Comparison Roundup at the Smart Road[7]

VII.1. Overview

"The regional pooled-fund project known as the Pavement Surface Properties Consortium is a research program focused on enhancing the level of service provided by the roadway transportation system through the optimization of pavement surface texture characteristics. The program was established in 2006 with support from the Federal Highway Administration (FHWA) and six state departments of transportation (DOTs): Connecticut, Georgia, Mississippi, Pennsylvania, South Carolina, and Virginia. The Consortium provides a practical mechanism to conduct research about pavement surface properties and explore their relationships with ride quality, friction, and noise. Complementing this effort is research focused on the review, testing, and evaluation of emerging technologies." Various friction testers and profilers were assessed during the 2013 equipment roundup. The objective of this year rodeo was to harmonize the participant friction tester's and profiler's measurements. There was also participation of three OBSI devices.

VII.2. Introduction

The Pavement Surface Properties Consortium hosts an annual event every year in May at the Virginia Smart Road in order to evaluate and compare various types of highway friction and profile measuring equipment. This event is called "the Surface Properties Rodeo". Five friction testers and eight high-speed profilers (plus two SURPRO reference profilers) participated in the 2012 Rodeo equipment roundup. The Departments of Transportation (DOTs) of Georgia (GA), Mississippi (MS), Pennsylvania (PA), the International Grinding and Grooving Association (IGGA) brought locked-wheel skid trailers. Virginia Tech Transportation Institute (VTTI) ran a Grip Tester, which is a Continuous Friction Measuring Equipment (CFME). The high-speed laser profilers included one from Georgia, one from Mississippi, two from South Carolina, and one from Virginia, one from Pennsylvania, one from AMES and one from VTTI (Figure 1).

Figure 1 High-speed Profilers participants in the 2013 Rodeo

[7] Prepared by Edgar de León Izeppi, Gerardo Flintsch, Kevin K. McGhee, Azzurra Evangelisti, Daniel Mogrovejo, and Ross McCarthy

VII.3. Purpose and Scope

The main objectives of the 2012 rodeo were as follow:

- Friction: Compare and evaluate the various friction testers' measurements, assessing the repeatability and reproducibility of the measurements.
- Profiler: Compare the measurements of the seven high-speed laser profilers and the reference profiler using ProVAL and the International Roughness Index (IRI) of the test sections, also assessing the repeatability and reproducibility of the measurements.

VII.4. Methods

Measurements for friction and profile were collected at the Virginia Smart Road. The procedure of data collection is explained in detail for each of these measurements. The summary of the results and analysis is also provided in each section.

VII.5. Friction

Friction Data Collection

Friction measurements were collected on May 22, 2013, at the Virginia Smart Road. Four locked-wheel skid trailers (LWST) and one Grip Tester (GT) unit participated. All of these devices took their measurements at 40 mph. Measurements were collected over 10 tests sections. To assess the effect of slope on the measurements of the moving devices, data were collected in both uphill and downhill directions on the same wheel-path. The tests with the LWST were performed in accordance with ASTM E-274. LWST measure the skid resistance of the paved surface and report a Skid Number (SN). The SN is the force required to slide the locked test tire at a stated speed, divided by the effective wheel load and multiplied by 100. LWST can use a smooth tire (ASTM E-524) or a ribbed tire (ASTM E-501). Mississippi and Pennsylvania tested with both test tires, while Georgia and IGGA used only the ribbed tire. The GT owned by VTTI used ASTM E-1844 smooth tires. Static friction tests were also performed with a Dynamic Friction Tester (DFT) as per ASTM E-1911. Table 1 is a summary of the friction tests. Figure 2 below shows a schematic of the test setup in the Smart Road in each different section.

Table 1 Summary of the friction tests.

Unit	Type	Tire	# test sections	Test Speed
MS skid trailer	Locked wheel	Smooth & ribbed	10	40 mph
PA skid trailer	Locked wheel	Smooth & ribbed	10	40 mph
GA skid trailer	Locked wheel	Ribbed	10	40 mph
IGGA skid trailer	Locked wheel	Ribbed	10	40 mph
VTTI Grip Tester	Fixed slip	Smooth	10	40 mph
DFT	Static test	Rubber sliders	10	20, 40, 60, 80 km/hr.

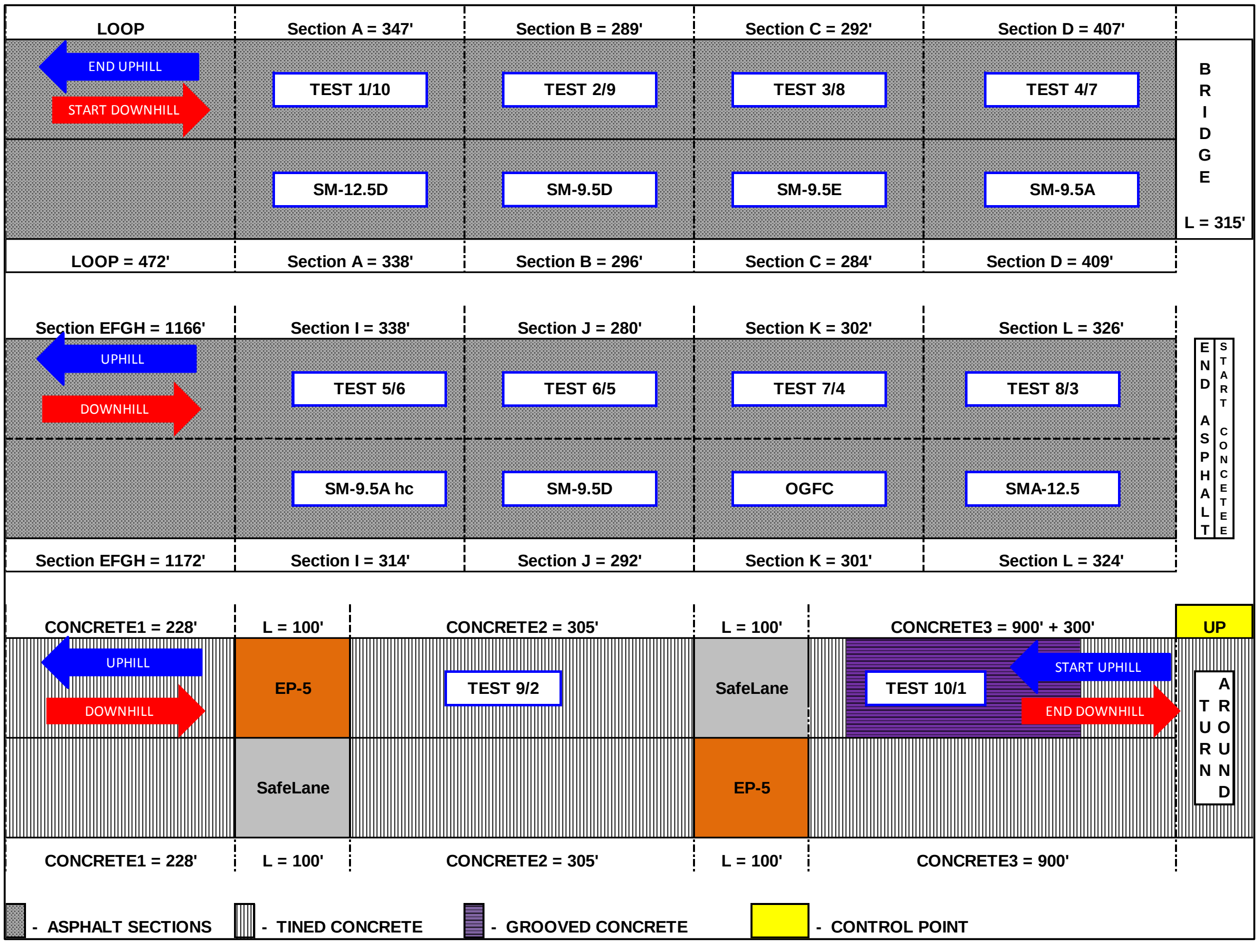
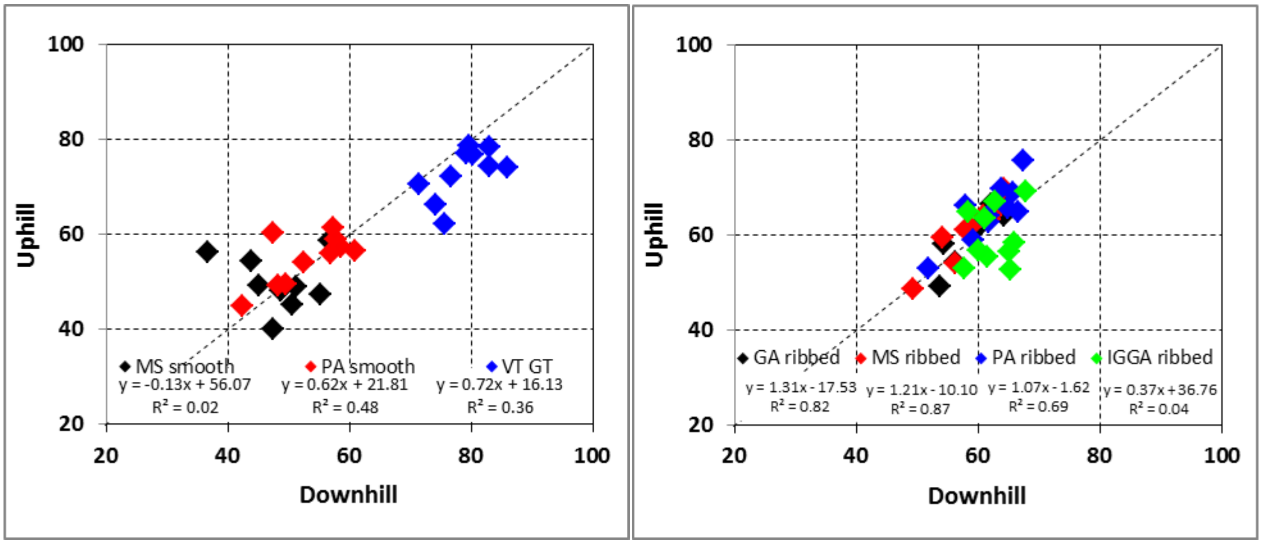


Figure 2 Schematization of the friction tests

Friction Results and Discussion

To compare the friction measurements made going downhill and uphill, and better visualize the data, plots with correlations for each unit and each tire were made and can be seen as Appendix A.1. A summary of these results for all the friction testers' measurements is shown below in Figure 3a and 3b for all the units using ribbed and smooth tires. Some correlations have a reasonably high coefficient of determination (R-square) and the measurements seem to be comparable in each direction, but some don't.

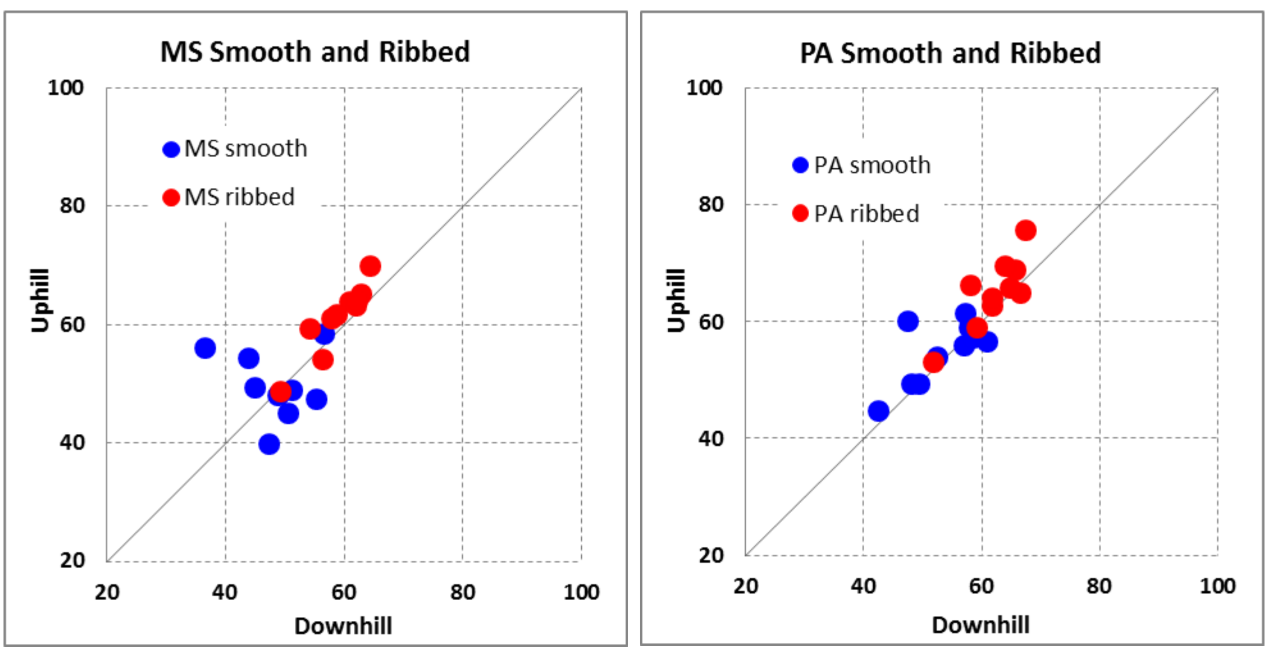
Overall, the correlations between ribbed tires seem to be better than those for smooth tires (higher R-square). This can be due to the higher sensitivity of smooth tires to the test condition and pavement macrotexture which can introduce noise in the measurements. Notice also the wide range in the measurements between each of the units, again being much wider for those units using a smooth tire than for those that use the ribbed tire. However, smooth tire devices seem to have a wider difference in their directional measurements, as evidenced by the data points being spread farther from the line of equality. This indicates greater bias due to the grade.



(a) Smooth Tires (b) Ribbed Tires

Figure 3 Correlations between friction tester measurements downhill and uphill

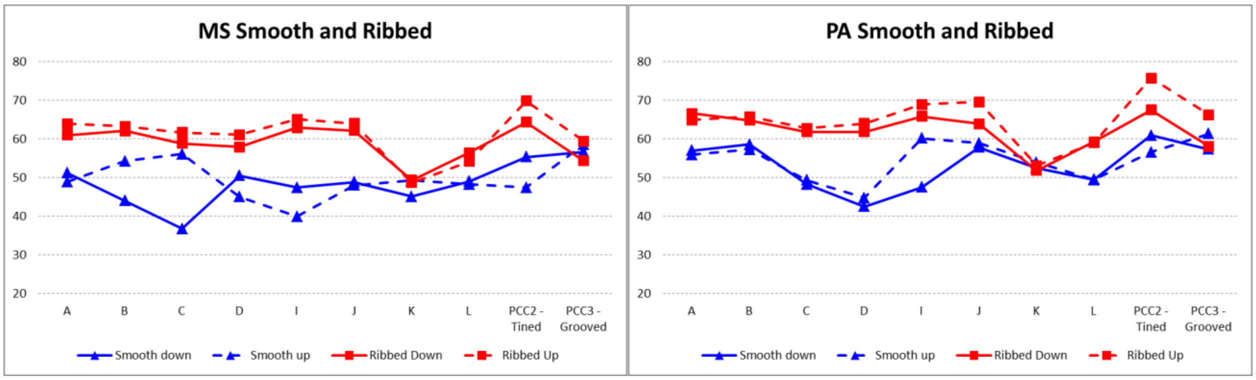
The devices using smooth tires have a wider range than that obtained by the devices using ribbed tires because the Grip Tester generally provides higher friction values, compared to those obtained with the LWST. If the comparison is made only with LWST, from the results of the MS and PA testers, both of which had results with both smooth and ribbed tires, it is also possible to see (Figure 4a and 4b) that in the SN range, the values obtained for the smooth tires are systematically lower than the values obtained with the ribbed tires. The smooth tires also have greater bias with the grade than the ribbed tires (the data is more scattered).



(a) MS smooth and ribbed (b) PA smooth and ribbed

Figure 4 LWST measurements downhill and uphill with smooth and ribbed tires

Another type of plot to evaluate the differences between downhill and uphill measurements for each device is shown in Figure 5a and 5b for the LWST from Mississippi and Pennsylvania, both of which used both types of tires. In this figure it is obvious that the measurements made going in each direction are not exactly the same ones made going in the other direction, usually the uphill measurements being higher than the downhill ones. It is also interesting to note that measurements made with both of these units are closer using the ribbed tire than with the smooth tire, and consistently higher with the ribbed tire than the smooth tire. The same device, in both cases, exhibit ribbed tire results that are less affected by the grade than the smooth tire results.



(a) MS LWST smooth and ribbed (b) PA LWST smooth and ribbed

Figure 5 LWST measurements downhill and uphill

Also notice that, for the ribbed tire, the largest difference in the measurements increases in the last two sections, which are the two concrete pavement sections. For the smooth tire, there is no specific section or pavement type that is more or less responsible for the largest in the directional measurements. A complete set of similar plots for all the units is included as Appendix A.2.

Finally, another way of comparing the data is to plot all the measurements for all the devices against each of the surface types. These plots can be practical to compare general trends in the behavior of a specific unit with all the other devices. Figure 6a below shows a plot of all of the devices with all the sections. In this plot, it is very hard to notice a lot of details except that MS Smooth is the lowest and GT is the highest, with a concentration of the rest of the devices in the middle without a pattern. If this analysis gets separated by tire type, more significant patterns can be examined, depending on the tire type. In Figure 6b and 6c, a more clear comparison can be made between the different devices (the Grip Tester measurements were multiplied by 100 to be comparable with locked wheel trailer measurements). General observations that can be made from Figure 6:

- Most measurements seem to be following a similar trend; however, there is a difference between the magnitudes of the measurements, depending on the tire.
- For locked-wheel skid testers with smooth tires, the MS unit's measurements are lower than those for PA. As expected, the GT measurements are higher than both MS and PA.
- For locked-wheel skid testers with ribbed tires, again PA unit's measurements are generally higher than the rest and IGGA seems to be lower in about half of the sections, on the uphill direction. However, the GA and MS are very similar. The Grip Tester data was placed on top of the ribbed tire devices for reference only.

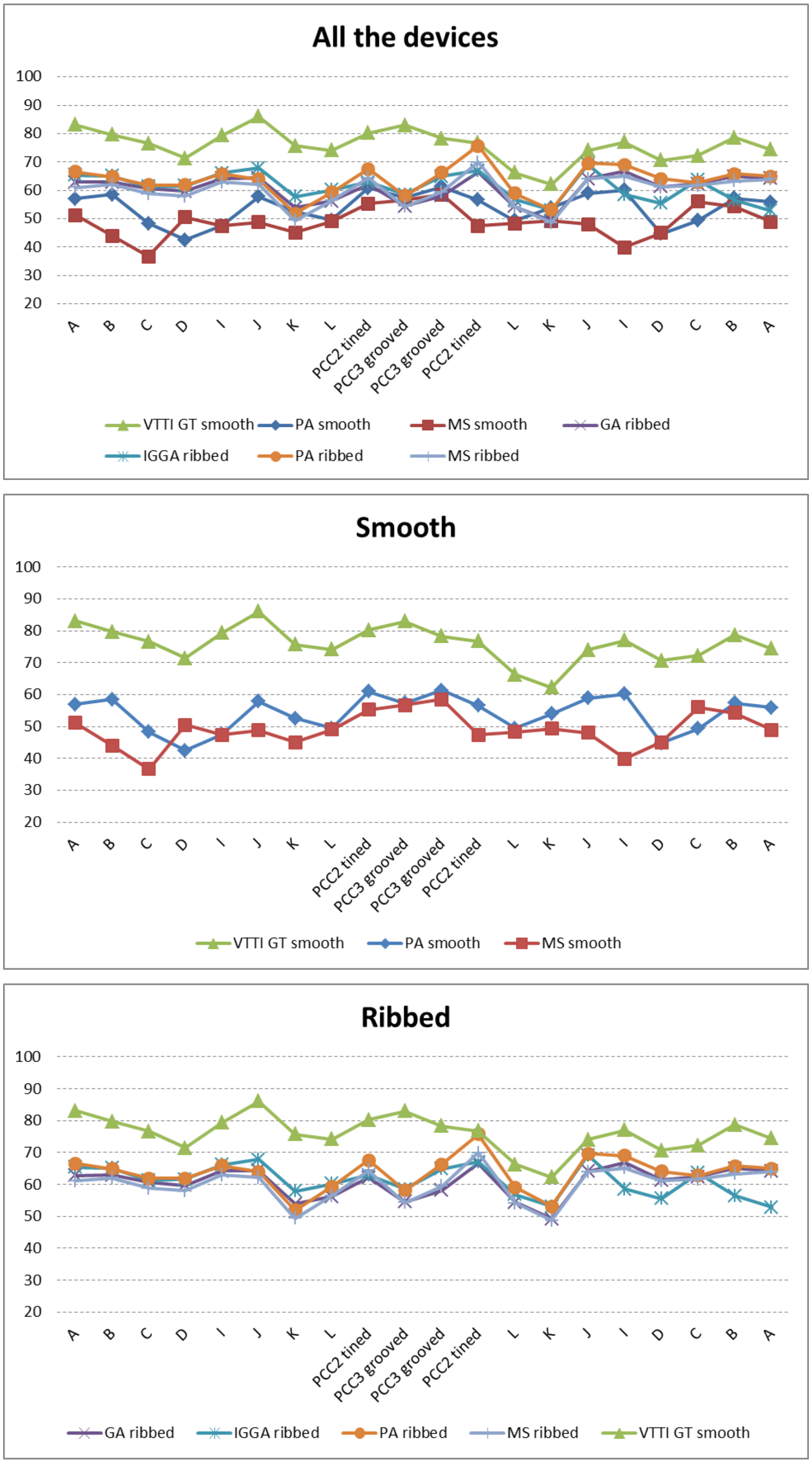
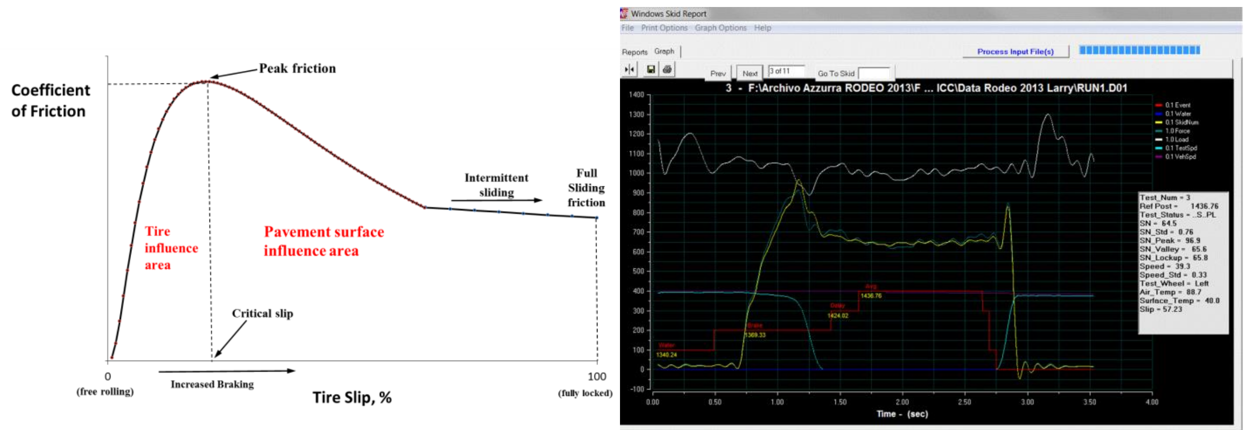


Figure 6 Friction measurements all devices and all sections, by tire type

LWST Peak Friction Analysis

Further comparisons were performed regarding the values obtained for the "peak" friction value of the GA and IGGA LWST. Figure 7a illustrates the relationship that exists between slip ratio and the coefficient of friction. In this plot, peak friction is shown and it is known to be approximately in between 10% to 20% fixed slip. Grip Tester's values are measured at 16% slip, and the normal values obtained with a LWST come from the 100% slip ratio or fully locked position of the curve. However, LWST manufacturers provide an estimate of the LWST "Peak" values, as can be seen in Figure 7b.



