INERTIAL AND INCLINOMETER BASED PROFILER REPEATABILITY AND ACCURACY USING THE IRI MODEL

Final Report

SPR 744

Oregon Department of Transportation

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Washington, DC 20590-0003

December 2012

Technical Report Documentation Page

1. Report No. FHWA-OR-RD-13-03	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Inertial and Inclinometer Based Profiler Repeatability and Accuracy Using the IRI Model		5. Report Date December 2012 6. Performing Organization Code
7. Author(s) Michael J. Olson, Ph.d. and Abby Chin		8. Performing Organization Report No
9. Performing Organization Name and Address Oregon State University 220 Owen Hall Corvallis, Oregon 97331		10. Work Unit No. (TRAIS) 11. Contract or Grant No. SPR 744
12. Sponsoring Agency Name and Address Oregon Department of Transportation Research Section 200 Hawthorne Ave. SE, Suite B-240 Salem, OR 97301-5192	and Federal Highway Administration 400 Seventh Street, SW Washington, DC 20590-0003	13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Oregon DOT is transitioning to use the International Roughness Index (IRI) for an incentive\disincentive program for pavement smoothness evaluation for newly paved roads. The IRI will typically be determined by contractors using inertial profilers. This research evaluated the procedures, site, and equipment used for establishing a reference profile for a certification process for inertial profilers. In a comparison of several profiling devices, the inclinometer-based profiler used by Oregon DOT for the reference profile showed sufficient results in repeatability and accuracy in profile measurement and calculation of IRI. However, the certification site shows significant variability in IRI across the site, which can lead to lower accuracy scores when the exact path is not followed. Further, significant differences in IRI were observed during repeat visits throughout the course of the study period.

This study also evaluated the use of a new technology, terrestrial laser scanning, for pavement analyses. At larger extents, terrestrial laser scanning (TLS) was compared to several current techniques to measure road profiles including digital levels, inclinometers, and inertial profilers. TLS is able to collect a large, dense set of data relatively quickly for the entire roadway and surrounding areas; hence, the data can not only be used for evaluating the pavement roughness but also can be used for other design parameters such as transverse and longitudinal slope. The results show that profiles derived from TLS data determined accurate IRI values and cross-correlation with the reference profile. At a finer scale, micron resolution 3D laser scanners can be utilized to determine the influence of predominant aggregate size on the texture of the pavement.

17. Key Words INERTIAL PROFILERS, INCLINOMETER, ROUGHNESS, IRI, LASER SCANNING, PAVEMENT		18. Distribution Statement Copies available from NTIS, and online at http://www.oregon.gov/ODOT/TD/TP_RES/	
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 117	22. Price

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					**LENGTH**		
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
		AREA					**AREA**		
in^2	square inches	645.2	millimeters squared	mm^2	mm^2	millimeters squared	0.0016	square inches	in^2
ft^2	square feet	0.093	meters squared	m^2	m^2	meters squared	10.764	square feet	ft^2
yd^2	square yards	0.836	meters squared	m^2	m^2	meters squared	1.196	square yards	yd^2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	kilometers squared	km^2	km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME					**VOLUME**		
fl oz	fluid ounces	29.57	milliliters	ml	ml	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
	NOTE: Volumes greater than 1000 L shall be shown in m^3.								
		MASS					**MASS**		
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)					**TEMPERATURE (exact)**		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C	°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

ACKNOWLEDGEMENTS

We thank George Chang from Transtec for his comments and insights. Keith Williams, Jeremy Conner, John Raugust, Hamid Mahmoudabadi, William White, Mahyar Sharifi, and Kris Puderbaugh assisted in the field work. Hamid Mahmoudabadi developed code for the texture analysis. Keith Williams designed and built the custom scanner mount used for the texture scanning. Dean Chess at Oregon DOT was instrumental in helping this project get started. Michael Stennett (Oregon DOT), Larry ILG (Oregon DOT), Jim Huddleston (Asphalt Pavement Association of Oregon, APAO), and Anthony Boesen (FHWA) served on the Technical Advisory Committee. Leica Geosystems and David Evans and Associates provided equipment and software used for this study. Maptek I-Site also provided software used for this study

DISCLAIMER

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EXECUTIVE SUMMARY

Oregon DOT is transitioning to use the International Roughness Index (IRI) for an incentive\disincentive program for pavement smoothness evaluation for newly paved roads. The IRI will typically be determined by contractors using inertial profilers. This research evaluated the procedures, site, and equipment used for establishing a reference profile for a certification process for inertial profilers. In a comparison of several profiling devices, the inclinometer-based profiler used by Oregon DOT for the reference profile showed sufficient results in repeatability and accuracy in profile measurement and calculation of IRI. However, the certification site shows significant variability in IRI across the site, which can lead to lower accuracy scores when the exact path is not followed. Further, significant differences in IRI were observed during repeat visits throughout the course of the study period.

This study also evaluated the use of a new technology, terrestrial laser scanning, for pavement analyses. At larger extents, terrestrial laser scanning (TLS) was compared to several current techniques to measure road profiles including digital levels, inclinometers, and inertial profilers. TLS is able to collect a large, dense set of data relatively quickly for the entire roadway and surrounding areas; hence, the data can not only be used for evaluating the pavement roughness but also can be used for other design parameters such as transverse and longitudinal slope. The results show that profiles derived from TLS data determined accurate IRI values and cross-correlation with the reference profile. At a finer scale, micron resolution 3D laser scanners can be utilized to determine the influence of predominant aggregate size on the texture of the pavement.

1.0 INTRODUCTION

The specifications for pavement roughness are being transitioned by Oregon DOT from PI based measurements to IRI. Research has been conducted on the accuracy and repeatability of the inclinometer profiler. It is intended that the inclinometer profiler will be used to establish the reference profile with which inertial profilers will be calibrated against. In previous tests the instruments were unable to meet accuracy requirements established by AASHTO. Additional data was collected from inclinometer, inertial profiler, rod and level, and 3D laser scanning tests to further evaluate the accuracy and repeatability of the instruments. The goal of the study was to establish a certification test site, determine the repeatability and accuracy of the inclinometer, and develop procedures and guidelines for inclinometer based certification.

The current practices of ODOT are analyzed in this study and compared to those from other states. Included in this report are comments and suggestions for the certification procedure. Particularly, the establishment of a reference profile is critical to the certification procedures. Therefore, suggestions for this procedure are included. Current practices and procedures from other states are also included for comparison of QA procedures.

1.1 PROBLEM STATEMENT

ODOT will be implementing an International Roughness Index (IRI) based smoothness incentive/disincentive program with an inertial profiler certification and a Quality Assurance program. The development of the program has been based on AASHTO standards, which were based on extensive field studies such as FHWA profiler round-ups. Further studies from FHWA pooled fund benchmark studies continue to improve the standards for reference profiles.

ODOT has a “certification site” and an inclinometer based reference profiler. Guidance is needed to (1) ensure that the inclinometer-based profile provides a reference profile adequate to compare to inertial profilers, (2) verify that the site is appropriate for certification, (3) recommend improvements to the certification procedure, and (4) evaluate the potential of emerging technologies, such as Terrestrial Laser Scanning (TLS) for use in road profiling.

1.2 BACKGROUND AND SIGNIFICANCE OF WORK

ODOT attempted a field calibration process during the (2010) construction season with mixed success. The inertial profiler was successfully certified. However, the process of establishing a reference site within a paving project proved to be difficult for both time and safety. A second approach of establishing a site for inertial profilers for calibration showed promise by providing adequate time to establish the reference profile and to ensure better quality control. The site itself (Figure 1.1) is located on Century Drive in Albany, Oregon. The site is a low-traffic frontage road and has reduced safety concerns, as it is not located on a busy interstate highway with a high volume of fast moving vehicles. The inertial profiler that was certified at this site was able to show good repeatability, but could not meet the AASHTO accuracy criteria. Once testing guidelines are developed from this research, all contractors would be required to certify their systems at this site prior to performing work in Oregon.

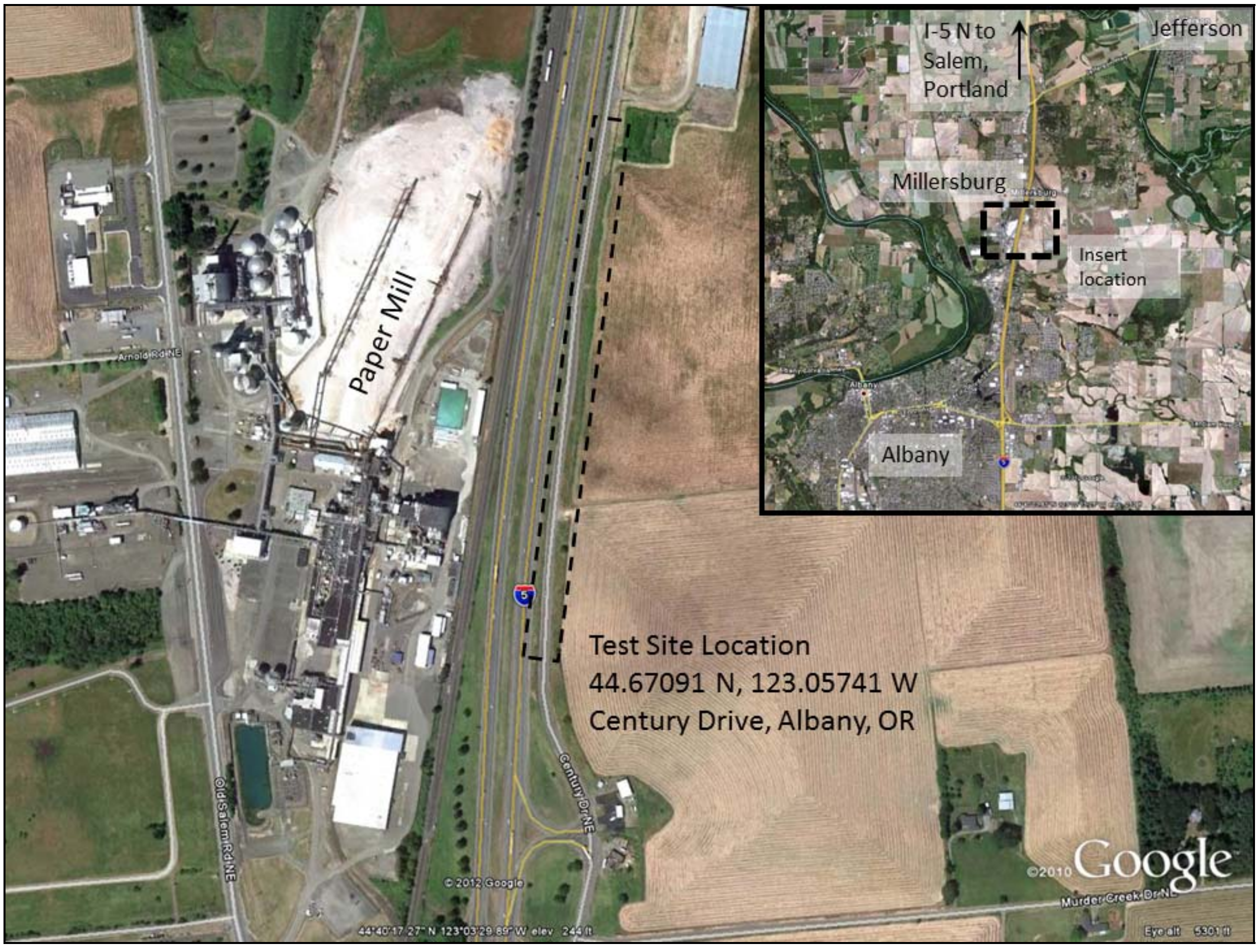


Figure 1.1: Certification site map.

The parameters and observations from this research provide the baseline standards for all inertial profilers used to evaluate pavement smoothness throughout Oregon. These standards will allow ODOT to ensure all inertial profilers, when operated according to manufacturer's guidelines, are able to provide accurate and repeatable smoothness assessments. The parameters will also help establish quality assurance tolerances to ensure an inertial profiler is continuing to report acceptable smoothness measurements on project sites.

Benefits of this research and certification program development to ODOT include: increased pavement life, accuracy of incentive and disincentive payments and defending against inaccuracies in incentive payments. Further, value has been found to the public from smooth pavements in the form of reduced wear on vehicles and fuel savings. A recent report by the National Center for Asphalt Technology (NCAT) (Jackson, et al. 2011) indicates that improvements to pavement smoothness can result in a 2-6% improvement in driver fuel efficiency.

1.3 OBJECTIVES OF THE STUDY

The overarching objective of this study is to provide ODOT with a certification site and methodology necessary to certify contractors performing smoothness measurements using inertial and inclinometer based profilers. More specifically, this research aims to:

- Establish an appropriate test site for profiler certification,
- Determine the repeatability and accuracy of the reference profiler,
- Develop the procedures/guidelines for an inclinometer based profiler certification, and
- Evaluate the effectiveness of new techniques such as TLS for road quality assessment.

2.0 LITERATURE REVIEW

Pavement smoothness is often the principal focus of the public perception of road quality; hence it is an important consideration for roadway construction acceptance. The Transtec Group (*2008*) discusses several benefits of smooth roads, including:

- Less maintenance, which reduces costs,
- Less dynamic loading compared to a rough surface,
- Structurally sound and increased durability, and
- Safer for drivers.

Many states now offer incentive/disincentive programs for smooth pavements. Requirements for these incentive/disincentive payouts are based upon measured smoothness indices (*The Transtec Group 2008*). Different states have diverse ways of determining the pavement smoothness, but the two most common indices are the Profile Index (PrI or PI) and International Roughness Index (IRI).

This document will discuss potential data acquisition systems for acquiring profile data and methodologies to evaluate this data to determine pavement surface characteristics.

2.1 PROFILE MEASUREMENT

The smoothness of a roadway can be described numerically using various smoothness indices. The two most common indices are the International Roughness Index (IRI) and Profile or Profilograph Index (PI or PrI). IRI and PI are obtained from a profile trace and determined using an algorithm that calculates a measure of smoothness (*The Transtec Group 2008*). Each index is shown in units of in/mi or m/km. PrI can either be obtained from Profilograph simulation based on profile traces or reduced from physical Profilograph traces. The roughness index provides an indication of the quality of the pavement; corresponding to different levels of roughness for IRI values are shown in Figure. This report will focus on IRI, as this is the focus of the Oregon Department of Transportation (ODOT) to transition to IRI.

Cross correlation is used in the comparison of road profiles. The accuracy and repeatability of profiling instruments are measured off of the cross correlation. This value provides more insight on the agreement between profiles than an IRI comparison (*S. M. Karamihas 2005*).

2.1.1 IRI – International Roughness Index

The IRI model can be implemented to evaluate the roughness of both new and existing pavement sections along a profile, and can be determined using measurements from a variety of devices. The IRI is more specifically defined as the average rectified slope referenced to a standard quarter car model travelling at 50 mph (80 km/h) (A*STM 2008*). The algorithm to compute IRI contains a moving average filter, quarter car filter, and the length of the section (*Sayers and Karamihas 1998*). The following are important considerations for calculating the IRI index:

- The profile data must be filtered to eliminate inaccuracies (*Sayers and Karamihas 1998*).
- The moving average filter applies a low pass filter of 9.85 in (250 mm) to smooth the profile by using the average values of adjacent points to emulate the tire enveloping effect.
- The IRI algorithm is based on the quarter-car model, which includes one quarter of the car and the mass supported by one tire; this is sometimes referred to as the "Golden Car".
- The IRI takes into account the length of the section measured, this puts the IRI in units of slope (*Sayers and Karamihas 1998*).
- The localized roughness is displayed separately since rough sections will be averaged out if a long length is used in reporting IRI. Localized roughness is any 25 ft (7.62 m) segment that contains IRI values that disproportionately affect the overall IRI (*AASHTO-R54-10 2010*).
- The IRI is sensitive to wavelengths from 4-98 ft (1.2-30 m) (*S. M. Karamihas 2005*).

Typical IRI ranges are shown in Figure 2.1 from the Little Book of Profiling:

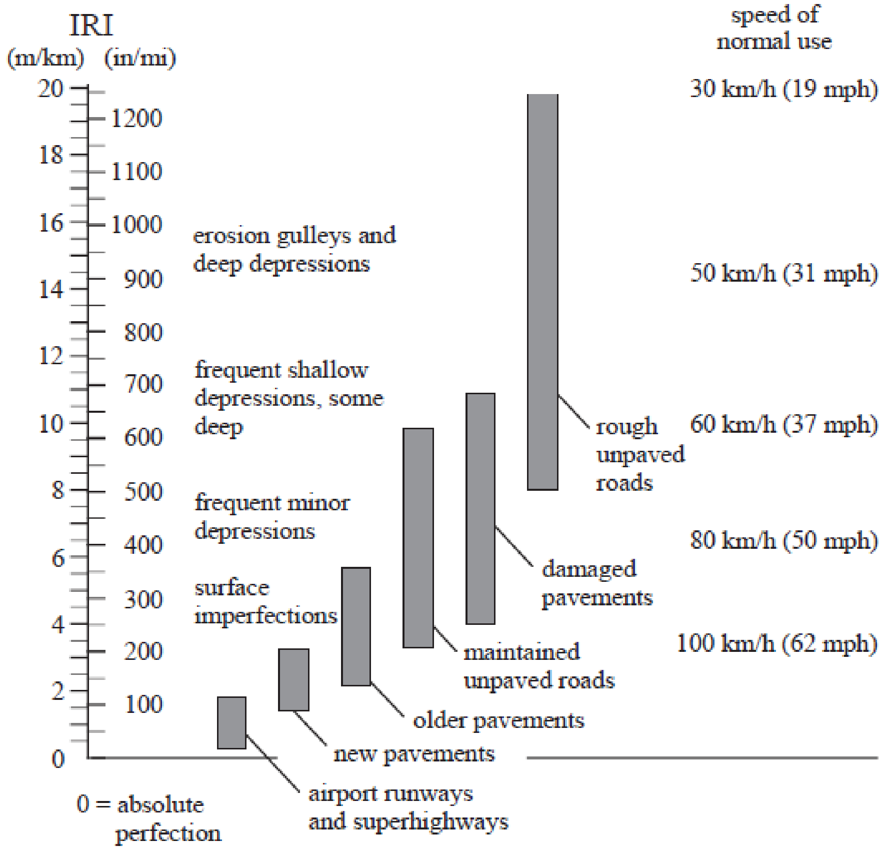


Figure 2.1: IRI values and corresponding implications (*Sayers and Karamihas 1998*)

States have different requirements for the respective incentive/disincentive programs based upon the IRI values determined for pavement sections. Data can be filtered using the freely available *ProVAL* software (www.RoadProfile.com). A high-pass filter can be used to restrict the wavelengths used in the IRI calculation or a low pass filter could be used to smooth the data (S. M. Karamihas 2005). A high pass filter can eliminate the grade in the road, enabling the user to clearly see any deviations in the roadway; this may be done with data from an inertial profiler (*Sayers and Karamihas 1998*). Note that this filter is only applied for viewing the data and is not applied during data comparisons.

2.1.2 Cross Correlation

The cross correlation provides an objective comparison between two profiles. Roughness must be located in the same spot along a profile to obtain a high cross correlation value (*S. M. Karamihas 2004*). This means that although two profiles may have similar IRI results, the cross correlation may not be high. Cross correlation values are used in many state specifications to determine the accuracy and repeatability of the inertial profiler compared to a reference profile.

The cross correlation between a reference profile and the measured profile will provide a better analysis on the agreement between the two profiles than the IRI values alone (*S. M. Karamihas 2005*). Two profiles with a high cross correlation have both the same shape and level of roughness. The roughness must occur in the same locations to achieve a high cross correlation. The cross correlation is calculated as the integral of the product of the two signals (P and Q) and includes the offset distance (*S. M. Karamihas 2004*).

$$CC = \frac{\min(\sigma_P, \sigma_Q)}{\max(\sigma_P, \sigma_Q)} \frac{1}{\sigma_P \sigma_Q} \sum_{i=1}^{N} \hat{P}_i \hat{Q}_{i+\delta/\Delta x}$$

(2-1)

where:

σ_P and σ_Q are the standard deviations of the two profiles,

N is the number of samples,

Δ_x is the sample interval,

δ is the offset value, and

$\hat{P}$ and $\hat{Q}$ are the vertically offset profiles from each device, and

CC is measured from -1 to 1, with 1 being an exact agreement.

The profiles are adjusted vertically so that the mean difference is 0 and the equation is normalized by the standard deviations of the two profiles. Lastly, a scaling factor is applied, which utilizes the minimum and maximum standard deviations of the profiles (*S. M. Karamihas 2004*).

It is important to note the difference between correlation and cross correlation. Commonly, a correlation analysis compares the elevation values of the two profiles and determines how well they agree; however, a cross correlation analysis will compare the incremental slope values and the location at which the roughness occurs. The comparison of elevation is influenced or "masked" by longer wavelength content. In other words, the rating will appear better when evaluating elevation, despite failing in shorter wavelengths, which may be penalized for IRI measurement. Hence, AASHTO R56 requires IRI filtering to remove this mask effect. The shortcomings of elevation comparisons are documented in (*S. M. Karamihas 2005; M. W. Sayers 1986; Robson 1979*).

However, because the comparison is based on incremental slope rather than exact elevation, relative (incremental) accuracy is more critical than network (overall) accuracy. Figure 2.2 shows a comparison of elevation profiles from inclinometer-based profiles in June 2011 and June 2012. Note that there is significant deviation in the elevation profiles due to drift (the loop was not closed for the June 2011 survey). However, comparison of incremental slope values shows excellent agreement, resulting in a cross correlation of 92.2%. The correlation between the elevation values, however, would be 99.9% despite a very large, average elevation disagreement of 1.2 in (maximum disagreement of 2.5 in). Ideally, the elevation values, when plotted against each other (Figure 2.3), would fit a 1:1 line. However, these profiles show a trend of 0.93 in/in.

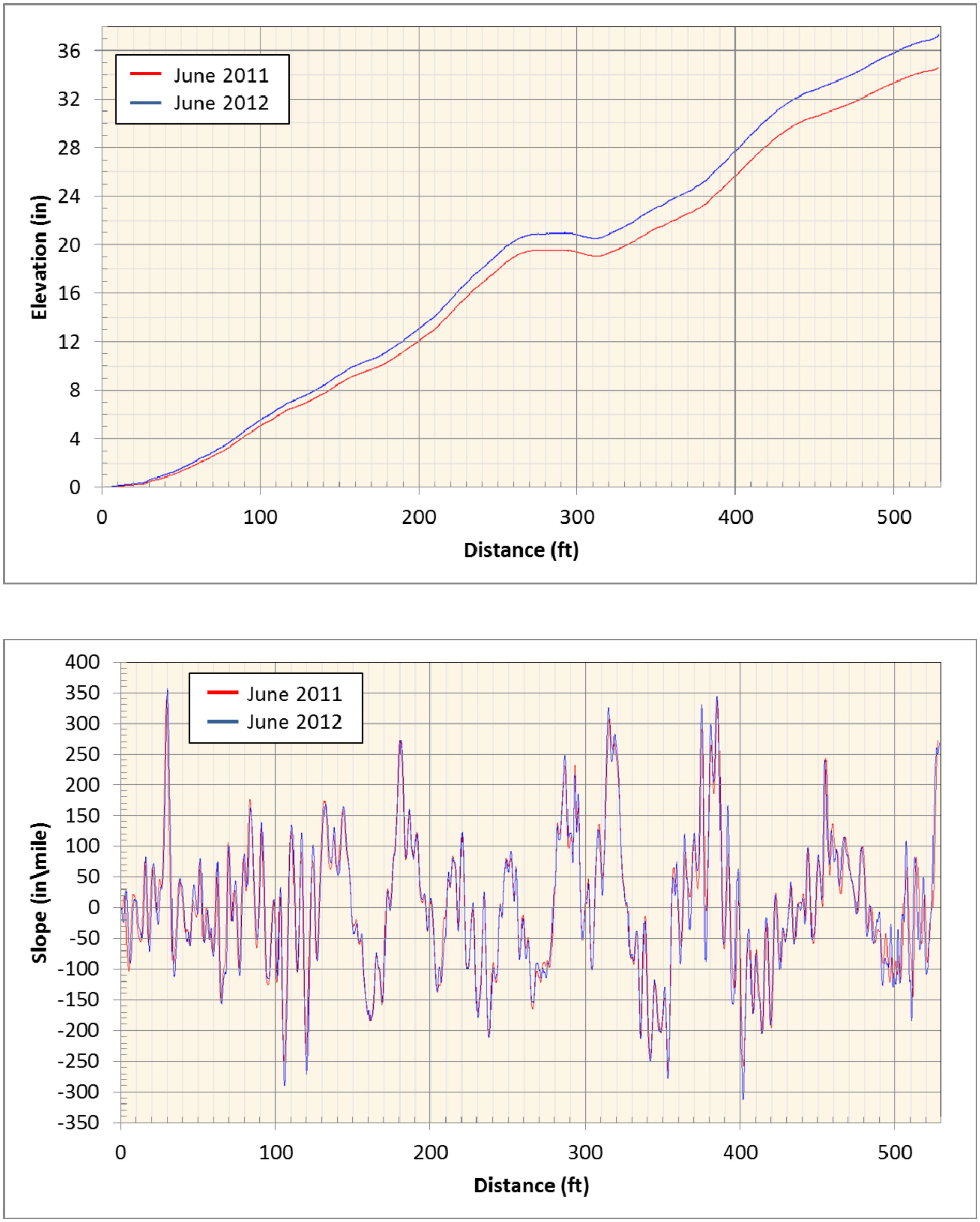


Figure 2.2: Comparison of (a) Elevation and (b) Slope between a June 2011 and June 2012 inclinometer-based profile.

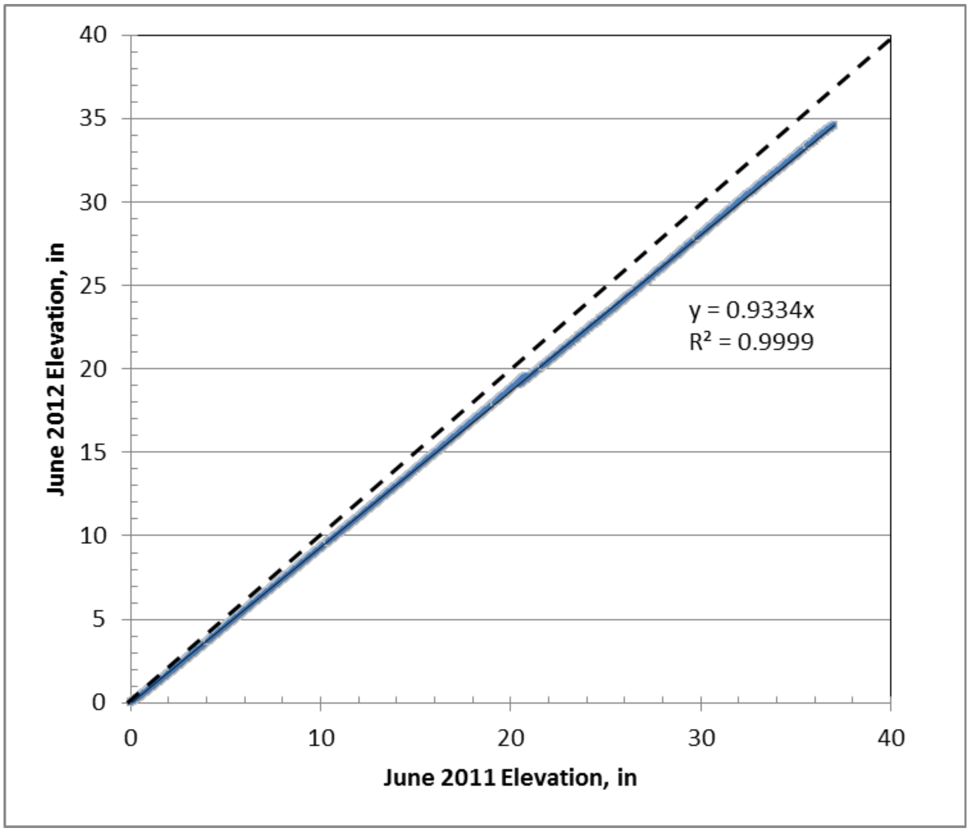


Figure 2.3: Elevation values from June 2011 and June 2012 plotted against one another and a 1:1 line (dashed line).

2.1.3 ProVAL Software

The Profile Viewing and Analysis (*ProVAL*) software analyzes data collected from several types of instrumentation, including inertial profilers. The US Department of Transportation (US DOT) Federal Highway Administration (FHWA) and the Long Term Pavement Performance Program (LTPP) sponsored the development of *ProVAL* (The Transtec Group 2011). The software performs a variety of analyses, some of which include determining the IRI, localized roughness, cross correlation, and profiler certification. *ProVAL* allows two profiles to be compared both visually and quantitatively. The cross correlation between two profiles can be determined, which is useful in examining the accuracy of the instrumentation when compared to a reference profile. It also enables determination of the repeatability by comparing multiple runs with the same instrument.

The program creates a standard file type which enables simplified data sharing and transfer. A variety of file types can be imported into the program (The Transtec Group 2011). This study uses the ERD file format, which was created by the University of Michigan Transportation Research Institute (UMTRI) Engineering Research Division (ERD). However, it should be noted that ERD is not a standard format; the ASTM E2560 is the only international profile format standard.

