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16. Abstract

This project aims to establish the impact of recent changes in profiling technology on TxDOT's implementation of the Department's Item 585 and SP247-011 ride specifications. Of particular importance to this research is verification of the ride statistics and defect locations determined from profile measurements with the traditional single-point and newer wide-footprint lasers. This verification would require ground truth measurements to establish benchmarks that may be used to identify where changes are required in the existing ride specifications and determine what these changes should be. Additionally, the project needs to evaluate the bump criteria in the existing Item 585 ride specification to establish an improved methodology that engineers can use to objectively determine the need for corrections based on measured surface profiles to fix defects that diminish road-user perception of ride quality.

To meet the research objectives, TxDOT divided the project into two phases. Phase I focuses on addressing the impact of new sensor technology on the Department's current ride specifications, while Phase II focuses on investigating relationships between the existing bump criteria and bump panel ratings. This report documents the research work conducted in Phase I. Based on findings from comparisons between international roughness indices determined from inertial and reference profile measurements, the report provides recommendations on using inertial profilers with different lasers for quality assurance testing of pavement smoothness.

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IMPACT OF CHANGES IN PROFILE MEASUREMENT TECHNOLOGY ON QA TESTING OF PAVEMENT SMOOTHNESS: TECHNICAL REPORT

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation. The engineer in charge of the project was Emmanuel Fernando, Texas P.E. #69614. The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

ACKNOWLEDGMENTS

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CHAPTER I. INTRODUCTION

The Texas Department of Transportation (TxDOT) has been implementing a smoothness specification based on inertial profile measurements since 2002 beginning with Special Specification (SS) 5880. Later, the current Item 585 ride specification of the 2004 standard specifications superseded SS 5880. For quality assurance (QA) testing, Item 585 includes pay adjustment schedules that are tied to the average international roughness index (IRI) computed at 528-ft intervals, and a localized roughness provision to locate defects on the final surface based on measured surface profiles. The acceptance criteria implemented in Item 585 are based on surface profile measurements collected with the traditional single-point lasers, which the department has been using over the years to monitor pavement smoothness over the state highway network. Since TxDOT began implementing its profile-based smoothness specification, developments in sensor technology have resulted in multi-point and wide-footprint lasers for non-contact height measurements. These developments came about in response to the observed effects of surface texture on IRIs determined from inertial profiles collected on certain textured pavements.

The effect of surface texture on IRIs was initially reported in a study conducted at Michigan for the American Concrete Paving Association. In this project, Karamihas and Gillespie (2002) reported findings from tests made of profiler repeatability on four different pavement sections consisting of a moderately rough (~150 inches/mile IRI) asphalt concrete pavement with a fine-aggregate surface, a new longitudinally tined jointed concrete pavement, an existing jointed concrete pavement with a broomed finish, and a new jointed concrete pavement with slightly variable transverse tining. After cross-correlating the IRI-filtered profiles from repeat runs made of the different profilers, they found that the longitudinally tined jointed concrete pavement section had the lowest IRI repeatability in terms of the average cross-correlation coefficient determined (for the most part) from three repeat runs of the profilers tested. The researchers noted that the very narrow footprint of the conventional lasers found in most profilers makes these sensors vulnerable to aliasing errors due to coarse texture or narrow dips at joints. Further, they explained that the slow drift of a height sensor with a narrow footprint into and out of the reservoirs on longitudinally tined concrete introduces significant content into the profile that would be misinterpreted as roughness. The researchers concluded that there is a need for a standard defining the most relevant method of filtering, averaging, or ignoring profile features with a duration equal to or shorter than the contact patch of a vehicle tire. Their conclusion essentially proposed a tire-bridging filter as a solution to address the effect of texture on IRI statistics computed from inertial profiles.

Since this Michigan study, equipment vendors have introduced profilers with non-contact height sensors having multiple lasers and wider footprints such as the sensors illustrated in Figures 1.1 to 1.3. Ames Engineering introduced its three-point (TriODS) laser system in 2003. Ames continued providing the TriODS as an option for its lightweight and high-speed portable inertial profilers until 2008 when the company decided to phase-out the TriODS in favor of LMI/Selcom's 100mm-wide Roline laser.

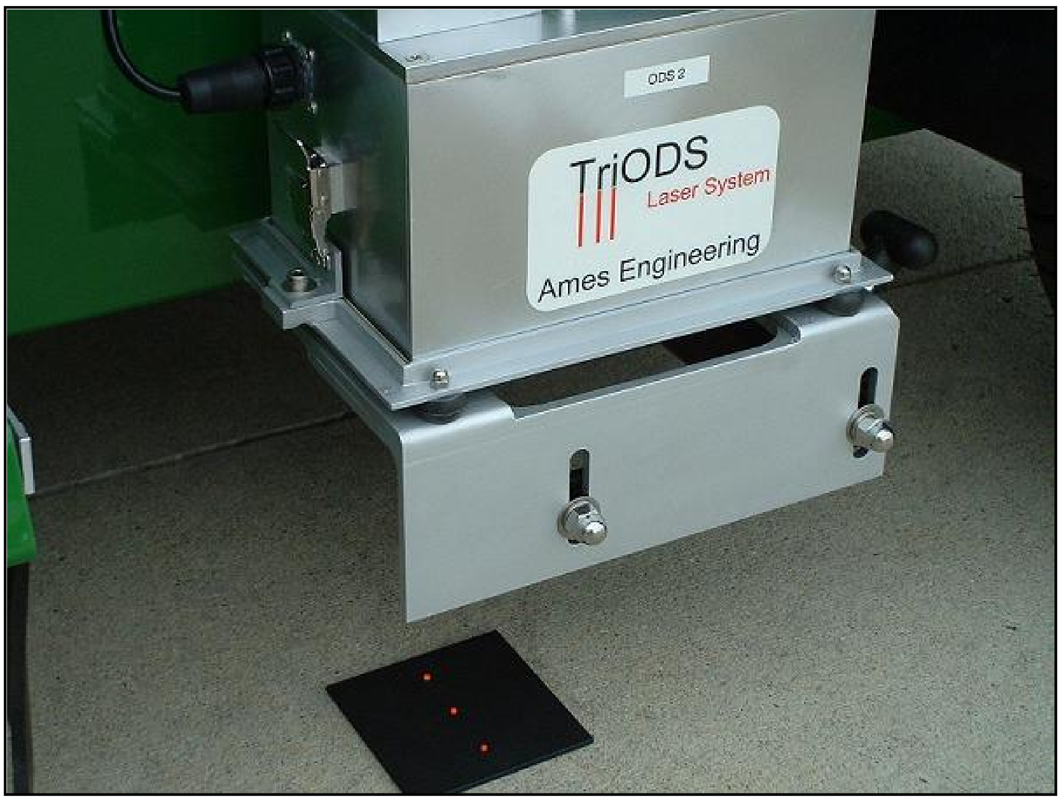

Figure 1.1. TriODS Three-Laser System from Ames Engineering.

Figure 1.2. 19mm Wide-Spot Laser from LMI/Selcom.

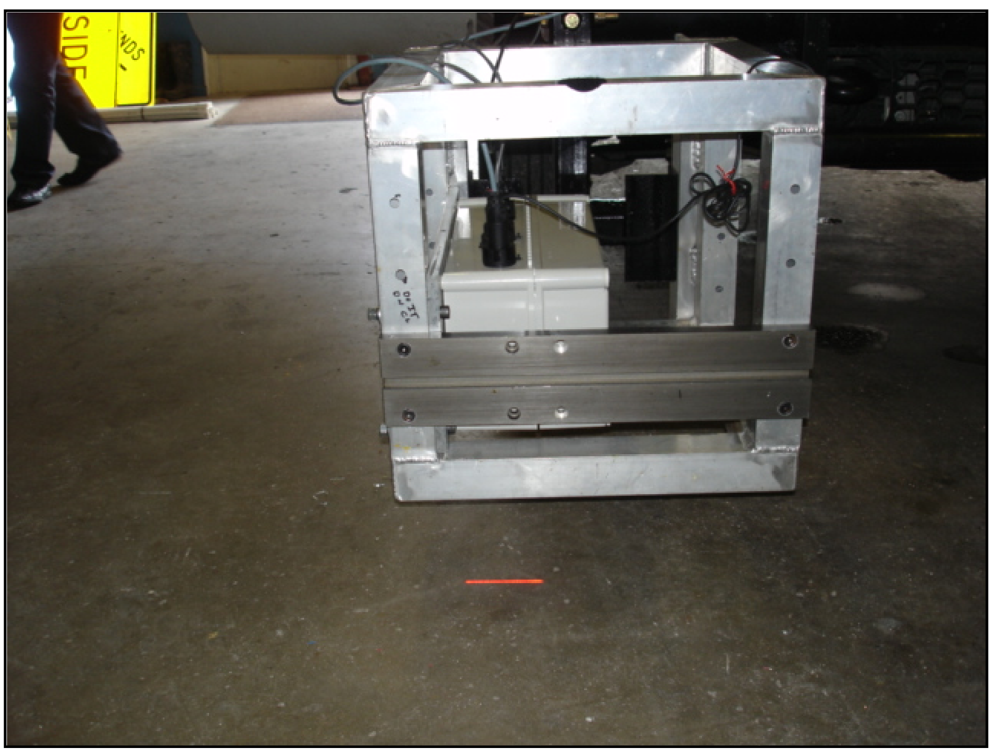

Figure 1.3. Roline 100mm-Wide Laser Footprint.

At the time of this report, five contractors and two service providers own and operate inertial profilers with Roline lasers for ride quality assurance testing in Texas. TriODS lasers are found on three Ames portable profilers owned and operated by two contractors and one service provider. The other currently certified inertial profilers used in Texas are either equipped with conventional single-point lasers or the 19mm LMI/Selcom wide-spot laser. Among these units, nine contractors and three service providers own and operate profilers equipped with conventional single-point lasers, while two profilers use the 19mm wide-spot lasers. TxDOT has 15 profilers with single-point lasers on the certified inertial profiler list.

RESEARCH OBJECTIVES

This research project aims to establish the impact of recent changes in profiling technology on TxDOT's implementation of the Department's Item 585 and SP247-011 ride specifications. Of particular importance to this research is verification of the ride statistics and defect locations determined from profile measurements with the traditional single-point and newer wide-footprint lasers. This verification would require ground truth measurements to establish benchmarks that may be used to identify where changes are required in the existing ride specifications and determine what these changes should be. Additionally, this research project aims to evaluate the bump criteria in the existing Item 585 ride specification to establish an improved methodology that engineers can use to objectively determine the need for corrections based on measured surface profiles to fix defects that diminish road-user perception of ride quality.

To accomplish these objectives, TxDOT divided the research project into two phases. Phase I addresses the impact of new sensor technology on TxDOT's implementation of the existing ride specifications, while Phase II investigates relationships between the existing bump criteria and bump panel ratings. This report documents the research work and findings from Phase I of the project.

RESEARCH WORK PLAN

To accomplish the Phase I objective, researchers carried out a comprehensive work plan that covered the following tasks:

- Gathered relevant information to assess the state-of-the-practice regarding applications of wide-footprint lasers for quality assurance testing of pavement smoothness.
- Developed a test plan for collecting data to compare profiles measured with different lasers and reference profile measurements.
- Set up portable profiling systems and conducted preliminary tests to verify the functional performance of these systems prior to field testing.
- Conducted a comparative evaluation of different lasers using test data on pavement sections that covered a wide range of pavement surfaces.
- Developed recommendations on the options available to TxDOT to accommodate the use of inertial profilers with wide-footprint lasers for quality assurance testing of pavement smoothness.

The following chapters of this report document each of the tasks conducted in Phase I of this research project.

CHAPTER II. LITERATURE REVIEW

Wide-footprint lasers have found increased interest within the paving industry in recent years. While the majority of certified profilers used in Texas are still equipped with conventional single-point lasers, profilers with Rolines and other similar wide-footprint lasers are expected to increase in number as older profilers are replaced and the road profiling community transitions to using wide-footprint lasers as the standard for inertial profile measurements. Given that historical inventory data and acceptance criteria on pavement smoothness are largely based on single-point laser measurements, several studies have been conducted to compare ride quality measurements between conventional single-point lasers and the non-contact height sensors introduced in recent years. The following sections document recent investigations conducted in this regard.

LABORATORY TESTS ON TEXTURED SPECIMENS

The road profile consists of long wavelengths with features such as hills, short wavelengths that are characteristic of bumps and dips, and much shorter wavelengths within the range of macro-texture features. The accelerometer is the primary sensor for measuring the lower frequency or longer wavelengths. The laser, on the other hand, measures the shorter wavelengths and is the sensor most affected by texture of the surface being measured. Thus, to investigate the effect of texture on ride quality determinations, its effect on laser measurements and the resulting calculations of pavement profile need to be studied.

In TxDOT project 0-4760, researchers from the Texas Transportation Institute (TTI) and the University of Texas at Arlington (UTA) conducted laboratory tests on specimens simulating different surface treatments using the test cart shown in Figure 2.1. For these tests, researchers positioned the laser above the specimen on a stand that is independent of the test cart. After the specimen is placed and secured onto the platter, the cart motor switch is turned on to rotate the specimen at the selected test velocity. Researchers then collected laser measurements along a circular track to determine the profile of the test specimen. Based on analyzing the data from these tests, researchers found a statistically significant relationship between the IRIs computed from single-point laser measurements, and surface texture as measured using the sand-patch test. Figure 2.2 shows this relationship. Researchers also found the IRIs based on the 19mm laser to be consistently lower than the corresponding IRIs from the single-point laser, with an average difference of about five inches per mile based on the laboratory test data. This finding pointed to the need for further investigating the potential impact of newer wide-footprint lasers on QA testing of pavement smoothness, given that the pay adjustment schedules in the current Item 585 ride specification are based on single-point laser measurements.

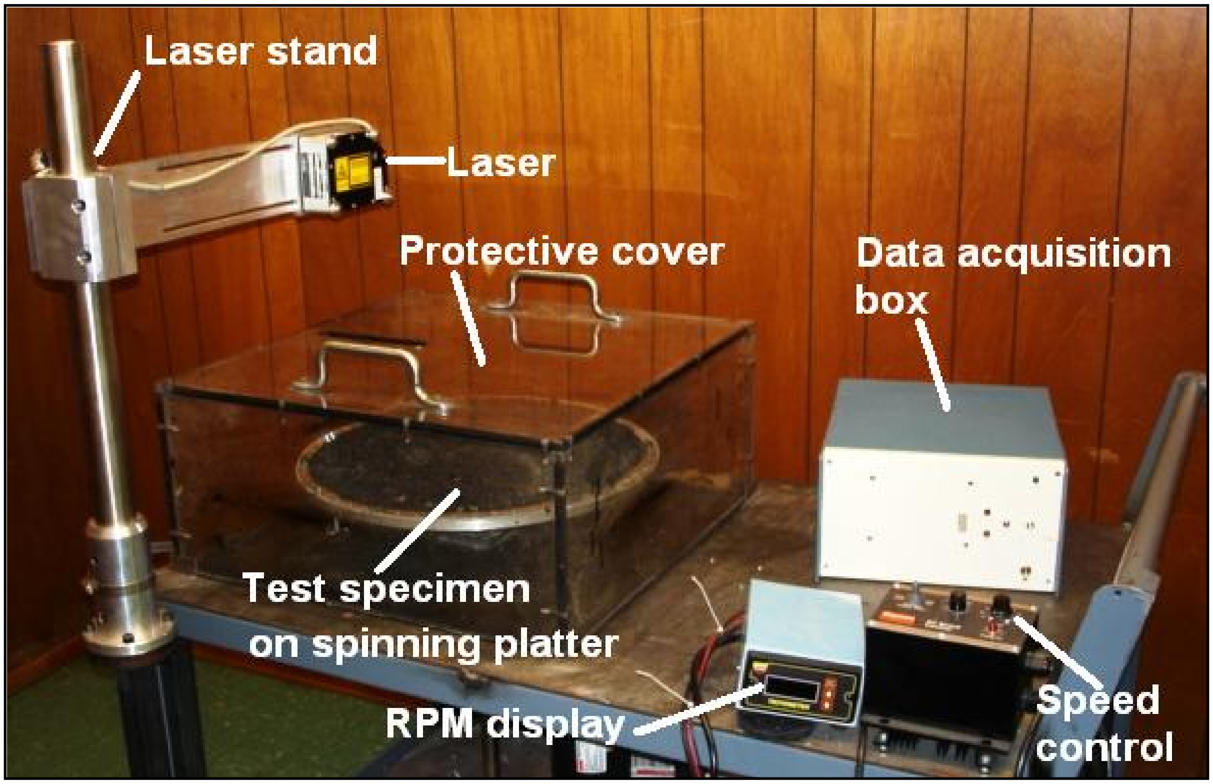

Figure 2.1. Test Cart Used for Laser Measurements on Textured Specimens (Fernando, Walker, Estakhri, 2008).

COMPARATIVE LASER TESTS DONE UNDER TEXAS SMOOTHNESS INITIATIVE

In 2009, TTI researchers working under the Texas Smoothness Initiative (TSI) collected data with different lasers on various pavement surfaces to assess the expected differences in computed IRIs between profiles collected with the 3 KHz Roline laser, the 19mm laser, the single-point laser, and the Ames TriODS. These tests were conducted using the setup illustrated in Figure 2.3 that permitted concurrent profile measurements with two different lasers at a time. Table 2.1 summarizes the surfaces tested on in-service pavements that covered hot-mix asphalt (HMA), seal coat, and continuously reinforced concrete pavement (CRCP) sections for a total of about 91 lane miles of pavement surfaces tested.

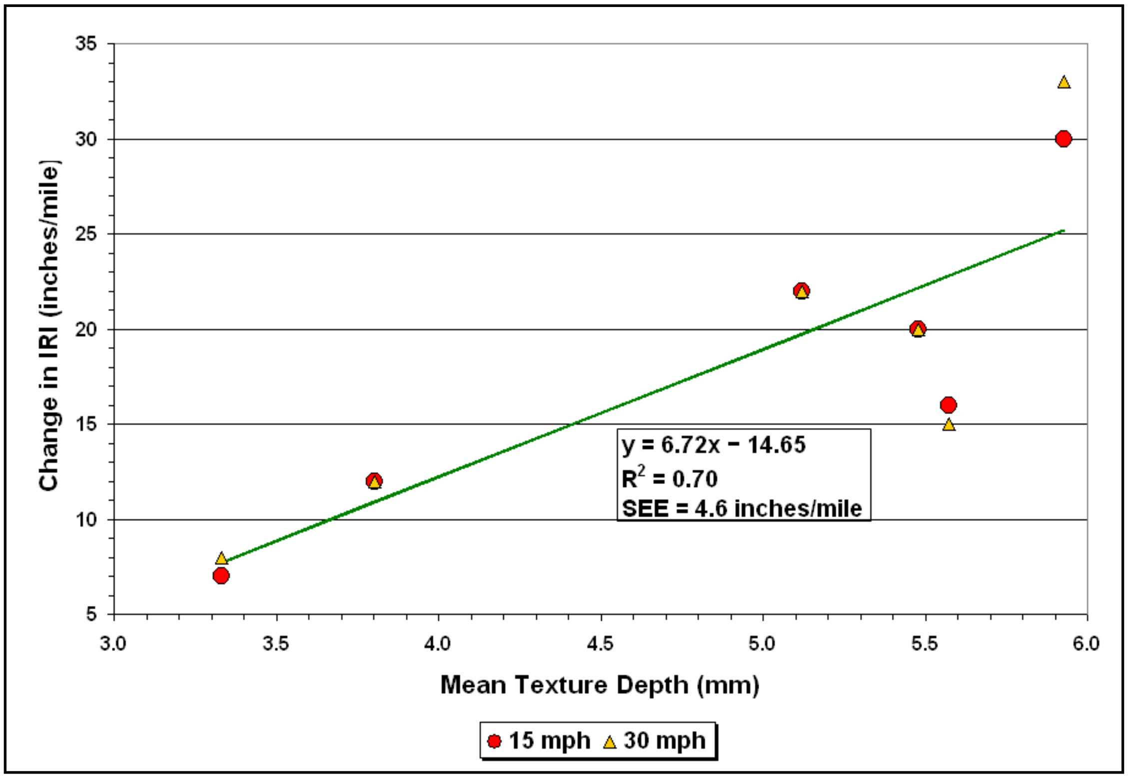

Figure 2.2. Relationship between IRI and Texture from Laboratory Tests (Fernando, Walker, Estakhri, 2008).

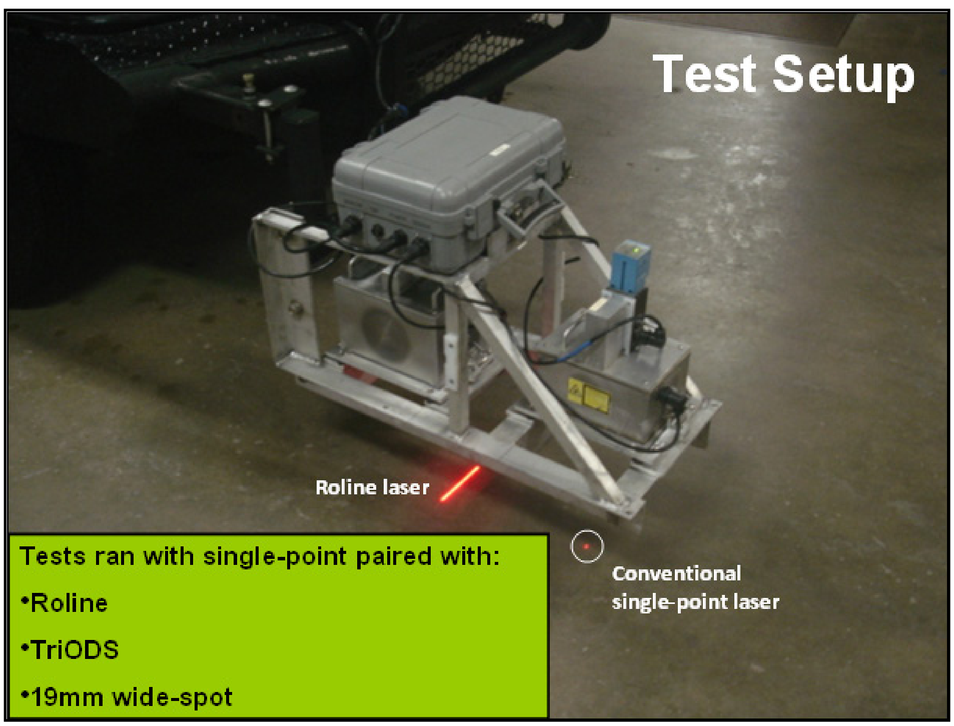

Figure 2.3. Test Setup Used on TSI Comparative Laser Testing.

Table 2.1. Summary of Surfaces Tested in TSI Comparative Laser Measurements.

Surface	No. of lane-miles tested	Highways tested
CRCP belt drag	0.56	IH35
CRCP carpet drag	0.93	SH36, IH35
CRCP conventional tining[1]	2.69	SH6, SH36
CRCP deep tines[1]	3.51	US287
CRCP skid abrader	4.54	US287
CRCP variable tining[1]	3.96	SH36, IH820
Total CRCP	16.19	
Grade 3 modified	9.58	FM50
Grade 3 seal coat	4.00	US90A
Grade 4 seal coat	24.34	SH21, US77, US290
Total seal coats	37.92	
Permeable friction course (PFC)	9.80	SH6
Stone matrix asphalt (SMA-C)	3.85	Loop 1 (MoPac)
SMA-D	1.49	FM734
Type C	14.40	FM2440, Loop 463,
Type D	7.75	US59, US77
Total hot-mix	37.29	
Total all sections	91.40	

[1]Transverse tines

Given that the existing pay adjustment schedules in Item 585 are based on ride quality measurements determined using single-point lasers, researchers collected profile data with the single-point laser paired with each of the other three lasers. For any given section, researchers made multiple runs to collect profiles for all three possible laser pairs, i.e., single-point with Roline, single-point with 19mm and single-point with TriODS. For each setup, researchers made five repeat runs on the given test section. In this way, concurrent measurements on the same wheel path were collected to compare IRIs computed using single-point profiles with corresponding IRIs determined from the other laser profiles.

Prior to running the field tests, researchers checked the profiling system against the certification requirements specified in TxDOT Test Method Tex-1001S. For this purpose, researchers collected data on the certification track located at the Texas A&M Riverside Campus. Three sets of runs were made to collect profiles on the right wheel path for each laser pair. Researchers then analyzed the data and verified that the system met the criteria specified in Tex-1001S for the three test setups. Tables 2.2 to 2.13 present the test statistics.

Table 2.2. Repeatability of Profile Measurements (Single-Point vs. 19mm Laser).

Laser	Section	Average Standard Deviation (mils)[1]
Single-point	Smooth	12
	Medium smooth	13
19mm	Smooth	14
	Medium smooth	15

[1] Not to exceed 35 mils per TxDOT Test Method Tex-1001S

Table 2.3. Repeatability of IRIs (Single-Point vs. 19mm Laser).

Laser	Section	Standard Deviation (inch/mile)[2]
Single-point	Smooth	1.14
	Medium smooth	1.30
19mm	Smooth	1.48
	Medium smooth	1.60

[2] Not to exceed 3.0 inches/mile per TxDOT Test Method Tex-1001S

Table 2.4. Accuracy of Profile Measurements (Single-Point vs. 19mm Laser).

Laser	Section	Average Difference (mils)[3]	Average Absolute Difference (mils)[4]
Single-point	Smooth	−1	13
	Medium smooth	1	15
19mm	Smooth	−1	13
	Medium smooth	1	19

[3] Must be within ±20 mils per TxDOT Test Method Tex-1001S
[4] Not to exceed 60 mils per TxDOT Test Method Tex-1001S

Table 2.5. Accuracy of IRIs (Single-Point vs. 19mm Laser).

Laser	Section	Difference between Averages of Test and Reference IRIs (inch/mile)[5]
Single-point	Smooth	3.55
	Medium smooth	1.70
19mm	Smooth	3.93
	Medium smooth	0.86

[5] Absolute difference not to exceed 6 inches/mile per TxDOT Test Method Tex-1001S
Positive difference indicates higher IRI from profiler relative to reference, and vice-versa

Table 2.6. Repeatability of Profile Measurements (Single-Point vs. TriODS).

Laser	Section	Average Standard Deviation (mils)[1]
Single-point	Smooth	12
	Medium smooth	14
TriODS	Smooth	8
	Medium smooth	12

[1] Not to exceed 35 mils per TxDOT Test Method Tex-1001S

Table 2.7. Repeatability of IRIs (Single-Point vs. TriODS).

Laser	Section	Standard Deviation (inch/mile)[2]
Single-point	Smooth	1.11
	Medium smooth	1.02
TriODS	Smooth	0.58
	Medium smooth	0.76

[2] Not to exceed 3.0 inches/mile per TxDOT Test Method Tex-1001S

Table 2.8. Accuracy of Profile Measurements (Single-Point vs. TriODS).

Laser	Section	Average Difference (mils)[3]	Average Absolute Difference (mils)[4]
Single-point	Smooth	−1	13
	Medium smooth	1	17
TriODS	Smooth	−1	12
	Medium smooth	0	19

[3] Must be within ±20 mils per TxDOT Test Method Tex-1001S
[4] Not to exceed 60 mils per TxDOT Test Method Tex-1001S

Table 2.9. Accuracy of IRIs (Single-Point vs. TriODS).

Laser	Section	Difference between Averages of Test and Reference IRIs (inch/mile)[5]
Single-point	Smooth	3.41
	Medium smooth	2.32
TriODS	Smooth	0.82
	Medium smooth	−0.11

[5] Absolute difference not to exceed 6 inches/mile per TxDOT Test Method Tex-1001S
Positive difference indicates higher IRI from profiler relative to reference, and vice-versa

Table 2.10. Repeatability of Profile Measurements (Single-Point vs. Roline).

Laser	Section	Average Standard Deviation (mils)[1]
Single-point	Smooth	11
	Medium smooth	11
Roline	Smooth	8
	Medium smooth	8

[1] Not to exceed 35 mils per TxDOT Test Method Tex-1001S

Table 2.11. Repeatability of IRIs (Single-Point vs. Roline).

Laser	Section	Standard Deviation (inch/mile)[2]
Single-point	Smooth	0.66
	Medium smooth	1.34
Roline	Smooth	0.42
	Medium smooth	0.62

[2] Not to exceed 3.0 inches/mile per TxDOT Test Method Tex-1001S

Table 2.12. Accuracy of Profile Measurements (Single-Point vs. Roline).

Laser	Section	Average Difference (mils)[3]	Average Absolute Difference (mils)[4]
Single-point	Smooth	−1	13
	Medium smooth	1	17
Roline	Smooth	−1	13
	Medium smooth	1	17

[3] Must be within ±20 mils per TxDOT Test Method Tex-1001S
[4] Not to exceed 60 mils per TxDOT Test Method Tex-1001S

Table 2.13. Accuracy of IRIs (Single-Point vs. Roline).

Laser	Section	Difference between Averages of Test and Reference IRIs (inch/mile)[5]
Single-point	Smooth	2.86
	Medium smooth	1.28
Roline	Smooth	−0.75
	Medium smooth	−1.89

[5] Absolute difference not to exceed 12 inches/mile per TxDOT Test Method Tex-1001S
Positive difference indicates higher IRI from profiler relative to reference, and vice-versa

After successfully verifying the profiling system, researchers proceeded with the field experiments. They subsequently analyzed the data to investigate the differences between IRIs computed using single-point profiles and corresponding IRIs determined from the other laser profiles. Given that data from any of the three laser pairs were collected concurrently, the researchers determined the differences in IRIs between lasers from each run made on a given test section. For each laser, they determined the differences in IRIs between lasers of the given pair for each 528-ft interval along the wheel path tested. This process was repeated for all runs made on the given section. Researchers then used the paired *t*-test to determine the statistical significance of the IRI differences between lasers and to compute confidence intervals for these differences. Figure 2.4 summarizes the paired *t*-test used to evaluate the IRI differences between lasers. Researchers used the two-sided *t*-test in their statistical analysis.

Null hypothesis H_0:
1. $\mu_d \leq D_0$ (D_0 is a specified value, often 0)
2. $\mu_d \geq D_0$
3. $\mu_d = D_0$

Alternate hypothesis H_a:
1. $\mu_d > D_0$
2. $\mu_d < D_0$
3. $\mu_d \neq D_0$

Test statistic:

$$\frac{\bar{d} - D_0}{\frac{s_d}{\sqrt{n}}}$$

Rejection region: For a level α Type I error rate and with $n - 1$ degrees of freedom (*df*):

1. Reject H_0 if $t \geq t_\alpha$
2. Reject H_0 if $t \leq -t_\alpha$
3. Reject H_0 if $|t| \geq t_{\alpha/2}$

The corresponding $100 \times (1-\alpha)$ % confidence interval on $\mu_d = \mu_1 - \mu_2$ is calculated as follows:

$$\bar{d} \pm t_{\alpha/2} \frac{s_d}{\sqrt{n}}$$

where n is the number of pairs of observations (and hence the number of differences), $\bar{d}$ is the average of the differences, s_d is the standard deviation of the differences, and $t_{\alpha/2}$ is the critical *t*-value for the specified confidence interval and for $df = n - 1$.

Figure 2.4. Summary of the Paired *t*-test (Ott and Longnecker, 2001).

The paired *t*-test is appropriate since measurements from the different lasers were made concurrently on any given section. In this analysis, researchers made the following pairwise comparisons based on IRI differences:

- Single-point IRI – Roline IRI.
- Single-point IRI – 19mm IRI.
- Single-point IRI – TriODS IRI.

Tables 2.14 and 2.15 summarize the IRI differences in terms of the 95 percent confidence intervals determined from the test data.

Table 2.14. 95% Confidence Intervals of IRI Differences on CRCP Sections.

Surface	Single-pt. vs. Roline	Single-pt. vs. 19mm	Single-pt. vs. TriODS
Conventional tines	0.24 to 0.65	7.68 to 8.64	6.23 to 6.88
Variable tines	−0.09 to 0.50	1.14 to 1.61	1.09 to 1.62
Deep tines	0.15 to 0.74	−2.00 to -1.36	0.44 to 1.01
Carpet drag	0.43 to 1.49	−1.22 to 0.17	0.53 to 1.91
Belt drag	0.41 to 1.67	−1.60 to −0.01	−0.03 to 1.41
Skidabrader	0.29 to 0.64	−1.61 to −1.13	−0.41 to 0.01

Table 2.15. 95% Confidence Intervals of IRI Differences on HMA and Seal Coat Sections.

Surface[1]	Single-pt. vs. Roline	Single-pt. vs. 19mm	Single-pt. vs. TriODS
PFC	10.28 to 10.65	3.92 to 4.34	8.60 to 9.03
Grade 3	2.95 to 3.31	2.88 to 3.36	3.40 to 3.83
Grade 4	5.77 to 6.08	1.35 to 1.66	4.81 to 5.21
SMA-C	2.62 to 2.96	−0.27 to 0.17	1.80 to 2.17
SMA-D	1.82 to 2.36	−3.36 to −2.33	0.04 to 0.76
Type C FM2440	0.94 to 1.05	−2.00 to −1.78	−0.08 to 0.08
Type C Loop463	3.48 to 3.88	1.83 to 2.21	1.20 to 1.58
Type D (US59)	1.86 to 2.07	−0.93 to −0.57	0.27 to 0.58
Type D (US77)	4.39 to 4.72	1.41 to 1.70	2.11 to 2.43

[1]All HMA sections except Grade 3 and Grade 4, which are seal coat sections

In these tables, confidence intervals that include 0 identify cases where the IRI differences are not statistically significant. These cases are shaded light green in the tables. Except for these cases, the IRI differences are statistically significant for most of the pairwise comparisons shown. However, researchers note that the magnitudes of the differences are generally within 6 inches/mile—the cutoff specified in Item 585 above which referee testing becomes mandatory. There are only five cases (shaded yellow in the tables) where the results indicate differences greater than this tolerance. On CRCP sections with conventional transversely tined surfaces, the IRI differences were found to be significantly higher than 6 inches/mile between the single-point and 19mm lasers, and between the single-point and the Ames TriODS, with higher IRIs from the single-point laser. On the other CRCP surfaces, the magnitudes of the IRI differences are generally within 2 inches/mile. Between the Roline, 19mm, and TriODS lasers, Table 2.14 shows that the Roline agreed best overall with the single-point laser.

On flexible pavement sections with permeable friction courses, the IRI differences were found to be significantly higher than 6 inches/mile between the single-point and Roline lasers, and between the single-point and Ames TriODS. In addition, Grade 4 seal coats showed differences between single-point and Roline IRIs that border around 6 inches/mile. While Item 585 does not apply to seal coats and surface treatments, the test results are useful in assessing the potential impact of using Roline lasers for measuring, monitoring, and reporting the ride quality of the state highway network, given the significant mileage of seal coats and surface treatments in the state.

Comparing the single-point and Roline lasers, Table 2.15 shows that the 95 percent confidence intervals all span a positive range, indicating that the single-point generally gave higher IRIs than the Roline. During discussions with the TSI panel, the question was raised as to whether this bias might be attributed to the test setup where the single-point laser was placed in the forward position shown in Figure 2.3. This possible bias was primarily of concern on the PFC and Grade 4 surfaces where the differences between single-point and Roline laser IRIs are considered significant based on current practice. The panel advised that additional tests be conducted where concurrent profile measurements are collected with two single-point lasers—one in the forward position, and the other at the rear closest to the front bumper. Table 2.16 identifies the sections in which researchers collected additional measurements. The CRCP, PFC, and Grade 4 sections shown in this table are on the same pavements surveyed previously.

Table 2.16. Sections Tested with Single-Point Laser Pair.

Surface	Lane-miles tested	Highways tested[1]
CRCP conventional tines	3.97	SH6, SH36
CRCP variable tines	1.61	SH36
PFC	2.14	SH6
Grade 4 seal coat	2.18	SH21
Type C	1.78	SH21
Type D	2.09	SH47

[1] SH6, SH21 and SH47 sections located in Bryan/College Station. SH36 sections located in Cameron.

As with the earlier analysis, researchers determined the differences between IRIs computed from corresponding front and rear single-point laser profiles. Table 2.17 summarizes the IRI differences in terms of the 95 percent confidence intervals. It is observed that the magnitudes of the differences are within 1.5 inches/mile. Based on current practice, these differences are not significant enough to conclude that the laser position affected the test results. In addition, the confidence intervals for the PFC and Grade 4 surfaces cover a range of IRI differences that are much smaller than the corresponding intervals given in Table 2.15 between the single-point and Roline lasers. This observation indicates that the IRI differences on the PFC and Grade 4 sections can primarily be attributed to the difference between the single-point and Roline lasers.

Table 2.17. Confidence Intervals of IRI Differences between Single-Point Lasers.[1]

Surface	95% confidence interval (inch/mile)[2]
CRCP conventional tines	−0.99 to −0.50
CRCP variable tines	−1.21 to −0.39
Permeable friction course	−1.04 to −0.21
Grade 4 seal coat	−0.67 to 1.33
Type C	0.47 to 1.29
Type D	−0.02 to 0.73

[1] IRI difference = Rear laser IRI – forward laser IRI
[2] Cells shaded green identify cases where IRI differences are not statistically significant

Owing to the significant IRI differences observed on the SH6 PFC section, researchers collected additional measurements to verify the differences between the single-point and Roline lasers on this surface type. For this purpose, researchers collected profiles on two other PFC sections located along IH10 and US59 in the Yoakum District. These surveys covered 11.21 lane-miles. Table 2.18 presents the 95 percent confidence intervals of the IRI differences from these additional measurements. It is observed that the range of IRI differences is significant but varies between the Yoakum and Bryan District PFC projects. The SH6 project in Bryan shows IRI differences much higher than 6 inches/mile while the Yoakum projects show differences bordering around 6 inches/mile.

In addition, there is significant overlap between the confidence intervals determined from the profiles collected along the IH10 and US59 PFC projects. Combining the data from all three projects, researchers determined that the IRI differences range from 8.58 to 8.98 inches/mile at the 95 percent confidence level. The results from the additional PFC tests further verify that the Roline laser gives significantly lower IRIs on PFC surfaces, which raises a concern about using the existing Item 585 pay adjustment schedules for quality assurance tests when profilers equipped with Roline lasers are used on PFC projects. Clearly, there is a need to establish which laser is giving the correct ride quality statistic. Researchers addressed this issue in the comparative laser tests conducted in this project.

Table 2.18. Confidence Intervals of IRI Differences on PFC Sections[1].

PFC project	95% Confidence interval (inch/mile)
IH10	6.15 to 6.67
US59	5.82 to 6.45
SH6	10.28 to 10.65
IH10 & US59 combined	6.10 to 6.51
SH6, IH10 & US59 combined	8.58 to 8.98

[1] IRI difference = Single-point IRI – Roline IRI

In addition to evaluating the differences between IRIs, researchers examined the correlations between IRIs determined using the single-point laser and the IRIs determined from the other lasers. Figures 2.5 to 2.7 illustrate the correlation between single-point and Roline laser IRIs from tests conducted on the SH6, IH10, and US59 PFC projects. These figures clearly show that the single-point IRIs are higher than the Roline laser IRIs. However, the IRIs from the two lasers are also highly correlated. In general, researchers found that the single-point IRIs show a high correlation with the IRIs determined from the Roline, 19mm, and TriODS lasers. This finding is evident in the Appendix, where the charts compare the single-point IRIs with the other laser IRIs.

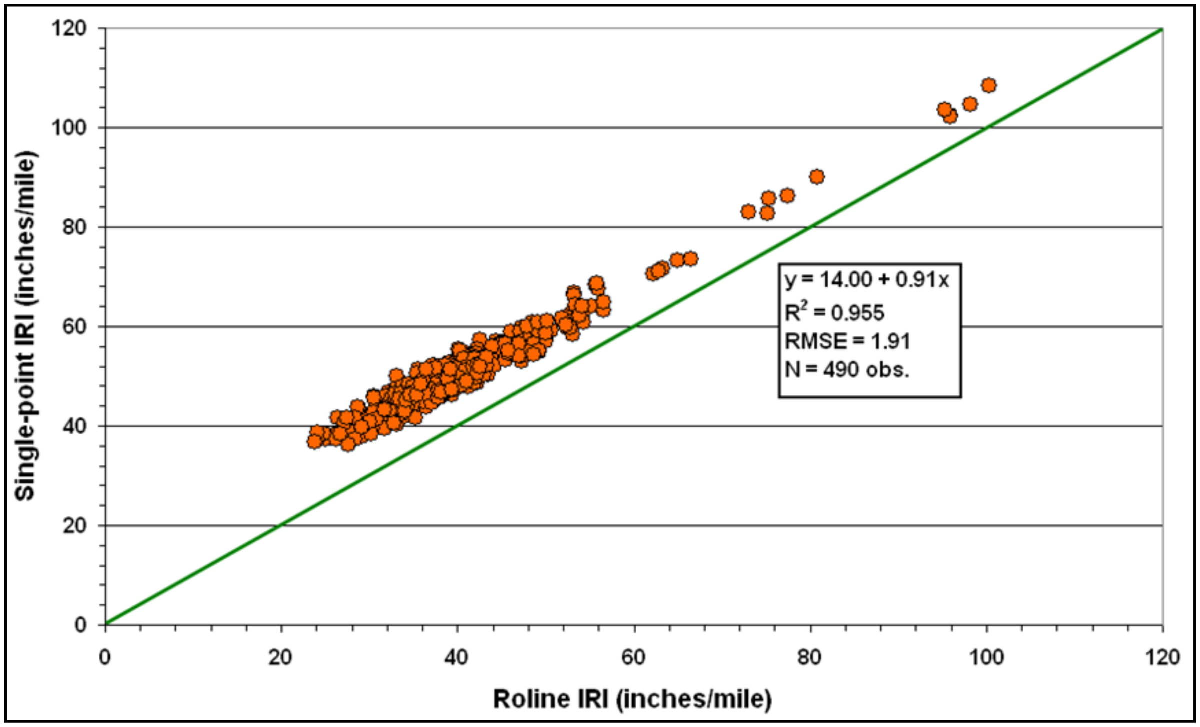

Figure 2.5. Comparison of Single-Point and Roline Laser IRIs on SH6 PFC Project.

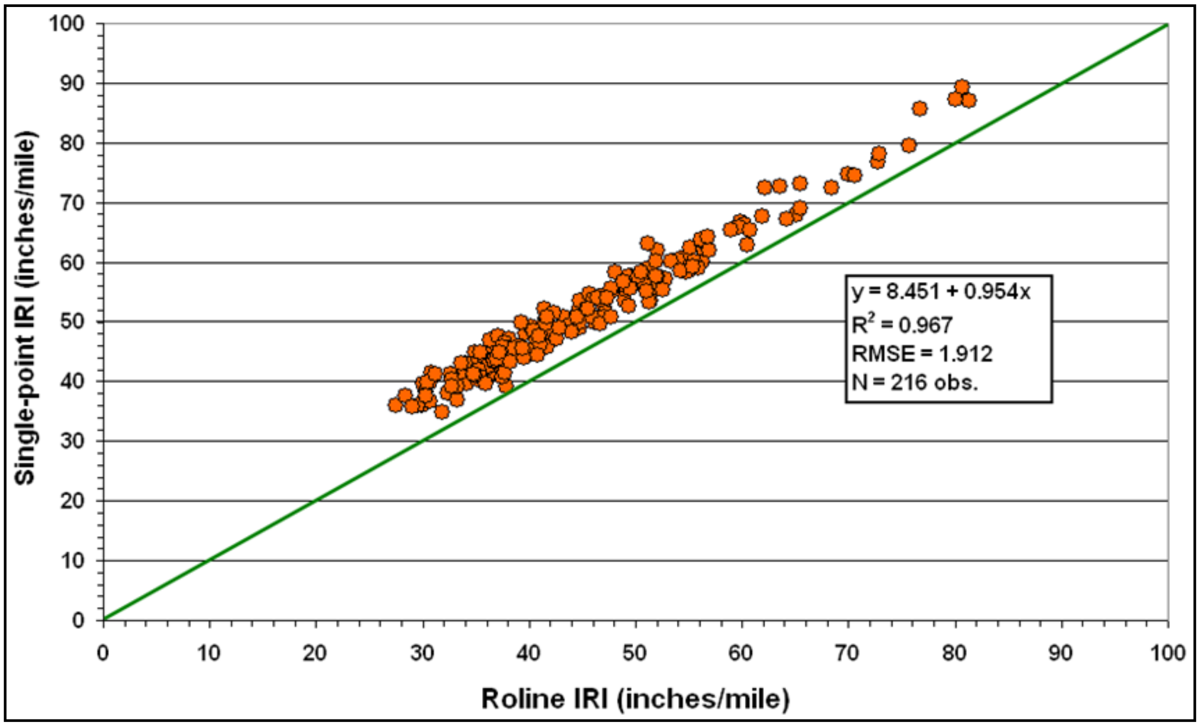

Figure 2.6. Comparison of Single-Point and Roline Laser IRIs on IH10 PFC Project.

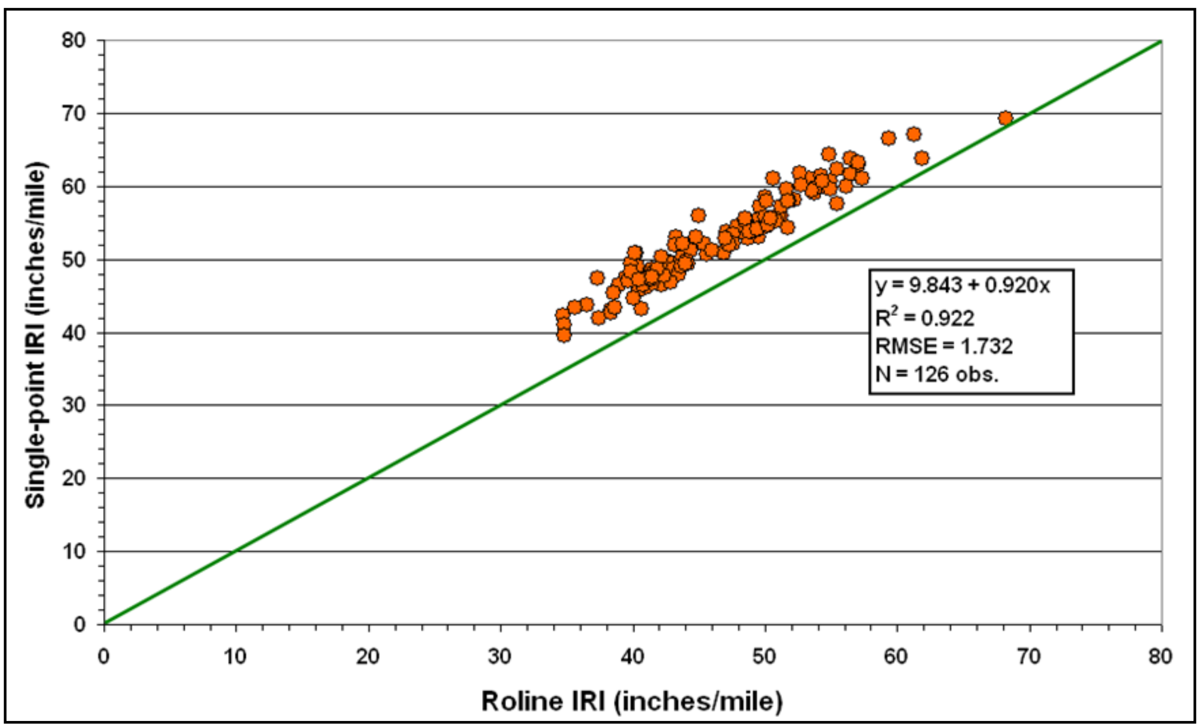

Figure 2.7. Comparison of Single-Point and Roline Laser IRIs on US59 PFC Project.

Aside from comparing IRIs, the researchers compared the defects found between the single-point and Roline laser profiles as determined using TxDOT's Ride Quality program. For this comparison, researchers ran the Ride Quality program using Schedule 1 of Item 585 along with the 5-ft bump penalty gap and no spike suppression. The defect locations from each laser were aligned with respect to the start of the section, and considering the offset between the laser footprints prior to comparing the defects from corresponding single-point and Roline laser profiles.

Figure 2.8 compares the number of defects found between the two lasers on the CRCP and asphalt concrete test sections. In this chart, the number of defects is read off the left vertical axis. The green bar gives the number of single-point laser defects found in a given section while the red checkered bar gives the corresponding count for the Roline laser. The yellow bar plotted for each section shows the difference between the defects found from each laser. The numbers above the yellow bars show the values of the differences in the defect counts as read off the right vertical axis of the chart. A positive difference indicates a higher number of defects found from the single-point laser profile compared to the Roline profile.

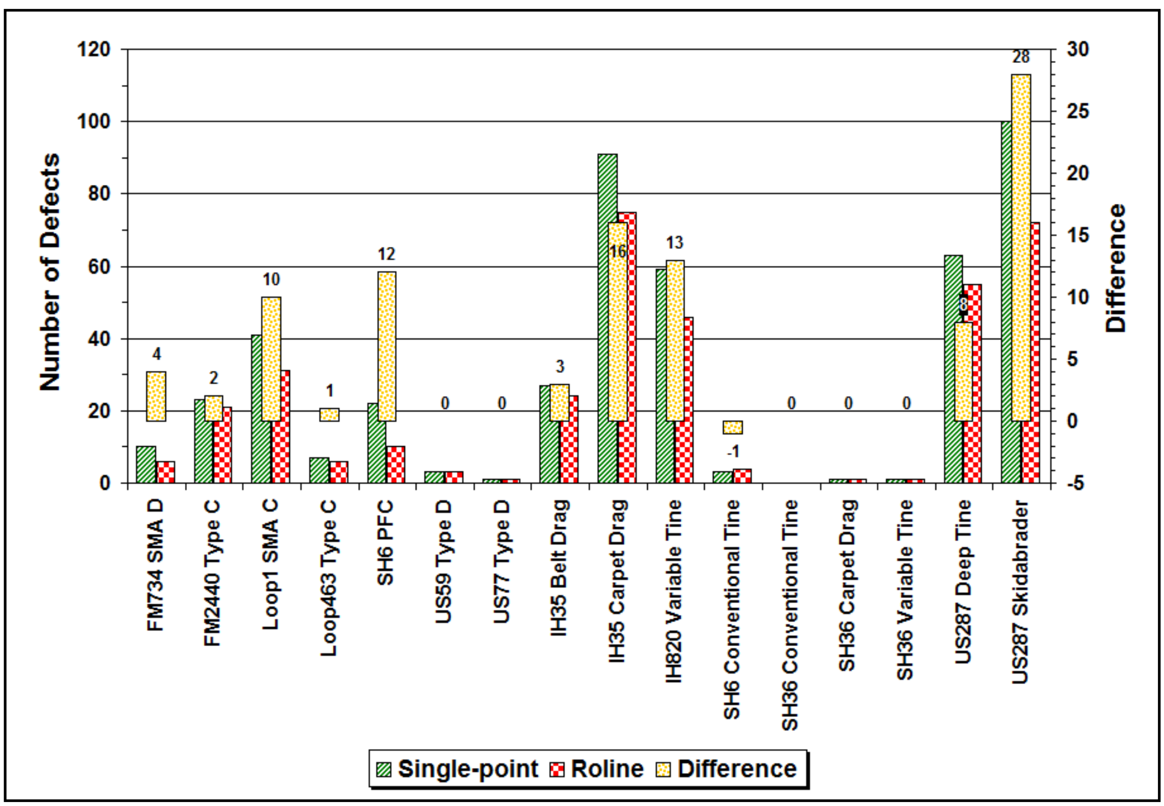

Figure 2.8. Comparison of Defect Counts between Single-Point and Roline Laser Profiles.

Figure 2.8 shows five sections where the defect counts for both lasers are the same (i.e., the difference equals 0), and another five sections where the single-point defects exceed the corresponding Roline defects by 10 or more. Figure 2.9 shows the penalties associated with these defects and the differences between penalties from the single-point and Roline laser profiles. In general, the single-point laser gave higher penalties for defects found on a given section. Only one project, the 2.2-mile SH6 CRCP section with conventional transverse tines, showed a $500 greater penalty for the Roline. Since the test sections differed in length, researchers also normalized the difference in penalties by the length of each section. Figure 2.10 shows the differences in penalties in terms of $/mile. On this basis, the IH35 carpet drag and variable tined sections showed the greatest difference in defect penalties among the sections tested.

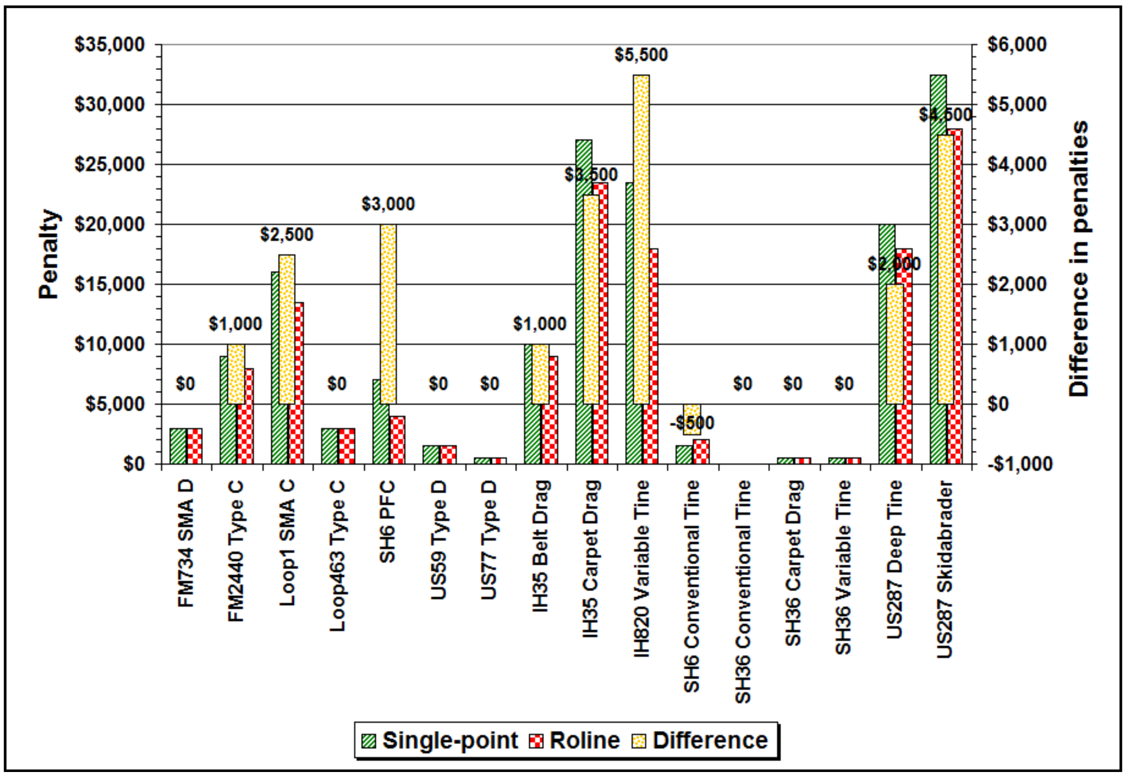

Figure 2.9. Comparison of Defect Penalties between Single-Point and Roline Laser Profiles.

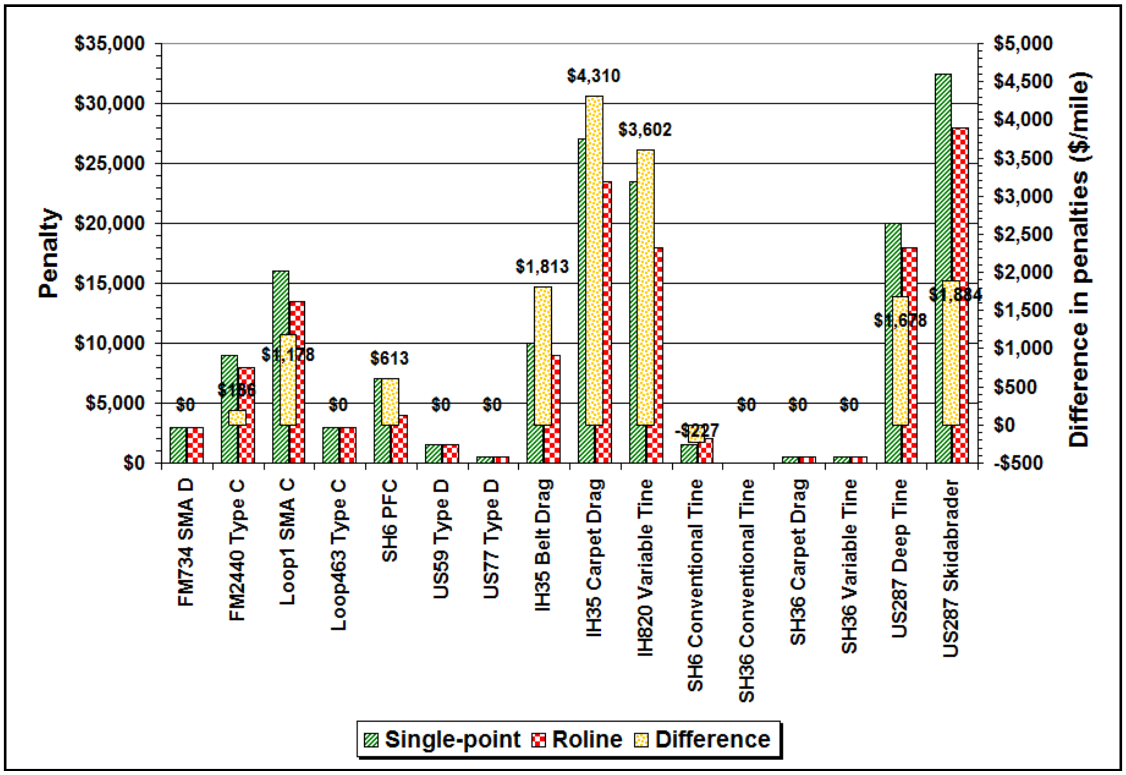

Figure 2.10. Differences between Defect Penalties in Terms of $/Mile.

In general, the following findings are noted from the comparison of single-point and Roline lasers based on the defects found in the measured profiles:

- Roline laser profiles showed fewer areas of localized roughness than conventional single-point laser profiles.
- There are generally few misclassified bumps or dips based on laser type. In this evaluation, misclassified is defined as "an occurrence in which the processed data from the two lasers classify a defect differently at the same pavement location" (e.g., dip vs. bump). However, the current bump template that TxDOT used generally finds less defects with Roline profile data.

Based on these results, use of the Roline laser for quality assurance testing will likely reduce the defect penalties for contractors based on the existing bump template.

COMPARATIVE LASER TESTS CONDUCTED IN MINNESOTA

The Minnesota Department of Transportation (MnDOT) has conducted tests at its MnROAD facility to compare IRIs from different lasers. As part of a recent project to investigate innovative grinding methods to reduce noise, and enhance safety and ride quality on concrete pavements, MnDOT is monitoring a number of jointed concrete pavement sections to assess the durability of surface characteristics on sections where alternative grinding techniques have been used. This monitoring effort includes measuring the ride quality of the test sections. For this purpose, MnDOT is using an Ames lightweight profiler equipped with Roline and TriODS lasers that permits concurrent profile measurements from both lasers on the test wheel path.

MnDOT provided researchers with a sample of the ride quality measurements collected at two different times on cell 9 of the MnROAD facility. This particular section received an innovative grind treatment that produced a surface similar to that shown in the right region of Figure 2.11. This innovative treatment was primarily designed for noise reduction. However, in cell 9, the raised strips above the groove (also known as the land area or riding surface), was further corrugated to enhance friction. The treatment applied on cell 9 produced a groove width, groove depth, and land width of 0.129, 0.291, and 0.501 inches, respectively. With the given groove and land widths, the center-to-center distance between grooves is 0.63 inches.