(a) Slip ratio – coefficient of friction (b) Results screen of LWST with "peak"

Figure 7 Slip ratios vs. coefficient of friction figures (Concept and LWST)

The peak values obtained for the GA and IGGA tester (both with ribbed tires), and the normal 100% slip values, are plotted in Figure 8. Also for comparison, the normal Grip Tester values are also plotted, considering Grip Tester Values are always measured very close to the "peak". With this plot, it was confirmed that LWST measurements with ribbed tires tend to measure a very different peak value than the Grip Tester. The difference between LWST peak and GT is around 15 points, equal to the difference between normal SN values and the Grip Tester values.

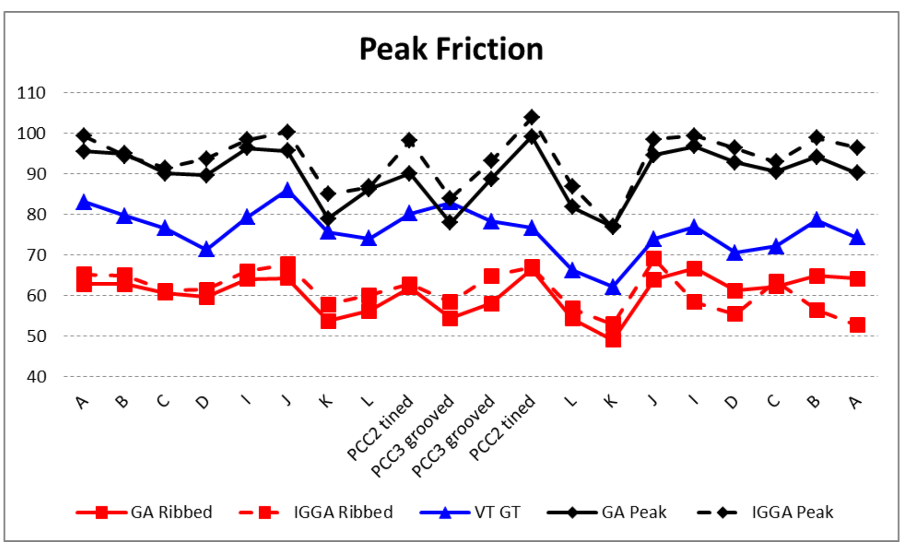


Figure 8 Normal and peak friction values for GT, GA, and IGGA units

Effect of Grade for each device

As has been discussed in the 2011 and 2012 Rodeo reports, correlation analysis is a method to compare measurements of the same property but it cannot be used to make any statistical inferences when both measurements are collected with errors. To account for the errors in measurement, a comparison of the repeatability and reproducibility of each unit is needed. The Limits of Agreement (LOA) method is preferred because LOA takes into consideration the error in each device by incorporating the signal to noise ratio (Mean Square Error) into the analysis. For example, consider how the Grip Tester measurements compare to the measurements for all other six devices going downhill, as shown on Figure 9. On average, each plot will show the mean difference in measurements and the range of values, at the 95% confidence level, between where all measurements for both devices are observed, and tabulated in Table 2 below.

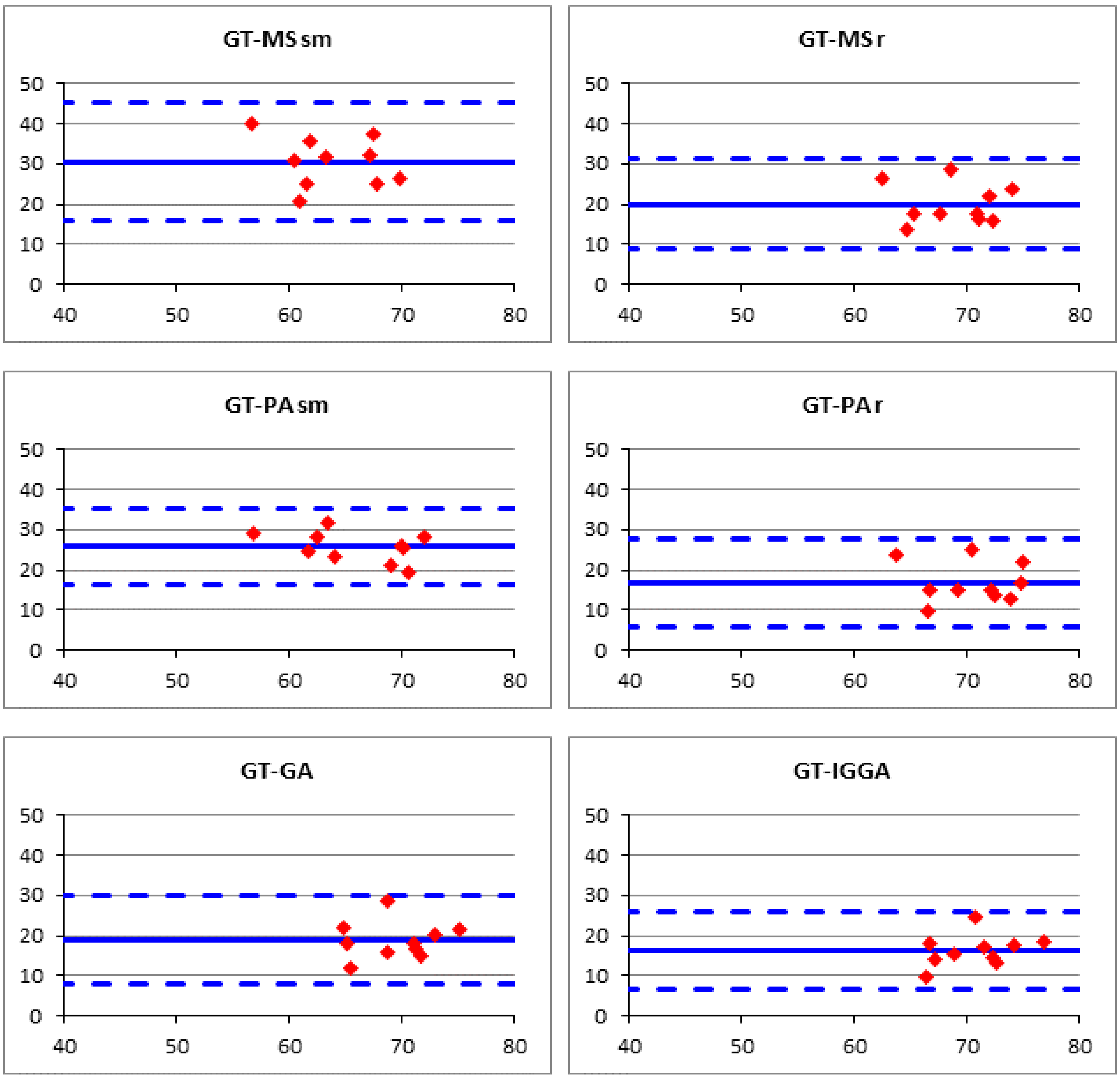


Figure 9 Friction measurements comparison for Grip Tester vs. all devices downhill

Table 2 Reproducibility of friction measurements for Grip Tester downhill for each device

Reproducibility

	Downhill		**Uphill**	
Friction Tester Units	**Bias**	**LOA**	**Bias**	**LOA**
VTTI GT vs. MS sm	**30.4**	**14.7**	**23.4**	**15.3**
VTTI GT vs. PA sm	25.7	9.4	18.3	11.4
VTTI GT vs. GA	18.8	10.9	11.9	8.9
VTTI GT vs. IGGA	16.3	9.7	13.3	23.1
VTTI GT vs. MS r	**20.0**	**11.0**	**11.9**	**8.2**
VTTI GT vs. PA r	16.8	11.1	8.0	8.7

The first two plots show how the GT values are, on average, 30.4 points higher than MS smooth tire and 20.0 points higher with the ribbed tire. However, with a 95% probability, the mean values with a between the GT and the MS smooth tire vary by + or – 14.7 points, whereas with the ribbed tire the mean values will vary by only + or – 11.0 points. Similarly, in the uphill direction, the bias is reduced to 23.4 for the smooth and 11.9 with the ribbed, and the ranges of values are also changed to 15.3 for the smooth and 8.2 for the ribbed. These values have been highlighted on table 2. It would appear that, on average there is more agreement when the measurements of the Grip Tester and the MS LWST uses the ribbed tire than when it uses a smooth tire (less bias and less range or LOA).

From Table 2 the reader can also notice that the bias or difference between the mean values of the Grip Tester and the other units varies positively for all cases. On average, LWST with smooth tires will measure about 28 points lower than the Grip Tester, whereas with the ribbed tires, this difference is about 18 points. However, on average, measurements tend to agree better with the ribbed tires (range is + or – 10.7 points) than with the smooth tire (range is + or – 12.0 points).

The results of all possible combinations for all the units with all of the tires tested for both directions are included in Appendix A.3 in tabular form. Another way of presenting these same results can be a matrix like the one shown below in Tables 3 and 4.

Table 3 Mean differences and ranges of LOA of friction measurements for all devices downhill

Downhill	**GT sm**	**+/-**	**MS sm**	**+/-**	**PA sm**	**+/-**	**GA r**	**+/-**	**IGGA r**	**+/-**	**MS r**	**+/-**	**PA r**	**+/-**
GT sm	**-**	**-**	**30.4**	**14.7**	**25.7**	**9.4**	**10.9**	**10.9**	**16.3**	**9.7**	**20.0**	**11.0**	**16.8**	**11.1**
MS sm	**-30.4**	**14.7**	**-**	**-**	**-4.7**	**15.2**	**-11.6**	**16.8**	**-14.2**	**15.7**	**-10.5**	**15.9**	**-13.7**	**15.5**
PA sm	**-25.7**	**9.4**	**4.7**	**15.2**	**-**	**-**	**-6.9**	**14.2**	**-9.5**	**13.2**	**-5.7**	**13.6**	**-9.0**	**13.7**
GA r	**-10.9**	**10.9**	**11.6**	**16.8**	**6.9**	**14.2**	**-**	**-**	**-2.5**	**6.4**	**1.2**	**6.1**	**-2.0**	**6.3**
IGGA r	**-16.3**	**9.7**	**14.2**	**15.7**	**9.5**	**13.2**	**2.5**	**6.4**	**-**	**-**	**3.7**	**6.9**	**0.5**	**7.2**
MS r	**-20.0**	**11.0**	**10.5**	**15.9**	**5.7**	**13.6**	**-1.2**	**6.1**	**-3.7**	**6.9**	**-**	**-**	**-3.2**	**4.0**
PA r	**-16.8**	**11.1**	**13.7**	**15.5**	**9.0**	**13.7**	**2.0**	**6.3**	**-0.5**	**7.2**	**3.2**	**4.0**	**-**	**-**

Table 3 allows the comparison of all smooth devices and all ribbed devices as a group. In the first quadrant of the table, the Grip Tester and the two LWST using smooth tires, show the results given above. In the fourth quadrant, all the ribbed tire LWST, show very small differences in means and ranges, at least in the downhill direction.

Table 4 Mean differences and ranges of LOA of friction measurements for all devices uphill

Uphill	GT sm	+/-	MS sm	+/-	PA sm	+/-	GA r	+/-	IGGA r	+/-	MS r	+/-	PA r	+/-
GT sm	-	-	23.4	15.3	18.3	11.4	11.9	8.9	13.3	23.1	11.9	8.2	8.0	8.7
MS sm	-23.4	15.3	-	-	-5.2	16.1	-11.6	18.6	-10.2	24.7	-11.5	18.3	-15.4	18.7
PA sm	-18.3	11.4	5.2	16.1	-	-	-6.4	14.6	-5.0	23.8	-6.4	14.2	-10.3	13.4
GA r	-11.9	8.9	11.6	18.6	6.4	14.6	-	-	1.4	23.9	0.1	6.1	-3.8	8.4
IGGA r	-13.3	23.1	10.2	24.7	5.0	23.8	-1.4	23.9	-	-	-1.3	23.1	-5.2	22.3
MS r	-11.9	8.2	11.5	18.3	6.4	14.2	-0.1	6.1	1.3	23.1	-	-	-3.9	6.1
PA r	-8.0	8.7	15.4	18.7	10.3	13.4	3.8	8.4	5.2	22.3	3.9	6.1	-	-

Table 4 show the same type of results for the runs going uphill. For the combinations of smooth tire devices the results are similar. For the ribbed tire results however, there seems to be a very large difference in the ranges for the comparisons made with the IGGA device, although the means are almost the same as those for the downhill.

Finally, Table 5 Repeatability explains the variability that each unit has, in each direction, with each tire. Most devices show acceptable repeatability, except for the MS LWST going downhill with a smooth tire and the IGGA LWST with the ribbed tire going uphill. In order for a pair of units to have good agreement in their measurements, their repeatability has to be low.

Table 5 Repeatability of friction measurements per direction

Repeatability				
	Smooth		Ribbed	
Friction Tester Units	Downhill	Uphill	Downhill	Uphill
VTTI GT	6.8	6.0	-	-
PA	5.9	8.0	6.2	5.8
MS	11.4	8.8	4.2	4.4
GA	-	-	6.6	7.1
IGGA	-	-	6.2	31.7
DFT60		7.5	-	-
DFT20		9.1	-	-

Repeatability numbers from PA smooth and the MS ribbed are significantly low, in each category respectively. However, PA also shows good repeatability using the ribbed tire. The overall results for the VTTI GT smooth and the GA ribbed LWST are also very good with each tire. Good repeatability is necessary when trying to reproduce measurements, and any comparison made has to take this into account.

VII.6. Static tests: CT Meter and Dynamic Friction Tester

Static tests were conducted with two devices: the Circular Track Meter (CT Meter) and the Dynamic Friction Tester (DFT). According to ASTM E 2157, the CT Meter has a displacement sensor which rotates at a fixed elevation from the surface. The profile is recorded in the computer memory and the software reports the processed data as Mean Profile Depth (MPD). The CT Meter was used to obtain static macro-texture measurements at five different locations in each section, separated by approximately 45 ft. All the measurements were collected on the left wheel path of the westbound lane. For each surface, the five sets of MPD measurements are summarized in Table 6.

Table 6 Macrotexture measurements (MPD)

Section	**Run**					**Average**	**Std. Dev.**
	1	**2**	**3**	**4**	**5**		
A	1.25	1.07	1.05	1.16	1.17	1.14	0.08
B	1.42	1.37	1.23	1.63	1.53	1.43	0.15
C	0.94	0.97	1.10	0.81	0.92	0.95	0.11
D	0.78	0.70	1.01	0.80	0.87	0.83	0.12
I	1.20	1.08	0.92	0.81	0.95	0.99	0.15
J	0.93	0.91	0.97	1.35	1.61	1.15	0.31
K	1.71	1.66	1.63	1.83	1.93	1.75	0.13
L	1.06	1.03	1.30	1.11	0.99	1.10	0.12
PCC2	0.78	0.84	0.88	1.08	1.27	0.97	0.20
PCC3	1.87	1.79	1.86	1.71	2.05	1.86	0.13

Use of the DFT device used for the tests is reported in ASTM E 1911. It was used in the same spots where the CT Meter was used and measurements were performed at 20, 40, 60, and 80 km/h. The results at 20 km/h are summarized in the Table 7 (all the data at the other speeds is reported in Appendix A.4).

Table 7: DFT measurements (SN) at 20 km/h

Section	**DFT Run**					**Average**	**Std. Dev.**
	1	**2**	**3**	**4**	**5**		
A	0.715	0.66	0.724	0.708	0.743	0.71	0.03
B	0.763	0.737	0.702	0.747	0.741	0.74	0.02
C	0.698	0.682	0.65	0.646	0.686	0.67	0.02
D	0.709	0.72	0.693	0.706	0.709	0.71	0.01
I	0.768	0.765	0.751	0.776	0.76	0.76	0.01
J	0.762	0.827	0.765	0.801	0.789	0.79	0.03
K	0.669	0.651	0.656	0.633	0.519	0.63	0.06
L	0.669	0.698	0.74	0.713	0.631	0.69	0.04
PCC2	0.732	0.694	0.682	0.716	0.681	0.70	0.02
PCC3	0.827	0.748	0.776	0.719	0.725	0.76	0.04

According to ASTM E1960, a comparison of the Friction Numbers provided by the Dynamic Friction tester (DFT) with all the data provided by the other devices can be approximately converted to a conventional speed of 60 km/h (this conversion includes the introduction of the macro-texture features of the pavements) called the International Friction Index (IFI). The converted numerical results are reported in Appendix A.5. Plots of the data, for each device, are also included in this appendix showing the comparison of the original friction measurement, the converted friction values and the ideal or "golden" values obtained with the DFT and the CT Meter. The three types of devices produced very different results as can be seen with the GT, the two LWST smooth and the four LWST ribbed, not consistent with the IFI golden values.

VII.7. Profile

Profiler Data Collection

Longitudinal road profile measurements are summarized using the International Roughness Index (IRI). The IRI represents the accumulation of all vertical movements of a "standard" vehicle across a given length of road, usually expressed in inches/mile (mm/km). If the sum of these movements is large, the surfaces are usually rough (not smooth or even), and travel over them is uncomfortable. If the sum is small, travel is more comfortable.

All agencies, other than VTTI participating in the Consortium used single-spot laser-based inertial profilers for measuring longitudinal profiles at two highway speeds and then computing the IRI values at project and network levels. VTTI used Ro-Line sensors which are high speed laser line sensors that utilize 100 laser scan points rather than a single laser point to acquire a surface profile. Both the Ro-Line 100 point laser and the single point laser are shown in Figure 10 below. The major problem associated with inertial profilers is the accuracy of the collected road profile measurements. The verification of these measurements can only be accomplished when compared to a stable, consistent scale. To verify the profilers' correct operations, the Consortium decided to implement a profiler verification site following available guidelines and specifications that test the compliance of the repeatability and accuracy of the profilers of its members.

Figure 10 The Ro-Line lasers are displayed on the left and the single point laser is displayed on the right.

Test Sections

The five Smart Road section characteristics are summarized in Table 108. Based on the general requirements set forth by AASHTO R-56 specifications (*1*), a decision was made to design five test sections on the uphill (westbound) lane of the facility to avoid having to measure under braking conditions. AASHTO R-56 requires the sections for the test comparisons to be at least one-tenth of a mile long (528 feet). The first two test sections were established in the JRCP (jointed reinforced concrete pavement) and the CRCP (continuously reinforced concrete pavement) pavements. It must be noted that both of these sections were grounded, and additionally the CRCP section was grooved, in January 2011. The rest of the test sections were over asphalt concrete pavements, each being about 300 feet long. Test section 3 was chosen from two coarse asphalt pavements (SMA and OGFC). The two remaining sections were chosen based on their initial roughness: one with a low IRI value and one with a high IRI value. Although sections E and F would have made a better match for the low IRI criterion, sections F and G were chosen for test section 4 because section E lies on a horizontal curve. Finally, sections A and B were chosen as test section 5 since the two had relatively high IRI values.

Table 8 Smart Road section pavement surfaces

Section	**Name**	**Surface Mix Type**	**Length** (feet)	**MPD Uphill** (mm)	**Test Section No.**	**Length** (feet)
1	Loop	SMA 19.0	N/A	0.80		
2	A	SM-12.5D	347	0.89	**5**	**528**
3	B	SM-9.5D	289	1.01		
4	C	SM-9.5E	292	0.79		
5	D	SM-9.5A	407	0.70		
6	E	SM-9.5D	268	N/A		
7	F	SM-9.5D	302	N/A	**4**	**528**
8	G	SM-9.5D	304	N/A		
9	H	SM-9.5D	292	N/A		
10	I	SM-9.5A(h)	338	0.73		
11	J	SM-9.5D	280	0.85		
12	K	OGFC	302	1.80	**3**	**528**
13	L	SMA-12.5D	326	1.08		
14	CRCP*	Tined	2,290	0.80	**2**	**528**
15	JRCP*	Grooved	591	N/A	**1**	**528**

* Both JRCP and CRCP sections were grounded, and the CRCP was grooved in January 2011.

Each of the test section wheel paths were marked every 10 feet with paint so that operators could align the profilers when traveling at the required speeds of 25 and 45 mph. The paint markings also helped reduce possible wandering errors. The left wheel path was marked 34.5 inches from the center line, and the right one was separated from the left by 69 inches. Each test section also had paint-marked, lead-in distances of 150 feet starting across a one-inch high electrical rubber cable cord protector that was placed as an artificial bump to indicate the start of each of the lead-in sections.

These bumps were intended to produce a spike in the profiles, which made it possible to determine the exact location of the test sections during subsequent analysis. The paint markings for the 150-foot lead-in areas were colored yellow, while the 528-foot test sections were colored green. Traffic cones with reflective material were also placed next to each bump before the lead-in areas of each test section to help the profiler operators become aware of the beginning location and to align properly in the marked wheel paths. A diagram of the profiler testing setup for each test section is shown in Figure 11.