2.2 INSTRUMENTATION

Various instruments are available to measure road surface profiles which will show the elevation changes of a road along the horizontal distance; these are summarized in Table. These profiles are necessary for pavement smoothness evaluation. Some instruments are specifically designed to be used immediately after construction, before the road has been opened to traffic, while others can be implemented at any time, including when the road is open to traffic.

These instruments should be calibrated and operated according to the proper manufacturer procedures. Note that the testing speed of the rod and level in Table 2.1 is the speed for the measurement of one wheel path and includes the set up time. With additional field crew, both paths can be acquired simultaneously. The testing speed for the TLS also includes the set up time.

Table 2.1: Comparison of instrumentation used to evaluate pavement smoothness

Instrument	Testing Speed mph (km/hr)	Road Closure Needed	Individual Measurement Accuracy	Wheel Paths Measured
Rod and Level	0.006 (0.01)	Yes	<0.04 in (<1mm)	One
Inclinometer	2.5 (4)	Yes	± 0.08 in/164 ft (2mm/50 m)	One
Profilograph	1.9-3.1 (3-5)	Yes	-	One
Inertial Profiler	50 (80)	No	-	Both
Terrestrial Laser Scanning (TLS)	~0.02 (0.04)	No	±0.2 in/ 164 ft (5 mm/50m)	Both
Mobile Laser Scanning	<= 50 (80)	No	-	Both

2.2.1 Rod and Level

A traditional rod and level survey provides a highly accurate (sub-millimeter) profile of the roadway, often termed the “true profile” because it can provide calibration for other systems. Standards for this type of survey are found in ASTM E 1364-95. The level provides the elevation for the road, while the height is determined by the rod reading relative to the reference elevation (*Sayers and Karamihas 1998*).

Distance measurements are also recorded for each rod reading. Setting the height measurements along the measured distance will produce a profile for the road section. Readings must be obtained at a maximum distance of 1 ft (0.3 m) between readings along the length of the test section (*Sayers and Karamihas 1998*). The data collected does not provide a thorough assessment of the roadway if readings are taken at more than 1 ft (0.3 m) intervals (*S. M. Karamihas 2005*). While this method produces accurate data, the manual measurements are time consuming and require road closures. Since only one wheel path may be measured at a time, further increasing the total time, there are increased safety concerns for this type of survey.

Typical surveying equipment used does not have the required accuracy needed for this process which adds additional costs for equipment since high accuracy digital levels are required (*S. M. Karamihas 2005*).

2.2.2 Inclinometer-based profilers

An inclinometer-based profiler, also called a “walking profiler” is a hand operated instrument (Figure 2.1) mounted on a rigid beam up to 12 in (0.3 m) in length to measure the road profile (Hays 2006). The profile is created by measuring the beam inclination, which progresses along the length of the pavement section in steps that are the length of the beam (*Hays 2006*). Both the distance and the elevation are recorded at each step in order to create the profile. The sampling distance of the SurPRO 3500 unit used by ODOT can range from 0.25-12 in (0.64-30.5 cm) (*SurPRO 2011*).

An inclinometer-based profiler is faster than a rod and level survey since it can be operated at speeds up to 2.5 mi/hr (4 km/hr) (SurPRO 2011). However, this method also requires road closure, and although faster than a rod and level, is still a time consuming process with concern for the safety of the workers.

Figure 2.1: SurPRO inclinometer-based profiler operated by ODOT

2.2.3 Profilograph

A profilograph travels at very slow speeds of 2-3 mi/hr (3-5 km/hr), requiring protection from traffic (*Blair and Tam 2009*). The instrument can be up to 33 ft (10 m) in length and consists of a 25 ft (7.6 m) truss and between 4-12 wheels (*Smith et al. 1997*). Only one wheel path may be measured at a time; hence, it is a very time consuming process. The extended time required for the operator on the road generates safety concerns. A wheel is located at the midpoint of the truss system and linked to a recorder. The distance between the pavement at the wheel and the datum established by the other wheels on the system is recorded on a paper strip chart with a scale of 25 ft/in (0.3 m/mm) on the horizontal (*Smith et al. 1997*). The wavelength limits of a profilograph are 1-75.5 ft (0.3-23 m) which creates a biased profile. The profilograph will amplify the data collected based upon the length travelled. Although not required, in some states measurements are viewed with a blanking band to determine the PI values. Use of the blanking band to determine PI will result in an incomplete observation of the roadway roughness (*FHWA 2002*).

2.2.4 Inertial Profiler

An inertial profiler combines a reference elevation, height relative to the reference and longitudinal distance to determine the road profile (*Sayers and Karamihas 1998*). The inertial profiler consists of a vehicle equipped with several components (*Sayers and Karamihas 1998*):

- A laser transducer to determine the vertical distance between the ground and the accelerometer,
- A distance measuring instrument in the vehicle to provide the longitudinal distance,
- A data acquisition and storage system, and
- An accelerometer to provide the reference elevation (*Lee and Chou 2010*). The accelerometer determines the amount of vertical acceleration occurring in the vehicle while driving over the pavement, which is used to filter the data during analysis (*Dyer and Dyer 2008*).

Figure 2.2: High speed inertial profiler (*Ames Engineering 2010*)

Inertial profilers can be lightweight or high-speed. Lightweight profilers are typically used for evaluating new pavements (The Transtec Group 2008) and must operate at a low speed, which means the road cannot be open to traffic. A high-speed profiler (Figure 2.2) is able to operate at a higher speed and can therefore be used on a road that is open to the traffic.

The equipment must be capable of (AASHTO-M328-10 2010):

- Maintaining a maximum speed of 70 mph (113 km/hr) for high speed, 25 mph (40 km/hr) for lightweight.
- Measuring IRI within the range of 5-300 in/mi for a 0.1 mi (161 m) interval.
- Sampling at every 2.0 in (5.1 cm) or less.
- Outputting the data in an ERD file.
- Calculating roughness indices, especially IRI.

Yi et al. (2009) describe the development of a similar system to an inertial profiler; however, measurements are made using 5 laser range finders in a bisymmetric structure without the need for inertial measurement. In testing, the system determined IRI values within 3% of rod and level measurements.

2.2.5 LiDAR

Light Detection and Ranging (LiDAR) is another form of technology that can be used to determine the road profile. Unlike the previous profiling technologies, LiDAR can measure and map the topographic features across the entire area in addition to determining the elevations along a profile. LiDAR utilizes laser pulses to collect data using a time of flight system (TOF) (*Shan and Toth 2009*). The instrument collects data with a rotating mirror inside the instrument while slowly rotating about the vertical axis. The distance from the laser scanner to an object in view is measured by the amount of time it takes for the laser pulse to hit the object and return to the scanner (*Shan and Toth 2009*). Systems can read multiple returns for each pulse but generally the first and last return pulses are measured (*Vosselman and Maas 2010*). LiDAR data creates a 3-Dimensional model of the area and objects scanned; the data is shown as a 3D point cloud (Figure 2.3).

Because of the density of data collected, LiDAR requires substantial computing resources and specialized software to process data efficiently. LiDAR data can be collected from three different platforms: airborne, static terrestrial, or mobile.

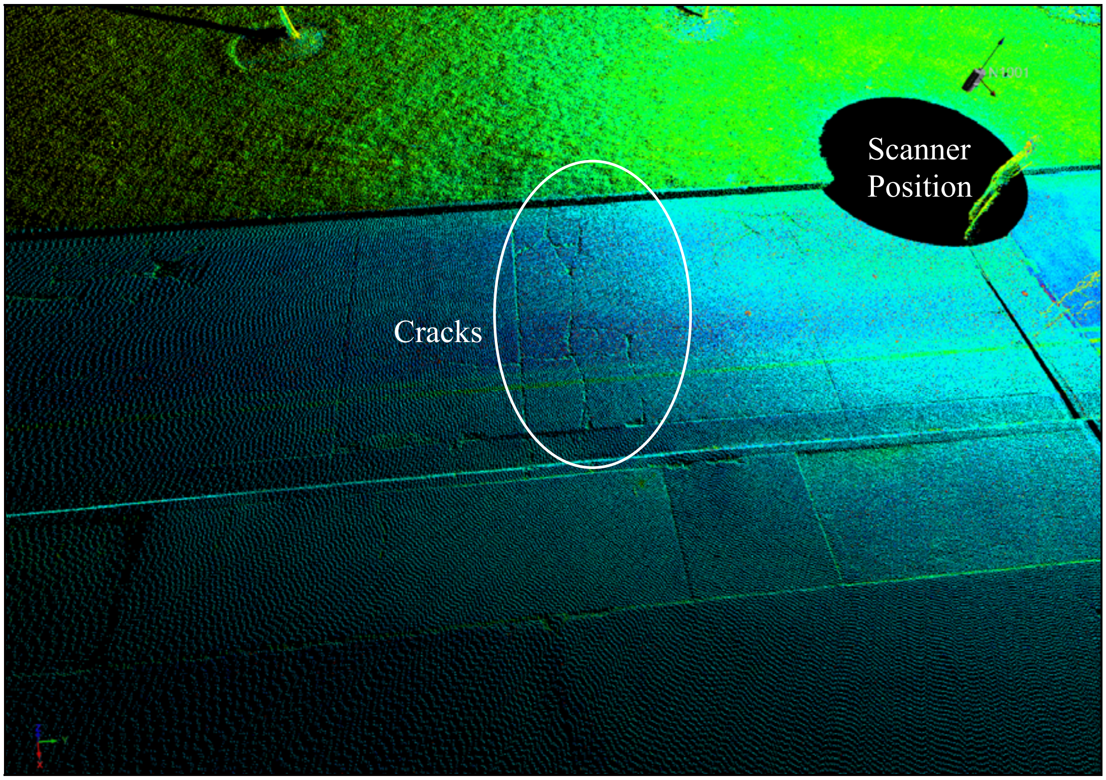


Figure 2.3: 3D point cloud from terrestrial laser scanner.
Note the decreasing sample density with distance from the scanner origin.

2.2.5.1 Terrestrial

Terrestrial laser scanners, Figure 2.4, are mounted on a tripod so data can be acquired from the side of the road. Multiple positions are usually required to fill in occlusions. Geo-referencing of the scan data is accomplished through reflective targets setup over control points or through a Global Positioning System (GPS) mounted on top of the scanner. A camera is also mounted or integrated into the system to obtain calibrated images with RGB color, corresponding to each scan position. Terrestrial laser scanning is ideal for creating 3D models of buildings and topography.

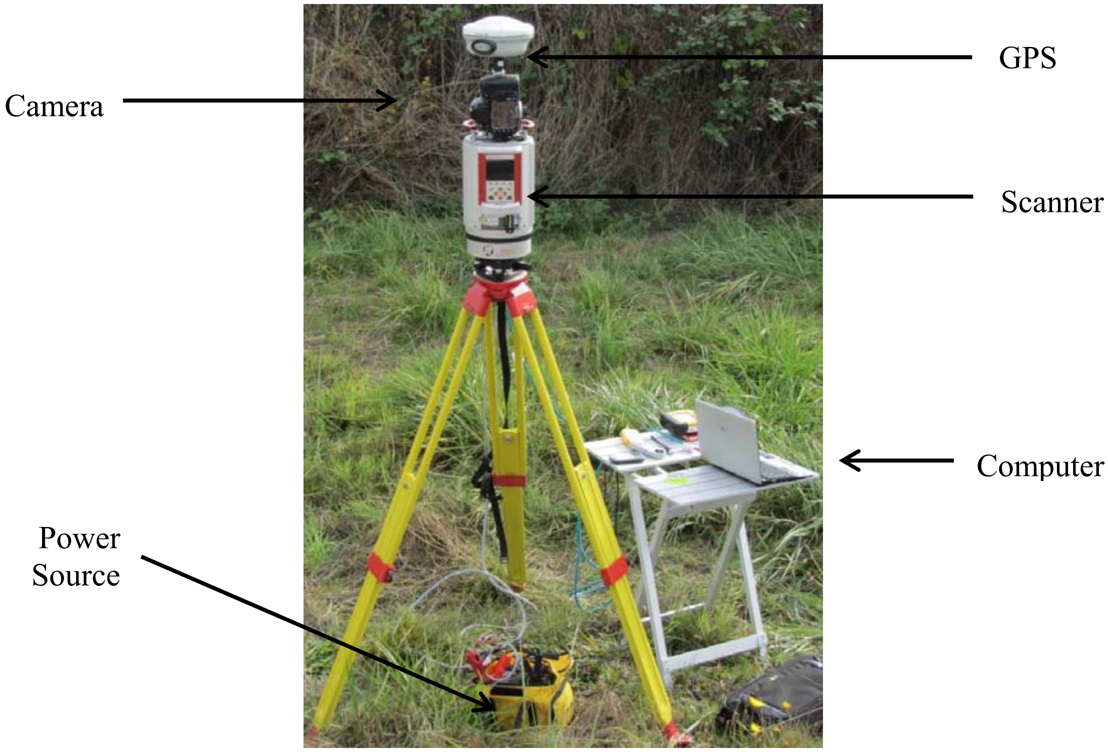


Figure 2.4: Terrestrial laser scanning system

There are a variety of scan systems on the market. Some are focused on short range applications while others are built for long range applications. An approximate maximum range for current terrestrial scanners is 820-3280 ft (250-1000 m) with nominal accuracies typically between 0.2-0.4 in (5-10 mm) (*Vosselman and Maas 2010*). However, actual accuracies will vary depending on scanning geometry, environmental conditions, and the materials to be scanned. Figure 2.5 shows how the resolution of TLS degrades with distance on flat surfaces because it scans on an angular increment.

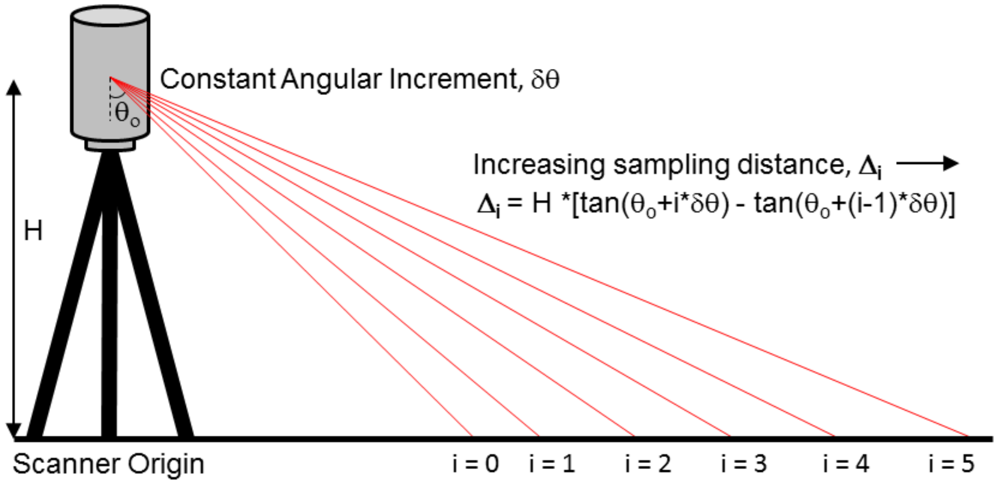


Figure 2.5: Effects of angle of incidence for LiDAR (*modified from Olsen et al. 2012, In press*)

2.2.5.2 *Airborne*

Airborne, or aerial, laser scanning enables a large area to be covered in a short amount of time, usually from a helicopter or fixed wing aircraft (*Vosselman and Maas 2010*). The systems can be used for topographic mapping as well as bathymetry (Shan and Toth 2009). Both GPS and an Inertial Measurement Unit (IMU) are used with the laser scanner to collect the position and orientation of the airplane during scanning. Cameras can also be used to collect images of the area. Data must be collected using parallel flight lines flown with enough overlap between lines to cover the entire area and ensure that there are no data gaps (Vosselman and Maas 2010). Generally, most available airborne LiDAR data would not be accurate and dense enough for evaluating pavement smoothness, unless obtained from a low flying helicopter. Logistics can also be difficult for obtaining airborne LIDAR.

2.2.5.3 *Mobile*

Mobile laser scanners are similar to terrestrial; however, instead of being mounted on a tripod the system is mounted to a moving vehicle, enabling faster data collection. Figure 2.6 shows the mobile scan system operated by ODOT.

Figure 2.6: Oregon DOT's mobile laser scanner

Data is obtained by moving the vehicle along the specified path and operating the scanner in a 2D (line) profile mode (Vosselman and Maas 2010). A 3D point cloud is generated by integrating measurements from the scanner, GPS receivers and IMU along the driven pathway (Vosselman and Maas 2010). An odometer can also provide improved positioning information on some mobile scan systems. Mobile mapping systems are ideal for rapid, 3D mapping of long sections of roadways. Further, the system operated by ODOT is an asset-management grade system, which does not meet requirements for use in profiling applications. However, there are systems that are being developed that show promise for providing scan data of sufficient accuracy for road profiling. For example, Yu et al. (2006) describe a multi-sensory mobile mapping system collecting high resolution data to create surface models for analyzing cracks.

2.2.5.4 Using LiDAR to Determine IRI

Some research has already been done to investigate the use of LiDAR for measuring pavement roughness. Chang *et al.* (2006) performed tests to compare the use of 3D laser scanning, Multiple Laser Profiler (MLP), and rod and level surveys (*2006*). Three test sections, each 100 m in length with varying levels of roughness were used. The results of this study are briefly described in this section.

The nominal accuracy of the laser scanner used was 3 mm at 50 m range. The scanner was able to collect data up to a distance of 100 m; however, it was observed that the density of the point cloud was reduced past 50 m due to a poor angle of incidence (Figure 2.5).

For this study, two scan set ups were used to collect data over each 100 m section. The MLP collected data on multiple paths with 500 mm spacing between the paths. To check for any variability within the measurements, 5 test runs were performed.

Comparison of the data showed that the use of LiDAR accurately measured the IRI values of the roadways. A statistical test between the rod and level survey and laser scanning showed a 95% correlation between the measured elevation values. A coefficient of correlation of 99% was calculated between the laser scanning and MLP data. The conclusion of the Chang et al. (*2006*) study indicate that terrestrial laser scanning is able to be used as an effective tool for measuring road roughness. However, note that the Chang et al. (*2006*) study did not evaluate cross correlation (See section 2.1.2), which is based on slope rather than elevation. Current road profiling requirements are based on slope cross correlations rather than elevation correlations.

2.2.5.5 Other Relevant Uses of LiDAR

TLS data have the ability to be used in many transportation applications aside from roughness. Jaselskis et al. (2005) present a case study showing benefits of LiDAR for several aspects of construction including elevation, smoothness, camber, and volumetric measurements. Safety, time and economic considerations compared to traditional photogrammetric techniques were also discussed. Researchers examined the use of TLS on road construction applications to determine the earthwork quantities (Slattery *et al*. In Press). For this study, scan data were used to create traditional cross sections to determine earthwork quantities. TLS is advantageous since all cross sections can be obtained anywhere along the road construction site and not just at specified locations.

A recent case study (Johnson and Johnson, In Press) was focused on the use of TLS for highway applications. The study examined the best practices for the use of TLS based upon the quality of the data collected using various techniques. The cross slopes were calculated using the elevations at the edge of the travel lanes from the TLS data and compared to data collected from a total station and GPS. Testing determined that a higher point density resulted in a lower vertical root mean square error. The cross slope root mean square errors increased for points collected beyond a 150 ft range from the scanner (Johnson and Johnson In Press).

2.2.6 Comparisons

(*S. Karamihas 2011*) performed a study testing several profiler devices including Rod and Level, Dipstick, Inertial Profiler, and an inclinometer-based profiler. The inclinometer-based profiler showed generally the highest accuracies and repeatabilities of the devices, particularly at shorter wavebands. This study also evaluated the ability to measure profiles on a variety of asphalt (dense-graded, pervious hot mix asphalt, and chip seal) and concrete (transverse tining, longitudinal tining, and with diamond grinding) surfaces.

2.3 EXISTING GUIDELINES

Existing guidelines provide specifications to calibrate, check calibration, and operate inertial profilers. These specifications vary between different states, and AASHTO. Information on calibration of inertial profilers is summarized in Table 2.1 and Table 2.2. Three tests are performed to check the vertical and horizontal calibration as well as the measurement system of the inertial profiler. Table 2.3 provides a brief comparison of the specifications for the use of inertial profilers.

Table 2.2: Comparison of specifications to calibrate inertial profilers

Specification	Calibration		
	Vertical	**Horizontal**	**Bounce Test**
AASHTO	Measure 1 and 2 in blocks, accurate to within 0.001 in	Measure 528 ft to within 0.05%	-
TexDOT 1001-S	Measure 1 in thick plate to within 0.001 in	Measure 528 ft to within 1 ft	-
Ohio DOT Supplement 1058	Measure height to within 0.01 in	Measure distance to within 0.1%	Simulate 0.1 mi, measure IRI below 10in/mi

Table 2.3: Comparison of specifications to check calibration of inertial profilers

Specification	Calibration		
	Vertical	**Horizontal**	**Bounce Test**
AASHTO R57-10	Measure 1 and 2 in blocks, accurate to within 0.01 in	Measure 528 ft to within 0.15%	Simulate 0.1 mi, measure IRI below 8 in/mi
TexDOT 1001-S	Measure 1 in thick plate to within 0.01 in	Measure 528 ft to within 2 ft	-
Ohio DOT Supplement 1058	Measure height to within 0.02 in	Measure distance to within 0.2%	Simulate 0.1 mi, measure IRI below 15 in/mi

Table 2.4: Comparison of state and AASHTO specifications for inertial profiler certification (*AASHTO-R56-10 2010; Mn/DOT 2011; ODOT 2009; Wilson 2010; Watkins 2010; ODOT 2011*)

Specification	Accuracy and Repeatability Check	Test Length	Number of Runs	Lead in Distance
Minnesota DOT	Length must be measured to within 0.2%, average IRI must be within 5% of the reference, COV less than or equal to 3%, 90% correlation for the average of the 5 runs	-	6 (select 5 best)	-
Wisconsin DOT	92% repeatability required and 90% accuracy	500ft	5	100 ft
Mississippi DOT	92% repeatability and 90% accuracy	528 ft	10	-
Ohio DOT	Average IRI of five runs should be within 7% or 5 in/mi of the reference, whichever is greater. Within four runs per subsection the IRI must be within 5% of the average for that subsection	-	10 (2 sub-sections)	-
Oregon DOT	90% repeatability required and 88% accuracy	528ft	5	200ft
AASHTO	92% repeatability required and 90% accuracy	528ft	10	-

2.3.1 Testing

Procedures for inertial profiler testing depends upon which set of guidelines are being followed. For example, the minimum test length varies from 528 ft (161 m) (AASHTO and Tex-DOT) to 1056 ft (322 m) (*ASTM*). A longer test segment will result in a lower IRI since the data used to calculate the IRI is averaged over the entire length (*The Transtec Group 2008*). Hence, areas of localized roughness may be overlooked using one IRI value for the entire segment, so IRI is generally reported separately for different sections (*The Transtec Group 2008*).

2.3.2 Calibration Verification and Certification

Prior to use, the systems must be calibrated according to the manufacturer instructions. That calibration must be checked and the profiler must be certified according to state specifications. Procedures for calibration verification and certification vary between states; this document highlights some of the standards. Most calibration verification testing and certification is performed at a test site. However, research has been performed regarding using laboratories to check the system calibration, which eliminates the need for a test site.

During certification, a reference device is used to verify the profiles and roughness index obtained (*S. M. Karamihas 2005*). The agreement between two profiles will provide more pertinent information than agreement between the roughness indices since the roughness index can be altered by a compensating error. Additionally, the profiles will show areas of localized roughness which can be used to determine how errors are occurring. A tolerance for the precision must be used since two profiles will never show complete agreement. It should be noted that the reference device data should be able to be compared with older methods of data collection.

2.3.2.1 Errors

There are many errors associated with profiling. These errors can result from the user, profiler or the road itself. Considerations for error include:

- Road variability – profilers will measure a single cross section on a roadway, but different cross sections will have different profiles.
- Lateral wandering – the longitudinal and lateral position of the profiler may also vary during testing since it is difficult for the operator to follow a straight line (Sayers and Karamihas 1998).
- Starting point – drivers often have difficulty determining the exact starting location on the test.
- Variable speed – drivers may be unable to keep a consistent speed (Lee and Chou 2010).
- Section length – the operator will generally drive very long segments of roadway during testing, compared to the relatively short calibration section.

In order to eliminate these errors from the profiler, the entire system must be checked and certified prior to use. The operator has to be certified prior to any testing. For repeatable results the same line on the roadway should be used during calibration checks and certification tests.

2.3.2.2 Lab Calibration Verification

Testing has been done to investigate the calibration verification of a profiler using a surface with a known roughness inside of a laboratory. A laboratory is a more ideal place to perform tests since it is difficult to check for accuracy and repeatability using a test section, where one must rely on the driver to remain on the exact same path for each test run (*Lee and Chou 2010*). Lee and Chou (*2010*) performed laboratory tests in order to eliminate operator errors such as lateral wandering and speed discrepancies. The study simulated a roadway and was able to test the inertial profiler system using a consistent wheel path and speed. Vibrations were applied to the front axle first then both the front and rear axles. Since the vibrations applied were known, they were able to be compared with values measured in the system. The testing was successful in showing that calibration verification can be performed in a lab setting. Various combinations of frequency (1 Hz – 8 Hz) and amplitude (1 mm – 3mm) were used to simulate different IRI values. Testing combinations such as 5 Hz and 3 mm, or 8 Hz and 2 mm, produce poor results. Therefore, the study recommends maintaining a combination for an IRI less than 5.5 m/km (*Lee and Chou 2010*).

Schwartz *et al*. (*2002*) also performed testing to determine if calibration of an inertial profiler system could be verified in the laboratory instead of on a test roadway section. Tests were performed using a simulated pavement to eliminate user and road errors. The resulting profiles were then compared to the actual roughness of the simulated surface. Because the tests were performed using a variety of frequencies and amplitudes, the results showed that very high and very low frequency values did not provide valid results, similar to the tests performed by Lee and Chou (*2010*). The best results were obtained from frequencies ranging from 3.2-7.5 Hz with accelerations of 0.1 g, 0.45 g, and 0.8 g, and poor results were collected at frequencies outside of the 1.6-12.8 Hz range. Comparable IRI values were computed with the acceptable frequencies and were in agreement with the simulated road surface profile. The testing showed that the calibration checks of an inertial profiler can be done in a laboratory instead of outside on a test roadway section. The testing produced reliable results for IRI less than 10 in/mi to 1000 in/mi (*Schwartz et al. 2002*). Currently, however, no state in the US allows a lab test for determining profiler repeatability and accuracy.

2.3.3 ODOT TM 772

Current specifications used by the Oregon Department of Transportation (ODOT) for examining road roughness are found in ODOT TM 772, “Determining the International Roughness Index with an Inertial Laser Profiler” (*2011*). Included in the document are methods and requirements for performing calibration checks and certification. The required resolution of the profilers is 0.001 in and readings must be taken at a maximum of 2 in apart. Calibrations should be completed according to manufacturer instructions.

The following is required to check the calibration of the inertial profiler:

- A vertical calibration check must be completed measuring a smooth base plate, 0.25 in, 0.50 in, and 1.00 in block. For each block one reading should be obtained on the base plate and one on the block, the thickness of the blocks must be measured within 0.01 in of the actual thickness.
- A horizontal check must be performed over a distance of 528 ft three times. The average of the three runs must be within 1 ft of 528 ft.
- A bounce test must be performed. First, the vehicle must be kept stationary for the amount of time it would take to travel 0.15 mi and the IRI reading should be less than 3.0 in/mi. Next, the vehicle moved vertically 2 in to create a bounce; this should be done for the amount of time it takes to travel 0.10 mi. The IRI reading must be less than 8.0 in/mi.

The inertial profiler calibration must be checked prior to starting testing. To do this the profiler must be run over a 528 ft section two times and the IRI between consecutive runs should be within 4.0 in/mi.

The following is needed for quality control:

- The lead-in and lead-out distances recommended by the manufacturer should be used; these must be a minimum of 200 ft.

- The data should be recorded at a maximum of 2.0 in intervals
- The horizontal distance should be measured within 1% or 53 ft/mi.

As a quality assurance the IRI of three 0.10 mi sections must be measured by the contractor and the QA vehicle for the left or right wheel path. The two instruments should have an IRI reading within 8.0 in/mi of each other using the two profiles with the best agreement.

2.3.4 ODOT TM 769

The Oregon DOT specification for certification of inertial profilers is listed under ODOT TM 769 (*2011*). Prior to certification the calibration of the instrument must be verified. The calibration verification includes:

- Testing of the distance measurement instrument (DMI) requires three 1000 ft runs. The average of the three absolute differences and the 1000 ft section can be no greater than 1.0 ft.
- A bounce test with a vertical displacement movement of 1 in to 2 in continued to simulate 528 ft of travel as well as a static test. The IRI for the static test must be less than 3 in/mi and 8.0 in/mi for the bounce portion.
- To test the vertical height measurements measure three blocks measuring 0.25 in, 0.50 in, and 1.00 in as well as a smooth baseplate. A reading is taken of the baseplate and the height of the block. The average of the absolute difference between the measured and known thickness can be no greater than 0.01 in.

The certification procedures require:

- Five runs must be completed over the 528 ft test site.
- Data must be recorded at intervals less than or equal to 2.00 in.
- The repeatability must be 90% and the accuracy must be 88%.