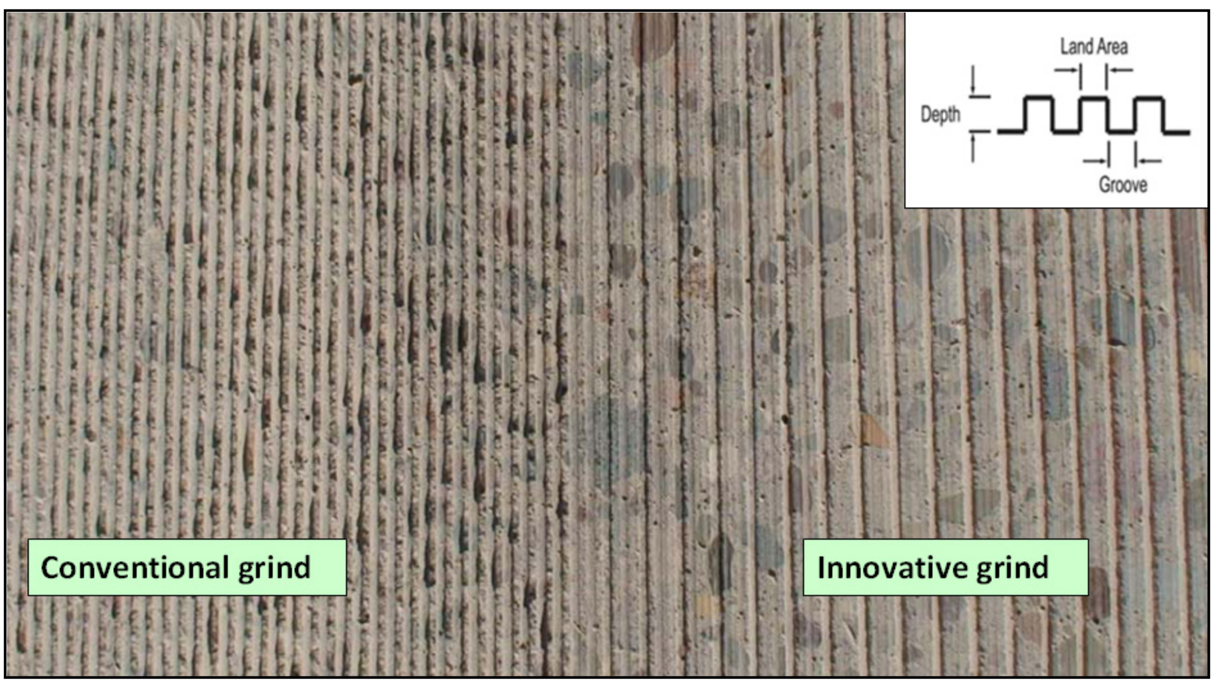

Figure 2.11. Surface Textures Associated with Conventional and Innovative Grind Treatments (Izevbekhai, 2007).

According to MnDOT, cell 9 produced the largest discrepancy between IRIs computed from Roline and TriODS laser profiles. This discrepancy is illustrated in Figure 2.12, where the Roline

IRIs are observed to be significantly lower than the IRIs from the TriODS. Considering that the section received grinding, the IRIs from the Roline profiles appear more reasonable than the corresponding IRIs determined from the TriODS profiles. Researchers inquired whether reference profile measurements were done on the section to verify the Roline and TriODS data. The MnDOT engineer replied that no reference profiles were collected on cell 9. However, he added that the Ames lightweight profiler passed MnDOT's inertial profiler certification requirements.

Examination of the profile data from concurrent measurements revealed spikes in the TriODS profiles (see Figure 2.13). Researchers brought up the MnROAD data with Ames Engineering. From this communication, it appears that the TriODS may have difficulty measuring profiles on a textured surface like that in cell 9. According to Ames, the TriODS was designed for ⅛-inch deep grooves on ¾-inch centers. The grinding method used on cell 9 produced grooves that are about 0.3-inch deep on 0.63-inch centers. Given that the Roline measures elevations across a 4-inch footprint, this laser would be less susceptible to differences in groove geometry than the three-point TriODS laser.

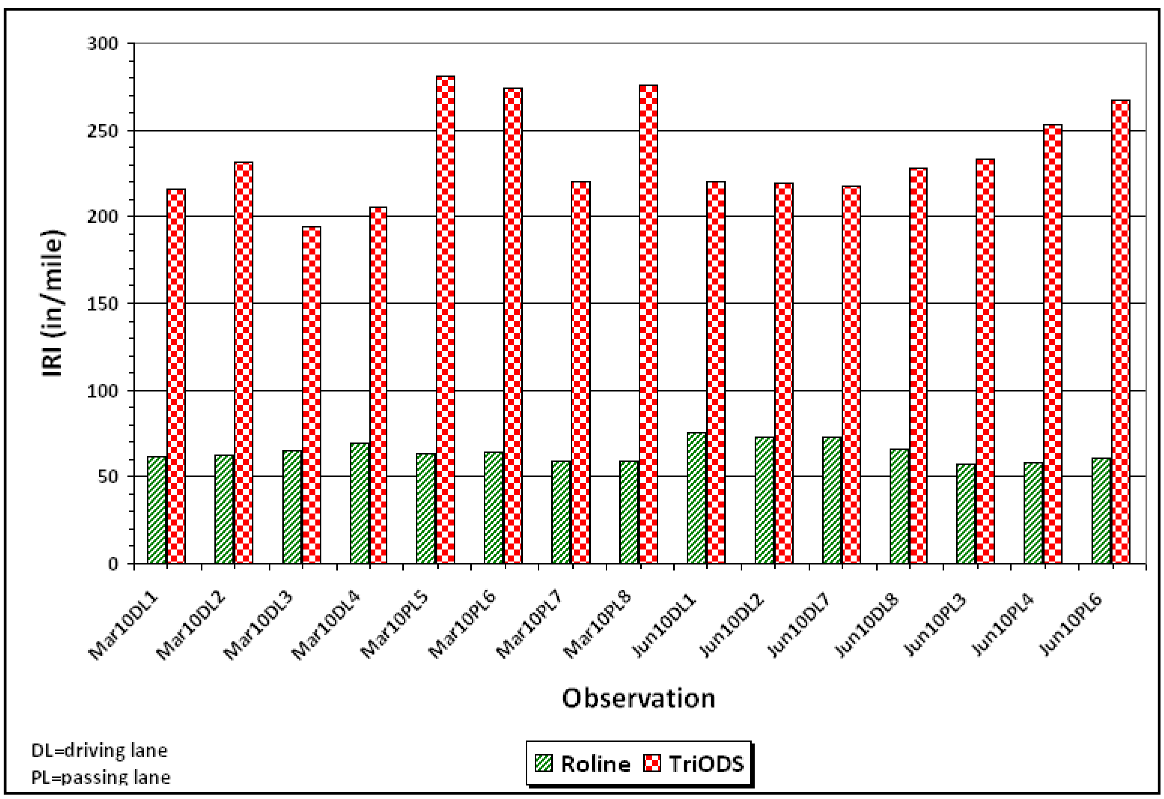

Figure 2.12. Comparison of Roline and TriODS Laser IRIs on MnROAD Cell 9.

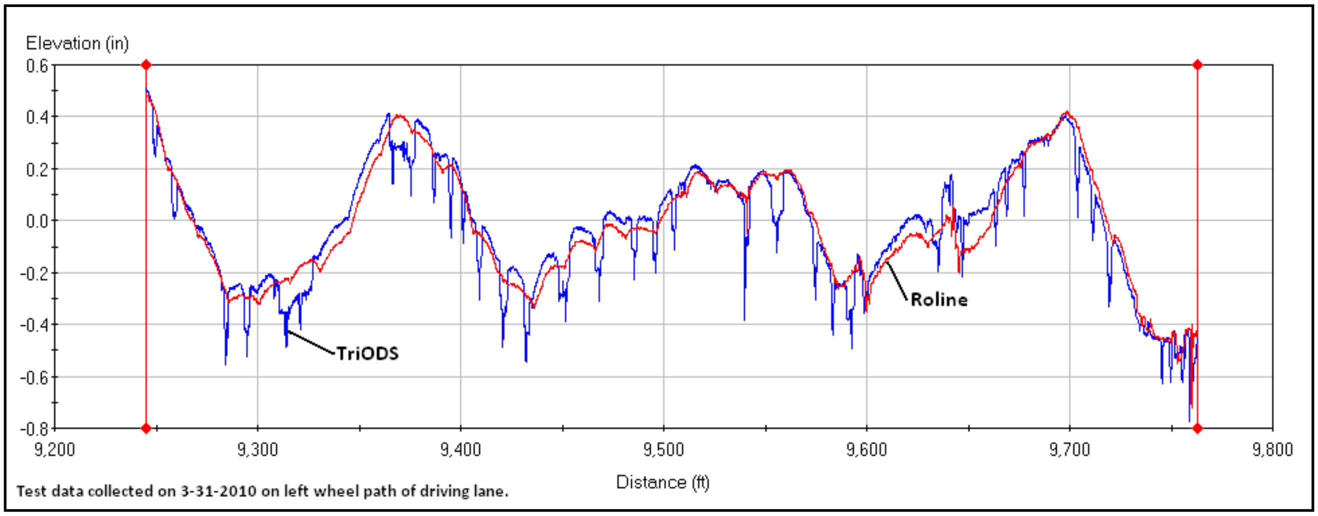

Figure 2.13. Comparison of Roline and TriODS Profiles on MnROAD Cell 9.

COMPARATIVE LASER TESTS CONDUCTED IN VIRGINIA

Habib, Nelson, and Tate (2010) reported findings from a study of the Virginia Department of Transportation (VDOT) that compared IRIs determined from single-point and Roline laser profiles collected on diamond-ground concrete pavements. Like most states that have implemented profile-based ride specifications, Virginia based its current specification on data collected with the conventional single-point laser. Given the recent literature regarding repeatability issues with this laser sensor on diamond-ground and longitudinally tined concrete pavement surfaces, Habib, Nelson, and Tate conducted a comparative evaluation of single-point and Roline lasers on two recent diamond-ground concrete projects where VDOT's ride specification was applied. Their intent was to evaluate differences between the lasers in a production environment as opposed to other recent studies that were done in more controlled field experiments. The two concrete projects used in their field evaluation are identified as the Battlefield Blvd. and the Interstate 66 (IS66) projects. On both projects, single-point laser profiles were collected using a VDOT inertial profiler. On the Battlefield Blvd. project, the contractor collected inertial profiles using an Ames profiler equipped with Roline lasers, while on the IS66 project, the Roline profiles were collected using the Federal Highway Administration's (FHWA) lightweight profiler.

Figure 2.14 compares the IRIs (computed at 0.01-mile intervals) from the single-point and Roline laser profiles collected on the Battlefield Blvd. project. VDOT engineers noted that the single-point IRIs were less repeatable compared to the Roline IRIs and were significantly higher. To further evaluate the repeatability of the data from each sensor, VDOT engineers used the ProVAL program to calculate the cross-correlations between repeat runs. Table 2.19 compares the correlation statistics determined from this analysis. This table shows that the average cross-correlations associated with the single-point data varied from 18.6 to 49.8 percent, which reflect the lack of repeatability between runs on the Battlefield project. In contrast, the average cross-correlations for the Roline data range from 57.7 to 80.1 percent. Habib, Nelson, and Tate noted that the repeatability is fairly good between the two Roline runs that the contractor provided, but are not as high as cross-correlation statistics reported in previous investigations. They surmised that this result may be due to differences between the controlled tests reported in previous investigations versus the production environment within which they conducted their evaluation.

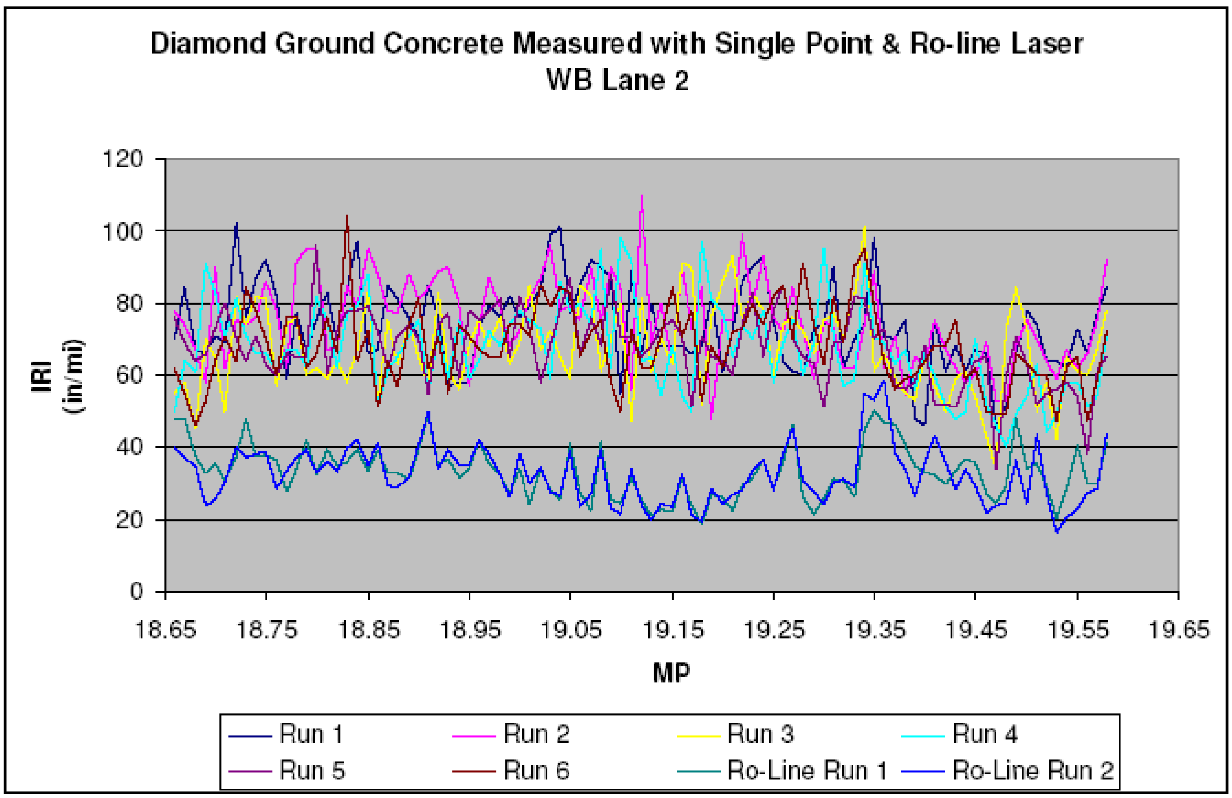

Figure 2.14. Comparison of Single-Point and Roline Laser IRIs on Battlefield Blvd. Project (Habib, Nelson and Tate, 2010).

Table 2.19. Comparison of Cross-Correlation Statistics between Single-Point and Roline Data on Battlefield Blvd. Project (Habib, Nelson, and Tate, 2010).

Lane	Average cross-correlation (%) from 6 runs of VDOT single-point profiler	Average cross-correlation (%) from 2 runs of Roline profiler
Eastbound lane 1	41.0	57.7
Eastbound lane 2	28.9	69.7
Eastbound lane 3	44.1	62.3
Eastbound lane 4	49.8	80.1
Eastbound lane 5	38.2	59.2
Westbound lane 1	42.2	73.0
Westbound lane 2	34.5	66.1
Westbound lane 3	18.6	73.4
Westbound lane 4	26.7	75.7
Westbound lane 5	27.6	64.4
Average	35.1	68.2

Figure 2.14 also shows the Roline IRIs to be much lower than the corresponding single-point values. Habib, Nelson, and Tate calculated the average IRIs for each lane and reported the differences between lasers as shown in Table 2.20. They found the differences to be significant and commented that the low IRIs from the Roline are not supported by "seat of the pants" values. They brought up the need to check the accuracy of the IRIs from the Roline laser. However, no reference profile measurements were made in their study.

On the IS66 project, VDOT engineers made two runs with the single-point laser. Only one run was made with the Roline laser. On this project, the cross-correlation between the two single-point runs was determined to be 64.7 percent, which is within the range of the average cross-correlations determined for the Roline laser on the Battlefield Blvd. project. The average project IRIs based on the single-point and Roline lasers were determined to be 108 and 82 inches/mile, respectively.

Table 2.20. Comparison of Average IRIs from Single-Point and Roline Data on Battlefield Blvd. Project (Habib, Nelson, and Tate, 2010).

Lane	Average IRI (inch/mile)		Percent Difference
	Single-Point	Roline	
Eastbound lane 1	62	33	46
Eastbound lane 2	58	38	35
Eastbound lane 3	67	41	40
Eastbound lane 4	63	40	36
Eastbound lane 5	61	38	37
Westbound lane 1	66	39	42
Westbound lane 2	70	33	53
Westbound lane 3	65	32	51
Westbound lane 4	64	34	46
Westbound lane 5	77	36	53
Average	65	36	44

It is interesting to note the higher cross-correlation of the two single-point runs on the IS66 project. To further evaluate the repeatability of single-point ride quality measurements on diamond ground projects, VDOT engineers collected additional data on a concrete project located along Interstate 664 (IS664). Six runs were made with VDOT's single-point profiling system and the average cross-correlations between replicate runs were determined. Table 2.21 shows the resulting statistics from this analysis. It is observed that the average cross-correlations vary from 49 to 71 percent, which overlap with the range of cross-correlations based on the Roline data collected on the Battlefield Blvd. project.

Table 2.21. Average Cross-Correlations between Replicate Single-Point Runs on IS664 Project (Habib, Nelson, and Tate, 2010).

Lane	Average cross-correlation (%)
Eastbound lane 1	49
Eastbound lane 2	66
Eastbound lane 3	71
Westbound lane 1	65
Westbound lane 2	66
Westbound lane 3	63
Average	64

Thus, among the three diamond ground projects on which test data were collected, Habib, Nelson, and Tate found that the repeatability of single-point ride quality measurements varied between the three projects, with the lowest repeatability observed on the Battlefield Blvd. project. Relative to the repeatability of the Roline measurements on the Battlefield project, these VDOT researchers noted that fairly repeatable data at the production level is possible with the single-point system depending on the grinding operation used on a given project. They noted that a somewhat smaller spacer was used for grinding on IS664 compared to the Battlefield Blvd. project, which was confirmed from visual observation of the ground surfaces on both projects. They recommended that issues related to the grinding operation need to be further investigated before ruling out the use of single-point lasers on diamond ground surfaces. They also indicated the need for reference profile measurements to check the IRIs from the Roline laser, particularly on the Battlefield project where the low Roline IRIs are not supported by "seat of the pants" values. They also recommended that a standard algorithm for Roline data processing (tire bridging filter) needs to be established before Roline profiling systems can be implemented.

COMPARATIVE LASER MEASUREMENTS CONDUCTED BY DYNATEST

In October 2009, Dynatest Consulting evaluated a 3 KHz Selcom Roline 1140 wide spot laser to determine the effect of the wider laser footprint on longitudinal profile measurements and the international roughness index (Briggs, 2009). Figure 2.15 shows the test vehicle used for this comparative evaluation. The test vehicle had two profiling systems:

- A Mark III profiling system with two SLS5200 single-point lasers in front.
- A Mark IV system with Selcom 19mm and Roline lasers at the rear.

The 19mm laser on the Mark IV system was mounted on the left wheel path with the Roline positioned on the right such that the footprint was oriented at an angle of 30° from the horizontal. On both the Mark III and Mark IV systems, Dynatest staff positioned each laser ±34.5 inches from the van centerline. Thus, the front and rear lasers tracked the same wheel paths on any given run. Each system also had its own distance encoder and start sensor. This configuration permitted the operator to independently trigger the profile measurements to the same starting location, thus, lining up the test profiles from each system. Prior to testing, the distance encoders were calibrated over a known distance to a reproducibility of better than 1 in 25,000 according to

Dynatest. In addition, the 3 KHz Roline laser was tested at the TTI test track where it met the certification requirements specified in TxDOT Test Method Tex-1001S.

Figure 2.15. Dynatest Profiler Van Used in 2009 Comparative Laser Testing.

Dynatest collected profiles on selected pavement sections tested by TTI under the Texas Smoothness Initiative. The pavements surveyed included the Grade 3 surface treatment along FM50, the CRCP section along SH6 and the Grade 4 seal coat along SH21. In addition, Dynatest ran its profiler on a 350-ft longitudinally tined concrete bridge deck located along SH47. Dynatest staff ran each test section once, with profile elevations collected at 3-inch intervals and IRIs computed at 0.1-mile intervals except on the SH47 bridge deck.

The profiling systems were set to measure profiles with a cutoff wavelength of 200 ft as specified in Test Method Tex-1001S. Figures 2.16 to 2.20 compare the IRIs computed from the single-point and Roline laser profiles collected on the FM50, SH21, and SH6 sections. In addition, Table 2.22 compares the IRIs computed from the profiles collected on the longitudinally tined SH47 bridge deck.

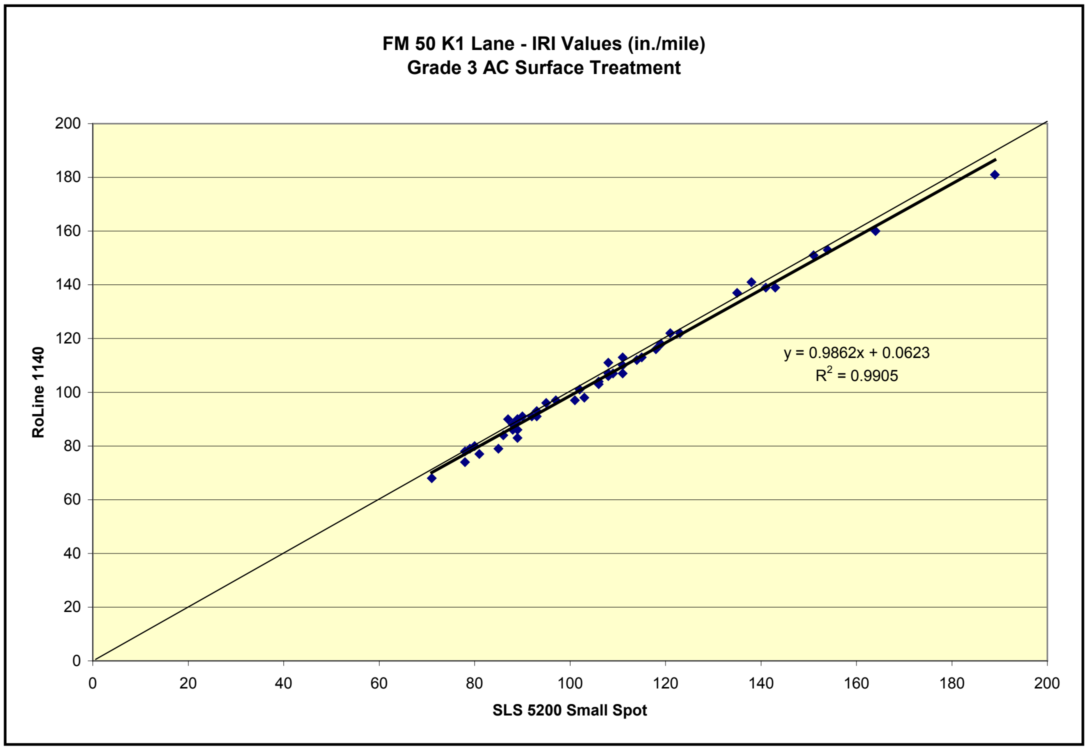

Figure 2.16. Comparison of Roline and Single-Point IRIs on K1 Lane of FM50 Grade 3 Surface-Treated Section (Briggs, 2009).

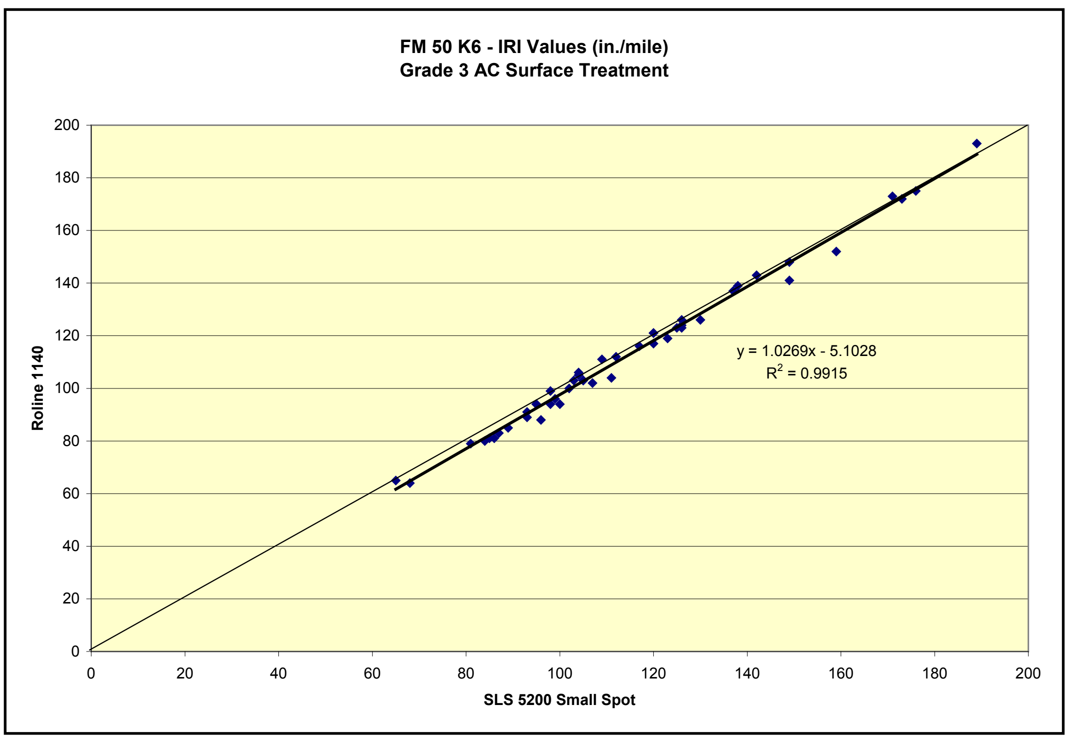

Figure 2.17. Comparison of Roline and Single-Point IRIs on K6 Lane of FM50 Grade 3 Surface-Treated Section (Briggs, 2009).

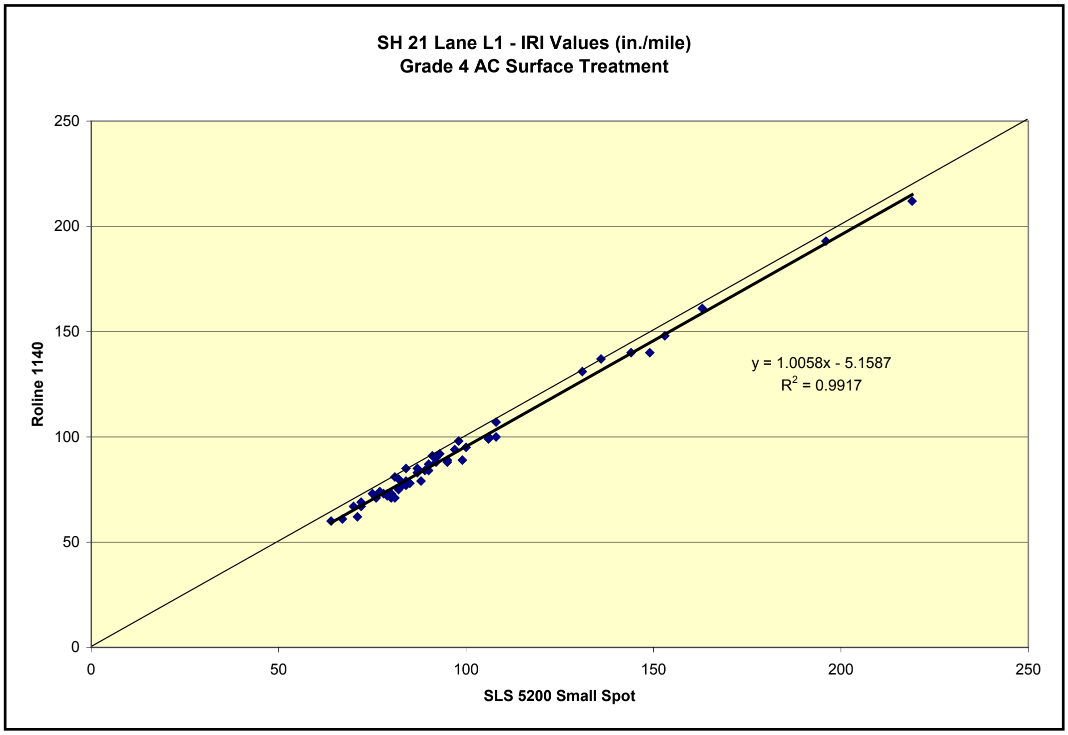

Figure 2.18. Comparison of Roline and Single-Point IRIs on L1 Lane of SH21 Grade 4 Seal Coat Section (Briggs, 2009).

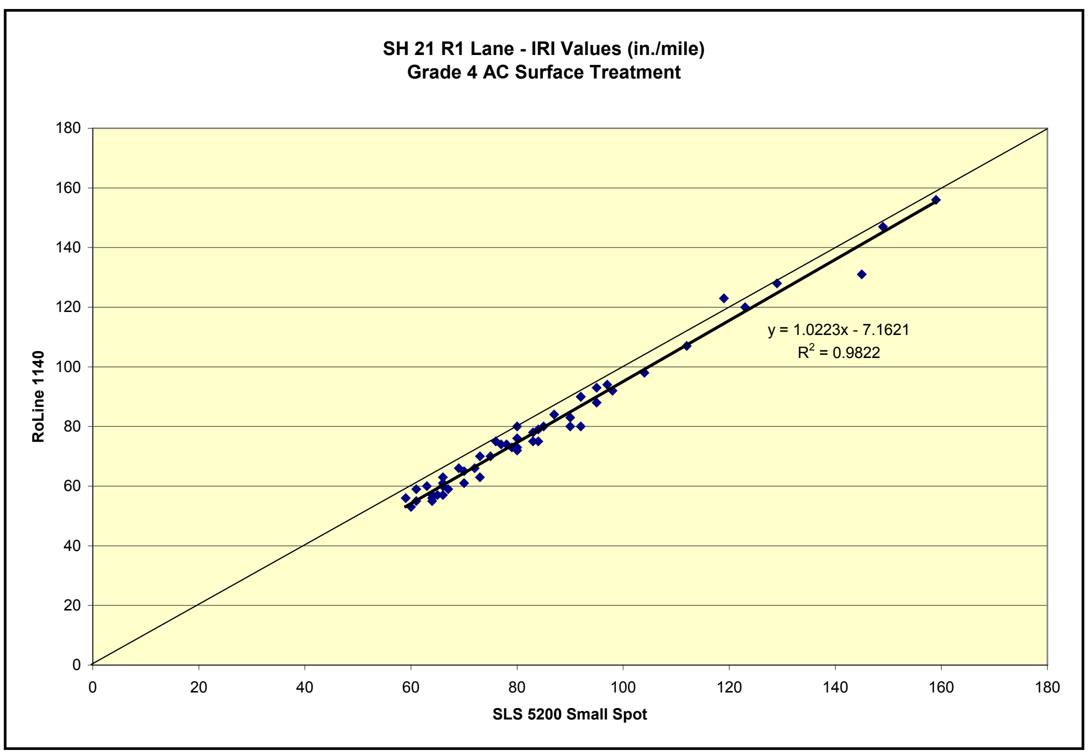

Figure 2.19. Comparison of Roline and Single-Point IRIs on R1 Lane of SH21 Grade 4 Seal Coat Section (Briggs, 2009).

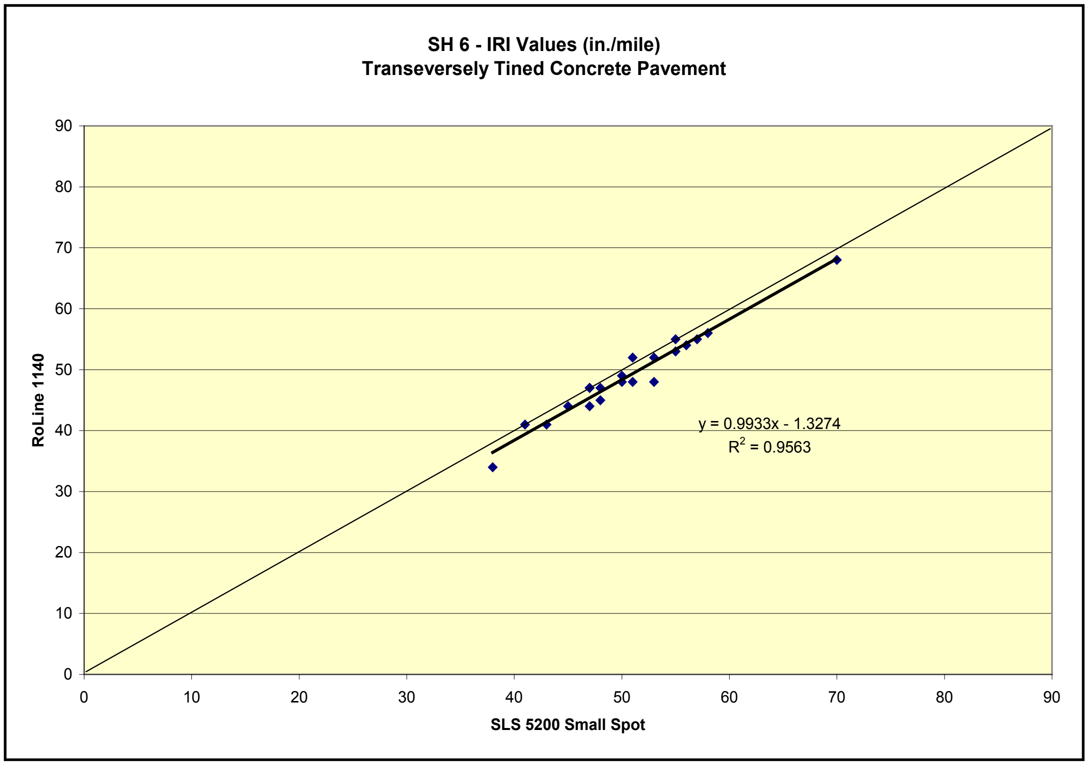

Figure 2.20. Comparison of Roline and Single-Point IRIs on L1 Lane of SH6 CRCP Section (Briggs, 2009).

Table 2.22. IRIs Computed from Profiles Collected on SH47 Bridge Deck (Briggs, 2009).

Profiling system	IRI (inch/mile)		Laser Type	
	Left wheel path	Right wheel path	Left wheel path	Right wheel path
Mark III	210	222	Single-point	Single-point
Mark IV	192	207	19mm	3 KHz Roline

Based on analysis of the data collected, Briggs (2009) noted the following findings from the comparative evaluation Dynatest conducted:

- On the K1 lane of FM50, only slight systematic differences are observed between the single-point and Roline IRIs. On the K6 lane, slight systematic differences are also observed, but the differences diminish at higher levels of IRI. In both lanes, the Roline IRIs are lower than the single-point IRIs. The IRI differences appear to be consistent with the data from the TSI tests.

- The Grade 4 sections on SH21 exhibit consistently lower IRIs from the Roline laser compared to the single-point. The IRI differences appear to range from 5 to 6 inches per mile based on the data shown in Figures 2.18 and 2.19, and are consistent with the data from the TSI tests. Although the Grade 3 surface treatment has larger aggregates than Grade 4, the Grade 4 seal exhibited the largest differences in IRI between the two sections. A visual inspection revealed that the Grade 3 surface is an older seal. The aggregate has somewhat embedded into the asphalt binder and some bleeding has occurred, resulting in reduced macro-texture.
- On the transversely tined SH6 CRCP section, the Roline laser seems to smooth the profiles slightly to produce marginally lower IRI values compared to the single-point. However, the differences are not regarded as significant.
- Between the Roline and single-point lasers, the Roline IRI is significantly lower than the corresponding single-point value on the longitudinally tined SH47 concrete bridge deck. On such surfaces, the single-point footprint runs in and out of the grooves, giving the false impression of pavement roughness by inflating IRI values. The wider footprint of the Roline coupled with its tire-bridging filter minimizes this bias. While the trends are reasonable, there are no reference measurements to verify the IRIs from the different lasers. However, the difference between the Roline and single-point IRIs is considered significant.

REVIEW OF CURRENT PRACTICE

Researchers polled a number of state DOTs and vendors of profiling equipment to:

- Gather information on how agencies are implementing wide-footprint lasers for quality assurance testing of pavement smoothness.
- Determine whether agencies are using wide-footprint lasers to measure ride quality over the highway network for pavement management.
- Gauge the current usage of these lasers for inertial profile measurements to determine ride quality.

For this review, researchers solicited information from contacts with state departments of transportation in Florida, Maryland, Minnesota, Ohio, Virginia, and Washington. A couple of these agencies (Minnesota and Virginia) shared information from comparative evaluations of single-point and Roline lasers that were reported in earlier sections of this chapter. Among manufacturers of profiling equipment, researchers communicated with Ames Engineering, Dynatest, International Cybernetics Corporation (ICC), Pathway, and Surface Systems and Instruments (SSI). All these vendors have sold profilers to government agencies and paving contractors that are used for network level surveys of pavement rideability and project level quality assurance testing of pavement smoothness. Three of these vendors (Ames, Dynatest, and SSI) have profilers that Texas contractors and service providers currently use for QA testing of pavement smoothness on projects where Item 585 or SP247-011 are included in the plans. The findings from the review of current practice are presented in the following section, and reflect the information obtained at the time of the surveys.

Agency Practice with Respect to Implementing Wide-Footprint Lasers in Current Ride Specifications

All DOTs surveyed implement ride specifications with provisions for quality assurance testing of pavement smoothness based on inertial profile measurements. In this regard, the acceptance criteria used in the relevant specifications are based on data taken with the conventional single-point laser. Because existing criteria are tied to this laser, a number of DOTs have conducted tests comparing IRIs between single-point and Roline laser profiles. In addition to the comparative evaluations reported in this technical memorandum, Ohio and Maryland have conducted in-house comparisons but on a much more limited scale compared to tests conducted in Texas, Minnesota, and Virginia. Maryland has run its Roline-equipped inertial profiler in all of the department's asphalt test sites and verified that the Roline provides a reasonable match to other working profilers for test sites with no aggressive surface texture. Because of this finding, Maryland has not modified its existing ride specification to incorporate new acceptance criteria for the Roline. At the time of this survey, the department planned to purchase a SurPRO 3500 reference profiler to verify ride quality measurements from profiles collected with single-point and Roline lasers, particularly on pavement sections with more challenging surface textures.

Just like Maryland, the ride specifications that Minnesota and Ohio currently implement do not differentiate between single-point and wide-footprint lasers. Any laser on a duly certified profiler can be used for quality assurance testing on projects where the ride specification is used.

In Ohio, all concrete paving contractors have certified profilers equipped with Roline lasers. In the DOT's opinion, the contractors in the state understand that if they are measuring on a longitudinally patterned surface, a wide-footprint sensor works to their advantage.

With respect to the department's inertial profilers, most are equipped with conventional single-point lasers. However, Ohio owns one profiler with a K.J. Law infrared laser that has five slightly bigger dots arranged in a row transverse to the direction of travel. In addition, the department upgraded its Ames profiler with Roline lasers in 2010.

Based on tests conducted in-house, Ohio has not seen a significant issue with using single-point lasers on diamond-ground surfaces. The department believes that this finding is largely due to the high quality grinding that is typically achieved. Also, the blade width and spacers used with grinding machines are about the same across projects in the state.

Like Maryland, Ohio was planning to acquire a reference profiler at the time of this survey. The department plans to move from certifying profilers based on IRI to certifying equipment based on their ability to measure profile. At the time of this survey, the Ohio DOT was looking forward to the findings from FHWA's pooled fund study, TPF-5(063) on *Improving the Quality of Pavement Profiler Measurement*, for guidance on equipment that agencies can use to certify profilers. Researchers note that this pooled fund study completed an evaluation of reference profilers on which findings are presented shortly in this chapter.

Like Maryland and Ohio, Minnesota's bituminous and concrete ride specifications do not differentiate between laser types. The same pay schedules are used for all lasers. Contractors can use any laser as long as their profilers meet MnDOT's certification requirements. In cases where the contractor's results are questioned, MnDOT's engineer has the option of requiring a retest on any portion of the project. For these cases, the engineer can decide if the contractor, an independent testing firm, or the department will do the retest. If this last option is used, MnDOT will retest the surface using its high-speed profiler equipped with two Roline lasers.

For profiler certification, MnDOT uses an ICC SurPRO profiler to collect reference profiles and establish the reference IRIs on its certification sections. The department maintains two sections: one transversely tined concrete pavement and one dense-graded bituminous mix. Each contractor is required to submit unfiltered longitudinal profiles from five runs made on each section. MnDOT then compares the data from these runs against the reference profiles to determine if an inertial profiler passes or fails certification. In this regard, the following requirements are stipulated:

- The average IRI from the five runs on each section must be within 5 percent of the reference IRI.
- The standard deviation of the IRIs from a given section must be no greater than 3 percent of the average IRI computed from the five runs.
- Each IRI filtered test profile must correlate to the corresponding reference profile by at least 85 percent and the average cross-correlations from the five runs must be at least 90 percent.
- All five runs on a given section must be within 0.2 percent of the actual section length.

The other states surveyed (Florida, Virginia, and Washington) do not yet have provisions to use the Roline for quality assurance testing of pavement smoothness. Based on results from the comparative tests reported previously, the Virginia DOT thinks that the existing Roline system is not yet ready for implementation, and that a standard tire-bridging algorithm needs to be established before Rolines can be used in practice. The department is working with Virginia Tech to install some longitudinally grooved/ground sections at its Smart Road facility to run further tests.

The Florida and Washington State DOTs are implementing ride specifications that use the conventional single-point laser for quality assurance testing of pavement smoothness on asphalt concrete projects. In both agencies, QA tests are conducted using department-owned and -operated inertial profilers equipped with conventional single-point lasers. For portland cement concrete projects, both DOTs implement a ride specification with options of using the profilograph or the straightedge for acceptance testing of pavement smoothness on these pavements. At the time of this survey, both agencies did not have inertial profilers with Roline lasers. Washington DOT is concerned about the effects of using the Roline on the year-to-year trends in the department's asphalt concrete ride quality data and on the pay schedules for asphalt concrete contracts. All agencies surveyed do not have plans to use the Roline for network level surveys of pavement smoothness. This annual data collection effort will still be performed using inertial profilers with conventional single-point lasers.

Survey of Profiler Manufacturers

Researchers surveyed profiler manufacturers to gauge the current usage of profilers with wide-footprint lasers. Between the manufacturers polled, researchers found a wide range in the number of profilers sold with wide-footprint lasers. Without identifying specific manufacturers, sales of these units varied from none for one vendor to over 100 Roline lasers sold on profilers purchased from another. For this other vendor, there were 64 three KHz Roline lasers sold over the past two years compared to 26 single-point lasers purchased within the same period. All wide-footprint lasers that vendors surveyed in this task have sold are Roline lasers from LMI/Selcom. One vendor reported running tests with another wide-footprint laser from Bytewise. However, the company pulled this laser out of the market in 2010. At the time of this survey, no other wide-footprint lasers for profiling applications other than the Rolines were commercially available.

The vendor with the highest sales of Roline units also mentioned that the lasers were positioned such that the footprint was perpendicular to the direction of travel on all such units sold. However, another vendor who has sold over 20 Roline systems over the past several years mentioned that his company usually mounts the Roline laser with the beam perpendicular to the direction of travel less 5° to 10° to avoid any recurring capture of a transverse tine. This same vendor also added that his systems do not use the entire 4-inch width of the Roline footprint as they found the quality of the points near the outer edges of the beam array to be less optimal. This vendor also offered the following noteworthy comments:

> *Agencies have not enacted detailed specifications for the mounting orientation or the tire-bridge filter parameters. Over the past few years, there is some evidence that Roline systems were released into the field perhaps before the sensor was fully tested and optimized. We have seen some questionably low IRI values (and smoother profile traces) based on what could be attributable to over-filtering of the Roline sensor data built into the design of the profiling system. A legitimate issue/concern may exist as to whether some DOT agencies are paying bonuses on very smooth pavements where some degree of the smoothness is being achieved through over-filtered Roline data (as opposed to the actual features on the road surface).*

A similar sentiment regarding the absence of a standard tire-bridging filter was echoed by the Virginia DOT. To the researchers' knowledge, most vendors use the tire-bridging algorithm built into the Roline by LMI/Selcom. However, vendors can vary the filter settings. There is one vendor researchers know of that developed its own tire-bridging algorithm and uses this algorithm as the standard on Roline equipped profilers it sells. Without a national standard, consideration should be given to adding a specification on tire-bridge filter settings in Test Method Tex-1001S as part of implementing wide-footprint lasers for QA testing of pavement smoothness in Texas. Vendors are receptive to any guidance or directions from DOTs on this issue.

In terms of establishing which lasers or what system settings are giving the "correct" ride quality measurements, the proposed approach in this project is to compare the different laser profiles against reference measurements. In this regard, FHWA's pooled fund study TPF-5(063) completed an evaluation of reference profilers that assessed the accuracy and repeatability of profiles from three different systems provided by vendors that participated in the study. Tables 2.23 and 2.24 provide an overall summary of the test results from information provided by FHWA. Looking at the cross-correlation coefficients presented in Tables 2.23 and 2.24, the ICC SurPRO 3000+ (also identified as the SurPRO 3500 from other communications with the pooled fund study group and ICC) showed the best overall performance among the reference profilers tested.

The following observations are noted from Table 2.23.

- All three candidate devices gave good performance in terms of the accuracy of long wavelength components of measured profiles where the cross-correlations are all above 0.9.
- All three devices showed poor performance in terms of the accuracy of short wavelength components.
- In terms of the accuracy of IRI-filtered profiles, only the SurPRO 3000+ profiler achieved cross-correlations of at least 0.9 on all surfaces tested.

Relative to the benchmark profiler, Table 2.24 shows that the SurPRO 3000+ and SSI CS8800 reference profilers generally gave excellent repeatability on the long and medium wavelength components and on IRI-filtered profiles. The SurPRO is the only profiler that got cross-correlations of at least 0.9 on repeatability of short wavelength components. It is interesting to note that the benchmark profiler showed poorer repeatability on the short wavelengths compared to the SurPRO. However, none of the three reference profilers agreed with the benchmark profiler on the short wavelengths (see Table 2.23).

Thus, it appears that the SurPRO reference profiler from ICC would be the recommended device from the pooled fund study. The pooled fund project manager confirmed this recommendation with the research supervisor during the January 2011 TRB meeting. Since that time, TTI has upgraded its SurPRO reference profiler to the 3500 model. This reference profiler was used to verify ride quality measurements from different laser profiling systems tested in this research project. The results from these tests are presented later in this report.

Table 2.23. Agreement of Candidate Reference Profiling Devices with Benchmark Profiler from Pooled Fund Study TPF-5(063).[1]

Surface tested	Profiling device	IRI	Waveband		
			Long	Medium	Short
Dense-graded AC	Auto rod and level	0.730	0.985	0.688	0.052
	SSI CS8800	0.880	0.990	0.845	0.093
	SurPRO 3000+	0.980	0.993	0.960	0.235
12.5mm SMA	Auto rod and level	0.904	0.982	0.881	0.157
	SSI CS8800	0.856	0.949	0.821	0.025
	SurPRO 3000+	0.964	0.985	0.948	0.100
Chip seal	Auto rod and level	0.764	0.992	0.664	0.125
	SSI CS8800	0.869	0.983	0.838	0.013
	SurPRO 3000+	0.985	0.998	0.972	0.045
Transversely tined	Auto rod and level	0.587	0.968	0.490	0.088
	SSI CS8800	0.864	0.990	0.809	0.019
	SurPRO 3000+	0.916	0.994	0.818	0.094
Diamond ground	Auto rod and level	0.591	0.984	0.429	0.099
	SSI CS8800	0.733	0.996	0.473	0.035
	SurPRO 3000+ [2]	0.902	0.999	0.787	0.075
Longitudinally tined	Auto rod and level	0.828	0.946	0.861	0.074
	SSI CS8800	0.897	0.931	0.904	0.034
	SurPRO 3000+	0.949	0.953	0.934	0.190

[1]Agreement measured in terms of cross-correlation between test profiles and benchmark profiles. Cross-correlations closer to unity indicate better agreement.
[2]Second visit to the test section.

Table 2.24. Repeatability of Reference and Benchmark Profilers Tested in Pooled Fund Study TPF-5(063).[1]

Surface tested	Profiling device	IRI	Waveband		
			Long	Medium	Short
Dense-graded AC	Benchmark profiler	0.979	0.991	0.975	0.485
	Auto rod and level	0.900	0.985	0.896	0.200
	SSI CS8800	0.977	0.989	0.972	0.159
	SurPRO 3000+	0.997	1.000	0.996	0.922
12.5mm SMA	Benchmark profiler	0.978	0.996	0.973	0.611
	Auto rod and level	0.919	0.993	0.905	0.272
	SSI CS8800	0.965	0.968	0.972	0.678
	SurPRO 3000+	0.997	0.999	0.996	0.952
Chip seal	Benchmark profiler	0.991	0.999	0.977	0.655
	Auto rod and level	0.879	0.996	0.860	0.305
	SSI CS8800	0.940	0.967	0.953	0.591
	SurPRO 3000+	0.994	0.999	0.991	0.905
Transversely tined	Benchmark profiler	0.971	0.992	0.965	0.659
	Auto rod and level	0.868	0.984	0.871	0.267
	SSI CS8800	0.986	0.995	0.978	0.314
	SurPRO 3000+	0.997	0.997	0.992	0.925
Diamond ground	Benchmark profiler	0.978	0.999	0.959	0.355
	Auto rod and level	0.767	0.988	0.737	0.235
	SSI CS8800	0.958	0.995	0.842	0.189
	SurPRO 3000+ [2]	0.993	1.000	0.980	0.921
Longitudinally tined	Benchmark profiler	0.994	0.997	0.992	0.615
	Auto rod and level	0.873	0.967	0.882	0.244
	SSI CS8800	0.991	0.987	0.993	0.544
	SurPRO 3000+	0.997	0.998	0.997	0.945

[1]Repeatability measured in terms of cross-correlation between repeat runs from a given device. Cross-correlations closer to unity indicate better repeatability.
[2]Second visit to the test section.

CHAPTER III. FIELD TEST PLAN

To determine the impact of wide-footprint lasers on quality assurance tests conducted under TxDOT's existing ride specifications, the research work plan included a task to collect field test data to determine where differences in ride quality measurements between lasers are observed, and the expected range of these differences for various surface types. This chapter presents the field test plan researchers developed to guide the comparative laser measurements conducted in this project. The test plan follows closely the test matrix proposed in the project work plan.

TEST PLAN FOR COMPARATIVE LASER MEASUREMENTS

Table 3.1 shows the proposed test matrix for collecting field measurements to compare profiles and ride quality statistics determined from different lasers. The following sections described the elements of this test matrix.

Table 3.1. Proposed Test Matrix for Comparative Laser Measurements.

Type of profile measurement	Pavement/ Surface type	Testing Level			
		Level 1	Level 2		
		TTI	TxDOT1	TxDOT2	Other profiler
Inertial • Single-point/ texture laser • Wide-footprint • 19mm laser	Flexible • Dense-graded • SMA • PFC	F1~F12	F2,F6,F8	F2,F6,F8	F2,F6,F8
	Rigid • Trans. tined • Carpet/Belt drag	R1~R12	R1,R4,R7	R1,R4,R7	R1,R4,R7
	Surface-treated road/primed flexbase	S1~S12	S3,S6,S9	S3,S6,S9	S3,S6,S9
Reference (ground truth)	Flexible • Dense-graded • SMA • PFC	F2*a*, F6*b*, F8*c*			
	Rigid • Trans. tined • Carpet/Belt drag	R1*a*, R4*b*, R7*c*			
	Surface-treated road/primed flexbase	S3*a*, S6*b*, S9*c*			

Profile Measuring Equipment

Both inertial and reference profile measurements are included in the test plan. On this project, researchers used the SurPRO 3500 for the purpose of establishing ground truth measurements with which to assess the profiles and IRIs determined from the different lasers. The SurPRO 3500 (shown in Figure 3.1) is the same profiler used to collect reference data on the profiler certification track maintained by TTI. This device came out of the Federal Highway Administration pooled fund study TPF-5(063), which conducted an evaluation of reference profilers that assessed the accuracy and repeatability of profiles from three different systems provided by vendors that participated in the study. The results from this evaluation were summarized in the previous chapter. Based on the results obtained from comparative testing, the FHWA pooled-fund study recommended the SurPRO as the reference profiler device for evaluating measurements made with other inertial profilers.

Figure 3.1. SurPRO 3500 Reference Profiler.

With respect to the types of lasers to be used for comparative testing, researchers put together the inertial profiling system shown in Figure 3.2, which consists of three portable profiler modules that permit concurrent measurement of surface profiles using the 3 KHz Roline, 19mm, and 64 KHz texture lasers. The decision to use these lasers was made in consultation with the project monitoring committee (PMC). Among these lasers, the Roline projects the widest footprint, measuring 100mm in length while the texture laser projects a single-dot footprint similar to the conventional lasers used on TxDOT's profilers. To date, the Roline is the only wide-footprint laser used on commercially available inertial profilers. This finding is based on the survey of profiler and laser sensor manufacturers conducted in this project.

The portable texture laser module provided single-point profiles and texture statistics from tests made with the three-laser profiling system shown in Figure 3.2. The Roline profiler module in this system was set up to collect scan data in free mode to get the elevations along the laser footprint as opposed to collecting data in bridge mode, which provides only a bridged value of the elevation measurements along the laser footprint at a given station. Collecting Roline data in free mode permitted researchers to evaluate optimal tire-bridge filter settings based on reference profile measurements collected with the SurPRO 3500 reference profiler in this project. This evaluation is presented later in this report.

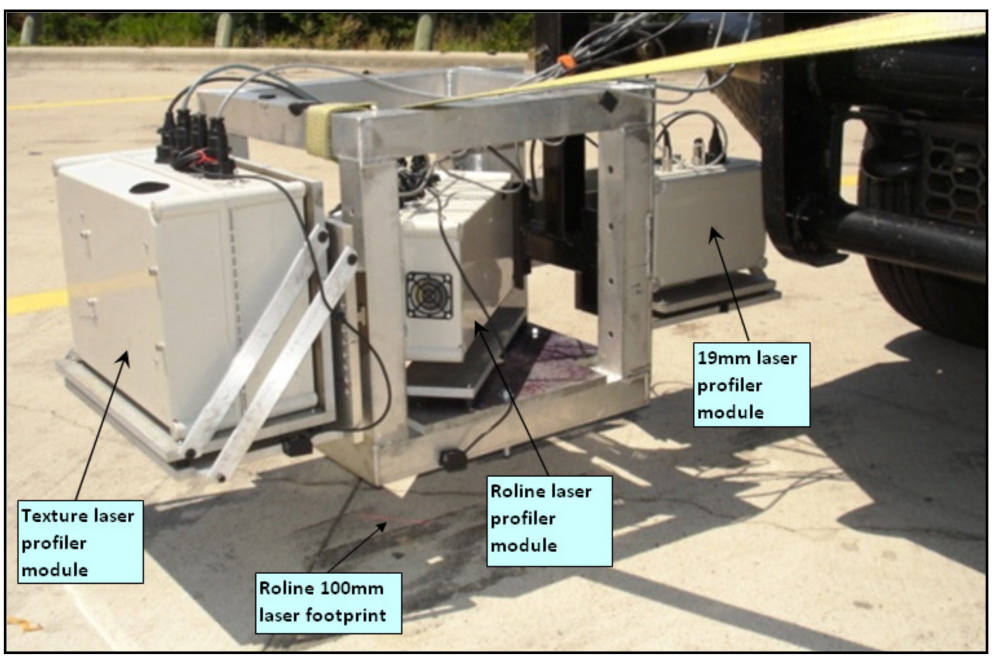

Figure 3.2. Three-Laser Profiling System for Comparative Laser Testing.

Pavement Test Sections

The test matrix shown in Table 3.1 identifies the types of pavement surfaces researchers proposed to test in this research project. The surface types cover dense-graded asphalt concrete mixtures, stone-matrix asphalt mixes, permeable friction courses, transversely tined continuously reinforced concrete pavements, concrete pavements with carpet or belt dragged surfaces, and primed flexible base surfaces. The test matrix included tests on primed flexible base to consider the potential impact of the newer wide-footprint lasers on quality assurance tests conducted under SP247-011. Of particular interest to this project are tests on covered or inverted prime coats (RC250 with Grade 5 aggregate) that are used as temporary wearing courses prior to placement of the surface treatment. The texture of these prime coats and the effect of this texture on the IRIs computed from different laser profiles were investigated in this project.

Table 3.1 was later expanded to include tests on longitudinally tined CRC pavements and seal coat surfaces. While the current practice is to transversely tine concrete pavements in Texas, the department has placed experimental sections of longitudinally tined CRC pavements along FM1938 in Tarrant County, as part of ongoing investigations to address noise issues on concrete pavements. TxDOT is presently considering developing specifications for construction of these pavements to address noise issues associated with transverse tines.

With respect to testing seal coat surfaces, TxDOT does not currently have any ride quality specification applicable to these pavements. However, seal coats make up a significant percentage of the state-maintained highway network that the department profiles annually to monitor ride quality for pavement management purposes. Thus, seal coat surfaces were added to the test plan during the course of the project to assess the need for measuring the ride quality on seal coat pavements using profilers equipped with wide-footprint lasers.

Field Tests Planned on Pavement Sections

The proposed test matrix in Table 3.1 shows two levels of testing. Underneath these levels of testing are labels (e.g., F1, R1, and S1) that represent the sections to be tested. For example, F1 might stand for a dense-graded flexible pavement section located along a highway of a given district, while S1 might identify a surface treated road with an inverted prime. F2 might identify a PFC section while R1 might flag a CRCP section with conventional transverse tines. The two levels of testing were meant to account for different sources of variability that can affect the differences in ride statistics determined from different laser profiles. Under Level 1 testing, laser measurements were conducted concurrently using the three-laser profiling system shown in Figure 3.2. Given that the same TTI vehicle, operators, and profiling algorithm are used, and given that concurrent laser measurements are made, the data from Level 1 tests provided comparisons of differences in IRIs and surface defects (bumps and dips) based largely on the differences between the lasers tested. Thus, Level 1 tests are meant to provide estimates of the expected range of the differences between the single-point and the other lasers when the possible sources of variability due to the test vehicle, operator, wheel path tracking, and profile algorithm are eliminated or minimized. The differences in computed ride statistics can largely be attributed to the differences between the single-point and the other lasers.

While Level 1 tests are meant to estimate the inherent differences between lasers, quality assurance tests (in practice) are conducted with the contractor's own equipment and operator. Verification and referee tests are also done using TxDOT's inertial profiler and operator. Thus, it becomes important to compare different lasers under test conditions that resemble more closely the conditions under which quality assurance tests are conducted. For this reason, the proposed test matrix in Table 3.1 includes Level 2 tests with different profilers and operators, and no concurrent measurements other than the operators trying to follow the same wheel path tested on a given section. The proposed plan required TxDOT's assistance in providing TxDOT profilers and operators for Level 2 testing. To have a commercial profiler represented in these tests, TTI executed an agreement with Dynatest Consulting to provide profile data collection services using a test vehicle equipped with Roline, 19mm, and conventional single-point lasers. To make the test plan manageable, researchers proposed using only a subset of the test sections established for the comparative laser measurements. This approach is illustrated in Table 3.1 where only three sections are represented for profile measurements under Level 2.

The test plan included reference profile measurements to evaluate proposed adjustments in the existing ride specifications to account for differences in IRI statistics computed from different laser profiles. Due to the relatively time-consuming nature of these measurements, the researchers proposed using only a subset of the sections established for the field tests, and running reference profiles on 528-ft segments of the selected sections (e.g., F2*a*, F6*b*, and F8*c* where the letters indicate the selected segments in Table 3.1). For these tests, TxDOT provided traffic control on sections located along in-service pavements so that researchers can collect reference profiles using the SurPRO. Researchers made three repeat SurPRO runs on each segment.

The test plan also included tests on CRCP sections where profiles from the Roline laser are collected at two different orientations. TxDOT added this variable to the test plan to consider concerns that the paving industry raised about the effect of transverse tining on the IRI values computed from inertial profile measurements. Thus, researchers fabricated the mounting platform shown in Figure 3.2 to permit the operator to position the Roline at 0°, 30°, or 45°. The base orientation of 0° is where the Roline footprint is perpendicular to the direction of travel, which simulates data collection with the single-point laser on which the pay adjustment schedules in the current Item 585 specification are based. The other orientation that researchers proposed for testing is where the Roline footprint is oriented at 45°. This recommendation is based on findings from preliminary work conducted to develop the field test plan, which is documented in the following section.

ROLINE LASER TESTING AT DIFFERENT ORIENTATION ANGLES

As noted previously, the test configuration shown in Figure 3.2 permits one to position the Roline such that the laser scan is at 0°, 30°, or 45° from the lateral axis of the test lane. While the mounting hardware could have been set up to permit data collection at higher inclinations of up to 90°, there was a concern that higher inclinations could potentially mask roughness at transverse construction joints due to averaging of the elevations across the joint. Thus, researchers conducted tests on concrete pavement sections to compare IRIs determined from runs made with the Roline at 0-, 30-, and 45-degree angles. Researchers performed these tests on CRCP pavement sections located along SH6 south of College Station, and along SH36 in Cameron. The surfaces tested covered conventional transverse tines (SH6 and SH36) and variable transverse tines (SH36). On each section, researchers collected data along the right wheel path using the three-laser inertial profiling system shown in Figure 3.2.