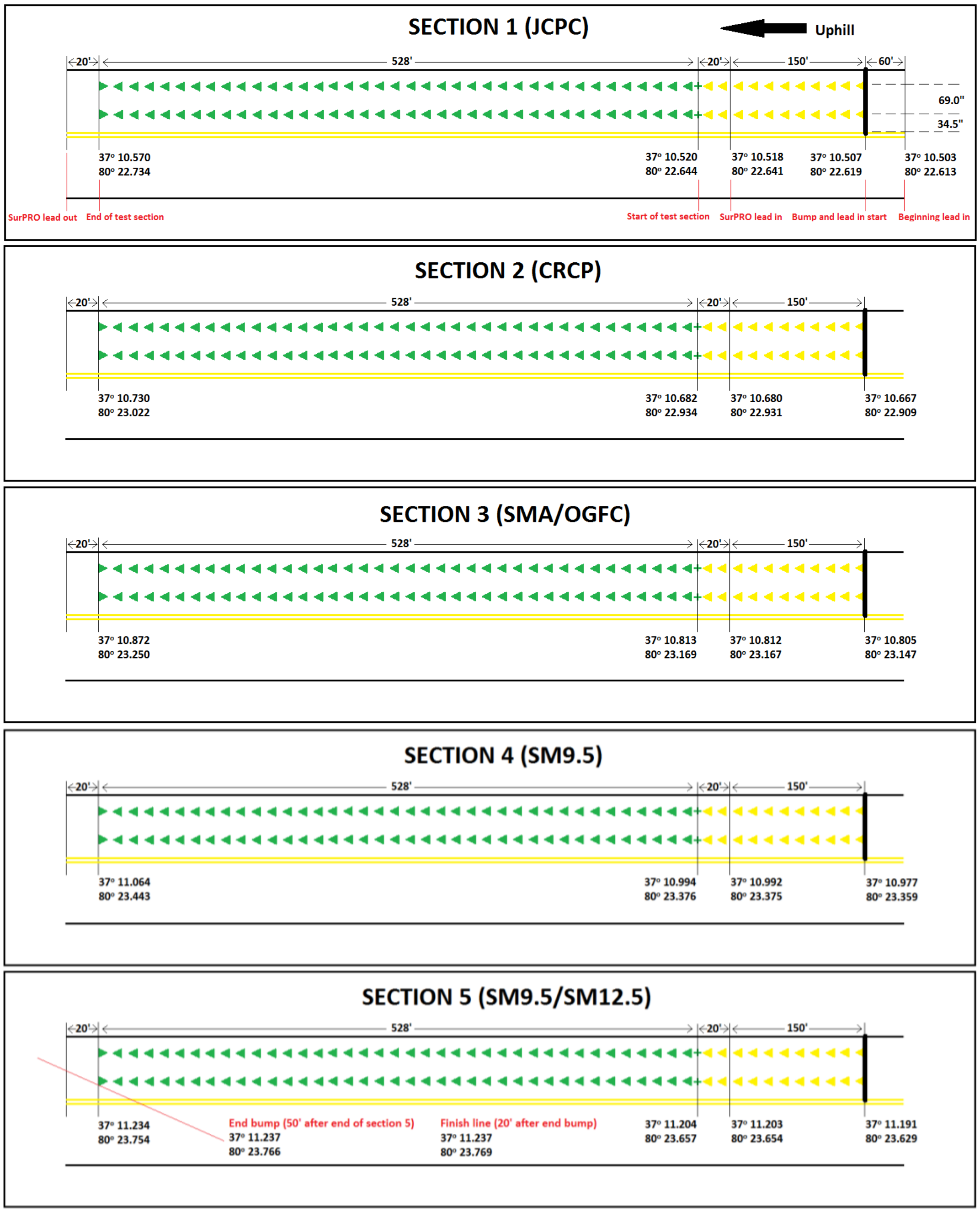


Figure 11 Smart Road profiler test section setup for 2013 Rodeo

Reference Data Collection

Reference Profilers

Two ICC (International Cybernetics Corporation) SURPRO walking profilers were used to measure the reference profile of each of the five test section along the left and right wheel paths. Due to a restraint of time, in 2013 only one closed loop was made on both wheel paths to compute the IRI value of each wheel path in each section. Figure 10 shows the two SURPROs during reference measurements.

Figure 12 Reference profile measurements using the two SURPRO profilers.

The results of the two SURPRO profilers are shown on Table 9 below; cross-correlation and the IRI computed for each. The cross-correlations were not the 98% recommended in the standard.

Table 9 Smart Road SURPRO walking profilers results for reference profiles

	IRI					
	VTTI		**MS**		**Cross-Correlation**	
	Left	**Right**	**Left**	**Right**	**Left**	**Right**
SECTION 1	122.1	92.0	118.8	94.2	92.1	94.1
SECTION 2	52.4	43.1	45.7	36.7	72.8	66.6
SECTION 3	129.6	129.0	124.9	128.5	91.7	92.0
SECTION 4	100.4	96.8	98.1	94.3	91.9	90.2
SECTION 5	131.9	123.1	125.3	122.9	89.7	92.8

High-speed Profilers

Eight profilers were used to obtain measurements for comparison to the reference measurements made with the two SURPRO devices. Data were collected following the procedures mentioned in AASHTO R-56. Pre-test system calibration, including block, bounce, and distance calibrations, were also performed. The block tests were conducted with blocks provided by each profiler manufacturer and with a standard set of calibration blocks purchased by the Virginia Tech Transportation Institute (VTTI). Bounce tests were performed for each unit as recommended by each manufacturer (e.g., ICC, Dynatest, etc.). These tests are designed to detect any serious malfunctions outside the permissible limits during the normal operation of the height and accelerometer sensors.

A distance measuring instrument (DMI) calibration section with a length of 1,000 feet was to calibrate the DMI as per normal operating recommendations by manufacturers. All profilers then collected profile data 10 times at a constant speed of 45 mph and 5 times at a constant speed of 25 mph, trying to avoid sudden speed changes throughout the sections.

Profiler Results and Discussion

The analysis methods included in the Profile Viewing and Analysis (ProVAL) software were used to determine the ride statistics, repeatability, and reproducibility assessments for all data collected were calculated, ProVAL software were developed under the sponsorship of FHWA (*2*). The following is a brief description of the results.

Ride Statistics

IRI values of all profile runs for all test sections were computed using ProVAL. The averages of the 5 to 10 runs (depending on the speed) from each profiler were computed. All IRI computations made in ProVAL applied a 250 mm moving average filter (*2*). The IRI results from all profilers for all sections are shown in Figures 13, 14, 15, and 16, and individually for each section in Appendix B.1.

From these plots several observations can be made. In general, the LWP IRI values are always higher than the RWP IRI values for all profilers on most sections. In particular for Section 1 JRCP these differences are the highest, on average an IRI difference of 22 in/mile for both the 25 mph and the 45 mph runs. However, for Section 3 SMA/OGFC, all profilers had the opposite results where the LWP IRI were higher on average by 5.2 in/mile for the 25 mph runs and by 4.7 in/mile for the 45 mph runs. For the other three sections, the RWP IRI were higher, most significantly for section 2 at 45 mph, an average of 13 in/mile while all the other sections at both speeds the difference was lower than 5 in/mile higher for the RWP IRI.

The second general observation that can be made is referring to the inability of all the single-spot (SS) profilers to correctly read Section 2 CRCP, which is the grooved concrete, showing the highest IRI values for both wheel paths for all the five sections for both constant speeds. This is very different for the VTTI profiler which has the Ro-Line or wide-line sensor. The SS profilers are measuring an average of 85 in/mile more roughness, on both wheel paths, at both speeds when compared to the average IRI measured by the reference profiles obtained with the SURPRO. The Ro-Line profiler, on the other hand, measured around 11 in/mile *less* than the reference values on both wheel paths at both speeds.

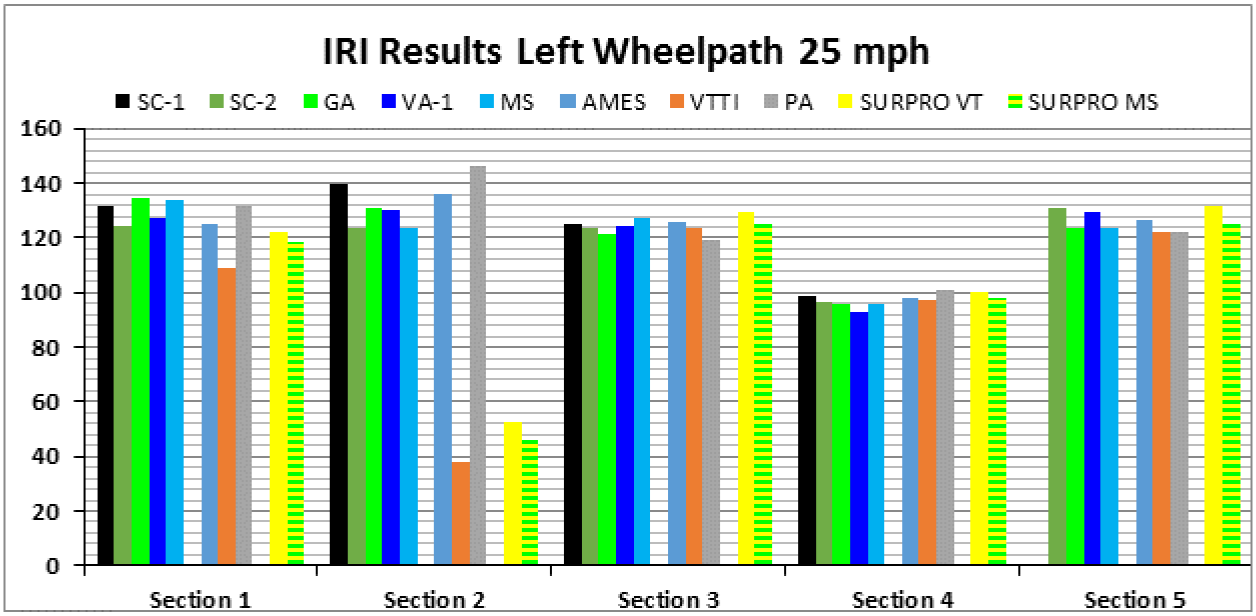


Figure 13 Left wheel path ride statistics for 25 mph

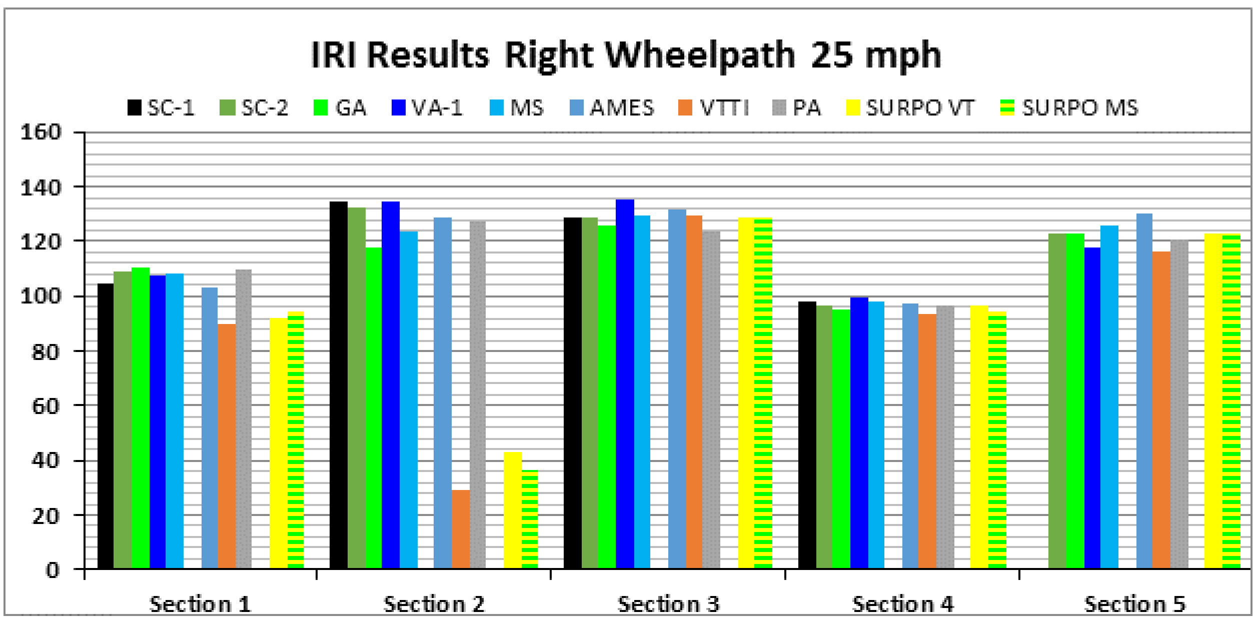


Figure 14 Right wheel path ride statistics for 25 mph

The third general observation that can be made is that the SS profilers generally had on average higher results than the SURPROs while the Ro-Line generally had lower results, and these differences where, except for Section 2, usually higher for the Ro-Line than for the SS. This just means that the results of the SS profilers, except for grooved or JRCP, are usually closer to the results of the SURPRO results than those of Ro-Line profilers. Under measuring by a greater quantity to what is considered to be the reference value is going to give that type of profilers a worse cross correlation value than it would for the SS profilers which are over measuring by less. A verification of the validity of taking the SURPRO measurements as reference is required to make sure that these measurements are compared correctly.

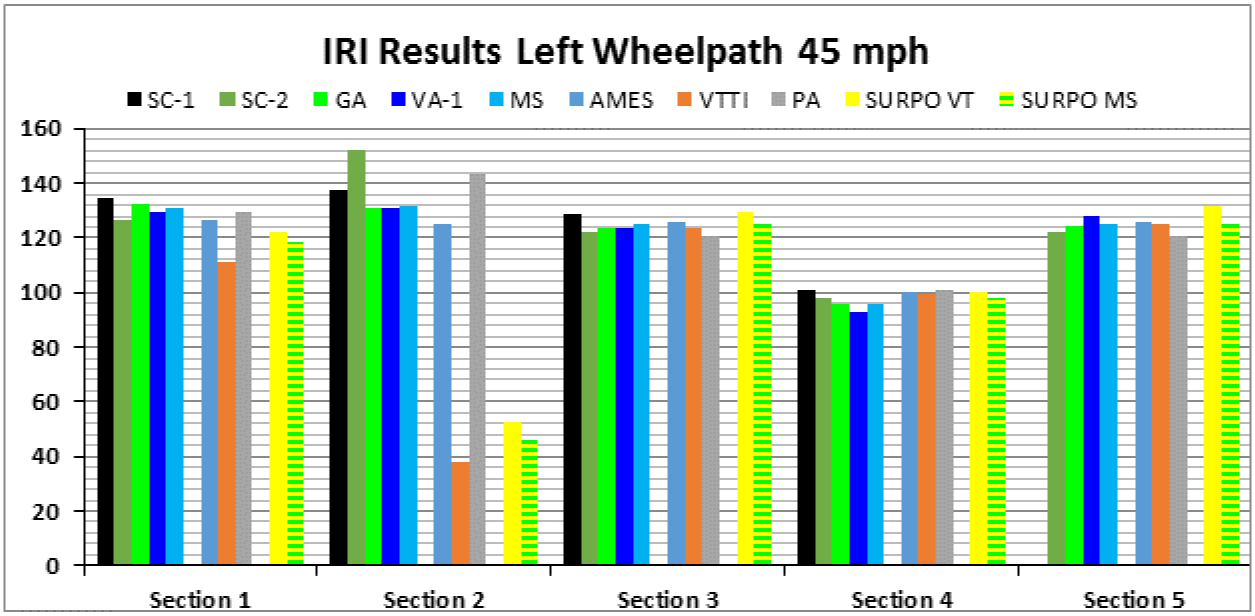


Figure 15 Left wheel path ride statistics for 45 mph.

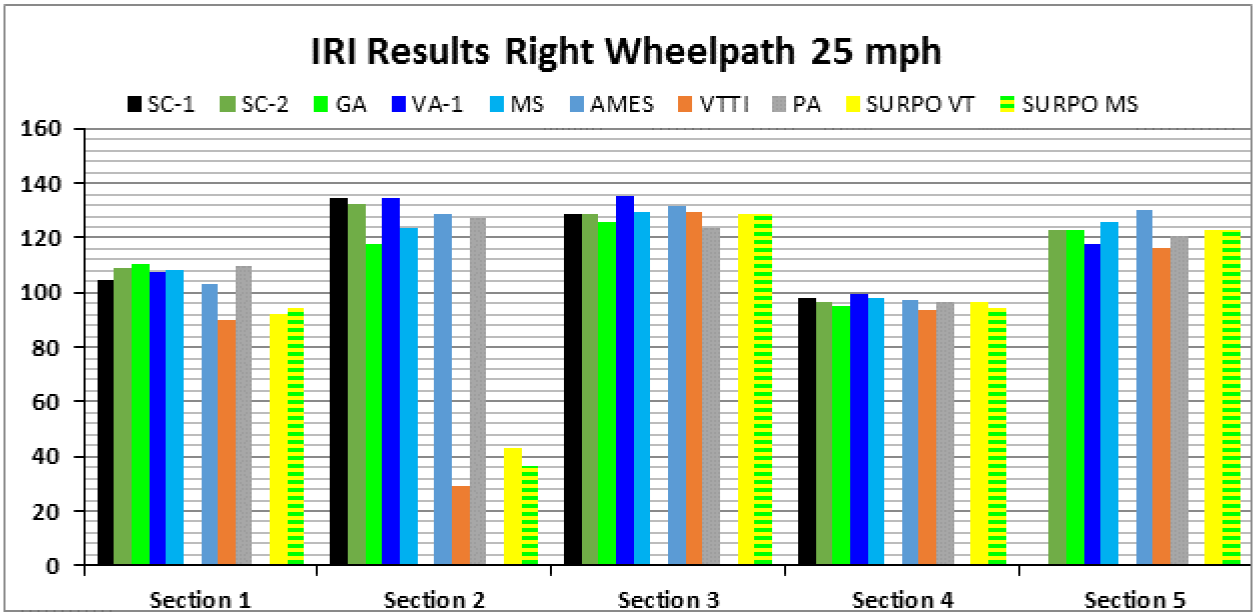


Figure 16 Right wheel path statistics for 45 mph

Finally, in general it can be said that the coarser textured pavement found in test section 3 and the high cracking damage of test section 5 caused the IRI values for these sections to be high. Section 4 probably has a lower IRI value than the aforementioned asphalt sections and the overall lowest IRI value of all test sections, although it is section 2 that has the lowest IRI if the measurements found by both the SURPROs and the Ro-Line laser profiler are correct and it is accepted that this is probably caused by the wander of the single spot laser as it moves in the grooves (*3*).

Repeatability

Repeatability results illustrate how well each unit obtains the same profile measurements during each of the 5 or 10 runs. For this study, cross-correlation was performed on the profile data to evaluate both profiler repeatability and reproducibility. For repeatability, AASHTO R-56 requires an average cross-correlation of at least 92% when each profile is compared with the remaining four to nine runs (90 comparisons). The repeatability results for each of the laser sensors (i.e., left and right) as computed with ProVAL are shown in Tables 10 & 11 for each test section. Red bold numbers indicate those that did not pass the repeatability criteria.

Table 10 Average repeatability cross-correlations for all profiler units traveling at 25 mph.

	Average Repeatability 25 mph									
	Section 1		Section 2		Section 3		Section 4		Section 5	
Profiler	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
SC1	**78**	**76**	**14**	**13**	92	94	**91**	**90**	-	-
SC2	**79**	**69**	**18**	**10**	93	95	95	94	**80**	**89**
GA	**75**	**71**	**16**	**11**	**91**	94	95	93	**76**	**89**
VA-1	**72**	**74**	**13**	**12**	94	95	94	**91**	**87**	**90**
MS	**84**	**76**	**14**	**12**	94	96	93	93	93	**89**
AMES	**76**	**78**	**12**	**10**	94	96	94	94	**81**	**88**
VTTI	98	97	**74**	**88**	98	97	97	97	**87**	**89**
PA	**81**	**76**	**17**	**12**	94	96	97	92	94	**90**

Table 11 Average repeatability cross-correlations for all profiler units traveling at 45 mph.

	Average Repeatability 45 mph									
	Section 1		Section 2		Section 3		Section 4		Section 5	
Profiler	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
SC1	**81**	**75**	**13**	**12**	94	96	93	94	-	-
SC2	**82**	**72**	**14**	**13**	93	95	94	93	93	**80**
GA	**79**	**72**	**15**	**11**	93	95	94	**91**	**72**	**82**
VA-1	**73**	**71**	**13**	**11**	94	94	94	**91**	**86**	**87**
MS	**81**	**75**	**16**	**12**	95	96	93	94	**81**	**83**
AMES	**87**	**75**	**16**	**13**	92	**90**	95	93	**74**	**78**
VTTI	96	97	**81**	**90**	96	95	97	95	**74**	**77**
PA	**80**	**67**	**13**	**11**	93	95	96	94	93	**91**

The profilers that were present at the rodeo included one from Georgia DOT (GA), one from Mississippi DOT (MS), two from South Carolina Department of Transportation (SC1 and SC2), one from Virginia DOT (VA), one from Pennsylvania DOT (PENN), one from Iowa (AMES), and one from Virginia Tech Transportation Institution (VTTI). The repeatability results for Section 3 and Section 4 show ideal correlation between the various runs in all sections. All but two of the profilers failed all the repeatability tests with values of more than 92% for section 1. None of the profilers passed the repeatability tests in section 2 for both wheel paths and Section 5 right wheel path, only South Carolina 1 (SC1) profiler passed the repeatability test for section 5 left wheel path.

Reproducibility

Reproducibility results were obtained by comparing the highest cross-correlation repeatability for each wheel path based on the SURPRO profiles to the 5 to 10 runs (depending on speed) from each participant profiler. Power Spectrum Density (PSD) plots of the data collected with the SURPRO indicated that a moving average filter had already been applied to the data. Hence, no separate moving average was required for the SURPRO runs, and the IRI-filtered cross-correlation was only applied to the data of the profilers (*2*). The results from the profiler certification (reproducibility) module are shown in Tables 12 through 15.

According to AASHTO R-56, a profiler passes the reproducibility test if it has a cross-correlation value of more than 90% when compared with the respective reference profile. As can be seen in Tables 10 through 13, the reproducibility cross-correlations (IRI filtered) between both SURPRO units and all profilers are relatively low. Section 2, which displayed poor repeatability results in the previous section, also displays the lowest reproducibility. Bold red numbers indicate those that did not pass the repeatability criteria. Cross correlations with the VTTI SURPRO had two devices with two sections passing vs. only one device in one wheel path in one section passing with the MS SURPRO.

Table 12 Average reproducibility cross-correlations for all profiler units at 25 mph with VT SURPRO

	Average Reproducibility (VTTI) 25 mph									
	Section 1		Section 2		Section 3		Section 4		Section 5	
Profiler	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
SC1	**56**	**44**	**6**	**3**	**79**	**79**	**75**	**73**	**-**	**-**
SC2	**74**	**59**	**10**	**5**	**84**	**79**	**73**	**70**	**66**	**77**
GA	**74**	**60**	**12**	**5**	**79**	**76**	**73**	**74**	**70**	**77**
VA-1	**59**	**56**	**8**	**4**	**75**	**76**	**68**	**67**	**64**	**60**
MS	**78**	**63**	**13**	**5**	**88**	**88**	**82**	**82**	**76**	**67**
AMES	**75**	**71**	**9**	**4**	**86**	**89**	92	90	**81**	**82**
VTTI	**73**	**78**	**43**	**28**	**88**	90	94	90	**57**	**49**
PA	**74**	**63**	**9**	**5**	**86**	**85**	**89**	**88**	**85**	**87**

Table 13 Average reproducibility cross-correlations for all profiler units at 45 mph with VT SURPRO

	Average Reproducibility (VTTI) 45 mph									
	Section 1		Section 2		Section 3		Section 4		Section 5	
Profiler	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
SC1	**58**	**49**	**7**	**3**	**78**	**80**	**74**	**72**	-	-
SC2	**71**	**55**	**8**	**5**	**83**	**78**	**67**	**63**	**72**	**68**
GA	**75**	**62**	**12**	**5**	**82**	**79**	**76**	**75**	**68**	**76**
VA-1	**68**	**58**	**7**	**4**	**77**	**79**	**70**	**68**	**69**	**65**
MS	**78**	**63**	**12**	**5**	**88**	**86**	**83**	**83**	**76**	**73**
AMES	**72**	**64**	**11**	**6**	**84**	**83**	91	90	**76**	**79**
VTTI	**75**	**79**	**61**	**37**	**88**	**86**	95	93	**76**	**67**
PA	**72**	**60**	**8**	**5**	**88**	**85**	**88**	**88**	**82**	**87**

Table 14 Average reproducibility cross-correlations for all profiler units at 25 mph with MS SURPRO

Profiler	Average Reproducibility (MS) 25 mph									
	Section 1		Section 2		Section 3		Section 4		Section 5	
	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
SC1	39	33	5	3	74	79	71	69	-	-
SC2	72	59	9	5	82	80	77	72	67	80
GA	73	61	11	4	78	77	75	74	73	69
VA-1	55	54	7	3	74	74	70	65	60	60
MS	73	61	11	4	85	87	82	78	64	48
AMES	75	75	8	4	84	86	91	88	76	72
VTTI	64	69	47	30	84	89	85	81	39	35
PA	77	68	9	4	87	86	89	86	87	75

Table 15 Average reproducibility cross-correlations for all profiler units at 45 mph with MS SURPRO

Profiler	Average Reproducibility (MS) 45 mph									
	Section 1		Section 2		Section 3		Section 4		Section 5	
	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
SC1	45	40	5	2	71	79	69	67	-	-
SC2	68	55	8	4	82	79	68	64	78	66
GA	73	62	11	5	81	80	79	76	71	73
VA-1	64	56	6	3	76	78	71	66	65	61
MS	73	62	10	3	86	87	84	80	68	57
AMES	75	70	11	5	82	82	90	87	76	75
VTTI	74	78	67	39	86	85	89	87	59	51
PA	75	65	8	5	88	86	89	87	88	84

VII.8. Noise

Noise Data Collection

Tire/Pavement Noise testing was made with the On Board Sound Intensity (OBSI) Methodology that uses dual microphone probes for sound intensity measurements. The noise testing procedure followed the American Association of State Highway and Transportation Officials (AASHTO) standard TP 76-12, "Measurement of Tire/Pavement Noise Using the On-Board Sound Intensity (OBSI) Method" *[1]*.