2.3.5 ASTM E 1364-95

The “Standard Test Method for Measuring Road Roughness by Static Level Method”, ASTM E 1364-95 (*2005*), reviews the requirements for a rod and level survey to obtain the profile of a test site. Generally, this procedure is too time consuming for practical implementation on new roadways; however, it can be used for calibration of inertial or inclinometer based systems. It also requires high-precision, digital levels.

In order to complete the testing the following is required:

- A minimum of two persons; one to hold the rod and one to operate the instrument. However, a third person is ideal to record the data if the level is incapable of data storage.
- A steel tape that is accurate to within 2% of the total length should be used to measure the length of the test section.

- A marking should be made at every 1 ft (0.3 m) using the steel tape.

During the rod and level survey, the surveyor should implement and/or consider the following:

- The instrument must be set up on the wheel path.
- A reading must be taken at least every 1 ft (0.3 m) and should be recorded both in the instrument and on standardized field forms.
- The field notes should indicate when an instrument has been moved and that the measurements were repeated. Each time the instrument is moved, the new height should be measured and the rod should be kept in the same location so that location can be measured again. Comparison of the two measurements from the different setups will help ensure that the resolution requirements are met.
- In order to maintain the required resolution for the survey, measurements should be checked at several locations throughout the survey.

Following the field data collection, the IRI value is calculated and compared to the filtered data obtained from an inertial profiler. The resolution of a rod and level survey can be impacted by the distance between the rod and level, wind fluctuations, and the surface texture. The lower the instrument is to the ground the more the errors will be minimized; the height of the instrument should be measured and recorded.

There are two classes (1 and 2) of accuracy obtained from IRI values:

- Class 1:
    - Measurement error of less than 2%
    - Minimum measurement resolution required is 0.005 in (0.127 mm).
- Class 2:
    - Measurement error of less than 5%
    - Minimum measurement resolution required for Class 2 is 0.01 in (0.254 mm).

Class 1 is generally used in inertial profiling calibration.

2.3.6 ASTM E 950

The “Standard Test Method for Measuring the Longitudinal Profile of Traveled Surfaces with an Accelerometer Established Inertial Profiling Reference” (*ASTM-E-950 2009*) provides requirements for the testing and equipment set up.

The following should be noted for testing equipment:

- The testing equipment is capable of computing recording and measuring the profile of the road surface.

- The profilers must also have three separate transducers to obtain (1) the vertical acceleration, (2) the height between the accelerometer and the ground, and (3) the longitudinal distance.
- Each of the transducers must be calibrated prior to use.
- Since two wheel paths are to be measured at once, the displacement transducers must be mounted at 5-6 ft (1.5-1.8 m) spacing.
- A lead in section of 492 ft (150 m) is required and the testing length must be 1056 ft (320 m) with markings every 1 ft (0.3 m).

During testing the following is required:

- The test section must be marked at the start, end, and intermediate locations.
- The start and end locations must have the ability to be automatically detected by profiling equipment.
- The speed during testing must be a minimum of 15.5 mph (25 km/h); however, exceptions are made for very rough roadways where the speed may be as low as 5 mph (2 m/s).
- Ten repeat measurements are required to insure accuracy and repeatability.

Two methods may be used to determine the IRI: (1) the spatial based method is dependent only upon the distance traveled by the vehicle while the (2) time based method is dependent upon the speed of the vehicle. ASTM E 950 is currently being modified to become compatible with AASHTO R56.

2.3.7 AASHTO R 56-10

AASHTO provides standards for the "Certification of Inertial Profiling Systems" in specification R 56-10 (*2010*). These standards suggest three test sections: (1) smooth section, IRI 30-75 in/mi, (2) medium smooth section, IRI 95-135 in/mi, and (3) medium rough (distressed) section, IRI up to 200 in/mi.

The following should be implemented during the certification process:

- A 528 ft test section should be used that contains minimal horizontal curvature and no significant grade or grade change.
- Ten repeat runs should be completed, 5 at maximum speed and 5 at the minimum speed.
- A 90% or greater cross correlation is required for accuracy.
- A 92% agreement is required for repeatability and IRI values must be have a 95% confidence level.

The following steps must be taken to properly cross correlate the data:

- Remove any gradation from the reference profile with a high pass filter that is set at least 3 times the longest wavelength. Apply the filter to all traces involved in the cross correlation. Apply the IRI filter at this time as well.
- Cross correlate the profiles by shifting one profile up to 3 ft in either direction, always shift the candidate profile if it is being compared to the reference.
- The cross correlation value is the best possible value determined from shifting over the 6 ft range.

2.3.8 AASHTO R 57-10

AASHTO R-57-10 reviews the standards for "Operating Inertial Profiling Systems" (*2010*). The procedures for verifying calibration are:

- Measure the length of the test section (528 ft minimum) to within 0.15%
- Perform a block test to the manufacturer instructions by measuring the height of a smooth base plate, 0.25 in, 0.50 in, 1.00 in, and 2.00 in blocks. The minimum requirements are to test the base plate, 1.00 in, and 2.00 in blocks. The blocks and plate must be measure in three different positions on each site. The average of the absolute difference between the measured and known thickness must be less than or equal to 0.01 in.
- Perform a bounce test by measuring the profile for 828 ft of static motion, 528 ft of 1 in to 2 in vertical motion followed by 828 ft of static motion. Using the first and last 300 ft as lead in and lead out distances, the IRI from the static portion must be less than 3.0 in/mi and 8.0 in/mi for the bounce portion.

The standards also review the requirements at a control section. This site consists of a 0.1 mi section having an IRI less than 120 in/mi. The site must have a consistent profile over a certain time period to allow for daily checks. An inertial profiler that has been certified within the previous 90 days may be used to determine the IRI at the site. The average value from a minimum of five runs may be used as the IRI of the control section. However, the cross correlation must be 88%. Once the control site IRI has been established it can be used to check inertial profilers, no IRI should differ from the control IRI by more than 5%.

2.3.9 TexDOT 1001-S

Tex 1001-S (*2008*) is the standard for "Operating Inertial Profilers and Evaluating Pavement Profiles" for the state of Texas. The standards are meant for QA testing and when inertial profilers are to be used for QC testing, similar to the AASHTO standards (*2008*). The two standards are also in agreement that re-calibration is not necessary following minor adjustments to the system.

The calibration procedure is as follows:

- The test section should be 528 ft (161 m) in length and must be measured to within 1 ft (0.3 m).

- A 1 in (2.54 cm) thick base plate must be measured to within 0.001 in (0.0254 mm).
- Ten passes should be completed.
- The standard deviation for the ten runs should not exceed 35 mils.
- The standard deviation of the IRI for the ten runs should not exceed 3.0 in/mi.
- The accuracy of the measurements should be checked against those obtained from another instrument such as a rod and level, dipstick or walking profiler. The absolute differences and the differences between the profiles are computed and averaged. The average of the absolute differences should not exceed 60 mils and the average of the differences should not exceed 20 mils.

The specifications to check the calibration of the system include:

- The length of 528 ft (161 m) should be measured to within 2 ft (0.61 m).
- The 1 in (2.54 cm) plate must be measured to within 0.01 in (0.0254 cm).

During testing the following requirements must be met:

- A 200 ft (61 m) lead in length is required.
- The first and last 100 ft (30.5 m) of the roadway should be left out of any measurements.
- The inertial profiler should be operated at a constant speed of at least 12 mph (19 km/hr).
- The system must be able to collect readings at a minimum of every 3 in (7.62 cm) and should be capable of recording automatically at specified locations.

2.3.9.1 Ohio DOT Supplement 1058

The Ohio Department of Transportation Supplement 1058 (2009) “Surface Smoothness Equipment and Operator Requirements” contains specifications for use of inertial profilers.

The specifications for calibration are:

- The inertial profilers must be calibrated each year.
- The distance must be measured to within 0.1%.
- The height must be measured to within 0.01 in (0.0254 cm).
- The bounce test readings should be less than or equal to 10 in/mi for a 0.1 mi (161 m) simulation.

The calibration must also be checked assuring the following:

- The distance must be measured to within 0.2%.

- The height must be measured to within 0.02 in (0.0508 cm).
- The bounce test readings must be less than or equal to 15 in/mi.

Ohio DOT requires the following for certification:

- Two sets of five test runs must be made.
- Four subsections should be created within the ten data sets; each run must be within 5% of the average of the IRI values within each subsection.
- The average IRI of the five runs should be within 6% of the reference value or 5 in/mi or the IRI for the subsection, whichever is greater.

2.3.9.2 Mn/DOT Inertial Profiler Certification Program

The DOT in Minnesota used a SurPRO profiler to establish an inertial profiler certification site (Mn/DOT 2011). The requirements for certification of an inertial profiler are:

- The average IRI of five test runs must be within 5% of the reference value.
- The profile for each run must have at least 85% correlation to the reference.
- The average profile correlation must be at least 90% to the reference.
- The maximum IRI standard deviation for the five test runs is 3% of the average.
- The length must be measured to within 0.2%.

2.4 ADDITIONAL RESEARCH NEEDED

Additional research is needed on the implementation of IRI based specifications as states continue to switch to IRI based smoothness measurements. The FHWA currently is conducting a pooled fund study to work on improving the pavement profiler measurements (*2012*). The study aims to establish verification centers and provide maintenance guidelines for states to use. Other pooled fund studies from the FHWA include: “Interpretation of Road Roughness Profile Data” (*2002*); “Design, Construction, and Rehabilitation of Continuously Reinforced Concrete Pavements” (*2002*); and “Investigation of Aggregate Shape Effects on Hot Mix Performance Using an Image Analysis Approach” (*2002*). The Minnesota DOT is also participating in a pooled fund study to examine “HMA Surface Characteristics related to Ride, Texture, Friction, Noise, Durability” (*MnRoad 2012*). This study seeks to find a pavement design that will reduce noise and provide an alternative to building noise walls.

2.4.1 Oregon Department of Transportation Specifications

Further research is being conducted for ODOT to verify the inclinometer profiler. The repeatability and accuracy of the device must be checked. The data from ODOT’s inclinometer profiler will be compared to data collected from terrestrial LiDAR, a rod and level survey, and inertial profilers. The correlations between the different profiles can be determined using *ProVAL*.

ODOT is implementing an IRI based incentive/disincentive program. Using the data collected and existing specifications, new guidelines will be developed for the certification of inertial profilers.

2.4.2 Using LiDAR to Investigate Pavement Smoothness

LiDAR has the potential to create a "true profile" more efficiently than using a rod and level. Data can be collected quickly; however individual measurements are not as precise as rod and level data. LiDAR acquires a large quantity of data that is missed in traditional rod and level surveys. LiDAR offers a significant advantage by providing information across the entire road surface rather than just in one profile. Additional research is needed to improve the accuracy of these 3D models, particularly when derived from mobile LiDAR. The use of mobile LiDAR would be advantageous in this work since the instrumentation can be driven along the roadway much like an inertial profiler, enabling a large amount of data to be collected quickly. The data collected from laser scanning could provide a better profile of the roadway through statistical filtering as this could remove data noise. The type of filtering, as well as the amount, needs investigation to ensure that the data does not become over-filtered and lose accuracy. Over-filtering could smooth the data too much, rendering it difficult to detect areas of lesser roughness.

Some research has already been done on the use of LiDAR to study road roughness; however, there are other aspects that can also be investigated such as:

- *Filtering process*
- *Instrument comparison*
    - *Inertial profiler, inclinometer, mobile and static terrestrial laser scanning*
- *Cross slope measurements*
- *Longitudinal road slope measurements*
- Deviations from a flat road
- Areas of localized roughness
- Laser scanning automation
- Scanning process
    - Number of scans needed
    - Spacing of scans

These aspects require further research, particularly the automation of the laser scanning process. The four italicized topics are addressed in this research. Laser scanning can be more time consuming to collect and process the data than other methods, automation of the process would help reduce the time and make the process more efficient.

3.0 FIELD DATA COLLECTION

This Chapter discusses the data collection efforts implemented for this study.

A test site (Figure 1.1) was chosen by the Oregon Department of Transportation (ODOT) for the certification of inertial profilers. Data were collected along a 528 ft (161 m) stretch of the roadway located on Century Drive in Albany, Oregon. ODOT prepared the site by marking the wheel paths with paint as well as the start and end points of the test section. The lines were painted 6" (15.2 cm) to the left of the rut in the road since drivers have a tendency to stay to the right of the painted line. The four instruments shown in Figure 3.1 were used to complete this study.

3.1 INCLINOMETER AND INERTIAL PROFILER

Using an inclinometer-based profiler (IBP), a profile is collected by walking the instrument along the wheel path, one wheel path is measured at a time. A SurPro 3500 inclinometer-based profiler was run by ODOT on three occasions: June 2011, November 2011, and June 2012. The June 2011 and November 2011 surveys consisted of 5 runs on each wheel path. The June 2012 survey had 10 runs, 5 in the morning and 5 in the afternoon. The inclinometer surveys will be referred to herein as: *IBP_Date*.

The inertial profiler data was also provided by ODOT from some contractor runs. An inertial profiler is able to run at highway speeds while collecting a profile on each wheel path. Due to the high traveling speeds it is difficult to keep the profiler on the wheel paths; as a result the profiles may deviate from the paths. Four sets of data were provided and are referred to herein as IP_1, IP_2, IP_3, and IP_4. A total of five runs were completed for each data set.

No data processing outside of *ProVAL* was required for the inclinometer or inertial profiler. These files were provided as an ERD directly from ODOT.

3.2 ROD AND LEVEL

Two rod and level surveys (November 2011 and April 2012) were conducted following the ASTM E 1364-95 specifications (2005). The wheel paths at the test site had been previously marked by ODOT. Additional marks were made at 1 ft spacing along the wheel paths for comparison. A Leica DNA03 (0.03 mm precision) and DNA10 (0.09 mm precision) were used to collect the data on the left and right wheel paths, respectively. The data were input into an ERD file to be used in *ProVAL*. Repeat checks on control monuments and for at least 5 points spaced at 20' intervals along the profile were performed between each setup and all were within tolerances.

3.3 TERRESTRIAL LASER SCANNING (TLS)

The procedure for TLS collection and processing will be discussed in detail in Chapter 4. TLS data were collected on October 23, 2011.

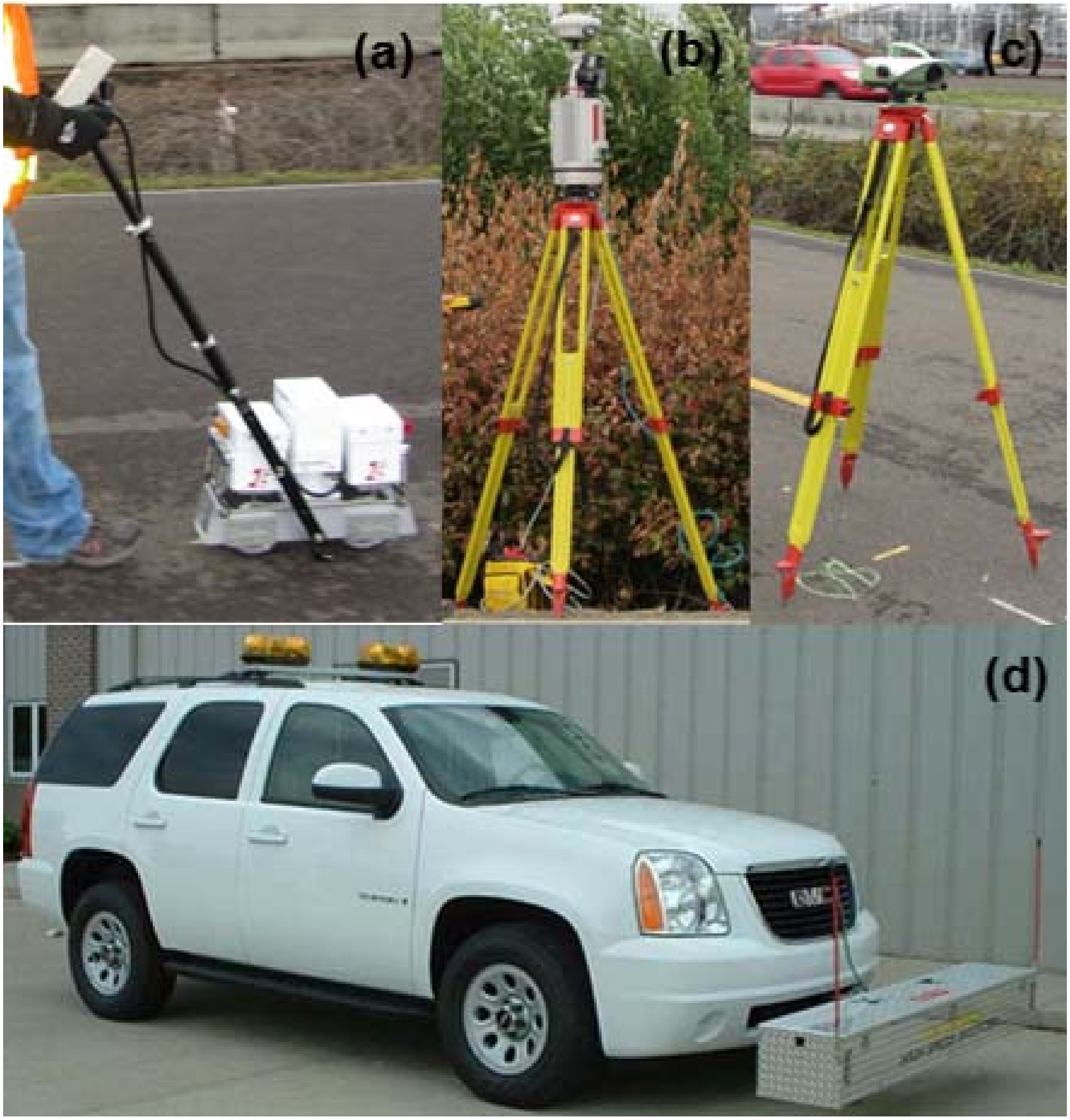


Figure 3.1: Instrumentation used for the study – (a) inclinometer, (b) laser scanner, (c) digital level, and (d) inertial profiler (from Ames Engineering, 2010).

4.0 USE OF TERRESTRIAL LASER SCANNING

Terrestrial laser scanning (TLS) is a new technology that shows promise to be a useful method to obtain longitudinal roadway profiles and the corresponding IRI values. Each point within the scan has X, Y, Z coordinates; R, G, B color; and an intensity value. The data collected is shown as a 3D point cloud; an example of this is shown in Figure 4.1.

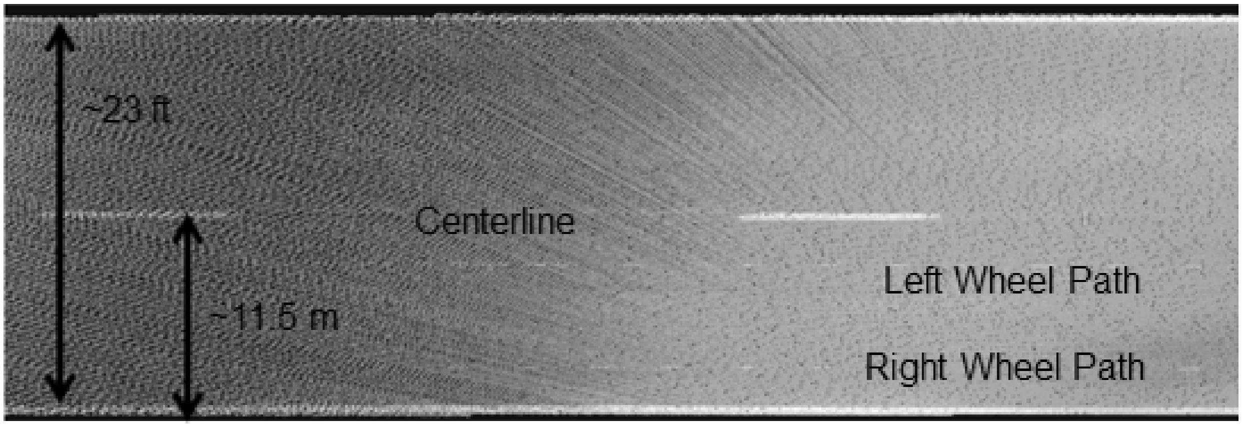


Figure 4.1: 3D point cloud image of the roadway section colored with intensity values

Benefits of TLS include:

- A dense data set (mm to cm-level resolution),
- Multiple profiles are collected simultaneously across the road surface,
- A variety of uses for the dataset since it obtains more than just the roadway (e.g., the data can be an as-built record, Figure 4.2), and
- The roadway does not need to be closed to traffic (increased safety) because scanning can be performed from the side of the road.

4.1 TLS DATA COLLECTION AND PROCESSING

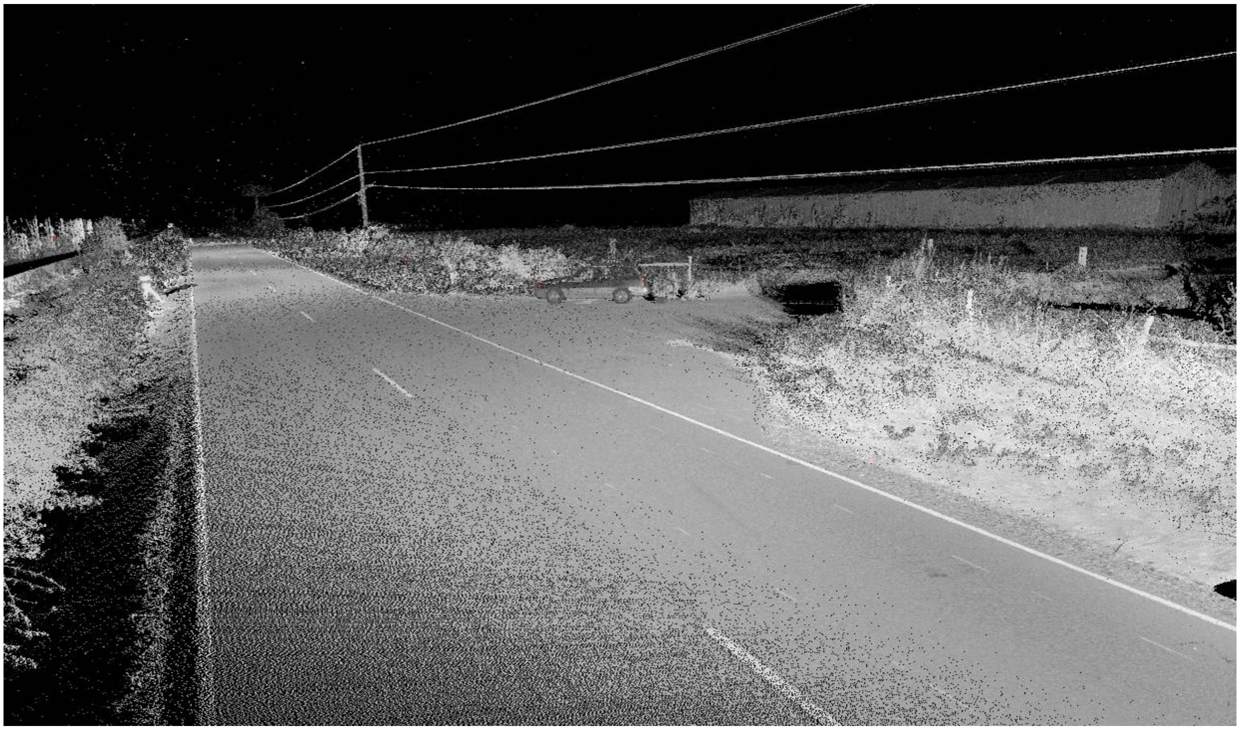


Figure 4.2: Laser scan point cloud showing features mapped in addition to roadway.

For this project, data was collected using six instrument setups spaced every 131 ft along the 528 ft section (Figure 4.3). Each 360 degree scan took approximately 5 minutes to complete. The nominal accuracy of the scanner is estimated to be 0.2 in within a 164 ft range. However, the actual accuracy depends on scanning geometry, environmental conditions, and the material scanned.

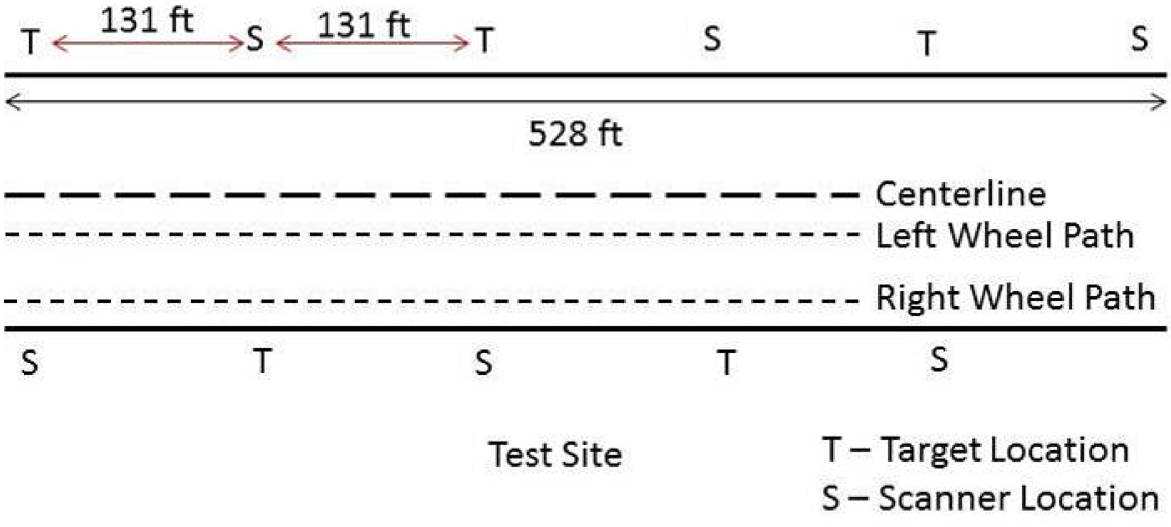


Figure 4.3: Test set up for TLS

The following processing steps were completed:

1. Each scan was first processed by filtering the data to eliminate points further than 328 ft from the scanner origin.
2. The scans were then trimmed to the roadway and noise from trucks was removed.
3. Three RTK GPS coordinates for the scan origin were averaged and applied to translate each scan into the Oregon Coordinate Reference System (OCRS) coordinate system.
4. The point clouds were then rotated about the z axis (centered at the scan origin) to obtain a rough alignment.
5. Following this, a cloud to cloud, least squares, surface matching was completed to refine the alignment. For this cloud to cloud alignment, the scans were constrained horizontally to the X and Y coordinates obtained via RTK GPS. The scans, however, were allowed to translate along the Z-axis and rotate about the X, Y, and Z axes. However, care was taken to ensure that the rotation about the X and Y axes did not vary substantially from inclination sensor readings.
6. Following pairwise matching between scans, a global registration was implemented for the final geo-referencing of the scans.
7. Each scan was then filtered to a 148 ft radius (slightly larger than the scan spacing) to remove points on the road at very oblique angles yet still fill in holes beneath each scan origin and provide overlap.
8. The scans were then rotated into a local coordinate system which aligned the roadway to the N-S axis to simplify future extraction.
9. The scans were merged and processes using a program “Bin and Grid” (*Olsen 2011*), which creates grids of elevation data with specified cell sizes. Within each grid, elevation values are statistically determined for each grid cell. This gridding process can eliminate outlying points caused from passing vehicles and reduce instrument noise.
10. Longitudinal profiles with uniform spacing were then extracted from the grid.
11. These profiles were then imported and analyzed in *ProVAL* to determine IRI and cross correlation values. A 250 mm (9.8 in) moving average filter was used.

4.2 TLS DATA ANALYSIS

The point cloud enables profiles to be obtained at any section along the roadway, unlike surveys from a rod and level, inclinometer, or inertial profiler, which are taken along a single path. This additional data enables the analysis of the wheel paths, variations in roughness across the roadway, localized depressions, and determination of cross slopes. It also ensures that a straight profile is obtained.

Comparisons between the four profiling methods can be drawn by determining road roughness (IRI values) and cross correlation between the profiles. These results enable for a closer examination regarding the use of laser scanning data for analysis of road roughness. Transverse, cross slope values can be calculated from the laser scanning data and slopes can be compared between the laser scanner and rod and level.

4.3 TLS SAMPLING INTERVAL

TLS collects data on at fixed angular increments; hence sampling on the ground is not uniform (dense close the scanner and sparser farther from the scanner). Further, multiple scan setups are combined into a single point cloud. To this end, the data need to be filtered (using the “Bin and Grid” procedure described above) and sampled on a regular interval for profile analysis. For this study, fifteen different sampling intervals were chosen: 1-12, 16, 20, and 24 in. Analyses were then run to determine the optimal sampling intervals. Initially, each profile was compared against the other sampling intervals for each wheel path. The outlying profiles tend to occur with sampling intervals of 10 in or more (Figure 4.4), indicating that the larger sampling interval for the filter creates a profiler that has been artificially smoothed. The profiles from Figure 4.4 show elevation differences (typically less than 0.2 ft) for a 10 ft section for profiles derived from each sampling interval.

Following this visual analysis, the IRI values from each sampling interval profile were examined Figure 4.5. Likely, the 1 in sampling interval does not eliminate all of the scanner noise and the surface appears rougher. The trend in the IRI curve flattens out between sampling intervals of 3 in and 10 in for both wheel paths. These values also agree very well with the IRI obtained from the IBP. The sampling intervals from 3 in to 12 in for both wheel paths provide profiles with no outlying points and are within or bordering the ±5% range from the IBP IRI.

