AN ABSTRACT OF THE THESIS OF

Abby Chin for the degree of Master of Science in Civil Engineering presented on May 8, 2012.

Title: Paving the Way for Terrestrial Laser Scanning Assessment of Road Quality

Abstract approved:

Michael J. Olsen

With the growing trend in use of 3D laser scanning technology for data collection, it is important to study the various potential applications of this revolutionary technology. One such application is the measurement of road roughness at both large and small scales. At larger extents, terrestrial laser scanning (TLS) is compared to several current techniques to measure road profiles including digital levels, inclinometers, and inertial profilers. An overall indicator of roughness (*e.g.* International Roughness Index, IRI) can be obtained from these road profiles and is used by state DOTs to determine the pavement quality. Since TLS is able to collect a large, dense set of data relatively quickly, this technology could provide states with an additional tool to both measure pavement roughness and collect data for the entire roadway.

TLS has the added benefit of being able to generate multiple profiles across the roadway efficiently.

At a fine scale, micron resolution 3D laser scanners can be utilized to determine the influence of asphalt mix designs on the roughness of the pavement. Of particular interest is the selection of predominant aggregate size within the mix.

Results showed that TLS can determine pavement profiles and comparable IRI results to those from current methods. The elevation values collected within the profile were accurate within expected ranges. However, cross correlations, which take into account the location of the roughness, were poor, indicating that TLS is not an effective method to determine a reference profile. TLS was used to determine the cross slopes across the roadway, something that cannot be done with data from an inclinometer or inertial profiler.

Paving the Way for Terrestrial Laser Scanning Assessment of Road Quality

by
Abby Chin

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented May 8, 2012
Commencement June 2012

Master of Science thesis of Abby Chin presented on May 8, 2012.

APPROVED:

Major Professor, representing Civil Engineering

Head of the School of Civil and Construction Engineering

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Abby Chin, Author

ACKNOWLEDGEMENTS

I would like to thank my committee members: Robert Schultz, Todd Scholz, and Michael Wing for their time and efforts in reviewing my thesis. I would also like to sincerely thank Michael Olsen for his guidance and patience over the last two years. Thank you for bringing me to Oregon State and introducing me to an entirely new aspect of civil engineering. I appreciate all of the time you spent working with me and helping me along during my time here.

A big thank you goes to those who helped with the field work and data collection: Keith Williams, Jeremy Conner, John Raugust, Hamid Mahmoudabadi, William White, Mahyar Sharifi, and Kris Puderbaugh. Thank you for braving the cold weather to complete the leveling. Many thanks in particular to Hamid for working with me on the texture analysis, and writing the code needed.

Thank you to the Oregon Department of Transportation for funding this research project (Project #SPR-744). To Michael Stennett and Dean Chess, thank you for providing data needed to complete this project.

To George Chang, thank you for assisting me with the use ProVAL.

Lastly, I would like to thank my family and friends for providing me with the love and support to get me to where I am today.

CONTRIBUTION OF AUTHORS

Dr. Michael Olsen assisted with the data analysis involved in Chapter 3 as well as the interpretation of results. He provided input on the methodology of the testing as well. Additionally, Dr. Olsen provided guidance, input, and editing for Chapter 4. Dr. Olsen also provided editing for all chapters.

Hamid Mahmoudabadi wrote the code for calculations in Chapter 4. He also provided input for testing and editing of the presentation of the final results.

Todd Scholz provided insight on Chapter 4 and provided pavement samples.

Keith Williams, Jeremy Conner, Hamid, Mahmoudabadi, John Raugust, William White, Mahyar Sharifi, and Kris Puderbaugh assisted in data collection.

Keith Williams built the scanner mount used for data collection in Chapter 4.

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

Page

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF SYMBOLS AND ABBREVIATIONS

Symbol/Abbreviations	Definition
3D	Three Dimensional
AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
FHWA	Federal Highway Administration
GPS	Global Positioning System
IMU	Inertial Measurement Unit
Incl	Inclinometer
IP	Inertial Profiler
IRI	International Roughness Index
LiDAR	Light Detection and Ranging
locRMSH	Local Root-Mean Squared Height
LTPP	Long Term Pavement Performance Program
MLP	Multiple Laser Profiler
ODOT	Oregon Department of Transportation
PAS	Predominant Aggregate Size
PCC	Portland Cement Concrete
PI/PrI	Profile Index
ProVAL	Profile Viewing and Analysis
QA	Quality Assurance
RMS	Root Mean Square
RMSH	Root Mean Square Height

TLS	Terrestrial Laser Scanner
TOF	Time of Flight
TopCAT	Topographical Compartment Analysis Tools
WPER	Within-Plot Elevation Range

Paving the Way for Terrestrial Laser Scanning Assessment of Road Quality

1 INTRODUCTION

The smoothness of pavement has a significant impact on the life cycle of the roadway. The general public will base its perception of the quality of the road construction on the pavement smoothness. Chapter 2 is a literature review providing a background on road profiling instrumentation and roughness measurements used to evaluate road quality. Details of state departments of transportation, AASHTO, and ASTM specifications for determination of road roughness are addressed in the literature review, as well.

The use of Three-Dimensional (3D) laser scanning, which uses Light Detection and Ranging (LiDAR), for pavement analysis applications is described in the journal manuscript in Chapter 3. This new technology obtains a detailed, 3D model of the scanned object. TLS was used in this study to determine road roughness over a profile length of 528 feet (0.1 miles). These profiles are compared to current measurement techniques including an inclinometer, inertial profiler, and rod and level.

Many states, including Oregon, are converting from Profile Index (PI) based smoothness specifications to International Roughness Index (IRI). Additionally, many states have implemented an incentive/disincentive program which includes IRI based standards. These programs include an incentive payout if pavement is below a certain IRI or a disincentive payout if pavement is above a specified IRI. In some cases it is required that areas above a specified IRI are repaired to meet the IRI requirements. The smoothness specifications need to be reviewed and revised to account for this new roughness index. Inertial profilers are now used to determine the IRI for new sections of highway. The systems are certified using a reference profile obtained with an inclinometer. Procedures must be developed to ensure the accuracy and repeatability requirements are met so that accurate values are obtained during field implementation.

Chapter 4 presents the results of a micron resolution 3D laser scanner which was used to study the effects of aggregate size on pavement roughness for small sections of pavement.

Chapter 5 contains a literature review focusing on Portland cement concrete (PCC) pavements. PCC and asphalt pavements are not constructed in the same manner. PCC pavements contain joints and headers, and the construction techniques have an impact on the roughness. As a result, direct correlations cannot be made for IRI based smoothness specifications between the two pavement types. Considerations for the development of IRI based smoothness specifications on PCC pavements are detailed in this study.

Laser scanning technologies are being used by many state departments of transportation because of its diverse capabilities. This benefit is important for states to consider as one data set can be used in multiple other applications in addition to the primary purpose it is collected for. Data collection is quick and provides the user with a dense set of data on the area of interest. It is important to test the limits of the laser scan data for a variety of uses, including pavement roughness analyses.

2 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. 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 a measured smoothness index (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 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. The roughness index provides an indication of the quality of the pavement; correlations for the IRI are shown in Figure 2.1. This report will focus on IRI, as this is the focus of the Oregon Department of Transportation (ODOT).

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 (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 travelling at 50 mph (80 km/h) (Dyer and Dyer 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 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.
- 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) (Karamihas 2005).

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

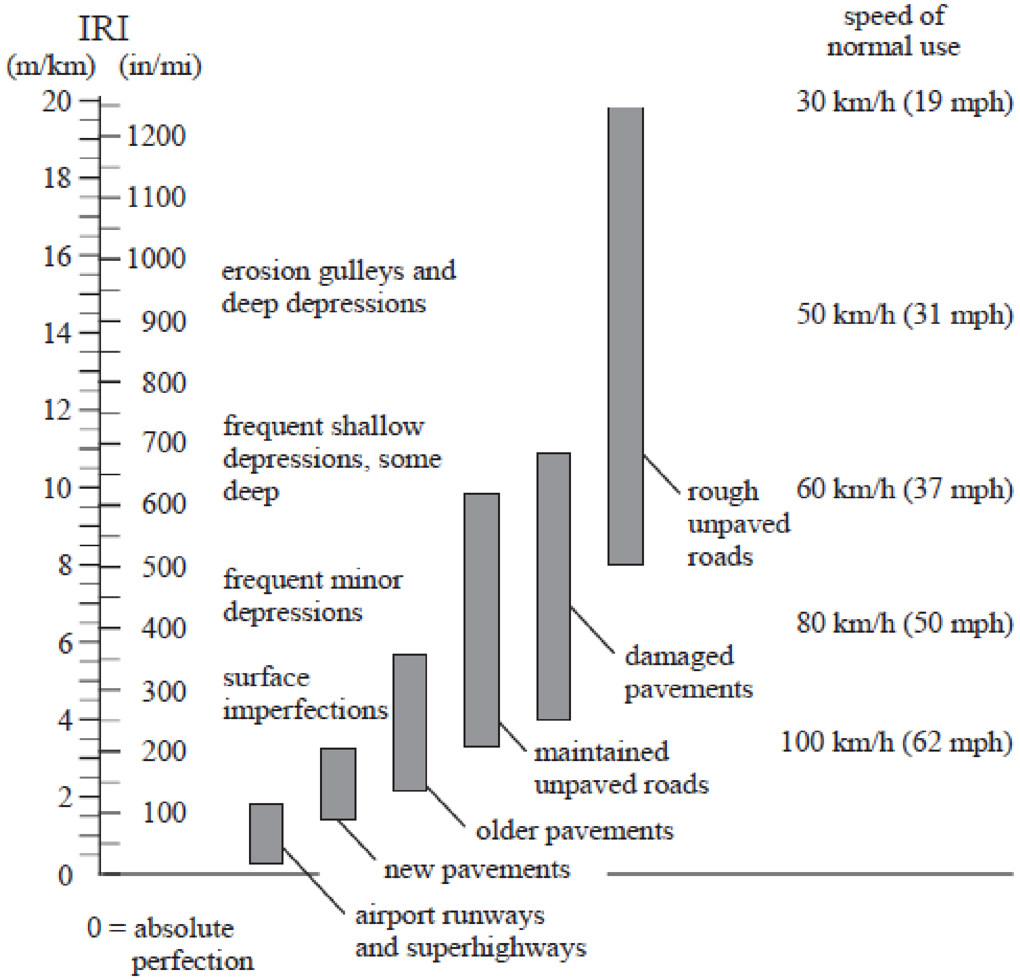


Figure 2.1: IRI values and corresponding implications (from Sayers and Karamihas 1998)

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. 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 (Karamihas 2005). A high pass filter will eliminate the grade in the road which allows the user to clearly see any deviations in the roadway; this may be done with data from an inertial profiler (Sayers and Karamihas 1998).