Tables 3.2 to 3.4 present the IRIs calculated from the Roline test data. Researchers compared the IRIs to evaluate the effect of the Roline footprint angle. For this evaluation, researchers performed pairwise comparisons of the IRIs calculated from the Roline profiles measured at different angles. Specifically, researchers examined the difference in IRIs between any two test angles for corresponding runs on each 0.1-mile section. Researchers then determined the 95 percent confidence intervals of the IRI differences, which are summarized in Table 3.5. In this analysis, the IRI differences were determined as follows:

- Comparison of IRIs between 0 and 30°: $IRI_{0°} - IRI_{30°}$.
- Comparison of IRIs between 0 and 45°: $IRI_{0°} - IRI_{45°}$.
- Comparison of IRIs between 30 and 45°: $IRI_{30°} - IRI_{45°}$.

Table 3.2. IRIs Calculated from Roline Profile Measurements on SH6 CRCP Section.

Laser Orientation	Distance Interval (ft)	IRI (inch/mile)			Average IRI (inch/mile)	IRI std. deviation (inch/mile)
		Run 1	Run 2	Run 3		
0°	0 to 528	53.6	55.8	57.0	55.5	1.72
	528 to 1056	63.8	66.0	66.9	65.6	1.59
	1056 to 1584	62.3	62.5	60.0	61.6	1.39
	1584 to 2112	77.1	75.5	74.5	75.7	1.31
	2112 to 2640	68.0	67.1	63.9	66.3	2.15
	2640 to 3168	62.3	60.6	66.6	63.2	3.09
	3168 to 3696	77.8	77.0	77.8	77.5	0.46
	3696 to 4224	81.4	76.4	81.8	79.9	3.01
30°	0 to 528	54.8	55.8	55.4	55.3	0.50
	528 to 1056	65.8	70.9	68.0	68.2	2.56
	1056 to 1584	61.3	63.7	61.5	62.2	1.33
	1584 to 2112	74.3	74.2	75.2	74.6	0.55
	2112 to 2640	64.8	65.9	69.2	66.6	2.29
	2640 to 3168	62.5	61.2	66.1	63.3	2.54
	3168 to 3696	84.7	79.0	78.3	80.7	3.51
	3696 to 4224	82.1	80.2	81.0	81.1	0.95
45°	0 to 528	53.3	56.0	57.8	55.7	2.26
	528 to 1056	63.4	64.9	62.6	63.6	1.17
	1056 to 1584	60.4	60.6	58.5	59.8	1.16
	1584 to 2112	76.3	76.1	73.6	75.3	1.50
	2112 to 2640	60.1	58.2	58.7	59.0	0.98
	2640 to 3168	59.4	59.9	60.1	59.8	0.36
	3168 to 3696	83.1	80.3	78.5	80.6	2.32
	3696 to 4224	78.9	79.6	78.1	78.9	0.75

Table 3.3. IRIs Calculated from Roline Profile Measurements on SH36 CRCP Section with Conventional Transverse Tines.

Laser Orientation	Distance Interval (ft)	IRI (inch/mile)			Average IRI (inch/mile)	IRI std. deviation (inch/mile)
		Run 1	Run 2	Run 3		
0°	0 to 528	86.8	88.2	88.1	87.7	0.78
	528 to 1056	78.1	77.8	80.8	78.9	1.65
	1056 to 1584	51.3	50.3	51.8	51.1	0.76
	1584 to 2112	60.4	59.3	59.1	59.6	0.70
	2112 to 2640	87.7	84.4	82.8	85.0	2.50
	2640 to 3168	72.1	71.2	73.5	72.3	1.16
	3168 to 3696	105.1	105.7	107.3	106.0	1.14
	3696 to 4224	80.9	79.7	78.7	79.8	1.10
	4224 to 4752	75.0	71.2	74.3	73.5	2.02
30°	0 to 528	86.1	83.7	82.1	84.0	2.01
	528 to 1056	79.5	77.3	77.9	78.2	1.14
	1056 to 1584	51.5	50.6	51.7	51.3	0.59
	1584 to 2112	58.8	57.4	55.7	57.3	1.55
	2112 to 2640	85.9	83.0	83.3	84.1	1.59
	2640 to 3168	69.9	68.6	68.1	68.9	0.93
	3168 to 3696	102.9	105.2	102.8	103.6	1.36
	3696 to 4224	75.1	76.0	77.2	76.1	1.05
	4224 to 4752	70.6	68.0	71.5	70.0	1.82
45°	0 to 528	83.5	83.7	83.0	83.4	0.36
	528 to 1056	76.6	75.4	78.8	76.9	1.72
	1056 to 1584	49.3	48.7	49.6	49.2	0.46
	1584 to 2112	55.4	54.8	56.9	55.7	1.08
	2112 to 2640	79.9	84.0	82.7	82.2	2.10
	2640 to 3168	68.4	67.9	68.2	68.2	0.25
	3168 to 3696	103.2	103.6	102.3	103.0	0.67
	3696 to 4224	74.0	76.1	74.7	74.9	1.07
	4224 to 4752	69.0	70.0	69.6	69.5	0.50

Table 3.4. IRIs Calculated from Roline Profile Measurements on SH36 CRCP Section with Variable Transverse Tines.

Laser Orientation	Distance Interval (ft)	IRI (inch/mile)			Average IRI (inch/mile)	IRI std. deviation (inch/mile)
		Run 1	Run 2	Run 3		
0°	0 to 528	97.5	96.5	95.5	96.5	1.00
	528 to 1056	90.5	87.6	96.7	91.6	4.65
	1056 to 1584	86.3	86.6	86.7	86.5	0.21
	1584 to 2112	98.0	97.3	99.0	98.1	0.85
	2112 to 2640	91.9	87.0	92.6	90.5	3.05
	2640 to 3168	77.9	78.3	83.4	79.9	3.07
	3168 to 3696	80.2	83.8	87.1	83.7	3.45
	3696 to 4224	88.6	94.2	91.8	91.5	2.81
30°	0 to 528	92.5	91.0	88.7	90.7	1.91
	528 to 1056	90.3	87.5	83.5	87.1	3.42
	1056 to 1584	80.6	81.6	80.8	81.0	0.53
	1584 to 2112	97.0	90.3	84.7	90.7	6.16
	2112 to 2640	92.6	92.6	91.0	92.1	0.92
	2640 to 3168	89.9	83.0	76.8	83.2	6.55
	3168 to 3696	92.0	85.6	81.1	86.2	5.48
	3696 to 4224	107.6	102.2	90.7	100.2	8.63
45°	0 to 528	88.4	90.4	91.7	90.2	1.66
	528 to 1056	83.2	83.0	89.5	85.2	3.70
	1056 to 1584	78.2	82.5	78.0	79.6	2.54
	1584 to 2112	92.4	85.5	84.7	87.5	4.23
	2112 to 2640	85.6	90.7	85.0	87.1	3.13
	2640 to 3168	78.6	77.1	76.3	77.3	1.17
	3168 to 3696	76.9	75.3	73.5	75.2	1.70
	3696 to 4224	90.4	82.1	87.1	86.5	4.18

Table 3.5. 95% Confidence Intervals of IRI Differences from Roline Angle Tests.

Highway	Surface Type	Test angles compared	Average IRI difference (inch/mile)	95% confidence interval of IRI differences (inch/mile)		Statistically significant?[1]
				Lower limit	Upper limit	
SH6	Conventional transverse tines	0° vs. 30°	−0.842	-1.879	0.196	No
		0° vs. 45°	1.554	0.125	2.983	Yes
		30° vs. 45°	2.396	1.052	3.740	Yes
SH36	Conventional transverse tines	0° vs. 30°	2.267	1.471	3.062	Yes
		0° vs. 45°	3.419	2.651	4.186	Yes
		30° vs. 45°	1.152	0.467	1.837	Yes
SH36	Variable transverse tines	0° vs. 30°	0.892	−2.464	4.248	No
		0° vs. 45°	6.204	4.288	8.120	Yes
		30° vs. 45°	5.725	2.675	8.775	Yes

[1]Confidence interval of IRI differences that includes zero within the interval identifies cases where the IRI differences are not statistically significant at the 95 percent confidence level.

Based on the results shown in Table 3.5, researchers note the following observations:

- Roline measurements collected at 45° tend to give the lowest IRIs. This observation is somewhat expected since this angle would average more of the elevation changes associated with the transverse tines.
- Pairwise comparisons show the IRI differences to be statistically significant at the 95 percent confidence level when the IRIs at 45° are compared with the IRIs at any of the other two angles. This result indicates that the IRIs determined at 45° are lower than the IRIs determined at 0° and 30°, and that the differences are statistically significant.
- In two of the three sites tested, the differences in IRIs between 0° and 30° are not statistically significant.
- Compared to measurements made on the SH6 and SH36 sites with conventional transverse tines, the range of the IRI differences is observed to be wider for pairwise comparisons of data from the SH36 site with variable transverse tines.

In view of the above results, the decision was made to test transversely tined concrete pavements with the Roline laser oriented at 0° and 45°. Given that the proposed test plan includes collection of reference profile measurements, the appropriate orientation angle can be established based on the reference profiles collected with the SurPRO. In addition, since the proposed plan calls for collecting Roline data in free mode, an analysis can be made to come up with recommendations on tire-bridge filter settings that reduce the differences between IRIs computed from the Roline and SurPRO profiles. Chapter V of this report presents this evaluation. In the next chapter, researchers document the work conducted to develop and verify the three-laser inertial profiling system shown in Figure 3.2.

CHAPTER IV. FIELD TEST PREPARATIONS

INTRODUCTION

Chapter IV describes work performed to set up hardware and software for collecting data using the three-laser inertial profiling system that researchers proposed to use in this project. The chapter also documents work performed to develop software for processing data collected with the system, and tests conducted to verify the performance of the system prior to field testing. The task of setting up the three-laser system and developing data processing software comprised the following subtasks:

- Subtask A included changes to existing data acquisition software for both field and laboratory testing. UTA researchers modified the current acquisition program for single-point lasers to collect both Ethernet network data from the Roline laser and analog data from the accelerometer, start, and distance sensors. The Roline 1145 provides either the Ethernet line values (free mode) or bridge values (bridge mode) computed in firmware provided with the laser. The laser line values have to be read via the Ethernet connection while the bridge data are read either through the Ethernet or through the Selcom high-speed serial link. Ames profilers use the line laser data directly to compute a bridge reading, whereas the other profiler manufacturers use LMI's tire-bridging filter. Similar to LMI, Ames uses its proprietary bridging algorithm directly on the laser line data for computing profiles. To permit the evaluation of tire-bridge filter settings that provide the best comparisons between IRIs determined from the Roline data and IRIs computed from SurPRO reference profiles, UTA researchers set up the portable Roline profiling system to collect scan data in accordance with the research work plan. Since software code for existing tire-bridging filters are not available, the other part of Subtask A was development of a bridging algorithm, similar to the LMI algorithm.
- Subtask B provided for any needed changes to TxDOT's Ride Console program to collect and report test results.
- Subtask C covered hardware modifications, component purchasing, module construction, mounting, and testing.

- Subtask D involved the development and/or investigation of analysis tools to provide both profile and texture results from data collected with the portable profiler/texture laser module. This subtask also investigated proper methods for handling the treatment of outliers in the texture data since outliers are not clearly defined in the current ASTM E-1845 specification on *Standard Practice for Calculating Pavement Macrotexture Mean Profile Depth* (ASTM, 2011).

SUBTASK A

As mentioned previously, Subtask A included changes to data acquisition software for both field and laboratory testing. Because different bridging algorithms were to be investigated, UTA researchers decided to use a two pass process for computing profile. The first pass involved acquiring the raw sensor data and saving the data to output files. A subsequent program would then read this data and compute the profile. This process has proven invaluable in investigating, not only the different bridging algorithms, but in dealing with other problems that occurred as discussed below.

The Roline 1130 vs. the Roline 1145

The first problem researchers encountered resulted in several changes in the data acquisition process. This problem resulted from incorrect information that researchers received regarding the use of both free mode and LMI bridge mode data. Researchers wanted to collect free mode and bridge mode data simultaneously so that the project bridge algorithm could be compared with the LMI bridge algorithm. The Roline 1130 line laser provides data in either free mode or LMI bridge mode via Ethernet packets, but not at the same time. LMI sales personnel indicated that if the 1130 was upgraded to the Roline 1145 model, the upgraded laser would then be able to output both bridge and free mode data at the same time. The bridge mode would be sent in serial form via the RS485/422 serial format. The free mode data would use the Ethernet packets. Table 4.1 summarizes this comparison. However, UTA researchers later determined that the 1145 can provide data in free mode or bridge mode, but not at the same time.

Table 4.1. Roline Laser Interface Comparison.

Roline Model	Laser Interface	Operating Mode
Roline 1130	TCP/IP	Bridge or free mode
Roline 1140	RS 485/522	Bridge mode only
Roline 1145	TCP/IP or RS 485/422	Bridge or free mode

By recording free mode data, various bridging algorithms can be investigated in accordance with the research plan. In addition, if LMI bridge values can be collected at the same time as the free mode data, various candidate bridging algorithms can be compared with the LMI bridge algorithm. However, since the Roline 1145 cannot provide both line and bridge data at the same time, it would not be possible to determine if the two algorithms used the same data as tracking the same wheel path on separate bridge and free mode runs would be highly unlikely.

Synchronization Issues

During development of the testing software for the Roline, the associated accelerometer and distance readings had to be synchronized with each free mode synchronization (sync) signal. The Roline laser outputs a digital pulse to signal the beginning of each scan. This signal is used to synchronize accelerometer readings to the associated scan. An initial method was developed that was used in profiler certification. However, this method proved to be a problem for collecting data on long sections. At the beginning of the project, researchers thought that the sync signal accompanying each free mode laser scan could be used as an external input to the Data Translation (DT) A/D module to signal the initiation of the corresponding signal conversion. Timing problems occurred in using the sync signal as originally planned. To solve this problem, UTA researchers decided to tie the sync signal to one of the A/D inputs in a similar manner used on the distance and infrared start signals. The data acquisition program was then modified to use the rising edge of each synch signal to synchronize the set of laser readings for each scan with the corresponding digitized sensor readings.

Multiple Laser Data Acquisition

Another issue had to be addressed in running the three-laser profiling system at the same time. Three different profiler modules had to be used. Since each module required an operator, three operators would be needed. Not only is this a logistic problem, it is more prone to operator errors. Additionally, a three-module program was not practical because of the different sampling rate required from the texture laser. Thus, the Roline software was modified so that one program could collect data from both the Roline laser and the 19mm laser. The texture laser was used to measure both profile and macro-texture. TTI researchers developed a mounting frame to hold the three portable profiler modules. This three-laser system setup, mounted on the test vehicle, was previously shown in Figure 3.2.

Both the Roline and 19mm profiling systems use DT9816A A/D converters, which are connected to the same computer. The Roline data collection program was modified to identify the ADCs connected to the computer during initialization. Each DT9816A converter must be related to the proper laser system to avoid a mix-up of data. To identify the laser system for the ADCs, the digital input lines of the ADC were used. For the 19mm laser system, the digital input channel 0 was set to ground, while the digital input signal on the ADC of the Roline system was set to 5 V. Two separate text files were created for the two laser systems, and data were written to these files accordingly. The modified data collection program then detects which module (19mm or Roline) is being read and the appropriate data file is used to record the readings. While both the systems used 5 analog input channels, the sampling rate of the Roline laser system was set to 15 KHz and that of the 19mm system was set to 3 KHz. UTA researchers also modified the callback function to identify the ADC associated with the buffer. The program was changed to assign one thread to set up and start the A/D converter for the 19mm and assign a second thread to initialize the Roline. Each A/D module signals the program when its corresponding buffer needs servicing. Another thread is initiated to read and store the analog data. Using this technique, data were collected from the two laser systems simultaneously. Figures 4.1 and 4.2 provide the general flow procedures for data collection for configuring multiple A/D boards. For configuring the Roline laser and setting it up for data collection, the laser has to be connected to the computer via an Ethernet port. Each Roline laser has a unique IP address, through which a connection can be established. The laser manufacturers supply basic functions that can be used to communicate with the laser. UTA researchers used these functions to connect to the laser and configure its mode of operation. Callback functions were written for receiving the laser data through the Ethernet. The laser data are sent as a collection of multiple TCP/IP packets. The actual data are extracted from these packets and written to a comma separated value (CSV) file, which is input to the profile computation program.

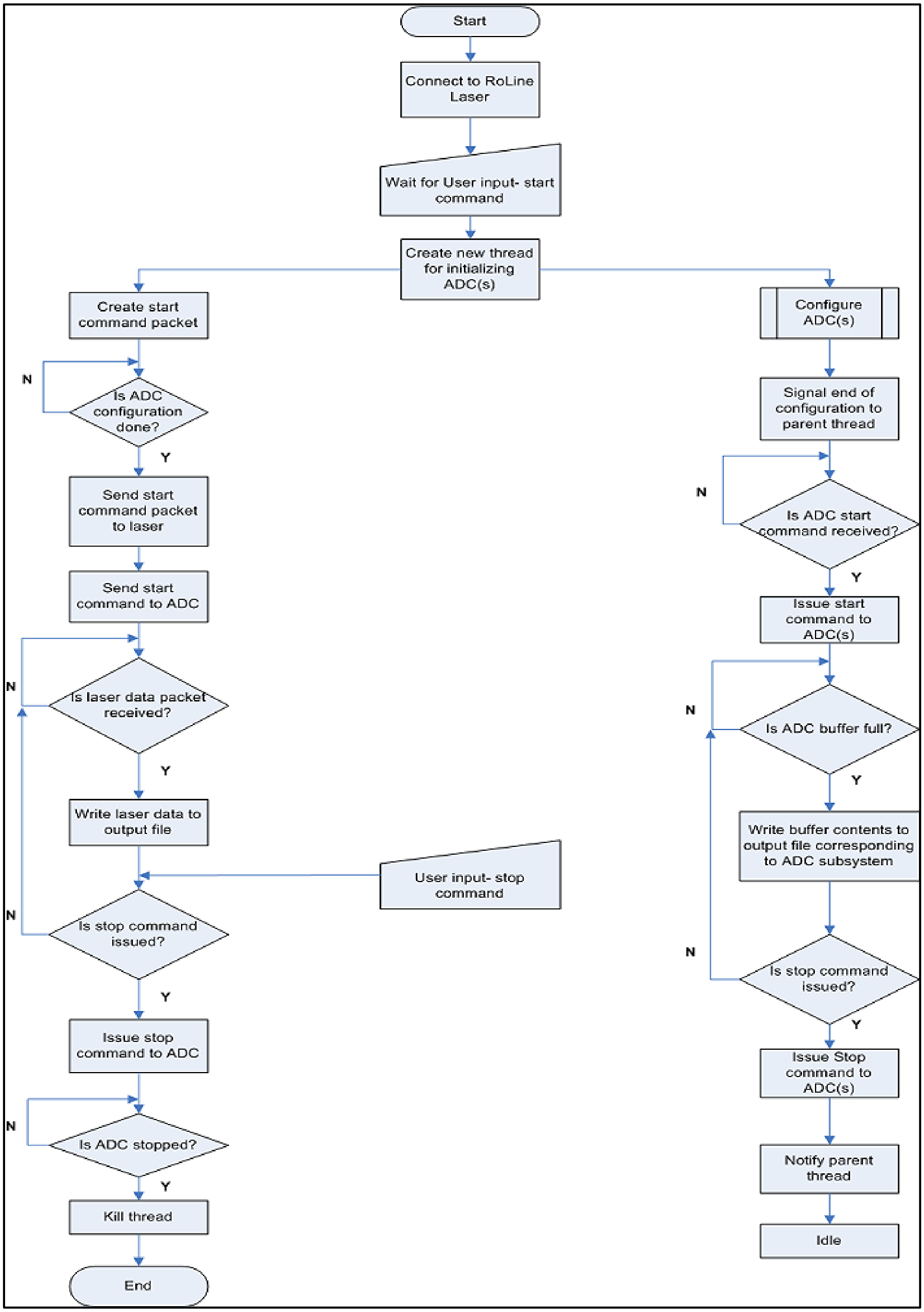

Figure 4.1. Flowchart for the Data Collection Process.

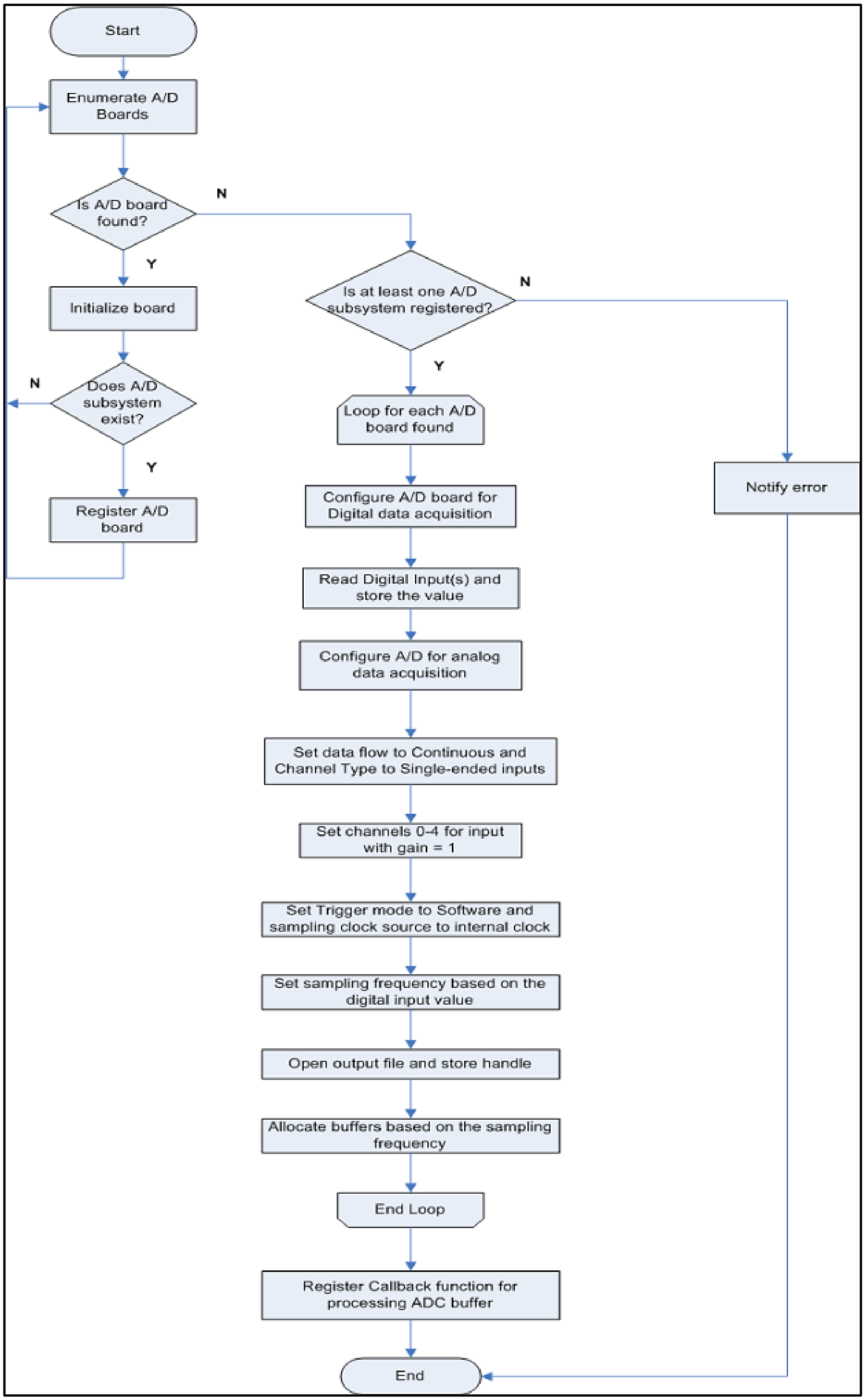

Figure 4.2. Flowchart for Configuring the ADC.

In the Roline data collection and profile computation programs, researchers wrote separate functions for extracting the data from the bridge mode or free mode. The bridge mode sends a single value per scan from the laser. This mode reduces the full scan data to an average value in accordance with the LMI bridging algorithm. The header information is extracted from each packet, and bridge values along with their attributes are stored in the file. The bridge values contain the distance to the target while the attributes field contains the sync index and tracking mode information. Each packet is configured to contain 100 bridge values corresponding to 100 scans of the laser.

The default mode for the Roline laser is the free mode. In free mode, the data for each point in the scan is sent from the laser. Each packet is configured to contain 100 scans of the laser. Each scan of the laser is configured to contain 80 points. These parameters can be changed by writing a new settings file to the laser. The distance value for each point in the scan is stored along with its attribute information.

For collecting the data from the A/D converter simultaneously with the laser, the A/D converter is configured as soon as a connection with the laser is established, and a Start command is received from the user. The driver software included with the DT9816A provides many APIs for configuring the A/D converter. When the Start command is issued, a new thread is created to configure the ADC. The APIs are used to set up the ADC with five analog input channels and to set the sampling frequency. An extra analog channel was provided in the program for any additional signal that may be necessary, such as operating temperature. The buffer size and the number of buffers are set up for the ADC, and a callback function is registered for receiving the data from the ADC when the buffers are full.

Once the configuration of the ADC is completed, the daughter thread sets a signal and waits for a semaphore from the parent thread. When the parent thread receives the signal from the daughter thread, it issues a Start command to the laser and signals to the daughter thread. On receiving the signal from the parent thread, the ADC starts its operation. The callback function for the ADC is called whenever the buffer is full. The data from the buffer contains the digital values of all the five channels and is written to a text file. The callback function for the laser writes the laser data to a CSV file. If the user enters the Stop command, this is conveyed to the ADC as well as the laser. After flushing the buffers to the file, the daughter thread is terminated.

The Roline Bridge and Free Modes

UTA researchers found complete details on the Roline laser from the user's manual (LMI, 2007) that came with the sensor. Finding a suitable bridging algorithm for the Roline laser entailed more effort than initially estimated. The LMI manual provides a general description of the bridging algorithm, but LMI does not provide the source code. With the exception of Ames Engineering, profiler manufacturers are using the LMI bridge mode and thus, the LMI bridging algorithm. Ames uses the free mode data and computes the bridge values using a proprietary method. Researchers investigated several bridging algorithms to develop a suitable alternative to the LMI algorithm. Based on the information presented in the user manual noted previously, this section provides a brief description of the pertinent parts of the Roline laser affecting the bridging algorithm.

Figure 4.3 illustrates the main components of the Roline laser measurement technique. As illustrated in the figure, the laser line projector projects a 2.6- to 5.4-inch wide laser scan across a target. A digital camera mounted at an angle to the laser plane then acquires images of the reflected light from the target. The distance to the target is calculated from the images taken by the digital camera based on the position of the laser line in the image.

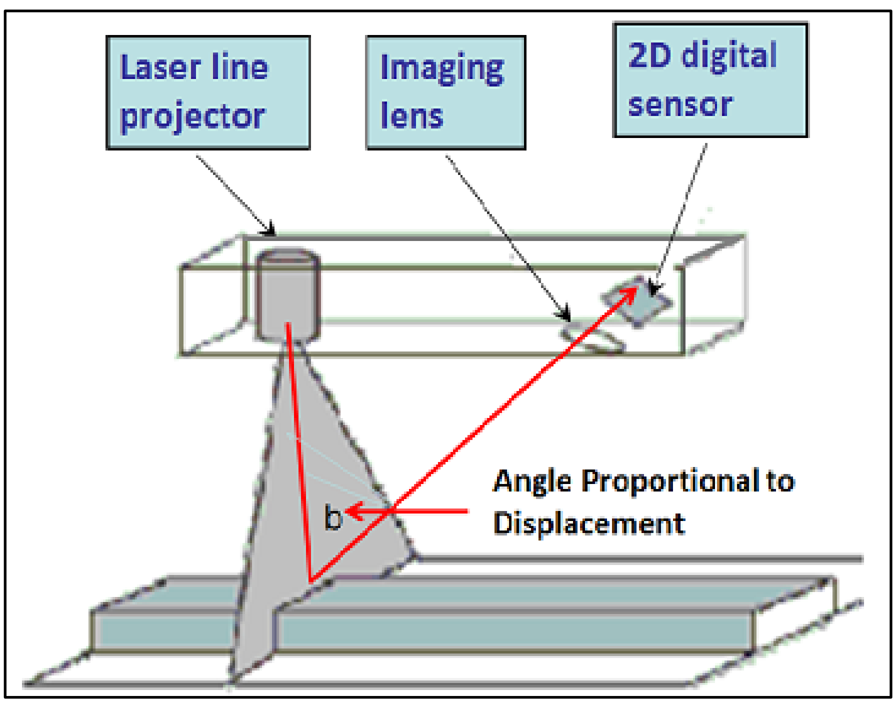

Figure 4.3. Roline Distance Measurement Principle (LMI, 2007).

The Roline 1130/1145 used on the project has a laser scanning rate of 3000 Hz with a stand-off of 200 mm or 7.9 inches. The measurement range (MR) is also 200 mm with a field of view (FOV) of 100 mm or 4 inches at the center of its measurement range. As described previously, the Roline 1130 delivers the output in the form of Ethernet packets while the Roline 1145 provides the option of delivering the output in either Ethernet packets or in the Selcom serial format. Since the Ethernet output format is used on both the free and bridge mode data, the RS485/RS 421 was not used in developing the portable Roline profiling system.

The Roline lasers output a 3000 Hz pulse that signals the start of a new scan. Since it is important for the profiling algorithm to get the accelerometer and laser data at the same instant, this sync pulse is used to synchronize with the accelerometer. The rising edge of the sync pulse coincides with the start of the laser scan and is used to latch to the accelerometer value at that instant. In addition, the laser data are tagged with an index called the sync index that counts the number of sync pulses transmitted since the start of data collection. Synchronization between the laser and accelerometer is achieved by matching the number of sync pulses with the sync index from the sensor data. Figure 4.4 provides a sample of the analog data signals that are connected to the ADC for computing profile.

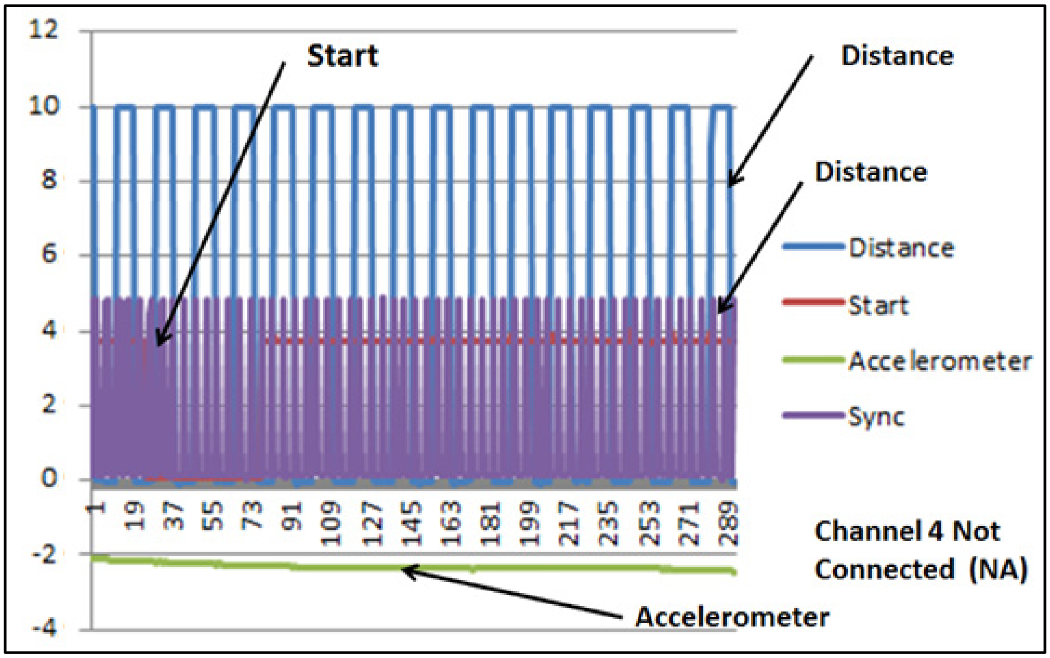

Figure 4.4. Illustration of the Analog Signals Collected by Roline Profiling System.

The LMI bridging algorithm, as described in the LMI Roline user's manual, gives a filtered average of the laser line profile. The user-selectable parameters summarized below specified the amount of filtering.

- First, a 'Region of Interest' is established. This region defines lower and upper bounds on the 197 points comprising the target or scan. When the LMI bridging algorithm is specified (bridge mode), the region of interest is the complete scan consisting of 197 points. In the example given in Figure 4.5, the line scan is segmented into 160 points, defined by the lower and upper bounds shown in the figure (10 and 169, respectively). This region is used in the bridging algorithm to collect data in free mode in this project.

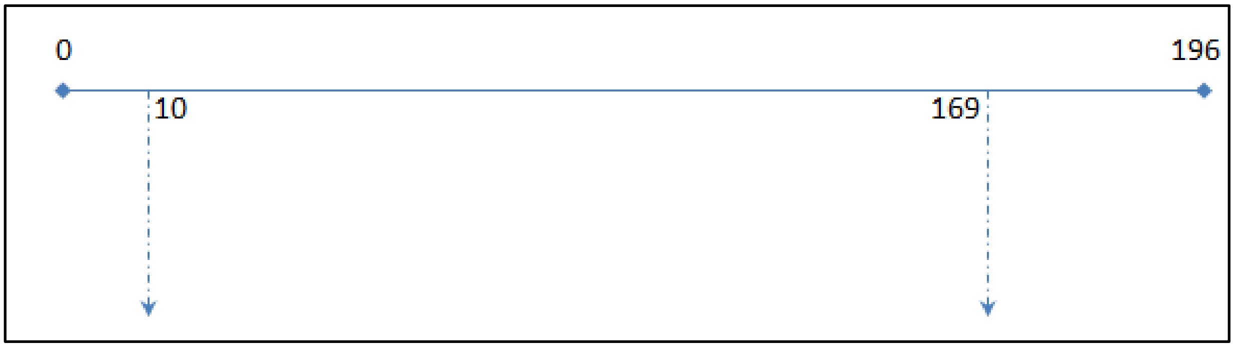

Figure 4.5. Defining the Region of Interest in Roline Scan Data.

- Next, readings where there is a loss of data or are above a user-definable limit (also known as invalids) are removed from the line scan. LMI defines this process as 'data qualification.' For invalid points in the scan, the sensor returns a large negative number (−32768), which distinctly identifies these points for removal.
- If the user selects the normalization option, the remaining points of the scan are sorted in ascending order of the elevation readings. The normalization process involves removing the first and second moments of each scan line (also referred to as detrending). LMI provides a pictorial view of the normalization process in the Roline user's manual, which is illustrated in Figure 4.6.

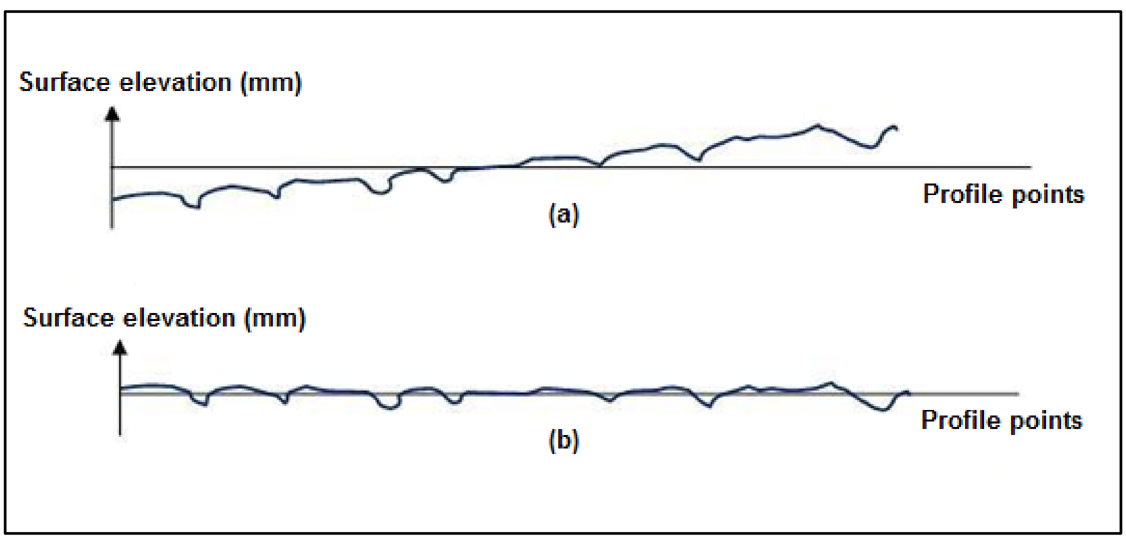

Figure 4.6. Normalizing the Line Scan Data: (a) before Detrending and (b) after Detrending (LMI, 2007).

- Three additional parameters, window size, skip size, and maximum number of invalid points complete the set of parameters for filtering the line scan data. The remaining points are then averaged providing the bridge value. Figure 4.7 illustrates the window size and skip size parameters.

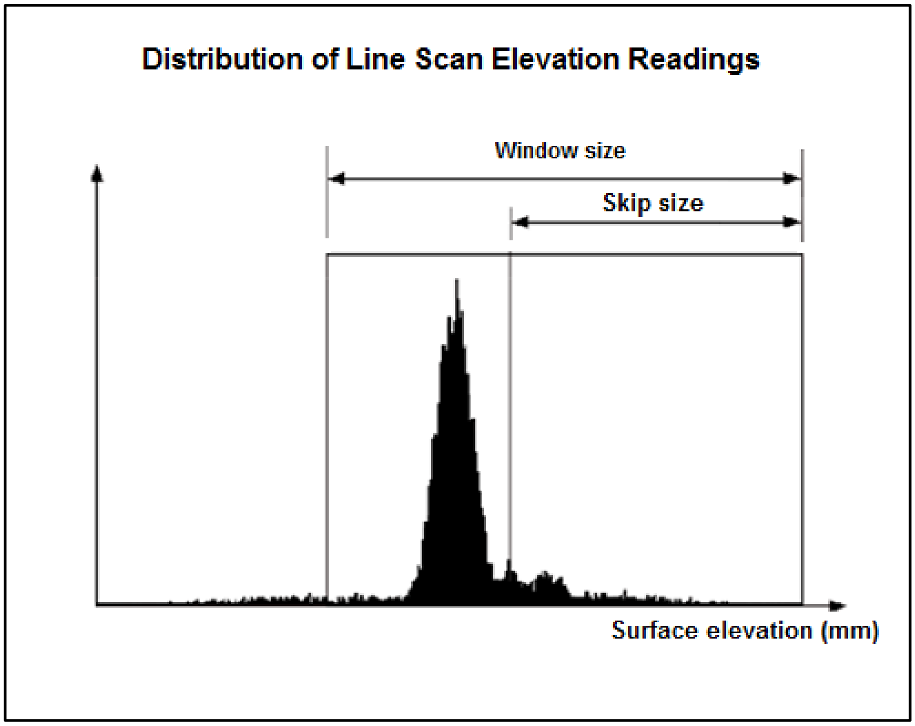

Figure 4.7. Window Size and Skip Size Parameters (LMI, 2007).

The following example illustrates the calculation of a bridge value assuming a region size of 26 points in the line scan data:

43 91 18 26 15 14 87 58 55 14 85 62 35 51 40 8 24 12 18
24 42 5 90 94 49 -32768

1. Remove invalid points (denoted by −32768).

43 91 18 26 15 14 87 58 55 14 85 62 35 51 40 8 24 12 18
24 42 5 90 94 49

2. Assuming the normalize option is selected, detrend the data to remove the slope.

48 96 24 32 21 20 93 64 61 20 91 68 41 57 46 14 29 17 23
29 47 10 95 99 54

3. Sort the points.

10 14 17 20 20 21 23 24 29 29 32 41 46 47 48 54 57 61 64
68 91 93 95 96 99

4. Select the elevation readings for the specified window size of 10 in this example.

54 57 61 64 68 91 93 95 96 99

5. Assuming a skip size of 5, filter the data further by skipping the following points:

91 93 95 96 99

6. Finally, after the last five points are removed, averaging the remaining points (54, 57, 61, 64, and 68) provides a bridge value of 60.8 in this example.

SUBTASK B

Figure 4.8 illustrates the bridging method used in this project to collect and process Roline laser scan data. UTA researchers modified TxDOT's existing Ride Console program to compute profiles from the sensor data collected with the portable Roline profiling system developed in this task. The resulting Roline Ride Console program uses a modified INI file that permits the user to specify the tire bridge filter parameters for the profile computation.

Figure 4.9 illustrates the parameters in this INI file for calculating bridge values in the Roline Ride Console program.

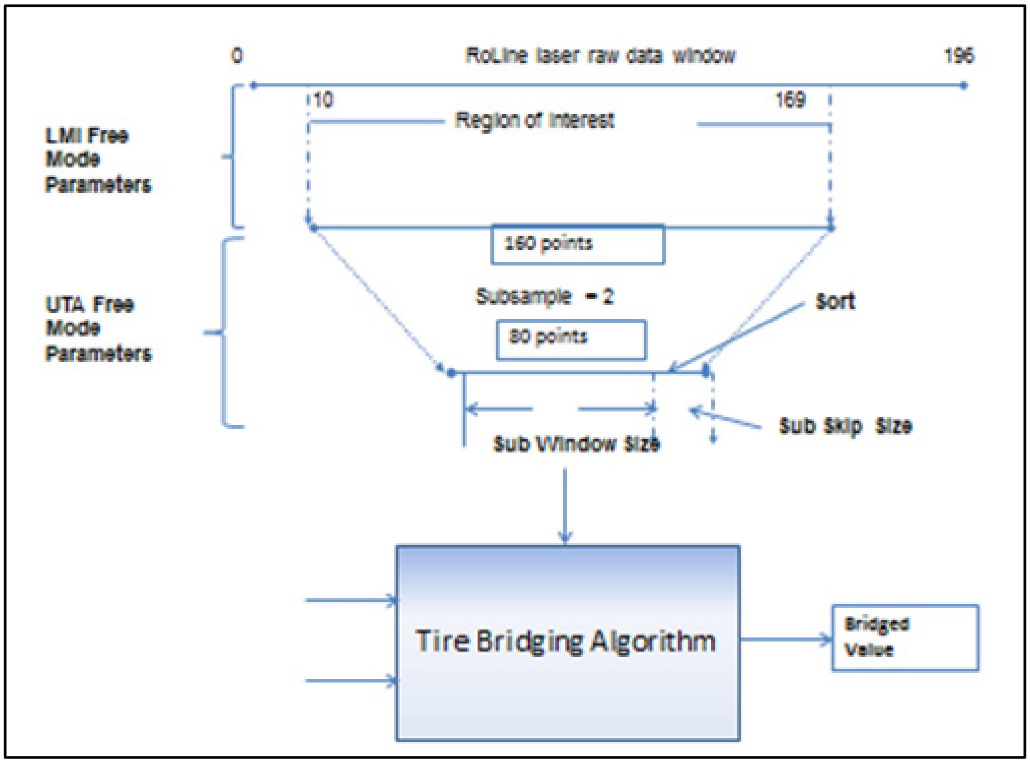

Figure 4.8. Tire Bridging Method Used in Portable Roline Profiling System.

BridgeAlgo_WindowSize, 80 or less;

##Default value = 80

BridgeAlgo_WindowSkip, less than 60;

##Default value = 0

NormalizeFreeModeScan – Normalize free mode data,

1 = normalize; 0 = do not normalize

##Default value = 0

UseBridgeFilter – Selects 2-D bridging algorithm

1 = Use 2-D bridge algorithm; 0 = Do not use 2-D bridge algorithm

#Default value = 0

Figure 4.9. Tire Bridge Parameters in INI File.

The window size and skip size typically used in profilers equipped with Roline lasers are 100 and 30, respectively, with the maximum number of invalids set at 150. Dynatest used these settings to collect data with the Roline laser on this project. UTA researchers also found these settings to be the default values when they first received the Roline laser purchased from LMI.

For the tests Dynatest performed using the company's three-laser inertial profiling system, the Roline laser was also configured to run in bridge mode, and the normalize scan option was used. In this project, researchers collected data with the Roline laser in free mode. Given the region of interest shown in Figure 4.8, and a subsample setting of 2, each line scan collected with the portable Roline profiler module consisted of 80 points. These line scans can then be processed, along with the accelerometer and distance data to compute profile using the Roline Ride Console program. Since the tire bridge filter parameters can be varied in the INI file, the test setup permits researchers to evaluate optimal tire bridge filter settings that provide the best agreement between IRIs determined from Roline and SurPRO profiles. This evaluation is presented in Chapter V of this report.

SUBTASK C

As noted in the beginning of this chapter, Subtask C covered hardware modifications, component purchasing, module construction, mounting, and testing. This task included improvements to the portable Roline profiling system, as well as designing and constructing an additional board to supply the power needed for field testing. Figure 4.10 shows the Roline profiling system. This system required a DC-DC power converter for delivering 48 volts DC compared to the 24 volts that the 19mm and texture laser profiling systems required Additionally, UTA researchers modified the filter module, and designed and constructed a Roline power printed circuit board to provide operating voltage for the 48 volt Roline laser. These boards are briefly described in the following sections.

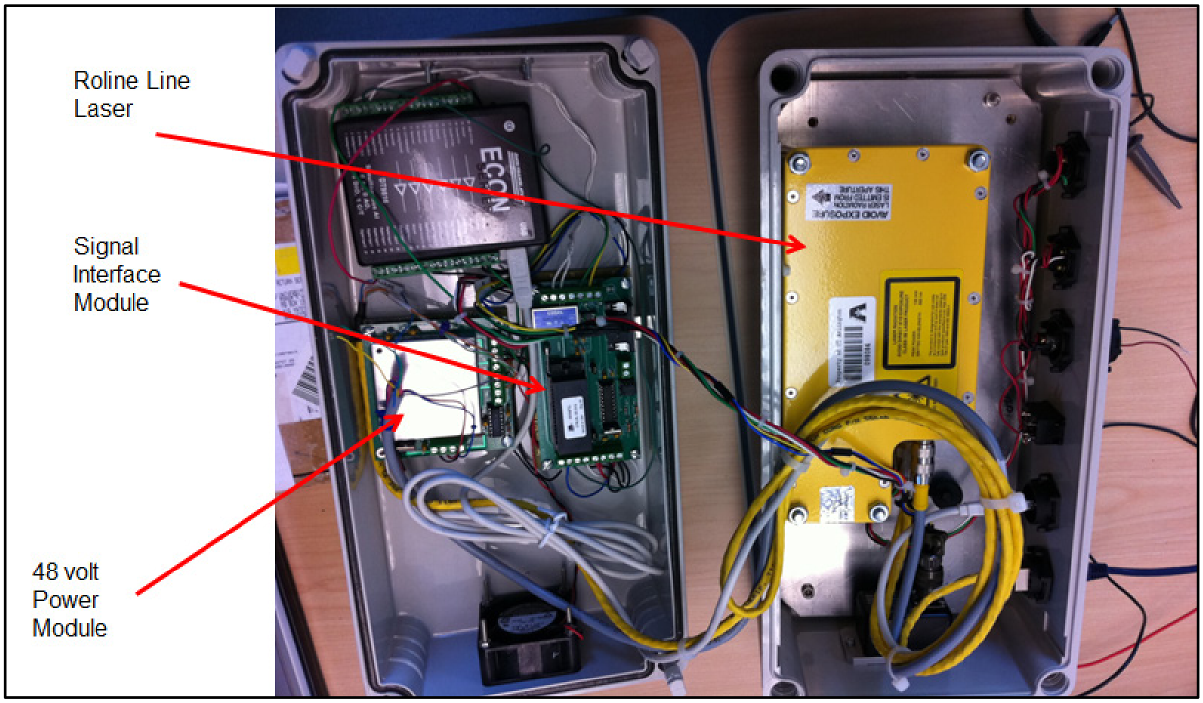

Figure 4.10. Roline Profiling System.

Signal Interface Board

UTA researchers modified the signal interface board used in previous inertial profiling systems to interface with the Roline laser system. The board uses a +12V to ±15V DC-DC converter to power the accelerometer. Two 100 Hz analog filters from Frequency Devices are used to filter the accelerometer and laser analog outputs. Since the Roline laser output is in digital format, the board was modified such that one 20 Hz or 100 Hz filter can be used for the accelerometer, keeping it backward compatible with the older profiling systems. A 7805 voltage regulator IC was added to the circuit to power the five volt chips on the board. Figure 4.11 shows the circuit diagram for the signal interface board.

Roline Power and Sync Board

UTA researchers designed and built a new power and sync board for the Roline profiling system to provide 48 volts DC to power the Roline. This board also interfaces the sync signal generated by the Roline laser to the ADC. The Roline laser generates an analog current signal for the sync pulse that is then converted to voltage via a 2 kΩ resistor located on the board. The voltage signal is connected to a Schmitt trigger and the output of this trigger is connected to the A/D converter. A 5 V voltage regulator was added to power the Schmitt trigger. Figure 4.12 shows the circuit diagram for the Roline power and sync board, while Figure 4.13 shows the connections between this board, the signal interface board, and the DT9816 module.

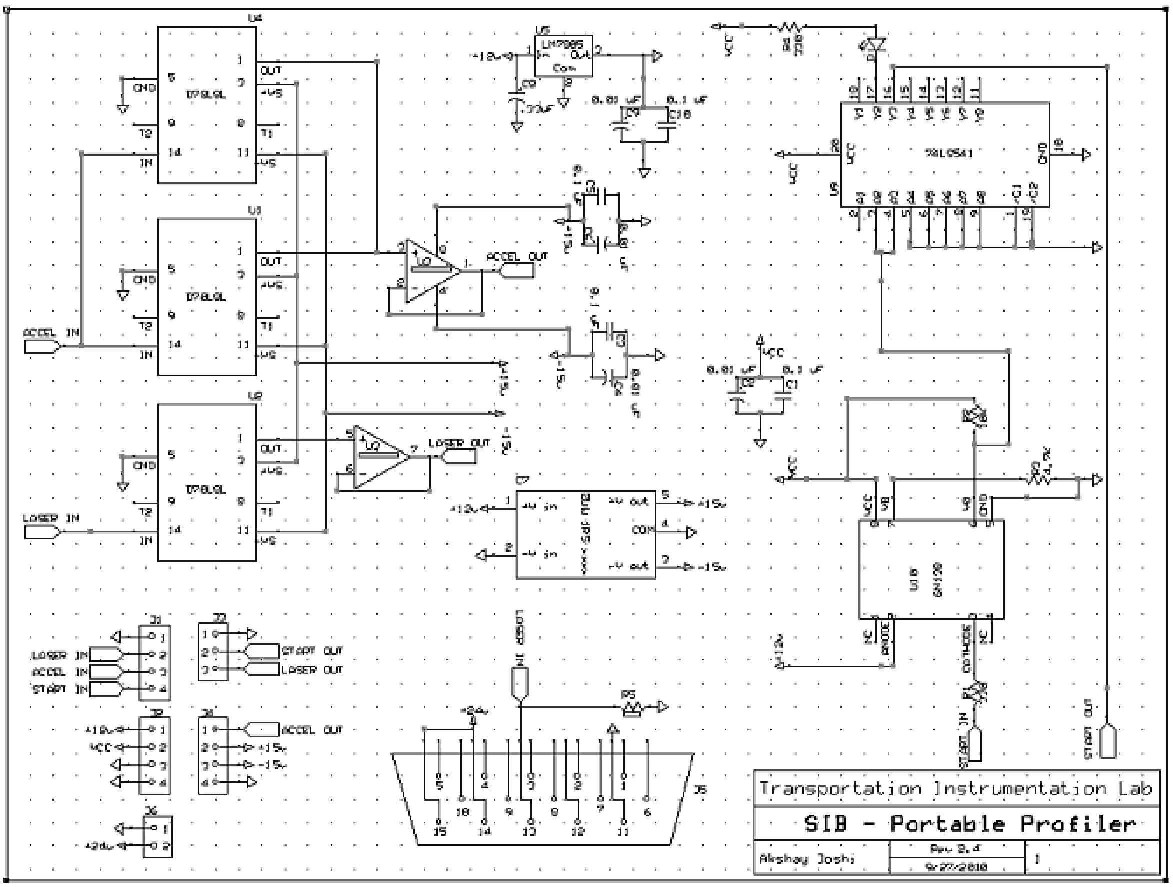

Figure 4.11. Roline Signal Interface Board.

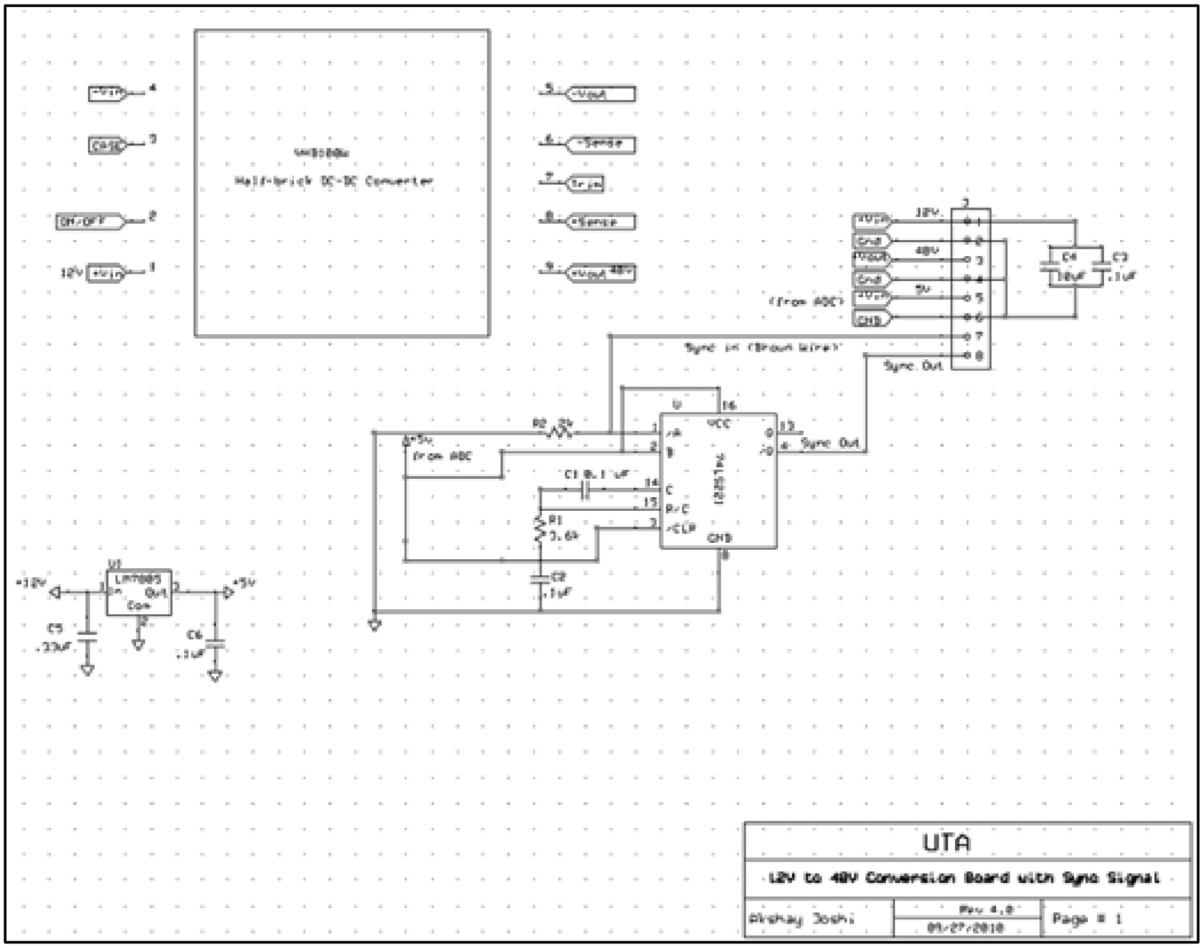

Figure 4.12. Power and Sync Board Schematic for Roline Profiling System.

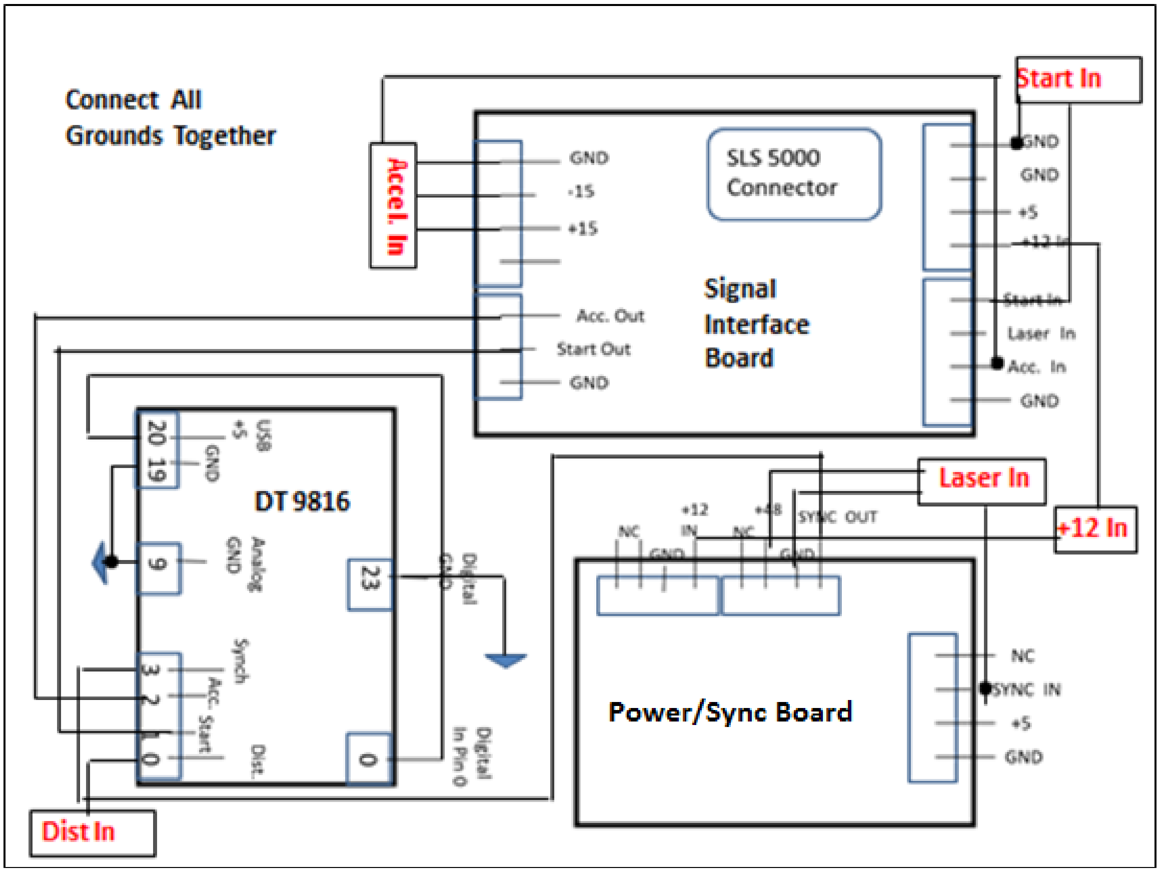

Figure 4.13. Signal Interface, Power/Sync, and DT9816 Connections.

SUBTASK D

Subtask D involved the development and/or investigation of analysis tools to provide both profile and texture results from data collected with the portable profiler/texture laser module. This subtask also investigated proper methods for handling the treatment of outliers in the texture data and developed software to compute mean profile depth, which UTA researchers used to evaluate the relationship between IRI and macrotexture from the data collected with the portable profiler/texture laser module. The following sections document the work conducted in this subtask.

Texture Laser Profiler

Using a method similar to the one used in constructing TxDOT's portable profiler module in Project 0-6004 (Walker and Fernando, 2010), the LMI single-point laser was replaced with the 78 KHz texture laser to construct a profile/texture module. When used in the profile mode, the texture module provides certifiable profile data. Thus, the IRI readings computed from the texture laser profile are very similar to IRIs computed from the LMI single-point and 19mm profiler modules. Figure 4.14 shows the profile/texture module mounted to the front of the test vehicle.