After determining the optimal sampling interval range for the TLS data, it was important to investigate the advantages of using TLS in road roughness applications. The ability to collect multiple profiles at one time and having a complete set of data for the road section allows for the calculation of cross slopes as well as the IRI to be calculated at specified spacing across the road. The IRI values for profiles spaced every 1 ft across the roadway are shown in Figure 4.6.

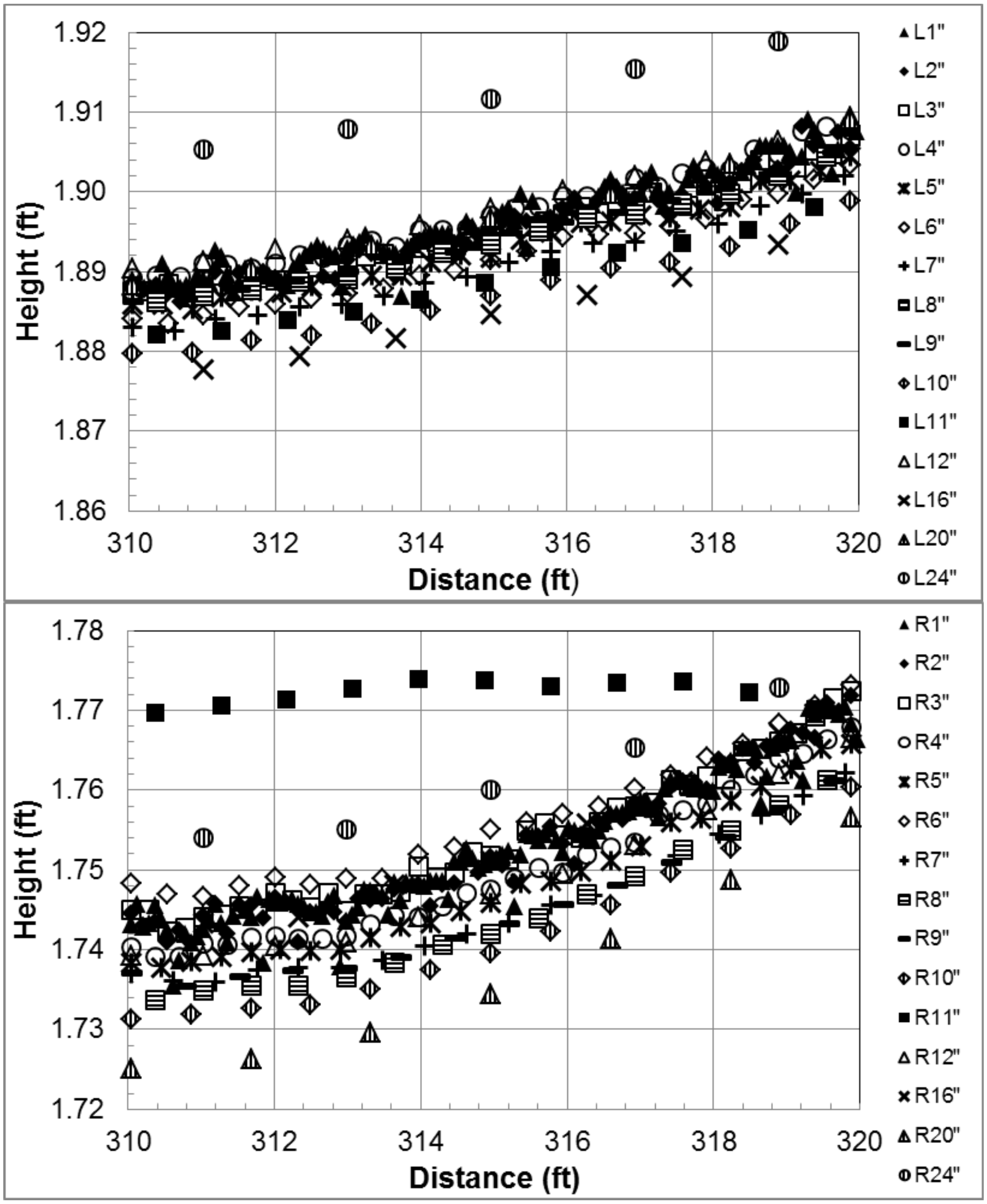


Figure 4.4: Profiles at varying sample intervals for the left (a) and right (b) wheel path

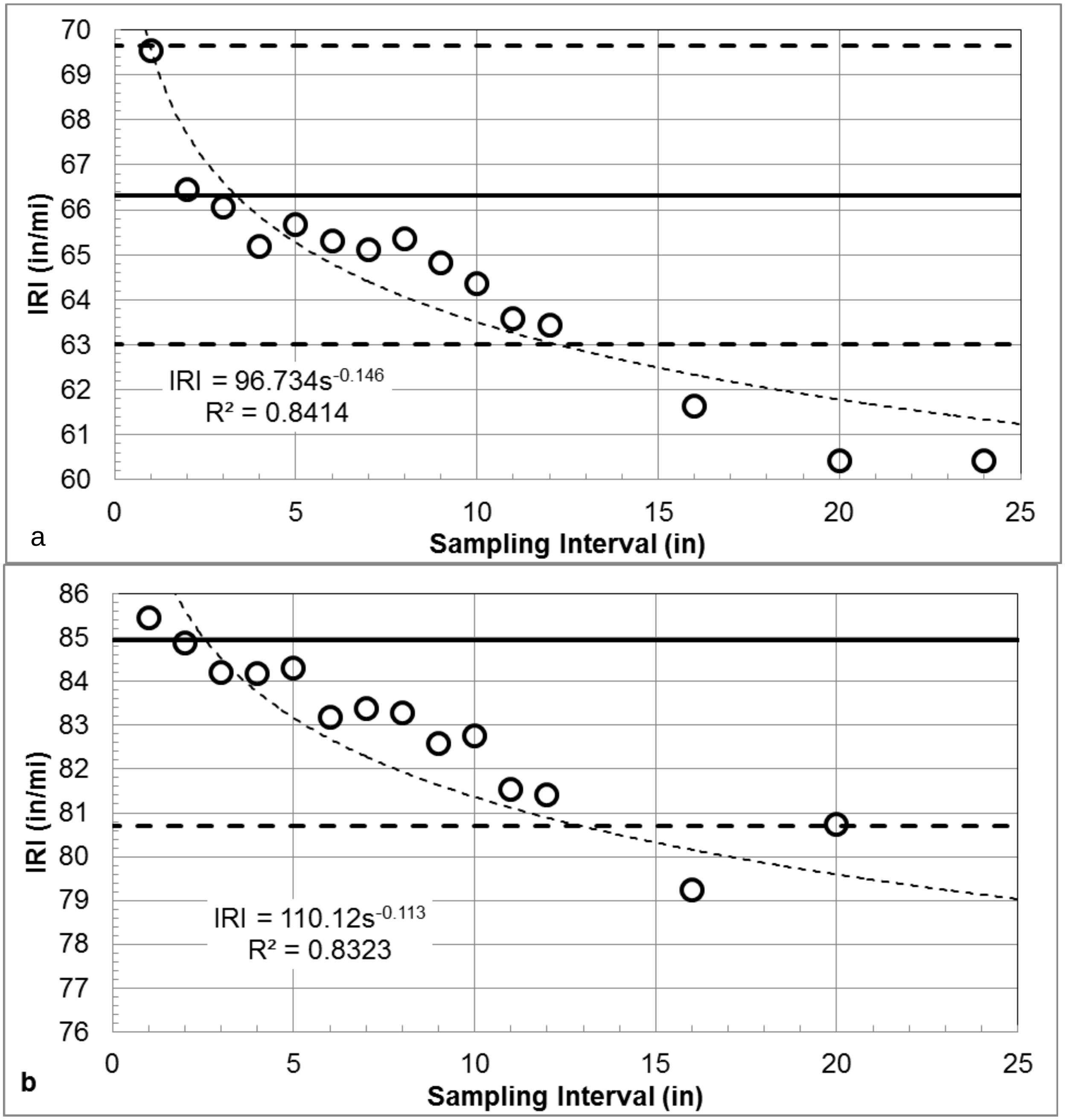


Figure 4.5: IRI values obtained from the TLS at varying sampling intervals with the dark line showing average of the June 2011 and November 2011 Inclinometer-based profiler runs and the dashed line showing +/- 5%; (a) left wheel path and (b) right wheel path.

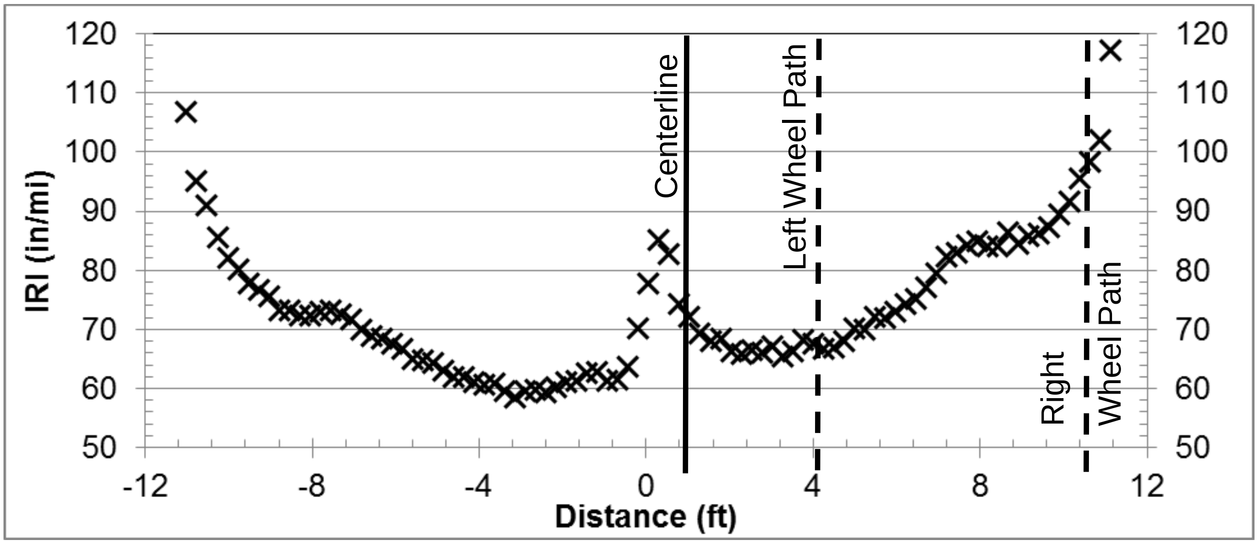


Figure 4-6: IRI values obtained for longitudinal profiles spaced every 3 in across the roadway with point spacing at 3 in

Figure 4.6 shows some variability in the IRI values to the left and right of the left wheel path and significant variability slightly to the left and right of the right wheel path, indicating that any deviation from the wheel path by the inertial profiler can influence the IRI values. This may have a greater effect on the cross correlation values since these are dependent upon the location of the roughness. The variability observed from obtaining multiple profiles along the roadway provides insight on the reasons for lower cross correlation values. It also provides a clearer picture of the actual roughness of the road rather than just in the wheel paths.

4.4 TLS CROSS SLOPES

Terrestrial laser scanning can also be used to obtain the cross slope values across the roadway. In order to first validate the measurements the cross slopes were compared between the rod and level and TLS using the profiles from the two wheel paths (Figure 4.7).

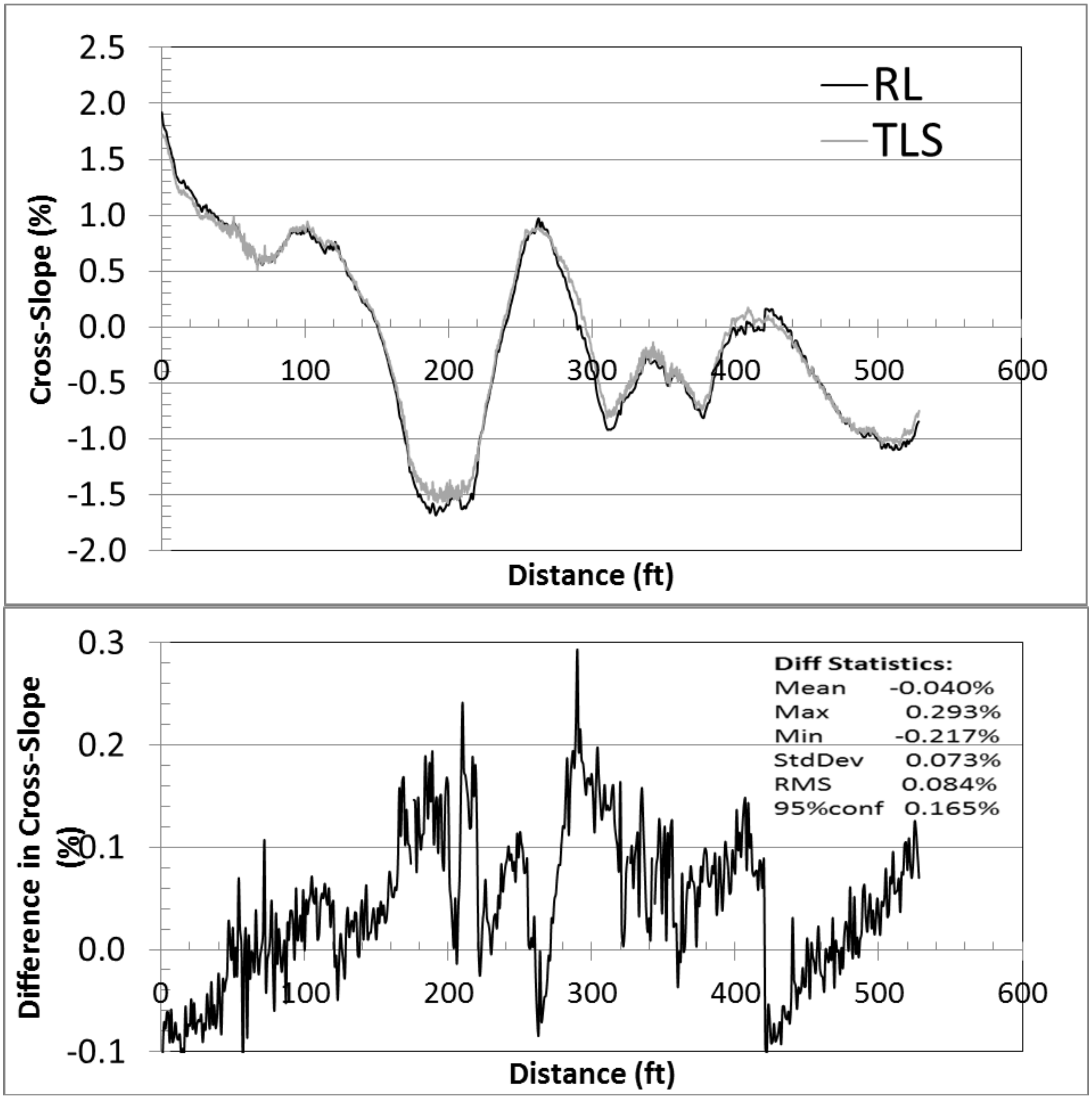


Figure 4.7: (a) Transverse, cross-slope comparison between wheel paths determined by rod and level and TLS data. (b) Differences in cross slope.

The cross slopes between the two instrument types differ by no more than 0.29% and on average differ by only 0.04%. Following that analysis, the cross slopes were obtained using the TLS data for the roadway section for both sides of the road (Table 4.1). Note that the East side of the road is where the profiling devices were tested.

Table 4.1: Transverse cross slopes every 25 ft from TLS data at 6 in sampling interval (positive slopes indicate road slopes away from centerline)

Distance (ft)	Cross Slopes (%)		Distance (ft)	Cross Slopes (%)	
	West	East		West	East
0	-1.98	1.70	275	-1.72	0.69
25	-2.17	1.02	300	-0.90	-0.22
50	-2.49	0.95	325	-0.63	-0.32
75	-2.56	0.60	350	-0.30	-0.55
100	-1.92	0.86	375	-0.59	-0.69
125	-1.46	0.62	400	-1.33	0.04
150	-1.02	0.04	425	-1.40	0.06
175	-0.58	-1.23	450	-0.54	-0.34
200	0.13	-1.43	475	0.82	-0.84
225	-0.56	-0.78	500	0.52	-0.98
250	-1.35	0.68	525	-0.43	-0.85

This section of the roadway does not generally have cross slopes of 2.0% to provide proper surface drainage. At 200 ft, the cross slope on the west side is almost 0% as well as at 400 ft on the east side. Hence, TLS can provide an additional check on the completed roadway construction to ensure that proper specifications were met.

4.5 CONSIDERATIONS FOR USE OF LASER SCANNING FOR PAVEMENT ANALYSIS

There are several key considerations for using scanning for pavement analysis. This section will discuss several of these considerations including laser characteristics, environmental conditions, surveying considerations, profile extraction considerations, and processing considerations.

4.5.1 Laser characteristics

Several key considerations of interaction with the laser and pavement surface are important.

- The laser beam increases in size (diverges) with distance, which creates blooming effects causing reflective surfaces appear larger at distance when the scan is colored by intensity.
- Highly reflective surfaces at close range can sometimes be problematic, creating saturation effects. The return signal is too strong such that peaks exceed the readable range of the receiver and thus cannot be accurately determined from the resulting waveform. This often results in the points on the ground object that tend to float slightly above the road surface.

- Dark surfaces at long ranges are problematic for some scanners because they do not reflect light well. Hence, scanning should be performed at close range (<50 m) to the pavement surface for best results.

4.5.2 Environmental Considerations

Environmental conditions can influence the result of TLS data collection. Many of these effects (temperature, pressure, and relative humidity) can be corrected for in the instrument or only using data for short ranges.

- Wet pavements will generally yield poor scanning results, as do conditions where refraction is present, for example due to steam, precipitation, or heat rising from surfaces.
- Generally, most laser scanners do not penetrate water.
- The configuration (orientation of lasers, viewpoint) of a MLS is important for its use in some applications. For example, specialized systems exist to capture very good pavement surface data, but are not configured to acquire data on surrounding features.

4.5.3 Surveying Considerations

The following should be considered when using performing survey work using laser scanning for pavement analyses:

- Scanning geometry (Position of scanner relative to object of interest) is important to determine how well objects are captured and to minimize data gaps.
- While the laser scanner will capture objects within range and line of sight of the vehicle, non-visible objects will not be mapped.
- Scans should be spaced close together to minimize oblique scanning on the road surface. Hence, more, lower resolution scans are better than few, higher resolution scans.
- Scans should be completed with a resolution of 1” or less on the road surface.
- Use of a Low-Distortion Projection System (LDP) is recommended since that will ensure that grid and ground measurements are nearly equivalent. Otherwise, scale factors need to be appropriately applied when comparing to other techniques.
- Relative accuracy is critical; network accuracy is less stringent for profile evaluation. However, the scan data may be used for a variety of other purposes, which will require network accuracy.
- Achieving high vertical accuracy is more important than horizontal accuracy. However, horizontal accuracy still needs to be sufficient to meet AASHTO’s DMI requirements.
- Pavement smoothness evaluation requires high sampling intervals (1-4”) and accuracies (mm vertical). Many generic MLS systems will not sufficiently meet these requirements. For example, Yen et al. (2011) found that typical MLS systems did not yet meet Caltrans standards for pavements for vertical accuracy.

- However, there are some specialized systems that focus solely on pavement for short sections that can meet these requirements.

4.5.4 Profile Extraction

When extracting the profile from the scan data, one should consider:

- Extraction from TLS data is easiest if the painted lines are straight.
- Performing the extraction in a local coordinate system, which aligns the profile to one axis will help extract a cleaner profile.
- Mapped images to the point cloud are helpful, but usually parallax issues due to the separation of camera and scanner. Hence, intensity shading should be used to extract the wheel paths.
- When painting lines for the profile, do not use overly reflective paint, which can result in blooming and saturation problems. However, some reflectance is needed, so that they are easy to distinguish in point cloud.
- Current resolution capabilities may not enable full analysis of small cracks (mm-level widths). However, larger cracks and potholes can usually be observed in the point cloud.

4.5.5 Processing considerations

When processing laser scan data for pavement analysis, one should consider:

- A localized cloud to cloud alignment may improve the relative accuracy of the scans over those achieved with targets.
- Processing often requires a variety of software packages.
- Data should be exported with sufficient digits (at least 4 after the decimal place) to avoid truncation.
- Care should also be taken to ensure that software packages do not truncate the data. Some software packages work with floating point precision (7 digits) instead of double precision (15 digits), which can be problematic for preserving numeric precision.
- The points in a point cloud natively do not have attributes other than XYZ coordinates and intensity values. Attributes such as RGB color and what the point represents are applied later through manual, semi-automatic, and/or automatic processing.
- Many algorithms for data processing are in research and development. Hence, much processing is either semi-automatic or manual, depending on the application. Very few completely automated procedures exist and those that do are generally in specialized software packages.
- Nonetheless, the technology and software are evolving rapidly and new features are available on a frequent basis.

5.0 PAVEMENT PROFILE TESTING

The collected profiles from the instruments were run through *ProVAL* software (described in the literature review) using each device as a reference profile. Comparisons were completed both between the IRI values and cross correlations.

The 250 mm (9.8”) filter to model the tire envelope was not applied to the level data (the spacing of the level data, 12”, is larger than the 9.8”), and the inclinometer-based profiler (the measurement system has a built-in mechanical filter since it uses wheels directly on the surface). However, a 250 mm filter moving average filter was applied to inertial profiler data and TLS data.

Prior to proceeding with the results, a few considerations for the inclinometer-based profiler data need to be discussed. Unfortunately, the inclinometer DMI was not calibrated with the closed loop run in June. As a result there was a compounding error in the elevation data resulting in a consistent bias seen in the profiles (Figure 2.3). However, this appears to have minimal effect on the incremental slope measurements, which appear to be sufficient. During the data collection in November, the wheels of the instrument were affected by the near-freezing temperatures, again possibly resulting in errors in the data.

5.1 IRI COMPARISONS

Figure 5.1 provides a comparison of the IRI values from the different instruments. Note that all except for the April 2012 rod and level survey fall within 5% of the Inclinometer-based profiler values.

The Inclinometer-based profiler consistently has the lowest standard deviation between runs, indicating high repeatability.

The IRI obtained from the rod and level tends to be higher than the IRI from the other devices for both wheel paths. This is likely due to the larger sample spacing (12”). Because only one rod and level survey was completed each day, a standard deviation cannot be computed.

The TLS data is based on the average IRI from the 2-5” sampling interval profiles. It should be noted that these are not additional runs.

The inertial profilers show the largest standard deviation of all of the devices. This is not surprising given the difficulty in navigating a straight path at highway speeds.

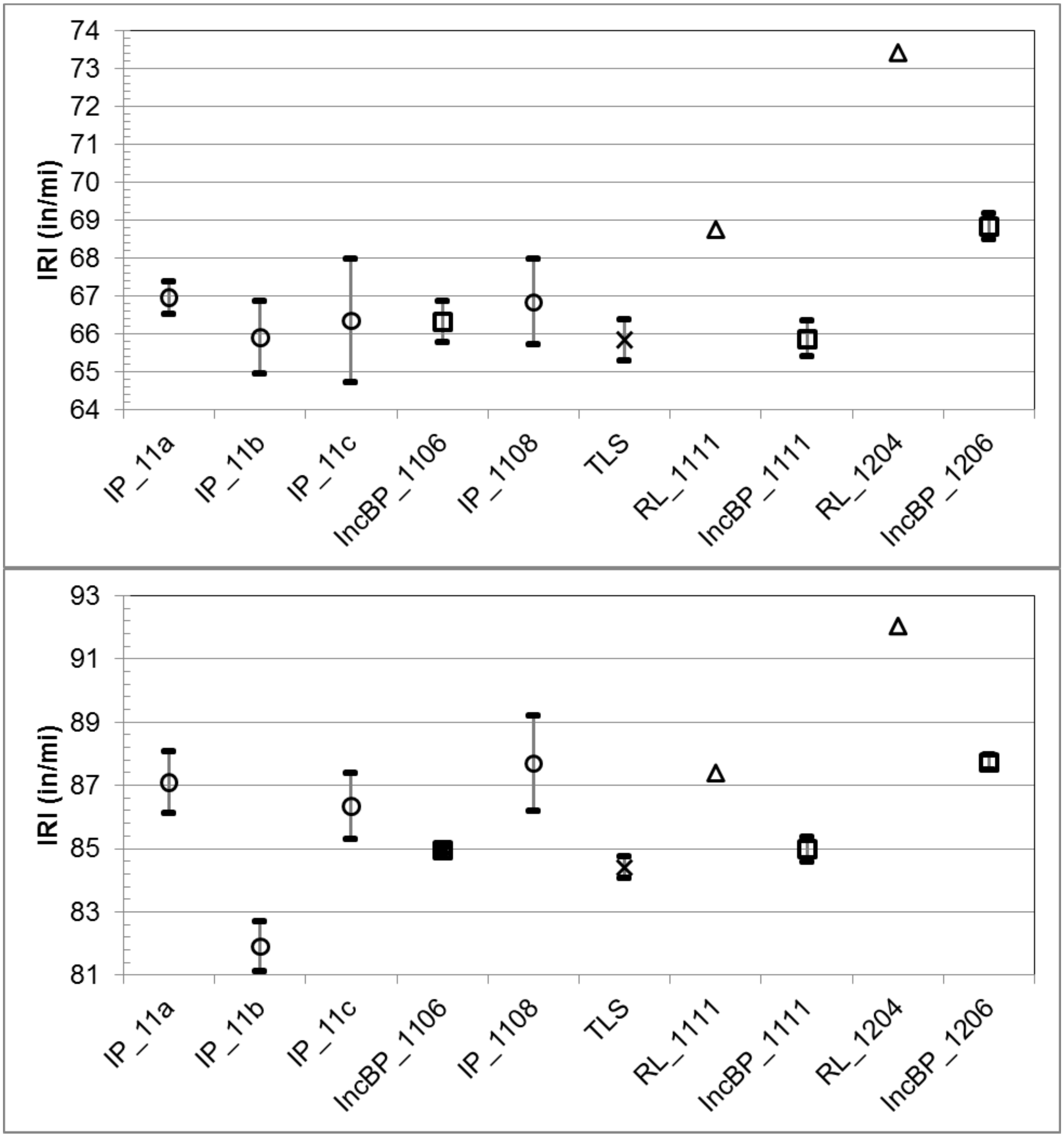


Figure 5-1: IRI values with standard deviation bars from each of the instruments used on the left (a) and right (b) wheel paths

5.2 PROFILE CERTIFICATION MODULE ANALYSIS

The profiler certification module was run in *ProVAL* software using the inclinometer-based profiler (Table 5.1), TLS (Table 5.2), and rod and level (Table 5.3) as reference profiles.

The evaluation was done using the current Oregon DOT requirements (90% repeatability and 88% accuracy) with the IRI filter. The common issue among these tables is the failure to meet accuracy on the left wheel path.

Table 5.1: Profiler certification testing with inclinometer reference profiles

	Comparisons to Nov. Inclinometer				**Comparisons to June Inclinometer**			
Statistic	Repeatability		Accuracy		Repeatability		Accuracy	
	Left	Right	Left	Right	Left	Right	Left	Right
	Passed Inertial Profiler							
Comparison Count	10	10	5	5	10	10	5	5
% Passing	100	100	0	0	100	100	20	100
Mean	97.4	97.2	72.6	78.8	97.4	97.2	86.4	93
Minimum	95	95	71	76	95	95	85	90
Maximum	99	99	74	82	99	99	88	96
Standard Deviation	1.2	1.3	1.1	2.8	1.2	1.3	1.3	2.2
Grade	Passed	Passed	**Failed**	**Failed**	Passed	Passed	**Failed**	Passed
	Failed Inertial Profiler							
Comparison Count	10	10	5	5	10	10	5	5
% Passing	100	100	0	0	100	100	100	100
Mean	93.8	94.5	75.8	82.6	93.8	94.5	90.8	94.2
Minimum	91	91	74	77	91	91	89	89
Maximum	95	98	77	85	95	98	92	97
Standard Deviation	1.5	2.9	1.3	3.4	1.5	2.9	1.1	3.1
Grade	Passed	Passed	**Failed**	**Failed**	Passed	Passed	Passed	Passed

Table 5.2: Profiler certification testing with TLS reference profiler

Statistic	**Passed Inertial Profiler**				**Failed Inertial Profiler**			
	Repeatability		Accuracy		Repeatability		Accuracy	
	Left	Right	Left	Right	Left	Right	Left	Right
Comparison Count	10	10	5	5	10	10	5	5
% Passing	100	100	100	100	100	100	100	100
Mean	97.4	97.2	94	93.4	93.8	94.5	93.6	90.6
Minimum	95	95	92	92	91	91	92	89
Maximum	99	99	96	94	95	98	95	93
Standard Deviation	1.2	1.3	1.4	0.9	1.5	2.9	1.1	1.7
Grade	Passed	Passed	Passed	Passed	Passed	Passed	Passed	Passed

Table 5.3: Profiler certification testing with rod and level reference profiles

	Comparisons to Nov. Level				**Comparisons to April Level**			
Statistic	Repeatability		Accuracy		Repeatability		Accuracy	
	Left	Right	Left	Right	Left	Right	Left	Right
Passed Inertial Profiler	Passed Inertial Profiler							
Comparison Count	10	10	5	5	10	10	5	5
% Passing	100	100	0	100	100	100	0	0
Mean	97.4	97.2	84.2	91.2	97.4	97.2	77.2	81.8
Minimum	95	95	83	90	95	95	76	81
Maximum	99	99	85	92	99	99	78	83
Standard Deviation	1.2	1.3	0.8	0.8	1.2	1.3	1.1	0.8
Grade	Passed	Passed	**Failed**	Passed	Passed	Passed	**Failed**	**Failed**
Passed Inertial Profiler	Failed Inertial Profiler							
Comparison Count	10	10	5	5	10	10	5	5
% Passing	100	100	0	100	100	100	0	0
Mean	93.8	94.5	84.2	92	93.8	94.5	77.8	84.6
Minimum	91	91	82	88	91	91	75	84
Maximum	95	98	85	94	95	98	79	86
Standard Deviation	1.5	2.9	1.3	2.3	1.5	2.9	1.6	0.9
Grade	Passed	Passed	**Failed**	Passed	Passed	Passed	**Failed**	**Failed**

An additional rod and level survey was completed in April 2012. The results of this survey show an IRI that is 5-6 in/mi higher than the IRI determined from the previous surveys. Further analysis was conducted to compare the two sets of rod and level data. However, the April level results in failed accuracy for the left and right wheel paths for the two inertial profiler tests.