2.1.2 Cross Correlation

The cross correlation provides an additional measure of comparison between two profiles. Roughness must be located in the same spot along a profile to obtain a high cross correlation value (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.

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 ERD files; the ERD file was created by the University of Michigan Transportation Research Institute (UMTRI) Engineering Research Division (ERD).

2.2 INSTRUMENTATION

Various instruments are available to create road surface profiles which will show the elevation changes of a road along the horizontal distance; these are summarized in Table 2.1. 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.

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 (2 mm/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/50 m)	Both
Mobile Laser Scanning	<= 50 (80)	No	-	Both

These instruments should be calibrated and operated according to the proper specification procedures. 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. The testing speed for the TLS also includes the set up time.

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 (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 (Karamihas 2005).

2.2.2 Inclinometer

An inclinometer, a hand operated instrument seen in Figure 2.2, uses a laser beam up to 12 in (0.3 m) in length to measure the road profile (Hays 2006).

Figure 2.2: SurPRO inclinometer operated by ODOT

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 can range from 0.25-12 in (0.64-30.5 cm) (SurPRO 2011). This method requires the road to be clear of traffic and manual operation. An inclinometer 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). 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.

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. In some states, measurements are viewed with a blanking band to determine the PI values, these are not required. 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 2.3: High speed inertial profiler (from 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 2.3) 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.

2.2.5 LiDAR

Light Detection and Ranging (LiDAR) is another form of technology that can be used to determine the road profile. However, unlike the previous technologies, LiDAR can measure and map the topographic features across an area in addition to determining the elevation. 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 2.4).

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.

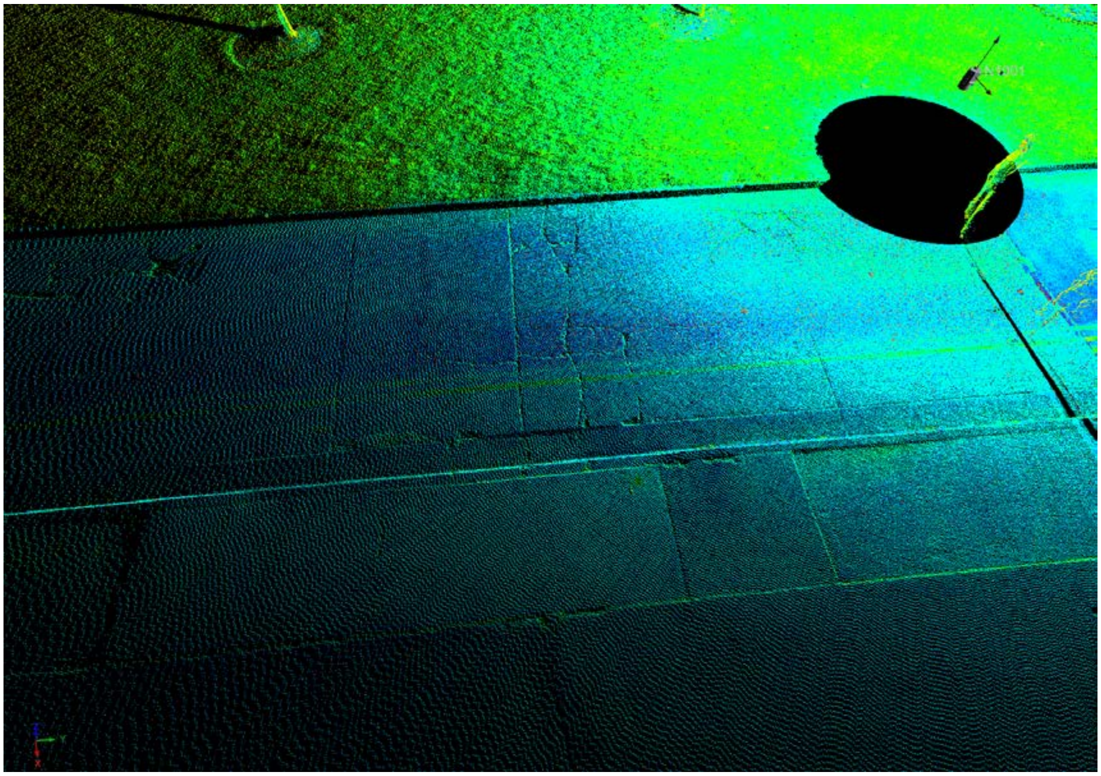


Figure 2.4: 3D point cloud from terrestrial laser scanner

2.2.5.1 Terrestrial

Terrestrial laser scanners, Figure 2.5, 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.

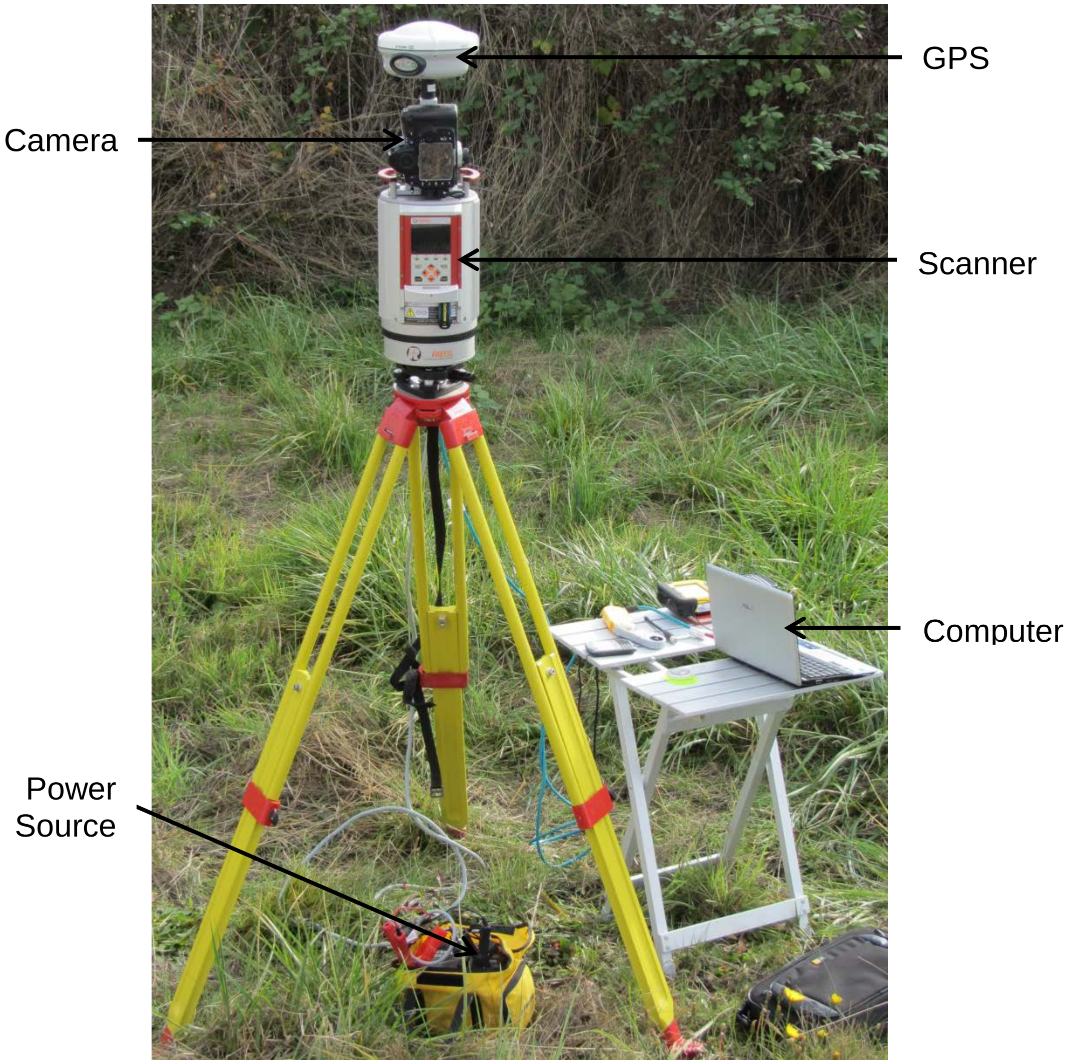


Figure 2.5: Terrestrial laser scanning system

An approximate maximum range for current terrestrial scanners is 820-3280 ft (250-1000 m) with accuracy of 0.2-0.4 in (5-10 mm) (Vosselman and Maas 2010). A camera is also mounted or integrated into the system to obtain images with RGB color, corresponding to each scan position. Terrestrial laser scanning is ideal for creating 3D models of buildings and cities.

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, airborne LiDAR data is not accurate enough for evaluating pavement smoothness.

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 from ODOT.

Figure 2.6: ODOT'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 roadways. The current accuracy of these systems does not meet requirements for use in profiling applications.

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.* 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 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 2.7).

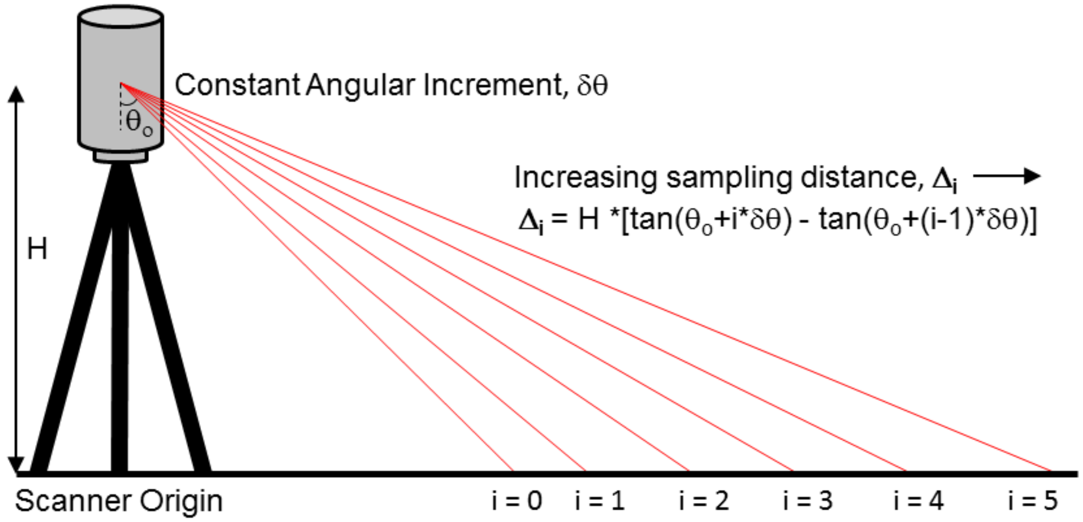


Figure 2.7: Effects of angle of incidence (modified from Olsen *et al*. In press)

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 values. A coefficient of correlation of 99% was calculated between the laser scanning and MLP data. These results show that terrestrial laser scanning is able to be used as an effective tool for measuring road roughness.