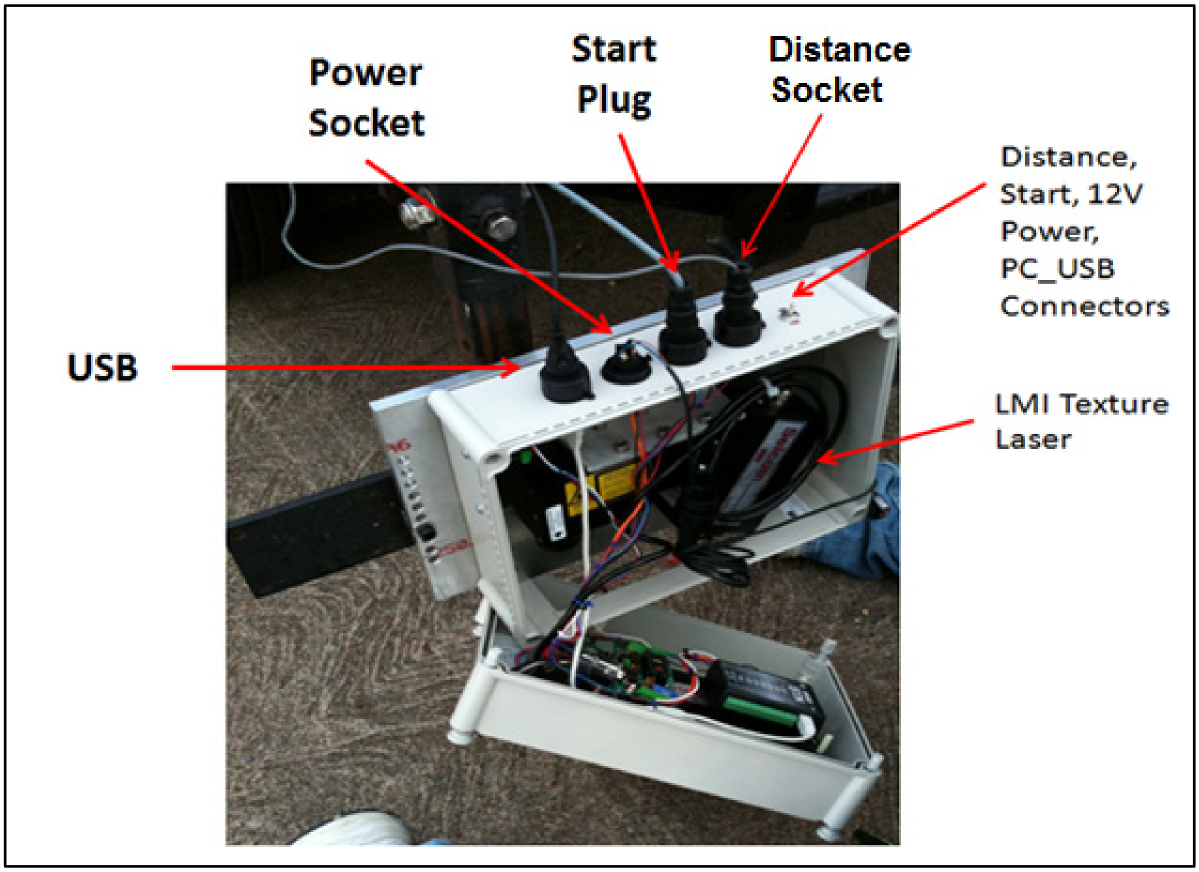

Figure 4.14. Profile/Texture Module.

As noted earlier in this chapter, UTA researchers used a two-pass process to compute profile, where raw sensor data are first collected and then processed to compute profile using the appropriate Ride Console program. This approach has permitted the collection of raw data for computing macro-texture and profile, as well as adjustments to the texture computation. The main focus in this subtask was on finding a suitable method to handle outliers in computing mean profile depth (MPD). Transportation engineers use MPD as one of the ways to measure texture according to ASTM E-1845. MPD is computed by determining the average height of the highest peaks in two equal segments of a 100mm section of texture profile (ASTM, 2011). At question is handling of the outliers. The method researchers decided to use is based on checking for readings that are more than a certain number of standard deviations σ from the mean μ of each 100 mm segment. Before computing MPD, this method identifies and removes outliers according to the following criterion: 90% outliers = |Reading ± mean| > 1.65*standard deviation.

Figure 4.15 illustrates raw data collected with the texture laser shown in Figure 4.14 before and after outliers are removed. The data illustrated are displacement data in millimeters offset by the laser's standoff. Observe how the method has removed spikes in the original data, resulting in the bright red band of readings shown in the middle of the chart.

The MPD texture program used early in the project was initially written in Matlab. UTA researchers converted this original program to C and used the revised program to compute mean profile depth from the raw data files collected using the profile/texture module. The results from this analysis are presented in the next chapter of this report.

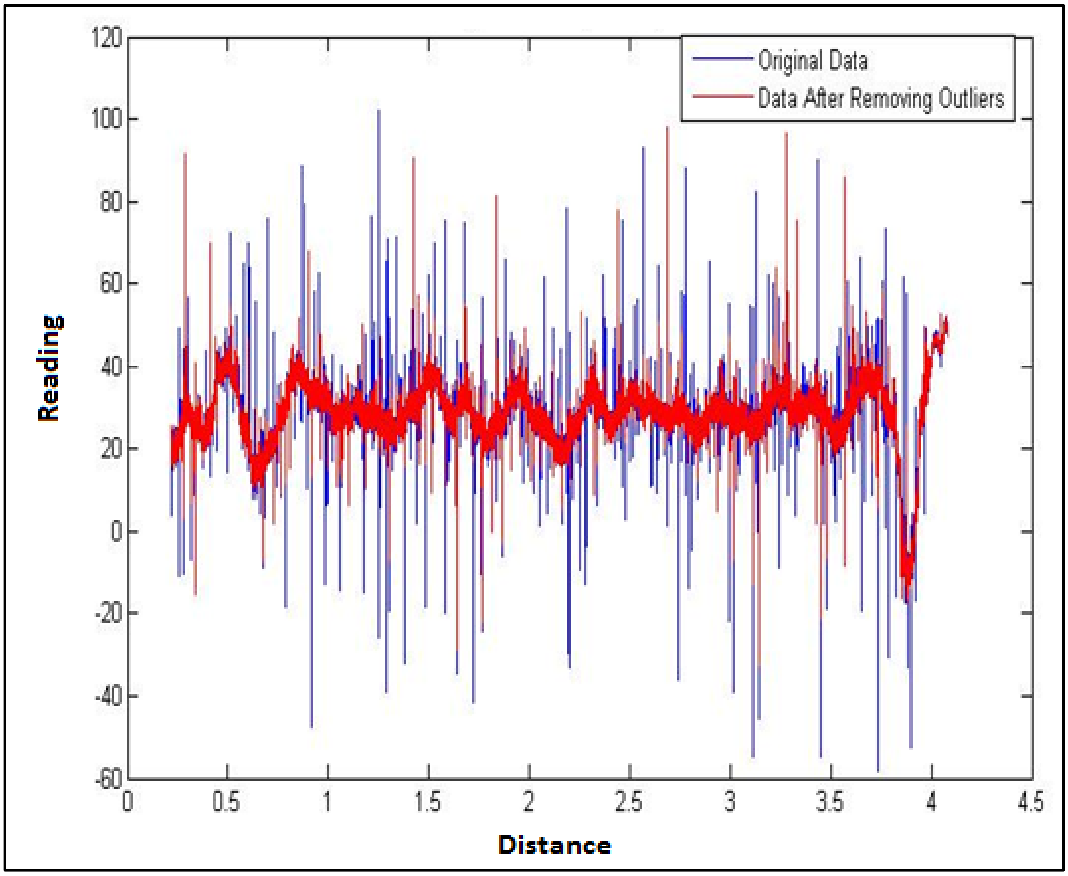

Figure 4.15. Illustration of Outlier Removal.

Texture Analysis

The portable profiler/texture laser module provided data to compute both profile and macrotexture of the wheel path tested, thereby giving researchers the opportunity to investigate the possible effect of texture on the IRI computed from the surface profile. Using the C texture analysis program discussed in the last section, researchers computed the MPDs on test pavements that covered the following 11 surface types:

1. Type C hot-mix asphalt (HMA).
2. Type D HMA.
3. PFC.
4. SMA.
5. CRCP with conventional transverse tines (CT).
6. CRCP with variable transverse tines (VT).

7. CRCP with half-inch transverse tines (HT).
8. CRCP with carpet drag (CD).
9. CRCP with longitudinal tines (LT).
10. Inverted prime (IP).
11. Flexible base (FB).

Researchers compared the MPDs and corresponding IRIs on the sections tested. First, the correlation between IRI and MPD for all sections was evaluated. This analysis showed a low correlation between IRI and MPD of 0.174. Since the correlation coefficient is only about 0.2, there is essentially no correlation between IRI and MPD across the range of surfaces tested. Note that a correlation coefficient of 1 suggests a perfect correlation between two variables, whereas a correlation of 0 suggests no correlation.

Next, researchers investigated the effect of MPD on the different surface types. For this investigation, researchers ran an analysis of variance (ANOVA) using the single factor Matlab *anova1* function to test the hypothesis that the means of the MPDs are the same across the different surface types. Table 4.2 summarizes the ANOVA test results. Based on the F-statistic given in the table, the analysis shows that the hypothesis should be rejected, i.e., there are differences in the MPDs between surface types. This finding is supported by the box plots given in Figure 4.16, which the *anova1* Matlab function also generated. These plots show the 25th and 75th percentiles of the MPDs computed for each surface type. The median value is the line in the middle of each box.

Researchers ran the Matlab multiple comparison function *multcompare* on the MPDs computed for the different surface types and found that the MPDs differ significantly between several surface types. The box plots in Figure 4.16 support this finding. For example, the box plot of the MPDs for PFCs is higher than the box plots for the other surface types, except for the flexible base box plot.

Figures 4.17 to 4.27 illustrate the relationship between IRI and MPD for each of the 11 surface types included in this evaluation. Figure 4.28 illustrates the overall relationship based on the data for all 11 surface types. These figures show only a weak relationship between IRI and MPD.

Table 4.2. ANOVA Test Results.

Source	Sum of squares	Degrees of freedom	Mean square	F-statistic
Surface type	138.516	11	12.5924	397.69
Error	17.32	547		
Total	155.036	550		

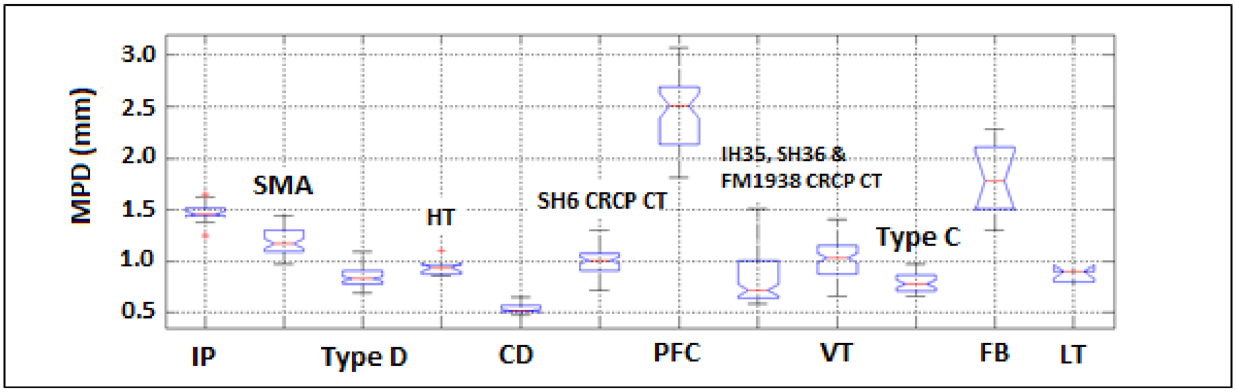

Figure 4.16. MPD Box Plots for Different Surface Types.

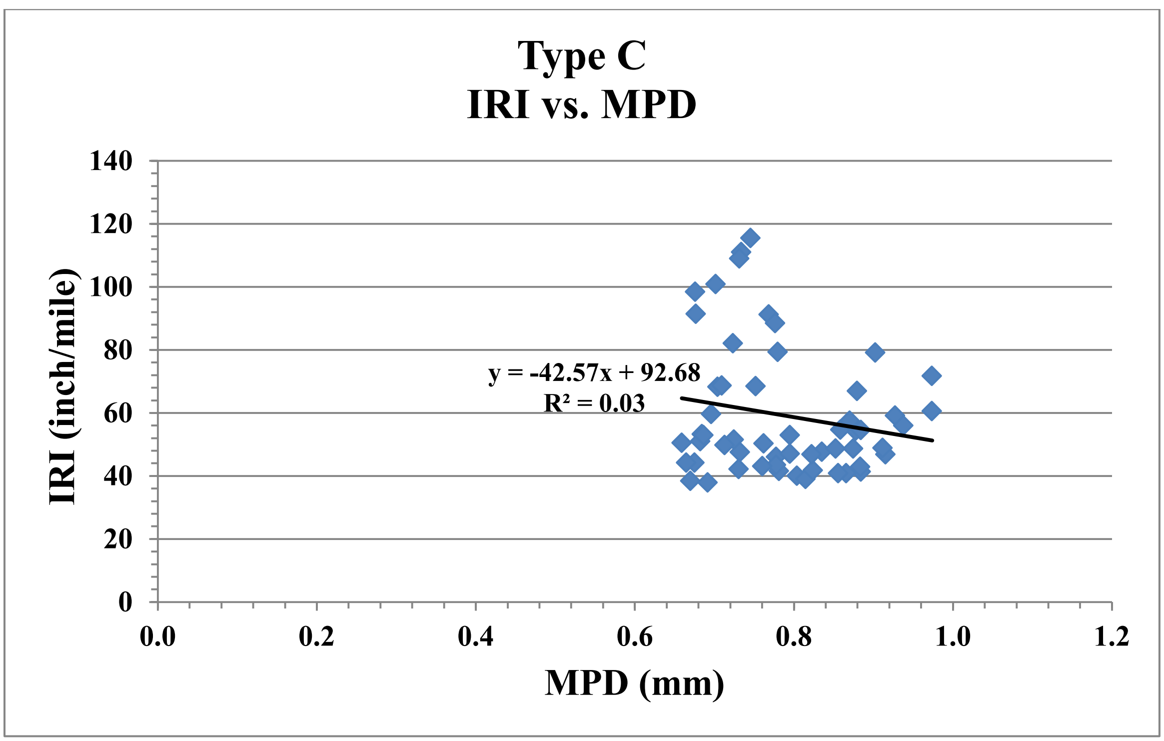

Figure 4.17. Plot of IRI vs. MPD for Sections with Type C Surface.

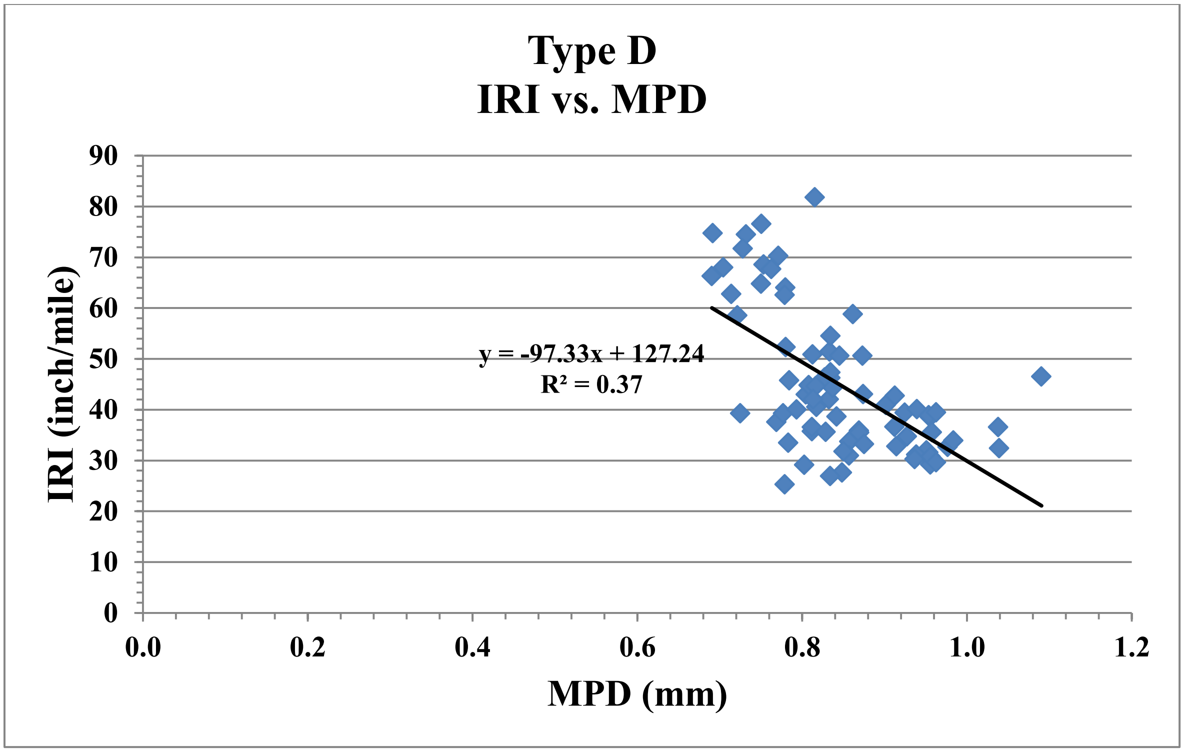

Figure 4.18. Plot of IRI vs. MPD for Sections with Type D Surface.

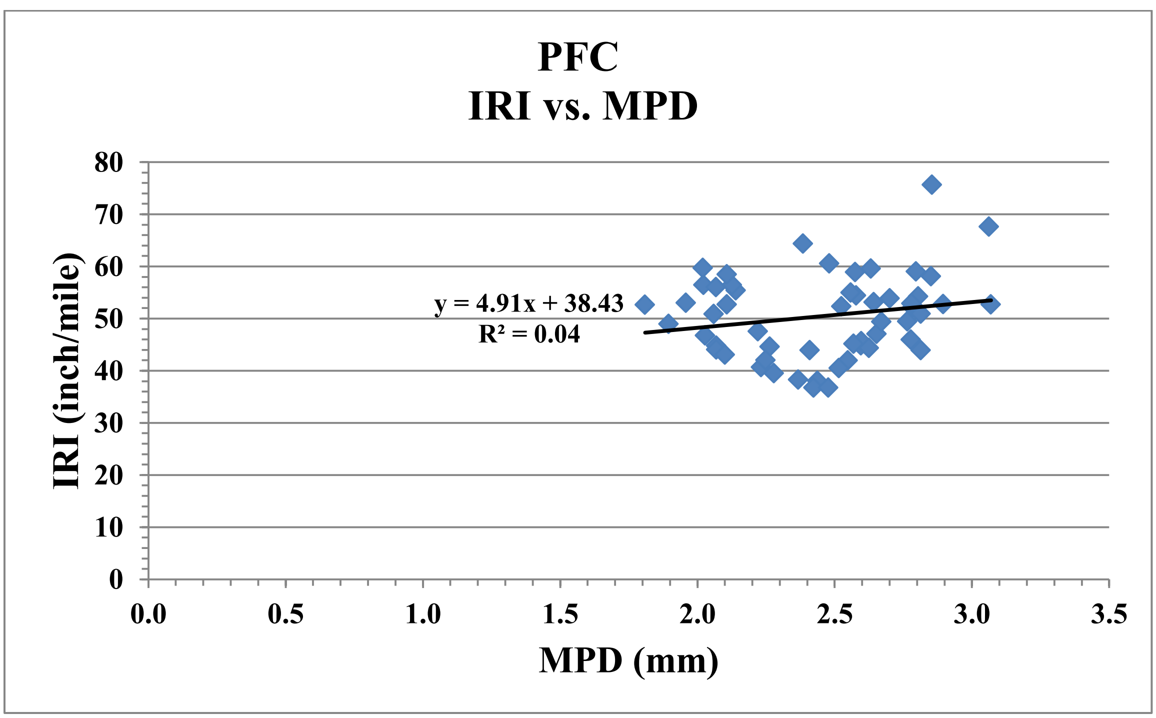

Figure 4.19. Plot of IRI vs. MPD for Sections with PFC Surface.

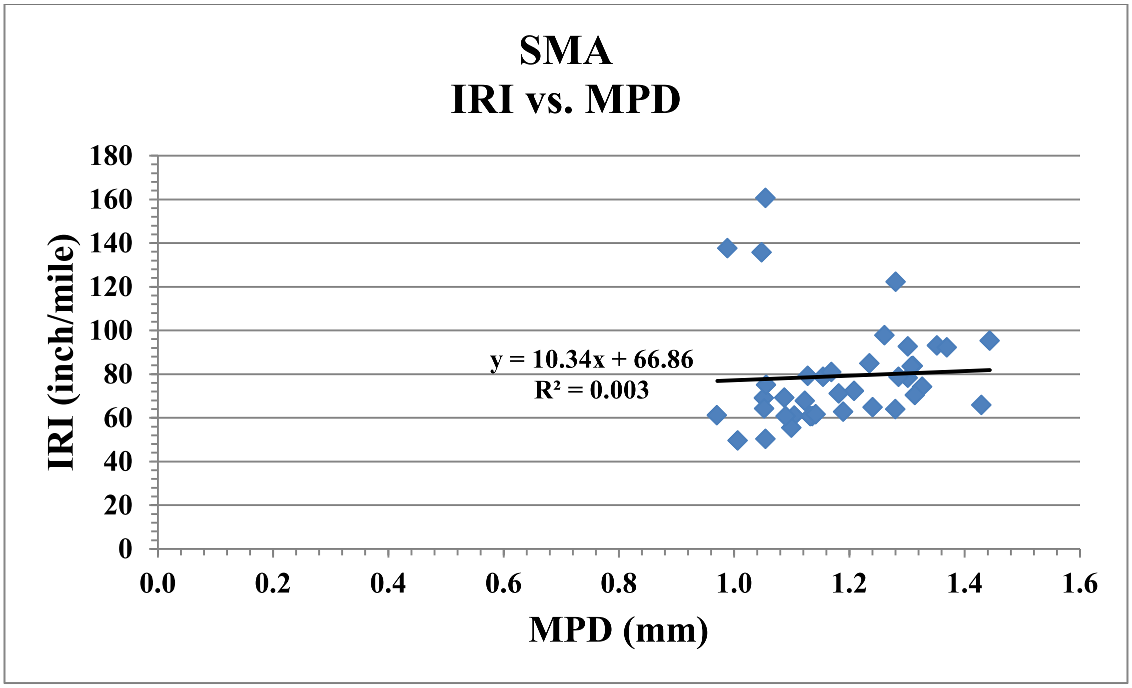

Figure 4.20. Plot of IRI vs. MPD for Sections with SMA Surface.

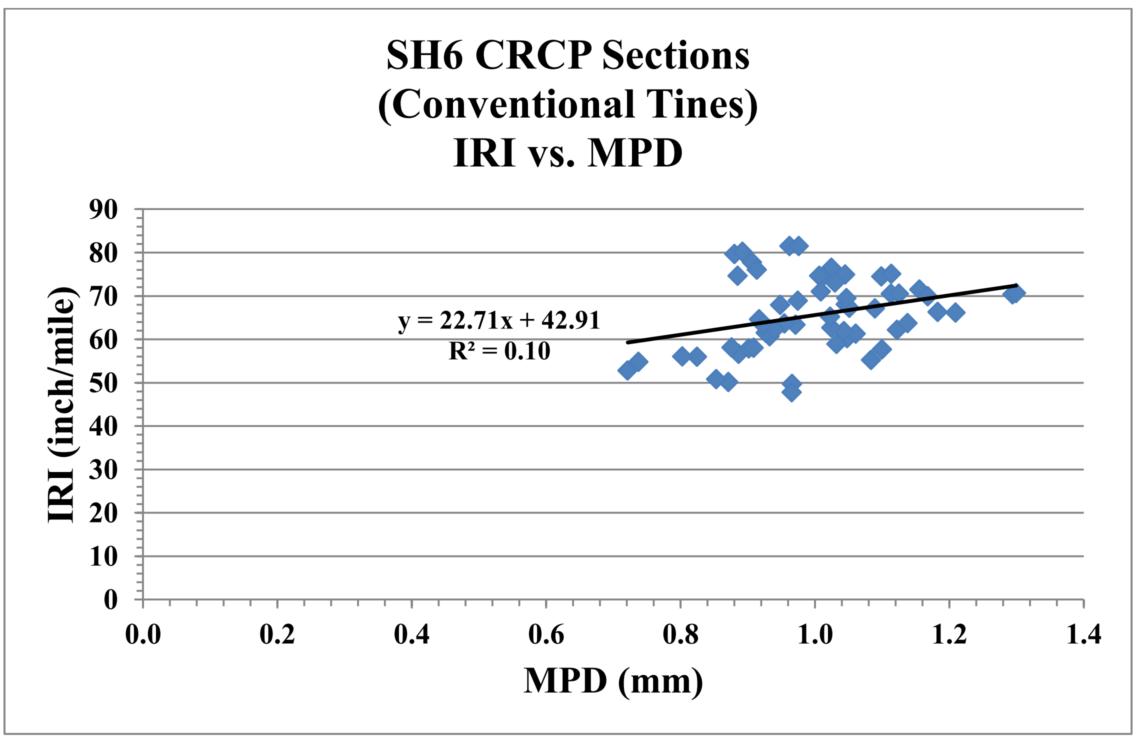

Figure 4.21. Plot of IRI vs. MPD for SH6 CRCP Sections with Conventional Transverse Tines.

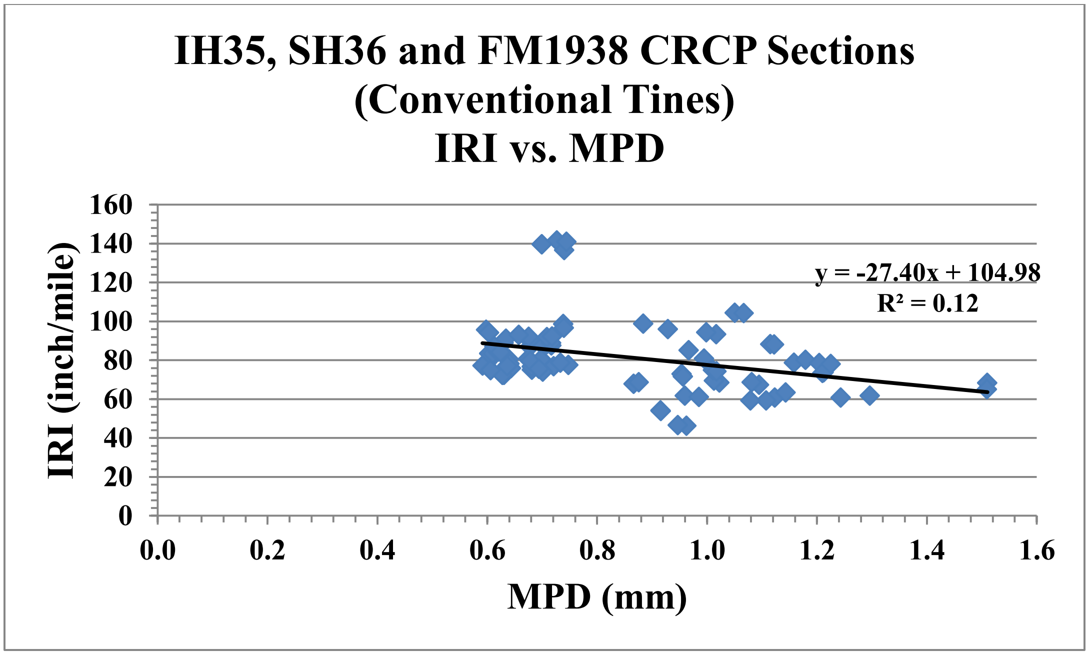

Figure 4.22. Plot of IRI vs. MPD for IH35, SH36 and FM1938 CRCP Sections with Conventional Transverse Tines.

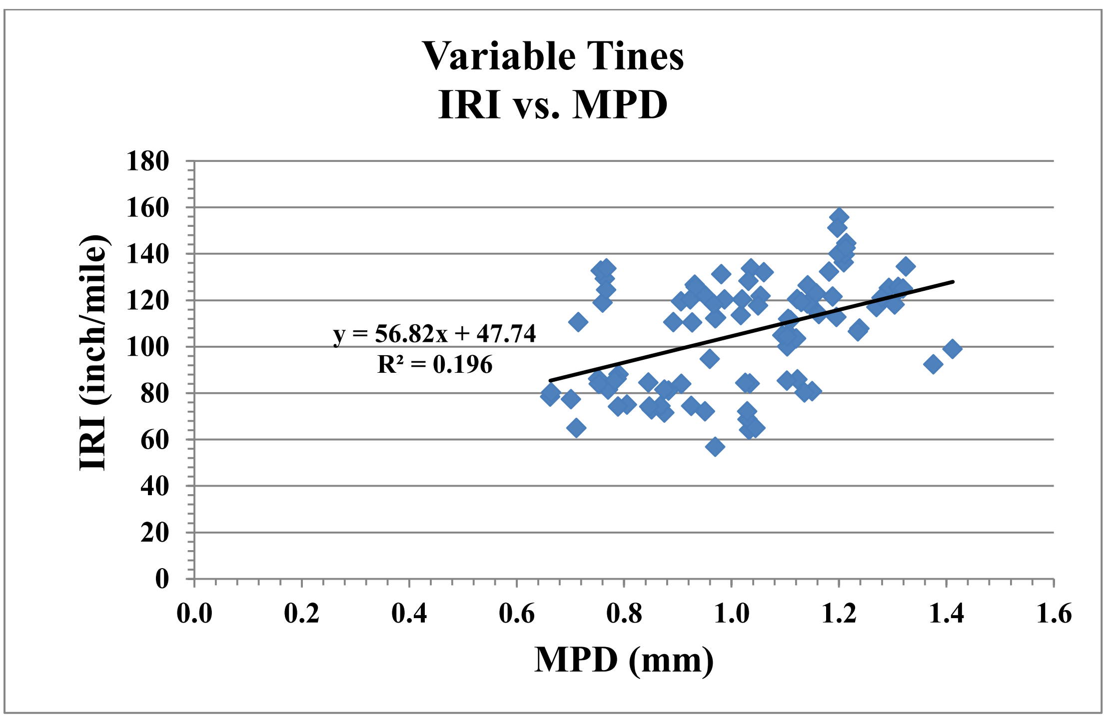

Figure 4.23. Plot of IRI vs. MPD for Sections with Variable Transverse Tines.

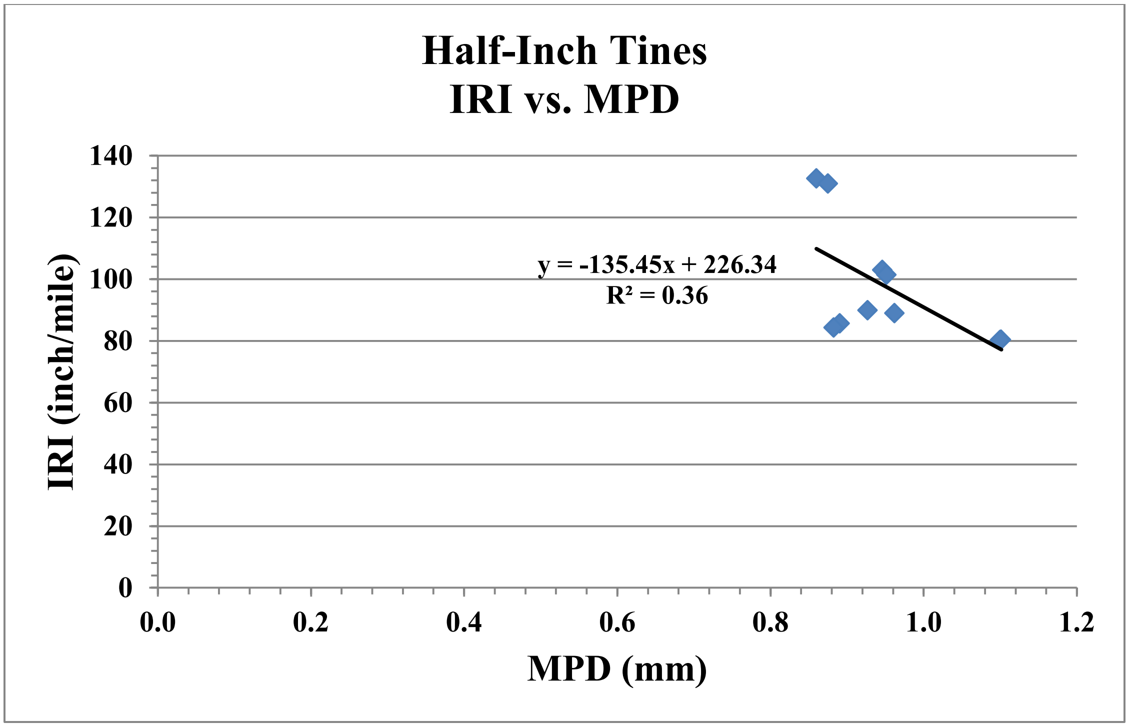

Figure 4.24. Plot of IRI vs. MPD for CRCP Sections with Half-Inch Transverse Tines.

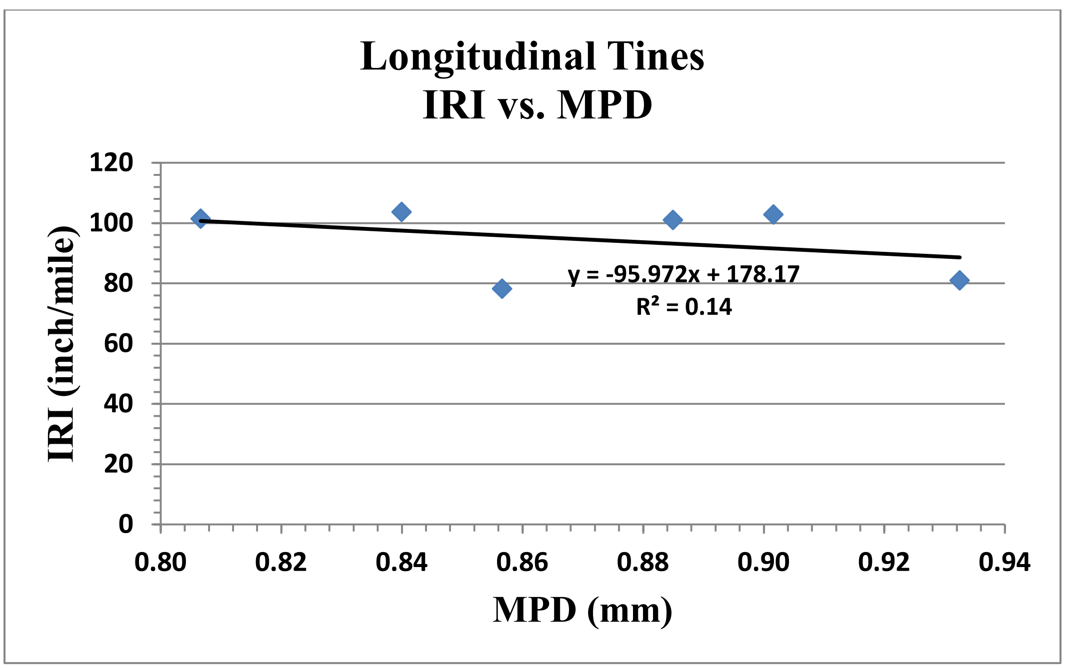

Figure 4.25. Plot of IRI vs. MPD for CRCP Sections with Longitudinal Tines.

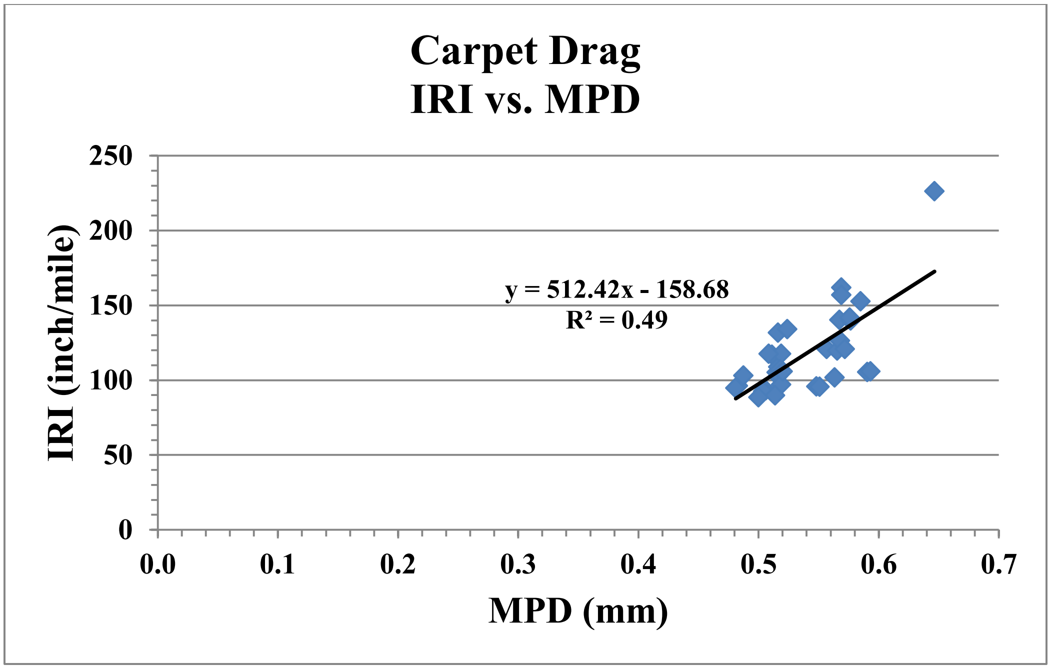

Figure 4.26. Plot of IRI vs. MPD for CRCP Sections with Carpet Dragged Surface.

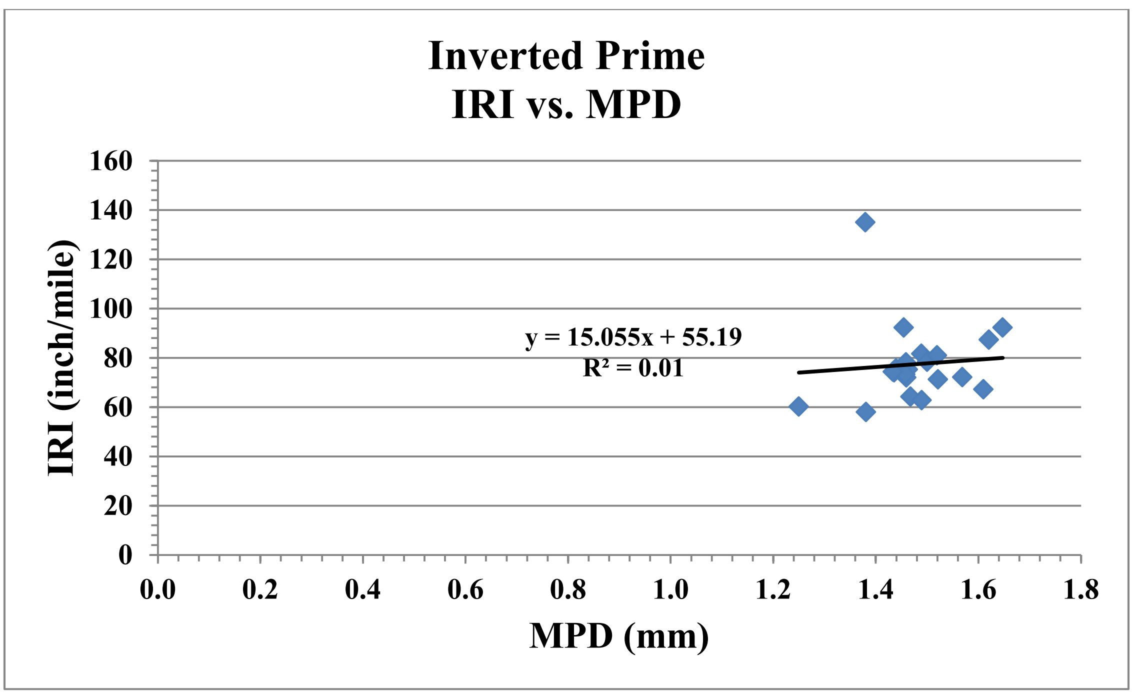

Figure 4.27. Plot of IRI vs. MPD for Inverted Prime Surface Type.

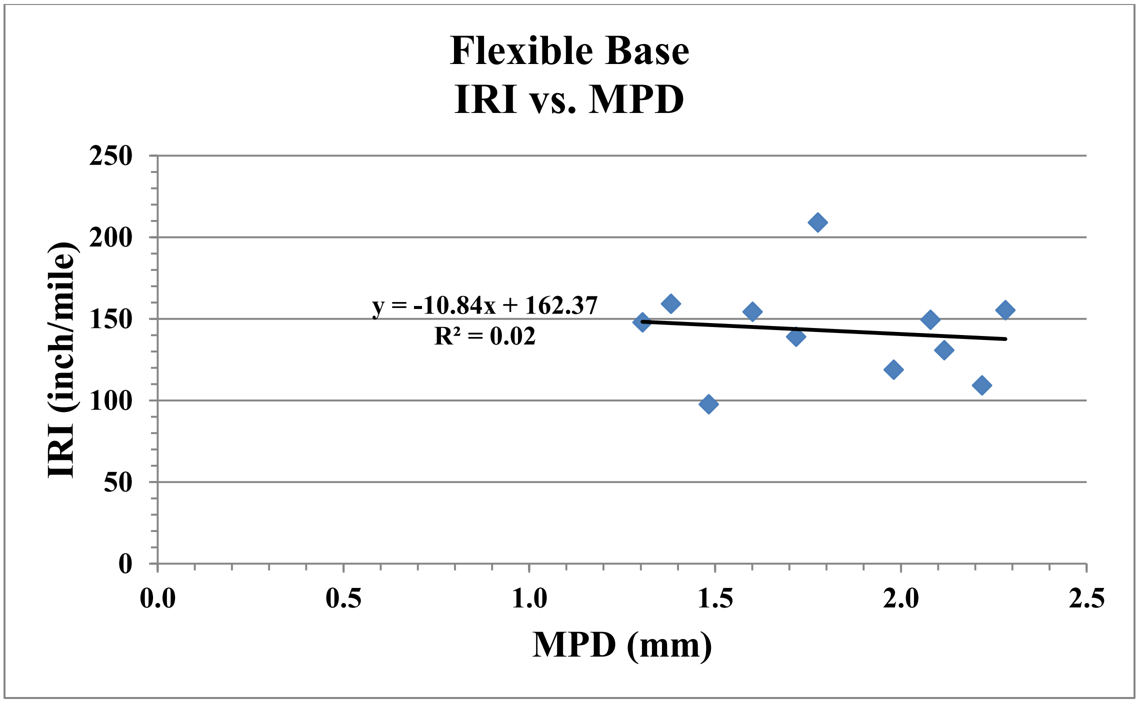

Figure 4.28. Plot of IRI vs. MPD for Flexible Base Surface Type.

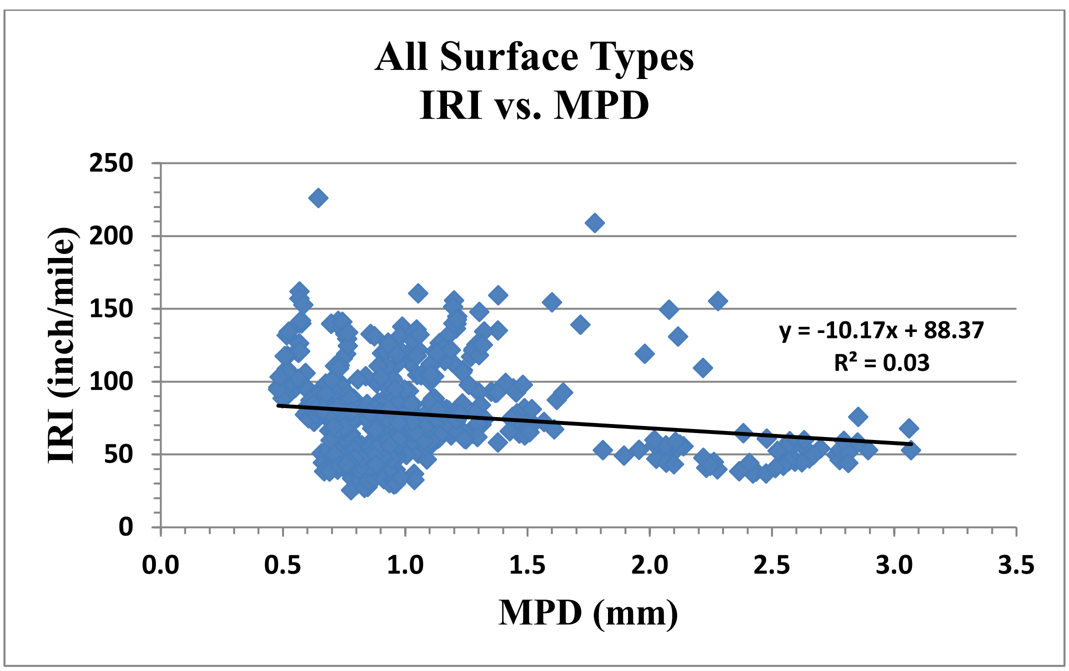

Figure 4.29. Plot of IRI vs. MPD for All Surface Types.

CERTIFICATION TESTING OF THREE-LASER PROFILING SYSTEM

Prior to running the field tests in this project, researchers conducted certification tests of the three-laser system to verify whether the system, as configured, meets the inertial profiler certification requirements stipulated in TxDOT Test Method Tex-1001S. The certification tests were conducted with the system configured as it would be used when collecting data on field test sections to evaluate differences in profiles and ride quality statistics between the Roline, 19mm, and 78 KHz texture lasers. Prior to running these tests, researchers performed laser, accelerometer, and distance calibrations on the three-laser profiling system. They then collected profile measurements on the certification track to evaluate the repeatability and accuracy of the profiles and IRIs determined from measurements made with the Roline, 19mm, and 78 KHz profiler modules. Measurements from 10 repeat runs were collected on the right wheel path of the sections used for certification. Tables 4.3 to 4.6 summarize the results from these tests.

Table 4.3. Repeatability of Profile Measurements.

Section	Profiler Module	Average Standard Deviation (mils)[1]
Medium smooth	19mm	19
	Roline	13
	Texture laser	22
Smooth	19mm	17
	Roline	11
	Texture laser	19

[1] Not to exceed 35 mils per TxDOT Test Method Tex-1001S

Table 4.4. Repeatability of IRIs Calculated from Profile Measurements.

Section	Profiler Module	Standard Deviation (inch/mile)[2]
Medium smooth	19mm	1.02
	Roline	0.90
	Texture laser	0.70
Smooth	19mm	0.45
	Roline	0.95
	Texture laser	0.81

[2] Not to exceed 3.0 inches/mile per TxDOT Test Method Tex-1001S

Table 4.5. Accuracy of Profile Measurements.

Section	Test Date	Average Difference (mils)[3]	Average Absolute Difference (mils)[4]
Medium smooth	19mm	3	34
	Roline	4	39
	Texture laser	3	24
Smooth	19mm	3	20
	Roline	4	21
	Texture laser	1	18

[3] Must be within ±20 mils per TxDOT Test Method Tex-1001S
[4] Not to exceed 60 mils per TxDOT Test Method Tex-1001S

Table 4.6. Accuracy of IRIs Calculated from Profile Measurements.

Section	Profiler Module	Difference between Averages of Test and Reference IRIs (inch/mile)[5]
Medium smooth	19mm	−0.71
	Roline	−1.72
	Texture laser	0.90
Smooth	19mm	0.02
	Roline	0.18
	Texture laser	2.02

[5] Absolute difference not to exceed 6 inches/mile per TxDOT Test Method Tex-1001S. Positive difference indicates higher IRIs from profiler relative to reference IRIs.

Comparing the test statistics in the above tables with the certification requirements in Test Method Tex-1001S, one observes that the profiling system passes certification. Researchers offer the following observations from the results presented:

- For a given module, the profile repeatability (as measured by the average standard deviation of elevation measurements from repeat runs) is very comparable between the smooth and medium smooth sections.
- All three modules showed very good IRI repeatability as measured by the standard deviation of the IRIs from repeat runs, which range from 0.45 to about 1 inch/mile.
- Comparing the average of the test profiles with the average of the corresponding filtered reference data, Table 4.4 shows that all three modules got similar profile

accuracy results, particularly on the smooth section. On the medium smooth section, the 19mm and Roline modules showed similar profile accuracy while the texture laser exhibited slightly better accuracy.

- All three modules showed very good IRI accuracy, with the magnitudes of the IRI differences ranging from close to 0 to about 2 inches/mile.

These results were obtained from tests where the Roline laser was positioned with its footprint oriented perpendicular to the direction of travel. Since data will also be collected on transversely tined concrete sections where the Roline is oriented at another angle, researchers also performed certification tests to collect data with the Roline footprint oriented at 30° and 45° from the lateral axis. Tables 4.7 to 4.10 present the results from these tests. It is observed that the Roline profiler module passed certification based on Test Method Tex-1001S for all three angles at which tests were conducted.

Table 4.7. Repeatability of Profiles from Roline Tests at Various Angles.

Section	Footprint angle	Average Standard Deviation (mils)[1]
Medium smooth	0°	13
	30°	11
	45°	12
Smooth	0°	11
	30°	10
	45°	12

[1] Not to exceed 35 mils per TxDOT Test Method Tex-1001S

Table 4.8. Repeatability of IRIs from Roline Tests at Various Angles.

Section	Footprint angle	Standard Deviation (inch/mile)[2]
Medium smooth	0°	0.90
	30°	0.91
	45°	1.36
Smooth	0°	0.95
	30°	1.21
	45°	1.02

[2] Not to exceed 3.0 inches/mile per TxDOT Test Method Tex-1001S

Table 4.9. Accuracy of Profiles from Roline Tests at Various Angles.

Section	Footprint angle	Average Difference (mils)[3]	Average Absolute Difference (mils)[4]
Medium smooth	0°	4	39
	30°	2	41
	45°	3	43
Smooth	0°	4	21
	30°	4	23
	45°	4	25

[3] Must be within ±20 mils per TxDOT Test Method Tex-1001S
[4] Not to exceed 60 mils per TxDOT Test Method Tex-1001S

Table 4.10. Accuracy of IRIs from Roline Tests at Various Angles.

Section	Footprint angle	Difference between Averages of Test and Reference IRIs (inches/mile)[5]
Medium smooth	0°	-1.72
	30°	-1.29
	45°	0.84
Smooth	0°	0.18
	30°	0.18
	45°	2.56

[5] Absolute difference not to exceed 6 inches/mile per TxDOT Test Method Tex-1001S.
Positive difference indicates higher IRIs from profiler relative to reference IRIs.

CHAPTER V. COMPARATIVE LASER EVALUATION

INTRODUCTION

This project aims to address the impact of newer wide-footprint lasers on the quality assurance tests conducted following TxDOT's existing ride specifications that use criteria developed from test data collected with traditional single-point lasers. To collect data for comparing profiles and ride quality statistics obtained with different lasers, this project used two different profiling systems to measure profiles on test sections that cover the range of surface textures found on TxDOT highways. One of these systems is the three-laser profiling system shown earlier in Figure 3.2 that researchers documented in the previous chapter. This system accommodates up to three portable profiler modules and permits concurrent measurement of surface profiles using the Roline, 19mm, and 78 KHz texture lasers. Among these lasers, the Roline projects the widest footprint—measuring 100mm in length—while the texture laser projects a single-dot footprint similar to the conventional lasers used on TxDOT's profilers. The Transportation Instrumentation Laboratory of the University of Texas at Arlington developed the profiler modules as well as the programs to collect and process data to generate surface profiles. TTI researchers fabricated the mounting hardware and distance encoder systems to collect field test data with the three profiler modules.

Figure 5.1 shows the other three-laser profiling system researchers used for the comparative laser testing. This particular system was equipped with a Roline laser mounted at the rear of the vehicle, and with 19mm and conventional single-point lasers at the front. All three lasers were mounted such that all track the same path, thereby permitting concurrent measurements during test runs. Dynatest collected data with this profiling system through a subcontract with TTI on this research project.

On the Dynatest profiling system, measurements with the Roline laser were collected in bridge mode, which is the most common method used in commercially available profilers equipped with Rolines. In this mode, the data from the line scan are processed using the laser's internal tire-bridging filter. The laser then outputs the bridged value at each location, which is an average of line scan readings taken at the given location. These bridge values are subsequently used with the data from the accelerometer and distance encoder to determine the surface profile along the wheel path tracked using the particular algorithm implemented in the inertial profiler.

Compared to the Dynatest system, the three-laser system assembled in this project permits Roline data to be collected in free mode, which provides the line scan readings at a given location. This ability contrasts with the bridge mode described previously. This setup enabled researchers to evaluate tire-bridge filter settings that provide the best comparisons between IRIs determined from the Roline data and IRIs determined from profile measurements collected with the SurPRO 3500 reference profiler. With the two three-laser systems shown in Figure 3.2 and Figure 5.1, researchers were thus able to:

- Collect data for comparing single-point and 19mm measurements with corresponding measurements collected using the Roline laser's built-in tire-bridging filter.
- Collect free-mode data for evaluating optimal tire-bridge filter settings, should examination of the bridge mode data find this evaluation to be necessary.

Figure 5.1. Dynatest Three-Laser System.

FIELD MEASUREMENTS

With assistance from several TxDOT engineers, researchers identified pavement sections that cover the range of surfaces included in the experimental plan developed for comparing different laser sensors based on ride quality statistics computed from the measured profiles. Table 5.1 identifies test sections on which profile measurements were collected in this project. As shown, researchers established test sections in the Austin, Bryan, Fort Worth, Lufkin, Waco, and Yoakum Districts that comprised the following pavement surface types:

- Dense-graded HMA (Type C and Type D).
- Stone-matrix asphalt (SMA-C and SMA-D.
- Permeable friction course.
- Transversely tined continuously reinforced concrete pavements consisting of sections with conventional 1-inch tines, ½-inch tines, and variable tines.
- Longitudinally tined CRCP.
- Carpet dragged CRCP.
- Flexible base.
- Inverted prime.
- Seal coats (Grade 3, Grade 4, and Grade 5).

Table 5.1. Highway Sections Used for Comparative Evaluation.

District	County	Highway	Lane	Beginning GPS coordinates	Length (miles)	Pavement surface
Austin	Lee	FM2440-1	K1	N30° 13.477′ W97° 1.022’	0.59	Type C hot-mix
Austin	Lee	FM2440-1	K6	N30° 3.389′ W97° 0.435′	0.59	Type C hot-mix
Austin	Lee	FM2440-2	K1	N30° 12.583′ W96° 59.090′	0.74	Type C hot-mix
Austin	Lee	FM2440-2	K6	N30° 12.487′ W96° 58.35′	0.74	Type C hot-mix
Austin	Travis	FM734	R2	N30° 22.466′ W97° 37.743′	0.75	SMA-D hot-mix
Austin	Travis	FM734	L2	N30° 22.176′ W97° 37.078′	0.75	SMA-D hot-mix
Austin	Travis	Loop 1	R3	N30° 16.071′ W97° 46.678′	1.70	SMA-C hot-mix
Austin	Travis	Loop 1	L3	N30° 14.968′ W97° 48.290′	2.10	SMA-C hot-mix
Bryan	Brazos	SH6	R1	N30° 26.268′ W96° 7.473′	1.00	CRCP CT tines
Bryan	Brazos	SH6	L1	N30° 25.514′ W96° 6.743′	1.00	CRCP CT tines
Bryan	Grimes	SH6	R1	N30° 14.760′ W96° 2.837′	1.00	PFC hot-mix

Table 5.1. Highway Sections Used for Comparative Evaluation (continued).

District	County	Highway	Lane	Beginning GPS coordinates	Length (miles)	Pavement surface
Bryan	Grimes	SH6	L1	N30° 14.016′ W96° 3.204′	1.00	PFC hot-mix
Bryan	Milam	SH36	K1	N30° 51.070′ W96° 58.325′	0.40	CRCP carpet drag
Bryan	Milam	SH36	K6	N30° 50.863′ W96° 57.995′	0.40	CRCP carpet drag
Bryan	Milam	SH36	R1	N30° 50.834′ W96° 57.891′	0.80	CRCP CT
Bryan	Milam	SH36	L1	N30° 49.429′ W96° 56.260′	0.80	CRCP CT
Bryan	Milam	SH36	R1	N30° 50.004′ W96° 56.674′	0.80	CRCP VT
Bryan	Milam	SH36	L1	N30° 50.457′ W96° 57.250′	0.80	CRCP VT
Bryan	Robertson	FM1940	K1	N31° 2.246′ W96° 18.969′	0.50	Inverted prime
Bryan	Robertson	FM1940	K6	N31° 1.868′ W96° 18.715′	0.50	Inverted prime
Bryan	Robertson	SH6	K1	N30° 47.099′ W96° 29.777′	1.00	PFC hot-mix
Bryan	Robertson	SH6	K6	N30° 46.345′ W96° 29.306′	1.00	PFC hot-mix
Ft. Worth	Parker	IH20	R1	N32° 44.597′ W97° 39.769′	1.40	Type D hot-mix
Ft. Worth	Tarrant	FM1938	L2	N32° 57.920′, W97° 11.155′	0.20	CRCP carpet drag
Ft. Worth	Tarrant	FM1938	L2	N32° 58.766′, W97° 11.125′	0.40	CRCP CT
Ft. Worth	Tarrant	FM1938	L2	N32° 58.177′ W97° 11.160′	0.50	CRCP HT
Ft. Worth	Tarrant	FM1938	L2	N32° 57.716’, W97° 11.147′	0.60	CRCP LT
Ft. Worth	Tarrant	IH35	A2	N32° 34.981’, W97° 19.149′	0.80	CRCP carpet drag
Ft. Worth	Tarrant	IH820	R4	N32° 47.762′, W97° 27.026′	1.59	CRCP VT
Ft. Worth	Tarrant	IH820	L4	N32° 48.244′, W97° 25.567′	1.53	CRCP VT
Lufkin	Nacogdoches	SH7	K1	N31° 32.093′, W94° 45.603′	0.92	Grade 3 seal coat
Lufkin	Nacogdoches	SH7	K1	N31° 32.545′, W94° 44.831′	1.00	Grade 4 seal coat
Lufkin	Nacogdoches	SH7	K1	N31° 31.610′, W94° 46.426′	0.98	Grade 5 seal coat

Table 5.1. Highway Sections Used for Comparative Evaluation (continued).

District	County	Highway	Lane	Beginning GPS coordinates	Length (miles)	Pavement surface
Waco	Hill	IH35	R1	N31° 58.830′, W97° 6.679′	1.00	CRCP CT
Waco	Hill	IH35	L1	N31° 59.484′ W97° 6.242′	1.00	CRCP CT
Yoakum	Austin	SH36	R1	N29° 49.093′, W96° 9.870′	0.50	Flexbase
Yoakum	Austin	SH36	R2	N29° 49.093′, W96° 9.870′	0.50	Flexbase
Yoakum	Colorado	IH10	L1	N29° 41.798′ W96° 51.496′	1.60	Type D hot-mix
Yoakum	Colorado	IH10	L2	N29° 41.798′ W96° 51.496′	1.60	Type D hot-mix
Yoakum	Fayette	FM1383	K1	N29° 46.067′ W96° 50.306′	1.00	Inverted prime
Yoakum	Fayette	FM1383	K6	N29° 45.194′ W96° 50.280′	1.00	Inverted prime
Yoakum	Jackson	US59	R1	N28° 59.286′ W96° 38.851′	1.00	PFC hot-mix
Yoakum	Jackson	US59	L1	N28° 58.811′ W96° 39.747′	1.00	PFC hot-mix
Yoakum	Victoria	Loop 463	R2	N28° 50.849′ W96° 57.760′	1.63	Type C hot-mix
Yoakum	Victoria	Loop 463	L2	N28° 49.965′ W96° 56.751′	1.43	Type C hot-mix
Yoakum	Victoria	US77	R1	N28° 41.658′ W97° 2.817′	2.00	Type D hot-mix
Yoakum	Victoria	US77	L1	N28° 39.90′ W96° 2.820′	2.00	Type D hot-mix
Yoakum	Wharton	US59	R1	N29° 18.000′ W96° 7.682′	1.00	Type D hot-mix
Yoakum	Wharton	US59	L1	N29° 17.162′ W96° 7.962′	1.00	Type D hot-mix

Table 5.2 shows the types of profile measurements performed on each section. These measurements were made along the right wheel path relative to the direction of travel on the test lane. In accordance with the experimental plan, researchers collected concurrent profile measurements with the Roline, 19mm, and single-point texture lasers using the three-laser system assembled in this project. These profile measurements were done on each pavement section as shown in Table 5.2. In addition, profile measurements were collected with the

Dynatest three-laser system and with a TxDOT profiler equipped with single-point lasers. These additional measurements were made on the selected set of pavement sections identified in Table 5.2, and were conducted at different times based on the schedule of each inertial profiler and its operator.

To provide a basis for comparing the international roughness indices computed from profiles measured with the Roline, 19mm, and single-point lasers, researchers ran the SurPRO reference profiler on the selected set of pavement sections identified in Table 5.2. These measurements covered the surface types identified previously. Prior to collecting data with the SurPRO, researchers delineated the test wheel path with paint dots at approximately 5-ft intervals, as illustrated in Figure 5.2. In addition, researchers marked the beginning location of each section, and measured a 528-ft segment on the delineated wheel path on which SurPRO closed-loop and distance calibrations were performed. These calibrations were made on-site prior to collecting data with the instrument. At least three repeat runs were made on each section with each profiling method identified in Table 5.2.