It is clear from the tables that the temperature was too low during the November inclinometer tests. The accuracy fails for both the left and right wheel paths. Therefore this inclinometer should not be used during the winter months, except on warm days.

5.3 CROSS CORRELATION ANALYSIS

The cross correlation provides a better analysis on the agreement of two profiles than IRI alone (see Section 2.1.2). Figure 5.2 compares the cross correlation values obtained by comparison of the TLS with varying sample intervals to the rod and level, inclinometer, and inertial profiler as reference profiles. It is likely that the results would agree better if (1) there were less variability across the road surface, minimizing wandering effects, and (2) the profiles were completed within a short time window.

Comparison to the rod and level shows the poorest correlation, likely due to the large spacing (12”) of the dataset. The inertial profilers and inclinometer-based profiler both generally show good cross correlation with the TLS data, particularly between 2” to 8” for both wheel paths. More scatter is observed for the right wheel path, likely due to the higher variability in roughness near the right wheel path (Figure 4.6). However, the left wheel path cross correlation values are consistently lower.

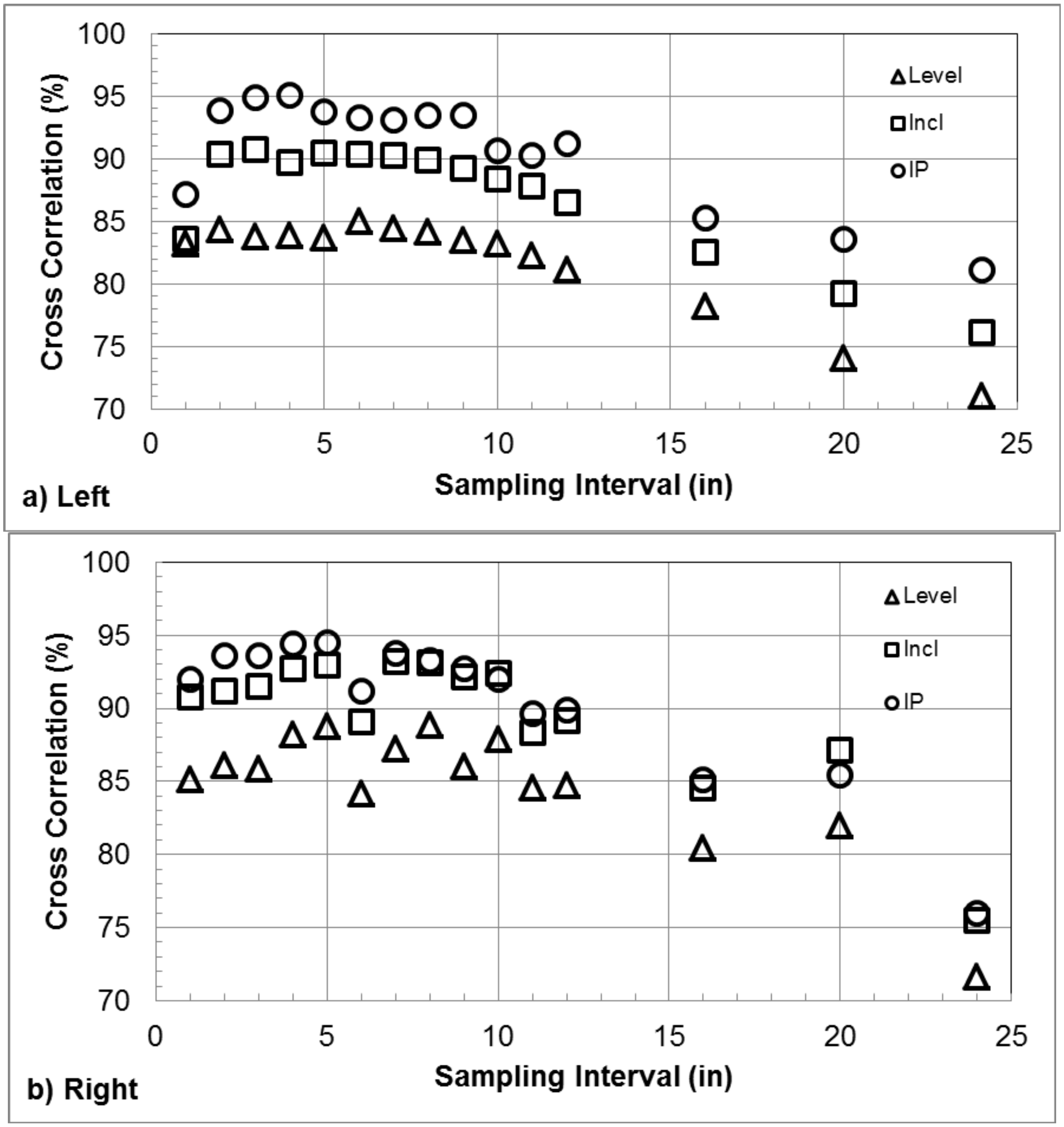


Figure 5.2: Cross correlation comparisons between TLS and other devices for the left (a) and right (b) wheel paths at varying sampling intervals

Table 5.4: Cross correlation values (with standard deviations) for reference and comparison profilers for the left and right wheel paths; bolded values meet current AASHTO (90% accuracy, 92% repeatability) requirements

Left Wheel Path						**REFERENCE**		**-->**										
Reference / Profile	**IBP_ 1106**		**IBP_ 1111**		**IBP_ 1206**		**RL_ 1111**		**RL_ 1204**		**TLS_ 1110**		**IP1**		**IP2**		**IP3**	
IBP_1106	**98.20**	**(0.32)**	**91.65**	**(0.76)**	87.61	(1.19)	83.27	(1.30)	75.52	(0.54)	**90.57**	**(0.60)**	87.54	(0.69)	**91.13**	**(0.74)**	72.01	(0.65)
IBP_1111	**92.19**	**(0.68)**	**99.00**	**(0.46)**	73.55	(0.98)	74.35	(0.79)	65.38	(0.85)	80.51	(0.80)	77.03	(0.75)	79.05	(1.02)	62.44	(0.98)
IBP_1206	86.78	(3.19)	72.10	(3.22)	**97.37**	**(1.49)**	85.70	(2.71)	84.26	(1.18)	86.79	(2.54)	86.40	(2.38)	**90.84**	**(2.16)**	69.47	(1.82)
RL_1111	88.44	-	77.99	-	86.21	-	-	-	83.87	-	88.48	-	88.36	-	**90.84**	**-**	67.30	-
RL_1204	80.73	-	68.93	-	72.46	-	83.87	-	-	-	82.37	-	81.98	-	84.59	-	64.21	-
TLS_1110	**90.32**	**(0.45)**	80.52	(0.52)	87.33	(0.84)	83.91	(0.30)	77.40	(0.56)	**97.63**	(0.69)	**94.40**	**(0.66)**	**93.54**	**(0.55)**	74.85	(1.27)
IP1	88.50	(1.15)	76.65	(0.72)	88.31	(1.06)	84.13	(0.62)	77.23	(0.90)	**94.56**	**(1.19)**	**98.06**	**(0.49)**	**94.52**	**(1.17)**	71.20	(1.58)
IP2	**90.84**	**(0.92)**	78.49	(1.59)	**90.48**	**(1.29)**	84.12	(1.09)	77.70	(1.55)	**93.79**	**(0.94)**	**94.55**	**(2.56)**	**95.14**	**(0.16)**	74.70	(1.43)
IP3	71.66	(2.29)	60.98	(2.00)	70.46	(2.44)	63.78	(1.76)	59.96	(1.73)	74.11	(2.67)	71.18	(2.62)	75.06	(2.58)	**94.12**	**(2.09)**
IP4	**93.88**	**(2.77)**	86.19	(2.94)	87.08	(3.62)	74.06	(1.92)	82.46	(1.67)	**90.75**	**(1.76)**	88.80	(1.91)	**91.29**	**(2.92)**	74.19	(1.05)

Right Wheel Path						**REFERENCE**		**-->**										
Reference / Profile	**IBP_ 1106**		**IBP_ 1111**		**IBP_ 1206**		**RL_ 1111**		**RL_ 1204**		**TLS_ 1110**		**IP1**		**IP2**		**IP3**	
IBP_1106	**99.02**	**(0.16)**	**92.38**	**(0.21)**	**92.23**	**(0.17)**	**93.37**	**(0.36)**	83.93	(0.66)	**91.42**	**(0.14)**	**94.22**	**(0.17)**	**96.92**	**(0.29)**	69.39	(0.40)
IBP_1111	**92.42**	**(0.72)**	**99.32**	**(0.19)**	79.75	(0.85)	84.90	(0.70)	77.94	(0.64)	84.15	(0.58)	83.40	(0.71)	87.39	(0.69)	62.48	(0.46)
IBP_1206	**92.39**	**(1.06)**	80.04	(1.30)	**99.24**	**(0.28)**	**92.90**	**(0.75)**	86.58	(0.33)	86.61	(0.99)	**91.90**	**(0.93)**	**95.37**	**(0.93)**	66.30	(0.63)
RL_1111	**95.82**	**-**	87.81	-	**91.18**	**-**	-	-	83.17	-	89.89	-	**92.47**	**-**	**94.73**	**-**	67.29	-
RL_1204	87.45	-	81.32	-	89.48	-	83.17	-	-	-	80.22	-	84.81	-	89.27	-	61.55	-
TLS_1110	**92.07**	**(0.88)**	84.67	(0.96)	86.37	(0.88)	87.21	(1.46)	78.34	(1.47)	**98.56**	**(0.10)**	**94.02**	**(0.50)**	**90.85**	**(0.80)**	72.12	(0.84)
IP1	**92.80**	**(2.29)**	81.86	(2.26)	**91.99**	**(1.22)**	**91.27**	**(0.94)**	81.69	(1.00)	**92.91**	**(0.84)**	**97.51**	**(1.46)**	**92.76**	**(1.67)**	72.26	(0.82)
IP2	**94.22**	**(2.99)**	84.91	(3.14)	**93.80**	**(1.24)**	**92.15**	**(2.28)**	84.76	(0.85)	**90.14**	**(1.70)**	**94.98**	**(1.65)**	**95.66**	**(3.40)**	70.41	(2.29)
IP3	69.64	(0.63)	62.33	(1.32)	65.92	(0.59)	64.36	(1.10)	58.19	(0.85)	70.48	(2.43)	71.98	(2.43)	76.81	(1.14)	**95.58**	**(1.41)**
IP4	**95.49**	**(1.81)**	**92.07**	**(3.06)**	**90.61**	**(2.19)**	**90.94**	**(0.87)**	82.94	(1.96)	87.47	(1.31)	89.56	(2.02)	**92.27**	**(2.81)**	68.20	(1.95)

The cross correlations were determined using various reference and comparison profiles (Table 5.4). The bold values were meet current AASHTO standards (90% accuracy and 92% repeatability). Note that current ODOT standards require 88% accuracy and 90% repeatability. The majority of these bolded values are from comparison for the right wheel path. There are again accuracy problems with the data from the left wheel path. The November inclinometer test had low cross correlation values on both wheel paths.

In this table, the diagonal elements represent repeatability within all of the runs with that instrument on the survey date. For the TLS data, this repeatability is based on comparing the 2, 3, 4, and 5” spacing intervals, rather than separate TLS surveys. The profile selected for the reference profile was the profile that showed the highest correlation with the other runs for that device and date.

5.4 STATISTICAL ELEVATION ANALYSIS

A traditional, statistical correlation analysis was completed to compare the profile elevations to compare to the findings of Chang et al. (*2006*) regarding the use of TLS. As discussed in Section 2.1.2, the IRI-based cross correlation focuses on slope variations rather than elevation variations because slope variations are more applicable to ride quality.

Herein, two forms of reporting accuracies are presented in Table 5.5: The root mean square (RMS, ~68% confidence interval) and the accuracy for a 95% confidence interval (=1.96*RMS for 1D). Since the cross correlation calculation adjusts the profiles so that the mean elevation value is zero, the RMS and 95% confidence intervals were computed both with and without a mean profile elevation adjustment. The November inclinometer was used in this analysis since there was no DMI calibration and closed-loop adjustment for the June inclinometer, which are critical for elevation comparisons. The inclinometer and level profiles show the best agreement. The TLS shows slightly better agreement to the inclinometer based profiler than the level. These values are reasonable given the typical accuracies of the equipment (TLS: nominal RMS accuracy 0.2 in, RL: nominal RMS accuracy: 0.04 in, IBP: nominal RMS accuracy 0.01 in/ 25 ft = 0.2 in for 528 ft).

Table 5.5: Statistical analysis of profile elevations for TLS, level and inclinometer

No Elevation Adjustment						
Parameter	TLS to Level		Inclinomenter to Level		Inclinometer to TLS	
	Left	Right	Left	Right	Left	Right
RMS (in)	0.2215	0.3435	0.1281	0.3088	0.2096	0.2213
95% Confidence (in)	0.4341	0.6732	0.2511	0.6053	0.4108	0.4338
With Mean Elevation Adjustment						
Parameter	TLS to Level		Inclinomenter to Level		Inclinometer to TLS	
	Left	Right	Left	Right	Left	Right
RMS (in)	0.2207	0.1987	0.1126	0.0919	0.1781	0.1980
95% Confidence (in)	0.4326	0.3895	0.2207	0.1802	0.3491	0.3881

A second statistical analysis (Table 5.6) was completed to compare the November and April rod and level surveys. The RMS values are also low (0.03-0.04 in) which shows a good correlation of the data, despite the large difference in IRI values (5-6 in/mi), which is based on incremental slope measurements.

Table 5.6: Statistical elevation analysis comparing November and April rod and level surveys

Parameter	No Adjustment		Elevation Adjustment	
	Left	Right	Left	Right
RM S (in)	0.02718	0.04354	0.02541	0.02354
95% Confidence (in)	0.05328	0.08534	0.0498	0.04614

5.5 WAVELENGTH ANALYSIS

Profile runs from each device were compared using ProVAL's Power Spectral Density analysis function. IRI filters were applied to all devices, with the 250 mm filter applied to the TLS and inertial profiler data. A comparison of elevation (Figure 5.3) and slope (Figure 5.4) wavelengths for the left wheel path show deviations below 4 ft/cycle and above 120 ft/cycle. A comparison of elevation (Figure 5.5) and slope (Figure 5.6) wavelengths for the right wheel path show deviations below 3 ft/cycle and above 200 ft/cycle. These trends are similar to the left wheel path except that the differences are much more pronounced below 3 ft/cycle. Also, note that at around 40 ft/cycle, the TLS shows some deviation. However, overall, the devices have good agreement in wavelength content. Given that the profile length was 528 ft, wavelengths greater than 100 ft would require a longer profile to accurately capture.

Comparisons of the TLS data only for each sampling interval are shown in Figure 5.7 (elevation) and Figure 5.8 (slope) for the LWP and Figure 5.9 (elevation) and Figure 5.10 (slope) for the RWP. Note that there is some variability in wavelength content, depending on the sampling interval. Particularly, the 7 in sampling interval shows some significant deviations for the LWP. However, for the shorter and longer wavelengths, these differences are typically less than those observed when comparing all devices. Note that these comparisons do not include the IRI filtering or 250 mm moving average filter.

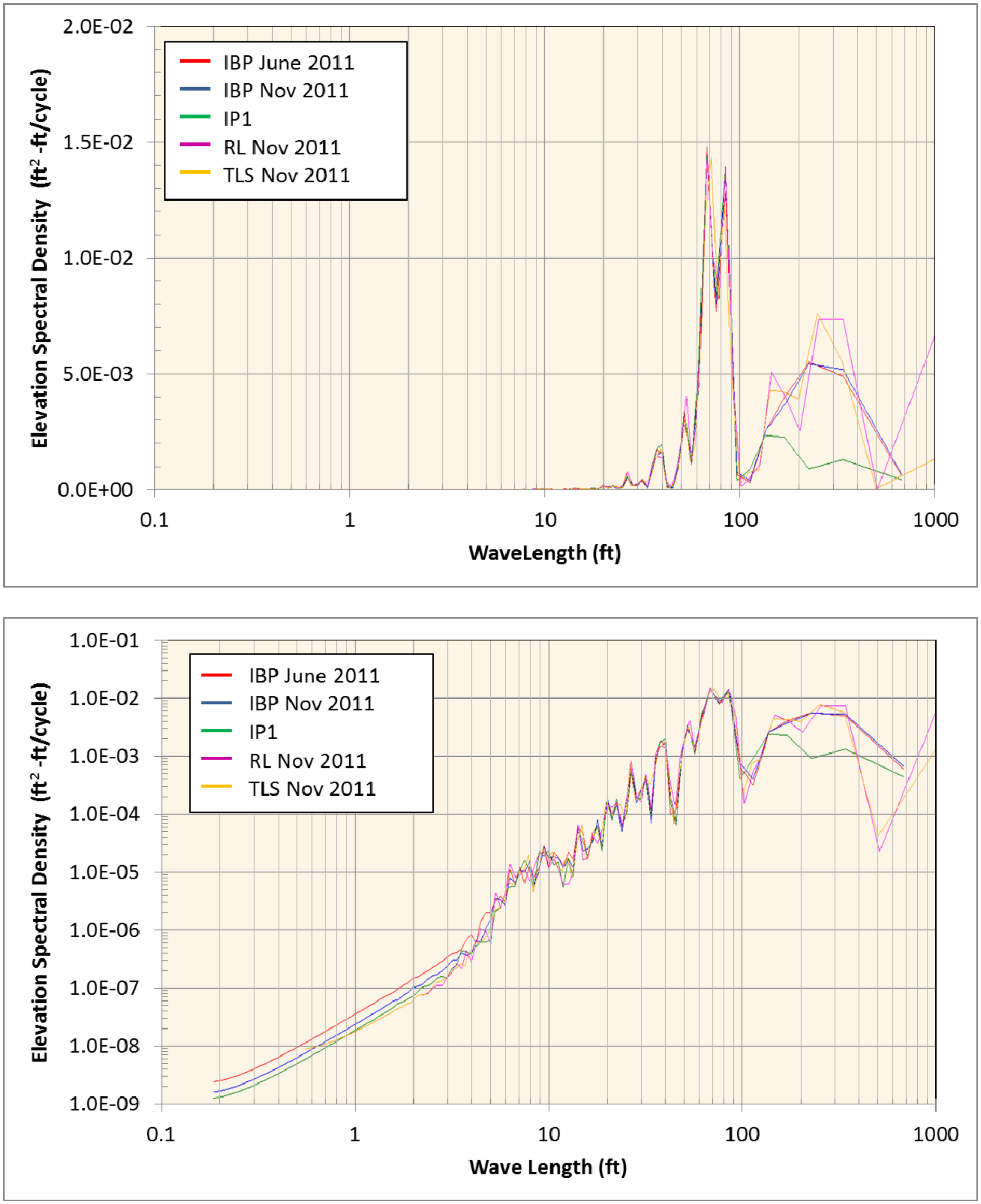


Figure 5.3: Comparison of wavelengths of elevations for the left wheel path with (a) arithmetic and (b) logarithmic vertical axes.

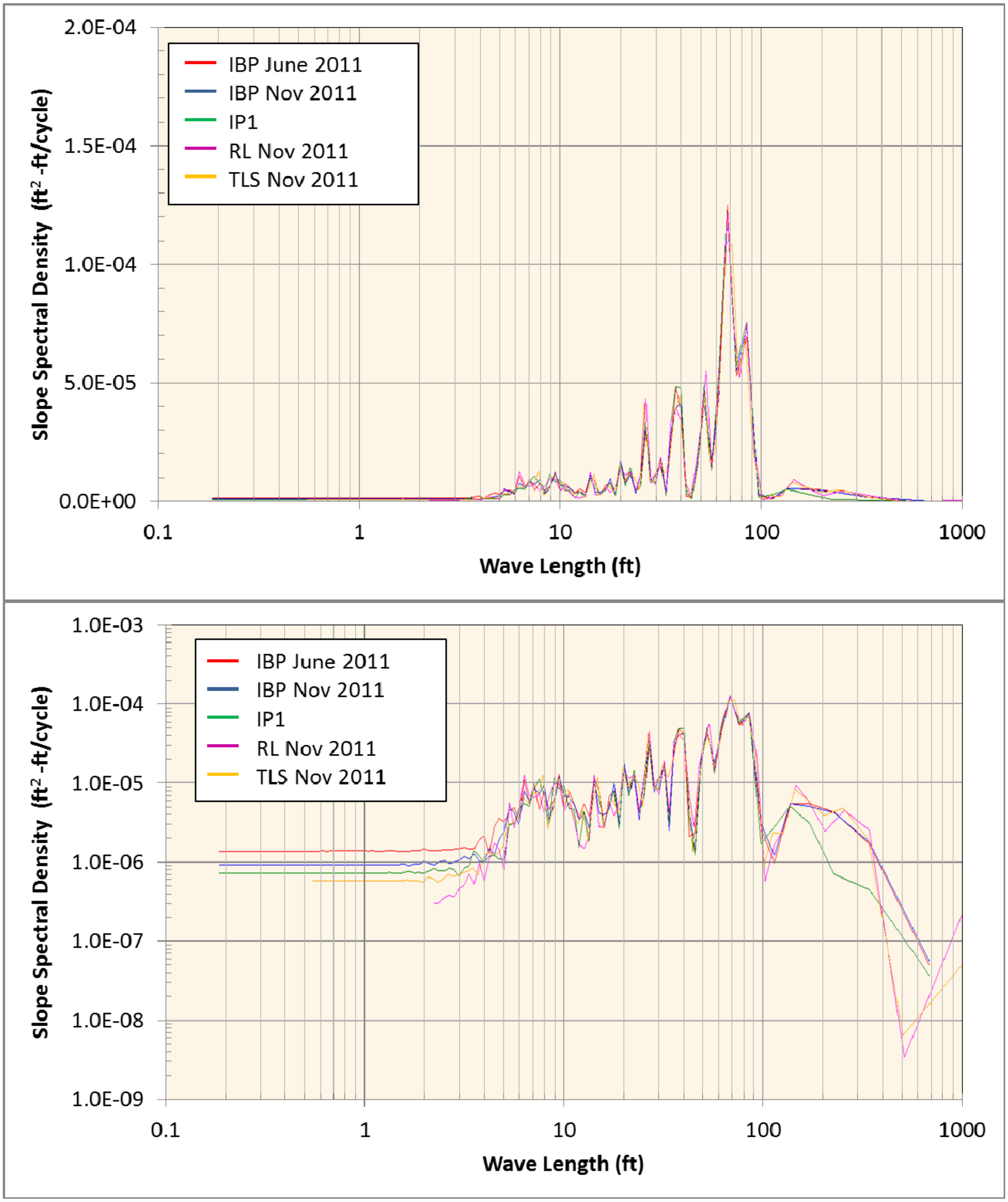


Figure 5.4: Comparison of wavelengths of slopes for the left wheel path with (a) arithmetic and (b) logarithmic vertical axes.

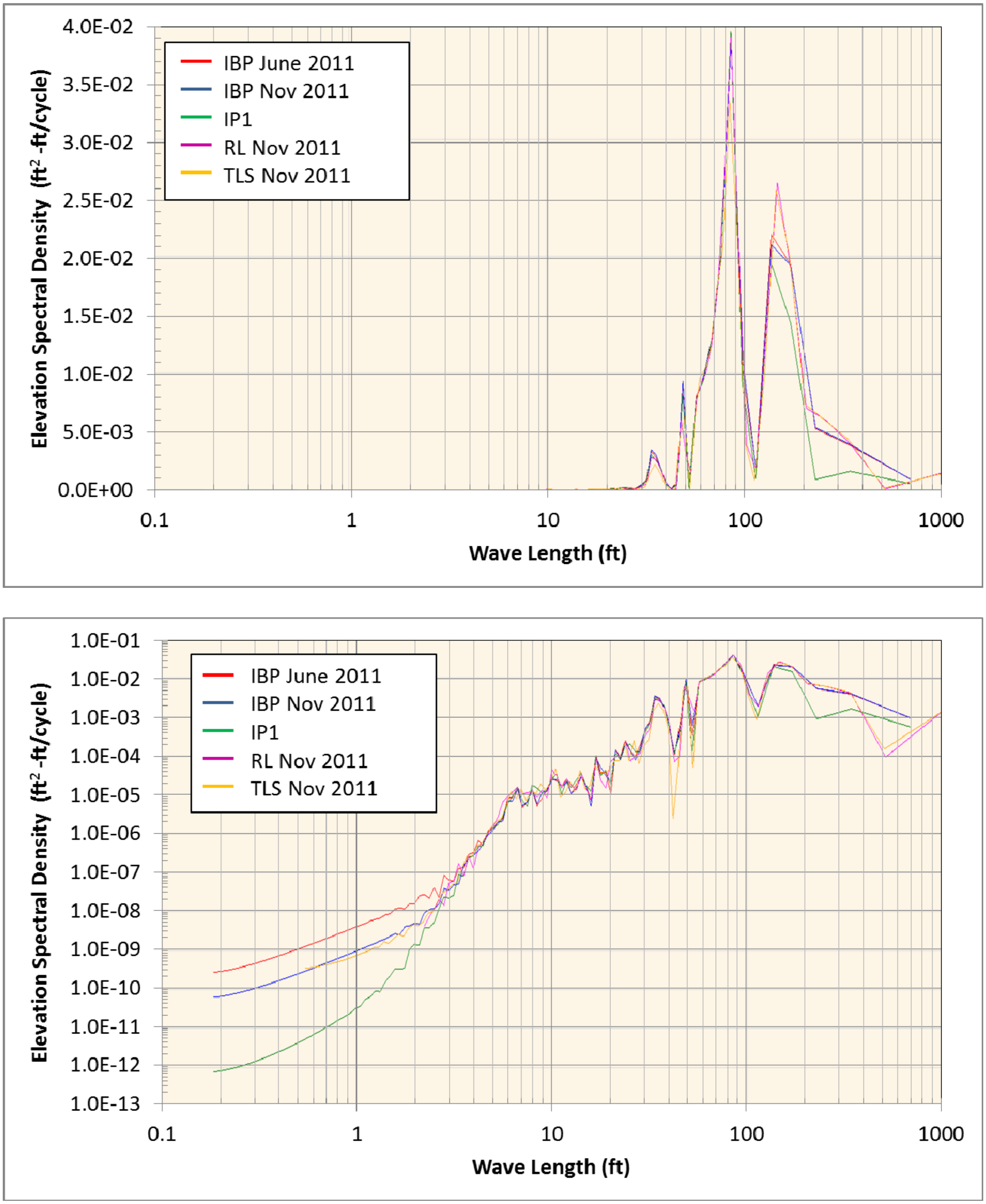


Figure 5.5: Comparison of wavelengths of elevations for the right wheel path with (a) arithmetic and (b) logarithmic vertical axes.