The measurements were made by three different equipments and all results were calculated using the A-weighted, one-third octave band levels. The participating teams: Virginia Tech Transportation Institute (VTTI), The International grooving and Grinding Association (IGGA), and Rutgers Center for Advanced Infrastructure Transportation (Rutgers).

Test Sections and equipment

Three sites with different sets of sections were chosen for testing. Nine different sections on Smart Road, four SM 9.5 D sections on US 460 between Glade Road and Toms Creek Road, and two

Microsurfaced sections on US 460 between South Main St. and Peppers Ferry Rd. Figures 1 through 3 show the locations of the sections. Figure 7 present the configuration of the probes for VTTI, which is similar for all three teams.

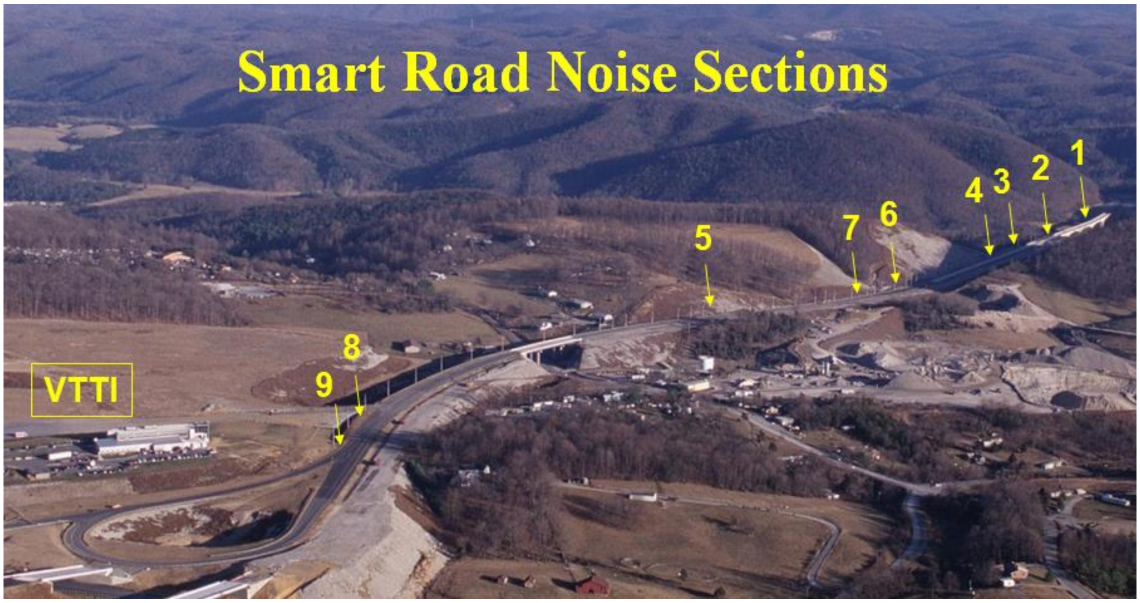


Figure 14 Smart Road Noise Sections

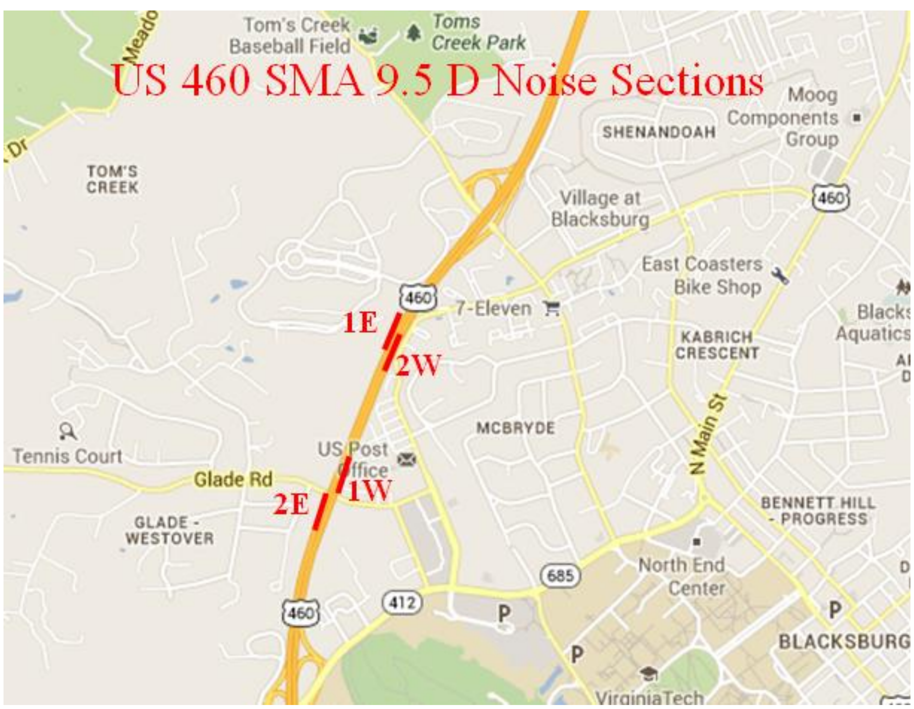


Figure 15 US 460 SMA 9.5 D Sections, between Glade Rd. and Toms Creek Rd.

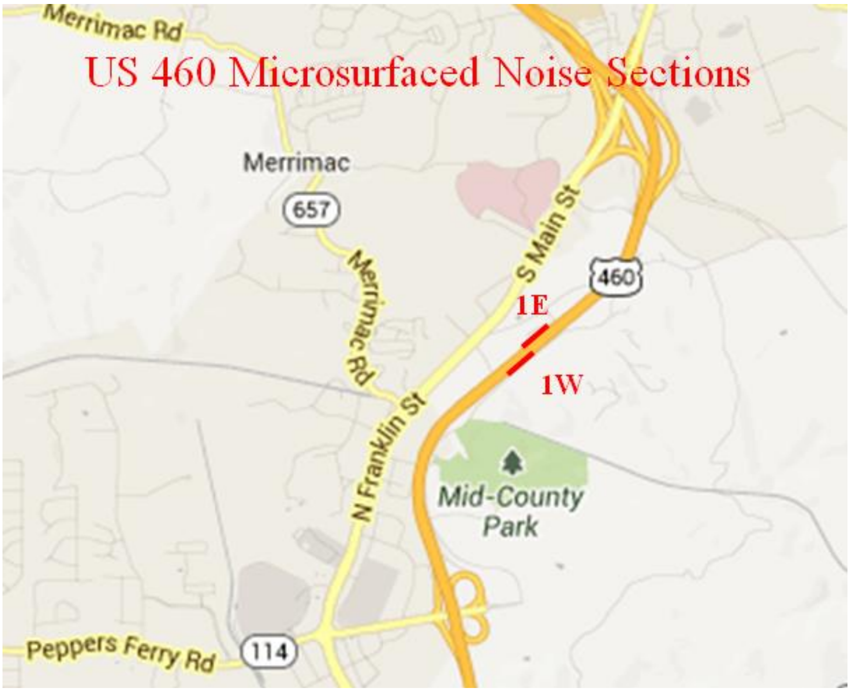


Figure 16 US 460 Microsurfaced Sections, between South Main St. and Peppers Ferry Rd.

Table 18 Noise sections.

Site	**Test SectionNo.**	**Name**	**Surface Type**	**Approx. uphill Section Length** (feet)	**Actual Test Length** (feet)
Smart Road	1	Smart Road Bridge	Concrete Transverse Tined	-	440
	2	JRCP	Longitudinal Grooved	591	440
	3	CRCP	Transverse Tined	600	440
	4	CRCP	Longitudinal Grounded and Grooved	528	440
	5	E,F, G and H	SM-9.5D	1175	440
	6	L	SMA-12.5D	336	220
	7	K	OGFC	276	220
	8	B	SM-9.5D	296	220
	9	A	SM-12.5D	342	220
US 460 SMA 9.5 D	1E	1E	SM 9.5D (placed in 2005)	-	440
	2E	2E	SM 9.5D (placed in 2005)	-	440
	1W	1W	SM 9.5D (placed in 2012)	-	440
	2W	2W	SM 9.5D (placed in 2012)	-	440
US 460 Microsurfaced	1E	1E	Microsurfaced	-	440
	1W	1W	Microsurfaced	-	440

Figure 17 OBSI Equipment used for testing.

Noise Results and Discussion

Three different software were used to gather and analyze the data, VTTI Software was developed by Acoustical and Vibrations Engineering Consultants (AVEC) [2], All the results are summarized in the Table 19 . The meteorological data is shown in Table 20.

Table 19 Average Overall Intensity Levels (IL) in dBA [3]

Site	Section / Name / Description	# 1			# 2			# 3			St. dev. between devices
		valid runs	St. dev.	Average IL (dBA)	valid runs	St. dev.	Average IL (dBA)	valid runs	St. dev.	Average IL (dBA)	
Virginia Smart Road	1 / Smar Road Bridge / Transverse Tined	7	0.05	**104.1**	3	0.06	**104.8**	4	0.10	**104.9**	0.44
	2 / JRCP / Longitudinal Grooved	8	0.16	**101.6**	3	0.50	**103.0**	4	0.14	**103.3**	0.91
	3 / CRCP / Transverse Tined	7	0.08	**103.4**	3	0.26	**104.1**	5	0.25	**104.1**	0.40
	4 / CRCP / Long. Ground & Grooved	6	0.15	**101.6**	3	0.23	**103.5**	3	0.17	**103.4**	1.07
	5 / E, F, G, H / SM-9.5D	7	0.11	**102.3**	2	0.07	**103.2**	4	0.10	**103.8**	0.75
	6 / L / SMA-12.5D	3	0.25	**101.1**	-		-	4	0.13	**102.0**	
	7 / K / OGFC	2	0.21	**99.7**	-		-	4	0.22	**101.0**	
	8 / B / SM-9.5D	5	0.22	**101.1**	-		-	5	0.08	**102.4**	
	9 / A / SM-12.5D	3	0.21	**100.7**	-		-	5	0.11	**101.8**	
US 460 SM 9.5 D	1E / 1E / SM 9.5D (placed in 2005)	2	0.00	**104.3**	3	0.29	**104.8**	4	0.10	**104.5**	0.25
	2E / 2E / SM 9.5D (placed in 2005)	2	0.07	**103.7**	3	0.42	**104.4**	5	0.11	**104.6**	0.47
	1W / 1W / SM 9.5D (placed in 2012)	3	0.23	**100.0**	3	0.12	**101.5**	3	0.21	**101.2**	0.79
	2W / 2W / SM 9.5D (placed in 2012)	5	0.22	**100.5**	3	0.15	**101.0**	5	0.12	**101.0**	0.29
US 460 Micro-surfaced	1E / 1E / Microsurfaced	3	0.35	**104.4**	3	0.40	**105.3**	3	0.15	**104.3**	0.55
	1W / 1W / Microsurfaced	2	0.14	**104.4**	3	0.71	**105.4**	4	0.24	**105.0**	0.50
								Average St. dev.			**0.58**

* St. dev. = standard deviation

Table 20 Meteorological data [3]

Project	Smart Road	US 460 SM 9.5 D	US 460 Microsurfaced
date	5/23/2013	5/23/2013	5/23/2013
time	13:00	10:42	11:24
Air temperature (°F)	70.7	70.4	70.4
Pavement temperature (°F) *	85.3	81.0	81.0
Barometric Pressure (inHg)	27.69	27.68	27.68
Air density (lb/ft^3)	0.0692	0.0692	0.0692
Wind speed (mph)	4.5	1.8	1.8
Durometer reading **	63	63	63

* at the momment of calibration, in a single spot

** on VTTI's SRTT Tire

Noise Statistics

In order to compare the results gathered for the three devices, the information presented in Table 19 was analyzed statistically, sorting the data by surface type and team. The analysis was made using a linear scale, converting the IL values in logarithmic scale into linear data using Equation 1, and then transforming those IL values back to the log scale with Equation 2.

$$IL_{\text{linear scale}} = 10^{\wedge}[IL_{\text{log scale}}/10]$$

$$IL_{\text{log scale}} = 10^{*} \log_{10} IL_{\text{linear scale}}$$

Figures 5 and 6 compare the noise levels for all the tested sections and for the three devices that were used. The figures show the mean, the median, the maximum and minimum, and the quartiles.

Finally, Figure 20 below depicts the overall noise distribution for all the tested sections and for all the devices. Notice that for Sections K, A, L, and B (sections less than 440 feet in length), there are no measurements with Device # 2 due to limitations in the software that only allow testing over sections 440 feet or more in length.

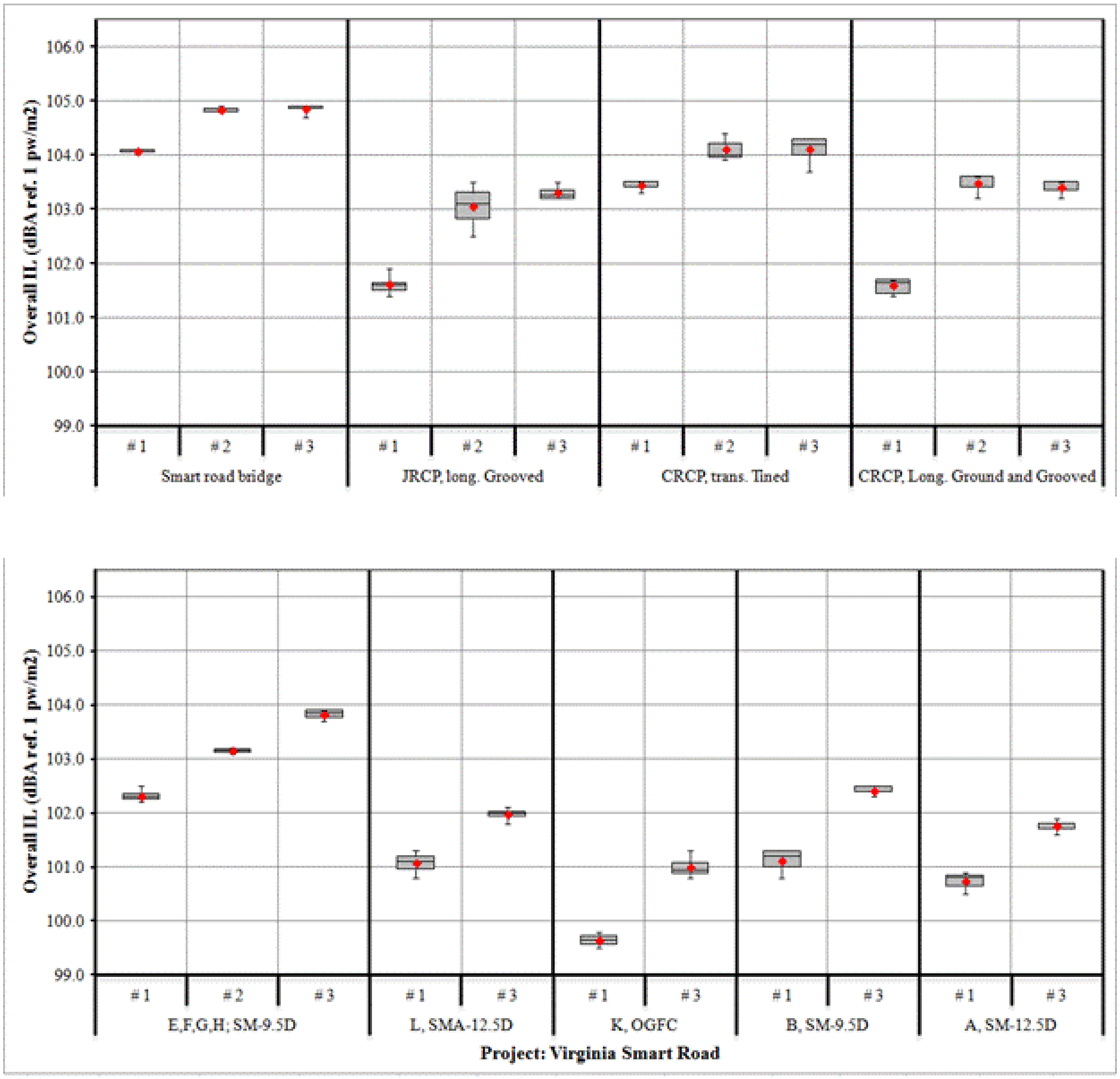


Figure 18. Box and Whiskers for Virginia Smart Road Sections [3]

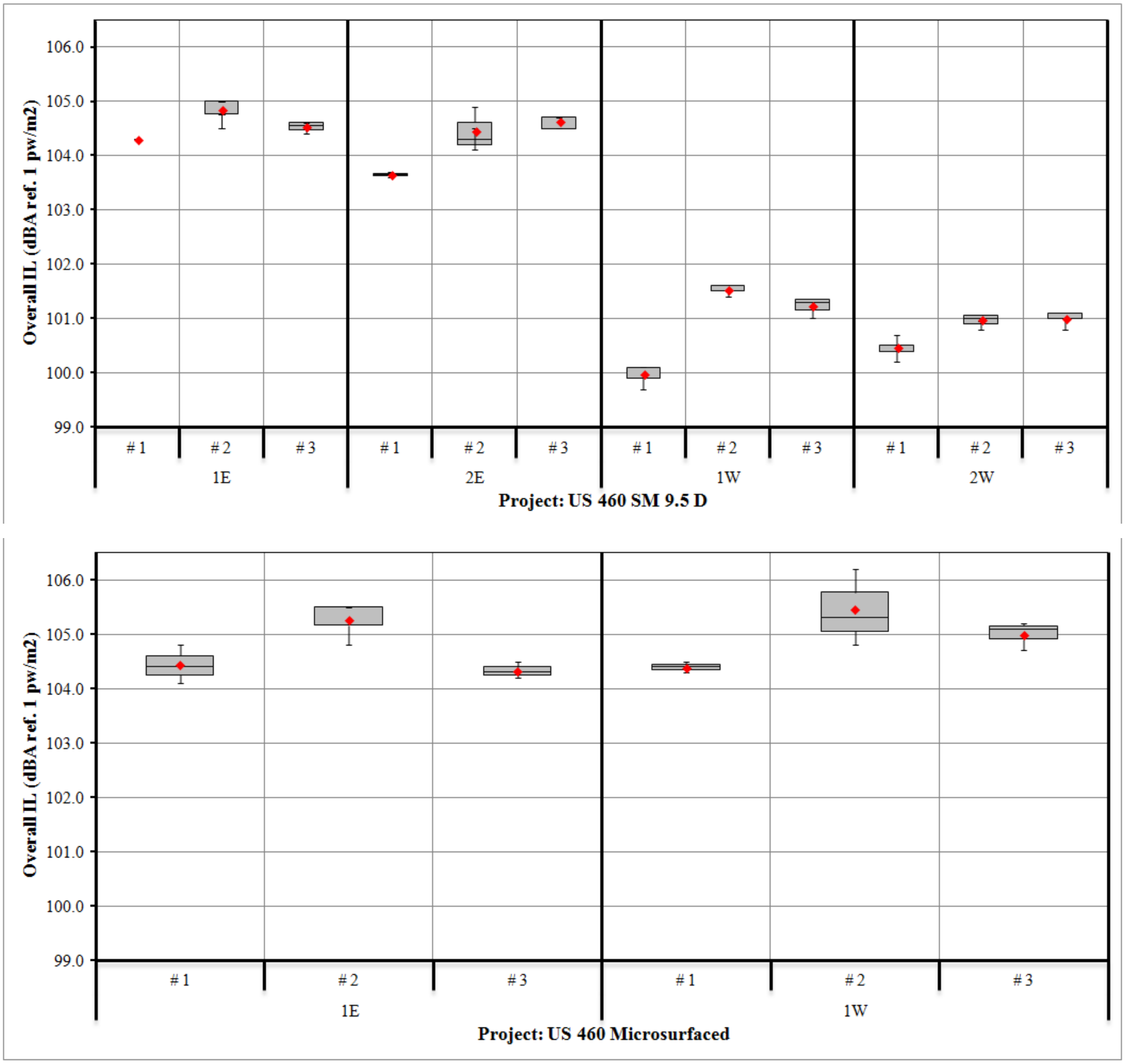


Figure 19. Box and Whiskers for US 460 Sections [3]

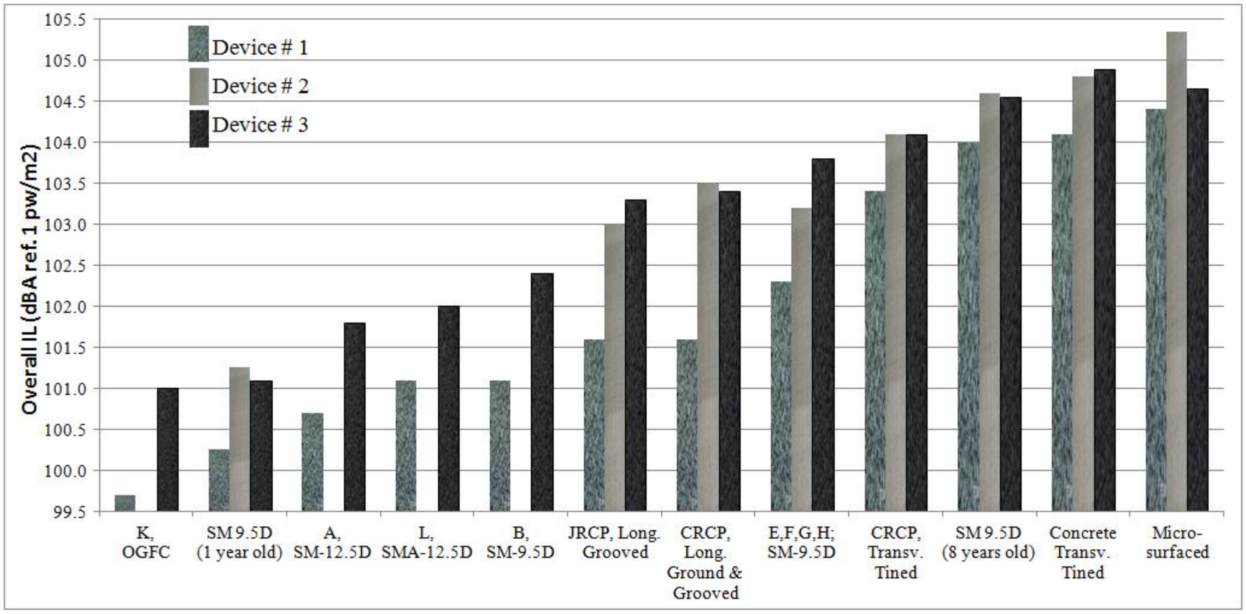


Figure 20 Increasing Spectrum of Average Overall OBSI levels for All the Sections and Devices [3]

VII.9. Conclusions and Recommendations

Friction

- The Grip Tester generally provides higher friction values, compared to those obtained with the LWST. The values obtained for the LWST with smooth tires are systematically lower than the values obtained with the LWST using ribbed tires. The smooth tires also have greater bias with the grade than the ribbed tires (the data is more scattered).
- Smooth tire devices seem to have a wider difference in their directional measurements, as evidenced by the data points being spread farther from the line of equality. This indicates greater bias due to the grade. Usually the uphill measurements are higher than the downhill ones, for all the LWST with both tires, although it is more variable with the smooth tires. On the other hand, for the GT it's the other way.
- LWST with ribbed tires exhibit the largest difference in the measurements in the two concrete pavement sections.
- LWST measurements with ribbed tires tend to measure a very different peak value than the Grip Tester. The difference between LWST peak and GT is around 15 points, equal to the difference between normal SN values and the Grip Tester values.
- On average, LWST with smooth tires will measure about 25 points lower than the Grip Tester, whereas with the ribbed tires, this difference is about 15 points. However, on average, measurements tend to agree better with the ribbed tires (10 point spread) than with the smooth tire (12 point spread).