DYNATEST THREE-LASER SYSTEM COMPARISONS

Researchers compared the IRIs determined from profiles collected with the Dynatest three-laser system to assess the differences between lasers based on computed IRI values from measurements made with a profiling system that is commonly used for ride quality assurance tests by contractors in Texas. There are 10 Dynatest profilers that are on the current list of certified inertial profilers in Texas of which 9 are used in the state for quality assurance testing of pavement smoothness under Item 585 and SP247-011. These 9 profilers show an even split between the three lasers used to collect data for the comparative evaluation reported in this technical memorandum. Three profilers are equipped with single-point lasers, 3 with 19mm lasers, and 3 with Roline lasers configured to collect data in bridge mode. From a practical point of view, it is of interest to compare the IRIs from these three lasers to assess the differences that might be observed on TxDOT projects where profilers with these lasers are used.

Table 5.2. Profile Tests Performed on Pavement Sections.

County	Highway	Lane	Pavement surface	Profile Tests Performed			
				3-laser	SurPRO	Dynatest	TxDOT
Lee	FM2440	K1	Type C hot-mix	✓		✓	
Lee	FM2440	K6	Type C hot-mix	✓		✓	
Lee	FM2440	K1	Type C hot-mix	✓		✓	
Lee	FM2440	K6	Type C hot-mix	✓		✓	
Travis	FM734	R2	SMA-D hot-mix	✓			
Travis	FM734	L2	SMA-D hot-mix	✓	✓ (6)*		
Travis	Loop 1	R3	SMA-C hot-mix	✓			
Travis	Loop 1	L3	SMA-C hot-mix	✓			
Brazos	SH6	R1	CRCP CT tines	✓	✓ (7)	✓	✓
Brazos	SH6	L1	CRCP CT tines	✓		✓	✓
Grimes	SH6	R1	PFC hot-mix	✓		✓	✓
Grimes	SH6	L1	PFC hot-mix	✓	✓ (10)	✓	✓
Milam	SH36	K1	CRCP carpet drag	✓		✓	✓
Milam	SH36	K6	CRCP carpet drag	✓	✓ (4)	✓	✓
Milam	SH36	R1	CRCP CT tines	✓		✓	✓
Milam	SH36	L1	CRCP CT tines	✓	✓ (8)	✓	✓
Milam	SH36	R1	CRCP VT tines	✓		✓	✓
Milam	SH36	L1	CRCP VT tines	✓	✓ (8)	✓	✓
Robertson	FM1940	K1	Inverted prime	✓		✓	✓
Robertson	FM1940	K6	Inverted prime	✓		✓	✓
Robertson	SH6	K1	PFC hot-mix	✓	✓ (8)	✓	✓
Robertson	SH6	K6	PFC hot-mix	✓		✓	✓
Parker	IH20	R1	Type D hot-mix	✓		✓	✓
Tarrant	FM1938	L2	CRCP carpet drag	✓	✓ (2)		
Tarrant	FM1938	L2	CRCP CT tines	✓			
Tarrant	FM1938	L2	CRCP HT tines	✓	✓ (5)		
Tarrant	FM1938	L2	CRCP LT tines	✓	✓ (6)		
Tarrant	IH35	A2	CRCP carpet drag	✓		✓	✓
Tarrant	IH820	R4	CRCP VT tines	✓		✓	✓
Tarrant	IH820	L4	CRCP VT tines	✓		✓	✓
Nacogdoches	SH7	K1	Grade 3 seal coat	✓	✓ (9)		
Nacogdoches	SH7	K1	Grade 4 seal coat	✓	✓ (9)		
Nacogdoches	SH7	K1	Grade 5 seal coat	✓	✓ (9)		
Hill	IH35	R1	CRCP CT tines	✓		✓	✓
Hill	IH35	L1	CRCP CT tines	✓		✓	✓
Austin	SH36	R1	Flexbase	✓	✓ (5)		
Austin	SH36	R2	Flexbase	✓	✓ (5)		
Colorado	IH10	L1	Type D hot-mix	✓			
Colorado	IH10	L2	Type D hot-mix	✓			

Table 5.2. Profile Tests Performed on Pavement Sections (continued).

County	Highway	Lane	Pavement surface	Profile Tests Performed			
				3-laser	SurPRO	Dynatest	TxDOT
Fayette	FM1383	K1	Inverted prime	✓	✓ (10)		✓
Fayette	FM1383	K6	Inverted prime	✓			✓
Jackson	US59	R1	PFC hot-mix	✓		✓	✓
Jackson	US59	L1	PFC hot-mix	✓		✓	✓
Victoria	Loop 463	R2	Type C hot-mix	✓		✓	✓
Victoria	Loop 463	L2	Type C hot-mix	✓		✓	✓
Victoria	US77	R1	Type D hot-mix	✓		✓	✓
Victoria	US77	L1	Type D hot-mix	✓		✓	✓
Wharton	US59	R1	Type D hot-mix	✓	✓ (8)		
Wharton	US59	L1	Type D hot-mix	✓			

* Number of 528-ft sections on which SurPRO measurements were collected

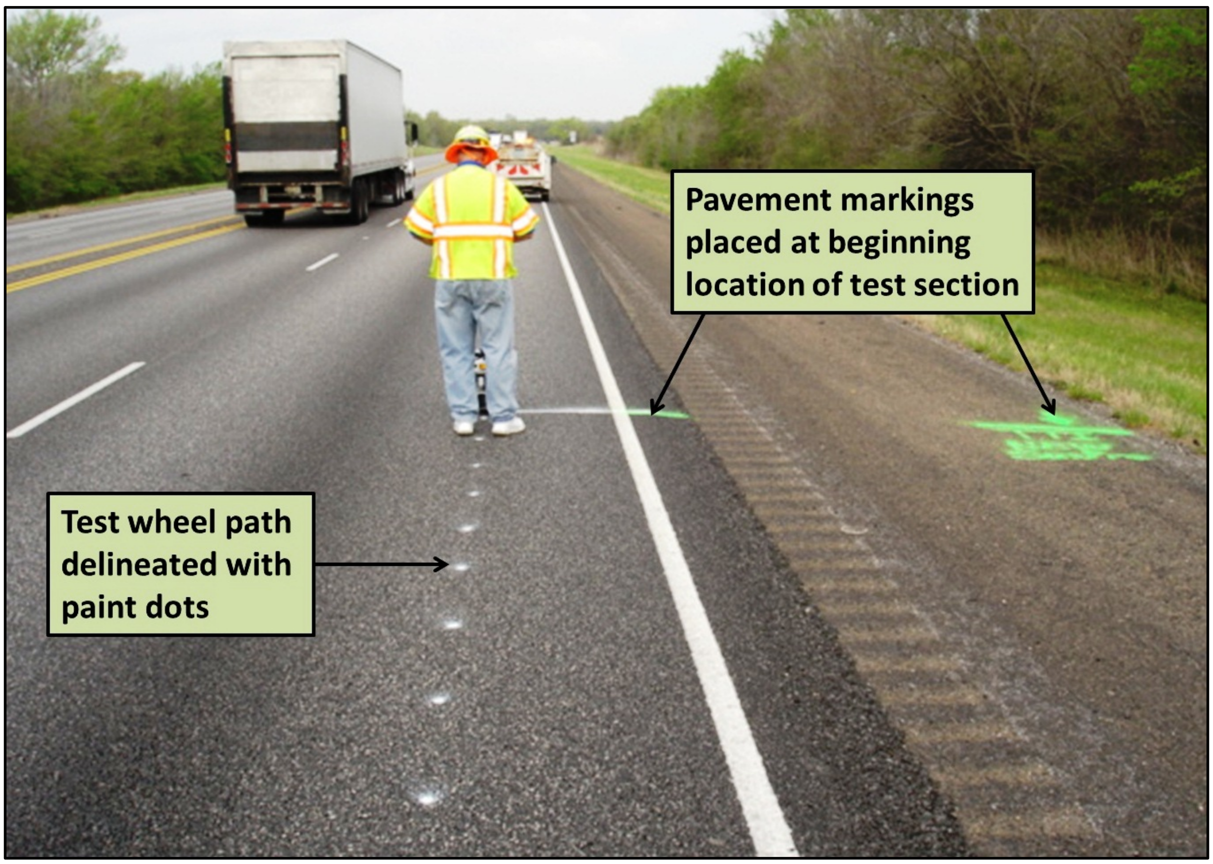

Figure 5.2. Test Wheel Path Delineated for SurPRO Profile Measurements.

Given that data from all three lasers were collected concurrently, researchers determined the differences in IRIs between lasers from each run made on a given test section. For each laser, researchers computed the IRIs at 528-ft intervals and determined the differences in IRIs between lasers for each 528-ft interval along the wheel path tested. This process was repeated for all runs made on the given section. Researchers then used the paired *t*-test to determine the statistical significance of the IRI differences between any two lasers and to compute confidence intervals for these differences. This analysis is appropriate since the measurements from the different lasers were made concurrently on any given section. In this analysis, researchers made the following pairwise comparisons based on IRI differences:

- Single-point IRI – 19mm IRI.
- Single-point IRI – Roline IRI.
- 19mm IRI – Roline IRI.

Researchers then determined the 95 percent confidence intervals of the IRI differences to assess the level of agreement (or disagreement) between the three lasers. Table 5.3 summarizes the results from this analysis by presenting the average of the IRI differences and the 95 percent confidence intervals of these differences for the pairwise comparisons noted above. For example, on the Type C section along the K1 lane of FM2440-1, the average of the IRI differences between the single-point and 19mm lasers is 0.597 inch/mile. The positive value of the average indicates that the single-point laser tended to give higher IRIs than the 19mm laser on this particular section, with the 95 percent confidence intervals ranging from 0.307 to 0.887 inch/mile. This range is on the positive side and does not include zero indicating that the IRI differences between the single-point and 19mm lasers on this particular section are statistically significant at the 95 percent confidence level. The average differences and confidence intervals on the other sections shown in Table 5.3 can be interpreted in a similar manner. It is observed that the average IRI differences are statistically significant on many of the sections tested. However, on these same sections, the confidence intervals of the IRI differences are, in the majority of cases, 3.0 inches/mile or less in magnitude, which is the threshold at which the Engineer is given the <u>option</u> to request referee testing according TxDOT's Item 585 ride quality specification. Cases where the confidence intervals include magnitudes of IRI differences more than 3.0 inches/mile are highlighted in yellow in Table 5.3.

Table 5.3. 95% Confidence Intervals of IRI Differences from Dynatest Data.

Highway	Lane	Surface Type	Lasers compared	Average IRI difference (inch/mile)	95% confidence interval of IRI differences (inch/mile)		Statistically significant?*
					Lower limit	Upper limit	
FM2440-1	K1	Type C	Single vs. 19mm	0.597	0.307	0.887	Yes
			Single vs. Roline	0.960	0.635	1.285	Yes
			19mm vs. Roline	0.363	0.029	0.697	Yes
FM2440-1	K6	Type C	Single vs. 19mm	0.178	−0.189	0.545	No
			Single vs. Roline	0.671	0.286	1.056	Yes
			19mm vs. Roline	0.493	0.220	0.766	Yes
FM2440-2	K1	Type C	Single vs. 19mm	0.142	−0.096	0.380	No
			Single vs. Roline	0.473	0.017	0.929	Yes
			19mm vs. Roline	0.331	−0.085	0.746	No
FM2440-2	K6	Type C	Single vs. 19mm	0.051	−0.204	0.306	No
			Single vs. Roline	0.674	0.137	1.210	Yes
			19mm vs. Roline	0.623	0.158	1.087	Yes
SH6	L1	CRCP CT	Single vs. 19mm	0.366	0.046	0.687	Yes
			Single vs. Roline	0.904	0.455	1.352	Yes
			19mm vs. Roline	0.537	0.096	0.978	Yes
SH6	R1	CRCP CT	Single vs. 19mm	0.007	−0.279	0.294	No
			Single vs. Roline	0.111	−0.373	0.595	No
			19mm vs. Roline	0.104	−20.294	0.502	No

*Confidence interval of IRI differences that includes zero identifies a case where the IRI differences are not statistically significant at the 95 percent confidence level.

Table 5.3. 95%Confidence Intervals of IRI Differences from Dynatest Data (continued).

Highway	Lane	Surface Type	Lasers compared	Average IRI difference (inch/mile)	95% confidence interval of IRI differences (inch/mile)		Statistically significant?*
					Lower limit	Upper limit	
SH6 (Grimes)	L1	PFC	Single vs. 19mm	2.192	1.584	2.800	Yes
			Single vs. Roline	3.211	2.505	3.916	Yes
			19mm vs. Roline	1.019	0.534	1.504	Yes
SH6 (Grimes)	R1	PFC	Single vs. 19mm	2.013	1.445	2.580	Yes
			Single vs. Roline	3.730	3.026	4.434	Yes
			19mm vs. Roline	1.717	1.116	2.319	Yes
SH36	K1	CRCP carpet drag	Single vs. 19mm	0.537	−0.263	1.337	No
			Single vs. Roline	2.917	1.797	4.038	Yes
			19mm vs. Roline	2.380	1.036	3.725	Yes
SH36	K6	CRCP carpet drag	Single vs. 19mm	0.513	−0.198	1.225	No
			Single vs. Roline	1.556	0.543	2.569	Yes
			19mm vs. Roline	1.042	−0.281	2.366	No
SH36	L1	CRCP CT	Single vs. 19mm	0.377	−0.076	0.830	No
			Single vs. Roline	0.675	0.020	1.330	Yes
			19mm vs. Roline	0.298	−0.287	0.884	No
SH36	R1	CRCP CT	Single vs. 19mm	0.622	0.193	1.050	Yes
			Single vs. Roline	0.829	0.195	1.464	Yes
			19mm vs. Roline	0.208	−0.388	0.803	No

*Confidence interval of IRI differences that includes zero identifies a case where the IRI differences are not statistically significant at the 95 percent confidence level.

Table 5.3. 95% Confidence Intervals of IRI Differences from Dynatest Data (continued).

Highway	Lane	Surface Type	Lasers compared	Average IRI difference (inch/mile)	95% confidence interval of IRI differences (inch/mile)		Statistically significant? *
					Lower limit	Upper limit	
SH36	L1	CRCP VT	Single vs. 19mm	0.406	0.125	0.687	Yes
			Single vs. Roline	0.392	−0.200	0.984	No
			19mm vs. Roline	−0.014	−0.649	0.621	No
SH36	R1	CRCP VT	Single vs. 19mm	0.882	0.515	1.248	Yes
			Single vs. Roline	1.422	0.872	1.972	Yes
			19mm vs. Roline	0.540	0.127	0.953	Yes
FM1940	K1	Inverted prime	Single vs. 19mm	−0.175	−0.854	0.503	No
			Single vs. Roline	0.775	−0.678	2.227	No
			19mm vs. Roline	0.950	−0.230	2.130	No
FM1940	K6	Inverted prime	Single vs. 19mm	−1.393	−2.451	−0.336	Yes
			Single vs. Roline	−0.381	2.419	1.658	No
			19mm vs. Roline	1.013	−0.982	3.007	No
SH6 (Robertson)	K1	PFC	Single vs. 19mm	2.906	2.410	3.402	Yes
			Single vs. Roline	6.773	6.315	7.231	Yes
			19mm vs. Roline	3.867	3.416	4.319	Yes
SH6 (Robertson)	K6	PFC	Single vs. 19mm	2.893	2.412	3.375	Yes
			Single vs. Roline	5.269	4.693	5.845	Yes
			19mm vs. Roline	2.376	1.911	2.840	Yes

*Confidence interval of IRI differences that includes zero identifies a case where the IRI differences are not statistically significant at the 95 percent confidence level.

Table 5.3. 95% Confidence Intervals of IRI Differences from Dynatest Data (continued).

Highway	Lane	Surface Type	Lasers compared	Average IRI difference (inch/mile)	95% confidence interval of IRI differences (inch/mile)		Statistically significant?*
					Lower limit	Upper limit	
IH20	R1	Type D	Single vs. 19mm	−1.120	−1.276	−0.964	Yes
			Single vs. Roline	−0.844	−1.095	−0.594	Yes
			19mm vs. Roline	0.276	0.029	0.522	Yes
IH35	A2	CRCP carpet drag	Single vs. 19mm	−0.534	−0.892	−0.176	Yes
			Single vs. Roline	0.334	−0.607	1.275	No
			19mm vs. Roline	0.868	−0.140	1.876	No
IH820	L4	CRCP VT	Single vs. 19mm	−0.295	−0.574	−0.016	Yes
			Single vs. Roline	−2.004	−2.774	−1.233	Yes
			19mm vs. Roline	−1.709	−2.387	−1.030	Yes
IH820	R4	CRCP VT	Single vs. 19mm	−0.611	−0.848	−0.374	Yes
			Single vs. Roline	−4.662	−5.158	−4.166	Yes
			19mm vs. Roline	−4.051	−4.513	−3.589	Yes
IH35	L1	CRCP CT	Single vs. 19mm	0.021	−0.267	0.309	No
			Single vs. Roline	−1.403	−2.265	−0.540	Yes
			19mm vs. Roline	−1.423	−2.280	−0.567	Yes
IH35	R1	CRCP CT	Single vs. 19mm	−0.064	−0.387	0.260	No
			Single vs. Roline	−0.584	−1.206	0.039	No
			19mm vs. Roline	−0.562	−1.166	0.042	No

*Confidence interval of IRI differences that includes zero identifies a case where the IRI differences are not statistically significant at the 95 percent confidence level.

Table 5.3. 95-percent Confidence Intervals of IRI Differences from Dynatest Data (continued).

Highway	Lane	Surface Type	Lasers compared	Average IRI difference (inch/mile)	95% confidence interval of IRI differences (inch/mile)		Statistically significant?*
					Lower limit	Upper limit	
US59	L1	PFC	Single vs. 19mm	0.820	0.241	1.399	Yes
			Single vs. Roline	3.723	3.277	4.169	Yes
			19mm vs. Roline	2.902	2.521	3.284	Yes
US59	R1	PFC	Single vs. 19mm	0.923	0.316	1.529	Yes
			Single vs. Roline	3.644	3.110	4.178	Yes
			19mm vs. Roline	2.721	2.364	3.079	Yes
Loop463	L2	Type C	Single vs. 19mm	0.047	-0.114	0.207	No
			Single vs. Roline	0.644	0.260	1.028	Yes
			19mm vs. Roline	0.597	0.169	1.026	Yes
Loop463	R2	Type C	Single vs. 19mm	−0.122	−0.338	0.093	No
			Single vs. Roline	0.150	−0.096	0.396	No
			19mm vs. Roline	0.272	0.030	0.515	Yes
US77	L1	Type D	Single vs. 19mm	0.056	−0.140	0.253	No
			Single vs. Roline	0.655	0.409	0.901	Yes
			19mm vs. Roline	0.598	0.354	0.843	Yes
US77	R1	Type D	Single vs. 19mm	0.189	0.018	0.360	Yes
			Single vs. Roline	0.774	0.515	1.033	Yes
			19mm vs. Roline	0.585	0.314	0.856	Yes

*Confidence interval of IRI differences that includes zero identifies a case where the IRI differences are not statistically significant at the 95 percent confidence level.

These cases occur on pavements with PFC, carpet drag, and variable tined surfaces. Among these cases, the single-point IRIs are observed to be greater than the Roline IRIs on PFC and carpet dragged surfaces, with the largest differences observed on the PFC section along the K1 lane of SH6 in Robertson County. This case is highlighted in red in Table 5.3. On this PFC section, the 95 percent confidence interval of the IRI differences between the single-point and Roline lasers ranged from 6.315 to 7.231 inches/mile with an average difference of 6.773 inches/mile. Hypothetically, if a contractor used a Roline for ride quality assurance testing on this section, and TxDOT performed verification testing with a single-point laser, referee testing would be mandatory according to Item 585 since the average IRI difference is more than 6.0 inches/mile. The question is, "Which laser is correct?"

Note that on the variable tined section along the R4 lane of IH820 in Tarrant County, the Roline IRIs are higher than the single-point IRIs. Also, the Roline IRIs are higher than the 19mm IRIs on this section. Thus, the direction of the IRI differences is opposite that observed on the PFC and carpet dragged surfaces. Researchers note that the Roline laser was oriented perpendicular to the direction of travel on the Dynatest three-laser system, which is the normal configuration on commercially available profilers equipped with Rolines.

The Roline laser with its wider footprint measures more of the road surface at any given location compared to the single-point and 19mm lasers. The surface features of the variable transverse tines on the IH820 section coupled with how the line scan tracked these features during testing could explain the higher IRIs. However, this particular case will not result in verification or referee testing under Item 585, given the direction of the IRI differences. Note that the average IRI difference between the single-point and Roline lasers is −4.662 inches/mile on this section. In addition, the test data on the other variable transverse tined section located on the L4 lane as well as the variable tined sections along SH36 in Milam County show magnitudes of IRI differences within 3.0 inches/mile. Thus, the test results are mixed unlike the results on the PFC sections, which are consistent.

To check which laser is correct, researchers compared the IRIs determined from the different lasers with the corresponding IRIs determined from profiles collected with the SurPRO reference profiler. Table 5.4 gives summary statistics on the IRIs determined from profile measurements collected on PFC sections with the SurPRO and Dynatest three-laser system. Table 5.5 gives similar statistics on the IRIs determined from tests conducted on CRCP sections in Brazos and Milam Counties. The tabulated IRIs are averages of the corresponding quantities determined from repeat runs on each section.

Table 5.4. IRIs Determined from SurPRO and Dynatest Measurements on PFC Sections.

Highway-Surface type (County)	Lane	528-ft seg.	SurPRO		Roline		19mm		Single-point	
			Avg. IRI	IRI std. dev.	Avg. IRI	IRI std. dev.	Avg. IRI	IRI std. dev.	Avg. IRI	IRI std. dev.
SH6-PFC (Grimes)	L1	1	38.40	1.23	35.37	0.61	37.98	0.48	41.33	0.66
		2	50.90	1.56	47.94	1.88	48.21	1.57	49.57	1.64
		3	52.30	1.21	49.42	1.98	52.00	1.00	52.31	1.79
		4	55.70	0.70	52.09	0.44	51.84	0.35	55.64	1.57
		5	55.93	1.17	47.93	0.15	48.08	0.56	49.76	0.21
		6	45.93	0.85	40.71	0.49	42.27	1.33	45.93	1.46
		7	42.77	0.60	45.03	1.10	46.14	2.08	47.24	0.97
		8	58.43	0.86	70.58	1.84	72.60	1.43	68.12	2.34
		9	53.97	0.55	52.00	0.81	51.42	0.21	54.02	0.25
		10	63.30	1.11	59.59	0.50	60.93	2.02	61.11	1.98
SH6-PFC (Robertson)	K1	1	36.53	0.96	29.44	0.38	32.18	0.30	36.37	0.94
		2	42.20	1.67	28.09	1.04	33.17	0.61	36.78	0.12
		3	42.77	1.06	29.37	0.54	33.18	0.45	36.29	1.18
		4	50.57	0.55	38.13	0.65	43.04	1.37	45.56	1.16
		5	40.33	0.81	36.84	1.71	39.22	0.92	42.11	2.21
		6	39.73	1.17	34.27	0.74	37.46	2.70	39.94	0.44
		7	35.80	1.25	30.56	1.34	34.91	1.86	38.02	0.77
		8	55.87	0.47	49.56	0.61	53.39	1.10	56.58	0.79

Table 5.5. IRIs Determined from SurPRO and Dynatest Measurements on CRCP Sections.

Highway-Surface type (County)	Lane	528-ft seg.	SurPRO		Roline		19mm		Single-point	
			Avg. IRI	IRI std. dev.	Avg. IRI	IRI std. dev.	Avg. IRI	IRI std. dev.	Avg. IRI	IRI std. dev.
SH36-CT (Milam)	L1	1	76.83	0.35	77.49	0.99	78.39	1.51	79.40	1.15
		2	76.27	0.78	72.35	0.21	72.83	0.72	72.89	1.15
		3	50.53	0.76	46.91	0.30	46.53	0.48	46.56	1.22
		4	61.73	3.37	53.41	0.95	54.71	0.99	54.24	1.40
		5	91.65	1.34	78.45	1.34	77.84	2.09	78.94	1.49
		6	79.30	2.83	62.84	2.58	64.29	2.01	65.66	1.87
		7	102.00	1.55	93.94	0.82	95.09	0.62	96.60	2.37
		8	73.03	1.10	72.56	1.98	70.69	2.66	70.79	2.41
SH6-CT (Brazos)	R1	1	68.60	1.35	60.56	1.89	60.83	2.48	60.10	2.21
		2	54.97	0.93	54.24	0.93	54.35	2.35	54.03	2.32
		3	64.27	0.40	64.44	1.44	63.89	0.71	63.63	0.32
		4	67.27	1.21	65.27	1.80	64.98	1.70	65.69	1.38
		5	71.60	0.95	66.23	0.30	66.64	0.48	68.41	2.74
		6	71.37	1.02	70.54	1.92	70.42	1.30	70.79	1.71
		7	78.30	1.37	75.12	1.49	76.48	1.68	75.93	1.22
SH36-VT (Milam)	L1	1	85.03	2.12	84.45	2.28	84.34	2.13	84.69	2.36
		2	82.30	0.46	80.60	0.13	80.59	0.68	80.94	1.18
		3	80.53	1.21	77.83	1.05	76.36	2.78	77.16	2.62
		4	91.00	2.62	84.47	1.13	86.00	1.82	85.85	1.65
		5	80.37	2.26	78.34	1.72	78.94	2.40	79.17	1.48
		6	68.70	0.30	65.94	0.43	64.86	0.65	65.31	0.45
		7	73.60	0.10	72.74	0.50	72.28	0.60	72.93	0.40
		8	77.87	0.25	67.35	2.51	68.62	1.74	69.13	1.77
SH36-carpet drag (Milam)	K6	1	110.73	0.49	104.09	2.57	104.87	3.11	106.44	3.43
		2	123.57	0.84	113.73	2.73	113.41	2.85	114.08	3.20
		3	108.87	1.05	94.91	0.63	96.11	0.94	95.54	2.33
		4	234.40	0.56	224.44	0.18	228.68	0.68	228.30	0.54

To compare the IRIs from each laser with the IRIs from SurPRO measurements, researchers performed the paired *t*-test on the differences between corresponding IRIs given in Tables 5.4 and 5.5. Researchers used this statistical test to make inferences about the differences in the IRIs for the following reasons:

- All profile measurements were made on the same sections. Thus, the IRI for any given laser is matched or paired with the IRI from the SurPRO, which means that the sample measurements from the different profiling methods are not independent. Thus, other statistical tests that require independent random samples to make inferences about differences in population means cannot be used.

- The SurPRO measurements were not done at the same time as the measurements from the Dynatest three-laser system. Thus, the measurement from the SurPRO for any given run (for example, run 1) cannot necessarily be matched with the measurements from the different lasers for that same run, unlike the comparisons made earlier between the IRIs from the laser measurements done with the Dynatest system.
- The average IRI determined from repeat measurements on any given 528-ft segment is the best IRI estimate for that segment based on the given profiling method (i.e., inertial profiler or SurPRO).
- In general, the IRIs from repeat runs are repeatable, as reflected in the standard deviations given in Tables 5.4 and 5.5.

Based on the above considerations, researchers used the average IRIs with the paired *t*-test to evaluate the differences between the IRIs from any given laser and the corresponding reference IRIs from the SurPRO. Specifically, researchers made the following pairwise comparisons on the average IRIs determined for the different 528-ft segments comprising a given section:

- Roline IRI – SurPRO IRI.
- 19mm IRI – SurPRO IRI.
- Single-point IRI – SurPRO IRI.

Table 5.6 presents the results from this analysis on the PFC sections while Table 5.7 shows the results for the CRCP sections. Table 5.6 shows that, at the 95 percent confidence level, the differences in IRIs from each laser and the SurPRO are not statistically significant on the PFC sections in Grimes County. However, the IRI differences are statistically significant on the PFC sections in Robertson County for the Roline and 19mm lasers, which give IRIs that are significantly lower than the corresponding reference IRIs from the SurPRO. If the data from the PFC sections in both counties are combined, the statistical analysis shows that only the Roline IRIs test to be significantly lower than the corresponding reference IRIs.

Table 5.6. Comparison of Laser and SurPRO IRIs on PFC Sections.

Highway-Surface type (County)	Laser compared to SurPRO[1]	Average IRI difference (inch/mile)	95% confidence interval of IRI differences (inch/mile)		Statistically significant?[2]
			Lower limit	Upper limit	
SH6-PFC (Grimes)	Roline	−1.697	−5.629	2.236	No
	19mm	−0.607	−4.860	3.646	No
	Single-point	0.741	−2.290	3.772	No
SH6-PFC (Robertson)	Roline	−8.443	−11.944	−4.942	Yes
	19mm	−4.657	−7.637	−1.676	Yes
	Single-point	−1.519	−4.461	1.423	No
SH6-PFC combined	Roline	−4.695	−7.642	−1.748	Yes
	19mm	−2.407	−5.049	0.236	No
	Single-point	−0.264	−2.249	1.722	No

[1]Roline laser set up in bridge mode with laser footprint oriented perpendicular to direction of travel.
[2]Confidence interval of IRI differences that includes zero identifies a case where the IRI differences are not statistically significant at the 95 percent confidence level.

The results for the CRCP sections are rather interesting. In all but one case, Table 5.7 shows that the IRIs from all three lasers are significantly lower than the corresponding SurPRO IRIs. Note the negative average IRI difference and the negative lower and upper limits of the 95 percent confidence intervals in these sections. Only the IRIs determined from single-point laser profiles collected on the SH6 CT sections in Brazos County are found to have no significant difference with the corresponding reference IRIs. This finding suggests that quality assurance tests performed with inertial profilers might already be giving an allowance to contractors working on CRCP projects, which compensates for the perceived roughness added by transverse tining or by the carpet drag.

Table 5.7. Comparison of Laser and SurPRO IRIs on CRCP Sections.

Highway-Surface type (County)	Laser compared to SurPRO[1]	Average IRI difference (inch/mile)	95% confidence interval of IRI differences (inch/mile)		Statistically significant?[2]
			Lower limit	Upper limit	
SH6-CT (Brazos)	Roline	−2.852	−5.572	−0.133	Yes
	19mm	−2.682	−5.203	−0.161	Yes
	Single-point	−2.541	−5.129	0.047	No
SH36-CT Milam	Roline	−6.677	−11.695	−1.659	Yes
	19mm	−6.372	−11.101	−1.643	Yes
	Single-point	−5.783	−10.299	−1.268	Yes
SH6/SH36 CT combined	Roline	−4.892	−7.695	−2.089	Yes
	19mm	−4.650	−7.295	−2.005	Yes
	Single-point	−4.270	−6.793	−1.748	Yes
SH36-VT Milam	Roline	−3.461	−6.297	−0.625	Yes
	19mm	−3.426	−5.791	−1.062	Yes
	Single-point	−3.027	−5.397	−0.657	Yes
SH36-carpet drag Milam	Roline	−10.098	−14.860	−5.336	Yes
	19mm	−8.622	−14.097	−3.146	Yes
	Single-point	−8.303	−14.635	−1.971	Yes

[1]Roline laser set up in bridge mode with laser footprint oriented perpendicular to direction of travel.
[2]Confidence interval of IRI differences that includes zero identifies a case where the IRI differences are not statistically significant at the 95 percent confidence level.

Given that the results presented are based on profiles collected with the same inertial profiling system, researchers also compared the IRIs determined from runs made on the same sections with TxDOT's inertial profiler, which have single-point lasers. Table 5.8 gives summary statistics on the IRIs computed from TxDOT profile measurements while Table 5.9 shows the paired *t*-test results from comparing the TxDOT profiler IRIs with the SurPRO reference IRIs. The results are consistent with those presented earlier. On the CRCP sections, the IRIs from TxDOT's profiler are significantly lower than the corresponding reference IRIs, while on the PFC sections, the IRIs from the same profiler are found to have no significant difference with the corresponding reference IRIs.

Table 5.8. IRIs Computed from TxDOT Profiler Data on CRCP and PFC Sections.

Highway-Surface type (County)	Lane	528-ft segment	SurPRO		TxDOT single-point	
			Avg. IRI	IRI std. dev.	Avg. IRI	IRI std. dev.
SH36-CT (Milam)	L1	1	76.83	0.35	75.83	0.90
		2	76.27	0.78	71.27	0.97
		3	50.53	0.76	46.00	0.76
		4	61.73	3.37	52.43	1.04
		5	91.65	1.34	79.20	2.10
		6	79.30	2.83	62.27	0.95
		7	102.00	1.55	95.37	0.91
		8	73.03	1.10	71.70	1.57
SH6-CT (Brazos)	R1	1	68.60	1.35	59.73	1.99
		2	54.97	0.93	54.73	1.52
		3	64.27	0.40	65.10	0.92
		4	67.27	1.21	63.63	0.31
		5	71.60	0.95	66.30	1.41
		6	71.37	1.02	68.67	0.65
		7	78.30	1.37	74.43	1.43
SH36-VT (Milam)	L1	1	85.03	2.12	82.07	1.29
		2	82.30	0.46	80.50	1.14
		3	80.53	1.21	76.40	0.56
		4	91.00	2.62	84.30	0.95
		5	80.37	2.26	80.07	3.15
		6	68.70	0.30	62.77	0.86
		7	73.60	0.10	69.03	0.35
		8	77.87	0.25	68.70	0.20
SH36-carpet drag (Milam)	K6	1	110.73	0.49	100.67	3.20
		2	123.57	0.84	110.37	1.47
		3	108.87	1.05	101.30	4.23
		4	234.40	0.56	226.63	5.55
SH6-PFC (Grimes)	L1	1	38.40	1.23	38.50	0.79
		2	50.90	1.56	38.20	1.55
		3	52.30	1.21	40.17	0.90
		4	55.70	0.70	48.33	2.72
		5	55.93	1.17	45.27	1.46
		6	45.93	0.85	42.07	1.48
		7	42.77	0.60	41.73	2.40
		8	58.43	0.86	58.80	2.86
		9	53.97	0.55	40.93	1.85
		10	63.30	1.11	48.57	2.18
SH6-PFC (Robertson)	K1	1	36.53	0.96	50.23	1.64
		2	42.20	1.67	56.93	2.66
		3	42.77	1.06	48.20	2.70
		4	50.57	0.55	42.53	0.80
		5	40.33	0.81	43.03	3.10
		6	39.73	1.17	61.07	4.97
		7	35.80	1.25	58.37	1.77
		8	55.87	0.47	59.10	5.62

Table 5.9. Comparison of TxDOT Profiler and SurPRO IRIs on CRCP and PFC Sections.

Highway-Surface type (County)	Average IRI difference (inch/mile)[1]	95% confidence interval of IRI differences (inch/mile)		Statistically significant?[2]
		Lower limit	Upper limit	
SH36-CT (Milam)	−7.16	−11.78	−2.54	Yes
SH6-CT (Brazos)	−3.40	−6.37	−0.42	Yes
SH6/SH36 CT combined	−5.40	−8.09	−2.72	Yes
SH36-VT (Milam)	−4.45	−6.81	−2.08	Yes
SH36-carpet drag (Milam)	−9.65	−13.83	−5.47	Yes
SH6-PFC (Grimes)	−0.87	−3.54	1.81	No
SH6-PFC (Robertson)	1.16	−1.913	4.23	No
SH6-PFC combined	0.03	−1.83	1.89	No

[1] IRI difference = TxDOT IRI – SurPRO IRI
[2] Confidence interval of IRI differences that includes 0 identifies a case where the IRI differences are not statistically significant at the 95 percent confidence level.

TxDOT is building a concrete profiler certification track on an ongoing implementation project. This track will consist of sections with conventional 1-inch transverse tines, ½-inch transverse tines, and longitudinal tines. The results presented here on the IRI differences from tests done on CRCP sections suggest a need to re-examine the current IRI accuracy criterion requiring a difference of 6 inches/mile or less between the test and reference IRI values for inertial profiler certifications. Specifically, there is a need to assess the applicability of this criterion on CRCP surfaces.

EVALUATION OF ROLINE TIRE BRIDGE FILTER SETTINGS

The findings presented on the IRI differences from comparisons made between the Roline laser and the other profiling devices show that on PFC and CRCP surfaces, the IRIs determined from Roline measurements can be significantly different from the IRIs determined from the other methods. These results suggest a need to evaluate the Roline tire-bridge filter settings to determine a set of tire-bridge filter parameters that can improve the agreement with the SurPRO reference IRIs. Researchers note that the results presented are based on Roline data collected using the laser's internal tire-bridging filter. To evaluate filter parameters that can provide better agreement with the SurPRO reference IRIs, researchers developed a portable Roline profiler module that permits data to be collected in free mode. This work also required development of software to process the free mode data based on the tire-bridge filter algorithm described in the LMI/Selcom Roline user's manual. This software development was necessary since the laser manufacturer did not make available the code for the laser's internal tire-bridge filter. Thus, UTA researchers wrote software to process the free mode data based on the description given about the filter in the Roline user's manual and communications with LMI/Selcom. Chapter IV of this report presents this development work along with a discussion of the tire-bridging algorithm.

Researchers used the software developed in this project to collect and process free mode data to determine surface profiles with the Roline laser. For the evaluation reported here, they varied the window size and window skip parameters of the Roline tire-bridge filter to determine the values that provide the best agreement between the IRIs computed from the Roline profiles and the IRIs determined from the SurPRO reference profiler. The search matrix covered 16 combinations of the following window size and window skip settings:

- Window size – 80, 70, 60, 50.
- Window skip – 0, 10, 20, 30.

In this evaluation, the tilt adjustment in the processing software was turned on to remove the slope in the line scan data according to the procedure described in the Roline user's manual.

Thus, for a given combination of window size and window skip parameters, researchers determined the IRIs from the resulting Roline profiles and compared the computed IRIs to the corresponding SurPRO reference IRIs. For the HMA, seal coat, and CRCP sections where tests were conducted with the Roline footprint oriented at 0° (i.e., perpendicular to the direction of travel), the optimal window size and window skip settings in terms of the lowest average absolute difference were found to be 50 and 0, respectively. At these settings, Table 5.10 shows the average of the absolute differences between the Roline and SurPRO IRIs for each surface material type along with the average IRI difference.

Table 5.10. Goodness-of-Fit Statistics at Window Size 50 and Window Skip 0.

Surface Material Type	Average Absolute IRI Difference (inch/mile)	Average IRI Difference (inch/mile)
HMA	2.6	−0.35
CRCP	4.7	1.56
Seal coat	2.8	−0.85
Flexible base (including inverted prime)	5.6	0.02

Researchers note that for the flexible base sections, the lowest average absolute difference of 5.3 inches/mile was obtained at window size and window skip settings of 60 and 30, respectively, with an average IRI difference of −1.75 inches/mile. In practice, the Roline laser would probably need to be configured using the same settings for profile measurements on all surfaces. In the opinion of the researchers, it would be problematic to have different Roline settings depending on the type of surface material to be tested. Thus, for consistency, they suggest using a window size of 50 and a window skip of 0 for testing flexible base with the Roline laser. At these settings, the average absolute difference of 5.6 inches/mile is just slightly higher than the statistic obtained for a window size and a window skip of 60 and 30, respectively. However, the average IRI difference is closer to 0 at the suggested settings.

IRI COMPARISONS BASED ON THREE-LASER SYSTEM AND SURPRO DATA

Researchers processed the free mode data collected with the three-laser system assembled in this project to determine profiles using the recommended window size and window skip settings of 50 and zero, respectively. They also computed the IRIs from the 19mm and texture laser measurements. Profiles from all three lasers were determined using the inertial profile algorithm implemented in TxDOT's profilers. Researchers then computed the IRIs from the three laser profiles and compared the IRIs from each laser with the corresponding values from the SurPRO measurements. These comparisons were made with the paired *t*-test on the IRI differences, using the same approach to analyze the data collected with the Dynatest three-laser system. The following sections present the results from this comparative evaluation.

Hot-Mix Asphalt Sections

Table 5.11 shows the 95 percent confidence intervals of the IRI differences on the HMA sections. The following observations from the results are noted:

- On the PFC sections, the IRI differences between the Roline and the SurPRO range from −3.60 to −0.16 inch/mile with an average difference of −1.88 inches/mile. While the Roline IRIs test to be significantly lower than the SurPRO IRIs on these sections, the IRI differences are smaller in magnitude compared to the differences between the Roline IRIs collected in bridge mode and the SurPRO IRIs. Figure 5.3 compares the Roline IRIs with the corresponding SurPRO values on PFC sections. Researchers observed that the bridge mode IRIs tend to be lower than the SurPRO IRIs.

  In the PFC sections, Table 5.6 shows that the 95 percent confidence interval of the IRI differences in bridge mode range from −7.64 to −1.75 inches/mile with an average difference of −4.69 inches/mile. Thus, the calibration of the Roline free mode data reduced the IRI differences significantly, albeit that the IRIs still test to be significantly lower than the corresponding SurPRO values. Researchers note that the recommended window size and window skip settings used to process the free mode data are based on the calibration results for all test sections. Over all the HMA sections, the IRI differences are not statistically significant. As shown in Table 5.11, the average IRI difference between the Roline and the SurPRO on these sections is −0.35 inch/mile, with a 95 percent confidence interval ranging from −1.55 to 0.85 inch/mile.
- On the PFC sections, the IRI differences for the single-point laser are not statistically significant based on the data from the Dynatest, TxDOT, and the three-laser system profiler assembled in this project.
- On the SMA sections, the IRI differences for the Roline and texture lasers are not statistically significant. However, the IRIs from the 19mm laser are significantly lower than the SurPRO IRIs, with a 95 percent confidence interval ranging from −4.74 to −0.51 inch/mile.
- On the Type D sections, the IRI differences for the Roline and texture lasers are statistically significant. However, the magnitudes of the differences based on the

95 percent confidence intervals are within 3.0 inches/mile. The IRI differences for the 19mm laser are not statistically significant on the Type D sections.

Table 5.11. Comparison of Laser and SurPRO IRIs on HMA Sections.

Laser compared to SurPRO	Surface type	Average IRI difference (inch/mile)	95% confidence interval of IRI differences (inch/mile)		Statistically significant?*
			Lower limit	Upper limit	
Roline (free mode)	PFC	−1.880	−3.596	−0.164	Yes
	Type D	1.375	0.200	2.550	Yes
	SMA	1.941	−0.718	4.599	No
	Overall	−0.350	−1.554	0.854	No
Texture (single-point footprint)	PFC	−0.497	−2.332	1.338	No
	Type D	−1.586	−2.867	−0.305	Yes
	SMA	−1.098	−3.353	1.156	No
	Overall	−0.882	−1.962	0.197	No
19mm	PFC	−1.675	−3.220	−0.130	Yes
	Type D	0.393	−1.420	2.205	No
	SMA	−2.628	−4.742	−0.513	Yes
	Overall	−1.337	−2.367	−0.306	Yes

*Confidence interval of IRI differences that includes 0 identifies a case where the IRI differences are not statistically significant at the 95 percent confidence level.

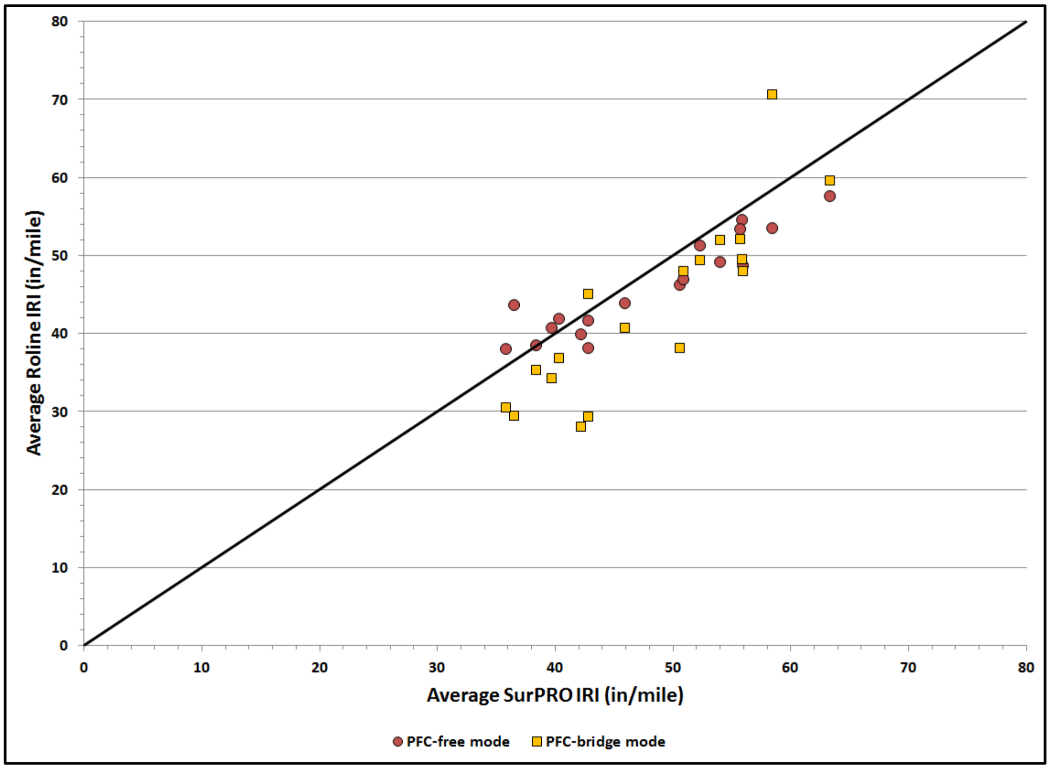

Figure 5.3. Comparison of Roline and SurPRO IRIs on PFC Sections.

Continuously Reinforced Concrete Pavement Sections

Table 5.12 shows the 95 percent confidence intervals of the IRI differences on the CRCP sections. The results from the paired *t*-tests are presented for the two laser footprint angles at which Roline free mode tests were conducted.

Table 5.12. Comparison of Laser and SurPRO IRIs on CRCP Sections.

Laser compared to SurPRO	Surface type	Average IRI difference (inch/mile)	95% confidence interval of IRI differences (inch/mile)		Statistically significant?*
			Lower limit	Upper limit	
Roline (free mode at 0°)	Conv. tines	1.919	−1.667	5.504	No
	½-inch tines	0.077	−4.907	5.061	No
	Var. tines	4.227	1.025	7.429	Yes
	Carpet drag	3.858	−4.451	12.168	No
	Long. tines	−3.934	−8.422	0.554	No
	Overall	1.563	−0.381	3.508	No
Roline (free mode at 45°)	Conv. tines	−0.371	−4.799	4.056	No
	½-inch tines	−2.631	−10.960	5.698	No
	Var. tines	2.448	−2.409	7.305	No
	Carpet drag	−6.974	−10.960	−2.988	Yes
	Overall	−1.206	−3.718	1.306	No
19mm	Conv. tines	−3.125	−6.493	0.243	No
	½-inch tines	−1.990	−3.028	−0.952	Yes
	Var. tines	−1.258	−3.766	1.249	No
	Carpet drag	−6.823	−10.082	−3.563	Yes
	Long. tines	−0.668	−5.987	4.650	No
	Overall	−2.796	−4.339	−1.252	Yes
Texture (single-point footprint)	Conv. tines	−4.606	−7.848	−1.364	Yes
	½-inch tines	−2.913	−4.820	−1.006	Yes
	Var. tines	−3.215	−5.423	−1.006	Yes
	Carpet drag	−5.846	−8.846	−2.846	Yes
	Long. tines	8.550	1.697	15.402	Yes
	Overall	−2.329	−4.417	−0.241	Yes

*Confidence interval of IRI differences that includes zero identifies a case where the IRI differences are not statistically significant at the 95 percent confidence level.

In one case, researchers set up the Roline so that the laser footprint is at a 0-degree angle relative to the transverse axis (perpendicular to the direction of travel). In the other case, researchers performed tests with the Roline laser footprint oriented at 45°. Researchers note the following observations from the results of the IRI comparisons on CRCP sections:

- The results presented earlier in Table 5.7 show that the Roline data in bridge mode consistently gave IRIs that are significantly lower than the corresponding SurPRO values on CRCP sections with conventional transverse tines, variable transverse tines, and carpet drag imprints. Table 5.12 shows that with calibration, the IRIs based on Roline free mode data collected at 0 show no significant difference with the SurPRO IRIs on the same CRCP sections with conventional transverse tines and carpet drag imprints that were tested with the Roline laser configured in bridge mode. Table 5.12 also shows that the IRI differences between the Roline and the SurPRO are not significantly different on CRCP sections with ½-inch transverse tines and longitudinal tines.

However, on sections with variable transverse tines, the IRIs based on the Roline free mode data collected at 0 ° are significantly higher than the corresponding SurPRO reference values. For these sections, the average IRI difference is 4.23 inches/mile with a 95 percent confidence interval ranging from 1.03 to 7.43 inches/mile. On these same sections, the Roline bridge mode IRIs are significantly lower than the SurPRO IRIs with an average difference of −3.46 inches/mile and a 95 percent confidence interval of −6.3 to −0.63 inches/mile from Table 5.7. Thus, while the calibration removed the negative bias seen in the Roline bridge mode IRIs on CRCP sections with conventional transverse tines and carpet drag imprints, the bias on sections with variable transverse tines switched from negative to positive.

- Researchers note that the recommended window size and window skip settings from the calibration are based on the data for all CRCP sections. For the variable transversely tined sections, the optimal window size and window skip settings are 60 and 20, respectively. At these settings, the differences between the Roline and SurPRO IRIs are not statistically significant, with an average difference of 2.79 inches/mile and a 95 percent confidence interval ranging from −0.59 to 6.17 inches/mile. However, as indicated previously, using different Roline settings depending on surface type would be problematic in practice. Thus, researchers recommend using the optimal window size and window skip settings of 50 and 0, respectively, which are based on the data for all CRCP sections. Over all these sections, the results in Table 5.12 show that the differences between the Roline and SurPRO IRIs are not statistically significant with an average difference of 1.56 inches/mile and a 95 percent confidence interval ranging from −0.38 to 3.51 inches/mile.

- For tests conducted with the Roline laser footprint oriented at 45°, the differences in IRIs between the Roline and the SurPRO are not statistically significant on CRCP sections with conventional transverse tines, ½-inch transverse tines, and variable transverse tines. However, the IRI differences are statistically significant on the carpet drag sections. Researchers note that these results are based on using the recommended window size and window skip settings determined from the Roline data collected at 0°. Thus, the recommended settings did not introduce a bias when applied to the 45° Roline data collected on CRCP sections with conventional transverse tines and ½-inch tines. This laser orientation also removed the bias in the Roline IRIs determined from tests on CRCP sections with variable transverse tines. However, a statistically significant negative bias is observed on sections with carpet drag imprints, where the Roline IRIs are significantly lower than the SurPRO IRIs. Considering the IRIs on all CRCP sections where Roline tests were conducted at 45°, the differences in IRIs between the Roline and the SurPRO are not statistically significant, with an average difference of −1.21 inches/mile and a 95 percent confidence interval ranging from -3.72 to 1.31 inches/mile.
- Comparing the Roline free mode IRIs at 0° and 45°, the statistical analysis shows that the IRIs at 0° are significantly higher than the IRIs at 45°, with an average difference of 3.74 inches/mile and a 95 percent confidence interval ranging from 1.61 to 5.86 inches/mile.
- The 19mm IRIs are not significantly different from the SurPRO IRIs on CRCP sections with conventional or variable transverse tines, and longitudinal tines. However, on the carpet drag sections, the 19mm IRIs are significantly lower than the corresponding reference values with an average difference of −6.82 inches/mile and a 95 percent confidence interval ranging from −10.08 to −3.56 inches/mile.
- The single-point laser IRIs are significantly lower than the corresponding SurPRO IRIs on all but the longitudinally tined CRCP sections. This negative bias on sections with transverse tines and carpet drag imprints is also observed in the results from the IRI comparisons made using the single-point laser data from the Dynatest and TxDOT inertial profilers. On longitudinally tined CRCP sections, the single-point laser IRIs are significantly higher than the SurPRO reference values with an average

difference of 8.55 inches/mile and a 95 percent confidence interval ranging from 1.70 to 15.40 inches/mile. Figure 5.4 illustrates the trends observed from comparing the texture laser IRIs with the SurPRO reference IRIs. Except for the longitudinally tined sections, the data points generally plot below the line of equality drawn on the chart. For the longitudinally tined sections, the data points plot above this line.

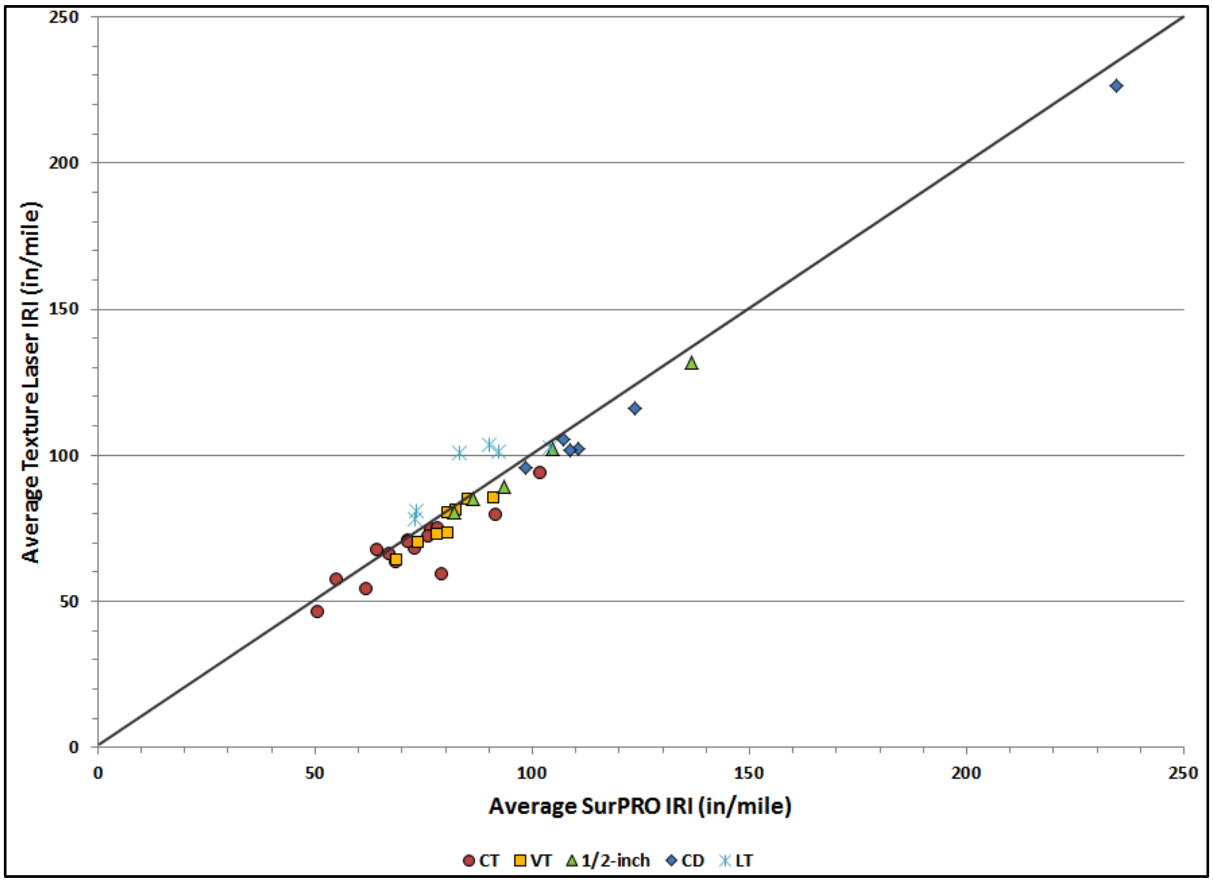

Figure 5.4. Comparison of Texture Laser and SurPRO IRIs on CRCP Sections.

Flexible Base Sections

Researchers ran tests on flexible base sections located along SH36 in Austin County. These tests were conducted on the flexible base before priming with MC-30. Previous experience with tests done three days after priming proved problematic as the tires of the test vehicle became coated with bitumen and aggregates. This coating would affect the distance measurements from the profiler. Tests were also conducted on inverted prime sections located along FM1383 in Fayette County. On both of these TxDOT projects, researchers collected SurPRO measurements as shown in Table 5.2. Table 5.13 shows the results from comparisons of the IRIs between the different lasers and the SurPRO reference profiler. These results show that the differences between the IRIs from the various lasers and the SurPRO are not statistically significant on the sections tested.

Table 5.13. Comparison of Laser and SurPRO IRIs on Flexible Base Sections.

Laser compared to SurPRO	Surface type	Average IRI difference (inch/mile)	95% confidence interval of IRI differences (inch/mile)		Statistically significant?*
			Lower limit	Upper limit	
Roline (free mode)	Inverted prime	−1.610	−5.451	2.231	No
	Flexbase	1.655	−4.729	8.038	No
	Overall	0.022	−3.423	3.467	No
Texture (single-point footprint)	Inverted prime	−2.231	−6.186	1.725	No
	Flexbase	0.709	−5.041	6.459	No
	Overall	−0.761	−3.982	2.460	No
19mm	Inverted prime	−2.723	−6.632	1.186	No
	Flexbase	0.174	−4.491	4.840	No
	Overall	−1.274	−4.102	1.553	No

*Confidence interval of IRI differences that includes zero identifies a case where the IRI differences are not statistically significant at the 95 percent confidence level.

Seal Coat Sections

There are currently no ride specifications on seal coat projects. Thus, test data on seal coat surfaces would not have direct relevance to evaluating the impact of new wide-footprint lasers on ride quality assurance testing. However, researchers collected test data on representative seal coat sections located along SH7 in Nacogdoches County to check whether profile surveys conducted to serve pavement management needs might show a bias since TxDOT presently collects ride quality data using profilers equipped with single-point lasers. For this evaluation, researchers collected data on Grade 3, Grade 4, and Grade 5 sections. Table 5.14 shows the results from the IRI comparisons between the different lasers and the SurPRO. On the Grade 3 and Grade 4 sections, the IRI differences are not statistically significant at the 95 percent confidence level for all three lasers tested. However, the texture and 19mm laser IRIs are found to have a statistically significant negative bias on the Grade 5 seal coats as shown in Table 5.14. Only the Roline laser showed no significant bias on all three seal coat grades but this result is expected since the Roline was calibrated to the SurPRO data.

The results from the seal coat tests conducted in this project thus indicate that ride quality measurements collected on Grade 5 sections using TxDOT's inertial profilers underestimate the roughness on these sections. Table 5.14 shows that the average difference between the texture laser and SurPRO IRIs is −4.30 inches/mile with a 95 percent confidence interval ranging from −7.47 to −1.13 inches/mile. Whether this bias is significant enough to justify upgrading all of TxDOT's profilers to change from single-point to Roline lasers is another question. Decision makers can simply consider this bias when reviewing ride data to identify substandard Grade 5 sections in the PMIS database.

At the suggestion of the TxDOT project manager, researchers conducted another set of measurements with the Roline laser to collect data at 45° on the seal coat sections. The first set of tests was conducted with the Roline laser footprint oriented at 0°, just like the tests performed on the HMA and flexible base sections. The purpose of collecting data at 45° was to compare the IRIs determined from tests conducted on seal coat sections at these two orientation angles. For these measurements, researchers assembled another Roline profiler module so that concurrent Roline measurements at both angles can be made. They then performed the paired *t*-tests on the run-to-run differences between the Roline IRIs at 0° and 45° to check if the IRI differences are statistically significant. Table 5.15 shows the average IRI differences as well as the 95 percent confidence intervals of these differences for the seal coal sections tested. In this analysis, the differences were computed as $IRI_{0°} - IRI_{45°}$.

The results indicate that the IRI differences between the two orientation angles are not statistically significant on the Grade 3 and Grade 4 sections. However, on the Grade 5 sections, the IRIs at 0° are significantly higher than the IRIs at 45° with an average difference of about 1.6 inches/mile and a 95 percent confidence interval ranging from about 0.7 to 2.52 inches/mile.

Table 5.14. Comparison of Laser and SurPRO IRIs on Seal Coat Sections.

Laser compared to SurPRO	Surface type	Average IRI difference (inch/mile)	95% confidence interval of IRI differences (inch/mile)		Statistically significant?*
			Lower limit	Upper limit	
Roline (free mode)	Grade 3	−0.874	−4.323	2.575	No
	Grade 4	0.165	−1.718	2.048	No
	Grade 5	−1.844	−4.743	1.054	No
	Overall	−0.851	−2.284	0.582	No
Texture (single-point footprint)	Grade 3	1.352	−2.182	4.885	No
	Grade 4	0.943	−1.646	3.531	No
	Grade 5	−4.300	−7.466	−1.134	Yes
	Overall	−0.669	−2.528	1.191	No
19mm	Grade 3	1.889	−1.703	5.481	No
	Grade 4	1.478	−2.857	5.812	No
	Grade 5	−3.837	−7.305	−0.369	Yes
	Overall	−0.157	−2.318	2.004	No

*Confidence interval of IRI differences that includes zero identifies a case where the IRI differences are not statistically significant at the 95 percent confidence level.