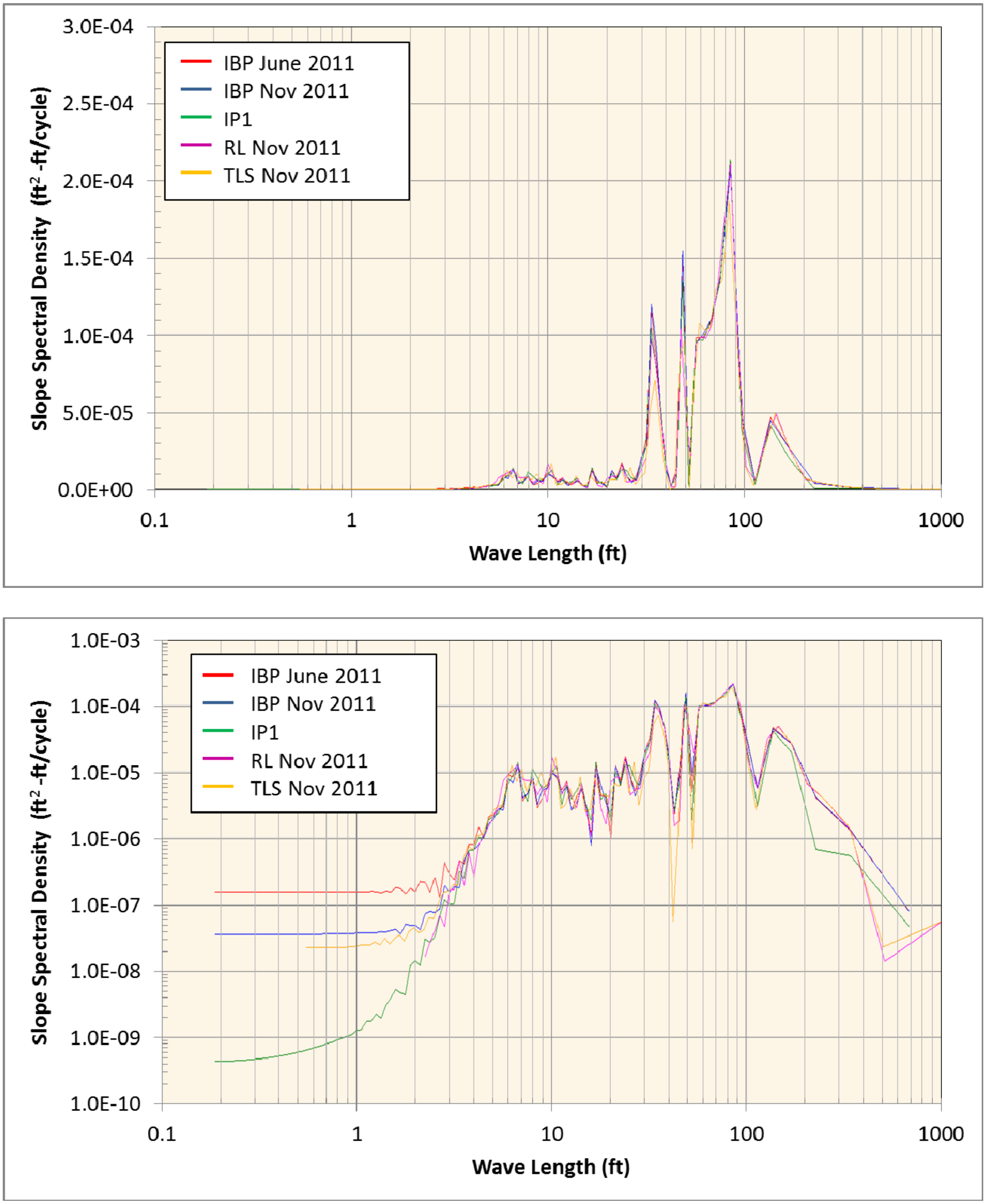
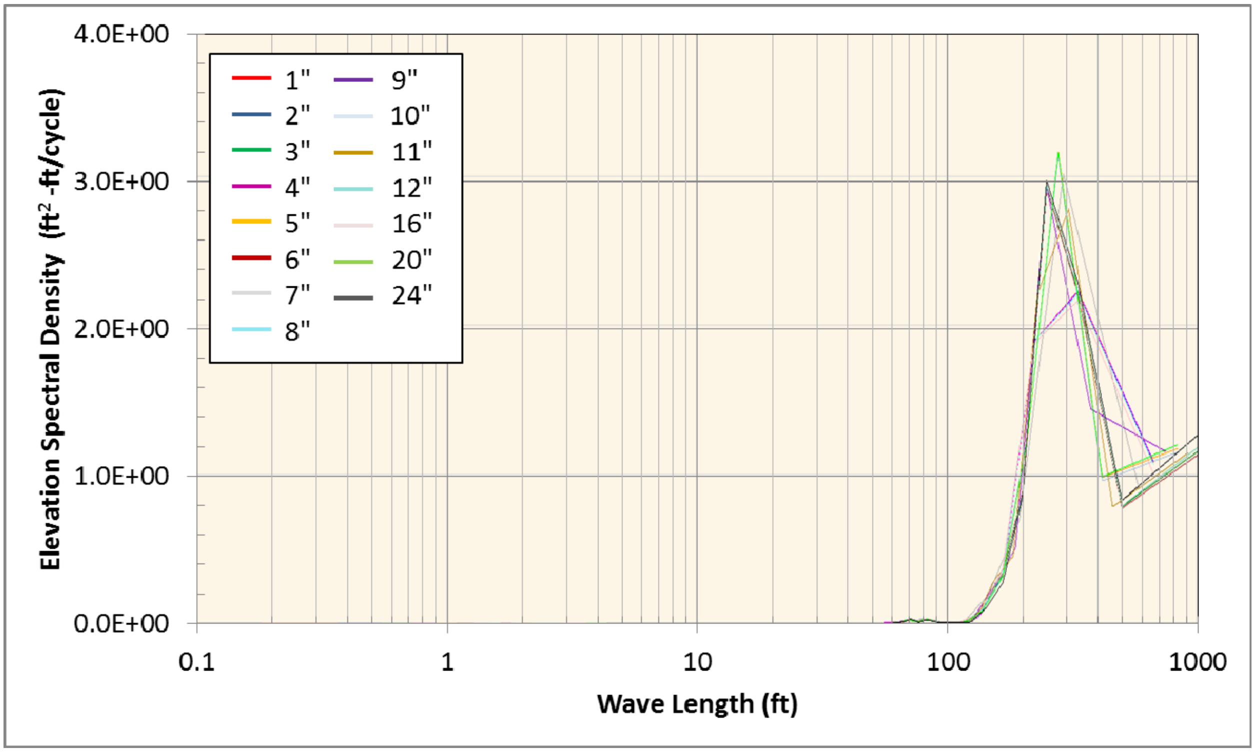


Figure 5.6: Comparison of wavelengths of slopes for the right wheel path with (a) arithmetic and (b) logarithmic vertical axes.



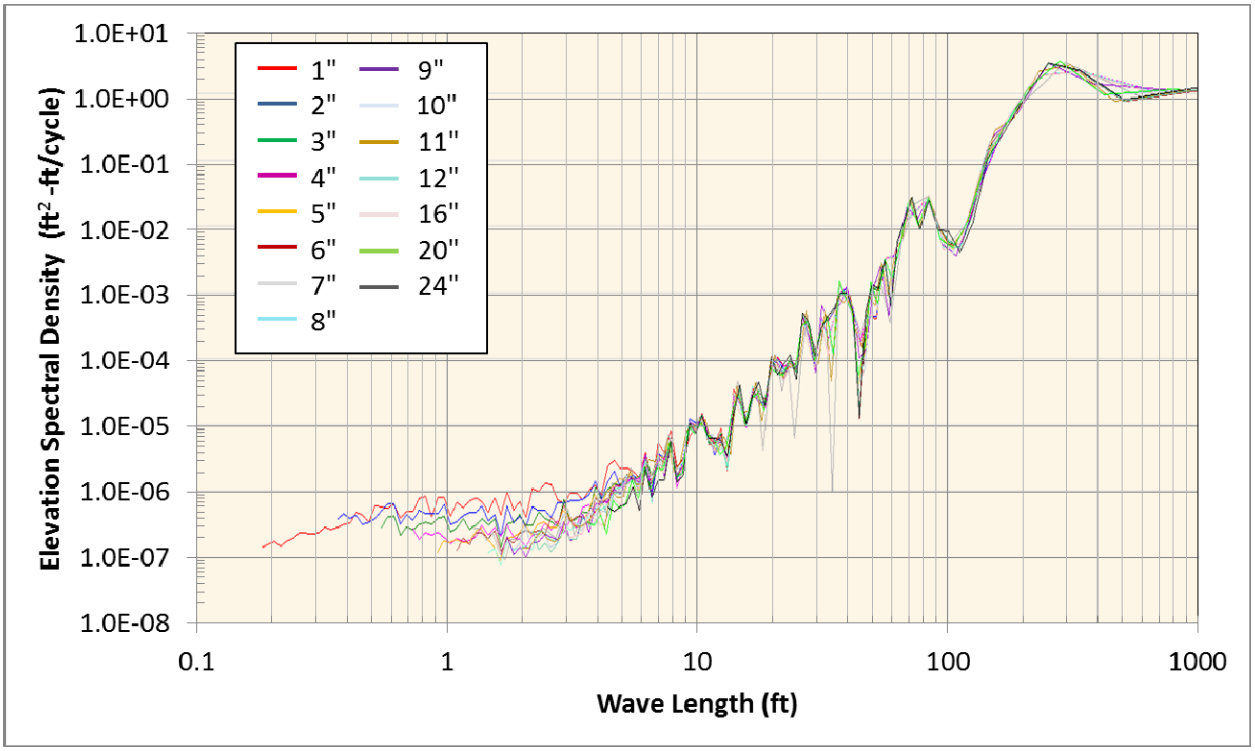
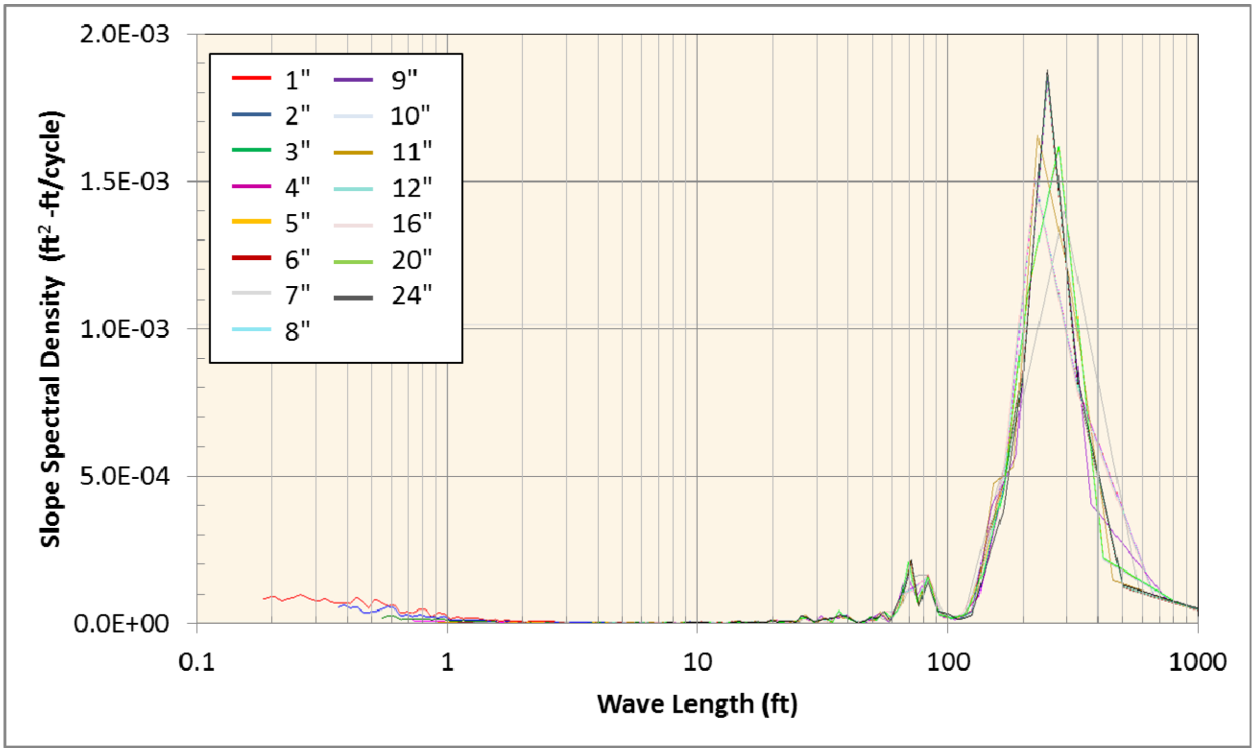


Figure 5.7: Comparison of wavelengths of elevations for the left wheel path for the TLS only (no –IRI filtering) with (a) arithmetic and (b) logarithmic vertical axes.



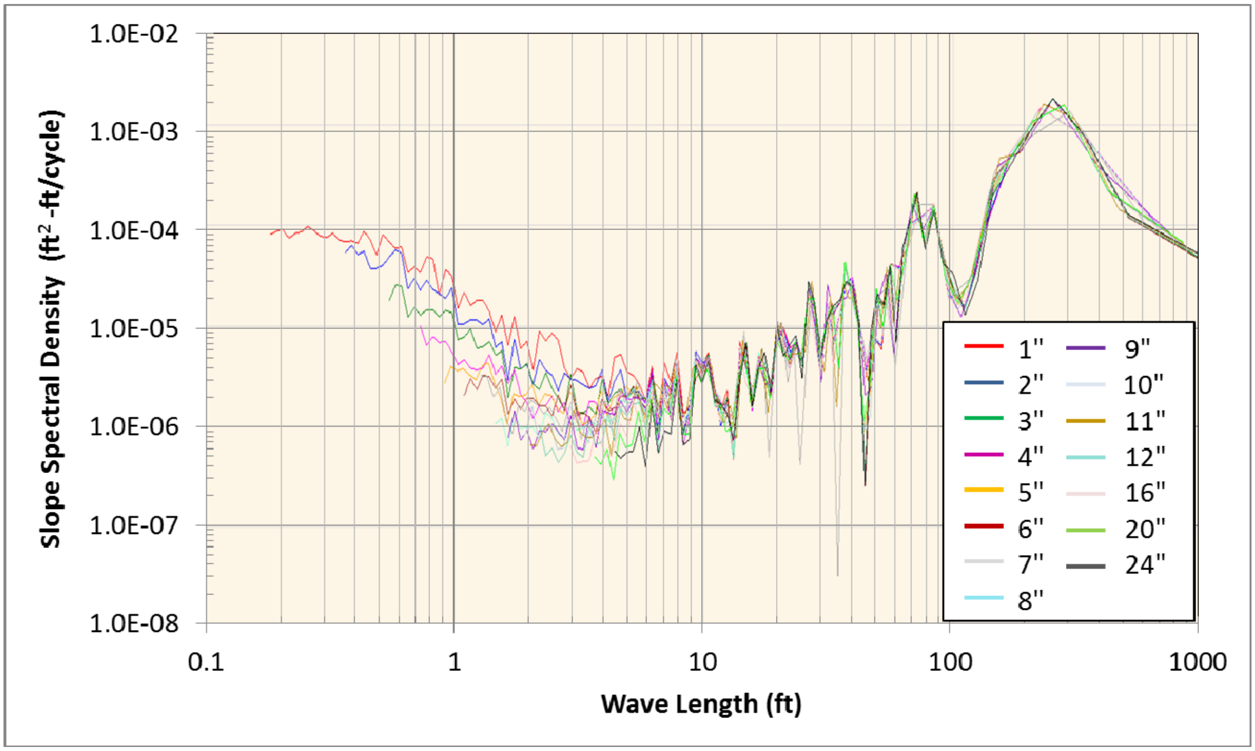
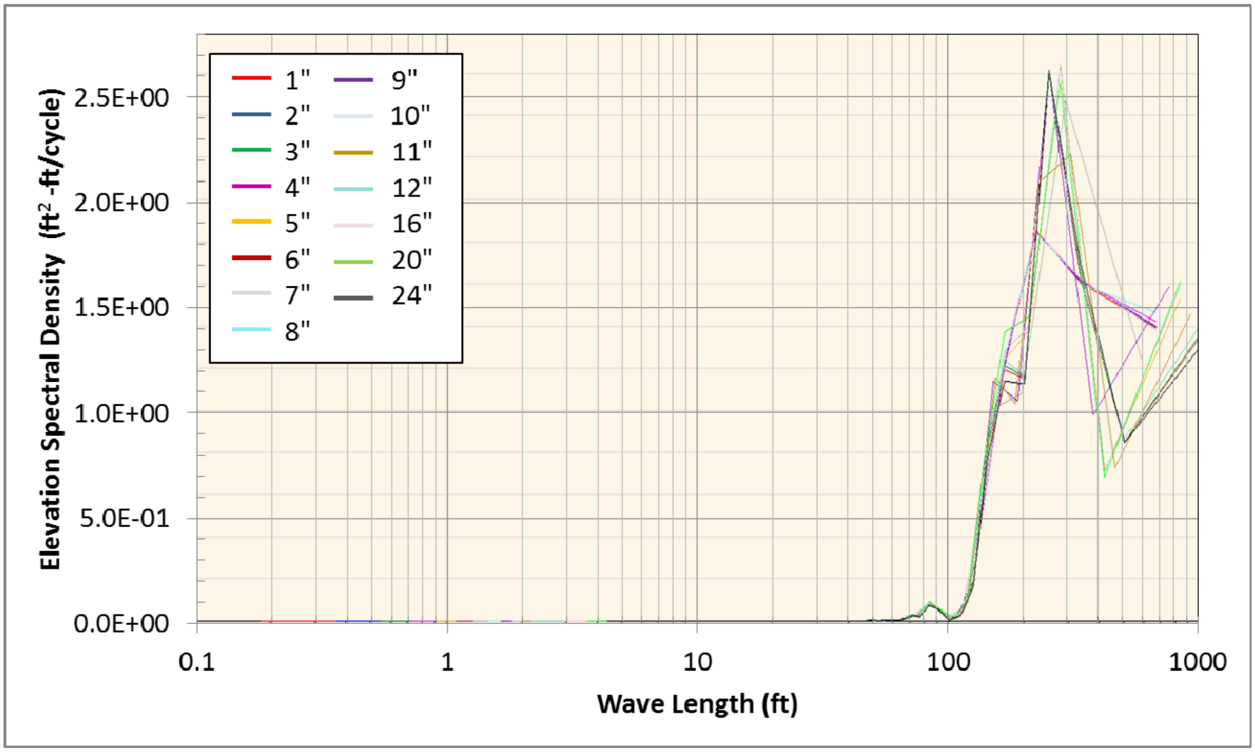


Figure 5.8: Comparison of wavelengths of slopes for the left wheel path for the TLS only (no –IRI filtering) with (a) arithmetic and (b) logarithmic vertical axes.



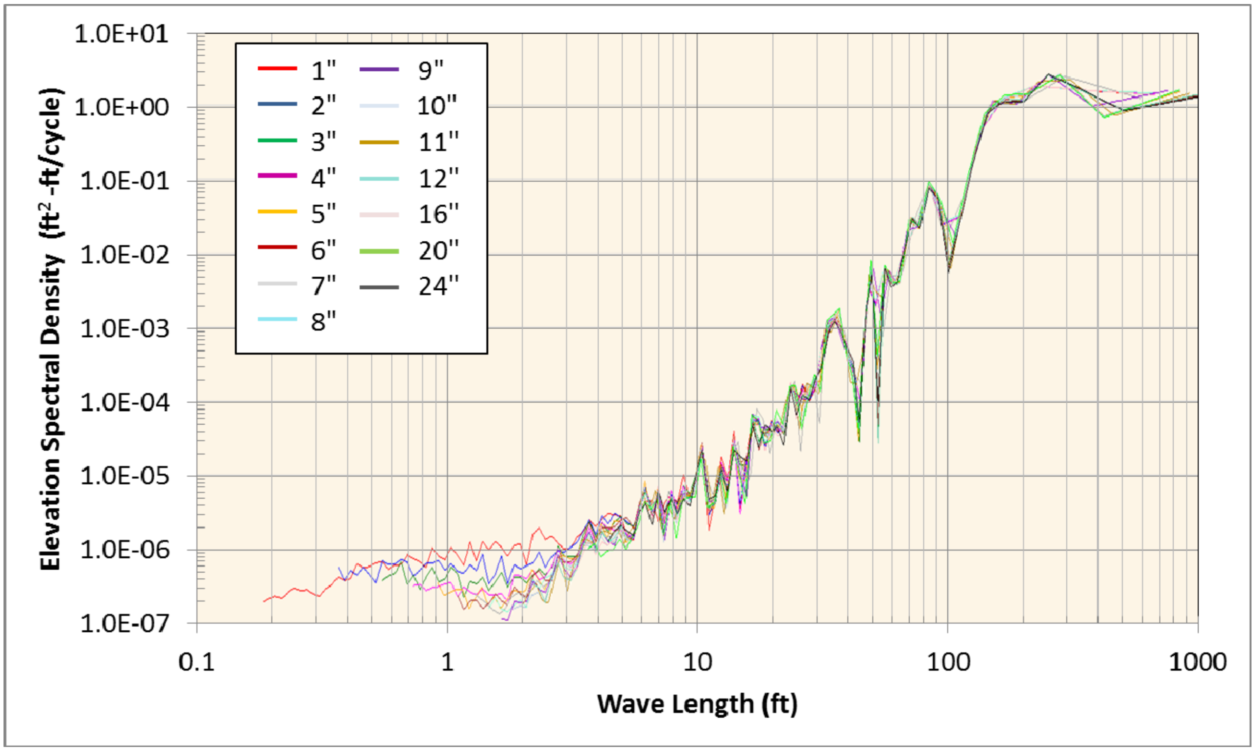


Figure 5.9: Comparison of wavelengths of elevations for the right wheel path for the TLS only (no –IRI filtering) with (a) arithmetic and (b) logarithmic vertical axes

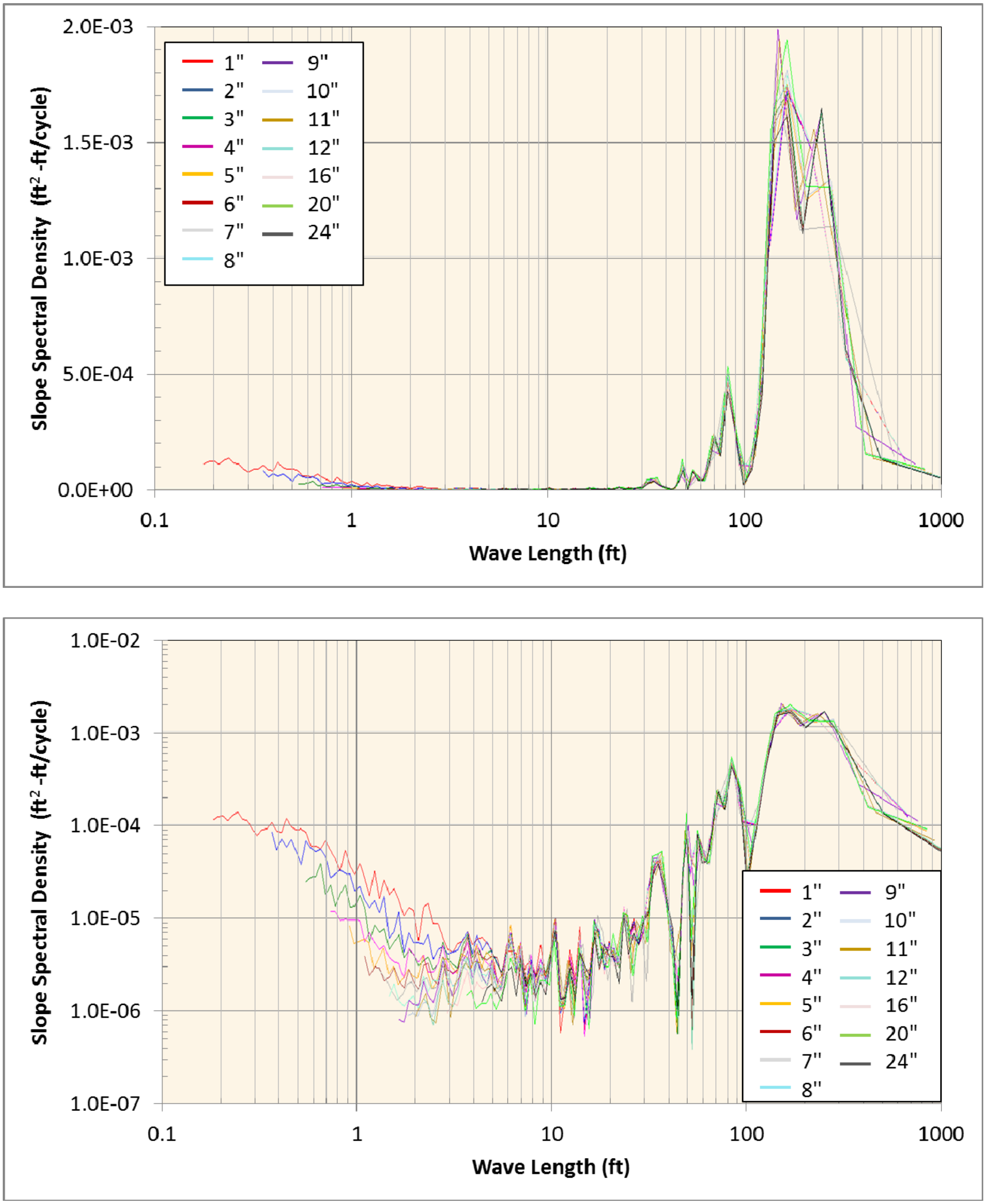


Figure 5.10: Comparison of wavelengths of slopes for the right wheel path for the TLS only (no –IRI filtering) with (a) arithmetic and (b) logarithmic vertical axes.

6.0 CURRENT PRACTICES AND PROCEDURES

The current ODOT test methods are found in ODOT TM 769: Method of Test for Certification of Inertial Profiler Equipment (ODOT 2011), and ODOT TM 772: Method of Test for Determining the International Roughness Index with an Inertial Laser Profiler (ODOT 2011).

ODOT TM 769 Section 5 lists the operator requirements, the operators are currently not required to be certified. It is recommended that this procedure is re-evaluated and that all inertial profiler operators are required to show proof of certification, in addition to the equipment certification. This will limit user error in inertial profiler data acquisition.

Most states' certification procedures tie specific operators to specific machines on an annual basis. Some states also require operators to be trained through National Highway Institute (NHI) and/or *ProVAL* smoothness classes, which ODOT may want to consider.

The calibration verification requirements are reasonable and correspond to the requirements found from other state specifications (Table 2.4) discussed in the literature review. However, the 8.0 in/mi bounce test requirement is lower than the 10 in/mi requirement found from other specifications.

The repeatability and accuracy requirements are currently lower than those from other states and AASHTO by 2% (Table 2.4). The AASHTO 90/92% accuracy and repeatability thresholds were established based on the FHWA 2004 profiler round up studies with 76+ devices on 5+ surfaces. Hence, they are very well supported by field data.

It is recommended that the repeatability score be increased from 90% to 92% to correlate with AASHTO and other state specifications. This is a requirement that is currently being met by the inertial profilers at the site.

However, the research results presented herein for the test site show some difficulty in meeting the 90% accuracy requirement at the test site. Given the large variability of IRI seen across the site, slight deviations in wheel paths can have a large influence when comparing devices. Further, the SurPro instrument used for the reference profile was recently re-calibrated following the June and November runs. This could lead to improved results that were not available for this study. It should also be noted that this study compared profiles collected across a large time span. It is very likely that accuracy results would improve if all profiles were collected within a short time frame.

One option ODOT can consider is to incrementally raise the accuracy requirement from 88% (current ODOT) to 90% (AASHTO) as the certification procedure matures. With time, ODOT personnel will receive more training and experience with the SurPro unit. Also, data from many certification runs will be available.

ODOT TM 772 specifically discusses the use of inertial profilers. The recommended certification frequency of once per year is reasonable. A clause should be added that any major repairs, modifications, adjustments, or damages to the equipment will require the profiler to be recalibrated. The requirements for the calibration check in ODOT TM 772 are also reasonable.

7.0 QUALITY ASSURANCE/QUALITY CONTROL

The current ODOT 772 (*2011*) procedures include a Quality Assurance section. For some projects, at ODOT's discretion, in order to use an inertial profiler at a project site, the contractor has to test the inertial profiler against a QA inertial profiler. Three test runs are completed and the IRI is obtained from the two runs with the closest IRI values. The requirement is that the IRI between the two instruments must be within ±8.0 in/mi. In the event that the error is larger than ±8.0 in/mi the profiler may have to be re-certified.

This specification is not as strict as those from other states. Michigan and Texas require the IRI to be measured to within 6 in/mi between the contractor and department (Wilde 2007). In an effort to keep current with other state DOTs it is recommended that the specification become more stringent and ODOT require an IRI agreement of ±6.0 in/mi. This seems reasonable given the results of this research, where IRI values were typically within +/- 5% (~3-4 in/mi) of each other.

However, with a strong certification program in place, QA procedures become less necessary. On-site QA can be more difficult to conduct.

8.0 ESTABLISHING A REFERENCE PROFILE

A question investigated in this research was the achievability of meeting AASHTO requirements when comparing inertial and inclinometer profilers. The Mn/DOT currently uses a SurPRO inclinometer as the reference profiler (*Mn/DOT 2011*). The certification requirements, as explained in the literature review, include an average cross correlation requirement of 90%, and the IRI must be within 5% of the reference. The data collected from this testing shows that the IRI is within 5% of the reference, and as previously mentioned, it is somewhat difficult to meet the 90% cross-correlation accuracy requirements.

The comparison of inertial and inclinometer profilers for repeatability shows that AASHTO requirements are still applicable and achievable.

Suggestions are included to improve the accuracy measurements using the SurPRO inclinometer as the reference:

- The inclinometer should not be used in freezing temperatures; it is recommended that certification is completed in the spring when temperatures have begun to stabilize.
- The DMI calibration is also a vital step to be completed prior to establishing the reference profile. Calibration for the DMI should be completed for both the inclinometer and the inertial profiler on the same test site. This will help to collect an accurate and reliable profile to use as a reference.
- It is also recommended that this profile be collect within one week of the start of the certification period to avoid environmental effects (such as expansion and contraction of the pavement itself, wear on the pavement surface, etc.).
- If a test site of Jointed Concrete Pavement is established, the test window for reference profiling should be even narrower (same day with minimal temperature variations, if possible) in order to minimize curl/warp effects.

Section 8.2.1 of AASHTO R56 provides guidance for site selection. While a current site has been established for the certification process, the following considerations are important in selecting a new site, should ODOT see the need in the future:

- The current site has significant IRI differences between the left and right wheel paths. This is beneficial in that it helps one spot a blunder of mis-labeling the wheel path quickly. However, as shown previously from the TLS data, there is substantial variability across the site. Hence, drift from drivers can have a large influence on the IRI values.
- The certification site should be centrally located with easy access.