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 2.2 and Table 2.3. Three tests are performed to check the vertical and horizontal calibration as well as the measurement system of the inertial profiler.

Table 2.4 provides brief comparison of the specifications on the use of inertial profilers.

Table 2.2: Comparison of specifications to calibrate intertial 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 10 in/mi

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

Specification	Calibration Check		
	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 (from 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	500 ft	5	100 ft
Mississippi DOT	92% repeatability required 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	528 ft	5	200 ft
AASHTO	92% repeatability required and 90% accuracy	528 ft	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 (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).

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 538 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 state 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.

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.

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 measure 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.

2.3.10 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.

2.3.11 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 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 **MANUSCRIPT CHAPTER**

Comparison of Road Profiling Instrumentation to Terrestrial Laser Scanning

Abby Chin[1] and Michael J. Olsen[2]

1. M.ASCE. Graduate Research Assistant, School of Civil and Construction Engineering, Oregon State University, 220 Owen Hall, Corvallis, OR, 97331, chinab@onid.orst.edu
2. M.ASCE. Assistant Professor, School of Civil and Construction Engineering, Oregon State University, 220 Owen Hall, Corvallis, OR, 97331, michael.olsen@oregonstate.edu

ASCE Journal of Surveying Engineering

http://ascelibrary.org/suo/

Manuscript not yet submitted.

3.1 ABSTRACT

Pavement roughness is indicated by the International Roughness Index (IRI). An inertial profiler, inclinometer, and rod and level are currently used to measure the longitudinal pavement profiles used in roughness determination. This study investigated the use of terrestrial laser scanning (TLS) to measure pavement profiles. TLS has the added benefit of acquiring a dense set of data across the entire roadway and providing additional information such as cross slopes, which cannot be done with some of the other techniques. TLS was used to determine the cross slopes across the roadway. This study also investigated the optimal sampling interval for filtering scan data to obtain a road profile, which was found to be within 5 in to 11 in. This range produces the highest correlation of IRI to the other instruments. A comparison of the IRI shows the majority of the profiles to be within 5% of the reference value. The study also found that elevation values collected with the scanner were consistent to other techniques, but a cross correlation measurement focused on wavelengths was found to be unacceptable. Each method of profile measurement produced highly repeatable results (greater than 90%) but the data did not meet accuracy requirements from state standards (88%).

3.2 INTRODUCTION

Current methods implemented to determine road roughness and longitudinal profiles are: rod and levels, inclinometers, and inertial profilers. The International Roughness Index (IRI) is the average rectified slope based on a quarter-car model (Dyer and Dyer 2008). The quarter car model is the mass of one quarter of the car supported by one tire. The IRI is calculated from an algorithm which applies a moving average filter, quarter car filter, and length of the test section to a measured longitudinal profile (Sayers and Karamihas 1998). The IRI provides an indication of the roughness of the pavement using collected profiles.

The correlation compares the elevation values of the two profiles and determines how well they align, the cross correlation will compare the elevation values and the location at which the roughness occurs. 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 (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 profiles (P and Q) and includes the offset distance (Karamihas 2004).

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

where:

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

N is the number of samples,

Δx 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 elevation 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 (Karamihas 2004).

Profiles are typically determined by inertial profilers and inclinometers, however Terrestrial laser scanning (TLS) has the potential to be an additional tool to measure IRI with the added benefit that profiles can be taken across the entire roadway and not only at the wheel paths. The scan data can be used to determine additional information such as cross slopes and road grades. Further, TLS does not require the roadway to be closed to traffic, as it can be performed from the side of the road, and can be completed in much less time than a rod and level survey. The fast data acquisition process collects a dense data set, which provides flexibility in multiple uses of the data aside from profiles. As TLS becomes more prevalent among state DOTs, it is important to investigate the various applications, procedures, and achievable results from TLS.

This study examines the use of TLS on pavement roughness evaluation. Data from the TLS is compared to a rod and level, inertial profiler, and inclinometer. The data were analyzed to determine the cross correlation and IRI obtained from each method. Many state DOTs will use these values to assess the accuracy and repeatability of IRI to certify inertial profilers. The Oregon DOT has current accuracy and repeatability requirements of 88% and 90% respectively (ODOT 2011). The analysis of pavement profiles was done using the Profile Viewing and Analysis (ProVAL) program created with the help of the Federal Highway Administration (FHWA) and the Long Term Pavement Performance Program (LTPP) (The Transtec Group 2011). The software will determine the IRI, cross correlation, accuracy, and repeatability of the input profiles using an input reference profile. Additionally, the program has wavelength filtering options that can be applied to the profiles. The program will also determine the wavelengths most influencing the collected profile.

Collected profiles were analyzed to determine if TLS is an acceptable method to measure roughness based upon the parameters from ODOT specifications. TLS data can be filtered and sampled at different intervals to create a profile. However, the different sample intervals can alter the IRI and cross correlation values.

Testing was completed by Chang *et al*. (2006) to examine the use of TLS on road roughness applications. Data were compared from TLS, Multiple Laser Profiler (MLP) and a rod and level. The study produced successful results with a 95% correlation between the rod and level and TLS. Note that this correlation is not the same as cross correlation, it is based on the analysis of elevation differences only. This study also provides a methodology to use TLS data for roughness evaluation. One objective of this study is to determine appropriate filtering methods and achievable results to investigate road roughness through TLS.

TLS data have the ability to be used in many transportation applications aside from roughness. 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).

3.2.1 Objective

The objective of this study is to compare multiple methods of collecting road profiles to analyze:

- TLS data filtering
- IRI calculations
- Cross correlations
- Cross slopes
- Statistical evaluations of profiles
- Wavelength content

3.3 DATA COLLECTION AND PROCESSING

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

A test site was chosen by the Oregon Department of Transportation (ODOT) for the certification of inertial profilers. Data were collected along a 528 ft 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 in 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.

3.3.1 Inclinometer and Inertial Profiler

An inclinometer profile is collected by walking the instrument along the wheel path, one wheel path is measured at a time. A SurPro 3500 inclinometer was run five times on each wheel path by ODOT on two occasions: first in June 2011 and then again in November 2011. The two inclinometer runs will be referred to as: date_Incl. The inertial profiler data was provided by ODOT. 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, etc. A total of five runs were completed for each data set.

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

3.3.2 Rod and Level

The rod and level survey was conducted following the ASTM E 1364-95 specifications. The wheel paths at the test site had been previously marked by ODOT. To prepare the site for the rod and level, steel tapes were used to measure out the sections of each wheel path. For convenience, markings were made every 1 ft with larger markings to indicate 20 ft intervals along the entire length. A Leica DNA03 and DNA10 were used to collect the data in meters. The Leica DNA03 is able to read to the ten thousandths of an inch while the DNA10 reads to the thousandths of an inch. Readings were taken at 1 ft intervals and saved to a memory card. As an extra precaution, and in accordance with ASTM E 1364-95, the data were also recorded manually. Two teams collected data, one team of three and one team of two. The team of two had one person to run the instrument and record data, and one to hold the rod. The team of three had one person to run the instrument, one to hold the rod, and one to record measurements. A three person party will speed up the time for data collection. A level bubble on the rod was used to ensure the rod was held vertical at the time of the reading.

The levels were first set up at 20 ft behind the 0 ft marking of the test section. Measurements were taken from 0 ft to 120 ft at 1 ft increments. The rod was then held at 120 ft while the instrument was moved to the 100 ft mark and measurements were taken again at 120 ft as well as repeat measurements from 0 ft to 80 ft at 20 ft increments. These repeat measurements were taken as an additional method to calculate error involved in the process. This process was continued for the 528 ft section with instrument set ups at each

100 ft increment. The left wheel path had a second set up at 80 ft instead of 100 ft after a wide load truck passed and forced the instrument to be moved.

The resolution requirements are divided into two classes (ASTM-E-1364-95 2005). Class 1 is preferred for the establishment of a test site. Class 1 resolution for IRI of 30-63 in/mi is 0.01 in and 0.02 in for IRI of 63-190 in/mi. The precision is checked by taking a reading at the first point measured at that set up before moving the instrument to the next set up. In the event that the required resolution is not met, the measurements should be repeated at that instrument position. The resolution was not determined during the first rod and level survey. However, a second survey campaign was recently conducted to correct for this.

The rod and level data are collected as distances and heights. In order to create a profile, the heights were converted to profile elevations by choosing an arbitrary initial height for the first point as a datum.

$$p_i = IH - R_i \qquad (2)$$

Each rod reading (R_i) was subtracted from the assumed height of the instrument (IH) to determine the profile elevation (p_i) at that point. This calculation was continued until the instrument was moved to a new location. At that point a new datum was determined to account for the change in instrument height.

$$IH_{new} = IH_{old} + R_{new} - R_{old} \qquad (3)$$

The new rod reading (R_{new}) for the second set up was added to the height of the instrument (IH_{old}) from the first setup and the rod reading from the first setup (R_{old}) was subtracted to calculate the new instrument height (IH_{new}).

These calculations were continued for the entire data set accounting for each new setup. The initial height was then set to zero and the rest of the data were corrected accordingly to determine the slope and elevation changes to be used in the analysis. The data were input into an ERD file to be used in ProVAL.

3.3.3 Laser Scanner

TLS data were collected using a Riegl VZ-400 3D laser scanner along with a Trimble R8 GPS and a Nikon SLR digital camera. Data were collected using the laser scanner with six scan positions and five cylindrical, retro-reflective targets. Spacing for the scanner locations and target positions were 131 ft as shown in (Figure 3.2).