Profile

- The results of the two SURPRO profilers cross-correlations were not the 98% recommended in the standard. Further work is suggested with several of these devices to understand and improve equipment compatibility that will guarantee adequate certifications. It is suggested that the Consortium requests a training and verification seminar on the use of SURPRO profilers for measurements used in profiler certifications.
- The SS profilers are measuring an average of 85 in/mile more roughness, on both wheel paths, at both speeds when compared to the average IRI measured by the reference profiles obtained with the SURPRO. The Ro-Line profiler, on the other hand, measured around 10 in/mile less than the reference values on both wheel paths at both speeds.
- The results of the SS profilers, except for grooved or JRCP, are usually closer to the results of the SURPRO results than those of Ro-Line profilers. A verification of the validity of taking the SURPRO measurements as reference is required to make sure that these measurements are compared correctly.
- Not one unit passed the AASHTO R-56 certification criteria for repeatability or reproducibility using two reference measurements on all sections. However, a quick analysis will show that the difference of using only IRI values to compare the measurements is, on average, for all devices, less than 3% with both reference profilers and for both speeds in the asphalt sections. The JRCP section shows an average of 13% difference and, as expected, the grooved CRCP is higher than 170%. This bears the question if the certification criteria are not too strict if, in the end, profilers will produce IRI numbers when measuring pavement profiles.

Noise

This study allowed drawing the following conclusions, this conclusions are the same presented in the paper: Tire-Pavement Noise Evaluation and Equipment Comparison Using On Board Sound Intensity Methodology over Several Pavement Surfaces in Virginia, presented on TRB in 2013 [3]:

- On average, the Open Grades Friction Course was the quietest section, with a minimum value of 99.5 dBA and an average of 100.4 dBA.
- On average, the Microsurfaced treatment placed on US 460 between South Main St. and Peppers Ferry Rd, in the westbound direction, was the loudest section, with a maximum value of 106.2 dBA and an average of 104.9 dBA
- For the twelve tested sections, asphalt surfaces are quieter than the concrete surfaces, except when compared to "CRCP Long. Ground & Grooved." This concrete surface achieve lower values than some of the asphalt surfaces due to noise reduction potentials offered by the longitudinal grounding, and grooving process.
- By looking at SM 9.5D surfaces placed on US 460 (eastbound 8 years old and westbound 1 year old), it is noticeable that traffic load and aging have a significant effect in the measured noise levels, with an average difference in noise levels of 3.5 dBA.
- The overall average difference in noise levels between devices (taking into account all section by section differences and comparing all devices to each other) is 0.6 dBA, with a maximum average difference of 1.3 dBA for a single section. This result is consistent with the literature.

- The average standard deviation between devices for all sections is 0.58, not high if compared with available information from previous rodeos.

VII.10. Acknowledgments

The Consortium for Pavement Surface Properties has been made possible thanks to the contributions of the Virginia Transportation Research Council (VTRC), the Federal Highway Administration (FHWA), the Connecticut, Georgia, Mississippi, Pennsylvania, South Carolina, and Virginia Departments of Transportation (DOT) and the Virginia Tech Transportation Institute (VTTI). CSTI personnel: William Hobbs, Daniel Mogrovejo, Shahriar Najafi, Ross McCarthy, James Bryce, and Azzurra Evangelisti collaborated with the data collection, and processing.

VII.11. References

- AASHTO, Standard Practice for Certification of Inertial Profiling Systems (PP49), The American Association of State Highway and Transportation Officials, Washington, D.C., 2007.
- AASHTO, Standard Method of Test for Measurement of Tire/Pavement Noise Using the On-Board Sound Intensity (OBSI) Method, in AASHTO Designation: TP 76-12. 2011, American Association of State Highway and Transportation Officials: Washington, 444 North Capitol Street N.W., Suite 249, D.C., United States of America
- AVEC, Software Board Sound Intensity (OBSI) software, licensed to Virginia Tech Transportation Institute, version 1.00 copyright © 2007-2011 AVEC, Inc. 2012, Acoustical and Vibrations Engineering Consultants.
- Chang, George, PROVAL Users Guide: Profile Viewing and Analysis Software, TRANSTEC, Austin, Texas, 2007.
- Flintsch, G., de León Izeppi, E., Valeri, S., and Najafi, S., 2011 Annual Equipment Comparison Roundup at the Smart Road, Blacksburg, Virginia, 2011.
- Mogrovejo, D.E., et al., Tire-Pavement Noise Evaluation and Equipment Comparison Using On Board Sound Intensity Methodology over Several Pavement Surfaces in Virginia. Transportation Research Board, 2013

VIII. 2014 Annual Equipment Comparison Roundup at the Smart Road[8]

VIII.1. Overview

"The regional pooled-fund project known as the Pavement Surface Properties Consortium is a research program focused on enhancing the level of service provided by the roadway transportation system through the optimization of pavement surface texture characteristics. The program was established in 2006 with support from the Federal Highway Administration (FHWA) and six state departments of transportation (DOTs): Connecticut, Georgia, Mississippi, Pennsylvania, South Carolina, and Virginia. The Consortium provides a practical mechanism to conduct research about pavement surface properties and explore their relationships with ride quality, friction, and noise. Complementing this effort is research focused on the review, testing, and evaluation of emerging technologies." Various friction testers, profilers, and reference profilers were assessed during the 2014 equipment roundup. The objective of this year rodeo was to harmonize the participant friction tester's and profiler's measurements.

VIII.2. Introduction

The Pavement Surface Properties Consortium hosts an annual event every year in the summer at the Virginia Smart Road in order to evaluate and compare various types of highway friction and profile measuring equipment. The Departments of Transportation (DOT) of Connecticut, Georgia, Pennsylvania, South Carolina, Mississippi, and Virginia came together this year in the event called "The Surface Properties Rodeo", with 6 locked–wheel friction testers, 12 high-speed laser profilers, and 4 SURPRO reference profilers to participate in the 2014 equipment roundup.

Figure 1 Reference Walking Profilers participants in the 2014 Rodeo

VIII.3. Purpose and Scope

The main objectives of the 2014 rodeo were as follow:

- Friction: Compare and evaluate the various friction testers' measurements, assessing the repeatability and reproducibility of the measurements, before and after calibration.

[8] Prepared by Edgar de León Izeppi, Gerardo Flintsch, Kevin K. McGhee, and Freddie Salado

- Profiler: Compare the measurements of the reference profilers with the high–speed profilers using PROVAL and the International Roughness Index (IRI) of the test sections, to assess the repeatability and reproducibility of the measurements. This year was also used to teach all the participants the correct procedures in the use of the SURPRO reference profilers.

VIII.4. Methods

Measurements for friction and profile were collected at the Virginia Smart Road. The procedure of data collection is explained in detail for each section of these measurements. A summary of the results and analysis is also provided in each section.

VIII.5. Friction

Friction Data Collection

Friction measurements were collected on May 19th and May 21st, 2014, at the Virginia Smart Road. Six locked–wheel skid trailers (LWST) participated on the final day (after calibration) and three did on the first day (before calibration), because not all trailers were calibrated. All of these devices took their measurements at 40 mph over 10 tests sections in both uphill and downhill directions on each lane. The tests with the LWST were performed in accordance with *ASTM E-274: Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire*. LWST measure the skid resistance of the paved surface and report a Skid Number (SN). The SN is the force required to slide the locked test tire at a stated speed, divided by the effective wheel load and multiplied by 100. LWST can use a smooth tire, as presented in the standard *ASTM E-524: Standard Specification for Standard Smooth Tire for Pavement Skid-Resistance Tests*, or a ribbed tire *ASTM E-501: Standard Specification for Standard Rib Tire for Pavement Skid-Resistance Tests*. Pennsylvania and Virginia run using a smooth tire while Connecticut, Georgia, and South Carolina use the ribbed tire (Table 1).

Table 1 Summary of the friction tests.

Unit	Type	Tire	Test Sections	Test Speed
CT skid trailer	Locked wheel	Ribbed	10 x 2	40 mph
MS skid trailer	Locked wheel	Ribbed	10 x 2	40 mph
PA skid trailer	Locked wheel	Smooth	10 x 2	40 mph
SC 1 skid trailer	Locked wheel	Ribbed	10 x 2	40 mph
SC 2 skid trailer	Locked wheel	Ribbed	10 x 2	40 mph
VA skid trailer	Locked wheel	Smooth	10 x 2	40 mph

Figure 2 below presents the layout of the test setup in the Smart Road in sections. The two lane 2.2 mile test track is composed of different types of Hot-Mix Asphalt (HMA) and Portland Cement Concrete (PCC) sections built with different texture types for testing purposes. The figure below shows the sections that were tested starting with HMA sections located in A, B, C, D, I, J, K, L and two Continuously Reinforced Concrete Pavement (CRCP) (PCC-2 and PCC-3), 3 tined sections and 1 ground and grooved section.

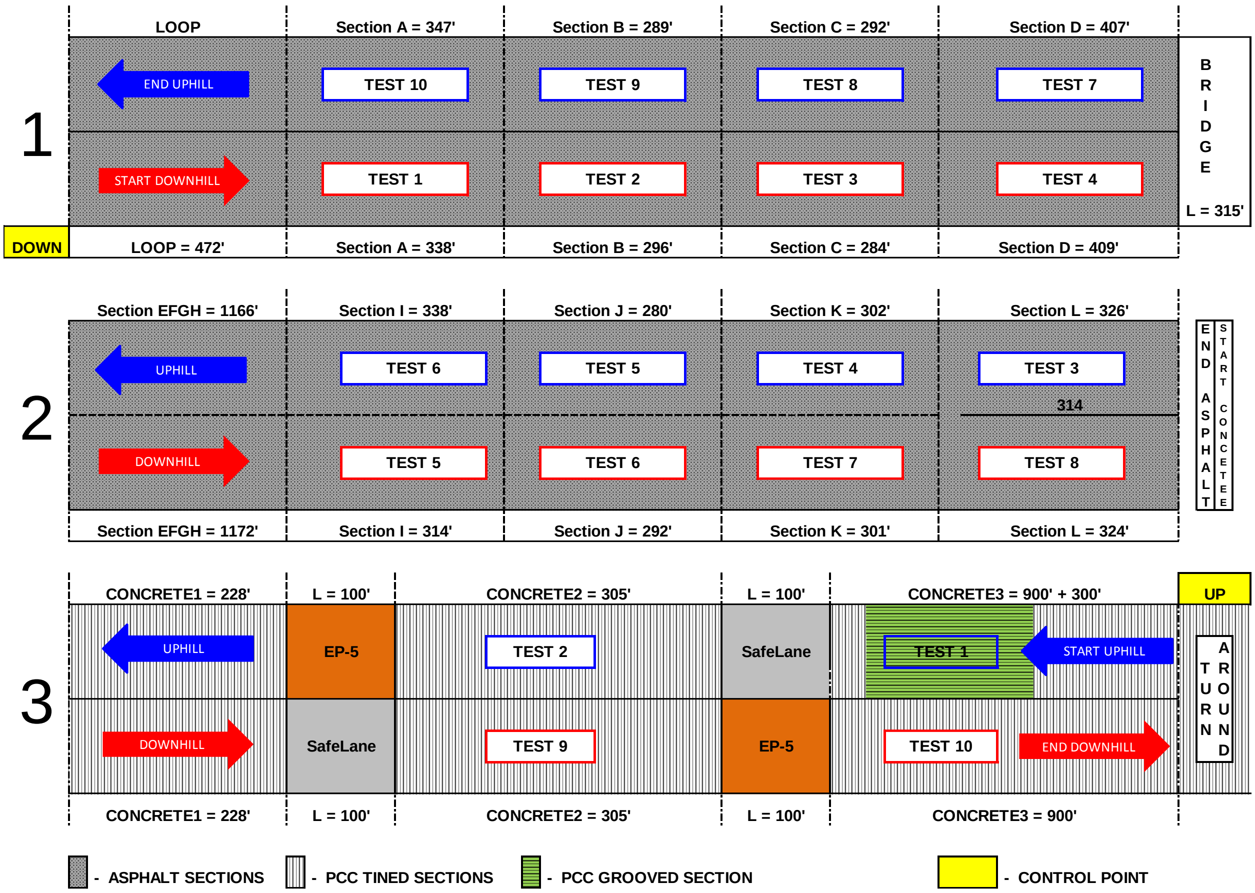


Figure 2 Friction test sections layout

Friction Results and Discussion

Table 2 below lists the coefficients of repeatability for the three skid testers that were calibrated during the 2014 Rodeo (SC1, SC2, and VA), both the pre-calibration results and the post-calibration results. The coefficient of repeatability, commonly referred to as "r", is a good indicator of the precision at which a device is working because it indicates the difference in the results of two tests with the same unit. Smaller "r" values are desired for the skid testers to be working more precisely. Results are shown for the measurements done downhill, uphill, and both.

Table 2 Repeatability coefficients for the calibrated skid testers

Unit	Pre-calibration			Post-calibration		
	Down	**Up**	**Both**	**Down**	**Up**	**Both**
SC 1 skid trailer	6.84	5.35	6.11	6.16	4.13	5.25
SC 2 skid trailer	5.19	4.65	4.92	5.21	5.08	5.14
VA skid trailer	10.97	6.73	9.31	9.31	11.31	10.36

Figure 3 below show the box-and-whiskers plots of the friction measurements taken downhill and uphill before, before and after each calibration for the three skid testers. These plots show that the calibration adjustments done to both of the South Carolina units decreased the size of the box plots which is a consequence of having better repeatability. However, the opposite is observed in the Virginia unit, where the boxes got bigger as a result of higher repeatability “r”.

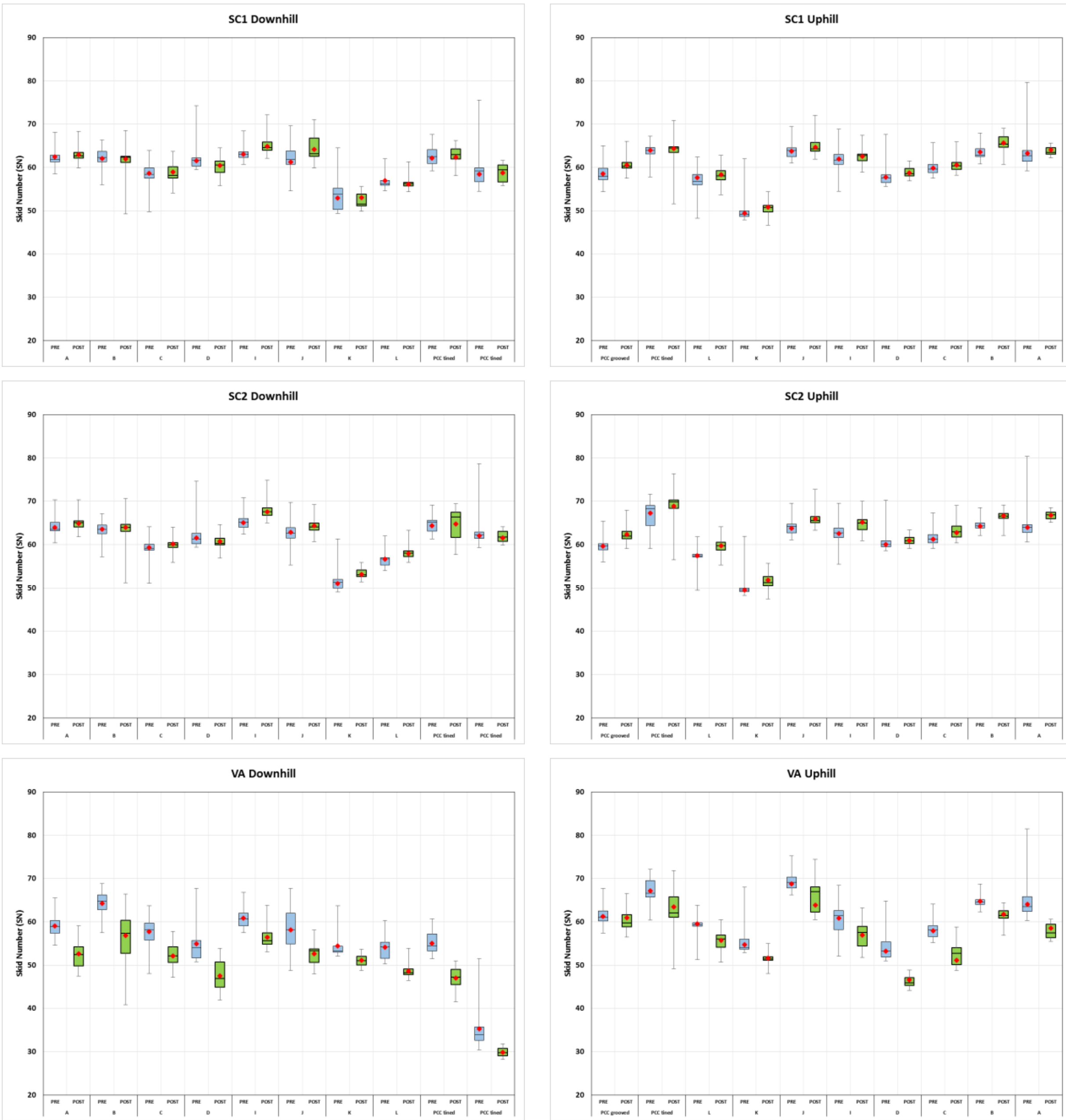


Figure 3 Individual friction results for pre and post calibrated units

Table 3 below has the coefficients of repeatability for the three skid testers that were not calibrated during the 2014 Rodeo (CT, MS, and PA). The results again are shown downhill, uphill, and both. Figure 4 below show the box-and-whiskers plots of the friction measurements taken downhill and uphill before, before and after each calibration for the three skid testers.

Table 3 Repeatability coefficients for the skid testers not calibrated

Unit	Post-calibration		
	Down	**Up**	**Both**
CT skid trailer	5.60	5.77	5.68
MS skid trailer	4.16	5.58	4.92
PA skid trailer	5.68	7.04	6.39

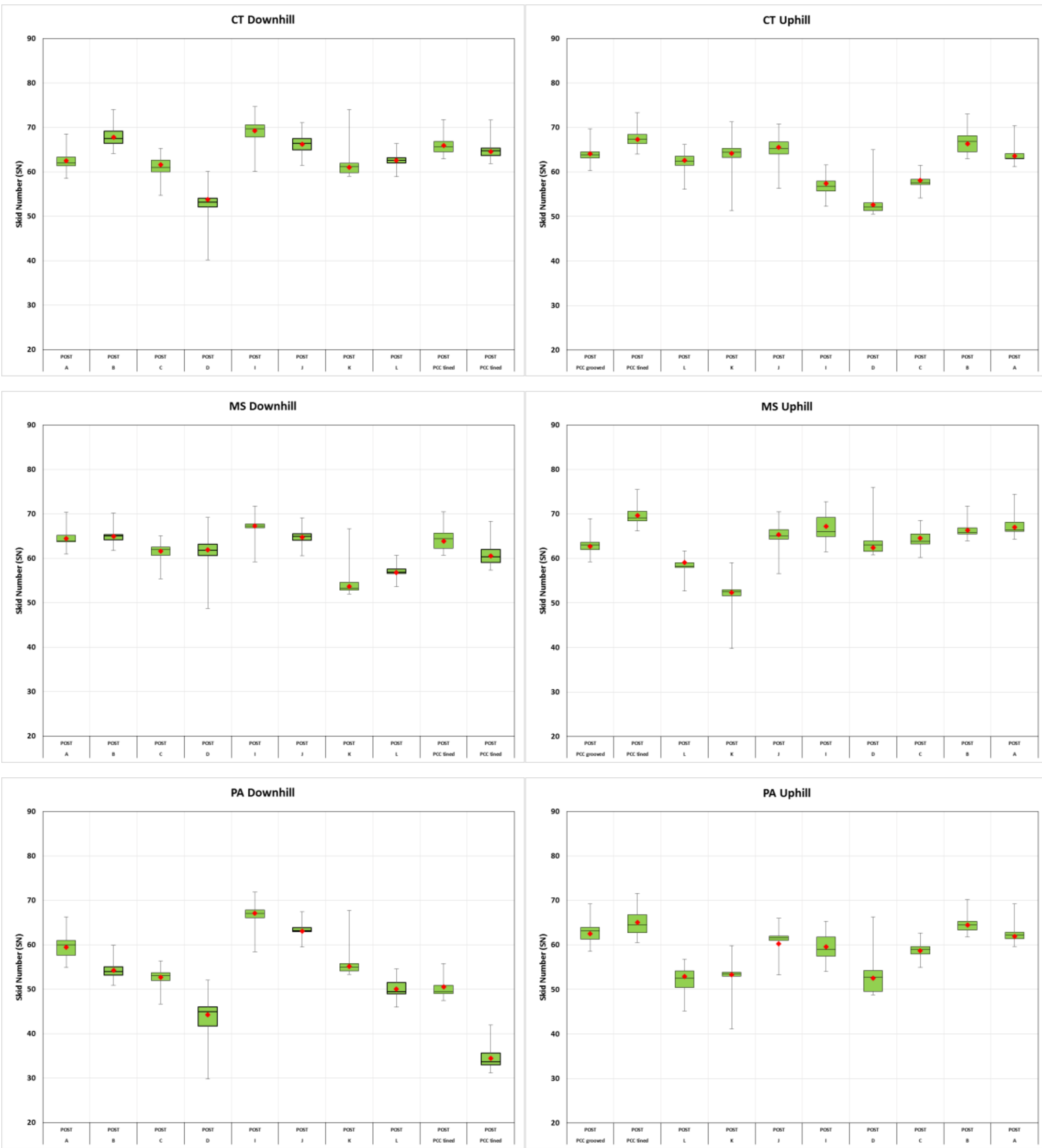


Figure 4 Individual Friction results for units not calibrated

Finally, a comparison of the friction numbers is made with the averages obtained with each of the different tires used. Two skid testers measured with a smooth tire and four with a ribbed tire. Figure 5 below present the average the results obtained with both tires on the sections tested with the ribbed and the smooth tires. As has been reported previously, the ribbed tires always report larger SN values than the smooth tires, unless those sections have high pavement macrotexture as is the case section K (both directions) and the grooved PCC (only uphill). This difference is also larger in the downhill than the uphill direction.