- The certification site should have limited traffic and obstructions. The test section should be set up in an area where there will be no cross traffic, drive approaches, etc. to minimize disruption during field work.
- The site should have a gentle grade.
- The site should enable speeds up to 45 MPH. Note that most roads in Oregon that have speed limits adequate for some high speed profilers (operational speed requirement of 50-60 MPH) are high traffic highways or freeways, which will prove difficult. Hence, it is difficult to find a site that would meet the needs of those high speed profilers.
- The road section used for the site should be in good condition (proper drainage, minimal cracking, no potholes, etc.).

9.0 MICRO TEXTURE ANALYSIS

9.1 OVERVIEW

This study utilizes 3D laser scanning to investigate the effects of typical aggregate sizes on the overall texture of the pavement surface. The study found that pavements with a predominate aggregate size of 1.9 cm had the highest measured texture compared to 0.6 and 1.3 cm, providing smoother surfaces. Texture can be calculated in a variety of ways; this study focuses on three methods: root mean square height (RMSH), within-plot elevation range (WPER), and roughness (triangular surface) ratio. This study also provides guidance to sampling strategies using micron resolution scanners for pavement applications. A common practice to help scan dark surfaces is to apply a thin coat of powder; however, the powder will alter the calculated texture. The optimal settings to provide the most complete scans consist of 388 points/cm2 density, neutral or light exposure settings, and scanning from a distance of 16 or 43 cm.

9.2 INTRODUCTION

The overall roughness of the pavement surface will have an impact on the service life of a roadway; a smoother road will have a longer service life (*Sayers and Karamihas 1998*). The roughness of pavement is impacted, among other things, by the sizes of the aggregate used in the mix. Normally, a variety of aggregate sizes can be found in a mix; however, each mix will tend to have a predominant aggregate size (PAS).

Fine-scale, 3D laser scanning (Figure 9.1) offers sub mm accuracy (0.1-0.4 mm) and can be used to evaluate the texture of small sections of pavement, which impacts the roughness. Laser scanning has been used to study particle size and roughness on soil. In one study, the roughness was computed in three different ways: within-plot elevation range (WPER), root-mean squared height (RMSH), and local root-mean squared height (locRMSH) (*Haubrock et al. 2009*). The results of the study showed that larger particles, as well as the edge of the scan boundary, result in larger deviations in the measurements (*Haubrock et al. 2009*).

Tutumluer et al. (*2005*) conducted a related study to investigate the effects of aggregate shapes on pavement performance. However, this study was done using three camera angles on various aggregate particles instead of using a 3D laser scanner. 3D laser scanning offers some improvements over traditional image analysis procedures, such as: 3D models, improved details, and does not rely on external lighting.

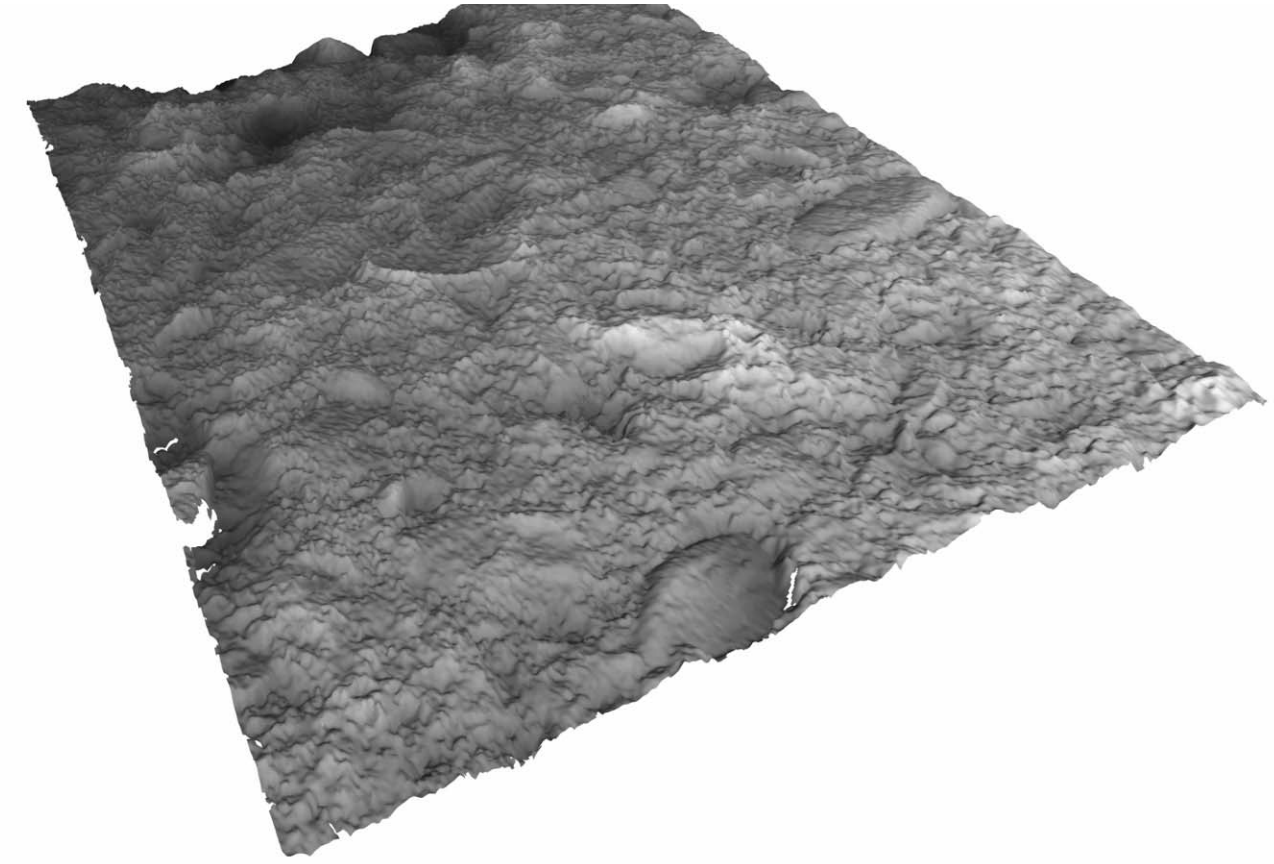


Figure 9.1: 3D texture model of pavement surface for a 125 x 100 mm section.

9.3 OBJECTIVES

The overarching objective of this study is to investigate the use of fine-scale 3D laser scanning in the determination of pavement texture. This chapter documents the findings from the effects of different aggregate sizes and scanning parameters to calculate texture roughness. The 3D laser scan settings varied between the distance mode, exposure settings, and sampling density settings. This study also evaluates the impact of using powder on the texture measurements. Powder is recommended by the scanner manufacturer to improve laser reflectivity on dark surfaces (e.g., asphalt).

9.4 ACQUISITION METHODOLOGY

Testing for this study was conducted using a Next Engine, micron-resolution, 3D laser scanner. The 3D laser scanner is able to obtain accuracies within ±0.127 mm. The scanner is equipped with three different distance settings: macro (16 cm), wide (43 cm), and extended (76 cm), each of which provides a different field of view. Scans can be collected at varying densities ranging from 248 points/cm^2 to 6,200 points/cm^2. In addition, the scanner can be adjusted according to the surface color (light, neutral, or dark). These options were evaluated to determine the best settings to use in the determination of the effect of aggregate size on local pavement surface texture.

The testing for this study was divided into two phases:

(1) Evaluation of scanner settings through scanning pavement samples in a laboratory. This phase determined the optimal settings for scanning dark pavement surfaces by using laboratory samples. The 3D laser scanner manual suggests applying powder to dark surfaces due to the difficulty in collecting data on dark surfaces (i.e., poor reflectance of light), resulting in several data gaps.

(2) Field scanning of in-situ pavement. The second phase was to collect data on small sections of field pavement with varying aggregate sizes: 0.6 cm, 1.3 cm, and 1.9 cm, using the desired settings obtained from the first phase.

9.4.1 Phase 1: Laboratory Sample Testing

For the first phase, pavement samples were scanned using various combinations of settings (distance, resolution, and exposure) on the scanner and with/without powder applied. A total of 36 scans were completed on each sample, 18 with, and 18 without powder (Table 9.1). For control purposes, a flat tabletop surface was also scanned using the light setting for the exposure and varying the resolution corresponding to scan settings 1-6 from Table 9.1. The laboratory sample tests were all completed at a distance of 16 cm, an estimated accuracy of ±0.127 mm, and a field of view of 8x13 cm.

Table 9.1: 3D laser scanner settings for laboratory sample tests taken at a distance of 16 cm (±0.127 mm accuracy, 8x13 cm field of view)

Scan No.	Exposure	Density (points/cm^2)	Scan No.	Exposure	Density (points/cm^2)	Scan No.	Exposure	Density (points/cm^2)
L1_L	Light	248	L1_N	Neutral	248	L1_D	Dark	248
L2_L	Light	388	L2_N	Neutral	388	L2_D	Dark	388
L3_L	Light	682	L3_N	Neutral	682	L3_D	Dark	682
L4_L	Light	1550	L4_N	Neutral	1550	L4_D	Dark	1550
L5_L	Light	2635	L5_N	Neutral	2635	L5_D	Dark	2635
L6_L	Light	6200	L6_N	Neutral	6200	L6_D	Dark	6200

9.4.2 Phase 2: In Field Pavement Scanning

Following evaluation of optimal parameters for asphalt scanning, scans of in-field pavement surfaces were completed on sections with three different aggregate sizes, with the settings listed in Table 9.2. The scans were completed using the test assembly in Figure 1, which enables the scanner to be mounted at 16 cm (Macro), 43 cm (Wide), and 76 cm (Extended) from the target. The further the scanner is from the target, the larger the field of view at the expense of resolution. The test assembly was not moved between scans. Data was collected on the pavement first without powder and then with powder applied, enabling the same pavement sample to be tested for both conditions.

Table 9.2: 3D laser scanner settings for field pavement testing

Scan No.	Exposure	Density (points/cm^2)	Distance (cm)	Field Size (cm)	Accuracy (mm)	Powder
F1	Light	248	16	8x13	0.127	No
F2	Light	1550	16	8x13	0.127	No
F3	Neutral	388	16	8x13	0.127	No
F4	Dark	388	16	8x13	0.127	No
F5	Neutral	388	43	25x33	0.381	No
F6	Neutral	388	76	41x56	0.381	No
F7	Light	388	76	41x56	0.381	Yes
F8	Light	388	43	25x33	0.381	Yes
F9	Neutral	388	43	25x33	0.381	Yes
F10	Light	388	16	8x13	0.127	Yes
F11	Neutral	388	16	8x13	0.127	Yes
F12	Neutral	2635	16	8x13	0.127	Yes

Figure 9.2: Pavement texture analysis scanner set up

9.4.3 Texture Roughness Calculations

The texture roughness of the pavement was calculated using three different methods: ratio, root mean square height (RMSH), and within plot elevation range (WPER). Note that each of these methods compute a global (i.e., entire section) value to represent texture. Further, the values calculated can consistently provide an indication of surface texture within a method but cannot be directly compared between methods.

The roughness ratio is simply calculated as the ratio of the 3D surface area to the 2D planar projected area. A rough section would have more surface area compared to a projected area due to curvature; whereas a flat section would have equivalent surface area and projected area, resulting in a roughness ratio of 1.

The RMSH method (*Haubrock et al. 2009*) is calculated by:

$$RMSH = \sqrt{\frac{1}{MN} * \sum_{c=0}^{M-1} \sum_{r=0}^{N-1} [z(x_c, y_r) - \mu]^2} \qquad \textbf{(9-1)}$$

where:

M and N are the number of columns and rows, respectively, in the scan grid

c and r are the column and row indices,

μ is the average elevation for the dataset,

z(xc,yr) is the elevation at each grid point.

The WPER method calculates the differences between the minimum and the maximum elevation values in the dataset for a quantification of texture (*Haubrock et al. 2009*).

9.5 RESULTS AND DISCUSSION

Following acquisition, the scans were analyzed to find the optimal 3D laser scan settings by comparing the texture values using all three calculation methods.

9.5.1 Sample Testing

The texture of the laboratory pavement samples were calculated using all three methods. Results from the roughness ratio calculations are shown in Figure 9.3 for Sample 2 and correspond to the settings from Table 9.2 first without powder (outline shapes) and then with (solid shapes).

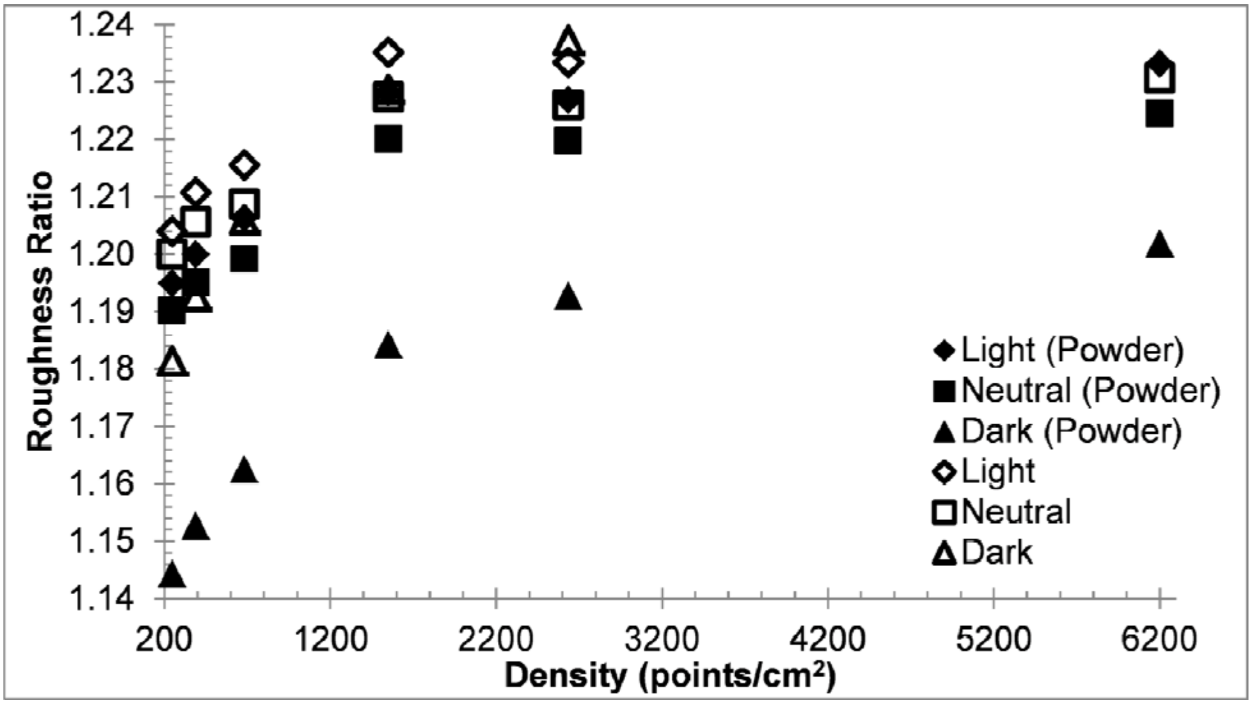


Figure 9.3: Lab Sample 2 roughness ratio versus density for samples with and without powder for light, neutral, and dark exposure settings at a distance of 16 cm from the scanner and increasing point density

From Figure 9.3, it can be determined that an increase in the density of the scan results in an increase in the texture measurement. This is an expected result since additional data points are being collected and analyzed in the higher density scans. However, the trend flattened out for tests with density settings of 1,550-6,200 points/cm2. This shows that the increase in scan density between that range will not have an effect on the calculated texture of the surface. The dark surface settings, as previously mentioned, did not obtain sufficient scan images, these images had many areas of missing data and therefore did not provide a reliable texture calculation.

The flat tabletop was used as a baseline reference for each of the methods. Scans of this surface showed roughness ratios nearly equal to 1, enabling validation of the methodology and code implementation. The WPER texture on a flat surface was calculated to be between 1.5-1.8 mm and the RMSH was 0.00-0.25 mm. Table 9.3 shows a more thorough comparison of the varying roughness values from a test sample with powder, as these scan images contained the least number of holes. The WPER and ratio methods exhibited the same trend of increasing texture at increased densities.

The texture calculations of the ratio and WPER methods from the scans with powder applied to the surface were consistently lower than scans without powder. The lower values are most likely a result of the powder filling the holes on the surface and therefore smoothing the surface. Although the powder is very fine, it is difficult to apply the powder evenly to ensure that it will not fill in the holes.

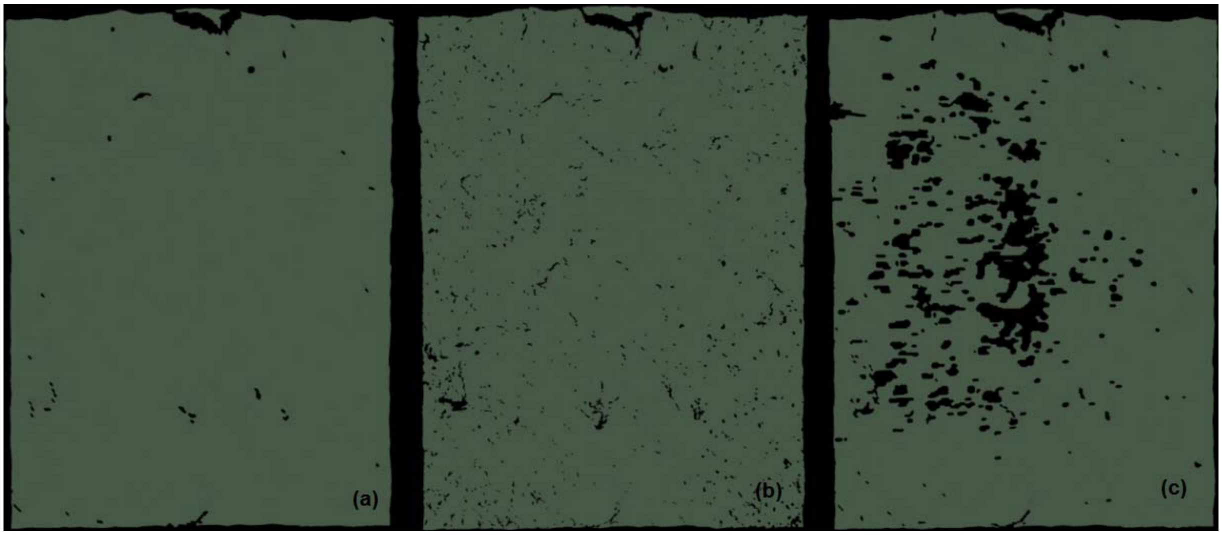


Figure 9.4: Sample test scan images at a 16 cm distance with powder
(a) good (neutral, 248 points/cm2), (b) fair (light, 2,635 points/cm2), (c) poor (dark, 388 points/cm2)

Table 9.3: Comparison of roughness calculation methods on a test sample with powder

Scan No.	Ratio	RMSH (mm)	WPER (mm)
L1_L	1.1167	1.6257	13.8947
L2_L	1.1321	1.5981	14.0015
L3_L	1.1533	1.5995	14.1013
L4_L	1.1750	1.6303	14.1721
L5_L	1.1850	1.6264	14.3127
L6_L	1.1895	1.6228	14.2806
Avg (StDev)	1.1586 (0.0297)	1.6171 (0.0144)	14.1272 (0.1616)
L1_N	1.1105	1.6084	13.7255
L2_N	1.1235	1.5826	13.8171
L3_N	1.1391	1.5922	13.9558
L4_N	1.1593	1.6180	13.9385
L5_N	1.1669	1.6191	14.0715
L6_N	1.1695	1.6171	14.0896
Avg (StDev)	1.1448 (0.0244)	1.6062 (0.0154)	13.9330 (0.1419)
L1_D	1.1153	1.6265	13.8158
L2_D	1.1306	1.5957	13.8901
L3_D	1.1508	1.6013	13.9919
L4_D	1.1819	1.6345	14.1254
L5_D	1.1963	1.6323	14.1635
L6_D	1.2018	1.6327	14.1906
Avg (StDev)	1.1628 (0.0359)	1.6205 (0.0173)	14.0296 (0.1547)

The sample lab test images were used to select the settings that would provide the most complete scans with minimal holes for the field pavement samples. Scans collected were not always complete; many scans had holes or sections of missing points (e.g., image c in Figure 9.4. Despite asphalt pavement being a dark surface, the dark settings on the scanner generally did not provide usable images. With large gaps in the data, poor scans provide an inaccurate pavement texture measurement. Scan settings were selected for pavement testing in an attempt to avoid poor scan images (images with many holes and areas of missing data) and the resulting inaccurate texture measurements. However, despite the use of optimal parameters, rough or broken pavement will produce occlusions (holes) in the scan image by blocking visibility, such as those seen at the top of the scans in Figure 9.4.

9.5.2 Pavement Testing

The pavement testing was completed using the same 3D laser scanner settings for pavement surfaces of each predominant aggregate size tested (0.6, 1.3, 1.9 cm). The settings for each scan number were previously presented in Table 9.2. The texture calculations from the three different methods were calculated, and it was determined that the RMSH calculations do not provide a valid assessment of texture for this work because the values did not correlate with the results from the other two methods. The RMSH calculations showed surfaces to be rougher than others when the ratio and WPER methods showed the surface to be smoother, as seen in Table 9.4. The changes in texture calculations are more clearly distinguished in Figure 9.5.

Table 9.4: Roughness calculation results for field pavement testing

		Roughness Ratio			WPER (mm)			RMSH (mm)		
	Scan Size	0.6 cm	1.3 cm	1.9 cm	0.6 cm	1.3 cm	1.9 cm	0.6 cm	1.3 cm	1.9 cm
No Powder	F1	1.0613	1.0468	1.1573	4.8836	3.4781	6.0056	0.7078	0.4227	0.8191
	F2	1.1115	1.0944	1.1997	5.3764	3.8562	6.1191	0.7349	0.4591	0.8351
	F3	1.0643	1.0515	1.1611	5.0281	3.4694	5.9940	0.7237	0.4408	0.8283
	F4	1.0717	1.0739	1.1670	5.2021	3.6402	5.8996	0.7289	0.4458	0.8283
	F5	1.0330	1.0275	1.1135	7.2435	4.4562	6.7349	1.0524	0.8032	0.9831
	F6	1.0333	1.0483	1.0869	6.5512	5.8541	10.0758	1.3390	1.6437	1.6598
Powder	F7	1.0406	1.0421	1.0828	5.4405	5.7044	10.8143	1.9207	3.8462	1.6636
	F8	1.0296	1.0264	1.1047	6.1651	4.5532	6.8140	0.9064	0.7828	0.9796
	F9	1.0281	1.0229	1.1042	6.3150	4.8899	6.8991	0.9097	0.7227	0.9797
	F10	1.0610	1.0496	1.1601	4.8909	3.6288	6.0641	0.7273	0.4717	0.8252
	F11	1.0566	1.0737	1.1539	4.9341	4.0066	6.0708	0.7335	0.4943	0.8213
	F12	1.0860	1.0459	1.1827	5.1020	3.6321	6.1947	0.7511	0.4736	0.8363
	AVG	1.0564	1.0502	1.1395	5.5944	4.2641	6.9738	0.9363	0.9172	1.0050
	STDEV	0.0254	0.0213	0.0391	0.7807	0.8415	1.6649315	0.3626	0.9841	0.314

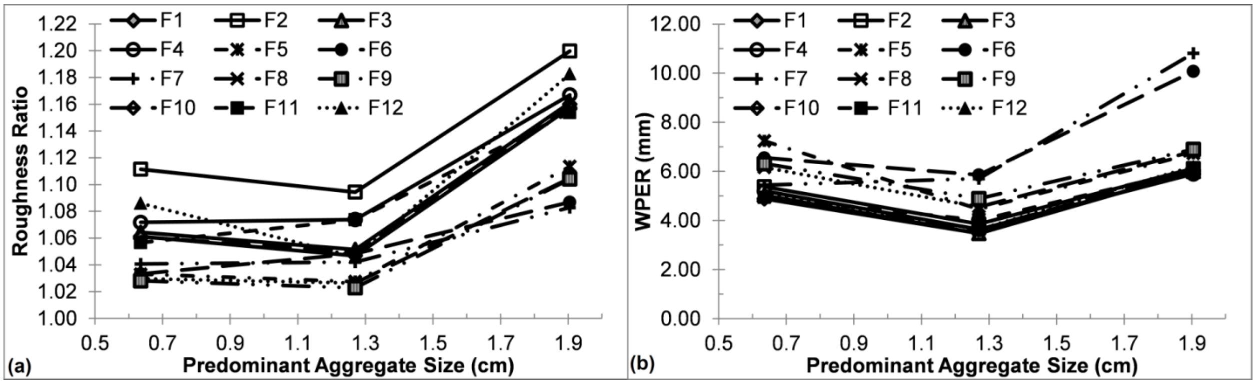


Figure 9.5: Roughness ratio and WPER results from in-field pavement testing

As expected, the larger aggregate size of 1.9 cm resulted in increased roughness calculations. However, it is interesting to note that the 0.6 cm aggregate pavement was slightly rougher than the 1.3 cm aggregate pavement. It would be assumed that the smaller aggregate sizes would decrease the texture of the surface but this was not seen in the data. However, the roughness ratio calculations show that the average texture for the 0.6 and 1.3 cm samples were very close: 1.0564 and 1.0502 respectively. The WPER plot and average calculations showed a larger texture deviation between the two pavement samples (1.3 mm), highlighting the influence of the various texture calculation methods. The roughness ratio results show similar trends.

Table 9.5: Settings and roughness results from the most complete 3D laser scan images

Aggregate Size	Optimal Settings				Roughness		
	Exposure	Density (points/cm^2)	Distance (cm)	Powder	Ratio	WPER (mm)	RMSH (mm)
0.6 cm	Neutral	388	16	No	1.0643	5.0281	0.7237
0.6 cm	Light	388	16	Yes	1.0610	4.8909	0.7273
1.3 cm	Neutral	388	16	No	1.0515	3.4694	0.4408
1.3 cm	Light	388	16	Yes	1.0496	3.6288	0.4717
1.3 cm	Neutral	388	16	Yes	1.0737	4.0066	0.4943
1.9 cm	Neutral	388	43	No	1.1135	6.7348	0.9831
1.9 cm	Light	388	43	Yes	1.1047	6.8140	0.9796

The scans shown in Table 9.5 were selected from the scans that provided the most complete image and, therefore, the most accurate texture. The wide setting produced scans with fewer holes for the 1.9 cm aggregate size but the macro setting had fewer holes for the 0.6 cm and 1.3 cm aggregates. The optimal exposure setting without powder was neutral, but with powder was light. Overall, the 388 points/cm^2 density setting produced the best images for scan analysis.

Unlike the texture results from the sample testing, the use of powder on the pavement testing did not always result in a lower texture measurement. However, due to the fact that good scan images can be obtained without the use of powder by adapting settings, it is not recommend that any powder be applied because of its effects on the calculated texture.

9.6 CONCLUSION

The micron resolution 3D laser scanner was able to distinguish texture variations of the surfaces using three methods: roughness ratio, WPER, and RMSH. The RMSH did not prove to be an effective way to measure the texture of the surface; it did not provide results that correlated to the roughness ratio or WPER methods.

Ironically, the dark exposure setting on the 3D laser scanner did not provide a complete image of the pavement surface, with several, large data gaps. The light exposure setting produced the best image when powder was used, and the neutral setting performed best when powder was not used. Since pavement, particularly newer pavement, is so dark, the use of powder may be required to obtain a scan image. However, this practice is not recommended. Although application of powder did not have a consistent effect on all pavement samples, it did affect the overall texture measurement. The powder decreased the texture when used on the lab sample tests, but had variable effects on the field pavement tests. It is difficult to apply an even layer of powder on the surface which accounts for some of the differences in texture measurements. The texture increased when powder was applied to pavements with a predominant aggregate size of 1.9 cm.

Predominant aggregate size plays an important role in the texture of the pavement surface. The larger aggregate size of 1.9 cm produces a rougher surface. Any aggregate particles that break apart from the surface will leave a larger gap on the surface which will impact the calculated texture. It is interesting to note that in general the 0.6 cm aggregate pavement is rougher than the 1.3 cm pavement.

Further research may provide insight on the reasoning for 0.6 cm aggregate pavement being rougher than 1.3 cm aggregate pavements. The effects of time could be studied by continuously monitoring pavement sections using the high resolution laser scanner. Such a study could provide insight on how well the various aggregate sizes in the pavement mix withstand the traffic and environmental effects of time.

10.0 CONCRETE LITERATURE REVIEW

10.1 INTRODUCTION

The measurement of roughness on portland cement concrete (PCC) pavements is being transitioned from PI to IRI in some states. There are 14 states using IRI and 5 states using IRI-defined localized roughness metrics (George Chang, Transtec, personal communication 7/17/2012). An IRI based measurement will allow highway agencies to track the roughness over the life of the road (*Perera et al. 2005*). Unfortunately however, the above two smoothness indices cannot be correlated with an equation. Studies have been conducted by agencies including the FHWA, Kansas DOT and Minnesota DOT on the use of IRI to measure PCC pavement roughness.