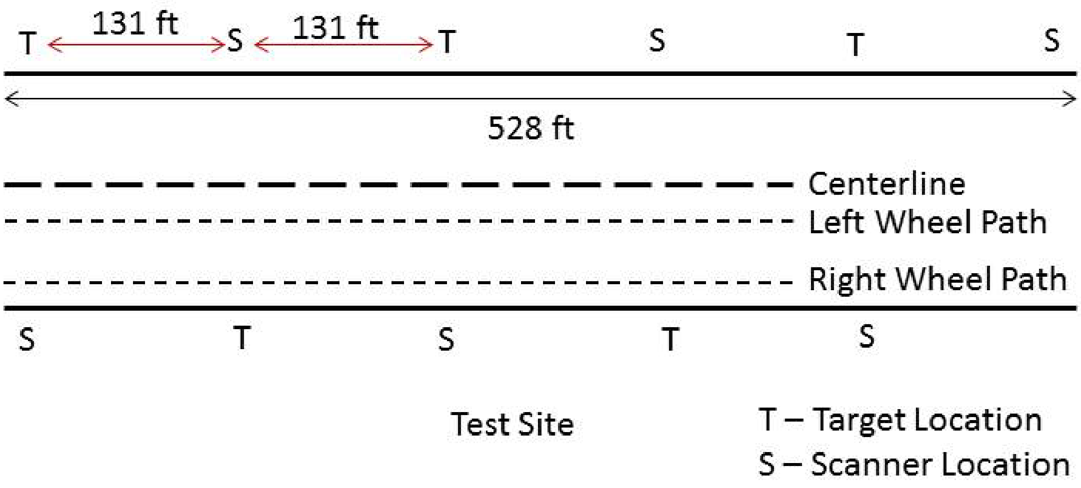


Figure 3.2: Laser scanning field test set up

Each 360 degree scan took five minutes to complete. The scanner has an estimated accuracy (RMS) of 0.2 in for a 164 ft range. However, actual error depends on material type and scanner geometry. Each 360 degree scan collected approximately 13.5 million points with roughly 3 million of those points on the roadway. Scan points were spaced at 0.1 in to 0.4 in. During each scan, three RTK GPS points based on 1 minute observations were obtained in addition to calibrated photographs.

The laser scan data were collected as a 3D point cloud. Each point has an X, Y, Z position and R, G, B color, and an intensity value (measure of signal degradation). At each scan position, the visible targets were rescanned at a higher resolution to assist in scan alignment.

The laser scan data can be aligned in a variety of ways (Olsen 2011). For this study, the GPS and targets were collected for alignment. A minimum separation filter of 0.39 in and an isolated point filter of 1.64 ft were used prior to alignment. The individual scans were filtered so that no point was further than 328 ft from the scan position. An initial alignment attempt was performed using the target scans. This alignment failed due to problems in the fine scans of each target. As a result, a cloud to cloud alignment was performed.

Prior to beginning the cloud to cloud alignment the GPS positions were applied to the scan locations. Scans were then rotated about the z axis to obtain an initial, rough alignment. Cloud to cloud matching was then used to refine the alignment. Surface matching was first done on the middle pair of scans (scan positions 2 and 3). This process allowed the rotation (about the z axis only) of both scans in the alignment process from Maptek I-Site. The scans were held level during this rotation since the laser scanner has an internal level compensator. Once scans 2 and 3 were aligned, scan 1 was added and aligned to scans 2 and 3. This process continued for all 6 of the scans. When the scans appeared to be closely aligned, a global registration process was run which evaluates all scans simultaneously.

Following the alignment process, the scans were rotated to align the roadway against north. The final step in the alignment process was to prune the data to show only the roadway surface (Figure 3.3).

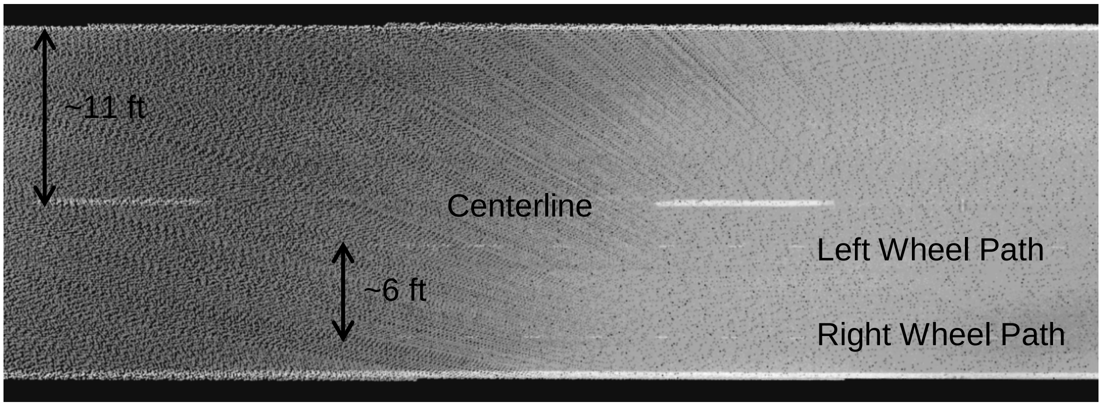


Figure 3.3: Intensity shaded point cloud of roadway section

The images taken with each scan setup provide a rough estimate of the start and end locations of the test section since the lines painted on the roadway are visible in the photograph, particularly given the fact that the roadway surface is oblique to the scanner. However, due to parallax these images do not map perfectly to the point cloud. Hence, the intensity values (Figure 3.3) provide better extraction of the start and end points of the test section. Scans colored with intensity were used to obtain the coordinates for the locations of the wheel paths.

A statistical filtering process, “Bin and Grid” (Olsen 2011), was used to obtain the mean elevation value for all points within a specified grid spacing, or sample interval. The bin and grid program separates the points into grid cells of specified spacing and provides the elevation value among the points in the grid based on the user selection of mean, minimum, maximum, etc. Sixteen cell sizes were used: 1-12, 15, 18, 21, and 24 in. This process reduces the noise in the data by eliminating the outlying maximum and minimum elevation values. For example, cars or other objects passing in front of the scanner can leave streaks in the data that can be filtered through this process. Prior to using the “Bin and Grid” program, the passing cars and other noise was manually removed from each scan. Hence, the mean elevation value was used to run the program.

Next, these filtered scans were imported to ArcGIS as a raster grid. Profiles for the left and right wheel paths were then extracted using a toolbar, TopCAT (Olsen *et al*. In Press) which extracts profiles from grids. The elevations for the 528 ft section were collected from TopCAT and an ERD file was created to be used in ProVAL (The Transtec Group 2011).

3.4 RESULTS AND DISCUSSION

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.

Comparisons between the four 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. Cross slope values can be calculated from the laser scanning data and slopes can be compared between the laser scanner, rod and level, and inclinometer. TLS and level data do not need to be analyzed with any wavelength filtering (Sayers and Karamihas 1998). However, a 250 mm filter moving average filter was applied to the inclinometer and inertial profiler data.

The inclinometer DMI was not calibrated with the closed loop run in June. As a result there was a compounding error in the data resulting in a consistent bias seen in the profiles. During the data collection in November, the wheels of the instrument were affected by the freezing temperatures, again possibly resulting in errors in the data. A new rod and level survey was conducted in April 2012.

3.4.1 Laser Scanning Profiles

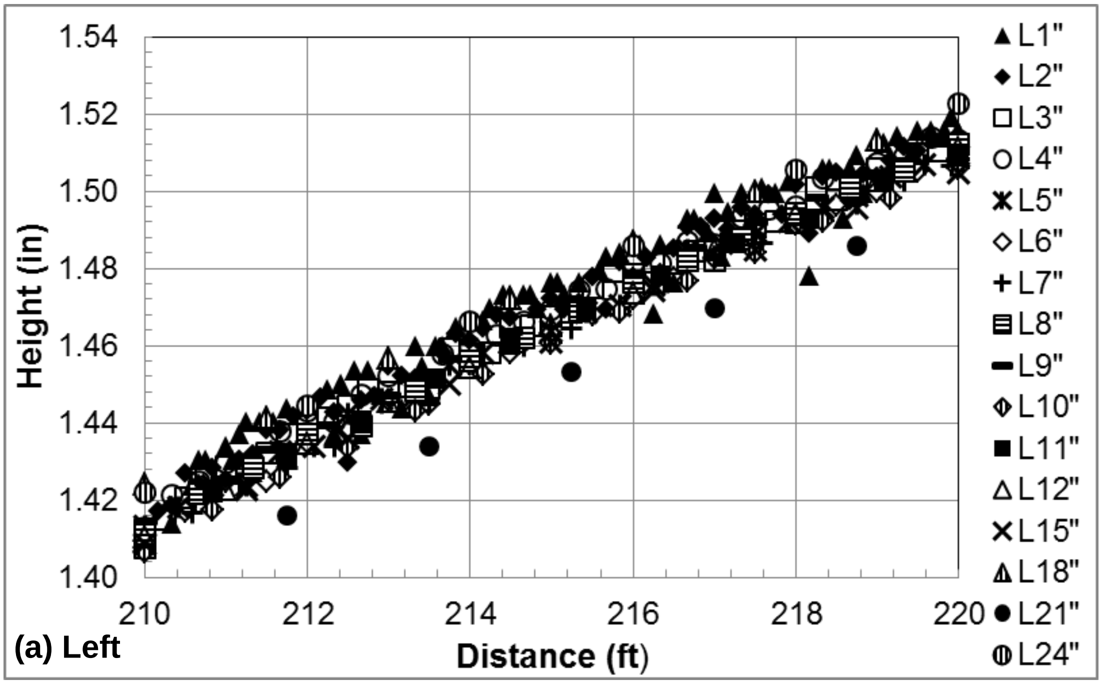
The laser scanning data were filtered at intervals ranging from 1 in to 24 in to determine the optimal sampling interval. From Figure 3.4, each sampling interval resulted in similar profiles. The outlying profiles for both wheel paths were from a sampling interval of 1 in and 21 in.

The right wheel path showed a slightly better alignment of the profiles. It is expected that a filtering that is too small or too large will result in outlying profiles as seen in the figure. It is clear at this enlarged scale that the profiles obtained from different point spacing correlated well with each other.

3.4.2 International Roughness Index Calculations

IRI values were computed for each sampling interval to further investigate the optimal sampling interval (Figure 3.5). Sixteen different values for sampling intervals were used; each interval designation resulted in a different IRI value.

The smallest sampling interval chosen, 1 in, showed a large deviation from the other IRI values and is approximately 100 in/mi higher. This occurred for the left and right wheel paths. At small sampling intervals, noise is not filtered effectively from the scan data when determining IRI, this noise is interpreted as surface roughness. The larger sampling interval, 18 in to 24 in, resulted in lower IRI values because the gridding process artificially smoothed the data. It is expected that as the sampling interval increases, the IRI values will decrease as the data are smoothed.