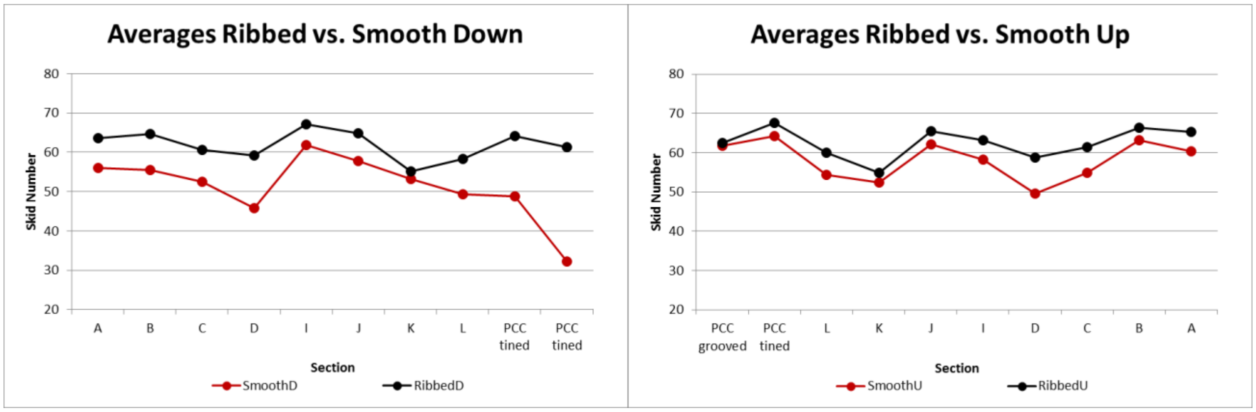


Figure 5 Average friction results by type of tire (smooth and ribbed)

On average, all of the locked-wheel skid testers seem to be measuring consistently similar. If all the measurements were to be done in the same direction, the standard deviations of all of the devices tested would be very close to the 2 SN recommended by the ASTM E274 standard, for all sections tested, as can be seen on table 4 below. The Virginia device needs more work to improve the results to the level of the other units.

Table 4 Standard Deviation of M

easurements for each locked-wheel skid tester (post-calibrations)

	CT	MS	PA	SC1	SC2	VA
Downhill	2.0	1.5	2.0	2.1	1.7	3.0
Uphill	2.0	1.9	2.3	1.5	1.8	3.5
Average	2.0	1.7	2.2	1.8	1.7	3.3

The general observations that can be made from the friction measurements:

- Two of the calibrated devices actually improved their repeatability after their calibrations. The only exception was the Virginia device which has been having problems with the water system which could be the cause of the large repeatability.
- Most devices with the same tire seemed to be following a similar trend; however, there are differences between the magnitudes of the measurements, depending on the tire, and the direction of the measurement (uphill or downhill).
- On average, all locked-wheel skid testers seem to be measuring consistently similar very close to the 2 SN recommended by the ASTM E274 standard, for all sections tested.

VIII.6. Profile

Profiler Data Collection

Longitudinal road profile measurements are summarized using the IRI. The IRI represents the accumulation of all vertical movements of a "standard" vehicle across a given length of road expressed in inches/mile (or mm/km). If the sum of these movements is large, the surfaces are usually rough and the ride will be uncomfortable. If the sum is small, travel is more comfortable.

Some of the agencies participating in the Consortium have started using the wide footprint lasers and others are still using the single-spot laser-based inertial profilers for measuring longitudinal profiles at highway speeds and then computing the IRI values. Every year the Rodeo intends to verify the profiler's correct operations with a profiler certification using the available guidelines and specifications that test the compliance of the repeatability and accuracy of the profilers of its members.

Test Sections

Based on the standard *AASHTO R-56: Certification of Inertial Profiler Systems* (*1*), five test sections on the uphill (westbound) lane of the facility are used to avoid having to measure under braking conditions. AASHTO R-56 requires the sections for the test comparisons to be one-tenth of a mile long (528 feet). The first two test sections are located in the JRCP and CRCP pavements. The rest of the test sections are over Hot-mix Asphalt concrete pavements (table 5), and are made up of two different Smart Road sections to get to 528 feet.

Table 5 Smart Road section pavement surfaces

<table>
<tr><th>Section</th><th>Name</th><th>Surface Mix Type</th><th>Length (feet)</th><th>MPD Uphill (mm)</th><th>Test Section No.</th><th>Length (feet)</th></tr>
<tr><td>1</td><td>Loop</td><td>SMA 19.0</td><td>N/A</td><td>0.80</td><td></td><td></td></tr>
<tr><td>2</td><td>A</td><td>SM-12.5D</td><td>347</td><td>0.89</td><td rowspan="2">5</td><td rowspan="2">528</td></tr>
<tr><td>3</td><td>B</td><td>SM-9.5D</td><td>289</td><td>1.01</td></tr>
<tr><td>4</td><td>C</td><td>SM-9.5E</td><td>292</td><td>0.79</td><td></td><td></td></tr>
<tr><td>5</td><td>D</td><td>SM-9.5A</td><td>407</td><td>0.70</td><td></td><td></td></tr>
<tr><td>6</td><td>E</td><td>SM-9.5D</td><td>268</td><td>N/A</td><td></td><td></td></tr>
<tr><td>7</td><td>F</td><td>SM-9.5D</td><td>302</td><td>N/A</td><td rowspan="2">4</td><td rowspan="2">528</td></tr>
<tr><td>8</td><td>G</td><td>SM-9.5D</td><td>304</td><td>N/A</td></tr>
<tr><td>9</td><td>H</td><td>SM-9.5D</td><td>292</td><td>N/A</td><td></td><td></td></tr>
<tr><td>10</td><td>I</td><td>SM-9.5A(h)</td><td>338</td><td>0.73</td><td></td><td></td></tr>
<tr><td>11</td><td>J</td><td>SM-9.5D</td><td>280</td><td>0.85</td><td></td><td></td></tr>
<tr><td>12</td><td>K</td><td>OGFC</td><td>302</td><td>1.80</td><td rowspan="2">3</td><td rowspan="2">528</td></tr>
<tr><td>13</td><td>L</td><td>SMA-12.5D</td><td>326</td><td>1.08</td></tr>
<tr><td>14</td><td>CRCP*</td><td>Tined</td><td>2,290</td><td>0.80</td><td>2</td><td>528</td></tr>
<tr><td>15</td><td>JRCP*</td><td>Grooved</td><td>591</td><td>N/A</td><td>1</td><td>528</td></tr>
</table>

* Both JRCP and CRCP sections were grounded, and the CRCP is also grooved, since January 2011.

Each of the test section wheel paths are marked every 10 feet with paint so that operators can align the profilers when traveling at the required speeds. Each test section has paint-marked lead-in distances of 150 feet starting across a one-inch high electrical rubber cable cord protector that was placed as an artificial bump to indicate the start of each of the lead-in sections. These bumps are intended to produce a spike in the profiles, which makes it possible to determine the exact location of the test sections during subsequent analysis. Traffic cones with reflective material are also placed next to each bump before the lead-in areas of each test section to help the profiler operators become aware of the beginning location and to align properly in the marked wheel paths.

The paint markings for the 150-foot lead-in areas were colored yellow, while the 528-foot test sections were colored green. A diagram of the profiler testing setup for each test section is shown in Figure 6.

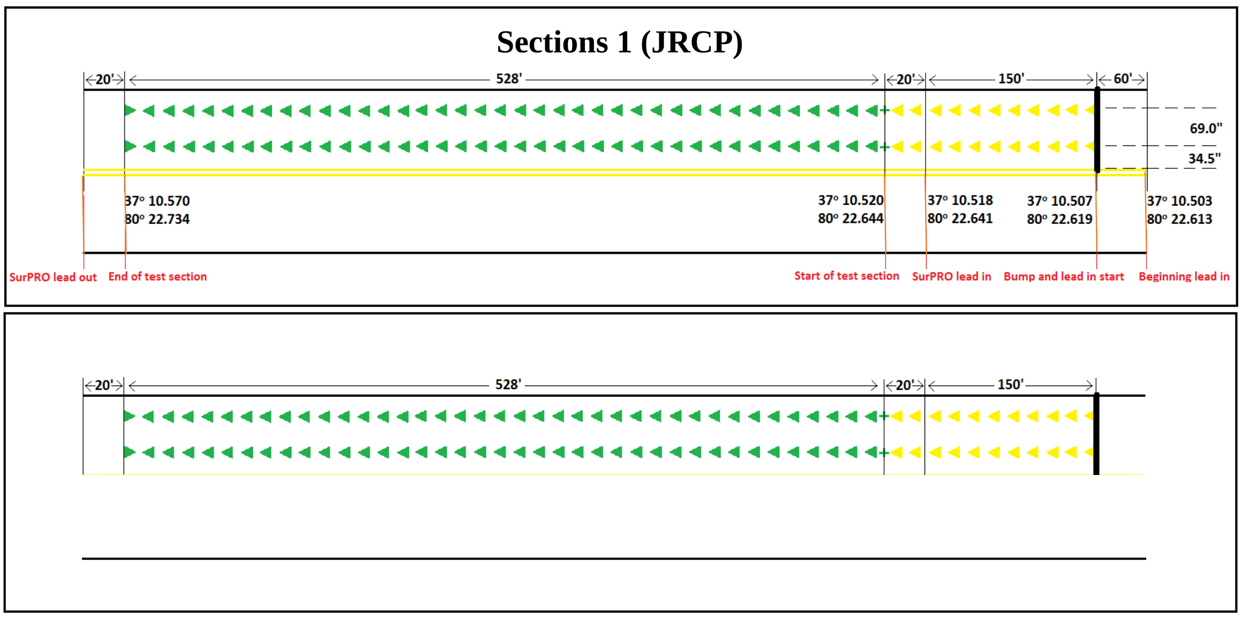


Figure 6 Smart Road profiler test section setup for 2015 Rodeo

VIII.7. Reference Data Collection

Reference Profilers

An ICC (International Cybernetics Corporation) SURPRO walking profiler was used to measure the reference profile of each of the five test section along the left and right wheel paths. The cross-correlation and the IRI results of the SURPRO profiler is presented in Table 6, which passed the standard (+98% CC) needed to be used as reference profile.

Table 6 Smart Road SURPRO walking profilers results for reference profiles

	IRI		Cross-Correlation	
	Left	**Right**	**Left**	**Right**
Section 1	105.4	84.3	99.0	98.9
Section 2	39.5	31.0	97.4	97.2
Section 3	128.3	126.4	98.5	98.4
Section 4	98.4	93.5	99.3	99.0
Section 5	141.2	124.9	97.8	98.3

High-speed Profilers

Twelve profilers were used to obtain measurements for comparison to the reference measurements made with the SURPRO device. Data was collected following the procedures mentioned in AASHTO R-56. Pre-test system calibration, including block, bounce, and distance calibrations, were also performed. Bounce tests were performed for each unit as recommended by each manufacturer (e.g., ICC, Dynatest, etc.). These tests are designed to detect any serious malfunctions outside the permissible limits during the normal operation of the height and accelerometer sensors.

All profilers collected profile data 10 times at a constant speed of 45 mph trying to avoid speed changes throughout the sections.

Profiler Results and Discussion

The analysis methods included in the Profile Viewing and Analysis (PROVAL) software, which was developed under the sponsorship of FHWA, were used to determine the ride statistics, repeatability, and reproducibility assessments for all data collected (*2*). The following is a brief description of the results.

Ride Statistics

IRI values of all profile runs for all test sections were computed using PROVAL. The averages of 10 runs from each profiler were computed. After all five sections were cropped from each profile, a 250 mm moving average filter was applied for the IRI computations to obtain the IRI for the Left Wheel Path (LWP) and Right Wheel Path (RWP) (*2*).

Figures 7 and 8 shows the IRI results in in/mile that were obtained from the LWP and RWP, respectively. Several observations can be made from the data shown on these two plots:

- The High Speed Profiler with a dual laser Gocator from PennDOT obtained the highest IRI values for both wheel paths.
- All the profilers produced an IRI almost similar to the reference profile in the sections, but in section 2 only 5 of 12 profilers acquired an IRI close to the Surpro.

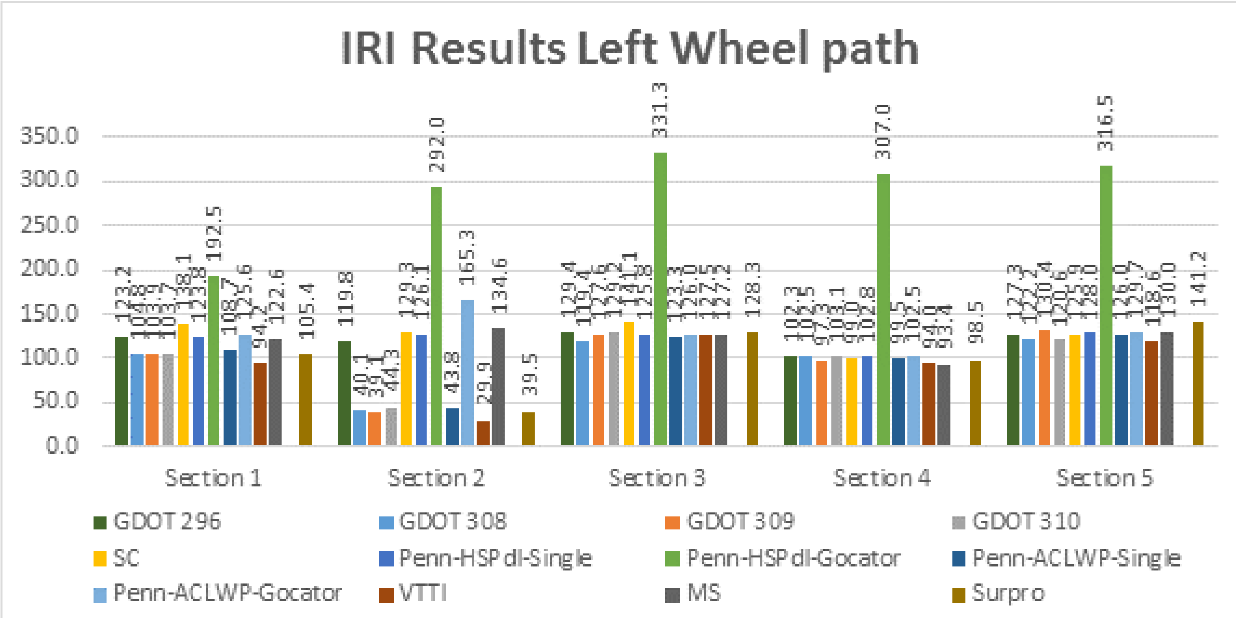


Figure 7 Left wheel path ride statistics IRI (in/mile)

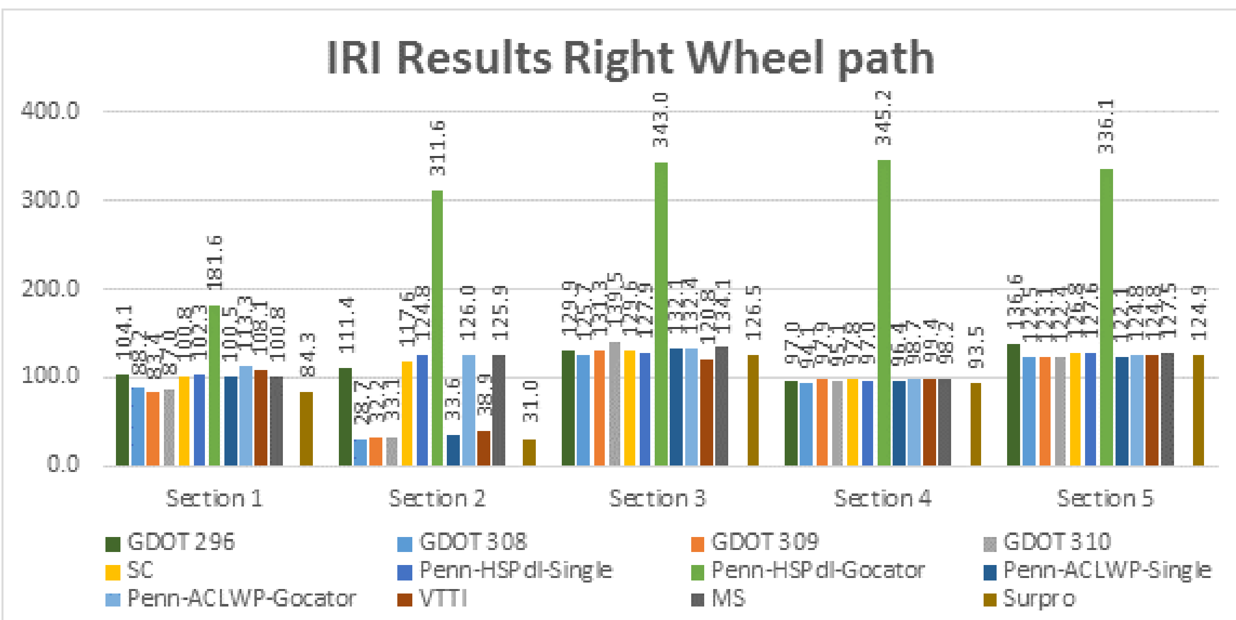


Figure 8 Right wheel path ride statistics IRI (in/mile)

Repeatability

Repeatability results illustrate how well each unit obtains the same profile measurements during each of the 10 runs. Cross-correlation was performed on the profile data to evaluate both profiler repeatability and reproducibility using the PROVAL software. For repeatability, AASHTO R-56 requires an average cross-correlation of at least 92% when each profile is compared with the remaining four to nine runs (90 comparisons). The repeatability results for each of the laser sensors are shown in table 6 for each test section. Red bold numbers indicate those that did not pass the repeatability criteria.

The repeatability results show that the measurement taken with the High Speed Profiler with a dual laser Gocator from PennDOT had a low repeatability in every section, which was the profiler with the highest IRI. Section 2 performed with the lowest repeatability compared to the other 4 sections.

Table 6 Average repeatability for all profiler units

Average Repeatability										
	Section 1		**Section 2**		**Section 3**		**Section 4**		**Section 5**	
Profiler	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
GDOT 296	88	80	17	14	92	94	93	92	93	95
GDOT 308	97	90	89	92	94	97	97	95	93	95
GDOT 309	96	97	70	89	96	95	94	93	88	89
GDOT 310	96	87	84	89	93	91	94	93	94	94
SC	64	82	18	14	61	94	90	91	89	88
Penn-HSPdl-Single	89	83	18	14	91	95	96	94	88	91
Penn-HSPdl-Gocator	46	33	13	13	20	20	22	15	25	24
Penn-ACLWP-Single	94	85	83	76	91	90	93	92	87	85
Penn-ACLWP-Gocator	85	79	16	13	90	89	92	90	83	83
VTTI	88	95	91	88	94	92	95	96	88	89
MS	89	84	15	15	92	90	93	93	80	85

Reproducibility

By following the same procedure as with the repeatability verification with the software PROVAL, the reproducibility results are obtained by comparing the cross-correlation reproducibility for each wheel path based on the SURPRO profiles and the 10 runs from each participant profiler. The results from the profiler certification (reproducibility) module are shown in Table 7.

Table 7 Average reproducibility cross-correlations for all profiler units at 45 mph with VT SURPRO

Average Reproducibility										
	Section 1		**Section 2**		**Section 3**		**Section 4**		**Section 5**	
Profiler	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
GDOT 296	79	64	13	7	90	93	91	90	53	75
GDOT 308	86	75	65	75	81	90	88	90	53	75
GDOT 309	86	82	71	83	93	91	92	88	57	76
GDOT 310	86	75	70	74	87	82	91	91	47	71
SC	54	55	13	6	54	82	77	75	49	67
Penn-HSPdl-Single	69	60	13	6	88	90	87	88	62	85
Penn-HSPdl-Gocator	36	26	4	2	14	14	10	8	15	14
Penn-ACLWP-Single	81	63	68	70	90	87	90	91	58	78
Penn-ACLWP-Gocator	71	54	8	5	91	88	89	89	59	80
VTTI	36	29	16	21	56	54	57	50	31	44
MS	69	56	10	5	86	83	84	84	58	78

According to AASHTO R-56, a profiler passes the reproducibility test if it has a cross-correlation value of more than 90% when compared with the respective reference profile. On section 3 and 4, the profiler 296 from GDOT was able to pass reproducibility verification for both wheel paths. Also in section 3 the profiler 309 from GDOT and in section 4 the profiler 310 from GDOT and the Artic Cat LWP Single from PennDOT manage to pass the verification of both wheel paths. In general, most profilers did not meet the requirement of a correlation of more than 90% when compared to the reference profiler. Once again the red bold numbers indicate those that did not pass the reproducibility criteria.

VIII.8. Conclusions

Friction

- On average, all locked-wheel skid testers seem to be measuring consistently similar numbers with the same variability.
- As is to be expected, there is a difference between the skid-numbers of the measurements depending on the tire used. Unexpectedly, most devices have varying friction numbers depending on the direction of travel going down or up the hill.
- Most of the calibrated devices actually improved their repeatability after their calibrations.

Profile

- The High Speed Profiler with a dual laser Gocator from PennDOT obtained IRI values of 100 in/mile or greater in every section compared to the reference profiler.
- 5 of 12 profilers obtained an IRI similar to the Surpro in section 2, but for the other 4 sections the IRI values were close to the reference profile.
- The repeatability results show that the High Speed Profiler with a dual laser Gocator from PennDOT had the lowest values.
- In the reproducibility test only the profiler 309 and 296 from GDOT was able to pass reproducibility verification for both wheel paths in section 3 and in section 4 was the profiler 296 and 310 from GDOT and the Artic Cat LWP Single from PennDOT.
- Most profilers in the reproducibility test do not meet the requirement of a correlation of more than 90% when compared to the reference profiler.
- The experience obtained in the use of the reference profiler SURPRO by all those who attended the training was positive. It allowed the users trained with the ability to set up calibration sites in their respective states.

VIII.9. Acknowledgments

The Consortium for Pavement Surface Properties has been made possible thanks to the contributions of the Virginia Transportation Research Council (VTRC), the Federal Highway Administration (FHWA), Georgia, Mississippi, Pennsylvania, South Carolina, and Virginia Departments of Transportation (DOT) and the Virginia Tech Transportation Institute (VTTI). Collaboration from the International Grinding and Grooving Association (IGGA), International Cybernetics Corporation (ICC), and WDM Limited is greatly appreciated. CSTI personnel collaborated with the data collection and processing for this report.

VIII.10. References

1. AASHTO, Standard Practice for Certification of Inertial Profiling Systems (PP49), The American Association of State Highway and Transportation Officials, Washington, D.C., 2007.
2. Chang, George, PROVAL Users Guide: Profile Viewing and Analysis Software, TRANSTEC, Austin, Texas, 2007.