Construction of PCC pavements can impact the overall ride quality if proper care is not taken. Dowels, headers, tensile strength, and aggregates are some examples of construction influences. It is important that proper procedures and checks are completed during construction for the road to have a low initial IRI and remain in good condition over time. Pavements will exhibit similar rates of roughness progression regardless of the initial IRI value (*Akhter et al. 2004*). However, this means that a lower initial IRI will not reach a level of unacceptable roughness as quickly as a roadway with a higher initial IRI. Unlike asphalt which is ready to be driven on hours after placement, PCC pavements require long curing times.

Studies have been conducted to determine the optimal time to measure the roughness. Since the concrete needs time to cure and smoothness is typically measured after completion of paving, a high speed inertial profiler cannot be used to measure the roughness immediately after paving (*Perera et al. 2005*). Instead, a light weight inertial profiler is used such as the one seen in Figure 10.1. However, the studies also discuss whether the roughness of the pavement needs to be measured so quickly after completion. Particularly since underlying soil consolidation settlement processes from the highway and/or embankment placement may take time to complete.


Figure 10.1: Example of a light weight inertial profiler (Ames Engineering 2010)

This literature review details the studies conducted on PCC pavements. Included are the implications of construction methods and the considerations for IRI measurement instead of PI.

10.2 FACTORS AFFECTING IRI

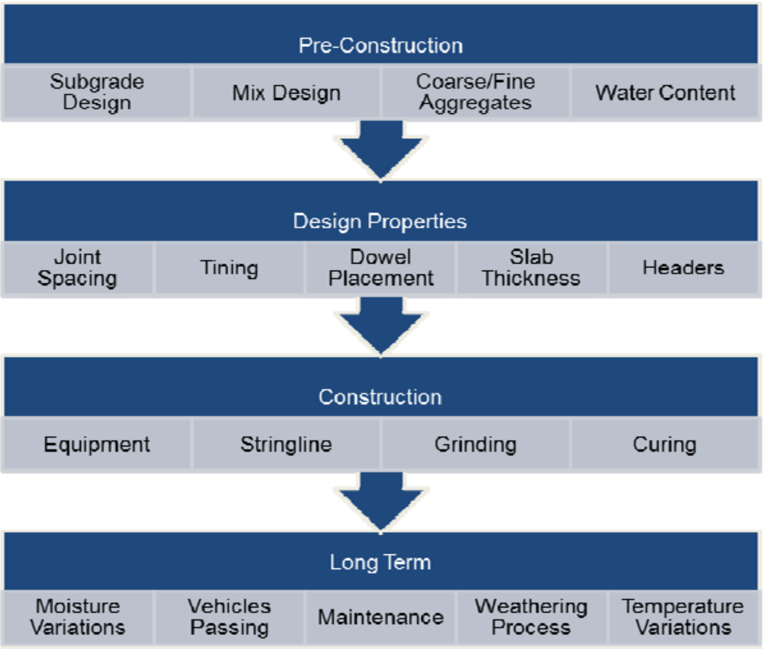


Figure 10.2: PCC pavement design and construction factors affecting IRI

Construction factors (Figure 10.2) will influence the level of roughness of the pavement surface. Precautions during construction can limit these factors and provide a smooth road surface. These factors are important both in the pre-construction mix design and paving stages of the construction process. Considerations for PCC pavements should also take into account the post construction implications of pavement roughness.

10.2.1 Pre-Construction

The concrete mix design is an important aspect of the overall roughness of the PCC pavement. Studies were conducted to determine if smoothness specifications would cause contractors to alter the mix design to create a smoother surface but would result in an increased rate of roughness progression (*Perera et al. 2005*). The FHWA report stated that this did not occur. There are still considerations for the concrete mix design to improve the life of the pavement.

Higher tensile strength PCC will remain smoother over time (*Perera et al. 2005*). This will ultimately increase the life of the pavement surface (*Akhter et al. 2004*). However, pavement with a high elastic modulus will become rougher faster.

Within the concrete mix, a higher coarse to fine aggregate ratio leads to better long term smoothness (*Perera et al. 2005*). Proper care must be taken during mixing since a higher water to cement ratio will cause the PCC pavement to deteriorate at a faster rate, which means that the surface will be rougher (*Akhter et al. 2004*).

10.2.2 Construction Factors

During construction of PCC pavements stringlines, headers, and dowel bars (in the case of JPCP or JRCP) are used. Improper implementation of each of these procedures can lead to an increased roughness. Diamond grinding can be used to smooth out areas of localized roughness along the roadway. Although grinding may eliminate some of the rough areas, this may also have implications on the progression of roughness over the lifetime of the pavement (*Akhter et al. 2004*). Hence, it is important to limit grinding depth.

Stringlines are used as a guide on slipform pavers and must be kept tight to reduce sag. Sagging is caused by changes in temperature and humidity and will result in an increased IRI (Kohn *et al*. 2008). The sag can be seen in analyzing profiles in *ProVAL* from the power spectral density plot since the locations of high IRI will be equally spaced. The analysis will show that the most wavelength influencing the IRI the most is the stake spacing and its sub-harmonics. From the study by Kohn, *et al*. (*2008*) the sag increase of 0.1 in (2.5 mm) resulted in an IRI increase of 12% and a sag increase of 0.5 in (12.7 mm) resulted in a 154% IRI increase. The study used 50 ft (15.2 m) stake spacing. However, shorter stake spacings are now typically used.

The header is a joint created by a wooden form or a cut back method and is constructed at a leave out, intersection, bridge, or the end of a day of paving. Headers will cause an increase in IRI and will be shown as localized roughness (*Kohn et al. 2008*). Grinding will not eliminate this area of localized roughness.

Dowel bars can increase the IRI from spring back of the dowel basket, damming at the dowel basket, reinforcement ripple, or lack of consolidation where the concrete will settle over the dowels (*Perera et al. 2005*). However, dowels will increase the smoothness over the lifetime of the surface, which means that the construction of dowel bars should be carefully monitored. Further, Dowel bar inserters on some slipform pavers can cause roughness issues.

Grinding will reduce the roughness caused by dowel spring back during the construction procedure (*Kohn et al. 2008*). However, it will not result in reduced rate of roughness progression; it will only provide temporary smoothness (*Akhter et al. 2004*). Grinding may cause additional harm since it will expose the aggregates to environmental effects.

In addition to the construction process, attention must be paid to the overall pavement design. A permeable subbase will increase the lifetime of the pavement since the surface will remain smoother for longer (*Akhter et al. 2004*). The subbase must be allowed to properly drain and stabilize the surface, the FHWA recommends constructing the base at least 3.3 ft beyond the slab edge (*Perera et al. 2005*).

10.2.3 Post Construction

Following the construction of PCC pavements, the surface may experience temperature curling. Curling of PCC pavements can occur in an upward or downward direction (*Perera et al. 2005*). This process may not be immediate and may occur months after paving is completed. Curling will cause an increase in the IRI. Temperature changes throughout the day will cause slab curling, while long term moisture changes within the slab will cause warping. Due to the temperature changes throughout the day the slab will typically curl upward in the morning when the top of the slab is cooler than the bottom. The slab will curl downward when the top of the slab is warmer than the bottom in the afternoon. Dowels can be used to prevent significant upward curvature. In a recent study on curling and warping of concrete pavements, (*Chang, et al. 2008*) have shown, however, that this may not always be the case. In this study, they developed a procedure to measure and characterize curvature and warping, a method to synchronize profiles and identify joint locations, a metric to quantify slab curvature, and a system to quantify the impact of curvature on ride quality for jointed concrete pavements.

The effects of slab thickness have also been analyzed. It was found that a thicker slab will have a smoother pavement surface due to a larger flexural rigidity (*Wen and Chen 2007*). This is true for pavement with and without dowels. The thicker slab will exhibit less curvature.

10.2.4 Long Term

Following the completion of paving, the surface is exposed to many environmental factors. A report from MnRoad found that environmental weathering and time have a greater impact on roughness progression of PCC pavements than traffic (*Thompkins et al. 2006*).

10.3 DIFFERENCES BETWEEN PI AND IRI

A study from the Kansas Department of Transportation concluded that PI and IRI values cannot be correlated (*Akhter et al. 2004*). The study collected data on jointed concrete pavements that were constructed after 1992 with lengths of 1 mi to 10 mi. It was found that the initial IRI is lower than the PI. Based upon the IRI smoothness specifications this would indicate that the road would remain smoother for a longer period of time. The study also found that the subgrade moisture content will stabilize and traffic will smooth minor defects causing the roadways with a high initial IRI to become smoother over time (*Akhter et al. 2004*).

The Minnesota Department of Transportation and Minnesota State University, Mankato conducted a study to investigate the implementation of IRI in pavement construction and rehabilitation (*2007*). The research is focused on PCC and the transition from PI to IRI. There are several aspects that have a different effect on PI than IRI such as joints, stringline sag, and tining.

The IRI and PI do not respond to different wavelength frequencies in the same way, as a result, there is a discrepancy between the two (*Wilde 2007*). For example, the IRI value will be more sensitive to a 15 ft wavelength (*e.g.* joint spacing). However, a 25 ft wavelength, corresponding to stringline spacing, will be more influential on the PI (*Wilde 2007*). This is an example where the size of the wavelength can be correlated to the construction process to determine the reason for localized roughness.

Another construction technique that will affect PI and IRI differently is tining. The PI will increase from tining but the effect on IRI is negligible (*Wilde 2007*). However, if the construction is not done properly and the depth of tining is larger than allowable, the IRI will increase.

10.4 RECOMMENDATIONS FROM STUDIES

The FHWA studied the smoothness of concrete pavements in addition to the long term performance (*Perera et al. 2005*). The study researched the long term performance of PCC pavements that had a high initial smoothness, as well as properties resulting in a high initial smoothness but poor long term performance. The smoothness of new PCC pavements was measured 1 day, 3 days, 7 days, and 3 months after the completion of paving. It is important to measure the IRI using an inertial profiler that has been certified on PCC pavement (*Perera et al. 2005*). An instrument certified on asphalt will not produce accurate data because of the differences in the overall construction of the surface such as joints (*Perera et al. 2005*). Additionally, inertial profilers produced by different manufacturers may create discrepancies between IRI values, the joints may not be measured the same way (*Perera et al. 2005*). Further, the aggressive surface texture caused by tining, burlap drag, and grinding introduce aliasing to the profile measurements, which can be more substantial than joint effects.

The study from the FHWA also determined that the IRI can be measured at any time within the first few months of paving completion (*Perera et al. 2005*). Quick identification is advantageous since the study concluded that paving equipment and the construction process has the largest effect on smoothness. Any errors in the process can be fixed before continuing to the next section and certain procedures can be more closely monitored.

Lightweight profilers allow the surface to be tested frequently during construction within a few days (typically 72 hours) of placement (*Kohn et al. 2008*). The profilers will not cause any damage if the concrete has been allowed sufficient time to harden. Collecting profile data following a day of construction can improve the construction process by finding errors and being able to immediately fix the problem rather than waiting until the end of the project.

The Minnesota Department of Transportation produced a report on the implementation of IRI (*Wilde 2007*). The report provides recommendations for IRI specifications stating that the IRI should be measured within the first 24 hours after the joints have been sealed and before the roadway has been opened to traffic. The report recommends that corrective action should be taken for PCC pavements with IRI above 90 in/mi. However, note that this report is based on a continuous roughness report using a 25 ft base-length moving average.

The Minnesota Department of Transportation also issued a report on combined smoothness testing (*Wilde and Nordstrom 2010*). The report includes a draft of the combined specifications for bituminous and concrete pavements with details of IRI requirements for a 0.1 mile segment (Table 10.1).

Table 10.1: Example of pay adjustments for PCC pavements from Mn/DOT where PCC-A is used for sites with a 45 mph or greater speed limit and PCC-B is for rehabilitation projects that requires concrete grinding (*Wilde and Nordstrom 2010*)

Equation	English		Metric	
	IRI (in/mi)	Pay Adjustment ($/0.1mi)	IRI (m/km)	Pay Adjustment ($/0.1609km)
PCC-A	< 50.0	890.00	< 0.79	890.00
	50.0 to 90.0	2940.00 - 41.000 X IRI	0.79 to 1.42	2940.00 - 2597.800 X IRI
	>90.0	Corrective Work to 71.7 in/mi or lower	> 1.42	Corrective Work to 1.13 m/km or lower
PCC-B	< 50.0	450.00	< 0.79	450.00
	50.0 to 71.2	1511.30 - 21.226 X IRI	0.79 to 1.12	1511.30 - 1344.900 X IRI
	71.3 to 90	0.00	1.13 to 1.42	0.00
	>90.0	Corrective Work to71.3 in/mi or lower	>1.42	Corrective Work to 1.1. m/km or lower

For concrete pavements, the specifications state that the testing site should begin 50 ft before and commence 50 ft after a terminal header. The state requires that a roughness report is submitted within 5 days of paving completion and before any corrective action is taken. Following corrective action, the report states that a new roughness report is submitted within 5 days. All testing is to be completed using an inertial profiler with an IRI roughness index.

10.5 CONCLUSION

States are transitioning from PI to IRI because IRI is more relevant to ride quality. The PI is based on distorted pavement surface deviation caused by the support wheel sets and the measuring wheel, which is not directly representative of ride quality. The differences between PI and IRI do not allow for a simple transition to IRI in smoothness specifications. The wavelengths are not measured the same; IRI is more sensitive to wavelengths from joint spacing and PI to stringline spacing. The Minnesota Department of Transportation and the FHWA have published reports on the transitions from PI to IRI for smoothness specifications. Both reports detail the effects of PCC pavement construction on overall roughness. Proper precautions need to be taken to ensure that the surface is carefully constructed and errors are minimized. Since roughness will progress at the same rate regardless of initial roughness, it is important that the initial roughness is low to extend the life of the pavement.

11.0 CONCLUSIONS

This research has analyzed ODOT's profiler certification procedure and equipment. Several key conclusions were made:

- The current guidelines and procedures for the use of inertial profilers on IRI based roughness correspond well to specifications provided from AASHTO and other state DOTs.
- The accuracy and repeatability requirements require slight improvement; however, an increase in these requirements may require transition time as ODOT becomes more comfortable with the certification process. It is recommended that ODOT increase the accuracy (90%) and repeatability (92%) requirements.
- The establishment of the reference profile should be done during the spring when temperatures are above freezing and strict DMI calibrations must be performed.
- The SurPro inclinometer based profiler used by ODOT creates highly repeatable and accurate profiles. This correlates with the research by (*S. Karamihas 2011*).
- The certification site shows significant variability in roughness across the road.

This research also studied the use of terrestrial laser scanning for generating road profiles and found that:

- TLS can produce accurate profiles, in addition to other data. However, processing procedures need to be improved to ease implementation.
- Mobile scanning systems may soon be able to provide sufficient data for profile evaluation, overcoming many of the limitations of the static systems.
- TLS also provides additional data across the entire road and on surrounding features; hence, it can be used for creating as-built records.
- Fine scale scanning can highlight differences in surface texture based on predominant aggregate size.

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APPENDIX A:
ERD WRITER CODE

ERD WRITER CODE

```
/*

ERD profile writer
Developed by:  Michael J. Olsen, Oregon State Unversity
Funded by: Oregon Department of Transportation, Federal Highway Administration
Written:  July 2012

This program inputs a profile from a csv file in the format dist, elevation
and converts it to the ERD format
(http://www.umtri.umich.edu/divisionPage.php?pageID=118)
for input into ProVAL software (http://www.roadprofile.com/).

The program will interpolate data gaps.

Sampling size is determined by the first two records.

The code can easily be modified if the input file has additional fields.

*/

//include files
#include <stdio.h>
#include <string.h>
#include <time.h>

//this lets the user decide if they want to print distances to the output file as well.
//Change from 1 for validation purposes only, since this will not conform to the ERD format.
int PRINTMODE = 1; //0 = dist+elev, 1 = elev only.

//This function inputs the file name (ofname), a pointer to the File (outFILE), the sampling interval (sInt),
//profile distance (dist), and the desired wheelpath (L or R) and writes the ERD header.
void writeERDheader(char*ofname,FILE* outFILE, double sInt, double dist,char wheelpath)
{
       //Counts
       int numsamples = dist/sInt+1;

       // current date/time based on current system
   time_t now = time(0);

   // convert now to string form
   char* dt = ctime(&now);

   //write out header information
       fprintf(outFILE,"ERDFILEV2.00\n");
       fprintf(outFILE,"\t1,\t%i,\t1,\t1,\t5,\t%lf,\t-1,\n", numsamples,sInt);
       fprintf(outFILE,"TITLE   %s \n",ofname);
       if (wheelpath =='L' || wheelpath == 'l')
       {
              fprintf(outFILE,"SHORTNAM LElev\n");
              fprintf(outFILE,"LONGNAME Left Elevation                       \n");
       }
```

```
	else if (wheelpath =='R' || wheelpath == 'r')
	{
		fprintf(outFILE,"SHORTNAM RElev\n");
		fprintf(outFILE,"LONGNAME Right Elevation                       \n");
	}
	else
	{
		fprintf(outFILE,"SHORTNAM Elev\n");
		fprintf(outFILE,"LONGNAME Elevation                       \n");
	}

	fprintf(outFILE,"UNITSNAMft      \n");
	fprintf(outFILE,"GENNAME Profile Elevation               \n");
	fprintf(outFILE,"XLABEL  Distance                        \n");
	fprintf(outFILE,"XUNITS  ft      \n");
	fprintf(outFILE,"FILEDATA=========================\n");
	fprintf(outFILE,"FILEDESC %s                                 \n",ofname,dt);
	fprintf(outFILE,"PROFINST VZ400 TLS     \n");

	fprintf(outFILE,"GLABEL13Additional Notes:  TLS derived profile, resampled to fill holes\n");
	fprintf(outFILE,"GLABEL14Pavement Type:HMC\n");

	fprintf(outFILE,"FWDSTEPS    %i\n",numsamples);
	fprintf(outFILE,"FDISTANC  %lf ft\n",dist);
	//fprintf(outFILE,"DATASECT=========================");
	fprintf(outFILE,"DESCRIPTThe following is elevation data in ft, at  %lf ft STEP distance intervals:  \n",sInt);
	fprintf(outFILE,"FORMAT  (f10.5) \n");
	fprintf(outFILE,"END     \n");

}

//Main function
void main (int argc, char**argv)
{
	//User inputs L or R wheel path
	char wpath = 'X';

	printf("L = Left Wheel Path, R = Right Wheel Path\n");
	scanf("%c",&wpath);
	getchar();

	//Loop through all input files
	for (int i = 1; i<argc; i++)
	{
		double currdist = 0;
		double currelev = 0;
		double dist1 = 0;
		double dist2 = 0;
		double elev1 = 0;
		double elev2 = 0;
		double distint = 0;
		double elevint =0;

		//set output file names.
		char* infilename = argv[i];
		int len = strlen(infilename);
```

```
char* appendname = "_resample.erd";
char* outfilename = new char[len+10];

strcpy(outfilename,infilename);
outfilename[len-4] = '\0';
strcat(outfilename,appendname);
outfilename[len+9] = '\0';

//Open files to write to
printf("Opening File: %s\n",infilename);
printf("Writing to file: %s\n", outfilename);
FILE* inFILE = fopen(infilename,"rt");
FILE* outFILE = fopen(outfilename,"wt");

//read input file to calculate sample interval
char buf[256];
fgets(buf,256,inFILE);
fscanf(inFILE,"%lf,%lf",&dist1,&elev1);
fscanf(inFILE,"%lf,%lf",&dist2,&elev2);

double sInt = dist2-dist1;
printf("Interval = %lf\n",sInt);
double thresh = sInt/10;

//continue reading file to calculate profile distance
while (!feof(inFILE))
{
       fscanf(inFILE,"%lf,%lf",&dist2,&elev2);
}
rewind(inFILE);

//keep track of initial distance and elevation to reset start to zero.
double startdist = dist1;
double startelev = elev1;

//write header,
writeERDheader(outfilename,outFILE,sInt,dist2-startdist,wpath);
//read header
fgets(buf,256,inFILE);
printf("Reading Profile Information\n");

//Read through entire input file and write output file.
while (!feof(inFILE))
{
       dist2 = -999.999;
       fscanf(inFILE,"%lf,%lf",&dist2,&elev2);

       //if statement to make sure there isn't a data gap.
       if (dist2>currdist+thresh)
       {
              //fscanf(inFILE,"%lf,%lf",&dist2,&elev2);
              //interpolate if there is a datagap.
              while (dist2>currdist-thresh)
              {
              //     printf("%lf vs %lf\n",dist1,currdist);

                     currelev = elev1 + (elev2 - elev1)*(currdist-
                     dist1)/(dist2-dist1);
```

```
                        if (PRINTMODE ==0)
                            fprintf(outFILE,"%lf%lf\n",currdist,currelev);
                        else
                            fprintf(outFILE,"%lf\n",currelev);
                        currdist+= sInt;
                        //print next
                    }
                    //fprintf(outFILE,"%lf,%lf\n",dist2,elev2);
                }
                else if (dist2>-999)
                {
                    //write out to file
                    if (PRINTMODE ==0)
                        fprintf(outFILE,"%lf%lf\n",dist2-startdist,elev2-
                        startelev);
                    else
                        fprintf(outFILE,"%lf\n",elev2-startelev);
                    //currdist+= sInt;
                }
                //store previous
                currdist = dist2+sInt;
                dist1 = dist2;
                elev1 = elev2;
            }

            //cleanup
            delete[] outfilename;
            outfilename = NULL;

            fclose(inFILE);
            fclose(outFILE);

        }

        printf("COMPLETE\n");
        getchar();
        //end program
    }
```

APPENDIX B:
TEXTURE ROUGHNESS CALCULATION CODE

TEXTURE ROUGHNESS CALCULATION CODE

```
/*Laser scan texture analyzer program
//Written by Hamid Mahmoudabadi
//Input from Abby Chin
//Supervised by Michael J. Olsen, Oregon State University
//Written March 2012
//funded by Oregon Department of Transportation, Federal Highway Administration
//
//This program inputs an obj file with laser scan data and calculated surface roughness

*/

//include directories
#include <stdio.h>
#include <math.h>

//data structures

// XYZ for poitn coordinates
struct XYZ
{
       double x,y,z;
};

//This structure includes vertices for triangles
struct TRI
{
       int v1,v2,v3,v4;
};

//This function reads an objfile and extracts the points and triangles.  It also counts
the number of points and triangles.
void readobjfile(char* thefilename, XYZ* &thepoints, int &npts, TRI* &thetriangles, int
&ntris)
{
       FILE* thefile = fopen(thefilename,"rt");

       npts = 0;
       ntris = 0;
       char buffy[256];
       char c;
       int count = 0;
       double sumz =0;
       double avg=0;
       double rmsh=0;

       //loop through file to count points.
       while (!feof(thefile))
       {
              buffy[0] = ' ';

              fgets(buffy,256,thefile);
              if (buffy[0] == 'v'  && buffy[1] == ' ')
              {
```

```
			//it is a vertex
			npts++;
		}
		else if (buffy[0] == 'f')
		{
			//it is a triangle
			ntris++;
		}
		count ++;
	}

	//allocate memory for points and triangles
	thepoints = new XYZ[npts]; //allocate memory for the points.
	thetriangles = new TRI[ntris]; //allocates memory for the triangles.
	npts = 0;
	ntris = 0;

	rewind(thefile);

	//loop through file to extract points and triangles.
	while (!feof(thefile))
	{
		buffy[0] = ' ';
		fgets(buffy,256,thefile);

		if ((buffy[0] == 'v' || buffy[0] == 'V') && buffy[1] == ' ')
		{
			sscanf(buffy,"%c %lf %lf %lf",&c,&thepoints[npts].x,
			&thepoints[npts].y, &thepoints[npts].z);
			sumz = sumz + thepoints[npts].z;
			npts++;
		}
		else if (buffy[0] == 'f')
		{
			//assume the triangles have normals as well
			sscanf(buffy,"%c %i%c%i %i%c%i %i%c%i",&c,
			&thetriangles[ntris].v1,&c,&thetriangles[ntris].v4,
			&thetriangles[ntris].v2,&c,&thetriangles[ntris].v4,&thetriangles[ntr
			is].v3,&c,&thetriangles[ntris].v4);

			//sscanf(buffy,"%c %i %i %i",&c, &thetriangles[ntris].v1,
			&thetriangles[ntris].v2,&thetriangles[ntris].v3);
			thetriangles[ntris].v1--;
			thetriangles[ntris].v2--;
			thetriangles[ntris].v3--;
			ntris++;
		}

	}
	//calculate average elevation
	avg =sumz/npts;

	//calculate RMSH
	for (int i=0;i<npts;i++)
	{
		rmsh =rmsh+ ((thepoints[i].z-avg)*(thepoints[i].z-avg));
	}
	rmsh = sqrt (rmsh/npts);
```

```
        printf("#points:  %i \n",npts);
        printf("#SUM:  %lf \n",sumz);
        printf("#AVG:  %lf \n",avg);
        printf("RMSH: %lf \n", rmsh);
        fclose(thefile);
}

//This function prints out verticies to the console, for debugging purposes only.
void printverticies(XYZ* thepoints,int npts)
{
        printf("The vertices are:\n");

        for (int i =0;i<4;i++)
        {
                printf("%lf %lf %lf\n",thepoints[i].x,thepoints[i].y, thepoints[i].z);
        }
        printf("%i \n",npts);
}

//This function prints out the triangles to the console, for debugging purposes only.
void printtriangles(TRI* thetriangles,int ntris)
{
        printf("The triangles are formed by verticies: \n");
        for (int i =0;i<5;i++)
        {
                printf("%i %i %i\n",thetriangles[i].v1,thetriangles[i].v2,
                thetriangles[i].v3);
        }
        printf("%i \n",ntris);
}

//This function calcualtes the surface area and projected area.
void area(TRI* thetriangles,int ntris, XYZ* thepoints,int npts)
{
        //variables for calucations
        double* p = new double [3];
        double* q = new double [3];
        double* crossresult= new double [3];
        double surface = 0;
        double projected = 0;
        p [0]=0;
        p [1]=0;
        p [2]=0;
        q[0]=0;
        q[1]=0;
        q[2]=0;

        //statistics variables
        double xmin=thepoints[0].x;
        double ymin=thepoints[0].y;
        double xmax=thepoints[0].x;
        double ymax=thepoints[0].y;
        double zmin=thepoints[0].z;
        double zmax=thepoints[0].z;

        //Loop through all triangles
        for (int i=0; i<ntris;i++)
```

```
        {
                p[0]= thepoints[thetriangles[i].v1].x-thepoints[thetriangles[i].v2].x;
                p[1]= thepoints[thetriangles[i].v1].y-thepoints[thetriangles[i].v2].y;
                p[2]= thepoints[thetriangles[i].v1].z-thepoints[thetriangles[i].v2].z;
                q[0]= thepoints[thetriangles[i].v3].x-thepoints[thetriangles[i].v2].x;
                q[1]= thepoints[thetriangles[i].v3].y-thepoints[thetriangles[i].v2].y;
                q[2]= thepoints[thetriangles[i].v3].z-thepoints[thetriangles[i].v2].z;

                //Calculate cross product and area
                crossresult [0]= pow(( p[1]*q[2] - p[2]*q[1]),2);
                crossresult [1]= pow(( p[0]*q[2] - p[2]*q[0]),2);
                crossresult [2]= pow(( p[0]*q[1] - p[1]*q[0]),2);
                double area = sqrt(crossresult [0]+crossresult [1]+crossresult [2])/2;
                double projet=sqrt(crossresult [2])/2;
                //printf(" area %lf \n",area);
                surface += area;
                projected += projet;
        }

        //update statistics
        for (int i=1; i<npts;i++)
        {
                if(thepoints[i].z <= zmin)
                {
                        zmin=thepoints[i].z;
                }
                else if(thepoints[i].z >= zmax)
                {
                        zmax=thepoints[i].z;
                }

                if(thepoints[i].x <= xmin)
                {
                        xmin=thepoints[i].x;
                }
                else if(thepoints[i].x >= xmax)
                {
                        xmax=thepoints[i].x;
                }
                if(thepoints[i].y <= ymin)
                {
                        ymin=thepoints[i].y;
                }
                else if(thepoints[i].y >= ymax)
                {
                        ymax=thepoints[i].y;
                }
        }
        //Calculate WPER
        double WPER=zmax-zmin;

        //Calculate Roughness Ratio
        double ratio=surface/projected;
        printf("min X: %lf  min Y: %lf  max X: %lf  max Y: %lf \n", xmin, ymin,
xmax,ymax);
        printf("min Z: %lf  max Z: %lf \n ", zmin, zmax);
        printf(" Surface Area %lf \n",surface);
        printf(" Projected Area %lf \n",projected);
```

```
        printf(" ***WPER: %lf ***\n",WPER);
        printf(" ***ratio: %lf ***\n",ratio);

}

//Main function
void main(int argc, char** argv)
{
        //create pointers for verticies and triangles.
        XYZ* mypoints = NULL;
        int npts =0;
        TRI* mytriangles = NULL;
        int ntris =0;

        //input file name
        //char* myfilename = "E:\\Texture
        Analysis\\20120402_GrafLot\\Outputs\\GrafOut_9.obj";
        char* myfilename = argv[1];

        //read obj
        readobjfile(myfilename,mypoints,npts,mytriangles,ntris);

        //debugging only
        //printverticies(mypoints,npts);
        //printtriangles(mytriangles,ntris);

        //calculate WPER and roughness ratio
        area(mytriangles, ntris, mypoints,npts);

        //Creates a pause to keep console from closing.
        getchar();
        getchar();
        getchar();
}
```