Table 5.15. Comparison of Roline Free Mode IRIs at 0° and 45° on Seal Coat Sections.

Surface type	Average IRI difference (inch/mile)	95% confidence interval of IRI differences (inch/mile)		Statistically significant?*
		Lower limit	Upper limit	
Grade 3	−0.487	−1.701	0.728	No
Grade 4	−0.143	−1.135	0.848	No
Grade 5	1.597	0.669	2.524	Yes
Overall	0.322	−0.293	0.937	No

*Confidence interval of IRI differences that includes zero identifies a case where the IRI differences are not statistically significant at the 95 percent confidence level.

RELATIONSHIPS BETWEEN LASER AND SURPRO IRIS

The preceding comparisons focused on examining the differences between IRIs and checking the statistical significance of these differences to assess the level of agreement (or disagreement) between IRIs determined from different laser profiles and corresponding reference values computed from SurPRO measurements. In addition to this analysis, researchers examined the relationships between the roughness indices determined from the different lasers and the SurPRO. While two methods may produce significantly different values of the response variable, the measured values from the two methods may show a significant relationship, which could be used to estimate one from the other. Thus, researchers fitted the following simple linear regression equation to the IRIs determined from the test data:

$$Y = \beta_0 + \beta_1 X \tag{5.1}$$

where

Y	=	SurPRO IRI,
X	=	laser IRI, and
β_0, β_1	=	coefficients determined by linear regression.

Tables 5.16 to 5.19 present the coefficients of equation 5.1 for the different groups of pavement surfaces tested in this project. For each equation, the tables also show the coefficient of determination (R^2), the standard error of the estimate (SEE), and the number of observations (N_{obs}) used to determine the regression coefficients.

In the regression analysis, researchers also checked the statistical significance of β_0 and β_1. Researchers found that, in all but two cases, the intercept β_0 of equation 5.1 was not statistically significant at the 95 percent level of confidence. Thus, researchers also fitted the test data assuming β_0 to be 0, and determined the revised slope β'_1 of the equation:

$$Y = \beta'_1 X \tag{5.2}$$

Tables 5.16 to 5.19 also give the results from this regression analysis. In these tables, SEE is a measure of the prediction error, and is determined from the square of the differences between the measured and predicted values of the dependent variable Y according to the following equation:

$$SEE = \sqrt{\frac{\sum_{i=1}^{n}(Y_i - \hat{Y}_i)^2}{df}} \qquad (5.3)$$

where

Y_i	=	the measured SurPRO IRI for section i.
$\hat{Y}_i$	=	the predicted SurPRO IRI for section i.
n	=	the number of sections.
df	=	the number of degrees of freedom, which is equal to (n – 2) for equation (5.1) and (n – 1) for equation (5.2).

Thus, for Y and X to show perfect agreement, β_0 and β_1 must equal 0 and 1, respectively, for which $R^2 = 1$ and SEE = 0. Tables 5.16 to 5.19 show that none of the regression coefficients satisfy this condition, which is generally the case for experimental data, unless the two variables are related by some physical law. For this reason, researchers are of the opinion that the results presented earlier on the analysis of IRI differences provide better information about the agreement between laser IRIs and corresponding reference values.

Nevertheless, in terms of predicting the SurPRO IRI given the index computed from a particular laser profile, the regression analysis gave statistically significant relationships between the SurPRO and laser IRIs on the different surfaces tested. Either equation 5.1 or equation 5.2 can be used to predict the SurPRO IRI, with the corresponding coefficients taken from the applicable table, given the surface type and the laser type. For this purpose, researchers recommend using the equation that gives the lower prediction error as the SEE had measured.

Table 5.16. Results of Regression Analysis of Relationships between Laser and SurPRO IRIs on HMA Sections.

Laser	Surface type	Eq. (1) regression results				Eq. (2) regression results		N_{obs}
		β_0[a]	β_1[b]	R^2	SEE (inch/mile)	β'_1[c]	SEE (inch/mile)	
Roline (free mode)	PFC	−9.573	1.249	0.864	3.177	1.044	3.339	18
	Type D	5.267	0.865	0.970	1.135	0.970	1.281	8
	SMA	−6.236	1.050	0.957	2.763	0.979	2.597	6
	Overall	3.002	0.951	0.963	3.284	1.001	3.357	32
Texture	PFC	2.101	0.966	0.806	3.793	1.009	3.696	18
	Type D	<u>9.117</u>	0.837	0.973	1.075	1.030	1.714	8
	SMA	−1.134	1.027	0.968	2.377	1.013	2.131	6
	Overall	1.101	0.996	0.968	3.042	1.015	3.010	32
19mm	PFC	0.548	1.024	0.862	3.196	1.036	3.102	18
	Type D	8.556	0.815	0.921	1.851	0.989	2.125	8
	SMA	−6.727	1.114	0.982	1.796	1.033	1.826	6
	Overall	−0.478	1.034	0.972	2.852	1.026	2.809	32

[a] Only β_0 coefficients shown underlined are statistically significant at the 95 percent confidence level.
[b] β_1 coefficients are all statistically significant at the 95 percent confidence level.
[c] β'_1 coefficients are all statistically significant at the 95 percent confidence level.

Table 5.17. Results of Regression Analysis of Relationships between Laser and SurPRO IRIs on CRCP Sections.

Laser	Surface type	Eq. (1) regression results				Eq. (2) regression results		N_{obs}
		β_0[a]	β_1	R^2	SEE (inch/mile)	β'_1[b]	SEE (inch/mile)	
Roline (free mode at 0°)	Conv. tines	−17.359	1.207	0.775	6.401	0.978	6.547	15
	½-inch tines	11.234	0.888	0.982	3.377	0.994	3.960	5
	Var. tines	11.316	0.815	0.721	3.886	0.949	3.722	8
	Carpet drag	−13.068	1.069	0.980	8.060	0.981	8.454	6
	Long. tines	5.982	0.975	0.872	4.770	1.047	4.346	6
	Overall	−1.861	1.003	0.958	6.158	0.985	6.105	40
Roline (free mode at 45°)	Conv. tines	−2.636	1.042	0.623	8.285	1.006	7.991	15
	½-inch tines	<u>24.861</u>	0.773	0.992	2.292	1.011	7.219	5
	Var. tines	28.362	0.626*	0.425	5.580	0.968	5.712	8
	Carpet drag	5.678	1.010	0.995	4.204	1.051	4.350	6
	Overall	−1.717	1.0333	0.950	7.238	1.016	7.150	34
Texture	Conv. tines	2.739	1.027	0.798	6.066	1.067	5.863	15
	½-inch tines	−2.744	1.058	0.998	1.108	1.031	1.117	5
	Var. tines	14.855	0.848	0.878	2.572	1.040	2.789	8
	Carpet drag	3.330	1.020	0.997	2.986	1.044	2.955	6
	Long. tines	4.622	0.861	0.720	7.066	0.909	6.346	6
	Overall	2.714	0.996	0.952	6.612	1.024	6.585	40
19mm	Conv. tines	−1.120	1.061	0.784	6.273	1.045	6.047	15
	½-inch tines	1.743	1.003	0.999	0.964	1.020	0.917	5
	Var. tines	8.230	0.911	0.814	3.174	1.015	3.022	8
	Carpet drag	2.367	1.036	0.998	2.838	1.053	2.690	6
	Long. tines	−4.500	1.061	0.823	5.623	1.008	5.058	6
	Overall	−1.192	1.047	0.976	4.706	1.034	4.660	40

[a] Only β_0 coefficients shown underlined are statistically significant at the 95 percent confidence level.
*β_1 coefficient not statistically significant at the 95 percent confidence level.
[b] β'_1 coefficients are all statistically significant at the 95 percent confidence level.

Table 5.18. Results of Regression Analysis of Relationships between Laser and SurPRO IRIs on Flexbase Sections.

Laser	Surface type	Eq. (1) regression results				Eq. (2) regression results		N_{obs}
		β_0[a]	β_1[b]	R^2	SEE (inch/mile)	β'_1[c]	SEE (inch/mile)	
Roline (free mode)	Inverted prime	−7.860	1.123	0.792	5.569	1.022	5.332	10
	Flexbase	7.194	0.935	0.832	9.356	0.987	8.888	10
	Overall	5.344	0.950	0.955	7.348	0.995	7.341	20
Texture	Inverted prime	−9.486	1.154	0.783	5.687	1.031	5.472	10
	Flexbase	7.266	0.941	0.864	8.423	0.994	8.020	10
	Overall	5.485	0.955	0.960	6.892	1.002	6.921	20
19mm	Inverted prime	−12.312	1.199	0.796	5.508	1.038	5.375	10
	Flexbase	−5.753	1.041	0.910	6.864	0.9995	6.525	10
	Overall	4.106	0.973	0.969	6.136	1.009	6.105	20

[a] β_0 coefficients are all not statistically significant at the 95 percent confidence level.
[b] β_1 coefficients are all statistically significant at the 95 percent confidence level.
[c] β'_1 coefficients are all statistically significant at the 95 percent confidence level.

Table 5.19. Results of Regression Analysis of Relationships between Laser and SurPRO IRIs on Seal Coat Sections.

Laser	Surface type	Eq. (1) regression results				Eq. (2) regression results		N_{obs}
		β_0[a]	β_1[b]	R^2	SEE (inch/mile)	β'_1[c]	SEE (inch/mile)	
Roline (free mode)	Grade 3	0.071	1.012	0.861	4.794	1.013	4.485	9
	Grade 4	0.193	0.994	0.957	2.618	0.997	2.449	9
	Grade 5	6.745	0.921	0.894	3.911	1.027	3.864	9
	Overall	2.819	0.969	0.899	3.677	1.012	3.638	27
Texture	Grade 3	−0.777	0.992	0.854	4.913	0.980	4.598	9
	Grade 4	2.460	0.947	0.922	3.536	0.984	3.338	9
	Grade 5	13.602	0.843	0.897	3.858	1.064	4.595	9
	Overall	9.317	0.865	0.850	4.494	1.006	4.734	27
19mm	Grade 3	−6.022	1.060	0.852	4.951	0.974	4.719	9
	Grade 4	0.620	0.968	0.774	6.017	0.977	5.629	9
	Grade 5	13.436	0.839	0.871	4.318	1.056	4.893	9
	Overall	8.211	0.875	0.785	5.375	0.999	5.463	27

[a] β_0 coefficients are all not statistically significant at the 95 percent confidence level.
[b] β_1 coefficients are all statistically significant at the 95 percent confidence level.
[c] β'_1 coefficients are all statistically significant at the 95 percent confidence level.

Figures 5.5 to 5.17 show charts of the SurPRO IRIs versus the corresponding laser IRIs for the different surfaces tested. The relationship between the SurPRO and laser IRIs is also given in each figure along with the goodness-of-fit statistics (R^2 and SEE) from the regression analysis. The relationship given in each figure is based on the data for all surface types tested within the given group of sections.

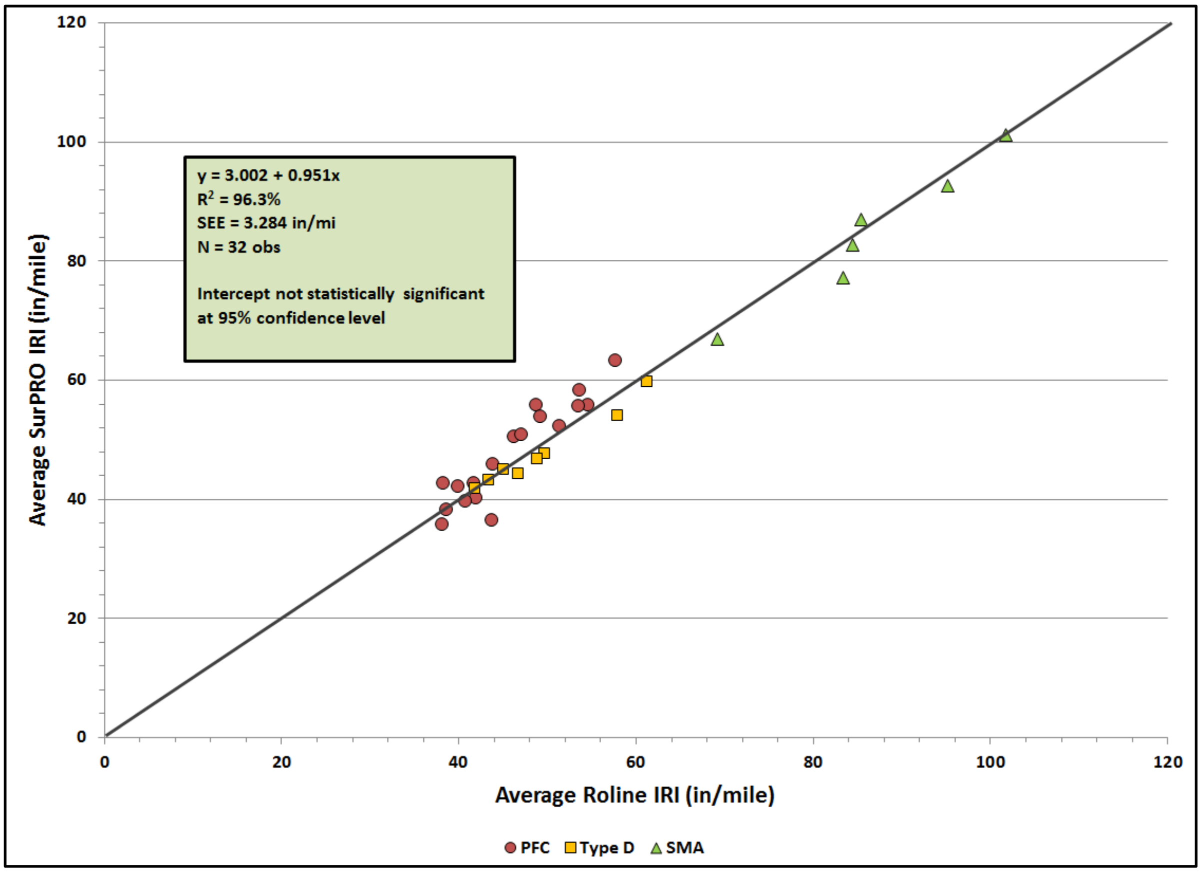

Figure 5.5. Comparison of SurPRO and Roline IRIs on HMA Sections.

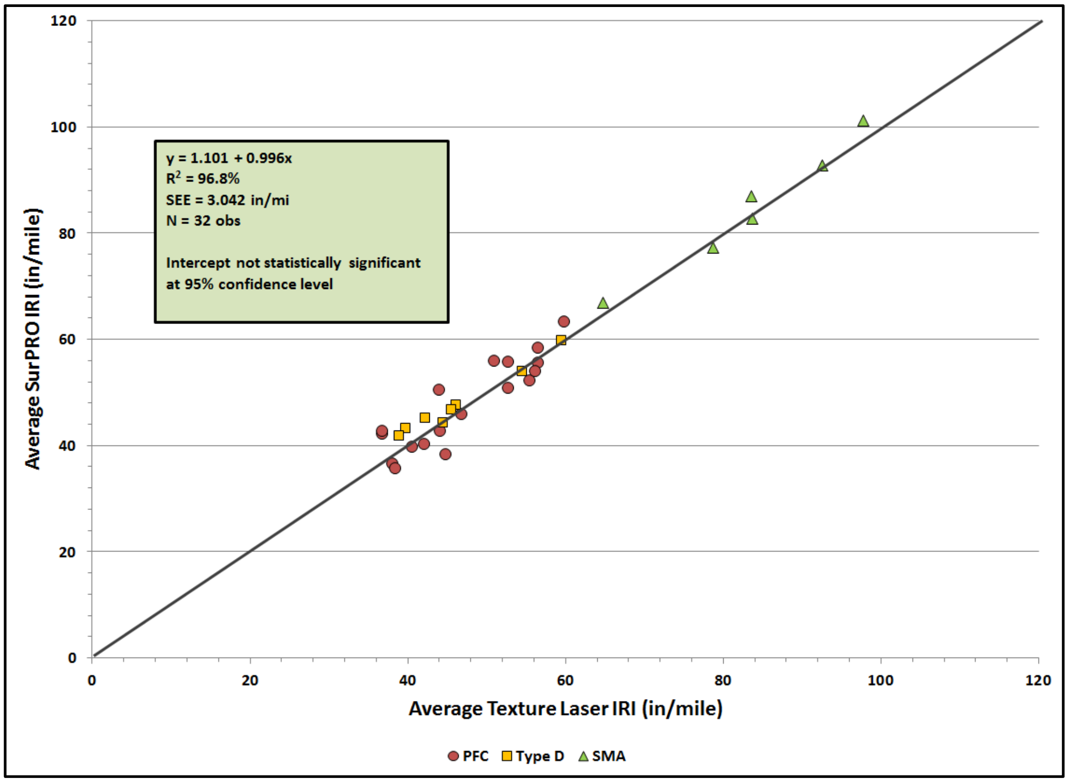

Figure 5.6. Comparison of SurPRO and Texture Laser IRIs on HMA Sections.

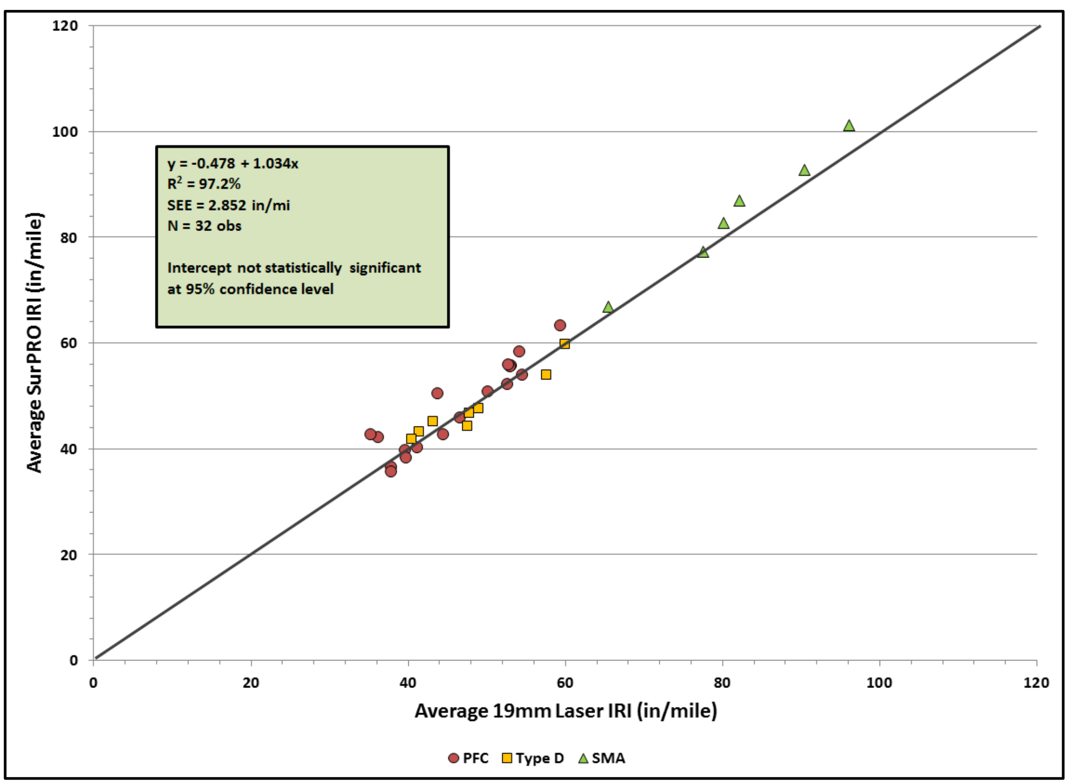

Figure 5.7. Comparison of SurPRO and 19mm Laser IRIs on HMA Sections.

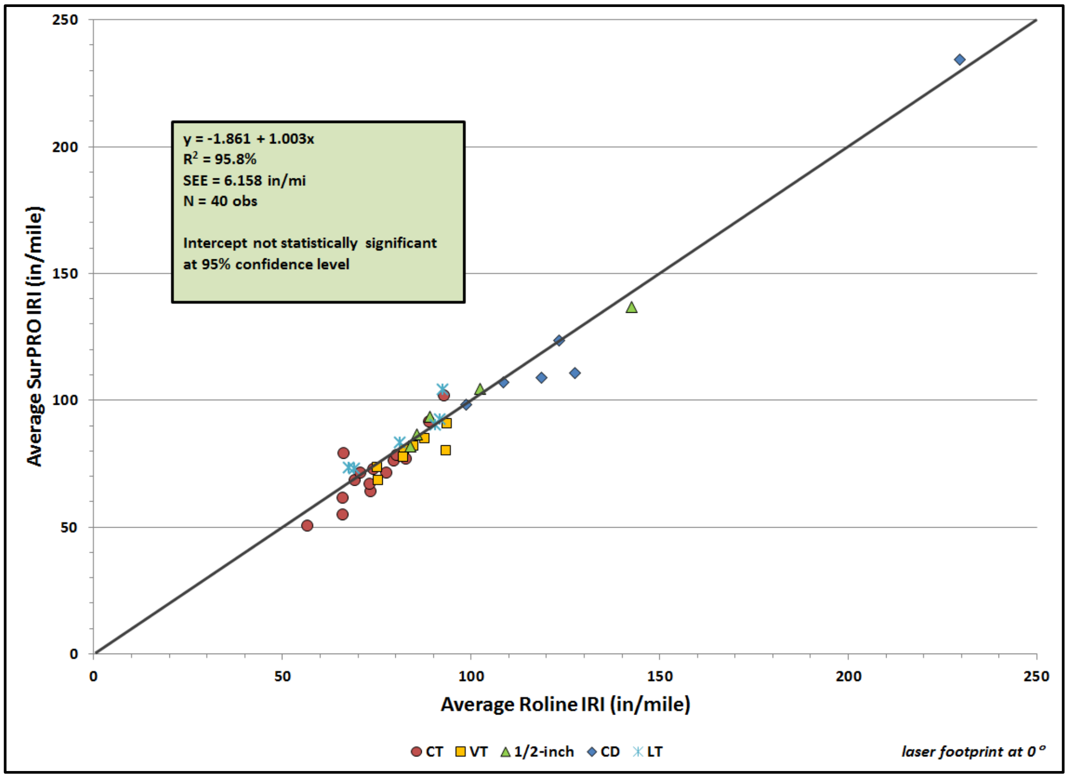

Figure 5.8. Comparison of SurPRO and Roline IRIs on CRCP Sections (Laser at 0°).

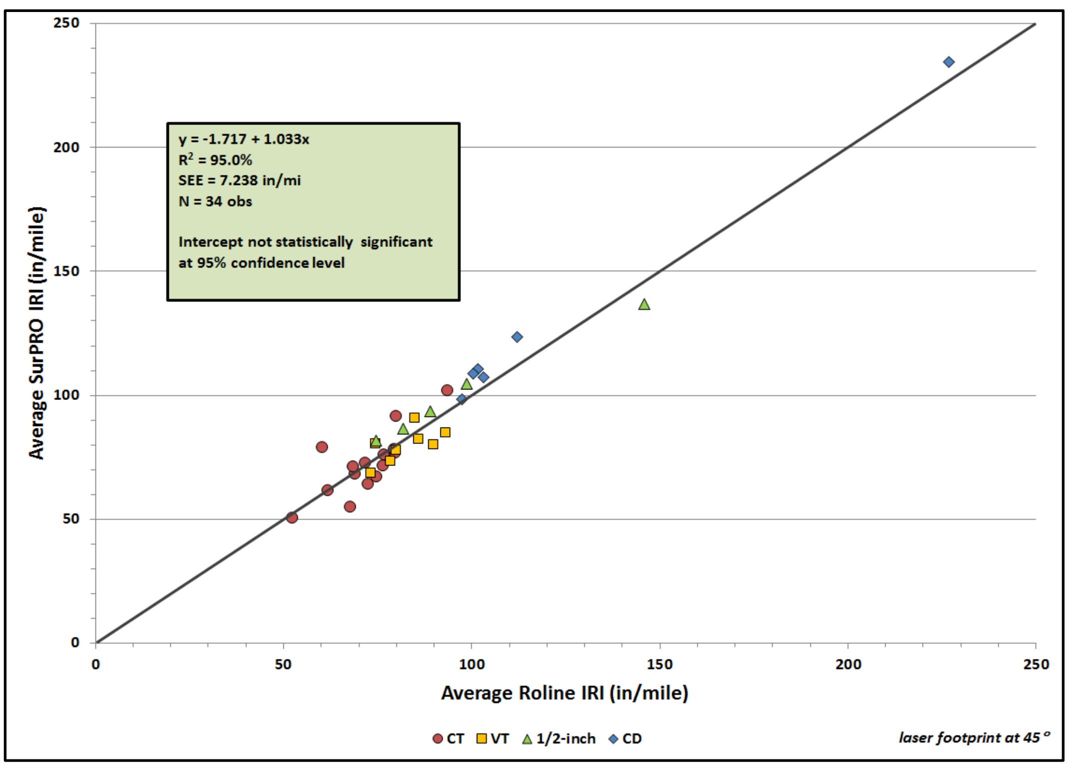

Figure 5.9. Comparison of SurPRO and Roline IRIs on CRCP Sections (Laser at 45°).

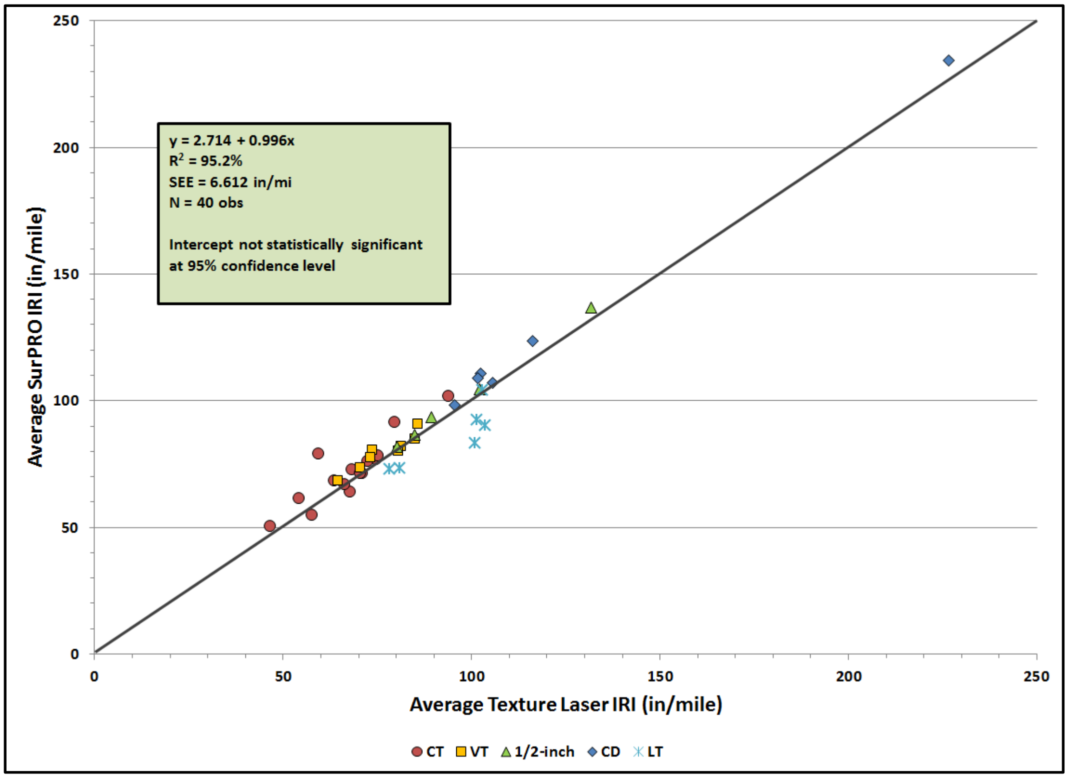

Figure 5.10. Comparison of SurPRO and Texture Laser IRIs on CRCP Sections.

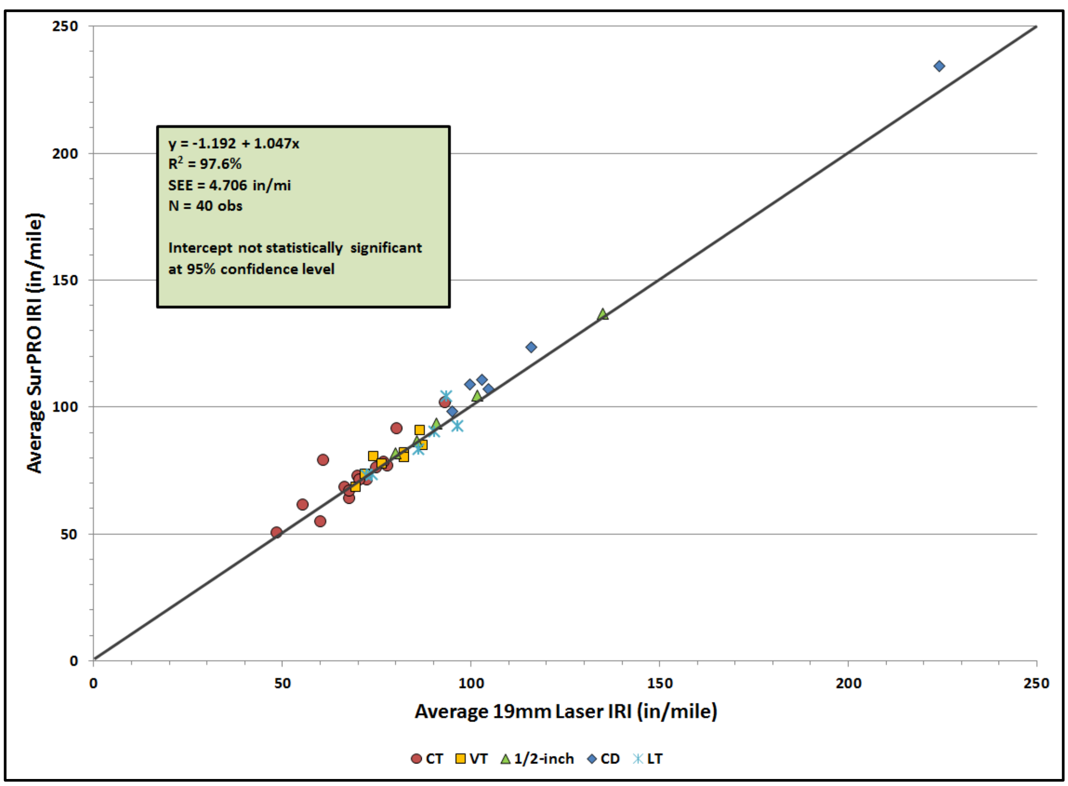

Figure 5.11. Comparison of SurPRO and 19mm Laser IRIs on CRCP Sections.

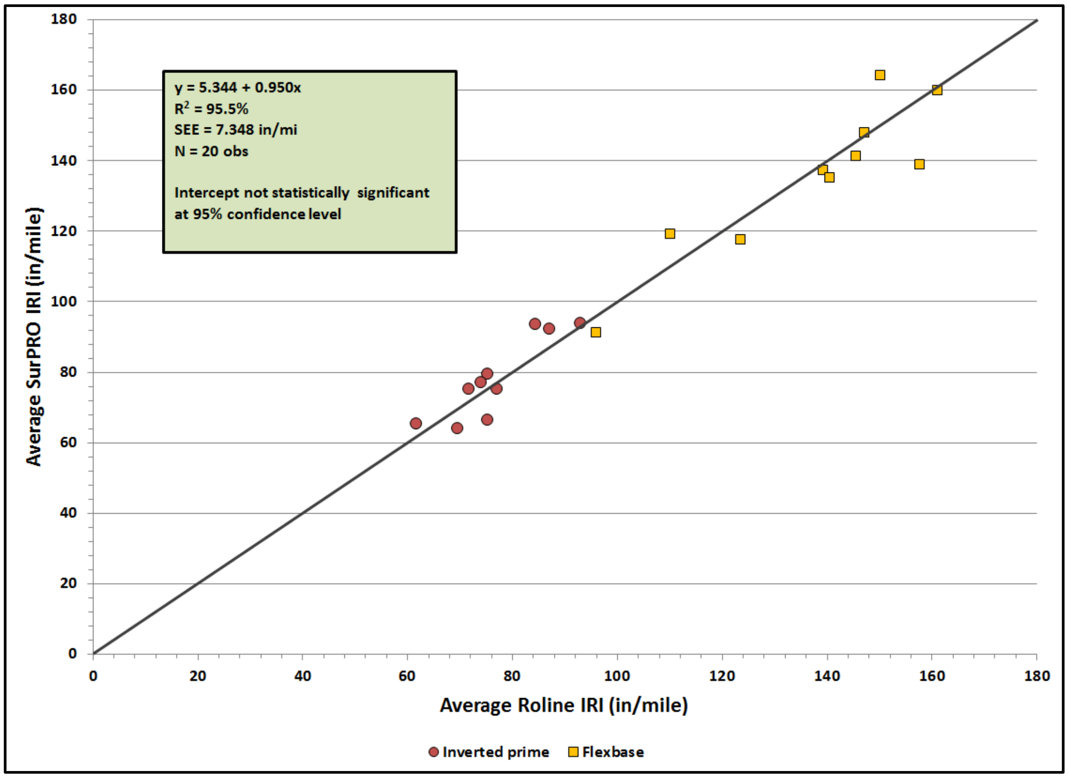

Figure 5.12. Comparison of SurPRO and Roline IRIs on Flexbase Sections.

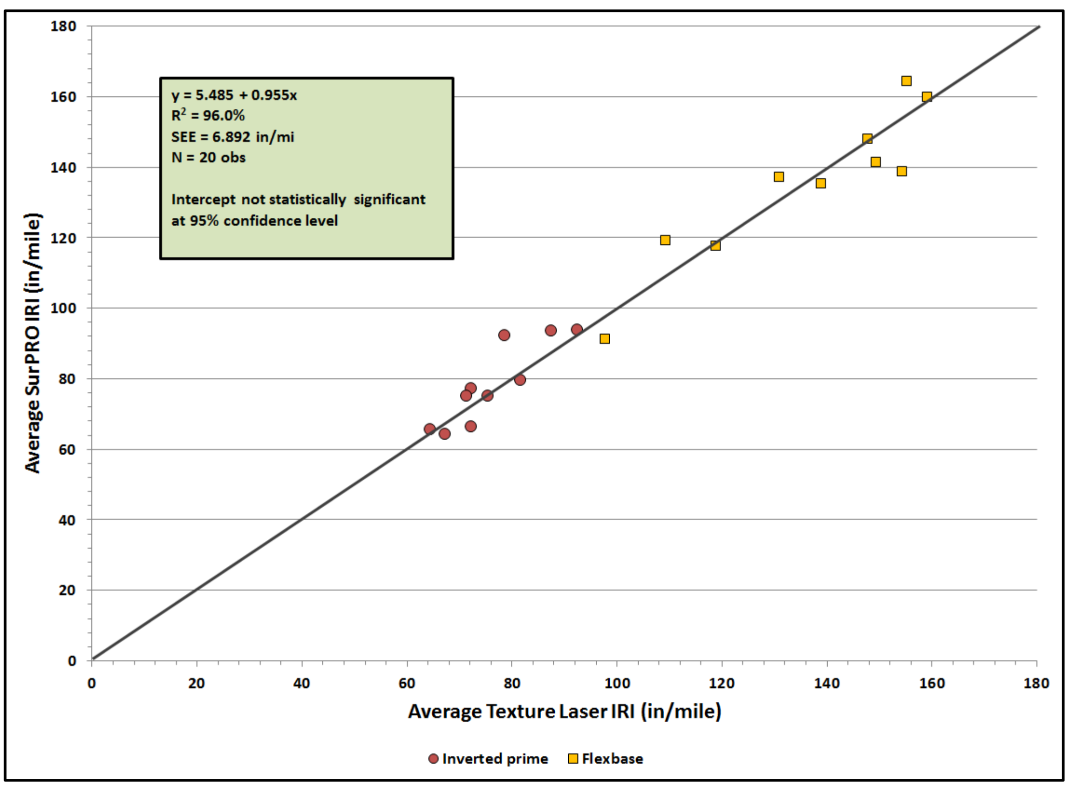

Figure 5.13. Comparison of SurPRO and Texture Laser IRIs on Flexbase Sections.

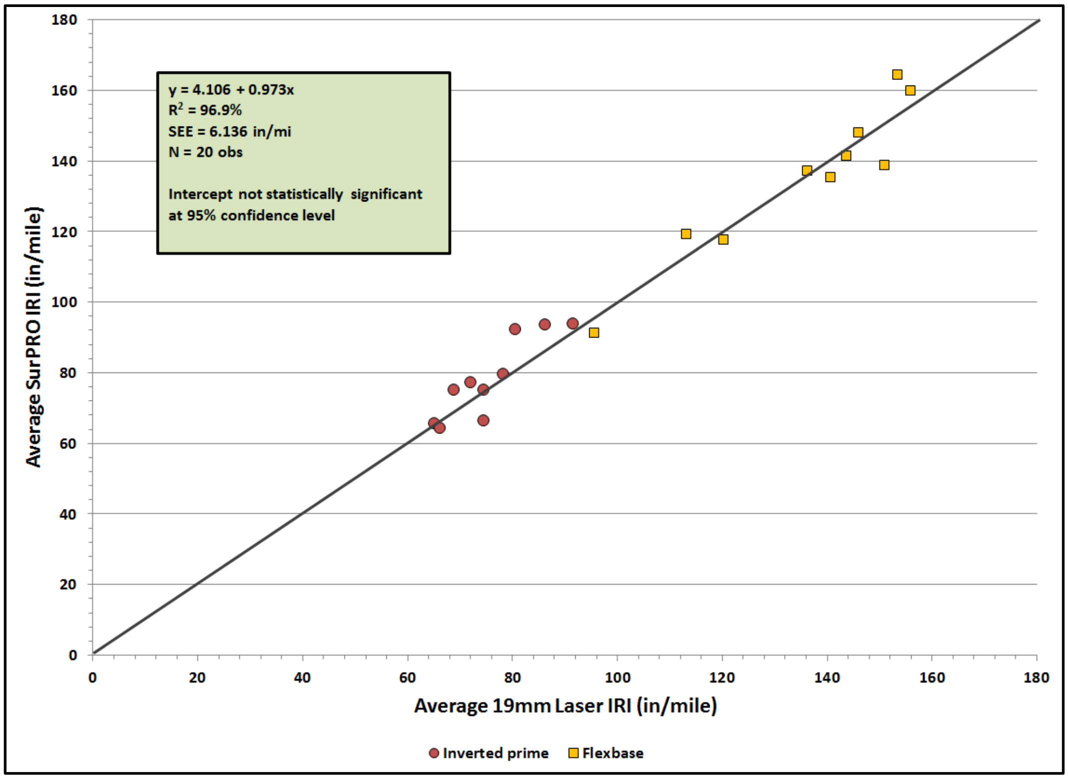

Figure 5.14. Comparison of SurPRO and 19mm Laser IRIs on Flexbase Sections.

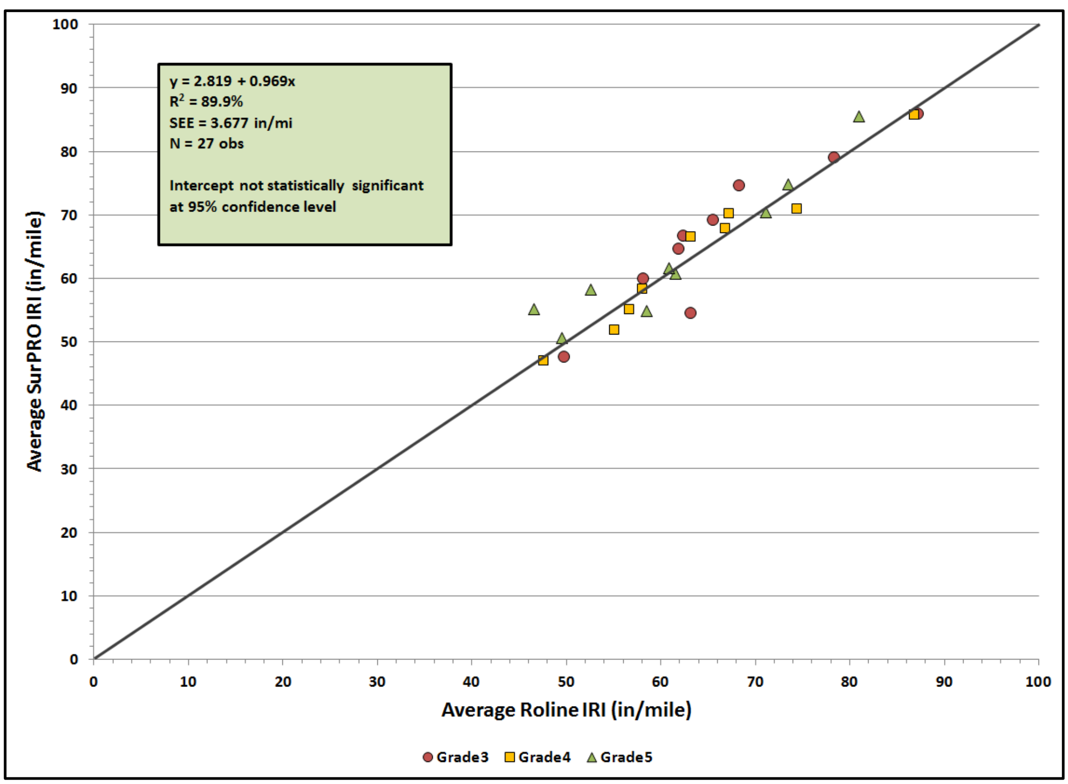

Figure 5.15. Comparison of SurPRO and Roline IRIs on Seal Coat Sections.

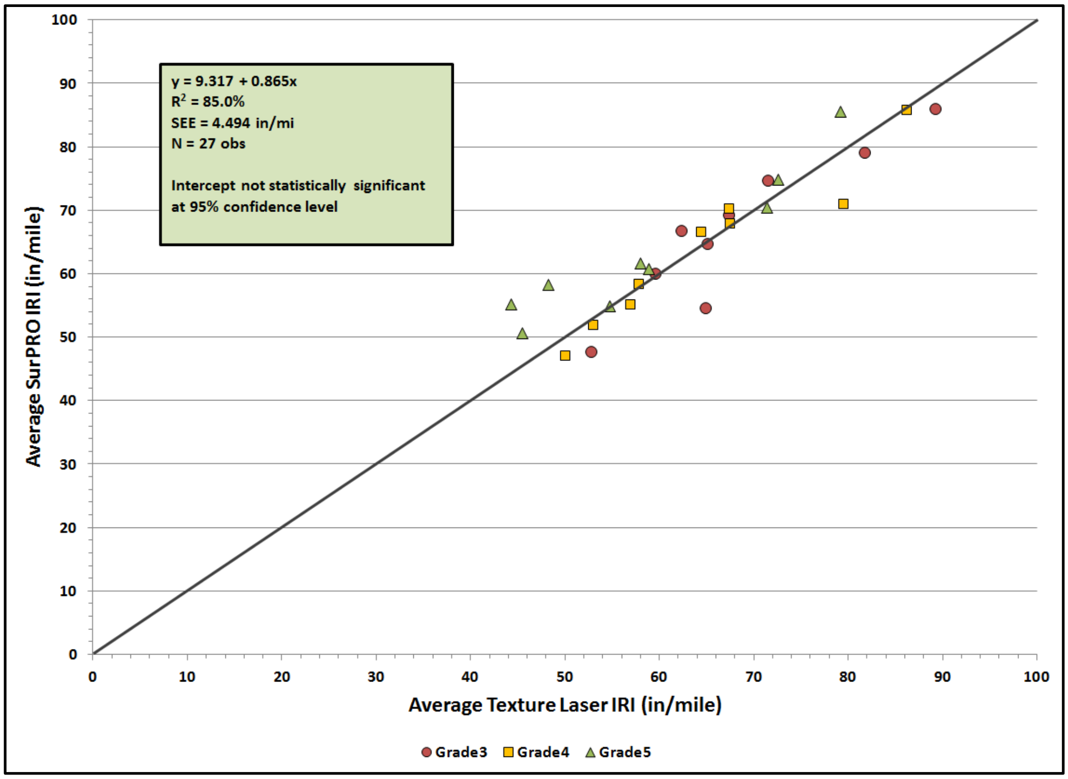

Figure 5.16. Comparison of SurPRO and Texture Laser IRIs on Seal Coat Sections.

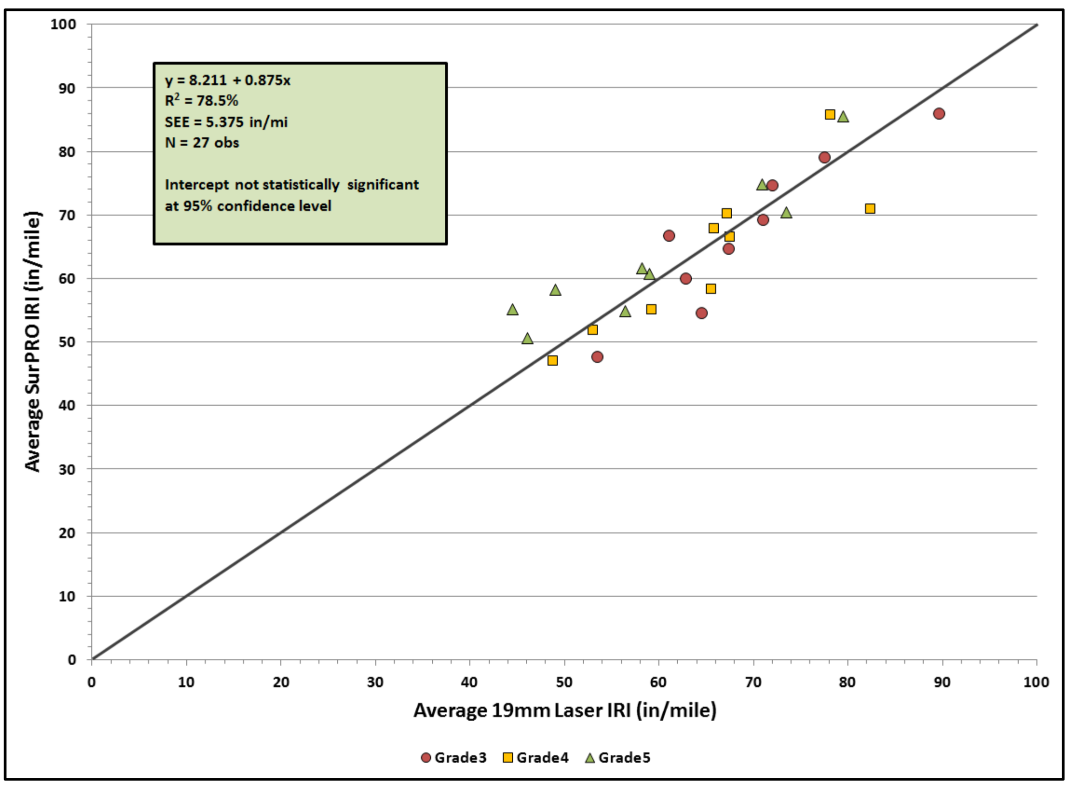

Figure 5.17. Comparison of SurPRO and 19mm Laser IRIs on Seal Coat Sections.

CHAPTER VI. SUMMARY OF FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

INTRODUCTION

The recommendations presented in this chapter are based on the results from the comparative evaluation of different lasers presented in the previous chapter. The relevant findings with respect to TxDOT's existing ride specifications are first summarized in the following section. After this summary, researchers provide recommendations on the options available to TxDOT to accommodate the use of inertial profilers with wide-footprint lasers for quality assurance testing of pavement smoothness.

SUMMARY OF FINDINGS FROM COMPARATIVE LASER TESTING

Researchers note the following findings from the comparative evaluation of different lasers conducted in this project:

- Pairwise IRI comparisons based on data collected with the Dynatest three-laser profiling system showed that that the average IRI differences between lasers are statistically significant on many of the sections tested. However, on these same sections, the confidence intervals of the IRI differences are, in the majority of cases, 3.0 inches/mile or less in magnitude. Cases where the confidence intervals include magnitudes of IRI differences more than 3.0 inches/mile were found on pavements with PFC, carpet drag and variable tined surfaces. Among these cases, the single-point IRIs were observed to be greater than the Roline IRIs on PFC and carpet drag surfaces.
- To check which laser is correct, researchers compared the IRIs determined from the different lasers with the corresponding IRIs determined from profiles collected with the SurPRO reference profiler. Combining the data from all PFC sections, researchers found that the Roline IRIs test to be significantly lower than the corresponding reference IRIs. For the single-point laser, the IRI differences on the same sections are not statistically significant at the 95 percent level of confidence. On the CRCP sections, the statistical analysis showed that the IRIs from the single point laser, 19mm laser, and the Roline laser configured in bridge mode are

significantly lower than the corresponding SurPRO IRIs on concrete surfaces with conventional tines, variable tines, and carpet drag.

- Researchers also compared the IRIs from TxDOT's profiler on the same PFC and CRCP sections. This verification produced results consistent with the above findings. The single-point laser data from TxDOT's profiler gave significantly lower IRIs than the corresponding reference values on the CRCP sections, while on the PFC sections, the IRIs from the same profiler are found to have no significant difference with the corresponding SurPRO IRIs.
- IRI comparisons based on the Roline data collected in bridge mode with the Dynatest three-laser system showed the need to evaluate tire-bridge filter settings that provide better agreement with the reference IRIs computed from SurPRO measurements. This evaluation found that for the HMA, seal coat, and CRCP sections where tests were conducted with the Roline footprint oriented at 0°, the optimal window size and window skip settings in terms of the lowest average absolute difference are 50 and 0, respectively. Researchers used these settings to process the Roline free mode data collected with the three-laser system assembled in this project.
- On the PFC sections, the differences between the Roline free mode IRIs and the corresponding SurPRO values range from −3.60 to −0.16 inch/mile with an average difference of −1.88 inches/mile. While the Roline IRIs were found to be significantly lower than the SurPRO IRIs on these sections, the IRI differences are smaller in magnitude compared to the differences based on the Roline laser configured in bridge mode. Researchers note that the recommended window size and window skip settings used to process the free mode data are based on the calibration results for all test sections. Over all HMA sections, the IRI differences are not statistically significant, with an average difference of −0.35 inch/mile and a 95 percent confidence interval ranging from −1.55 to 0.85 inch/mile.
- On the PFC sections, the IRIs determined from single-point laser profiles agree best with the SurPRO IRIs. The IRI differences for the single-point on these sections are not statistically significant based on the data from the Dynatest, TxDOT, and the three-laser inertial profiling system assembled in this project.

- Calibration of the tire-bridge filter to the SurPRO IRIs and application of the recommended window size and window skip settings to the free mode data removed the negative bias seen in the Roline bridge mode IRIs on CRCP sections with conventional transverse tines and carpet drag imprints. However, the bias on sections with variable transverse tines switched from negative to positive. Researchers note that, for variable tined sections, the optimal window size and window skip settings are 60 and 20, respectively. At these settings, the differences between the Roline and SurPRO IRIs are not statistically significant. However, for consistency in practice, researchers recommend using the optimal window size and window skip settings of 50 and zero, respectively, which are based on the data for all CRCP sections. Over all these sections, the results show that the differences between the Roline and SurPRO IRIs are not statistically significant with an average difference of 1.56 inches/mile and a 95 percent confidence interval ranging from −0.38 to 3.51 inches/mile.
- For tests conducted with the Roline laser footprint oriented at 45°, the differences in IRIs between the Roline and the SurPRO are not statistically significant on CRCP sections with conventional transverse tines, ½-inch transverse tines, and variable transverse tines. However, a statistically significant negative bias is observed on sections with carpet drag imprints, where the Roline IRIs are significantly lower than the SurPRO IRIs. Considering the IRIs on all CRCP sections where Roline tests were conducted at 45°, the differences in IRIs between the Roline and the SurPRO are not statistically significant, with an average difference of −1.21 inches/mile and a 95 percent confidence interval ranging from −3.72 to 1.31 inches/mile.
- Comparing the Roline free mode IRIs at 0° and 45°, researchers found that the IRIs at 0° are significantly higher than the IRIs at 45° on the CRCP sections tested, with an average difference of 3.74 inches/mile and a 95 percent confidence interval ranging from 1.61 to 5.86 inches/mile.
- The single-point laser IRIs are significantly lower than the corresponding SurPRO IRIs on all but the longitudinally tined CRCP sections. This negative bias on sections with transverse tines and carpet drag imprints is also observed in the results from the IRI comparisons made using the single-point laser data from the Dynatest and TxDOT inertial profilers. On longitudinally tined CRCP sections, the single-point

laser IRIs are significantly higher than the SurPRO reference values with an average difference of 8.55 inches/mile and a 95 percent confidence interval ranging from 1.70 to 15.40 inches/mile.

- Researchers collected profile data on flexible base and inverted prime sections using the three-laser system assembled in this project. The results from these tests show that the differences between the IRIs computed from profiles measured with the texture, 19mm, and Roline lasers, and the corresponding SurPRO reference IRIs are not statistically significant on the sections tested at a 95 percent confidence level.
- On seal coat sections, the IRI differences on Grade 3 and Grade 4 seal coats were not found to be statistically significant at the 95 percent confidence level for all three lasers tested. However, the texture and 19mm laser IRIs were found to have a statistically significant negative bias on the Grade 5 sections. Only the Roline laser showed no significant bias on all three seal coat grades but this result is expected since the Roline was calibrated to the SurPRO data.
- Comparison of the IRIs from Roline data collected at 0° and 45° show that the IRI differences between the two orientation angles are not statistically significant on the Grade 3 and Grade 4 sections. However, on the Grade 5 sections, the IRIs at 0° are significantly higher than the IRIs at 45° with an average difference of about 1.6 inches/mile and a 95 percent confidence interval ranging from about 0.7 to 2.52 inches/mile.
- Statistically significant linear relationships were found between corresponding SurPRO and laser IRIs. The accuracy of the predicted SurPRO IRIs as measured by the SEE varies between the groups of sections tested with the equations for HMA surface types giving the lowest SEEs, followed by the equations for seal coat sections.
- Researchers found only a weak relationship between IRI and MPD from the analysis of the data collected with the portable profile/texture laser module. The coefficients of determination (R^2 values) of the linear relationships between IRI and MPD range from 0.003 to 0.49 for the 11 surface types considered in the analysis. The R^2 statistic of the regression line based on the data for all surface types is only 0.03.

CONCLUSIONS AND RECOMMENDATIONS FROM COMPARATIVE LASER TESTING

Based on the above findings from the comparative laser testing, researchers offer the following conclusions and recommendations:

- There is no sufficient basis to switch to Roline lasers for testing pavement smoothness on HMA projects or pavement sections, for the purpose of quality assurance testing under the current TxDOT ride specifications or for monitoring the ride quality of HMA sections over the road network for pavement management. The single-point laser IRIs compared reasonably well with the SurPRO reference values on the HMA sections tested in this project.

  On the other hand, the Roline bridge mode IRIs significantly underestimated the reference IRIs on PFC sections. Researchers note that almost all profilers currently sold with Roline lasers are configured in bridge mode. The only profilers researchers know of where Roline lasers are configured in free mode are those manufactured by Ames Engineering. Thus, if Roline lasers are to be used for testing HMA sections, researchers recommend using the free mode settings determined in this project to reduce the negative bias found on pavements with PFC surfaces. Alternatively, TxDOT should consider introducing an IRI offset in the current Item 585 ride specification to address the negative IRI bias exhibited by Roline lasers on PFC sections when configured with the default bridge mode settings. In this regard, the statistical analysis conducted of the Roline bridge mode data showed an average IRI difference of −4.7 inches/mile on the PFC sections with a 95 percent confidence interval ranging from −7.6 to −1.7 inches/mile. Thus, for measurements collected with Roline lasers configured in bridge mode, TxDOT should consider introducing a +5 inches/mile offset on the IRIs computed from the Roline laser profiles. This recommendation would take out the average bias of −4.7 inches/mile determined from comparisons of Roline bridge mode and SurPRO reference IRIs on pavements with PFC surfaces.
- In terms of measuring ride quality on CRC pavements, researchers conclude that the primary justification to switch to Roline lasers is for testing CRCP sections with

longitudinal tines. Using Roline lasers on these pavements will provide IRI measurements that are more comparable to SurPRO reference values and which are more repeatable compared to IRIs determined from single-point profiles. While TxDOT does not build CRC pavements with longitudinal tines under current practice, the department is considering developing specifications for construction of these pavements to address noise issues associated with transverse tines.

In addition, research conducted at MnRoad (Izevbekhai, 2007) has identified innovative grinding methods to reduce road noise that involve texturing concrete pavement surfaces with longitudinal grooves. The need to provide quieter concrete pavements will drive the current practice towards texturing methods that reduce noise at the tire-pavement interface. It is from this perspective that researchers see the justification to switch to Roline lasers for measuring ride quality on concrete pavements.

- Researchers recommend using the free mode settings determined in this project for testing CRC pavements with Roline lasers. As noted previously, IRI measurements made with the Roline laser in bridge mode significantly underestimated the corresponding SurPRO reference values on CRCP sections with transverse tines and carpet drag. This negative bias was also observed in the single-point laser data collected on the sections tested. The recommended free mode settings will reduce this negative bias in test measurements made with existing lasers.
- Alternatively, TxDOT should consider introducing IRI offsets in the current Item 585 ride specification to address the negative IRI bias exhibited by single-point, 19mm, and Roline bridge mode lasers on CRCP sections with transverse tines and carpet drag imprints. Table 6.1 and Table 6.2 give summary statistics on the IRI differences determined, respectively, from profiles collected with the Dynatest three-laser inertial profiling system and TxDOT's profiler on CRCP sections with conventional transverse (CT) tines, variable tines (VT), and carpet drag (CD) imprints. The statistics shown in these tables are based on the difference between the IRI as determined from a given laser profile, and the corresponding SurPRO reference IRI. Thus, a negative IRI difference denotes a case where the IRI from a given laser

underestimates the corresponding reference IRI. The results presented in Table 6.1 and Table 6.2 show a distinct tendency in all three lasers to underestimate the reference IRIs. On average, the reference IRIs are underestimated by about:

  - 5 inches/mile on CRCP sections with conventional transverse tines.
  - 3 inches/mile on sections with variable transverse tines.
  - 9 inches/mile on sections with carpet drag imprints. Researchers recommend that TxDOT consider using the offset applicable to the CRCP surface tested to remove the negative IRI bias exhibited by single-point, 19mm, and Roline bridge mode lasers in the comparative laser tests conducted in this project.

- With respect to quality assurance tests conducted under TxDOT's flexible base ride specification (SP 247-011), researchers conclude that there is no compelling reason for contractors to switch to wide footprint lasers for testing projects where this specification is used. No significant bias was observed between the IRIs determined from the lasers and the corresponding SurPRO reference values from the tests conducted on flexible base and inverted prime sections.
- With respect to the angle at which the Roline laser footprint should be oriented for collecting data with this laser, the recommended settings from this project are based on the 0° scan orientation, which is the common angle used for testing all surface types in this project. The 45° angle was only used for testing CRC pavements in accordance with the work plan. Thus, there are no data to recommend using a 45° angle on non-CRC pavement sections. Further, since the comparison of Roline free mode IRIs at 0° and 45° showed the IRI differences to be statistically significant on Grade 5 seal coat sections, researchers do not believe it prudent to recommend a 45° angle for testing non-CRC pavements until more test data are collected on such sections to make this determination.
- The recommended Roline free mode settings from this project are based on collecting and processing free mode data using software developed during the project. Implementing Roline or Roline-type lasers for ride quality measurements will require working with manufacturers of profiling equipment and laser sensors to determine the best approach for deploying profilers with wide-footprint lasers in Texas. Consideration must be given on how the recommended settings can be implemented

that would have the least impact to existing software used by equipment manufacturers and contractors. Researchers recommend a follow-up project to implement the use of Roline lasers for ride quality assurance testing in Texas based on the results from this research project. This project should also include a task to collect additional Roline data at a 45° angle on HMA pavements.

- Since the time that comparative laser tests were completed in this project, LMI/Selcom has come out with a new Roline laser that gives system developers the option to output both the bridge elevation determined from the laser's internal tire-bridging filter, and the full scan data at a given location. Researchers recommend that tests be conducted with this new laser model to evaluate Roline bridge mode settings that provide the best correspondence with the Roline free mode settings determined in this project. These tests can be conducted as part of the work plan for the follow-up implementation project recommended in the preceding.

Table 6.1. Comparison of Laser and SurPRO IRIs on CRCP Sections Based on Dynatest Three-Laser System Data.