IX. 2015 Annual Equipment Comparison Roundup at the Smart Road[9]

IX.1. Overview

"The regional pooled-fund project known as the Pavement Surface Properties Consortium is a research program focused on enhancing the level of service provided by the roadway transportation system through the optimization of pavement surface texture characteristics. The program was established in 2006 with support from the Federal Highway Administration (FHWA) and six state departments of transportation (DOTs): Connecticut, Georgia, Mississippi, Pennsylvania, South Carolina, and Virginia. The Consortium provides a practical mechanism to conduct research about pavement surface properties and explore their relationships with ride quality, friction, and noise. Complementing this effort is research focused on the review, testing, and evaluation of emerging technologies."

Various friction testers and profilers were assessed during the 2015 equipment roundup. The objective of this year rodeo was to harmonize the participant friction tester's and profiler's measurements.

IX.2. Introduction

The Pavement Surface Properties Consortium hosts an annual event every year in the summer at the Virginia Smart Road in order to evaluate and compare various types of highway friction and profile measuring equipment. The Departments of Transportation (DOT) of Connecticut, Georgia, Pennsylvania, South Carolina, Virginia and the International Grinding and Grooving Association (IGGA) came this year in the event called "The Surface Properties Rodeo". Six friction testers, eight high-speed and one light weight profilers, plus the SURPRO reference profiler, participated in the 2015 Rodeo equipment roundup.

Figure 1 High-speed Profilers participants in the 2015 Rodeo

[9] Prepared by Edgar de León Izeppi, Gerardo Flintsch, Kevin K. McGhee, Freddie Salado, and Kenneth Velez

IX.3. Purpose and Scope

The main objectives of the 2015 rodeo were as follow:

- Friction: Compare and evaluate the various friction testers' measurements, assessing the repeatability and reproducibility of the measurements, before and after calibration.
- Profiler: Compare the measurements of the laser profilers and the reference profiler using PROVAL and the International Roughness Index (IRI) of the test sections, to assess the repeatability and reproducibility of the measurements.

IX.4. Methods

Measurements for friction and profile were collected at the Virginia Smart Road. The procedure of data collection is explained in detail for each section of these measurements. A summary of the results and analysis is also provided in each section.

IX.5. Friction

Friction Data Collection

Friction measurements were collected on June 1st and 3rd, 2015, at the Virginia Smart Road. Six locked-wheel skid trailers (LWST) participated on the final day, five did on the first day, before calibrating. All of these devices took their measurements at 40 mph over 6 tests sections in both uphill and downhill directions on the same wheel-path. The tests with the LWST were performed in accordance with *ASTM E-274: Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire*. LWST measure the skid resistance of the paved surface and report a Skid Number (SN). The SN is the force required to slide the locked test tire at a stated speed, divided by the effective wheel load and multiplied by 100. LWST can use a smooth tire, as presented in the standard *ASTM E-524: Standard Specification for Standard Smooth Tire for Pavement Skid-Resistance Tests*, or a ribbed tire *ASTM E-501: Standard Specification for Standard Rib Tire for Pavement Skid-Resistance Tests*. Pennsylvania and Virginia run using a smooth tire while Connecticut, Georgia, IGGA and South Carolina use the ribbed tire (Table 1).

Table 1 Summary of the friction tests.

Unit	Type	Tire	Test Sections	Test Speed
CT skid trailer	Locked wheel	Ribbed	6	40 mph
PA skid trailer	Locked wheel	Smooth	6	40 mph
GA skid trailer	Locked wheel	Ribbed	6	40 mph
IGGA skid trailer	Locked wheel	Ribbed	6	40 mph
SC skid trailer	Locked wheel	Ribbed	6	40 mph
VA skid trailer	Locked wheel	Smooth	6	40 mph

Figure 2 below presents the layout of the test setup in the Smart Road in sections. The two lane 2.2 mile test track is composed of different types of Hot-Mix Asphalt (HMA) and Portland Cement Concrete (PCC) sections built with different texture types for testing purposes. The figure below shows the sections that were tested starting with HMA sections located in I, J, K, L and the PCC sections (PCC-2 and PCC-3) which are a tined JRCP (jointed reinforced concrete pavement) and a ground and grooved CRCP (continuously reinforced concrete pavement), respectively.

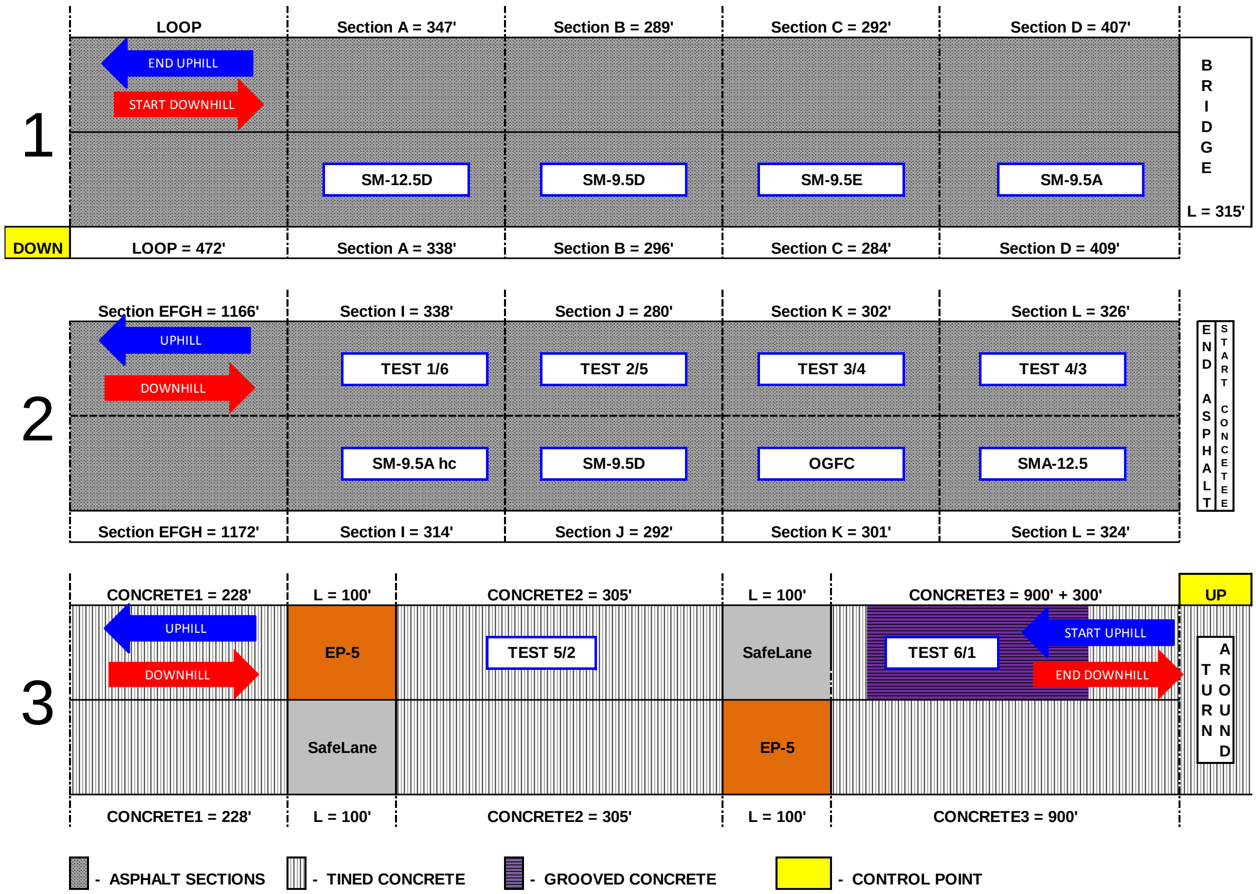


Figure 2 Friction test sections layout

Friction Results and Discussion

Plots of friction measurements taken downhill and uphill were prepared before and after the calibration conducted on each equipment calibrated. A summary of these results for all friction testers with the same tire are presented in Figure 3. A couple of devices malfunctioned after the calibration, so the plots represent only the averages of the devices that finished the comparison.

Figure 4 below presents the combined measurements of both tires on the sections tested with the ribbed and the smooth tires using the LWST. Notice that directionally the devices with ribbed tires had larger differences than those with smooth tires. As has been reported previously, the ribbed tires always report larger SN values than the smooth tires, and they are very similar in those sections with ample macrotexture such as the OGFC found on section K. On average, the difference of SN with these tires is around 10 SN.

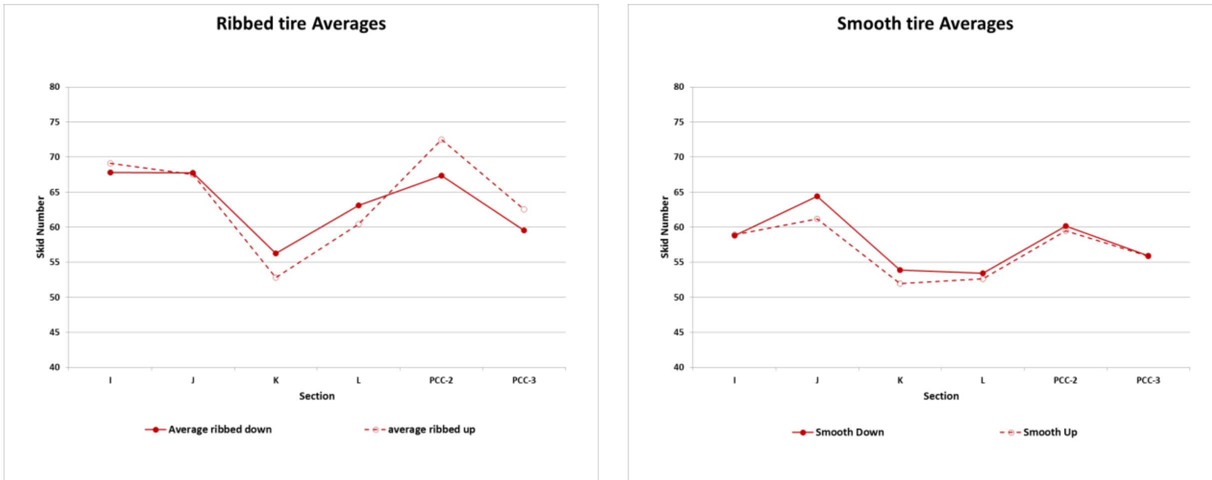


Figure 3 Individual Friction results with a) Ribbed and b) Smooth Tires

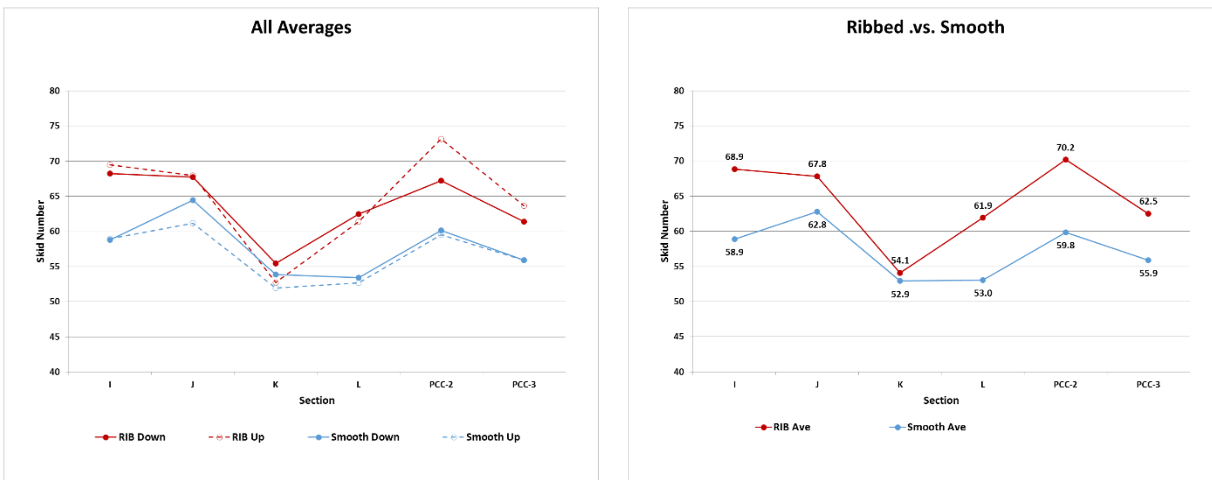


Figure 4 Friction results by a) Direction and b) Averaged with Ribbed and Smooth Tires

The general observations that can be made from the friction measurements:

- All of the five devices calibrated had lower standard deviations after the calibrations. Most devices with the same tire seemed to be following a similar trend; however, there are differences between the magnitudes of the measurements, depending on the tire, and the direction of the measurement (uphill or downhill).
- On average, all locked-wheel skid testers seem to be measuring consistently similar. If all measurements were to be done in the same direction, the standard deviations of all of the devices tested would be very close to the 2 SN recommended by the ASTM E274 standard, for all sections tested.
- During this year’s calibration, the consortium members discovered that calibrating the equipment is not necessarily a guarantee that the equipment is working correctly. All of the members will be made aware that it is very important to regularly check the output plots of the measurements to make sure the equipment is working correctly as specified in the ASTM standard.

IX.6. Profile

Profiler Data Collection

Longitudinal road profile measurements are summarized using the IRI. The IRI represents the accumulation of all vertical movements of a "standard" vehicle across a given length of road expressed in inches/mile (or mm/km). If the sum of these movements is large, the surfaces are usually rough and the ride will be uncomfortable. If the sum is small, travel is more comfortable.

Some of the agencies participating in the Consortium have started using the wide footprint lasers and others are still using the single-spot laser-based inertial profilers for measuring longitudinal profiles at highway speeds and then computing the IRI values. Every year the Rodeo intends to verify the profiler's correct operations with a profiler certification using the available guidelines and specifications that test the compliance of the repeatability and accuracy of the profilers of its members.

Test Sections

Based on the standard *AASHTO R-56: Certification of Inertial Profiler Systems* (*1*), five test sections on the uphill (westbound) lane of the facility are used to avoid having to measure under braking conditions. AASHTO R-56 requires the sections for the test comparisons to be one-tenth of a mile long (528 feet). The first two test sections are located in the JRCP and CRCP pavements. The rest of the test sections are over Hot-mix Asphalt concrete pavements (table 2), and are made up of two different Smart Road sections to get to 528 feet.

Table 2 Smart Road section pavement surfaces

<table>
<tr><th>Section</th><th>Name</th><th>Surface Mix Type</th><th>Length (feet)</th><th>MPD Uphill (mm)</th><th>Test Section No.</th><th>Length (feet)</th></tr>
<tr><td>1</td><td>Loop</td><td>SMA 19.0</td><td>N/A</td><td>0.80</td><td></td><td></td></tr>
<tr><td>2</td><td>A</td><td>SM-12.5D</td><td>347</td><td>0.89</td><td rowspan="2">5</td><td rowspan="2">528</td></tr>
<tr><td>3</td><td>B</td><td>SM-9.5D</td><td>289</td><td>1.01</td></tr>
<tr><td>4</td><td>C</td><td>SM-9.5E</td><td>292</td><td>0.79</td><td></td><td></td></tr>
<tr><td>5</td><td>D</td><td>SM-9.5A</td><td>407</td><td>0.70</td><td></td><td></td></tr>
<tr><td>6</td><td>E</td><td>SM-9.5D</td><td>268</td><td>N/A</td><td></td><td></td></tr>
<tr><td>7</td><td>F</td><td>SM-9.5D</td><td>302</td><td>N/A</td><td rowspan="2">4</td><td rowspan="2">528</td></tr>
<tr><td>8</td><td>G</td><td>SM-9.5D</td><td>304</td><td>N/A</td></tr>
<tr><td>9</td><td>H</td><td>SM-9.5D</td><td>292</td><td>N/A</td><td></td><td></td></tr>
<tr><td>10</td><td>I</td><td>SM-9.5A(h)</td><td>338</td><td>0.73</td><td></td><td></td></tr>
<tr><td>11</td><td>J</td><td>SM-9.5D</td><td>280</td><td>0.85</td><td></td><td></td></tr>
<tr><td>12</td><td>K</td><td>OGFC</td><td>302</td><td>1.80</td><td rowspan="2">3</td><td rowspan="2">528</td></tr>
<tr><td>13</td><td>L</td><td>SMA-12.5D</td><td>326</td><td>1.08</td></tr>
<tr><td>14</td><td>CRCP*</td><td>Tined</td><td>2,290</td><td>0.80</td><td>2</td><td>528</td></tr>
<tr><td>15</td><td>JRCP*</td><td>Grooved</td><td>591</td><td>N/A</td><td>1</td><td>528</td></tr>
</table>

* Both JRCP and CRCP sections were grounded, and the CRCP is also grooved, since January 2011.

Each of the test section wheel paths are marked every 10 feet with paint so that operators can align the profilers when traveling at the required speeds. Each test section has paint-marked lead-in distances of 150 feet starting across a one-inch high electrical rubber cable cord protector that was placed as an artificial bump to indicate the start of each of the lead-in sections. These bumps are intended to produce a spike in the profiles, which makes it possible to determine the exact location of the test sections during subsequent analysis. Traffic cones with reflective material are also placed next to each bump before the lead-in areas of each test section to help the profiler operators become aware of the beginning location and to align properly in the marked wheel paths (figure 5).

Figure 5 Installation of one-inch high electrical rubber cable cord

The paint markings for the 150-foot lead-in areas were colored yellow, while the 528-foot test sections were colored green. A diagram of the profiler testing setup for each test section is shown in Figure 6.

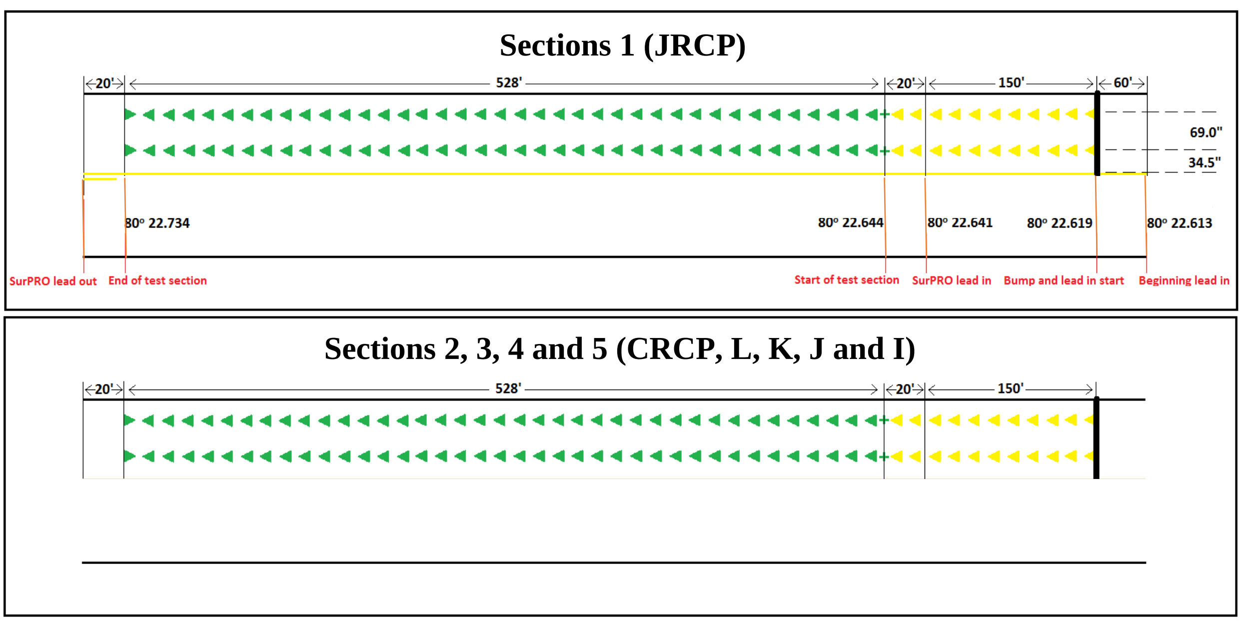


Figure 6 Smart Road profiler test section setup for 2015 Rodeo

Reference Data Collection

Reference Profilers

An ICC (International Cybernetics Corporation) SURPRO walking profiler was used to measure the reference profile of each of the five test section along the left and right wheel paths. The cross-correlation and the IRI results of the SURPRO profiler is presented in Table 3.

Table 3 Smart Road SURPRO walking profilers results for reference profiles

Section	**IRI**		**Cross-Correlation**	
	Left	**Right**	**Left**	**Right**
Section 1	105.4	84.3	99.0	98.9
Section 2	39.5	31.0	97.4	97.2
Section 3	128.3	126.4	98.5	98.4
Section 4	98.4	93.5	99.3	99.0
Section 5	141.2	124.9	97.8	98.3

High-speed Profilers

Nine profilers were used to obtain measurements for comparison to the reference measurements made with the SURPRO device. Data was collected following the procedures mentioned in AASHTO R-56. Pre-test system calibration, including block, bounce, and distance calibrations, were also performed. Bounce tests were performed for each unit as recommended by each manufacturer (e.g., ICC, Dynatest, etc.). These tests are designed to detect any serious malfunctions outside the permissible limits during the normal operation of the height and accelerometer sensors.

All profilers then collected profile data 10 times at a constant speed of 45 mph trying to avoid speed changes throughout the sections.

IX.7. Profiler Results and Discussion

The analysis methods included in the Profile Viewing and Analysis (PROVAL) software, which was developed under the sponsorship of FHWA, were used to determine the ride statistics, repeatability, and reproducibility assessments for all data collected (*2*). The following is a brief description of the results.

Ride Statistics

IRI values of all profile runs for all test sections were computed using PROVAL. The averages of 10 runs from each profiler were computed. After all five sections were cropped from each profile, a 250 mm moving average filter was applied for the IRI computations to obtain the IRI for the Left Wheel Path (LWP) and Right Wheel Path (RWP) (*2*). Figures 7 and 8 shows the IRI results in in/mile that were obtained from the LWP and RWP, respectively.