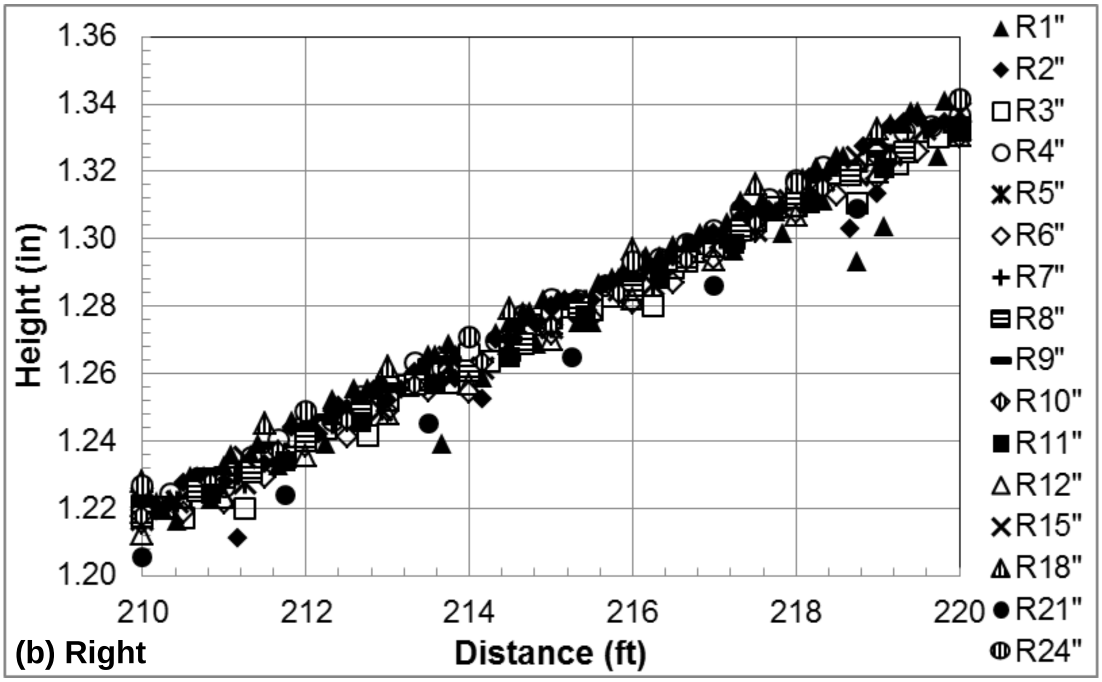


Figure 3.4: Profiles of (a) left wheel path and (b) right wheel path for different sampling intervals

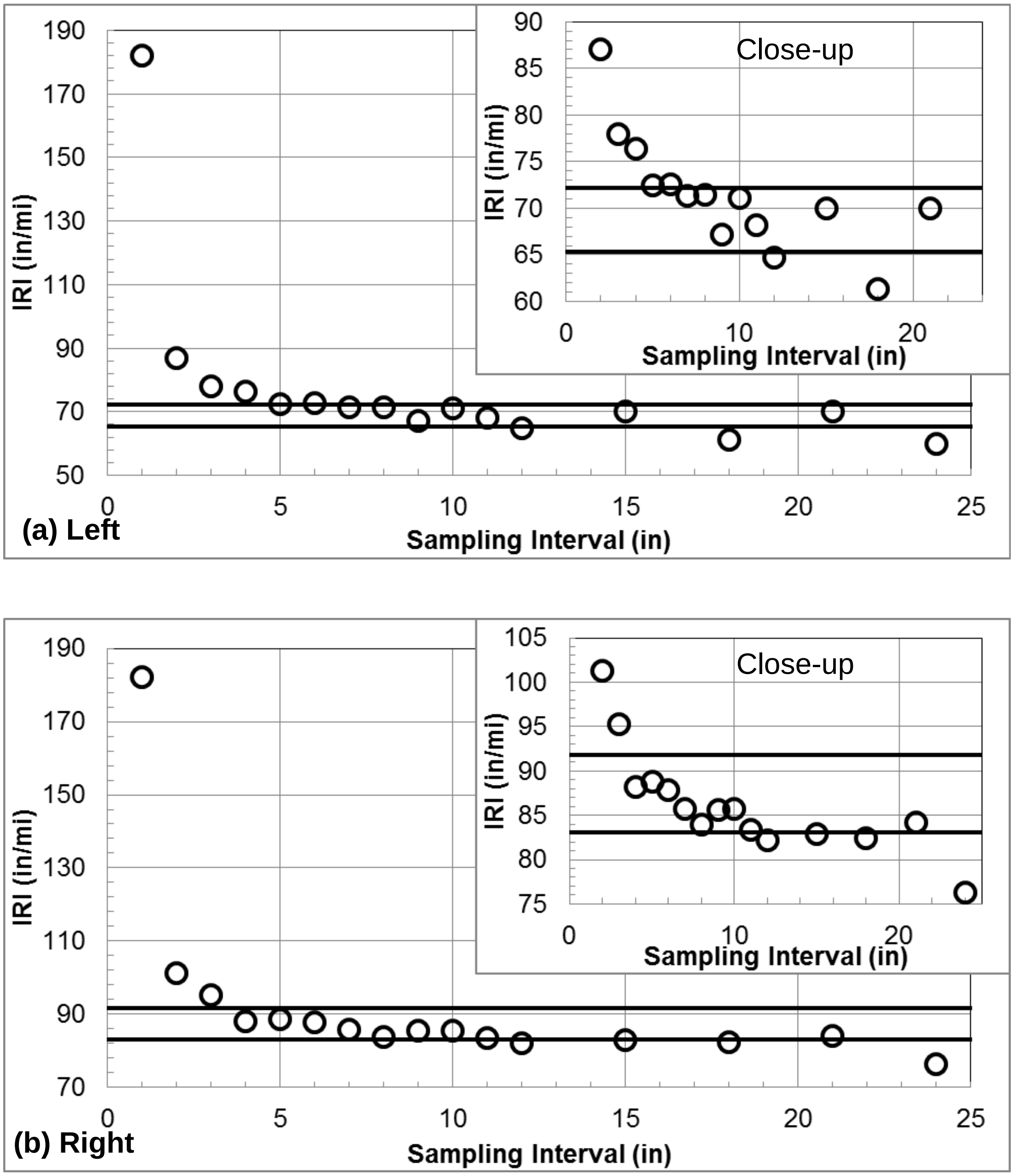
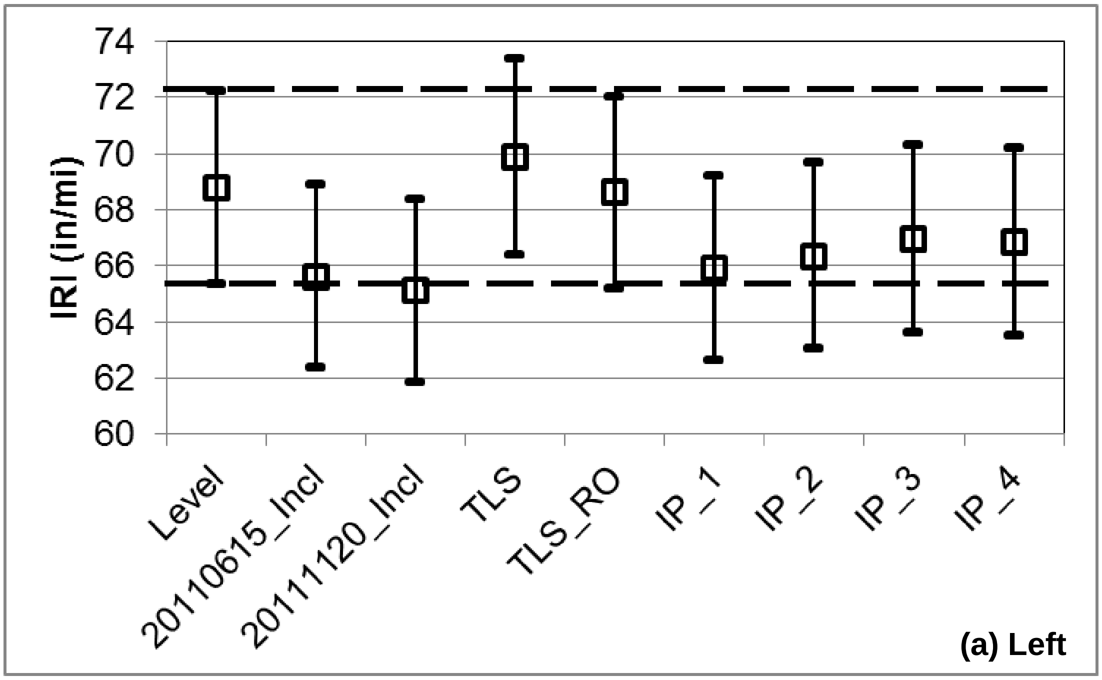


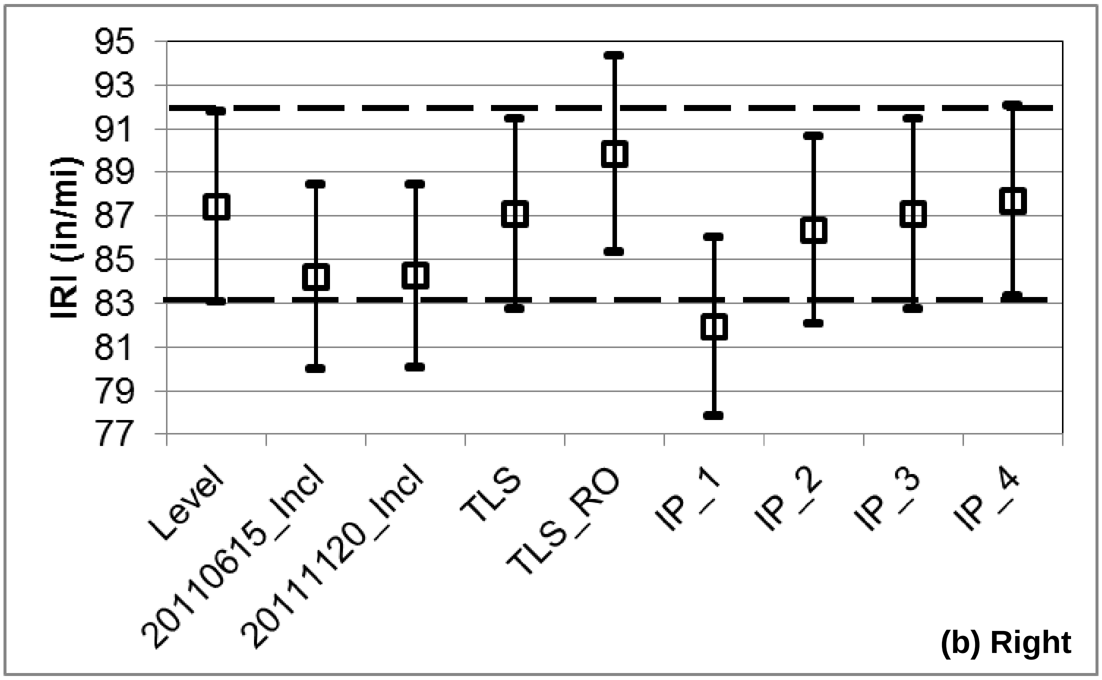
Figure 3.5: IRI values obtained from laser scanner at sampling intervals with the bands showing ±5% of the rod and level IRI; (a) left wheel path and (b) right wheel path with enlarged plots for 2 in to 24 in intervals

The trend in the IRI curve flattened out between 5 in and 11 in spacing for both wheel paths. Based upon the profile and IRI comparisons, an average IRI was obtained from the 5 in to 11 in interval. These sampling intervals provided profiles with no outlying points and were within or bordering the ±5% range of the IRI from the rod and level. After determining the IRI obtained from each method, comparisons can be drawn regarding the accuracy of the data and overall roughness of the roadway.