Highway-Surface type (County)	Laser compared to SurPRO[1]	Average IRI difference[2] (inch/mile)	95% confidence interval of IRI differences (inch/mile)		Statistically significant?[3]
			Lower limit	Upper limit	
SH6/SH36 CT combined (Brazos/Milam)	Roline	−4.892	−7.695	−2.089	Yes
	19mm	−4.650	−7.295	−2.005	Yes
	Single-point	−4.270	−6.793	−1.748	Yes
SH36-VT (Milam)	Roline	−3.461	−6.297	−0.625	Yes
	19mm	−3.426	−5.791	−1.062	Yes
	Single-point	−3.027	−5.397	−0.657	Yes
SH36-carpet drag (Milam)	Roline	−10.098	−14.860	−5.336	Yes
	19mm	−8.622	−14.097	−3.146	Yes
	Single-point	−8.303	−14.635	−1.971	Yes

[1]Roline laser set up in bridge mode with laser footprint oriented perpendicular to direction of travel.
[2]IRI difference = Laser IRI – SurPRO IRI
[3]Confidence interval of IRI differences that includes zero identifies a case where the IRI differences are not statistically significant at the 95 percent confidence level.

Table 6.2. Comparison of TxDOT Profiler & SurPRO IRIs on CRCP Sections.

Highway-Surface type (County)	Average IRI difference (inch/mile)[1]	95% confidence interval of IRI differences (inch/mile)		Statistically significant?[2]
		Lower limit	Upper limit	
SH6/SH36 CT combined (Brazos/Milam)	−5.40	−8.09	−2.72	Yes
SH36-VT (Milam)	−4.45	−6.81	−2.08	Yes
SH36-carpet drag (Milam)	−9.65	−13.83	−5.47	Yes

[1]IRI difference = TxDOT single-point laser IRI – SurPRO IRI
[2]Confidence interval of IRI differences that includes zero identifies a case where the IRI differences are not statistically significant at the 95 percent confidence level.

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APPENDIX: COMPARISON OF SINGLE-POINT IRIS WITH ROLINE, 19MM, AND TRIODS IRIS FROM TEXAS

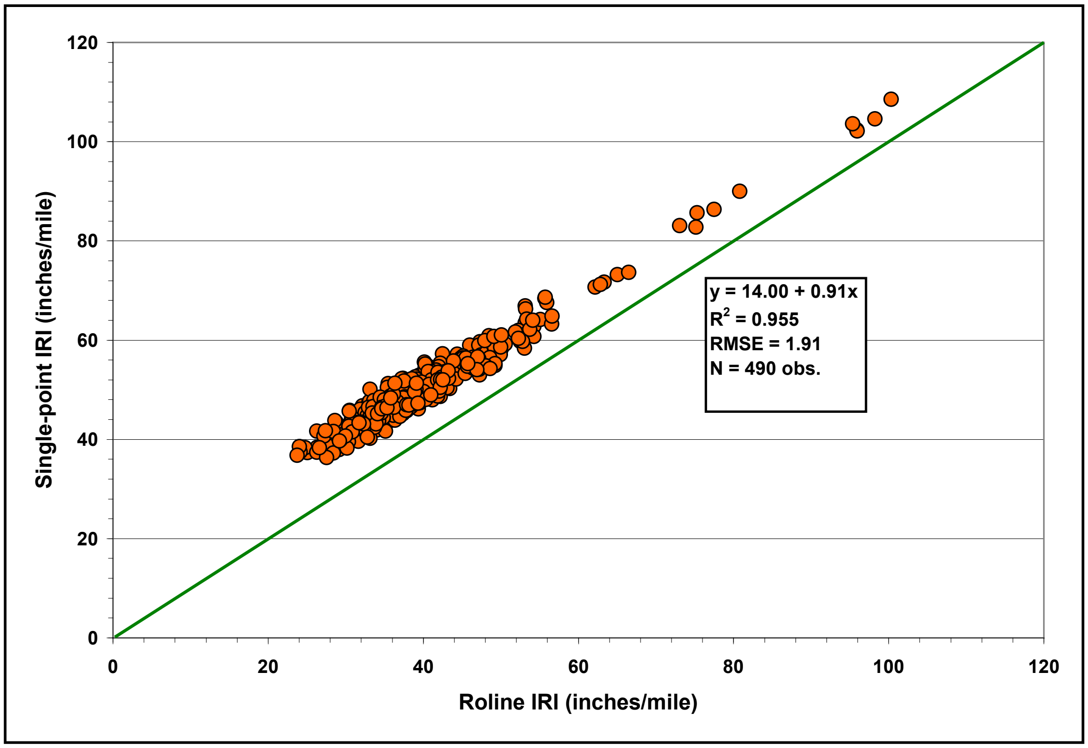

Figure A1. Comparison of Single-Point and Roline Laser IRIs on SH6 PFC Project.

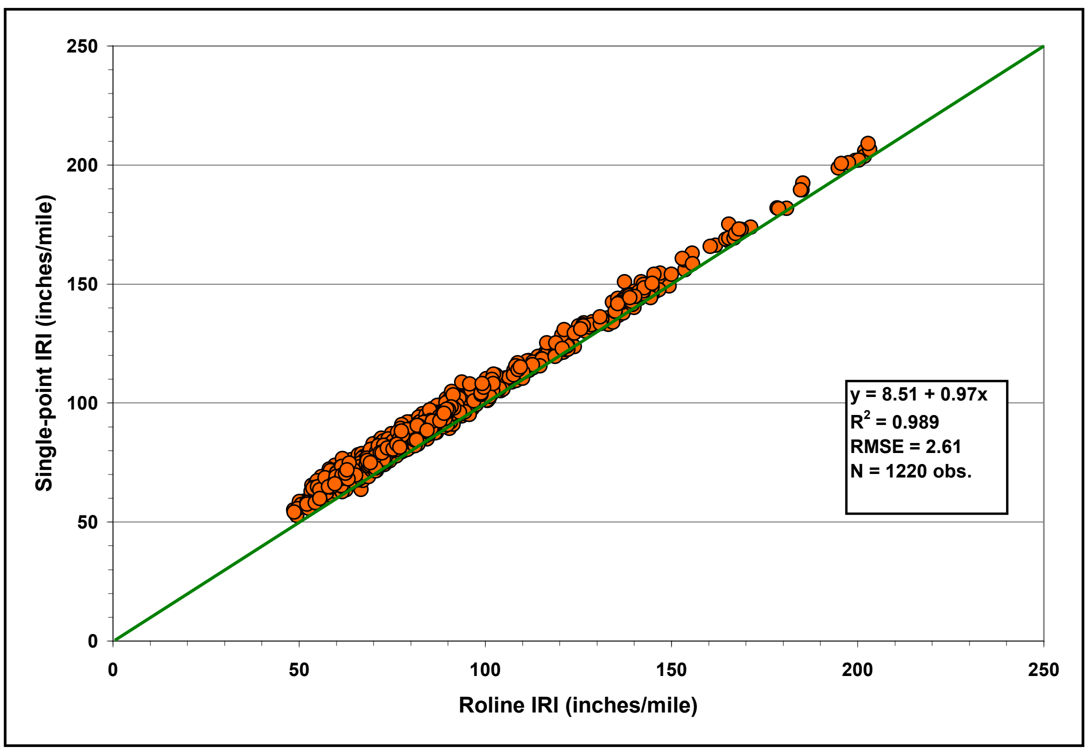

Figure A2. Comparison of Single-Point and Roline Laser IRIs on SH21, US77, and US290 Grade 4 Sections.

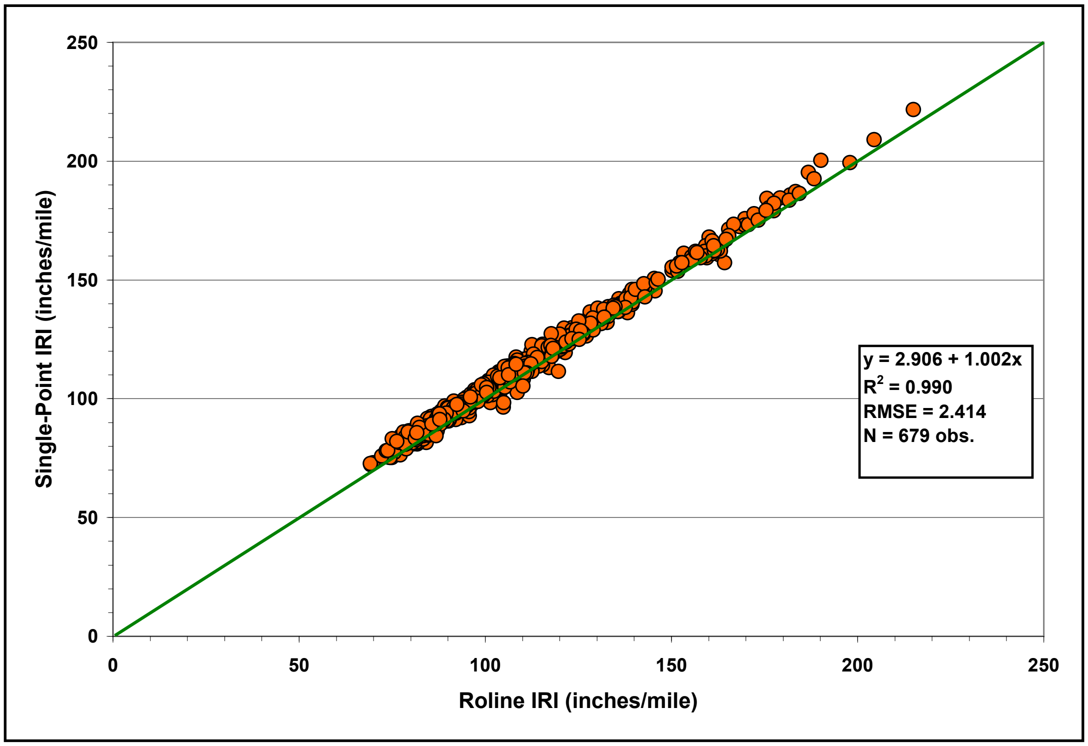

Figure A3. Comparison of Single-Point and Roline Laser IRIs on US90A and FM50 Grade 3 Sections.

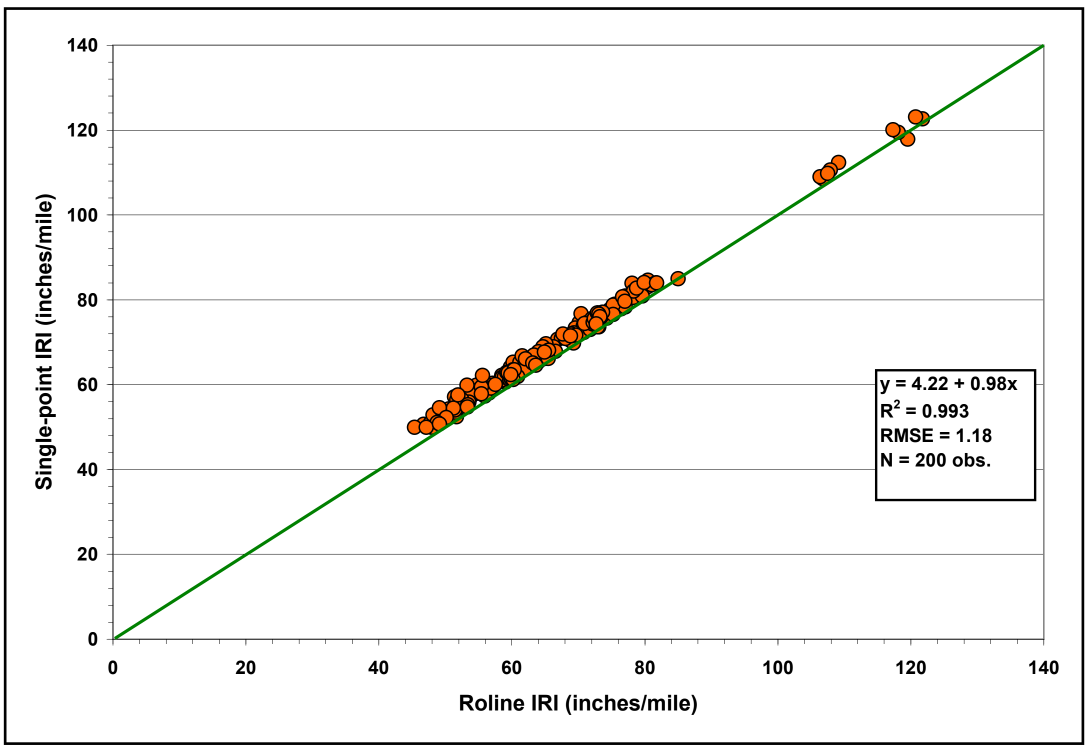

Figure A4. Comparison of Single-Point and Roline Laser IRIs on Loop 1 SMA-C Project.

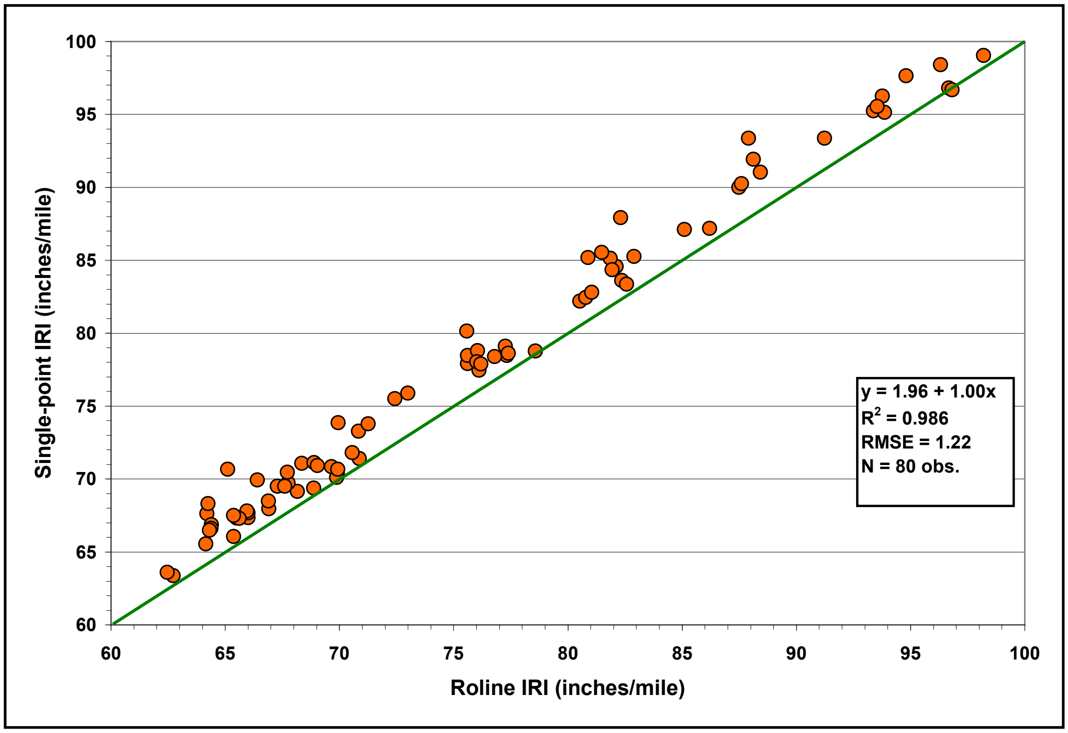

Figure A5. Comparison of Single-Point and Roline Laser IRIs on FM734 SMA-D Project.

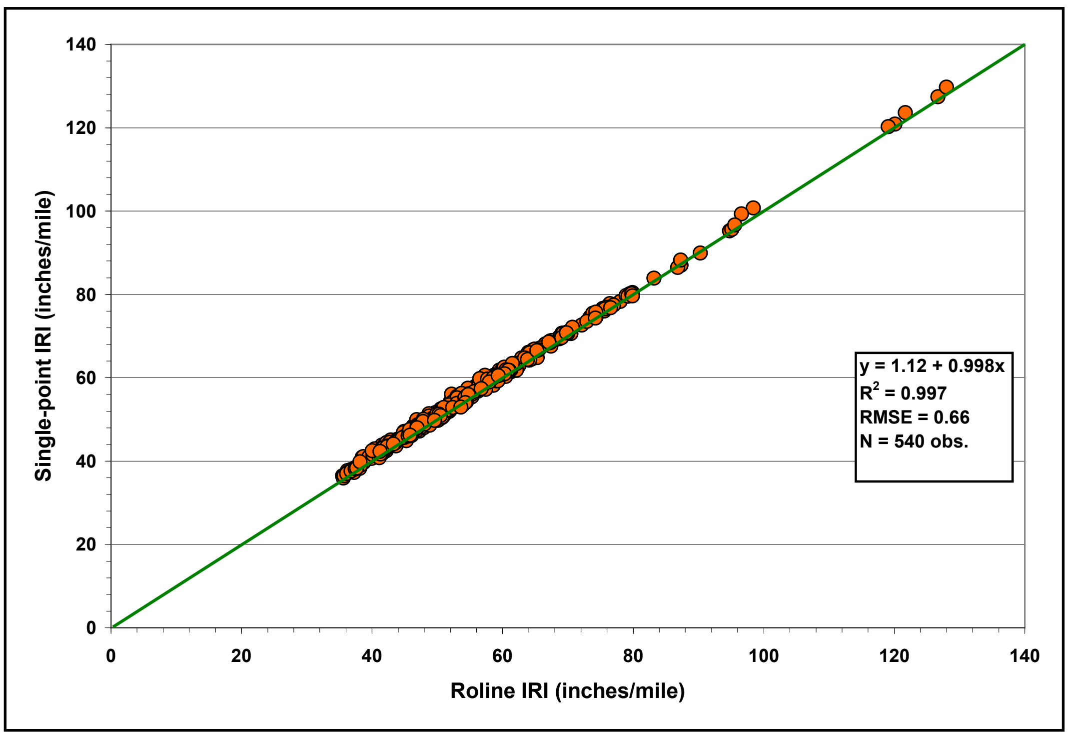

Figure A6. Comparison of Single-Point and Roline Laser IRIs on FM2440 Type C Project.

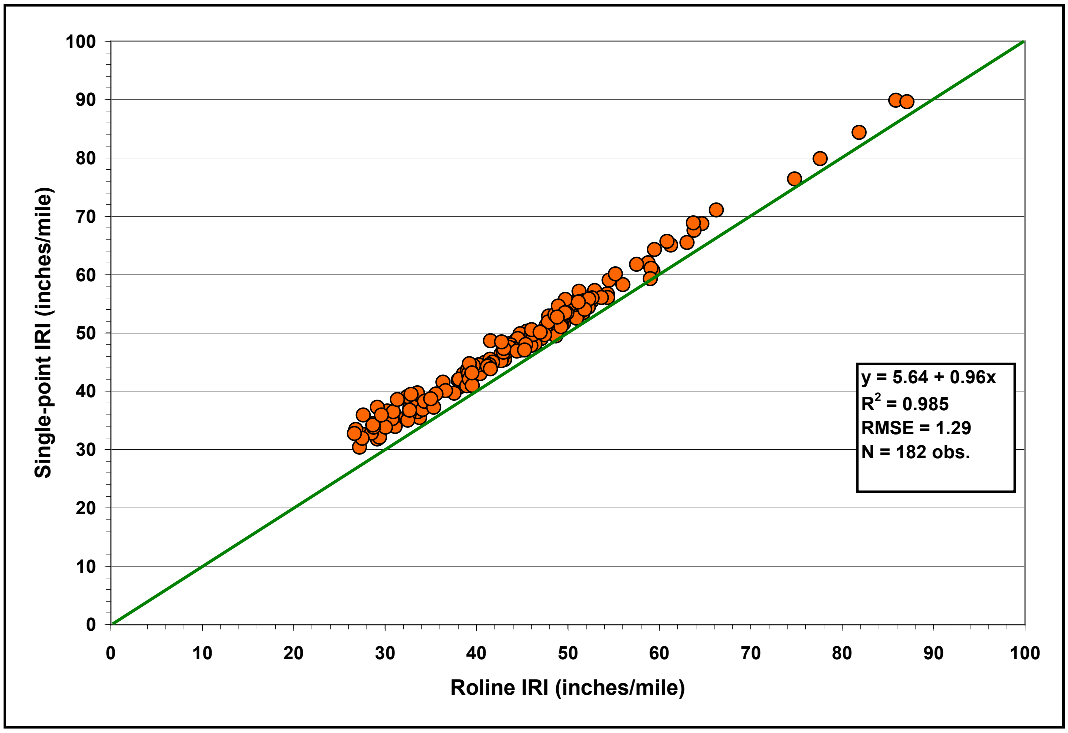

Figure A7. Comparison of Single-Point and Roline Laser IRIs on Loop 463 Type C Project.

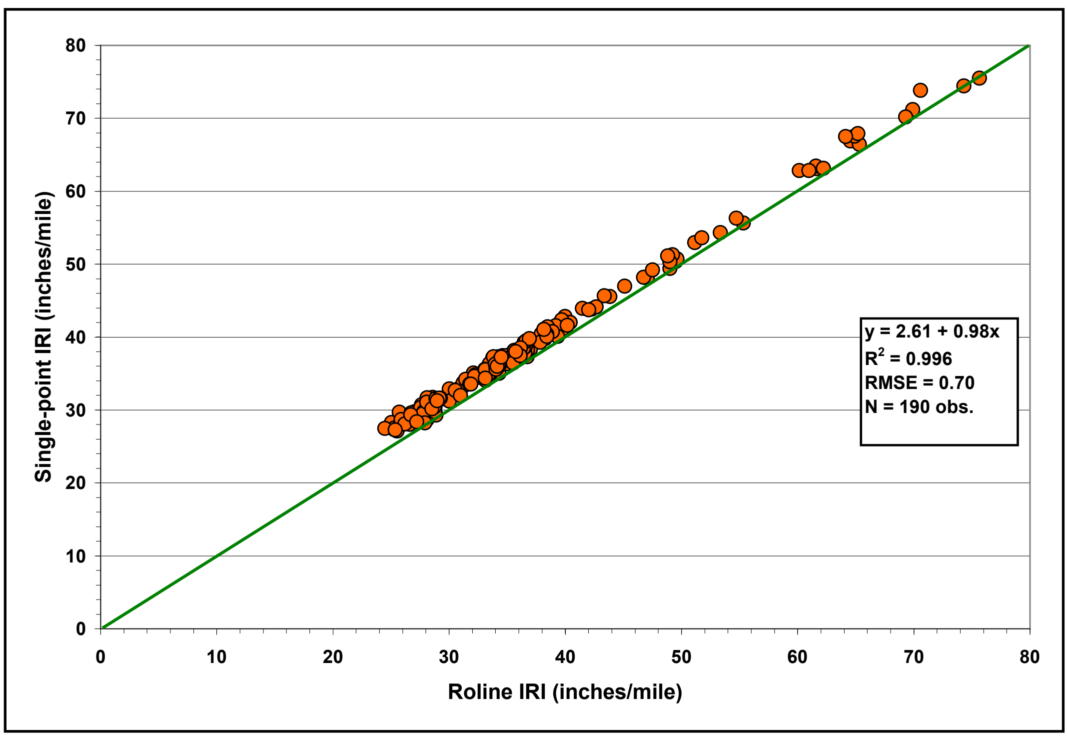

Figure A8. Comparison of Single-Point and Roline Laser IRIs on US59 Type D Project.

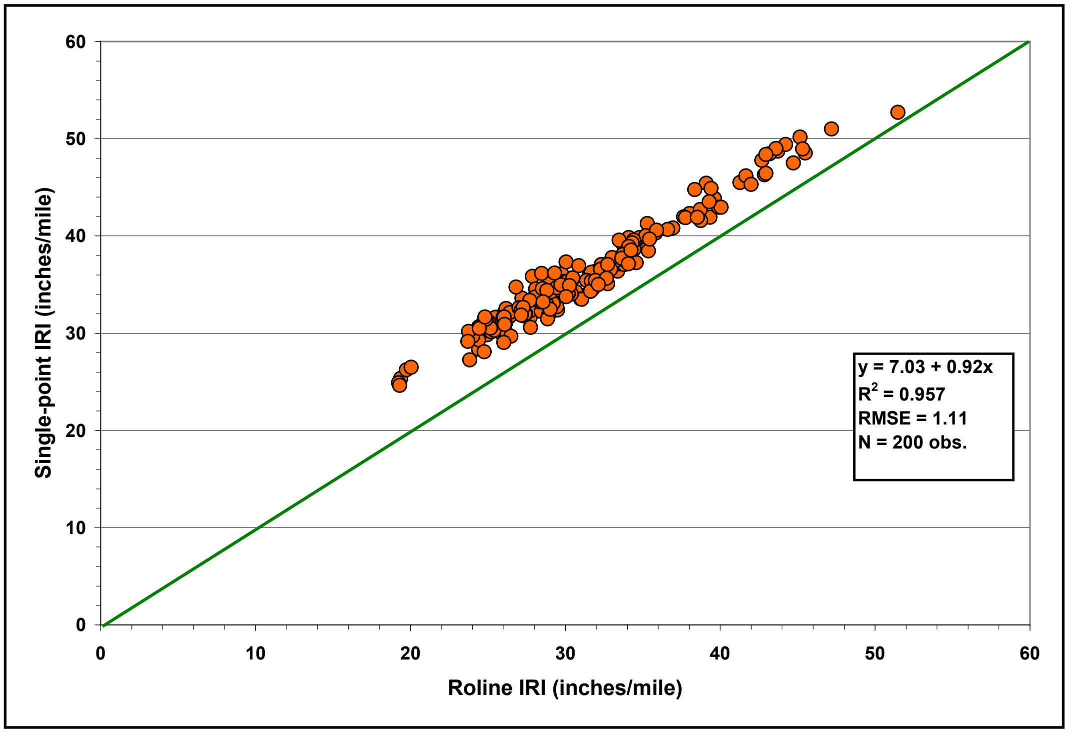

Figure A9. Comparison of Single-Point and Roline Laser IRIs on US77 Type D Project.

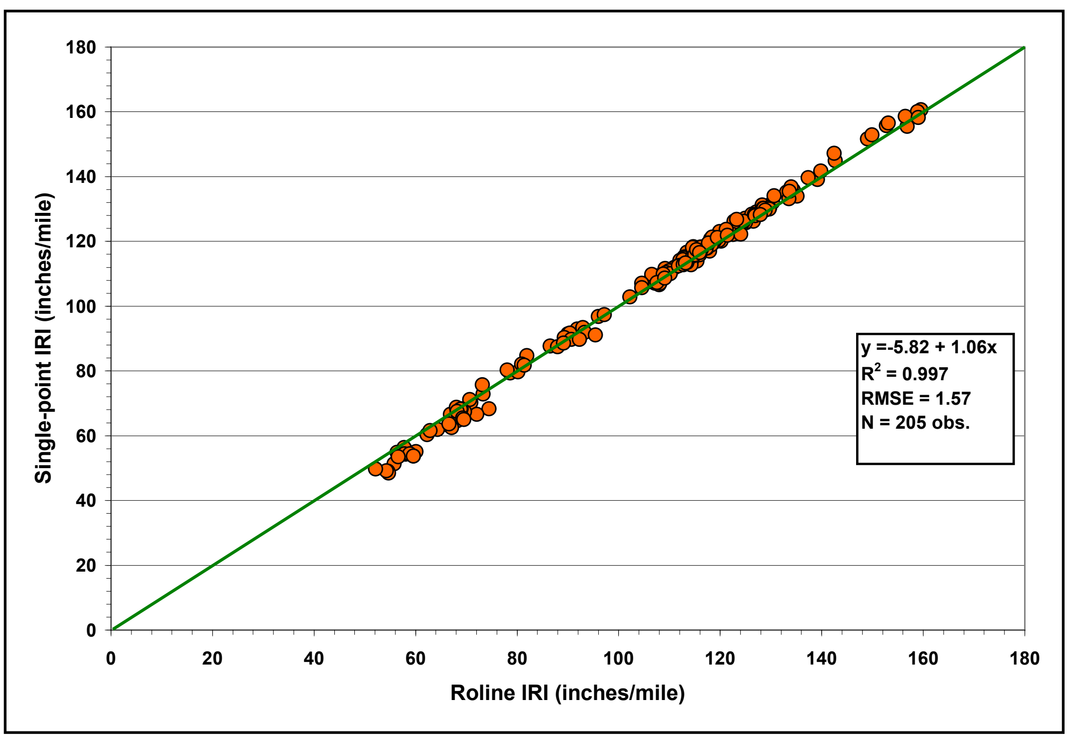

Figure A10. Comparison of Single-Point and Roline Laser IRIs on IH820 and SH36 CRCP Sections with Variable Transverse Tines.

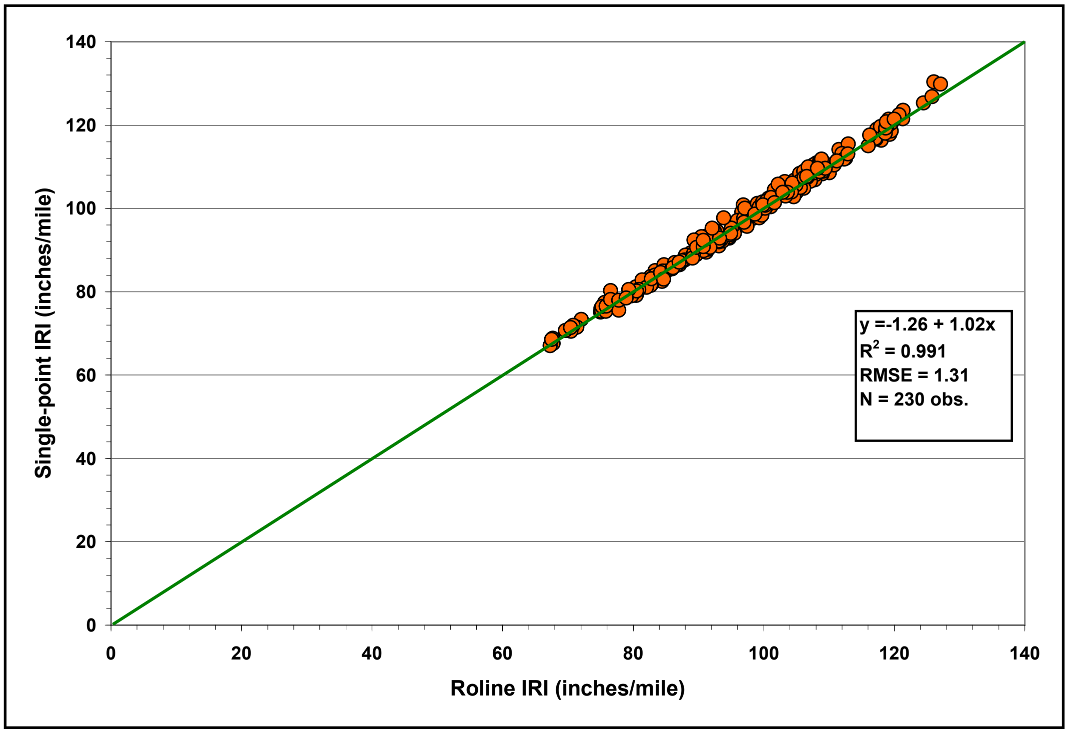

Figure A11. Comparison of Single-Point and Roline Laser IRIs on US287 CRCP Skidabrader Section.

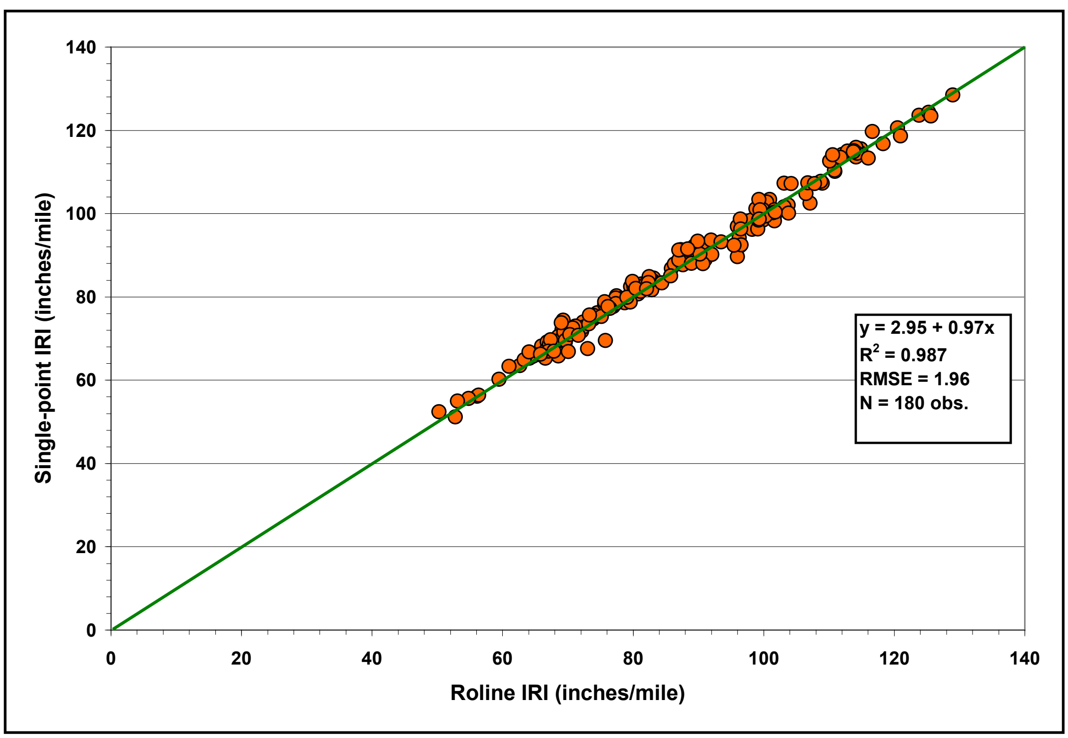

Figure A12. Comparison of Single-Point and Roline Laser IRIs on US287 CRCP Section with Deep Transverse Tines.

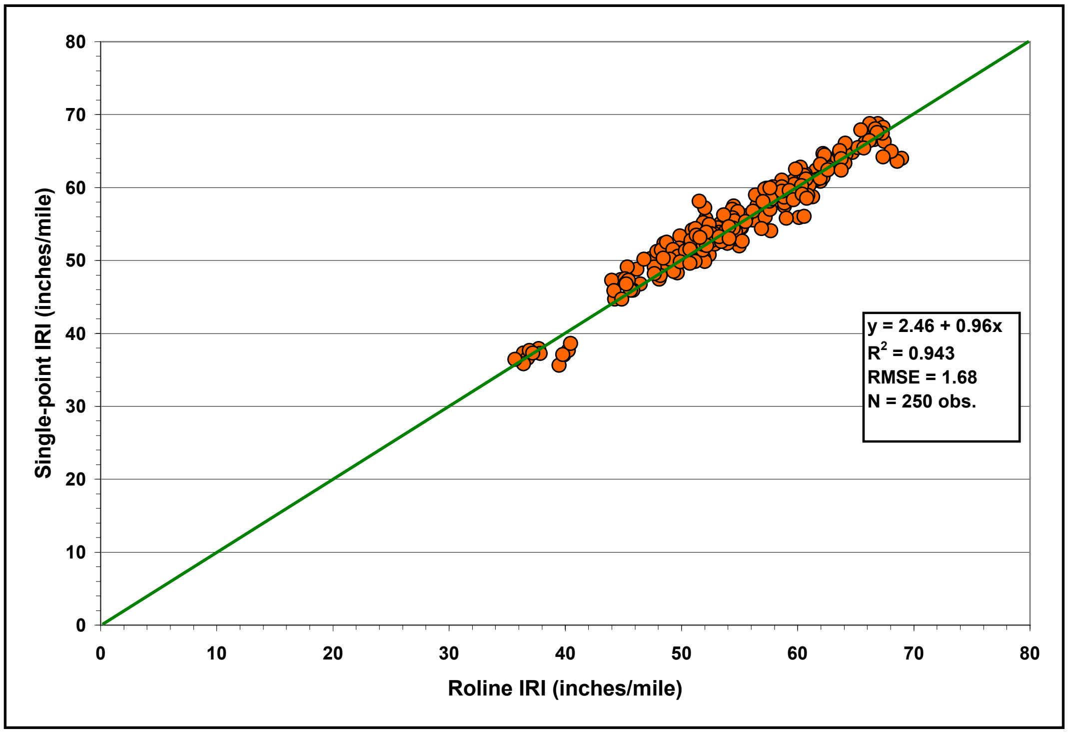

Figure A13. Comparison of Single-Point and Roline Laser IRIs on SH6 and SH36 CRCP Sections with Conventional Transverse Tines.

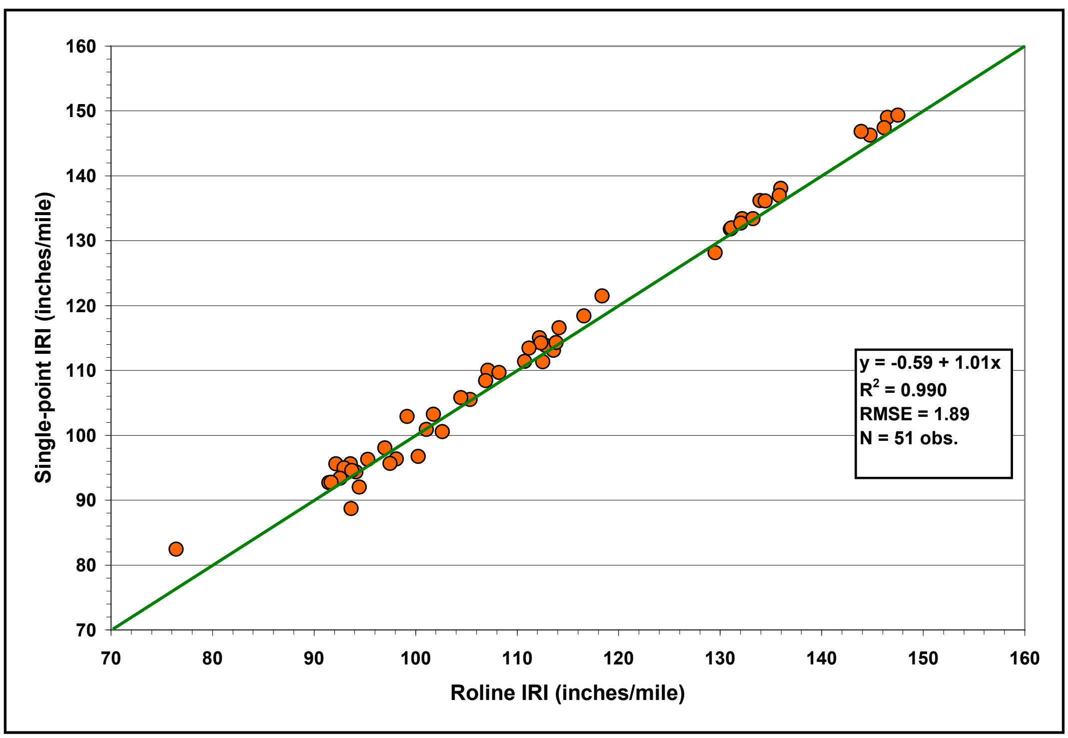

Figure A14. Comparison of Single-Point and Roline Laser IRIs on IH35 and SH36 CRCP Sections with Carpet Dragged Surface.

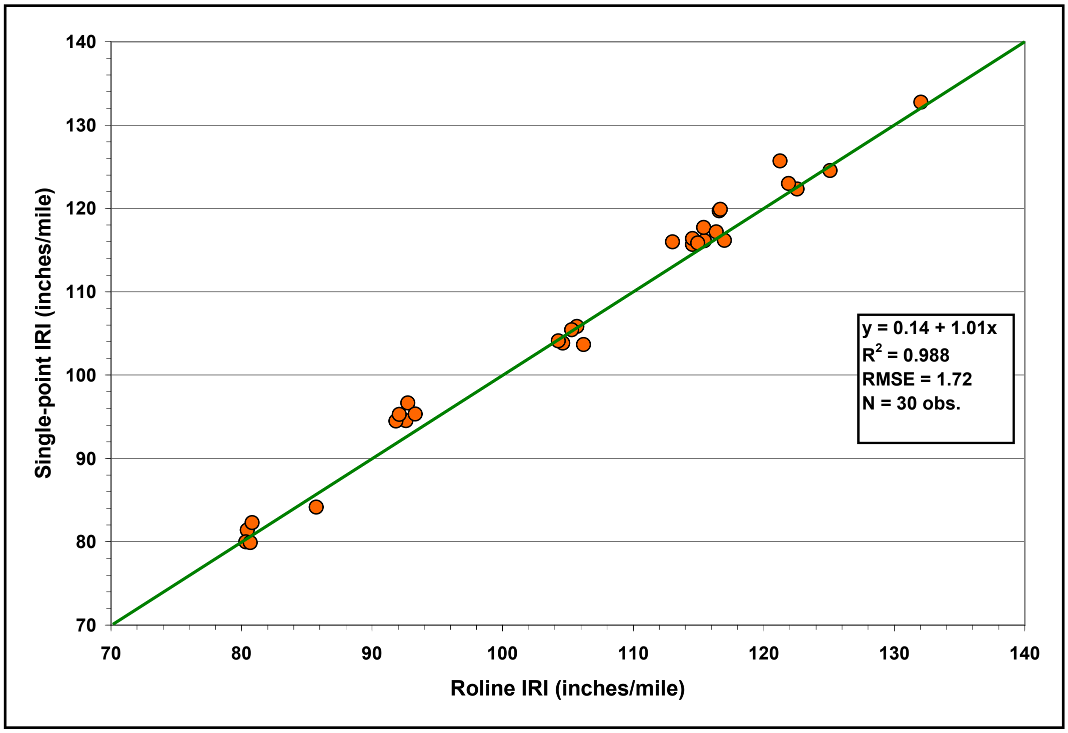

Figure A15. Comparison of Single-Point and Roline Laser IRIs on IH35 CRCP Section with Belt Dragged Surface.

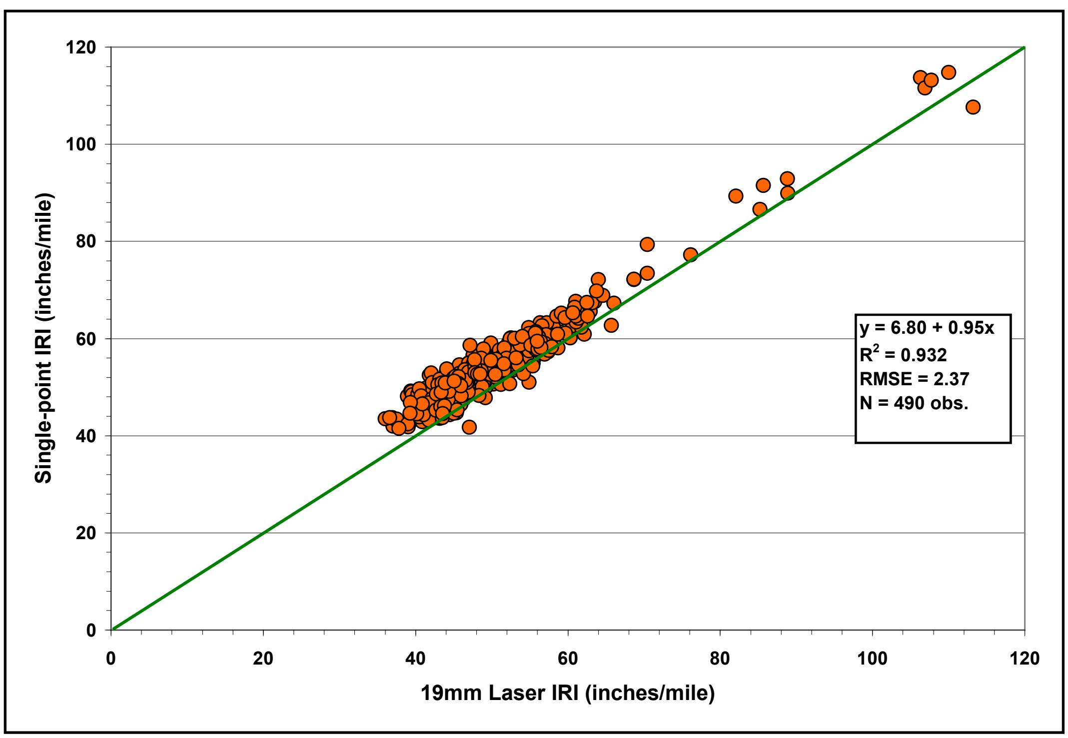

Figure A16. Comparison of Single-Point and 19mm Laser IRIs on SH6 PFC Project.

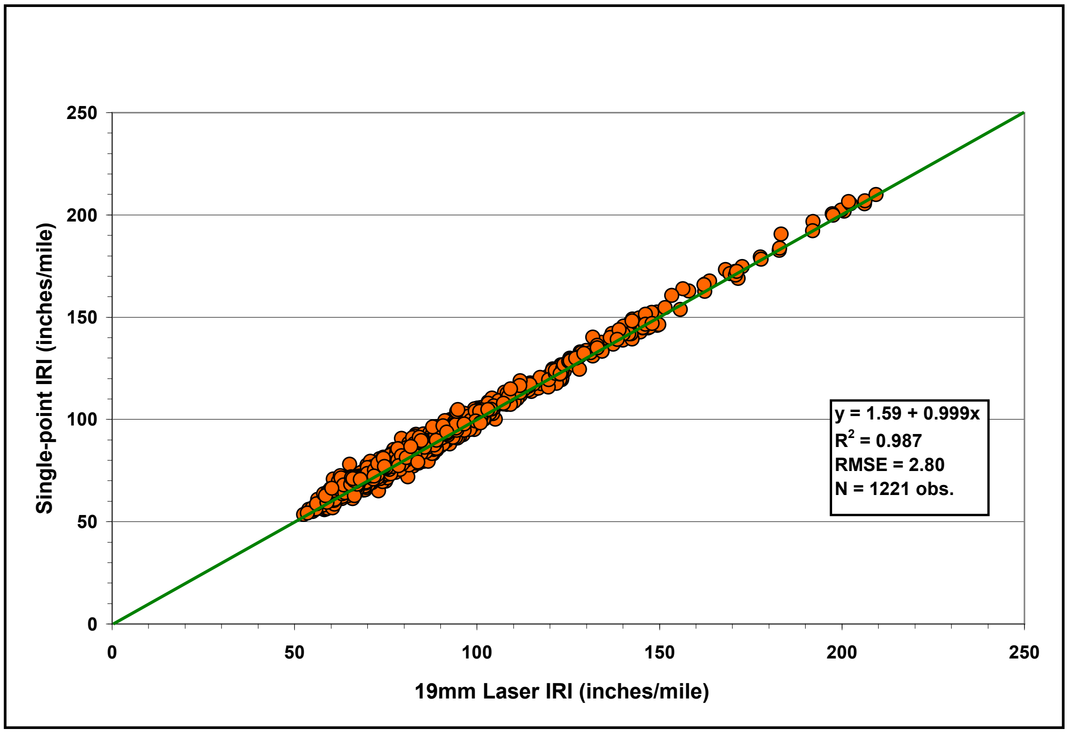

Figure A17. Comparison of Single-Point and 19mm Laser IRIs on SH21, US77, and US290 Grade 4 Sections.

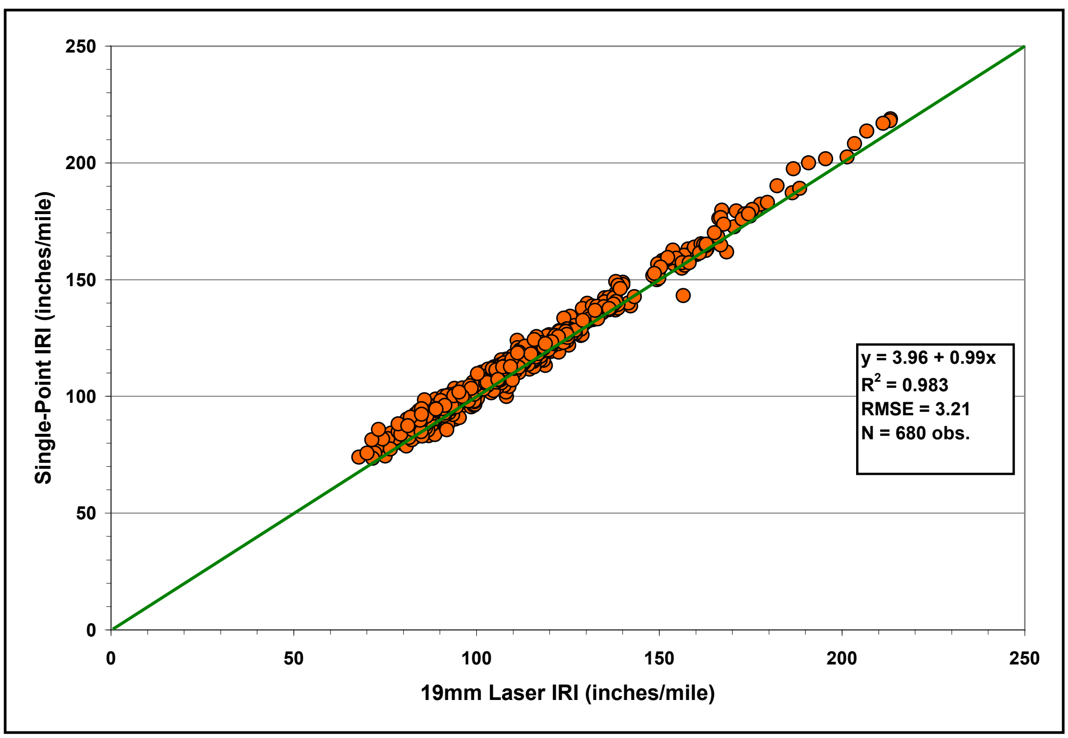

Figure A18. Comparison of Single-Point and 19mm Laser IRIs on US90A, and FM50 Grade 3 Sections.

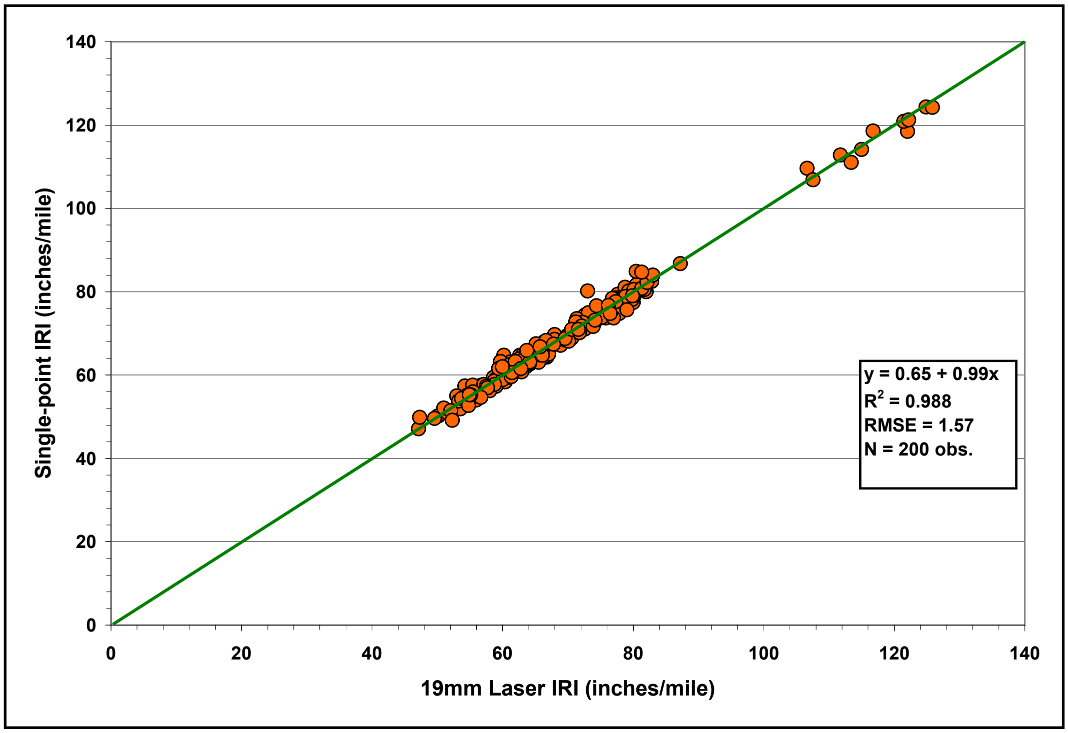

Figure A19. Comparison of Single-Point and 19mm Laser IRIs on Loop 1 SMA-C Project.

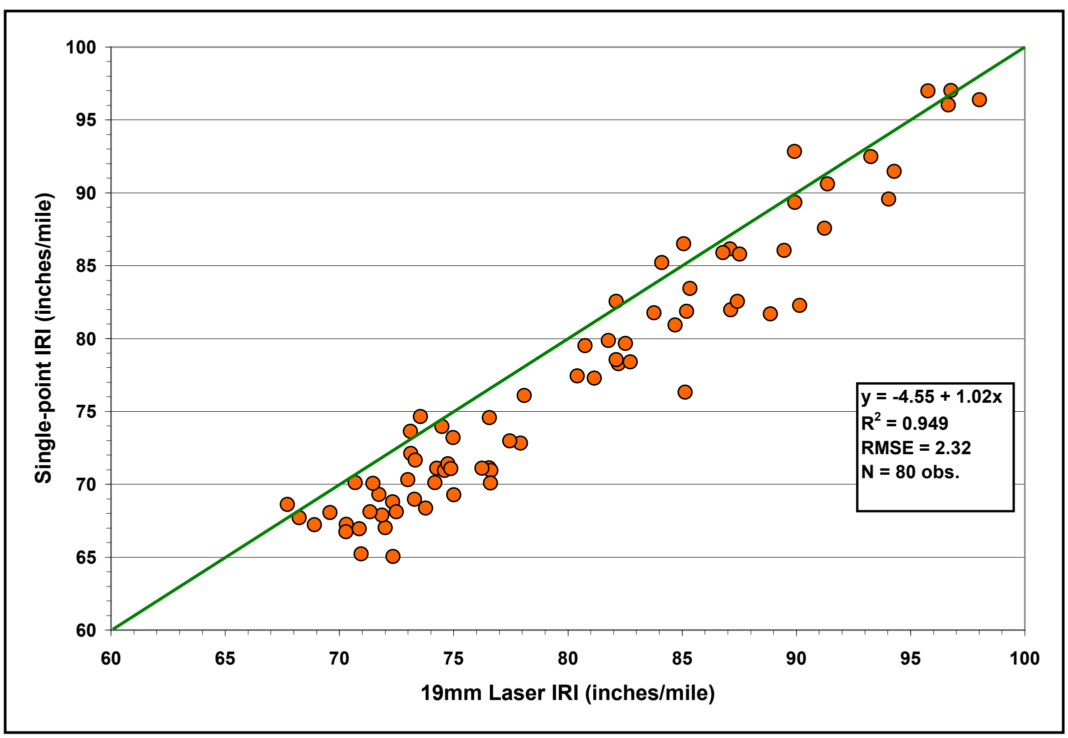

Figure A20. Comparison of Single-Point and 19mm Laser IRIs on FM734 SMA-D Project.

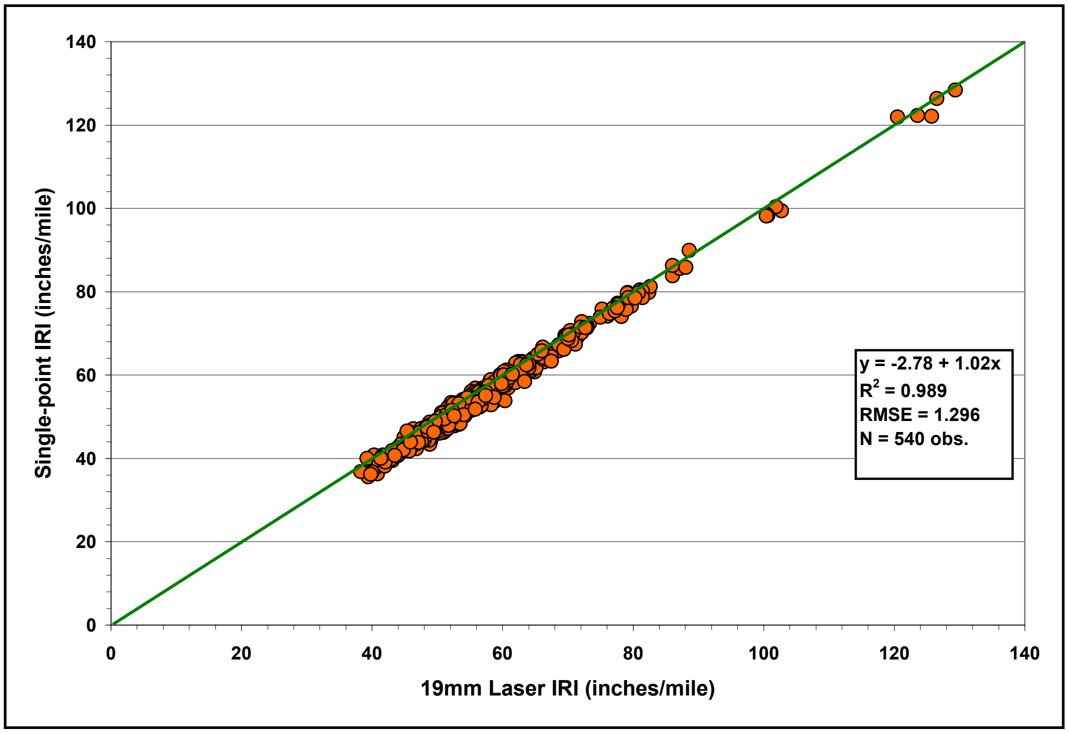

Figure A21. Comparison of Single-Point and 19mm Laser IRIs on FM2440 Type C Project.

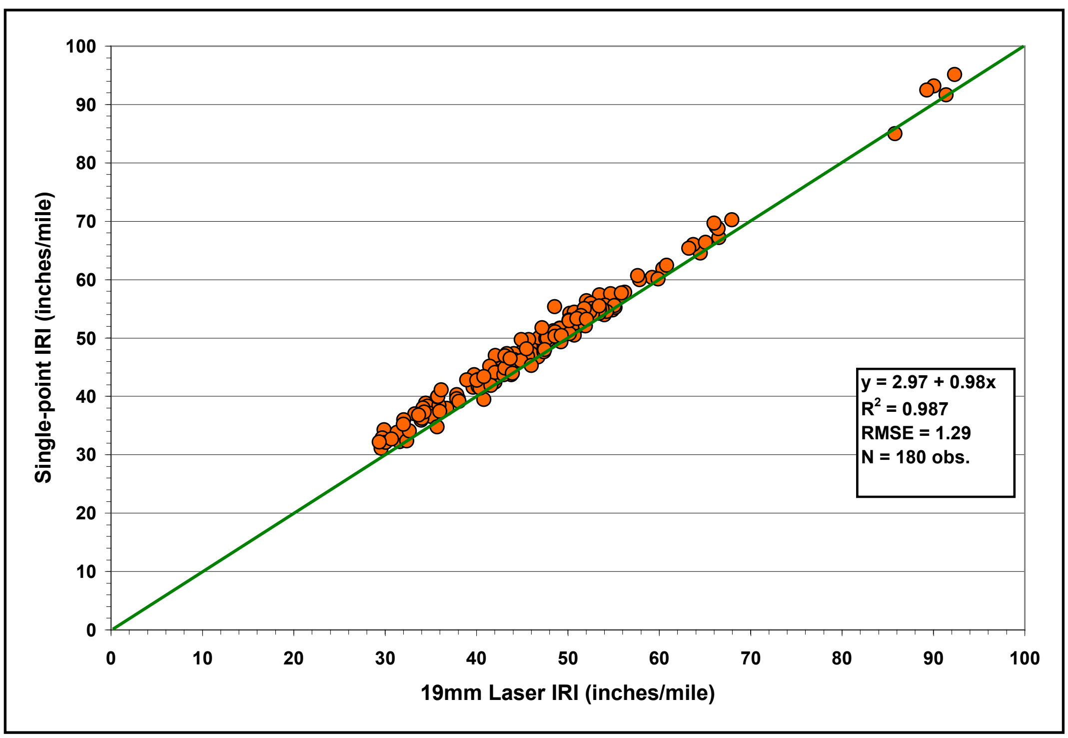

Figure A22. Comparison of Single-Point and 19mm Laser IRIs on Loop 463 Type C Project.