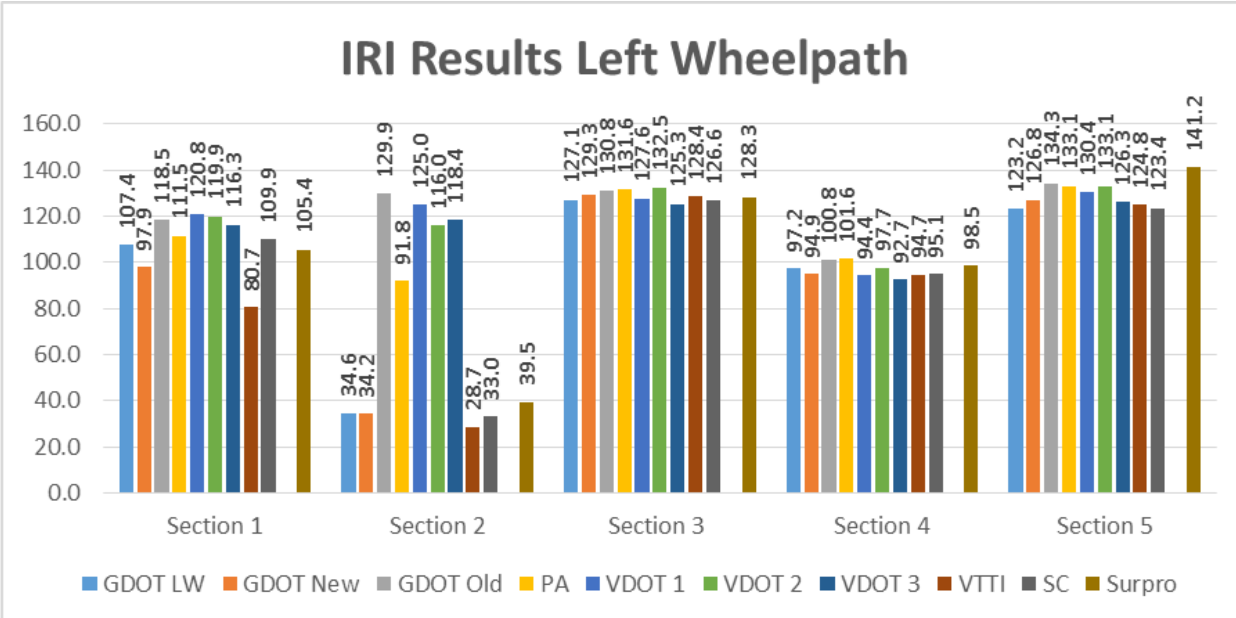


Figure 7 Left wheel path ride statistics IRI (in/mile)

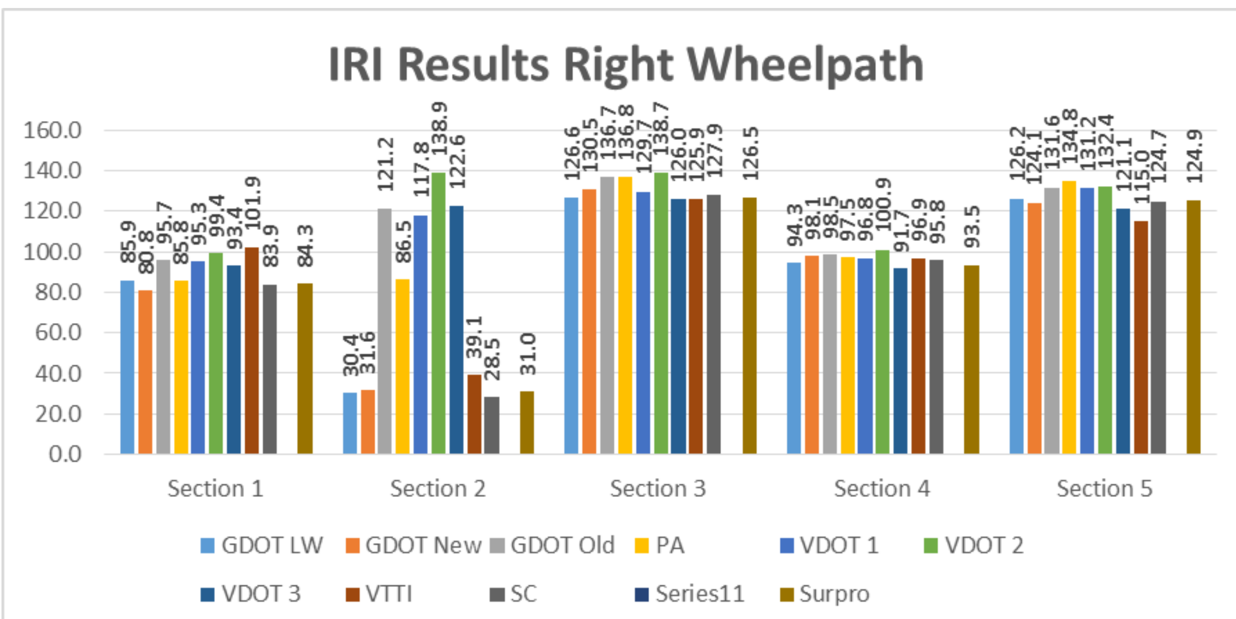


Figure 8 Right wheel path ride statistics IRI (in/mile)

Several observations can be made from the data shown on these two plots:

- All sections report a higher LWP IRI than the RWP IRI.
- In sections 1, most of the variability can be identified to the profiler from VTTI which has very low values on the LWP measurements, but that is not the case for the RWP where the values were similar to most profilers. Most all other profilers gave similar results.
- In section 2, the ground and grooved CRCP shows that only the four profilers with wide footprints (LW-GA, New-GA, VTTI, and SC) are similar to the SURPRO.
- In the HMA sections (3, 4, and 5), almost all profilers have the same value of IRI as the SURPRO, on both wheel paths. On section 5, the SURPRO has the only very high value reported by the SURPRO compared to the rest of the profilers.

Repeatability

Repeatability results illustrate how well each unit obtains the same profile measurements during each of the 10 runs. Cross-correlation was performed on the profile data to evaluate both profiler repeatability and reproducibility using the PROVAL software. For repeatability, AASHTO R-56 requires an average cross-correlation of at least 92% when each profile is compared with the remaining four to nine runs (90 comparisons). The repeatability results for each of the laser sensors are shown in table 4 for each test section. Red bold numbers indicate those that did not pass the repeatability criteria.

The repeatability results shows that only for section 3, the LWP and RWP meet the requirements of the AASHTO R56 with a value greater than 92%. This could be due to a minor change when the data was taken that does not imply that the profiler data does not correlate with the data from the reference profiler. As is the case in most Single-Spot profilers, the worse repeatability is found in section 2 and only the four wide footprint profilers meet the requirement, not so the other profilers which obtained lower repeatability.

Table 4 Average repeatability for all profiler units

Average Repeatability										
	Section 1		**Section 2**		**Section 3**		**Section 4**		**Section 5**	
Profiler	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
VTTI	99	99	95	91	97	98	97	98	95	93
GDOT New	97	97	85	92	98	97	96	94	95	93
GDOT Old	94	94	20	20	94	92	91	91	78	89
GDOT LW	41	42	88	95	97	97	98	97	97	97
PA	94	94	25	22	93	91	93	92	81	81
SC	98	98	88	96	99	98	98	98	97	97
VDOT 1	92	91	23	18	94	93	92	91	82	86
VDOT 2	94	93	22	18	96	92	94	91	88	86
VDOT 3	54	53	19	18	94	92	92	91	87	82

Reproducibility

By following the same procedure as with the repeatability verification with the software PROVAL, the reproducibility results are obtained by comparing the cross-correlation reproducibility for each wheel path based on the SURPRO profiles and the 10 runs from each participant profiler. The results from the profiler certification (reproducibility) module are shown in Table 5.

Table 5 Average reproducibility cross-correlations for all profiler units at 45 mph with VT SURPRO

Average Accuracy 40 mph										
	Section 1		Section 2		Section 3		Section 4		Section 5	
Profiler	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
VTTI	49	51	17	19	58	56	51	58	32	46
GDOT New	68	68	59	79	94	89	90	83	59	73
GDOT Old	72	68	11	6	88	83	89	87	69	79
GDOT LW	87	81	65	87	95	95	96	96	59	86
PA	88	85	24	11	91	87	92	91	58	67
SC	73	65	63	80	87	83	82	83	62	78
VDOT 1	70	59	13	5	84	82	78	81	59	72
VDOT 2	72	61	12	5	92	81	91	81	61	73
VDOT 3	72	59	13	6	84	82	80	82	54	72

According to AASHTO R-56, a profiler passes the reproducibility test if it has a cross-correlation value of more than 90% when compared with the respective reference profile. On most sections, only the Light Weight profiler from GDOT was able to pass reproducibility verification for both wheel paths located in section 3 and 4. The profiler from the PADOT met the requirement for section 4 and the LWP located in section 3. In general, most profilers did not meet the requirement of a correlation of more than 90% when compared to the reference profiler. Once again the red bold numbers indicate those that did not pass the reproducibility criteria.

IX.8. Conclusions

Friction

- Most measurements of the DOT's LWST with a smooth or ripped tire seem to be following a similar trend. As is to be expected, there is a difference between the magnitudes of the measurements, depending on the tire. Unexpectedly, some devices have varying friction SN depending on the direction of travel in the hill.
- For the LWST with ribbed tires, the general post calibration trend was found to be very similar. The trends for the smooth tire, were not very clear because there were only two devices running with this tire.

Profile

- The walking profiler SURPRO showed differences in values compared to the profilers in each section. In section 1 the SURPRO obtained an IRI in the LWP/RWP of 105/84 in/mile while the other profilers obtained greater values.
- The repeatability results shows that only section 3, allows the profilers to meet the requirements of the AASHTO R56 with a correlation greater than 92% when compared to the reference profile.
- In the reproducibility test only one lightweight profiler was able to pass reproducibility verification for both wheel paths in section 3 and 4.
- Most of the results in the reproducibility test do not meet the requirement of a correlation of more than 90% when compared to the reference profiler.

IX.9. Acknowledgments

The Consortium for Pavement Surface Properties has been made possible thanks to the contributions of the Virginia Transportation Research Council (VTRC), the Federal Highway Administration (FHWA), Connecticut, Georgia, Mississippi, Pennsylvania, South Carolina, and Virginia Departments of Transportation (DOT) and the Virginia Tech Transportation Institute (VTTI). Collaboration from the International Grinding and Grooving Association (IGGA), International Cybernetics Corporation (ICC), and WDM Limited is greatly appreciated. CSTI personnel collaborated with the data collection and processing for this report.

IX.10. References

1. AASHTO, Standard Practice for Certification of Inertial Profiling Systems (PP49), The American Association of State Highway and Transportation Officials, Washington, D.C., 2007.
2. Chang, George, PROVAL Users Guide: Profile Viewing and Analysis Software, TRANSTEC, Austin, Texas, 2007.

X. Summary of Phase I Outcomes

X.1. Reports:

1. Flintsch, G.W., and McGhee, K.K, de León Izeppi, E.D., and Najafi, S., *The Little Book of Tire Pavement Friction, Version 1.0*, September 2012.
2. de León Izeppi, E.D., Flintsch, G.W., and McGhee, K.K, *Field Performance of High-Friction Surface*, Virginia Transportation Research Council,, VTRC 10-CR6, , Jun 2010, Charlottesville, VA, 28 pp.

X.2. Peer-reviewed journal and conference papers produced based on the consortium studies:

1. Mogrovejo, D., Flintsch, G.W., Katicha, S.W., de León Izeppi, E.D., and McGhee, K.K., "Enhancing Pavement Surface Macrotexture Characterization by Using the Effective Area for Water Evacuation," *Journal of the Transportation Research Board* (Paper No. 16-1834, recommended for publication), **In Press**.

2. Najafi, S., Flintsch, G.W., and Khalleghianc, S., "Fuzzy logic inference-based Pavement Friction Management and real-time slippery warning systems: A proof of concept study," *Accident Analysis & Prevention*, 2016, Vol 90, pp 41-49,
doi: 10.1016/j.aap.2016.02.007, published online.

3. Najafi, S., Flintsch, G.W., de León Izeppi*, E., McGhee, K., Katicha*, S., "Evaluation of Repeatability and Reproducibility of Continuous Friction Measuring Equipment using Cross-Correlation," *International Journal of Pavement Engineering*
doi: 10.1080/10298436.2015.1095908, published online.

4. Najafi, S., Flintsch, G.W., and Medina, A., "Linking Roadway Crashes and Tire–Pavement Friction: A Case Study," Technical Note, *International Journal of Pavement Engineering*, 2015, doi: 10.1080/10298436.2015.1039005, published online.

5. Katicha, S.W., Mogrovejo, D.E., Flintsch, G.W., and de León Izeppi, E.D. "Adaptive Spike Removal Method for High Speed Pavement Macrotexture Measurements by Controlling the False Discovery Rate," *Journal of the Transportation Research Board*, 2015, vol. 2525, pp. 100-110
doi: http://dx.doi.org/10.3141/2525-11.
6. Mogrovejo, D.E., Flintsch, G.W., de León Izeppi, E.D., and McGhee, K.K. "Tire-Pavement Noise Evaluation and Equipment Comparison Using On Board Sound Intensity Methodology over Several Pavement Surfaces in Virginia," 2014, *Journal of the Transportation Research Board*, vol. 2403, pp. 17-27.
7. Evangelisti, A., Katicha, S., de Leon, E., Flintsch, G.W., D'Apuzzo, M., Nicolosi, V., "Measurement Error Models (MEM) regression method to Harmonize Friction Values from Different Skid Testing Devices," *Transport Research Arena*, Apr 14-17, 2014, Paris, France.
8. D'Apuzzo, M., Evangelisti, A., de León Izeppi, E.D., Flintsch, G.W., Estimation of Pavement Macrotexture from Hot-Mix Asphalt Properties," *17th International Road Federation World Meeting & Exhibition*, Nov 10-14, 2013, Riyadh, Kingdom of Saudi Arabia.
9. Najafi, S., Flintsch, G.W., de León, E., McGhee, K.K, "Assessment of Operational Characteristics of Continuous Friction Measuring Equipment (CFME)," *International Journal of Pavement Engineering*, 2013, Vol. 14(8), pp 706-714, Taylor & Francis, DOI: 10.1080/10298436.2012.667097.

10. de León Izeppi, E., Flintsch, G.W., and McGhee, K.K. “Effect of Water, Speed, and Grade on Continuous Friction Measurement Equipment (CFMEs),” ASTM STP 1555 *Pavement Performance: Current Trends, Advances, and Challenges*, 2013 (Choubane, B., Editor).

11. Mogrovejo, D.E., Flintsch, G.W., de León Izeppi, E.D., and McGhee, K.K. “Effect of Air Temperature and Vehicle Speed on Tire/Pavement Noise Measured with On-Board Sound Intensity Methodology,” paper 13-3765, *92nd Annual Meeting of the Transportation Research Board*, Jan 13-17, 2013, Washington, DC.

12. Zhao, G., Flintsch, G.W., “Comparative Analysis on Promising Algorithms for Pavement Homogeneous Segmentation,” paper 13-4650, *92nd Annual Meeting of the Transportation Research Board*, Jan 13-17, 2013, Washington, D.C.

13. De León, E., Flintsch, G.W., McGhee, K.K., “Limits of Agreement Method for Comparing Pavement Friction Measurements,” *Journal of the Transportation Research Board*, 2012, vol. 2306, pp. 188-195.

14. Fuentes, L.G., de León, E., Flintsch, G.W., Martinez, G., “Determination of Pavement Macrotexture Limit For Use in The International Friction Index (IFI) Mode,” *Journal of the Transportation Research Board*, 2012, vol. 2306, pp. 138-143.

15. de León Izeppi, E.D., Flintsch, G.W., Archilla, A.R., Sequeira, W., “Data Processing and Analysis Software for Continuous Friction Measurement Equipment,” *Journal of the Transportation Research Board*, 2011, TRR 2227, pp. 163-170.

16. El Gendy, A., Shalaby, A, Saleh, M, Flintsch, G.W., “Stereo-vision applications to reconstruct the 3D texture of pavement surface,” *International Journal of Pavement Engineering*, 2011, Vol. 12(3), pp. 263-273.

17. Flintsch, G.W., de León Izeppi, E., Saleh, H, “Infrared Stereo Vision for Pavement Texture Analysis,” *First T&DI Congress – Integrated Transportation and Development for a Better Tomorrow* (presentation only), Mar 13-16, 2011, Chicago, IL.

18. Najafi, S., Flintsch, G.W., de León, E.D., McGhee, K.K., “Implementation of Cross-Correlation to Compare Continuous Friction Measuring Equipment,” paper 11-2083, *90th Annual Meeting of the Transportation Research Board*, Jan 23-27, 2011, Washington, DC.

19. Saleh, M., Flintsch, G.W., de León, E.D., McGhee, K.K., Abbott, A.L., “Pavement Texture Analysis Using Infrared Stereo Vision,” paper 11-2739, *90th Annual Meeting of the Transportation Research Board*, Jan 23-27, 2011, Washington, DC.

20. Flintsch, G.W., de León Izeppi, E.D., McGhee, K.K., Najafi[*], S., “Speed Adjustment Factors for Locked-Wheel Skid Trailer Measurements,” *Journal of the Transportation Research Board*, 2010, TRR 2155, pp. 117-123.

21. Flintsch, G.W., de León Izeppi, E.D., McGhee, K.K., Shetty, S.S., “Profiler Certification Process at the Virginia Smart Road, paper 10-2513, *89th Annual Meeting of the Transportation Research Board*, Jan 10-14 2010, Washington, DC.

22. Flintsch, G.W., de León Izeppi, E.D., McGhee, K.K., Roa, J.A., “Review of High-Friction Surface Technologies: Constructability and Field Performance,” paper 10-2072, *89th Annual Meeting of the Transportation Research Board*, Jan 10-14 2010, Washington, DC.

23. Flintsch, G.W., de León, E.D., McGhee, K.K., Roa, J.A., “ “Field Performance Evaluation of High-Friction Surfaces,” International Seminar, *Maintenance Techniques to Improve Pavement Performance*, World Road Association (PIARC), Aug 24-26, 2009, Cancun, Mexico.

24. de León, E.D., Flintsch, G.W., Saleh, M.I., McGhee, K.K., “Stereo Vision Application for Macrotexture Measurement,” scheduled for presentation at the *Sixth International Conference on Maintenance and Rehabilitation of Pavements and Technological Control (MAIREPAV6)*, Jul 8-10 2009, Torino, Italy.

25. de León Izeppi, E., Flintsch, G.W., Saleh, M., and McGhee, K.K., "Area-Based Macrotexture Measurements: A Stereo Vision Approach." Paper 09-3067, *88th Meeting of the Transportation Research Board*, Jan 2009, Washington, DC (CD-ROM).

26. Flintsch, G.W., de León, E., Izeppi, Roa, J., McGhee, K.K., and Swanlund, M., "Evaluation of the International Friction Index Coefficients for Various Devices," *6th Symposium on Pavement Surface Characteristics*, *SURF 2008*, October 20-22, Portoroz, Slovenia (CD-ROM)..

27. Flintsch, G.W., de León, E., Izeppi, Saleh, M., McGhee, K.K., and Swanlund, M., "Area-Based Macrotexture Measurements using Stereo Vision," *6th Symposium on Pavement Surface Characteristics, SURF 2008*, October 20-22, Portoroz, Slovenia (CD-ROM).

28. Trifirò, F., Flintsch, G.W., Guerrera, G., de León E. and McGhee, K.K., "Comparison of Friction Measuring Devices and Preliminary Evaluation of the International Friction Index Coefficients," paper 08-1816, 87th *Annual Meeting of the Transportation Research Board*, Jan. 13, 2008 , Washington, DC (CD-ROM).

X.3. Publications from other projects that used data from the consortium (not a comprehensive list):

29. McGhee, K.K., de León Izeppi, E.D., Mogrovejo*, D.E., and Flintsch, G.W., "Virginia "Quieter" Pavement Demonstration Program," **Journal of the Transportation Research Board** (Paper No. 16-3833, recommended for publication), **In Press**.

30. Katicha, S.W., El Khoury, J., and Flintsch, G.W. "Assessing the effectiveness of probe vehicle acceleration measurements in estimating road roughness," *International Journal of Pavement Engineering*, 2015, DOI: 10.1080/10298436.2015.1014815, **In Press**.

31. Bryce, J., Katicha, S., Flintsch, G.W., Sivaneswaran, N., Santos, J. "Probabilistic Lifecycle Assessment as a Network-Level Evaluation Tool for the Use and Maintenance Phases of Pavements." *Journal of the Transportation Research Board*, 2015, vol. 2455 (1), pp. 44-53.

32. Fuentes, L.G., Flintsch, G.W., de León Izeppi, E.D., "Evaluation of the Use of the International Friction Index on Skid Data obtained using Friction Models, *Journal of Testing and Evaluation*, Nov. 2014, Vol. 42(6), DOI: 110.1520/JTE2013006.

33. Bryce, J., Joao Santos, Gerardo Flintsch, Samer Katicha, Kevin McGhee, and Adelino Ferreira, 2014. "Analysis of Rolling Resistance Models to Analyze Vehicle Fuel Consumption as a Function of Pavement Properties." *12th International Conference on Asphalt Pavements*, Kim, R. (ed.), June 2014, pp. 263-273. Taylor and Francis Group: London

34. Viner, H., Hargreaves, D., Dunford, A., Nesnas, K., Parry T., and Flintsch, G.W., "Development of a Prediction Model for Splash and Spray," proceedings of the *7th Symposium on Pavement Surface Characteristics* (SURF 2012), Sep. 18-21, 2012, Norfolk, VA

35. Tang, L., Flintsch, G.W., and Viner, H., "Exposure Model For Predicting Splash and Spray," *Proceedings of the 7th Symposium on Pavement Surface Characteristics* (SURF 2012), Sep. 18-21, 2012, Norfolk, VA.

36. Flintsch G.W., Williams, B., Gibbons, R., Viner, H., "Assessment of the Impact of Splash and Spray on Road Users - Controlled Experiment Results," *Journal of the Transportation Research Board*, 2012, vol. 2306, pp. 151-160.

37. Flintsch, G.W., Valeri, S., Katicha, S.W., de Leon, E.D., Medina-Flintsch, A., "Pilot Demonstration of the Use Probe Vehicle Dynamic Signatures to Measure Road Smoothness," *Journal of the Transportation Research Board*, 2012, vol. 2304, pp. 158-165.

X.4. Other presentations based on the results of the consortium:

38. de León Izeppi E., Toom, P., "Achieving High Correlations of Inertial Profilers with Reference Profilers at the Smart Road,: Pavement Evaluation 2014, Blacksburg, VA, Sept 15-18, 2014.

39. Flintsch, G.W., "Some Lessons Learned from Surf3ace Properties Research at the Virginia Smart Road," **2013 ASTM H.W. Kummer Lecture**, *ASTM Committee E17 on Vehicle - Pavement Systems*, Jacksonville, FL, Dec 10, 2013.

40. Flintsch, G.W. "Using Profile Data for Supporting Asset Management Decisions," invited presentation, *1st European Road Profiler User Group Meeting*, Copenhagen, Denmark, Sep 10-12, 2013.

41. S. Katicha, G.W. Flintsch, "Use of Probe Vehicles to Measure Road Ride Quality," *Road Profiler User Group Meeting*, San Antonio, TX, Sep. 16 to 19, 2013.

42. E. de León Izeppi, G.W. Flintsch, "Profiler Certification Process at the Virginia Smart Road," *Road Profiler User Group Meeting*, San Antonio, TX, Sep. 16 to 19, 2013.

43. de León, E.D., Flintsch, G.W., "Continuous Friction Measuring, Equipment (CFME) Loan Program: GripTester and DYNATEST HFT," *Pavement Evaluation 2010*, Roanoke, VA, Oct 24-26, 2010.

44. Najafi, S., Flintsch, G.W., de León, E.D., "Performance Characteristics of Continuous Friction Measurement Equipment (CFME)," *Pavement Evaluation 2010*, Roanoke, VA, Oct 24-26, 2010.

45. de León, E.D., Flintsch, G.W., "Continuous Friction Measuring, Equipment (CFME) Loan Program: GripTester and DYNATEST HFT," *Pavement Evaluation 2010*, Roanoke, VA, Oct 24-26, 2010.

46. Najafi, S., Flintsch, G.W., de León, E.D., McGhee, K.K., "Speed Adjustment Factors for the Locked-wheel Skid Trailer," *The 21st Annual Road Profiler Users' Group Meeting*, Dec. 9-11, 2009, Atlanta, GA.

47. Shetty, S.S., Flintsch, G.W., de León Izeppi, E.D., McGhee, K.K., "Preliminary Results from the Profiler Certification Exercise at the Virginia Smart Road," *The 21st Annual Road Profiler Users' Group Meeting*, Dec. 9-11, 2009, Atlanta, GA.