Figure 3.6 compares the average IRI from each method with error bars at ±5% of the rod and level (Level) as the reference. The average IRI value from the TLS was determined using sampling intervals from 5 in to 12 in. The 20111120_Incl from the left wheel path and the first inertial profiler (IP_1) from the right wheel path were not within 5% of the reference IRI. The average IRI from each of the other methods fit within the 5% of the reference from the rod and level. The inclinometers had a lower average IRI than the other instruments; however, there were errors associated with the data due to calibration and cold weather.



(a) Left



(b) Right

Figure 3.6: IRI values ±5% from each of the instruments used on (a) the left wheel path and (b) the right wheel path

As previously mentioned, the lines at the test site were painted 6 in to the left of the wheel path. The assumption is that the driver of the inertial profiler will tend to stay slightly to the right of the line. Additional profiles were obtained 6 in to the right of the painted line from the TLS data and are indicated by “TLS_RO” (right offset) in Figure 3.6, and are later used for comparisons with the inertial profilers.

The IRI values from the rod and level and TLS were very similar on the left wheel path and slightly higher than the inertial profiler IRI values. Both inclinometer runs produced the lowest IRI values; this is similar on the right wheel path with the exception of the first inertial profiler. The other three inertial profilers provided acceptable IRI results when compared to the rod and level and TLS.

The TLS had a similar IRI as the rod and level on the right wheel path. This data set shows the TLS as a good method to measure the IRI and can be used as a reference profile. However, the same is not true for the left wheel path. The IRI was slightly higher from the rod and level; as a result the inclinometer, and first and second inertial profilers, were not within 5% of the IRI. All of the IRI values for both wheel paths were within 7% of the rod and level and TLS. This means that the TLS data would meet the acceptable criteria from the Ohio DOT stating that the average IRI must be within 7% of the reference (ODOT 2009). It would not be acceptable for the Minnesota DOT which requires 5% (Mn/DOT 2011).

3.4.3 Cross Correlations

The cross correlation between two sets of data is another measure of the accuracy of the instrument. The cross correlations were determined varying the basis and comparison profiles. Average cross correlations and offsets are found in Table 3.1. The cross correlations obtained for the right wheel path were higher than the left wheel path. The Oregon DOT requires an accuracy of 88%. With the rod and level as a reference, this requirement was met only by the inertial profilers and the inclinometer run from June on the right wheel path. Using the June inclinometer as a reference baseline, the failed inertial profiler test had an average cross correlation above 88% on both wheel paths and the TLS and passed inertial profiler tests were above 88% on the right wheel path. The right wheel path cross correlation was above 88% when comparing TLS and the inertial profilers. Overall, the cross correlation values are lower for the November inclinometer runs.

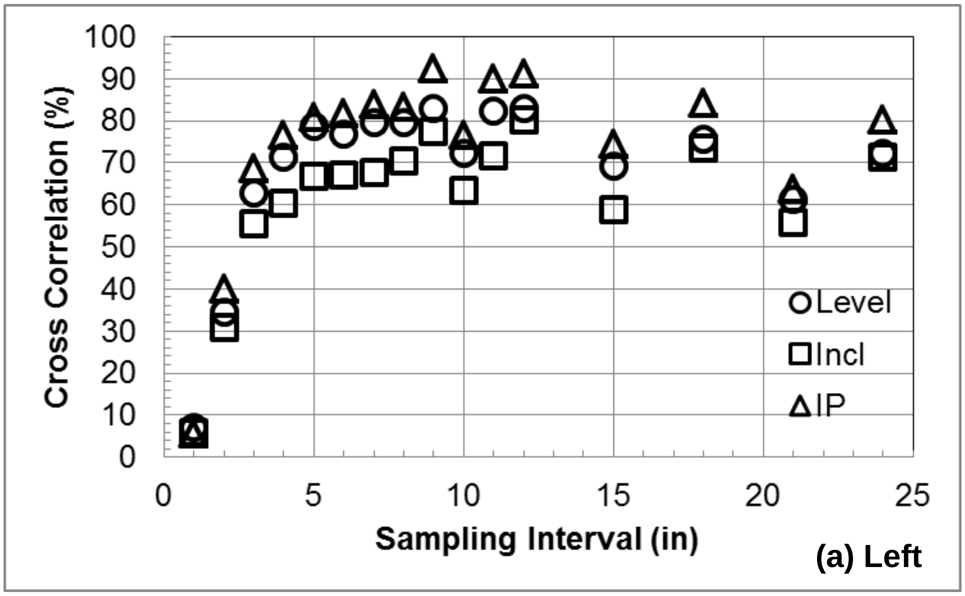
The profiles from the TLS on the wheel path and the TLS 6 in to the right of the wheel path were compared to the inertial profilers. It was expected that the offset profile would produce higher cross correlations than the profiles from the painted line. However, from Table 3.1, this was not the case.

Table 3.1: Cross correlation values with varying reference and comparison profiles for the left and right wheel paths, bolded values meet current ODOT requirements

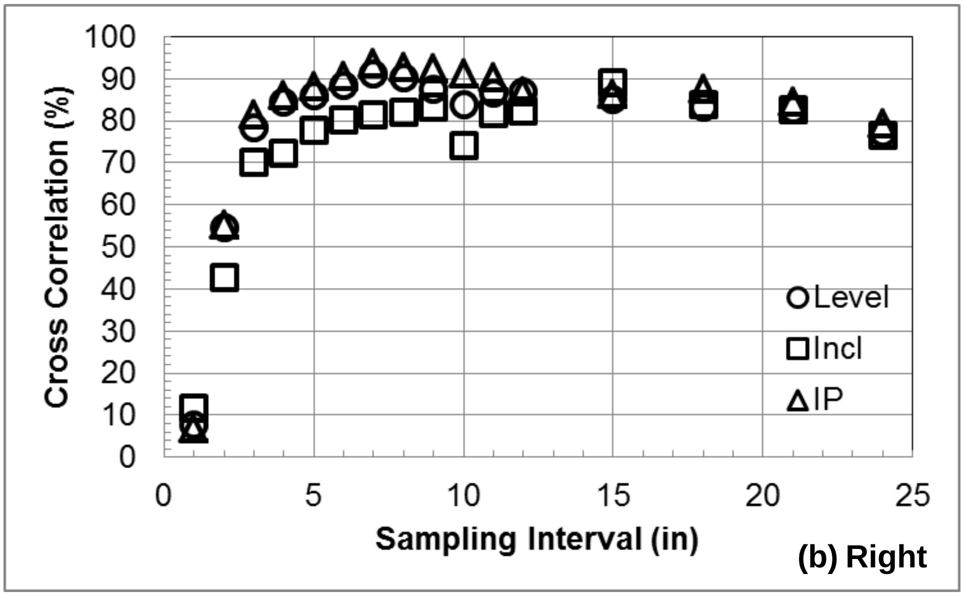
Reference	Comparison	Left	Right
		AVG (STDEV)	*AVG (STDEV)*
Level	TLS	79.38 (3.58)	87.58 (2.33)
Level	IP_3	84.12 (0.62)	**91.28 (0.95)**
Level	IP_4	84.12 (1.08)	**92.14 (2.31)**
Level	20111120_Incl	74.44 (0.81)	83.92 (0.74)
Level	20110615_Incl	84.30 (1.81)	**90.82 (0.42)**
20111120_Incl	IP_3	76.92 (1.64)	81.61 (2.19)
20111120_Incl	IP_4	79.02 (2.10)	84.66 (2.78)
20111120_Incl	TLS	70.56 (5.70)	80.32 (2.98)
20110615_Incl	IP_3	87.62 (1.39)	**92.48 (2.25)**
20110615_Incl	IP_4	**90.38 (0.73)**	**93.88 (3.12)**
20110615_Incl	TLS	77.90 (6.59)	**89.21 (1.76)**
LS_RO	IP_4	82.25 (1.43)	86.20 (3.28)
LS_RO	IP_4	82.21 (3.14)	85.06 (3.05)
TLS	AMES_F	84.38 (5.36)	**89.42 (2.80)**
TLS	AMES_P	84.88 (5.59)	**90.69 (2.30)**
20110615_Incl	20111120_Incl	**92.43 (0.94)**	**92.92 (0.74)**
IP_3	IP_4	**94.20 (2.87)**	**95.08 (2.05)**

The profiles from the wheel path provided better correlations to the inertial profilers, the right wheel path cross correlations were both above the 88% threshold. For comparison, the cross correlations from the inclinometers and inertial profilers were calculated and all above 88%. The left wheel path provided lower cross correlation values than the right. The only instrument that had cross correlations above 88% on both wheel paths was the June inclinometer as a reference for IP_4. However, since that inertial profiler test failed, it is not a reliable source of data to show the inclinometer from June as an acceptable reference profile. Based upon the table, the instruments showed good cross correlations within the same method, but poor cross correlations when comparing methods. These results indicate a bias between the instruments.

The cross correlation values can also be used to assist in the determination of an appropriate spacing interval. Cross correlation values decrease outside of the 5 in to 11 in range (Figure 3.7) further validating this choice in acceptable range. The cross correlations were determined with an inclinometer, inertial profiler, and level as the reference device for the TLS. There was a drop in the cross correlation for all methods at 10 in sampling interval indicating that this interval should not be chosen to determine the road profile.