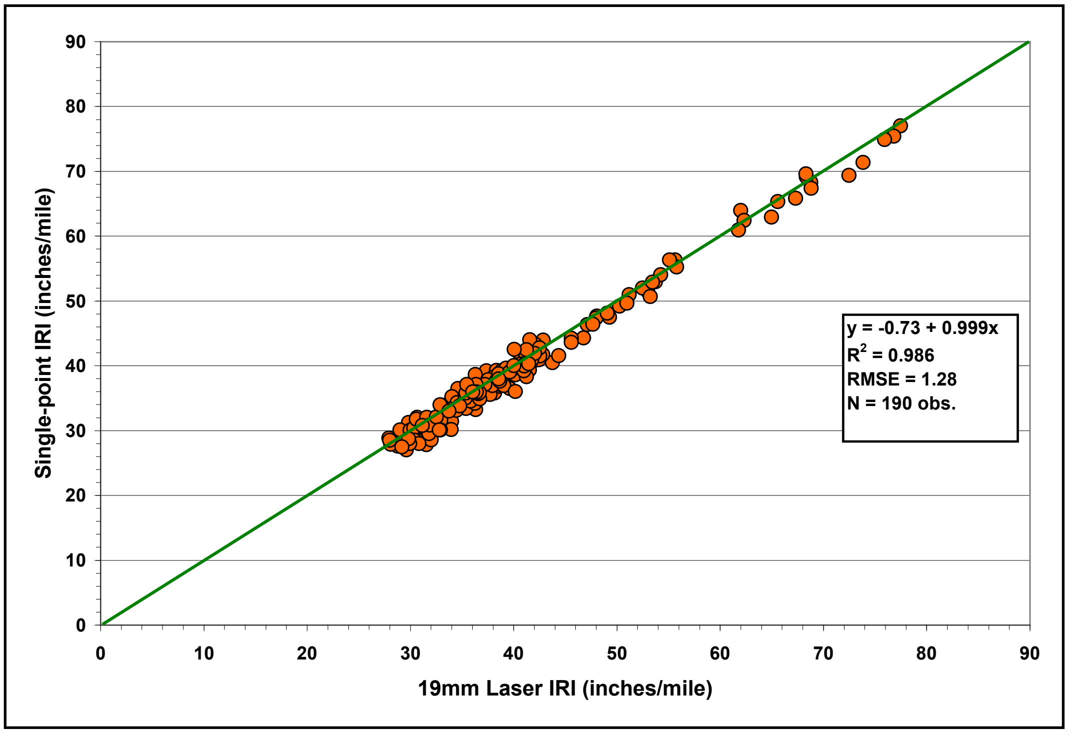

Figure A23. Comparison of Single-Point and 19mm Laser IRIs on US59 Type D Project.

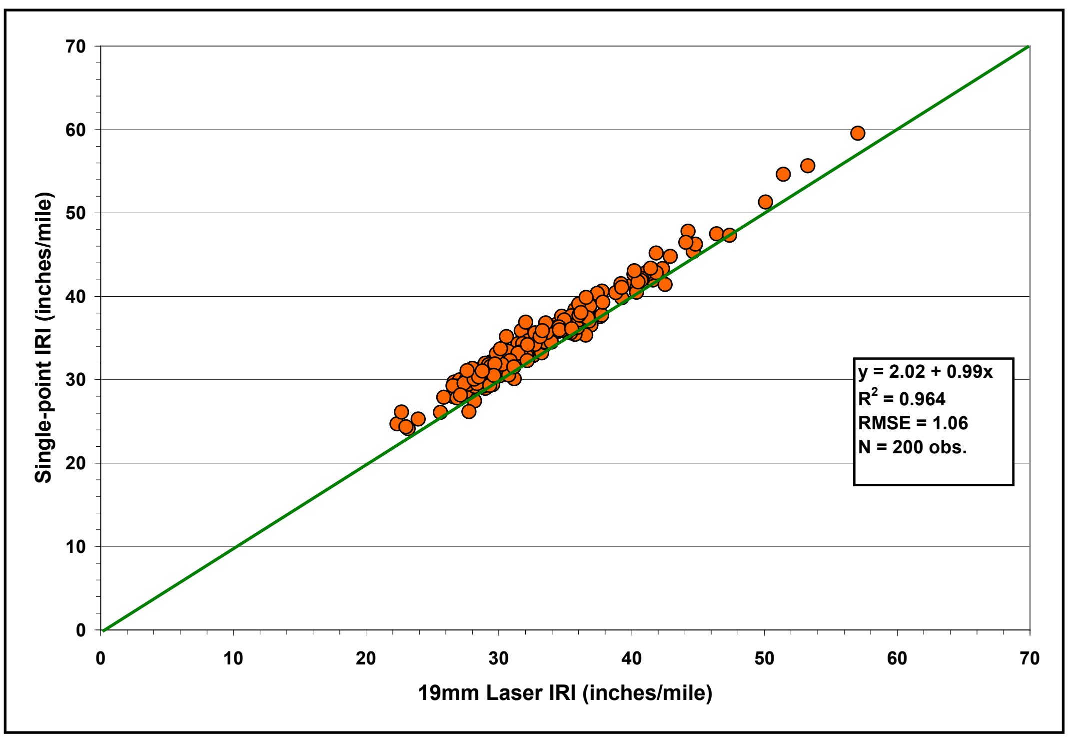

Figure A24. Comparison of Single-Point and 19mm Laser IRIs on US77 Type D Project.

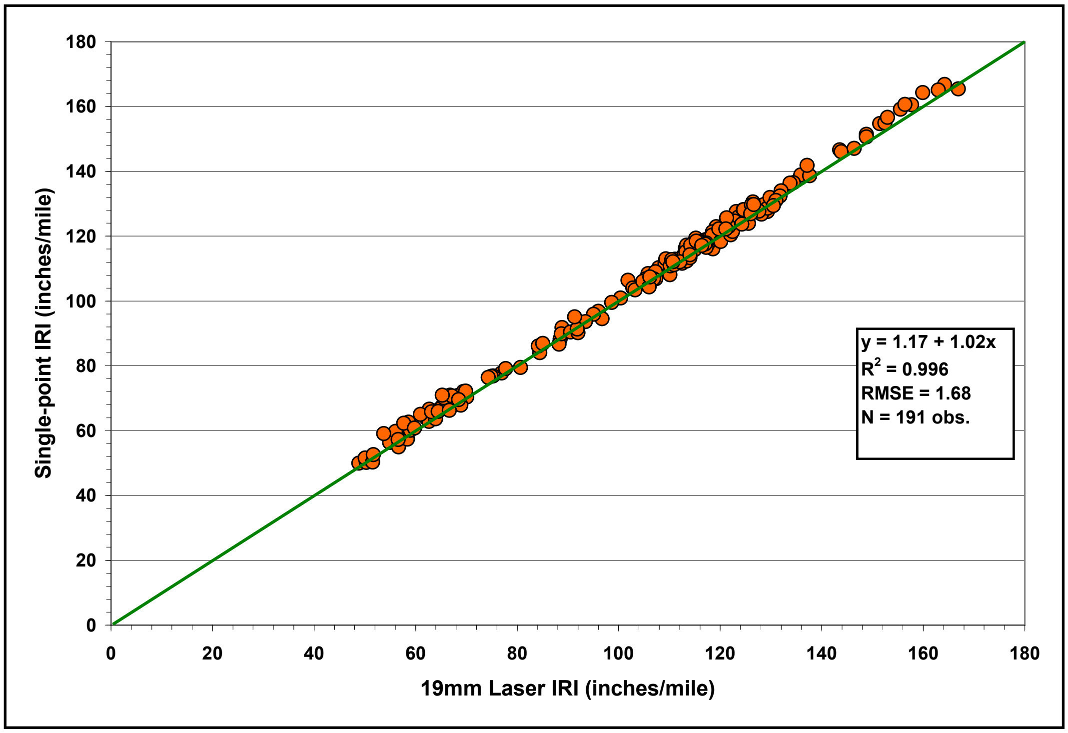

Figure A25. Comparison of Single-Point and 19mm Laser IRIs on IH820 and SH36 CRCP Sections with Variable Transverse Tines.

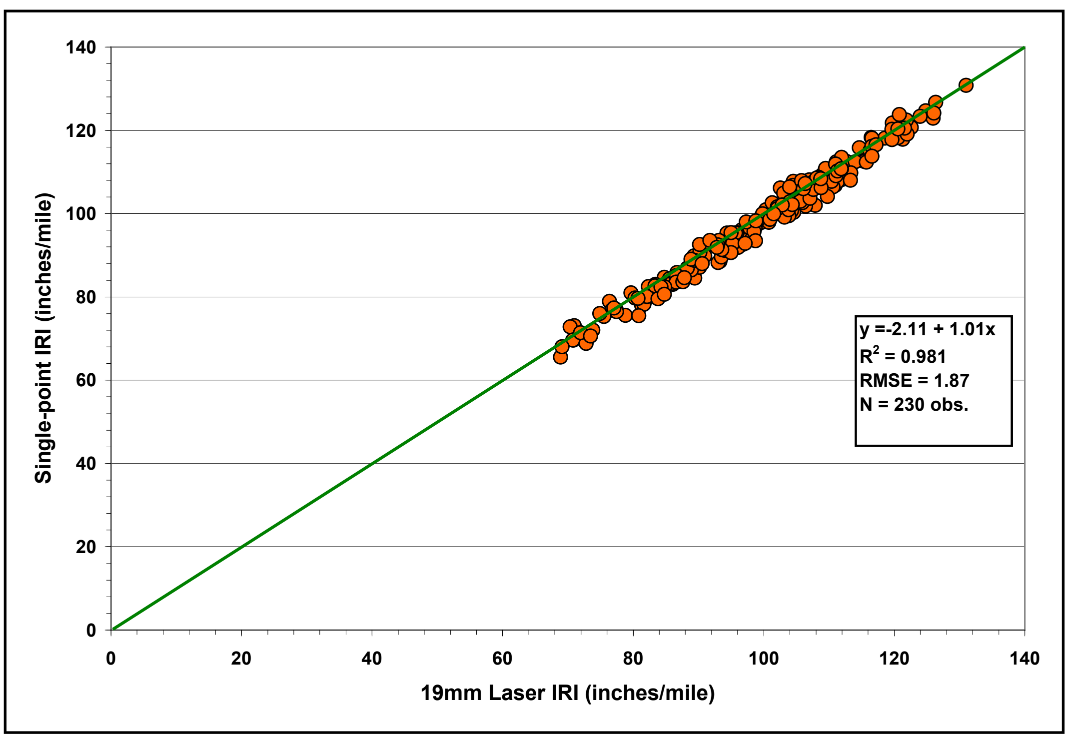

Figure A26. Comparison of Single-Point and 19mm Laser IRIs on US287 CRCP Skidabrader Section.

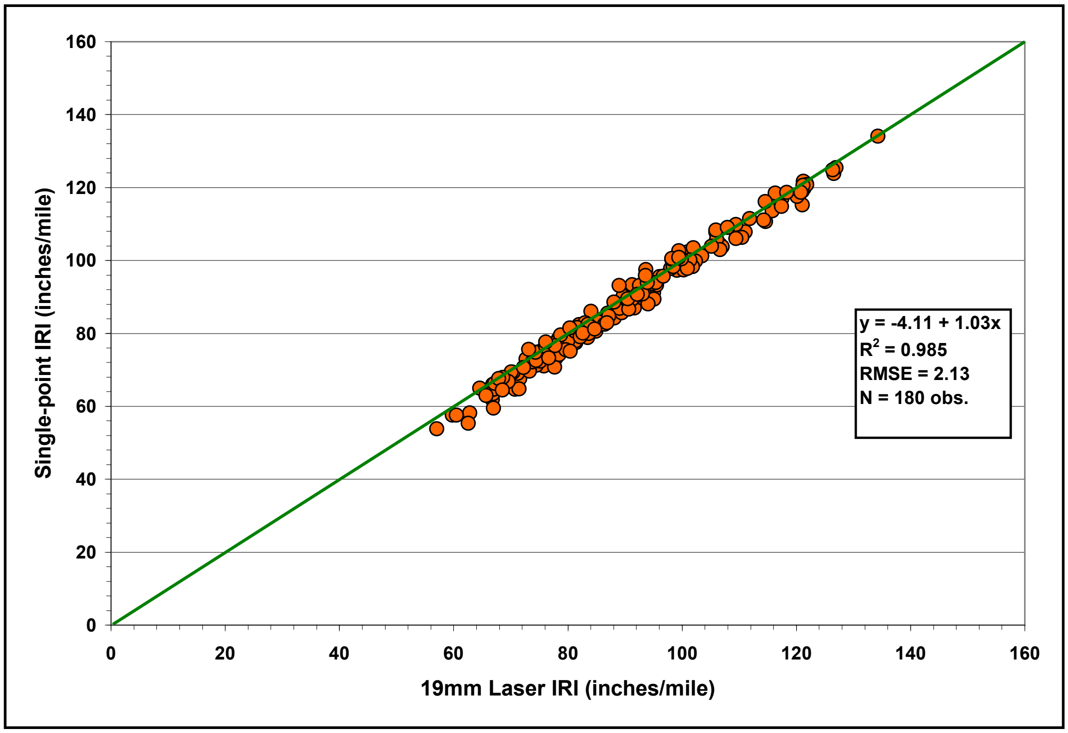

Figure A27. Comparison of Single-Point and 19mm Laser IRIs on US287 CRCP Section with Deep Transverse Tines.

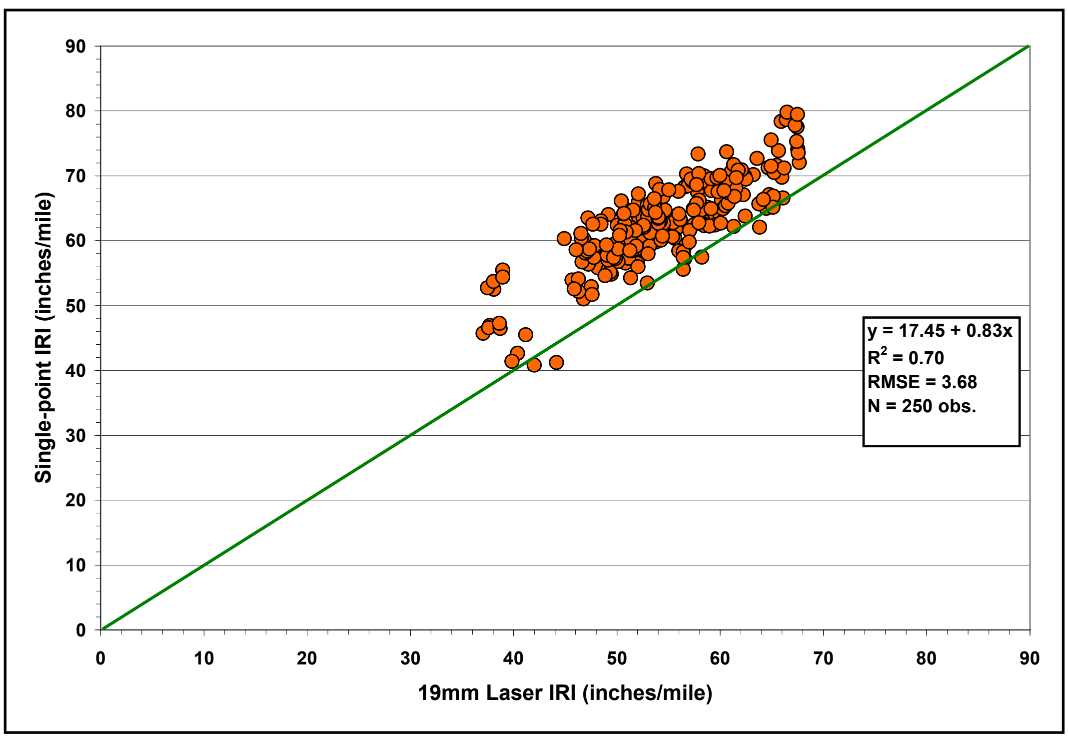

Figure A28. Comparison of Single-Point and 19mm Laser IRIs on SH6 and SH36 CRCP Sections with Conventional Transverse Tines.

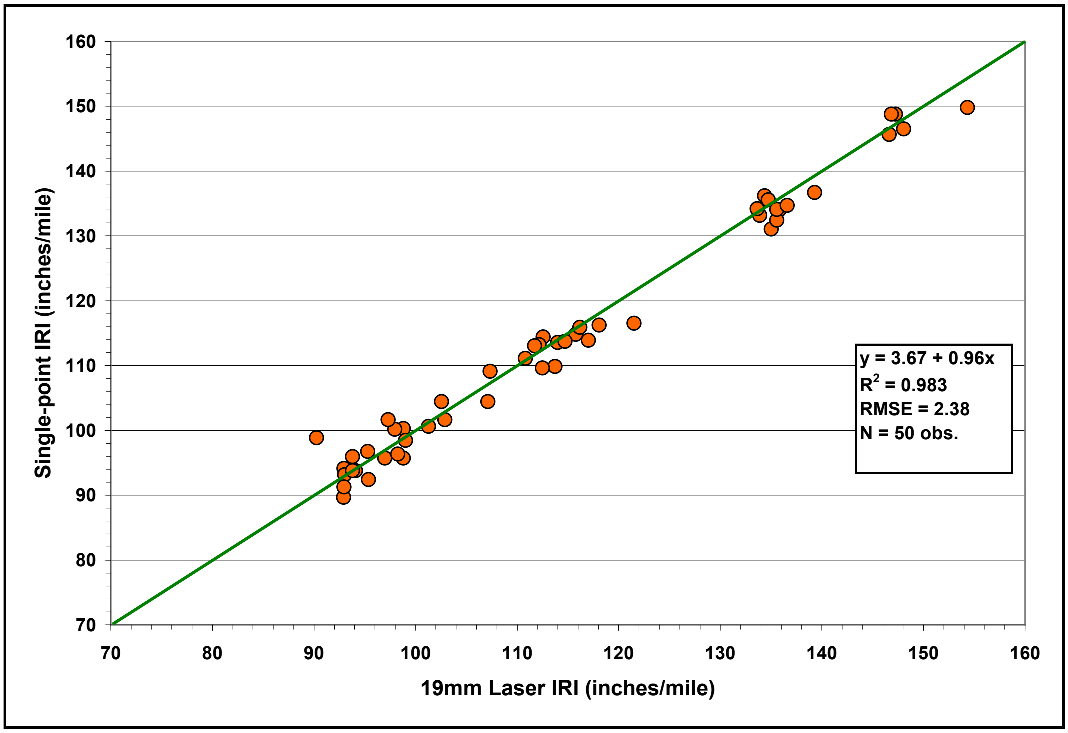

Figure A29. Comparison of Single-Point and 19mm Laser IRIs on IH35 and SH36 CRCP Sections with Carpet Dragged Surface.

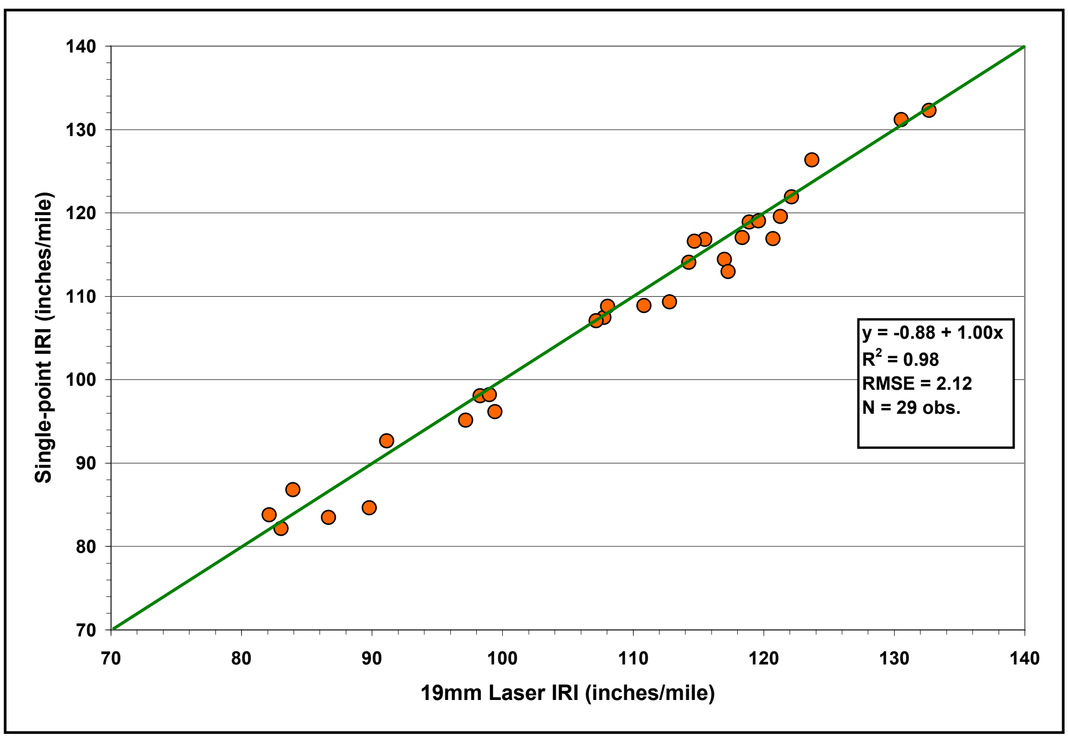

Figure A30. Comparison of Single-Point and 19mm Laser IRIs on IH35 CRCP Section with Belt Dragged Surface.

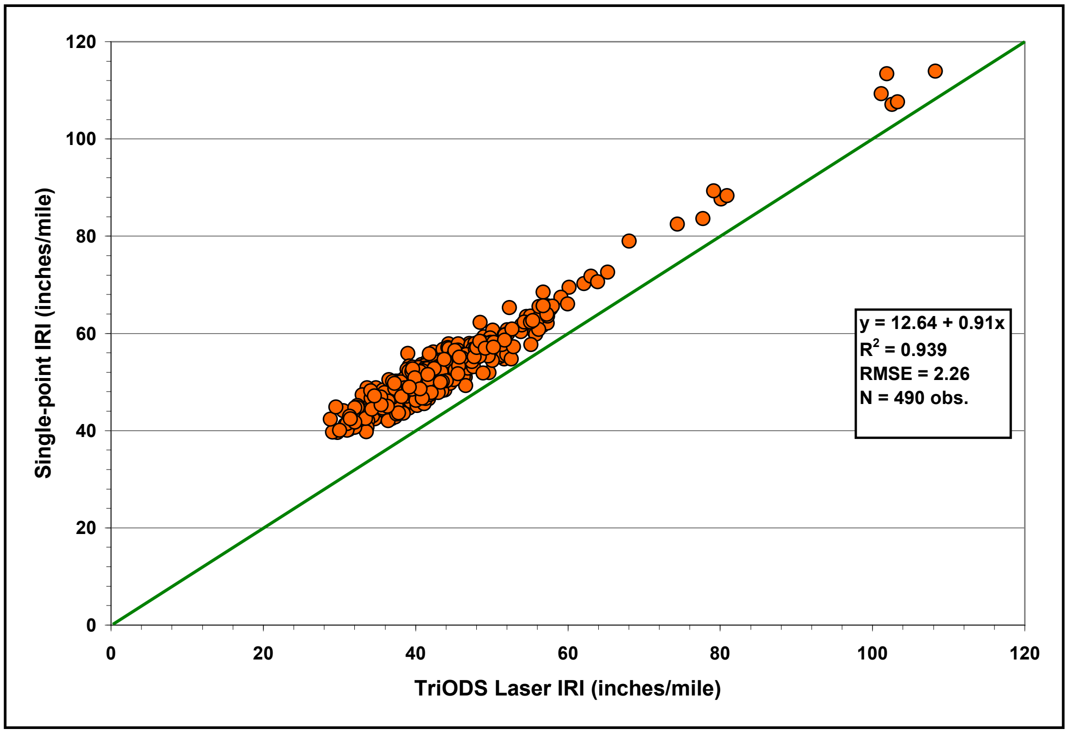

Figure A31. Comparison of Single-Point and TriODS Laser IRIs on SH6 PFC Project.

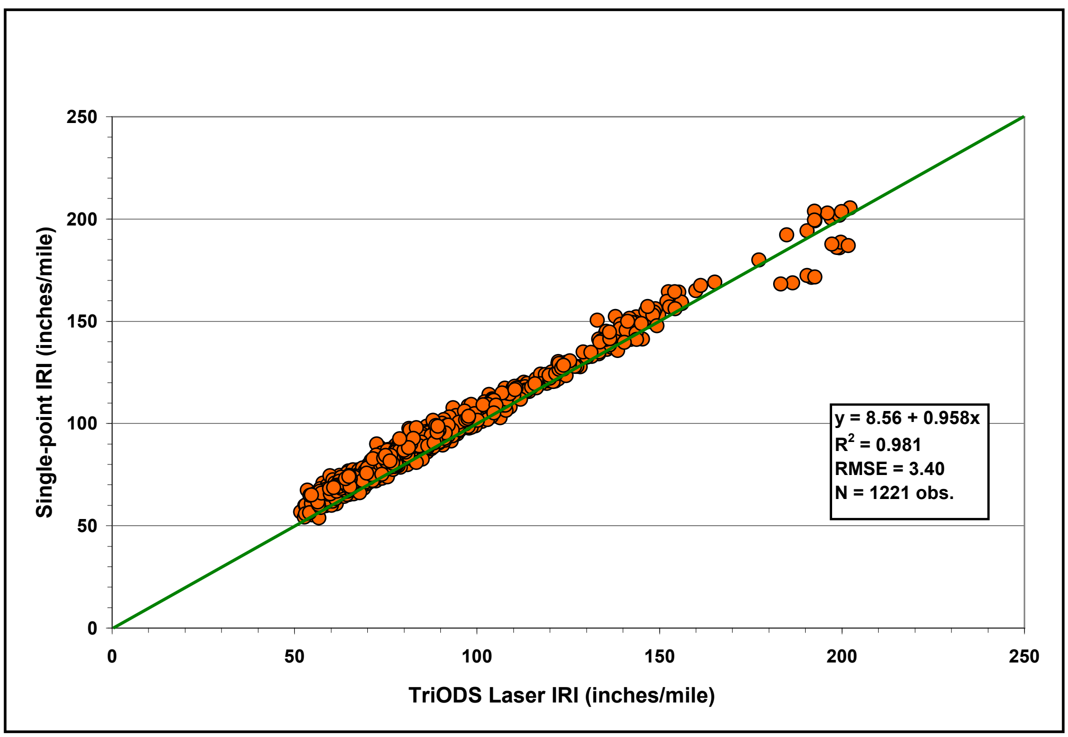

Figure A32. Comparison of Single-Point and TriODS Laser IRIs on SH21, US77, and US290 Grade 4 Sections.

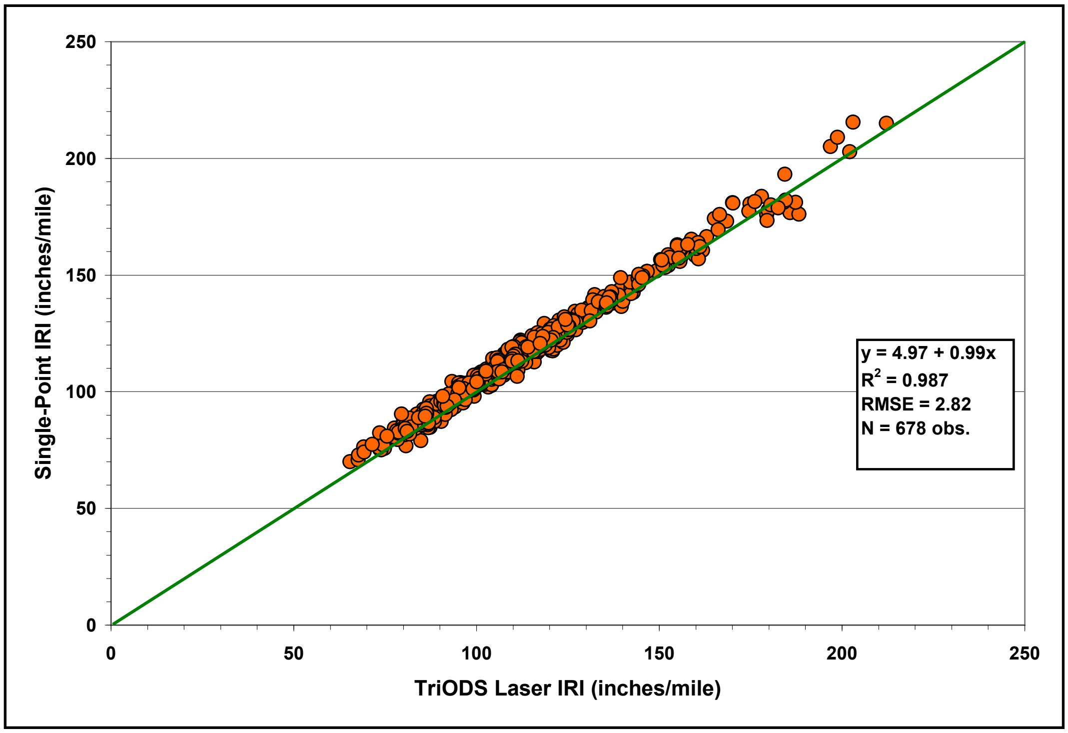

Figure A33. Comparison of Single-Point and TriODS Laser IRIs on US90A and FM50 Grade 3 Sections.

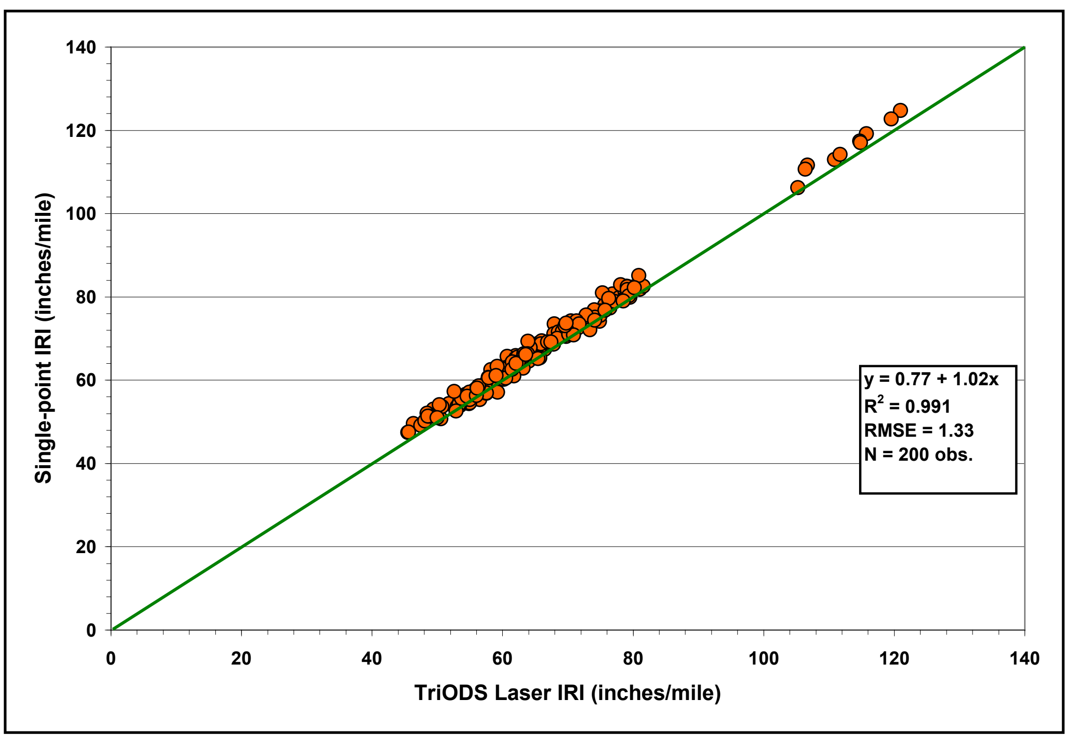

Figure A34. Comparison of Single-Point and TriODS Laser IRIs on Loop 1 SMA-C Project.

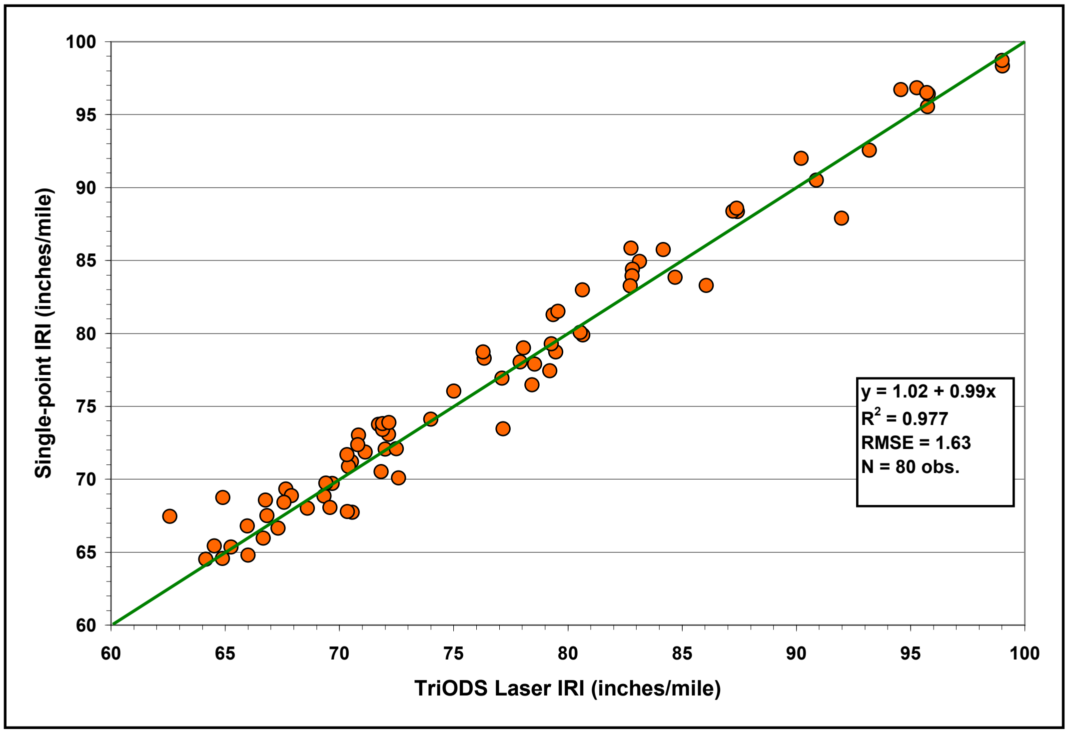

Figure A35. Comparison of Single-Point and TriODS Laser IRIs on FM734 SMA-D Project.

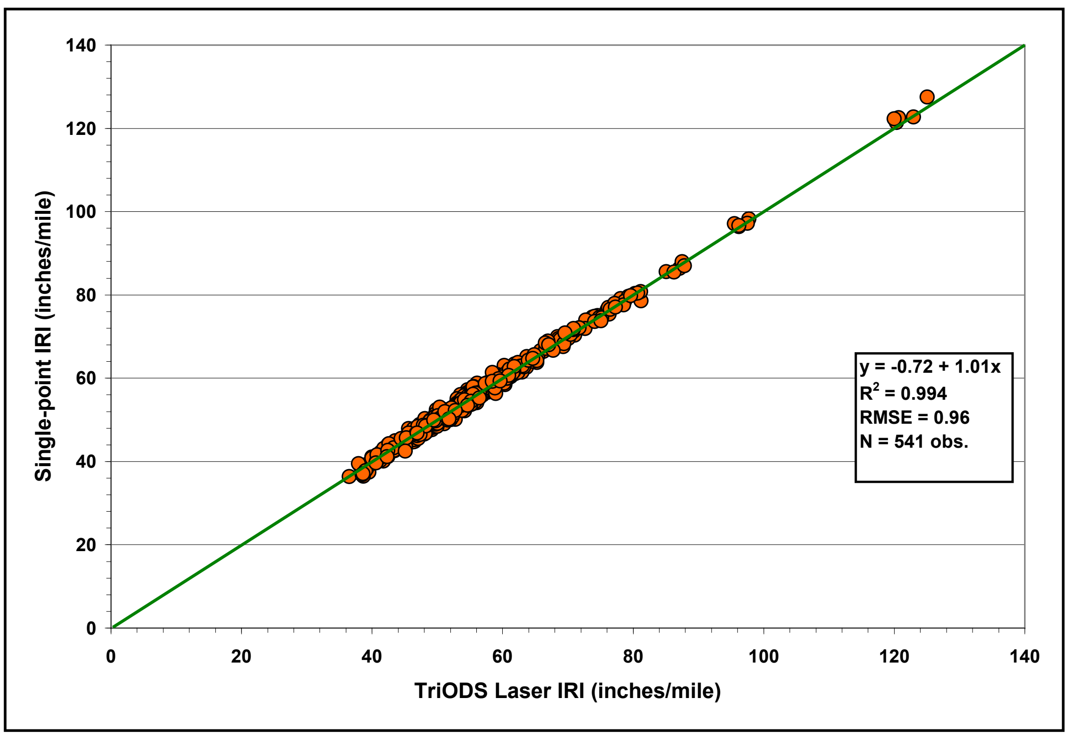

Figure A36. Comparison of Single-Point and TriODS Laser IRIs on FM2440 Type C Project.

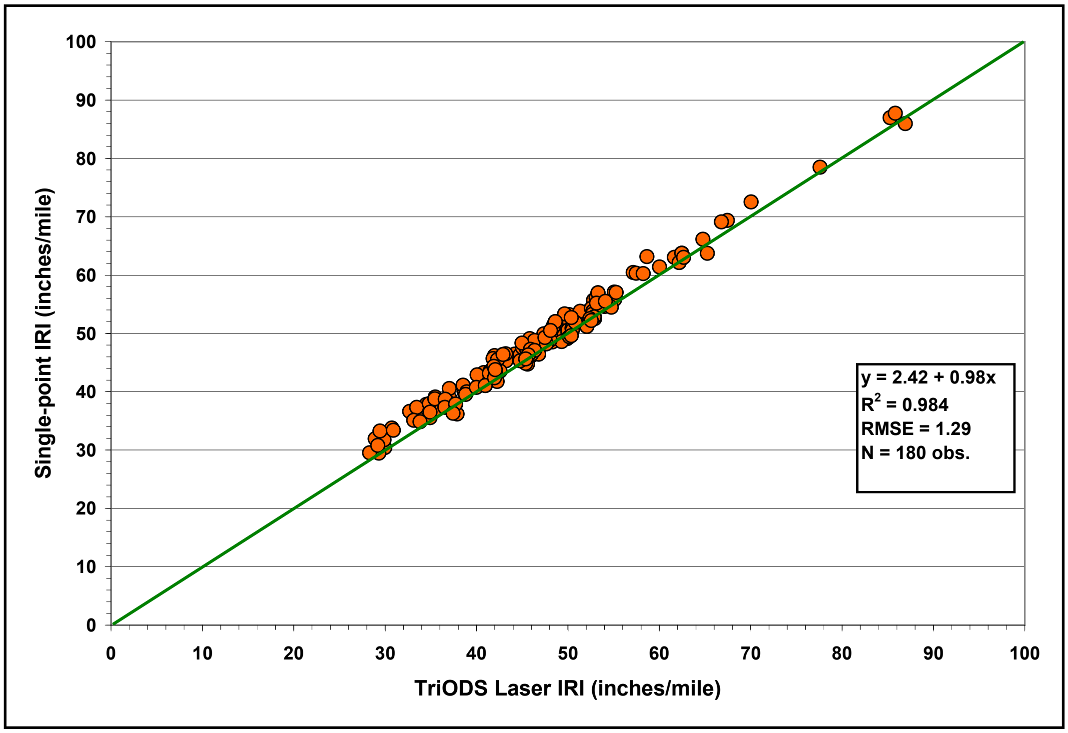

Figure A37. Comparison of Single-Point and TriODS Laser IRIs on Loop 463 Type C Project.

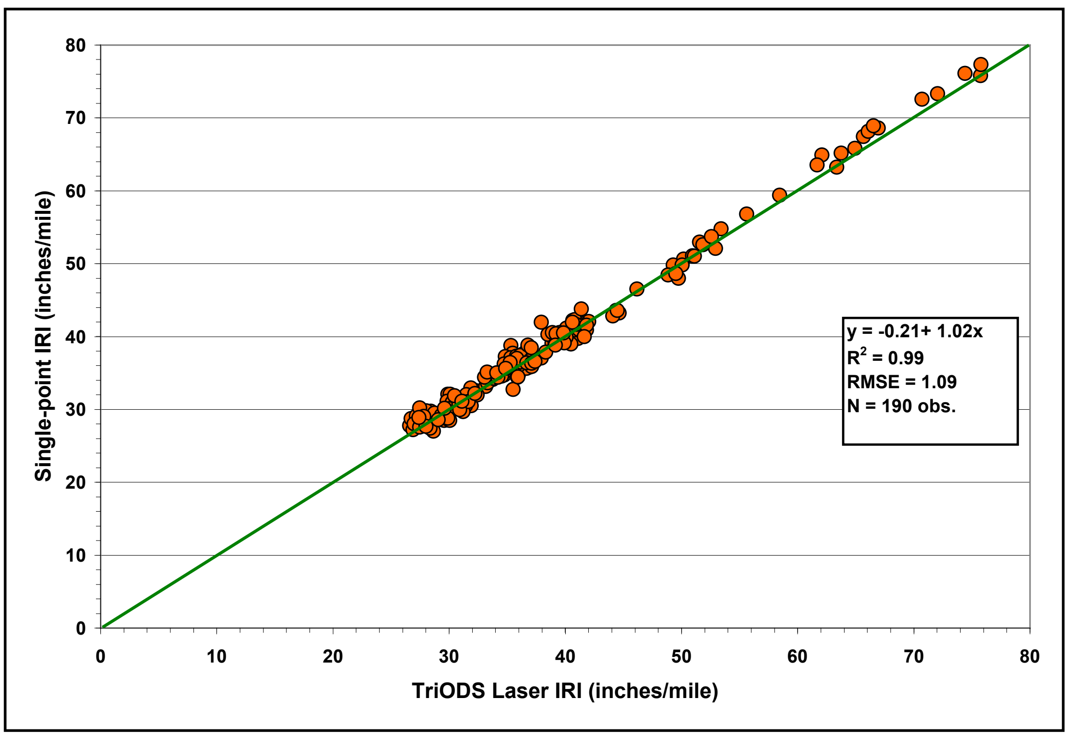

Figure A38. Comparison of Single-Point and TriODS Laser IRIs on US59 Type D Project.

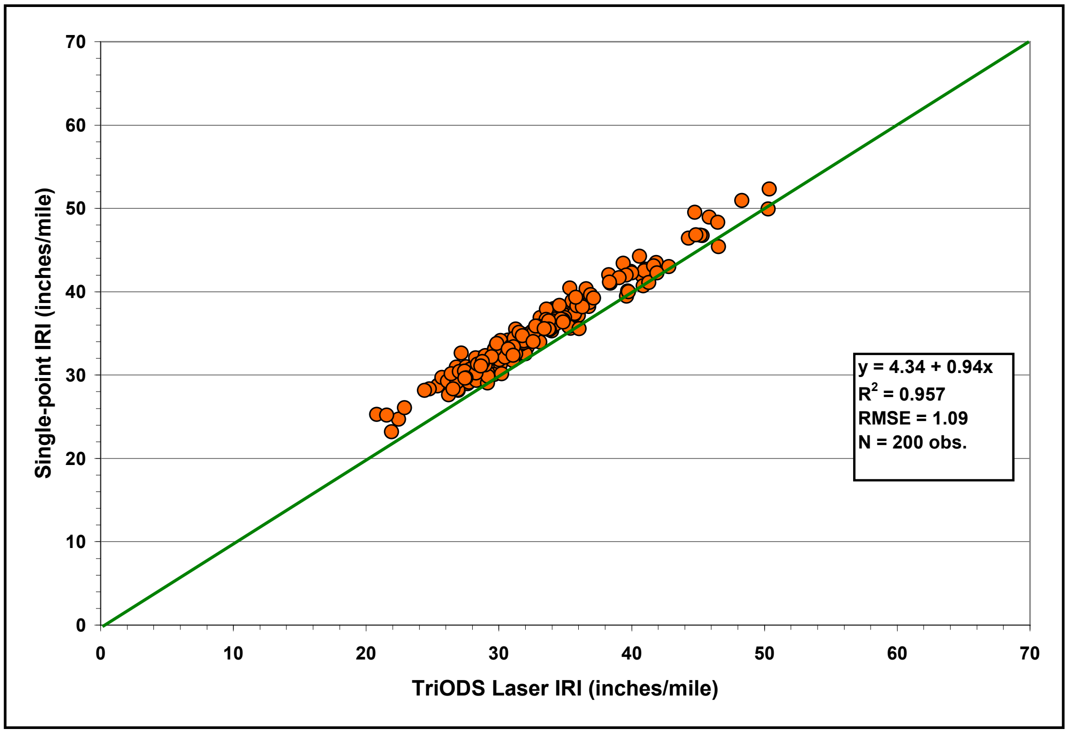

Figure A39. Comparison of Single-Point and TriODS Laser IRIs on US77 Type D Project.

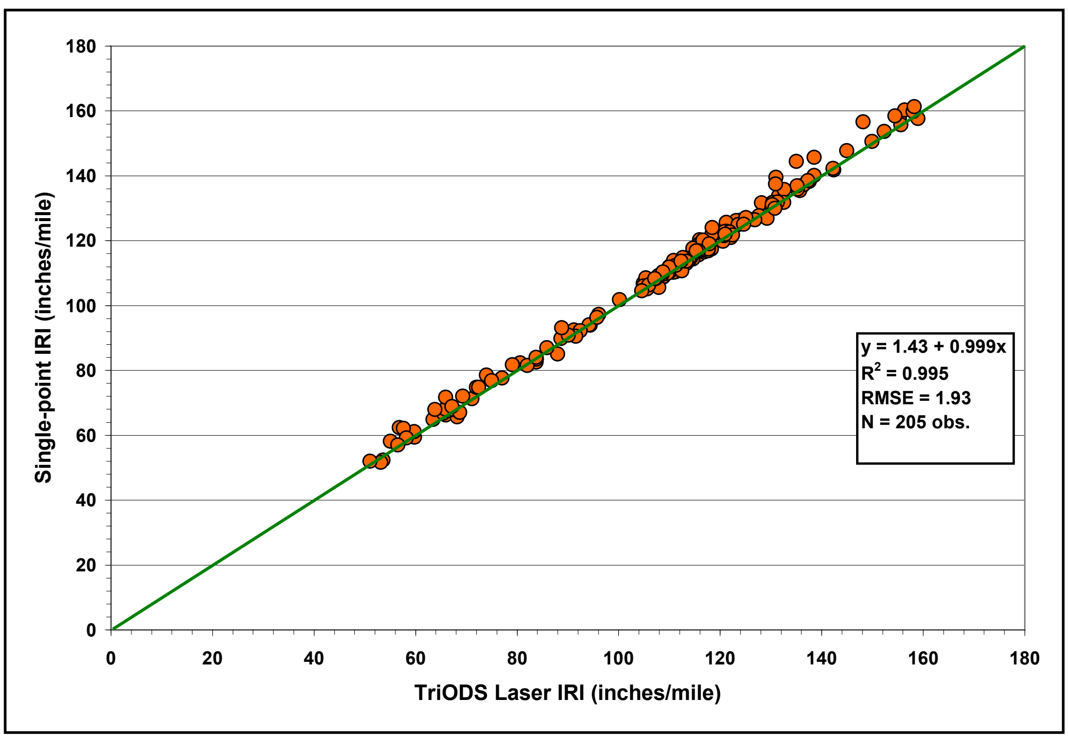

Figure A40. Comparison of Single-Point and TriODS Laser IRIs on IH820 and SH36 CRCP Sections with Variable Transverse Tines.

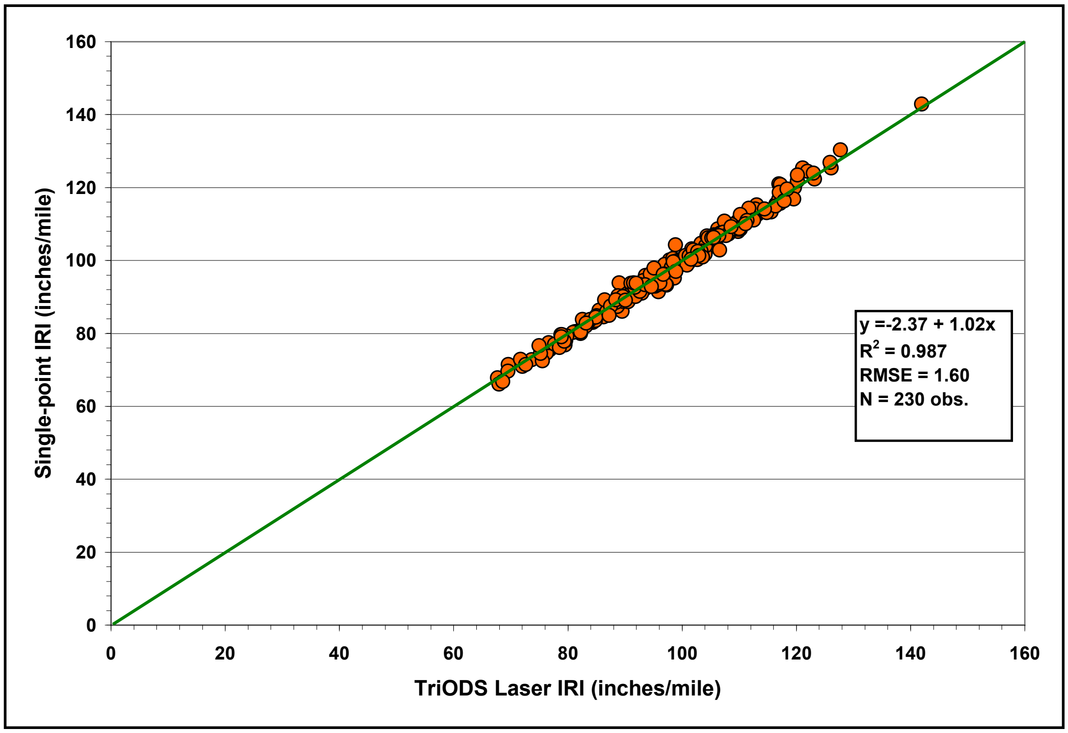

Figure A41. Comparison of Single-Point and TriODS Laser IRIs on US287 CRCP Skidabrader Section.

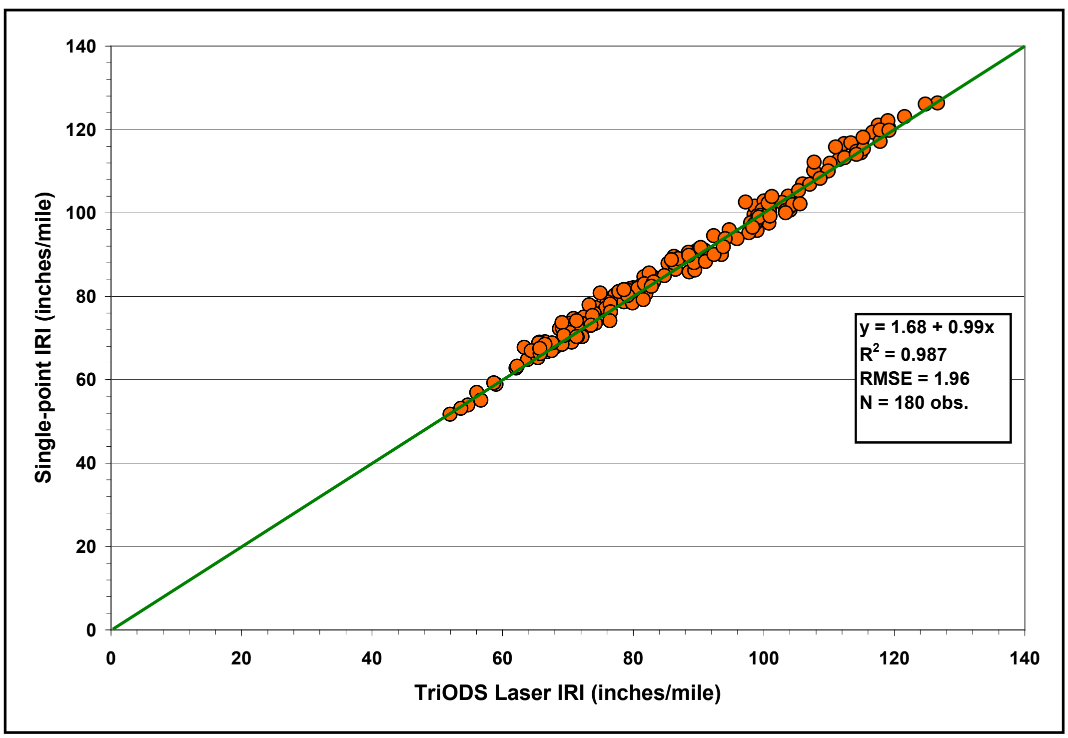

Figure A42. Comparison of Single-Point and TriODS Laser IRIs on US287 CRCP Section with Deep Transverse Tines.

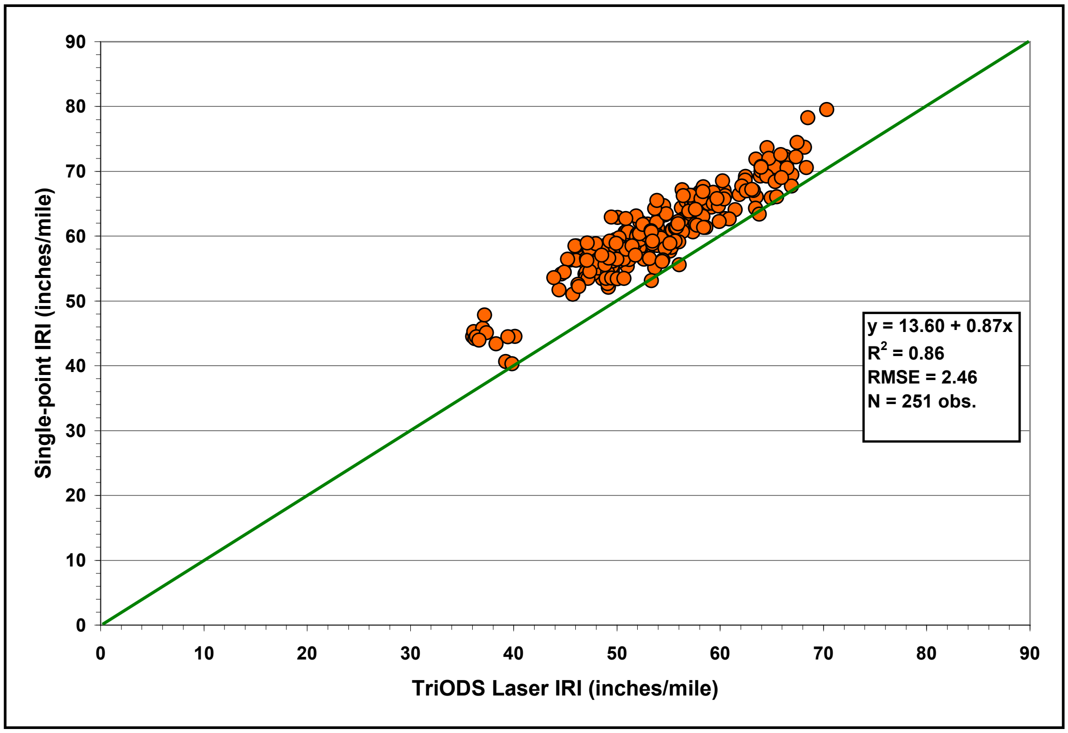

Figure A43. Comparison of Single-Point and TriODS Laser IRIs on SH6 and SH36 CRCP Sections with Conventional Transverse Tines.

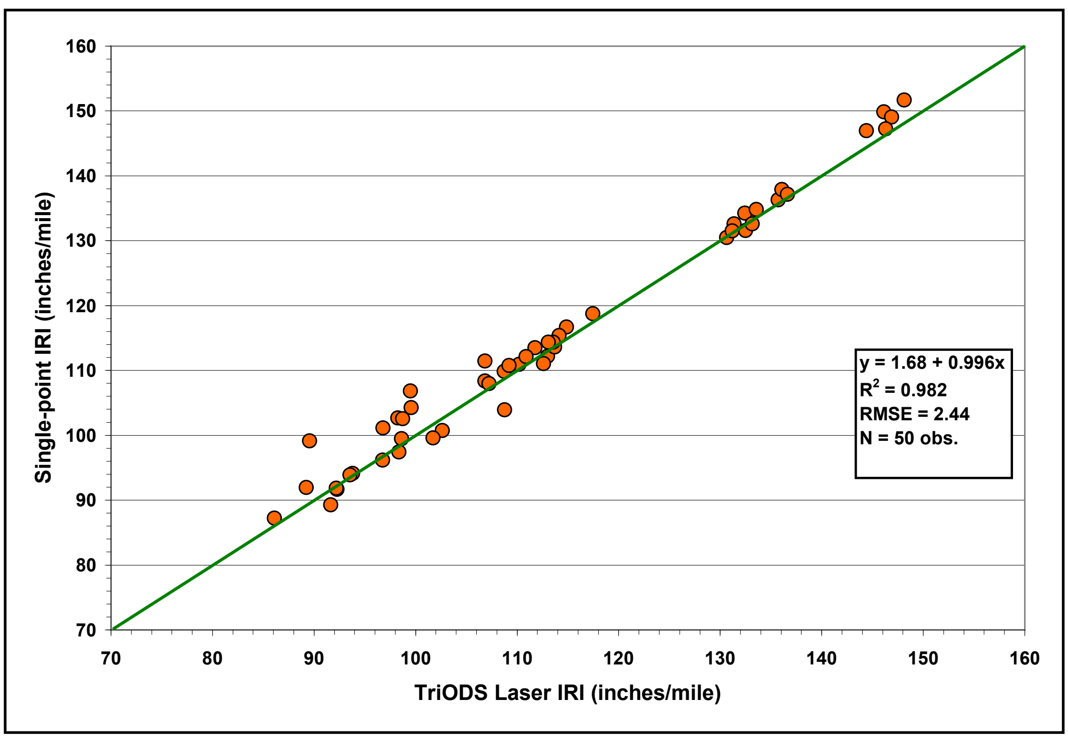

Figure A44. Comparison of Single-Point and TriODS Laser IRIs on IH35 and SH36 CRCP Sections with Carpet Dragged Surface.

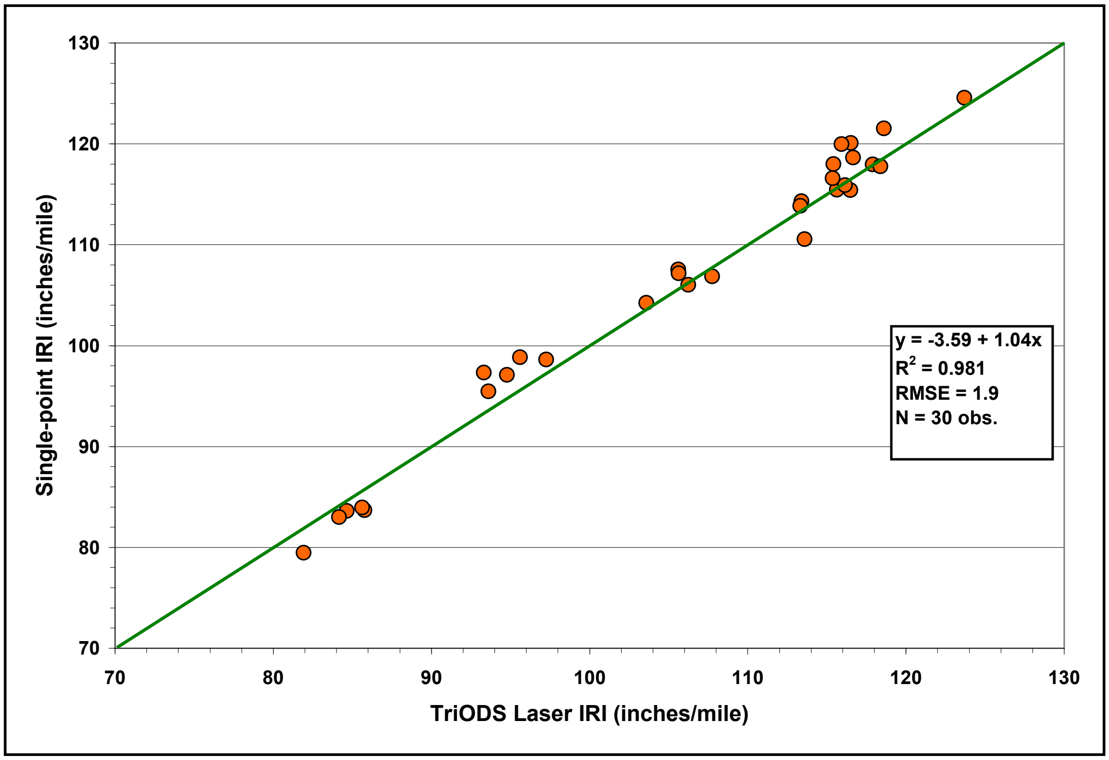

Figure A45. Comparison of Single-Point and TriODS Laser IRIs on IH35 CRCP Section with Belt Dragged Surface.