(a) Left



(b) Right

Figure 3.7: Cross correlation comparison using the level, inclinometer (Incl), and inertial profiler (IP) as a reference for the (a) left and (b) right wheel paths

After choosing an acceptable spacing interval, the IRI values were obtained from the TLS data using a 6 in spacing interval. Longitudinal profiles were collected at 1 ft intervals across the roadway, and shown in Figure 3.8 by the diamonds. The IRI values increased at the left and right edges of the pavement. IRI values from the centerline, left wheel path, and right wheel path are indicated by the squares on the figure.

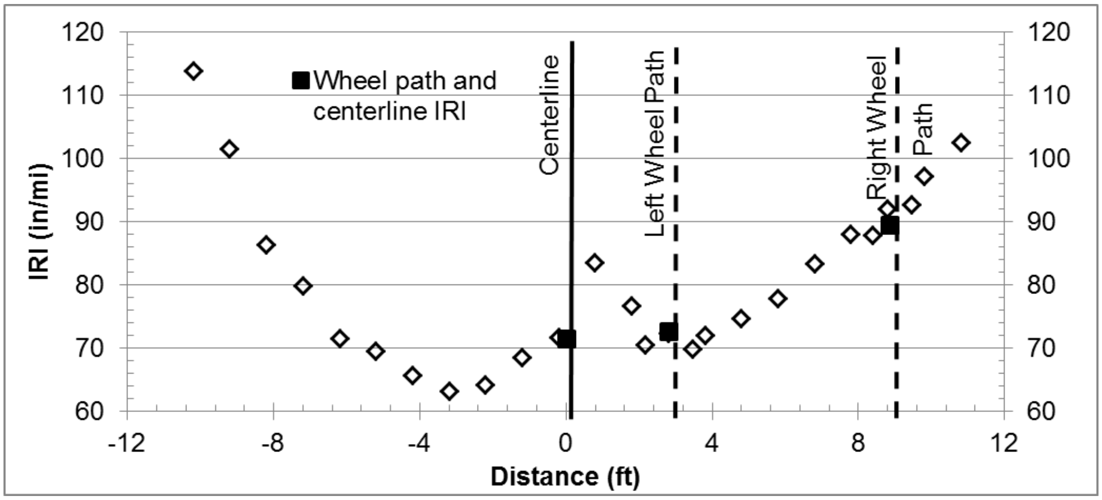


Figure 3.8: IRI values across the both lanes of the roadway, longitudinal profiles every 1 ft using 6 in sampling interval

The IRI range varied between 114 in/mi to 63 in/mi across the roadway with the maximum and minimum occurring to the left of the centerline. Additional profiles were obtained 6 in to the left and right of each wheel path and are also shown in Figure 3.8. The IRI was 2 in/mi higher at the location of the left wheel path than the profiles 6 in to the left and right. The right wheel path exhibited more significant deviations around the location of the wheel path.

The IRI was 2 in/mi less to the left of the right wheel path and 2 in/mi greater to the right of the right wheel path.

These differences in the IRI surrounding the wheel path may account for poor cross correlations at the test site. Although the differences in IRI were small, any deviation from the wheel path could cause an IRI variation of 2 in/mi. This deviation may have a greater effect on the cross correlation. Variations on the right wheel path may balance each other out with rougher profiles to the right and smoother profiles to the left. However, the left wheel path is rougher on the wheel path than to the left and right.

3.4.4 Cross Slopes

Cross slopes provide an additional method of post construction quality control. An inadequate cross slope will prevent proper drainage of the surface. Since TLS will collect points across the entire roadway, it is possible to determine the cross slope. The cross slopes in Table 3.2 were calculated using profiles with a 6 inch sampling interval from the left edge, centerline, and right edge of the surface. This roadway section does not display typical cross slopes of 2%. The cross slope was almost 0% at 200 ft on the left side and at 300 ft on the right side indicating a flat section of roadway. These values were checked by computing the cross slopes using an 8 in sampling interval, and similar cross slopes were calculated.

Table 3.2: Cross slope every 25 ft from laser scan data at 6 in sampling interval (positive slopes indicate road slopes away from the centerline)

Distance (ft)	Cross Slopes		Distance (ft)	Cross Slopes	
	Left (%)	Right (%)		Left (%)	Right (%)
0	1.93	-1.99	275	1.75	-0.79
25	2.17	-1.11	300	0.95	-0.03
50	2.49	-1.02	325	0.70	0.32
75	2.67	-0.83	350	0.53	0.25
100	2.05	-1.07	375	0.71	0.44
125	1.80	-0.93	400	1.34	-0.25
150	1.09	-0.27	425	1.43	-0.38
175	0.70	0.87	450	0.55	0.18
200	0.02	1.23	475	-0.60	0.82
225	0.58	0.57	500	-0.43	0.93
250	1.28	-0.89	525	0.33	0.79

To further validate the cross slope calculations the cross slope between the wheel paths for the rod and level and TLS were compared. Since similar points were measured from both wheel paths using the rod and level, the two profiles were able to be placed on the same datum. This allows for a comparison between the two instruments. A 12 in sampling interval was used for the TLS for the calculated slopes in Table 3.3. The cross slopes differed by no more than 0.40% but on average differ by 0.11%, the minimum difference was 0.03%.

Table 3.3: Slope comparison between wheel paths for rod and level and TLS with 12 in sampling interval

Distance (ft)	Cross Slopes		
	Level (%)	TLS (%)	Difference (%)
0	-2.05	-1.78	-0.27
25	-1.22	-1.03	-0.19
50	-1.06	-0.89	-0.18
75	-0.75	-0.59	-0.16
100	-1.06	-0.89	-0.16
125	-0.76	-0.62	-0.14
150	-0.17	-0.06	-0.12
175	1.67	1.27	0.40
200	1.45	1.51	-0.06
225	0.83	0.88	-0.06
250	-0.56	-0.63	0.06
275	-0.64	-0.58	-0.06
300	0.39	0.32	0.07
325	0.63	0.55	0.08
350	0.36	0.32	0.03
375	0.74	0.69	0.05
400	0.04	-0.08	0.12
425	-0.19	-0.09	-0.10
450	0.30	0.34	-0.05
475	0.79	0.83	-0.04
500	0.98	1.02	-0.04
525	0.93	0.88	0.05

3.4.5 Statistical Profile Elevation Comparison

The root mean square (RMS) calculations provide a check on the accuracy of the data collected. The cross correlation and IRI comparisons enable the comparison of the profiles from a roughness perspective, but if the data itself is inaccurate, these values are meaningless.

The calculation of cross correlation adjusts the profile elevations vertically so the average elevation difference is 0 in. The TLS profiles were adjusted based on the elevation difference so that the average difference was 0. The RMS values and 95% confidence interval values were then recalculated. Table 3.4 contains the RMS and 95% confidence interval calculations for the rod and level, November inclinometer, and TLS both before and after the vertical mean elevation adjustment. The June inclinometer was not used in calculations since there was not a strict DMI calibration and closed-loop.

Table 3.4: Statistical profile elevation comparisons for TLS, level, and November Inclinometer

No Elevation Adjustment						
Parameter	TLS to Level		Inclinomenter to Level		Inclinometer to TLS	
	Left	Right	Left	Right	Left	Right
RMS (in)	0.0259	0.0460	0.0255	0.0188	0.0484	0.0318
95% Confidence (in)	0.0508	0.0902	0.0500	0.0368	0.0948	0.0624
With Mean Elevation Adjustment						
Parameter	TLS to Level		Inclinomenter to Level		Inclinometer to TLS	
	Left	Right	Left	Right	Left	Right
RMS (in)	0.0141	0.0180	0.0122	0.0114	0.0198	0.0162
95% Confidence (in)	0.0277	0.0353	0.0240	0.0223	0.0389	0.0318

Assuming a normal distribution, the mean error between the three instruments was less than 0.05 in and the 95% confidence interval was 0.1 in. Adjusting the TLS profiles so the average difference is zero lowered the RMS to 0.02 in and the 95% confidence interval to 0.04 in. This showed a higher level of accuracy between the two instruments.

3.4.6 Wavelengths

The IRI is sensitive to certain wavelengths, particularly between 3.9 ft to 98.4 ft. The vehicle response to roughness is related to the wavelengths from the profile. Vibration of the vehicle is a result of short wavelengths while the longer wavelengths may cause riders to feel nauseas (Sayers and Karamihas 1998). Since TLS is not a current measurement technique for road profiles, the prominent wave lengths measured from each instrument were compared.

Figure 3.9 (a) and (b) show the left and right wheel paths respectively. From these plots it was clear that each instrument was measuring the same wavelengths from the profiles. Each instrument had the same peak wavelengths for the two wheel paths. Additionally, each instrument showed the same shape for the wave length versus slope spectral density plot. This further showed the reliability of TLS as a measurement technique since it displayed the same sensitivity to wavelengths as the current instruments.

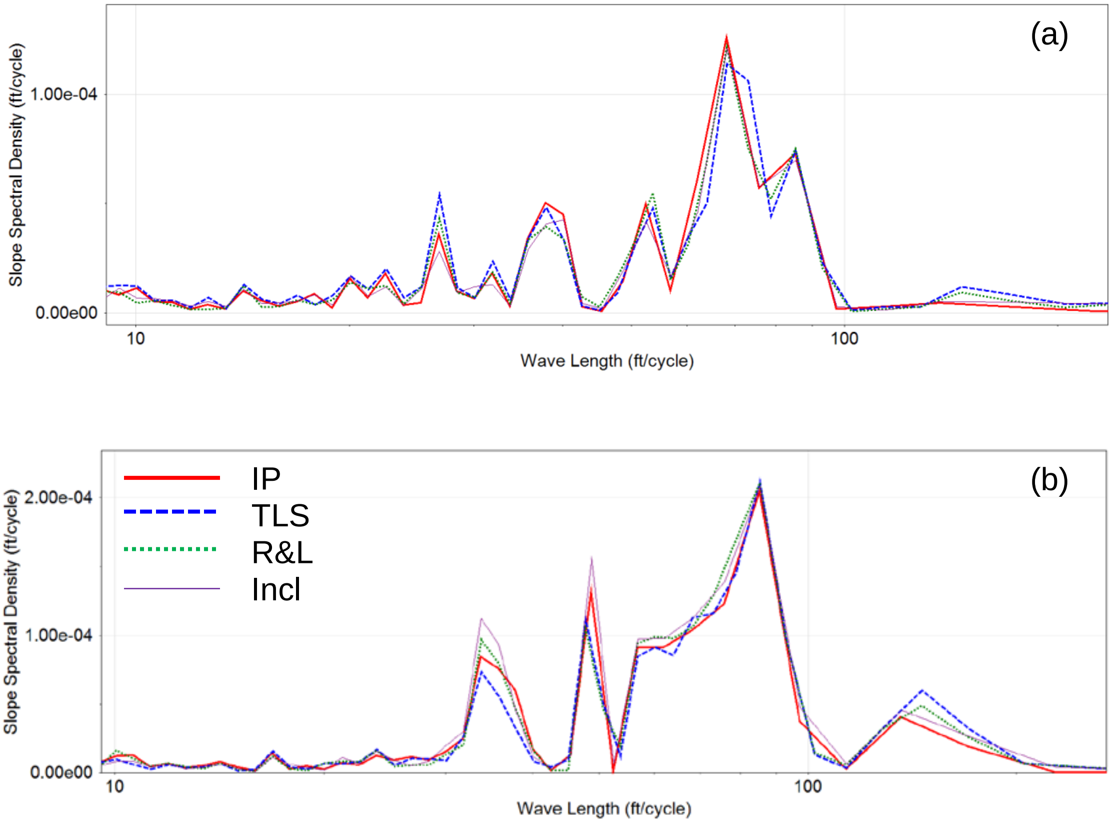


Figure 3.9: Primary wavelengths from inertial profiler, TLS, rod and level, and inclinometer on the (a) left wheel path and (b) right wheel path

3.5 CONCLUSION

TLS is not a current method to measure the roughness of the pavement surface. As a new technique it is important to measure the accuracy of the collected data as well as optimal data analysis strategies. It was found that 5 in to 11 in is the optimal sampling interval to use for scan data during filtering to smooth out noise without over-smoothing the profile. The IRI values from Figure 3.5 were consistent within the 5 in to 11 in range. The smaller sampling intervals reduced the data too much leaving holes in the profile resulting in a much higher and inaccurate IRI. As the data was filtered with larger sampling intervals the IRI was smaller. The data was being over-filtered at high sampling intervals and essentially smoothing out the surface. As a result, the IRI did not accurately reflect the roughness of the roadway. The sampling interval from 5 in to 11 in provided a consistent IRI on the left and right wheel paths.

The cross correlation values were steady between 5 in and 11 in and reduce outside of that range. The average cross correlation values from the rod and level and inertial profiler were above 88% for the right wheel path but approximately 79% for the left wheel path.

Although this study did not fully prove the successful use of TLS to evaluate pavement roughness, the proper filtering techniques were determined. The optimal sampling interval for TLS data was 5 in to 11 in. The cross slope calculations from the TLS were validated using the data from the rod and level and inclinometers. The cross slopes were able to be measured for the entire segment length and on both sides of the road. This is unable to be calculated from inertial profiler and inclinometer data.

The IRI values from the TLS were comparable to the other measurement techniques. These results were in agreement with the study from Chang *et* *al*., (2006) where the rod and level and laser scanner had a 95% correlation. However, when examining cross correlation, which takes into account the roughness location, the TLS did not perform satisfactorily. The sampling interval after filtering was also too large to be used as a reference device. The TLS allows for faster data collection than the rod and level, but the data collection is slower than the inertial profiler and inclinometer. The processing time is also much longer and requires additional software, whereas ProVAL is a freely available software package. The inertial profile and inclinometer are also able to collect points at similar intervals of less than 2 inches which allows for a better comparison and a better measurement of the pavement profile.

Despite the larger sampling intervals, the TLS was able to provide a dense data set with a range of capabilities. Cross slopes and multiple longitudinal profiles across the roadway were able to be determined using TLS. Additionally, this data may be used for as built surveys since data for the entire area is collected. As new technology is developed the accuracy of the instruments will improve. The improvement of mobile laser scanning would be beneficial for road profiling since angle of incidence would be reduced.

3.6 ACKNOWLEDGMENTS

This study was funded by the Oregon Department of Transportation under Project SPR744. The authors would like to thank Leica Geosystems, David

Evans & Associates, and Maptek I-Site for generously providing Oregon State University with training, equipment, and software. The authors also thank Jeremy Conner, Kris Puderbaugh, John Raugust, Keith Williams, Mahyar Sharifi, and William White for their assistance with the data collection.

4 MANUSCRIPT CHAPTER

The Use of 3D Laser Scanning on Pavement Micro-Texture Analysis

Abby Chin[1], Hamid Mahmoudabadi[2], Michael J. Olsen[3], and Todd Scholz[4]

1. M.ASCE. Graduate Research Assistant, School of Civil and Construction Engineering, Oregon State University, 220 Owen Hall, Corvallis, OR, 97331, chinab@onid.orst.edu
2. Graduate Research Assistant, School of Civil and Construction Engineering, Oregon State University, 220 Owen Hall, Corvallis, OR 97331, mahmoudabadi.h@gmail.com
3. M.ASCE. Assistant Professor, School of Civil and Construction Engineering, Oregon State University, 220 Owen Hall, Corvallis, OR, 97331, michael.olsen@oregonstate.edu
4. M.ASCE. Assistant Professor, School of Civil and Construction Engineering, Oregon State University, 220 Owen Hall, Corvallis, OR, 97331, todd.scholz@oregonstate.edu

Technical Note

Manuscript not yet submitted

4.1 ABSTRACT

To fully understand the impacts of construction designs on pavement performance, it is important to study pavement texture. This study utilizes 3D laser scanning to investigate the effects of the typical aggregate sizes on the overall texture of the pavement surface. The study found that pavements with a predominate aggregate size of ¾ in had the highest measured roughness compared to ¼ and ½ in, 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 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 roughness. The optimal settings to provide the most complete scans consist of 2,500 points/in^2 density, neutral or light, settings and scanning from a distance of 6.5 or 17 in.

4.2 INTRODUCTION

The overall roughness of the pavement surface will have an impact on the service life of the 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 offers sub mm accuracy (0.1-0.4 mm (0.004-0.016 in)) 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).

4.2.1 Objectives

Tutumluer *et al*. (2005) conducted a similar 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 a 3D laser scanner. As technology improves, 3D laser scanning can be used in place of these traditional image analysis procedures. 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 3D laser scan settings to calculate texture. The 3D laser scan settings varied between the mode, light settings, and sampling density settings. Also of interest is to evaluate the use of powder on the asphalt surface, which is recommended by the scanner manufacturer to improve laser reflectivity on dark surfaces; this study evaluates the impact of using powder on the texture measurements.

4.3 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 below ±0.005 in. The scanner has three different distance settings: macro (6.5 in), wide (17 in), and extended (30 in)), each of which provides a different field of field of view. Scans can be collected at varying densities from 1,600 points/in^2 to 40,000 points/in^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. The settings of the 3D laser scanner were tested on pavement samples during the first phase. This phase was needed to determine 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. The scanner is unable to obtain an adequate return from the laser off of a dark surface and the resulting scan has many holes and an incomplete data set. The second phase was to collect data on in field pavement samples with varying aggregate sizes: ¼ in, ½ in, and ¾ in using the desired settings obtained from the first phase.

4.3.1 Phase 1: Laboratory Sample Testing

For the first phase, pavement samples were scanned using various combinations of settings 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 4.1). A flat tabletop surface was also scanned using the light setting for the surface color and varying the resolution corresponding to scan settings 1-6 from Table 4.1. Using the sample scan images, the pavement tests outside were performed with the optimal settings on the three different aggregate sizes. The laboratory sample tests were all completed at a distance of 6.5 in, an accuracy of ±0.005 in, and a field of view of 3x5 in.

Table 4.1: 3D laser scanner settings for laboratory sample tests taken at a distance of 6.5 in (±0.005 in accuracy, 3x5 in field of view)

Scan No.	Surface Color	Density (points/in^2)
L1_L	Light	1600
L2_L	Light	2500
L3_L	Light	4400
L4_L	Light	10000
L5_L	Light	17000
L6_L	Light	40000
L1_N	Neutral	1600
L2_N	Neutral	2500
L3_N	Neutral	4400
L4_N	Neutral	10000
L5_N	Neutral	17000
L6_N	Neutral	40000
L1_D	Dark	1600
L2_D	Dark	2500
L3_D	Dark	4400
L4_D	Dark	10000
L5_D	Dark	17000
L6_D	Dark	40000

4.3.2 Phase 2: In Field Pavement Scanning

Scans of in field pavement surfaces were completed on sections with three different aggregate sizes with the settings listed in Table 4.2.

Table 4.2: 3D laser scanner settings for field pavement testing

Scan No.	Surface Color	Density (points/in^2)	Distance (in)	Field Size (in)	Accuracy (in)	Powder
F1	Light	1600	6.5	3x5	0.005	No
F2	Light	10000	6.5	3x5	0.005	No
F3	Neutral	2500	6.5	3x5	0.005	No
F4	Dark	2500	6.5	3x5	0.005	No
F5	Neutral	2500	17	10x13	0.015	No
F6	Neutral	2500	30	16x22	0.015	No
F7	Light	2500	30	16x22	0.015	Yes
F8	Light	2500	17	10x13	0.015	Yes
F9	Neutral	2500	17	10x13	0.015	Yes
F10	Light	2500	6.5	3x5	0.005	Yes
F11	Neutral	2500	6.5	3x5	0.005	Yes
F12	Neutral	17000	6.5	3x5	0.005	Yes

The scans were completed using the test assembly (Figure 4.1), which enables the scanner to be mounted at 6.5 in (Macro), 17 in (Wide), and 30 in (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.

Figure 4.1: Pavement texture analysis test set up

4.3.3 Texture Calculations

The texture of the pavement was calculated using three different methods: roughness ratio, root mean square height (RMSH), and within plot elevation range (WPER). Each of these calculation methods compute a global (*e.g.* entire section) value to represent texture. However, the values calculated can consistently provide an indication of surface texture within a method but cannot be compared between methods. The roughness ratio is simply calculated as the ratio of the 3D surface area to the 2D projected area.

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

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

where:

M and N are the total numbers 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,

$z(x_c,y_r)$ is the elevation at each grid point.

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

4.4 RESULTS AND DISCUSSION

The results of the scans were analyzed to find the optimal 3D laser scan settings based upon the collected scan images. The data was then processed to determine the texture values using the three calculation methods.

4.4.1 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 4.2 for Sample 2 and correspond to the settings from Table 4.1 first without powder (outline shapes) and then with (solid shapes).

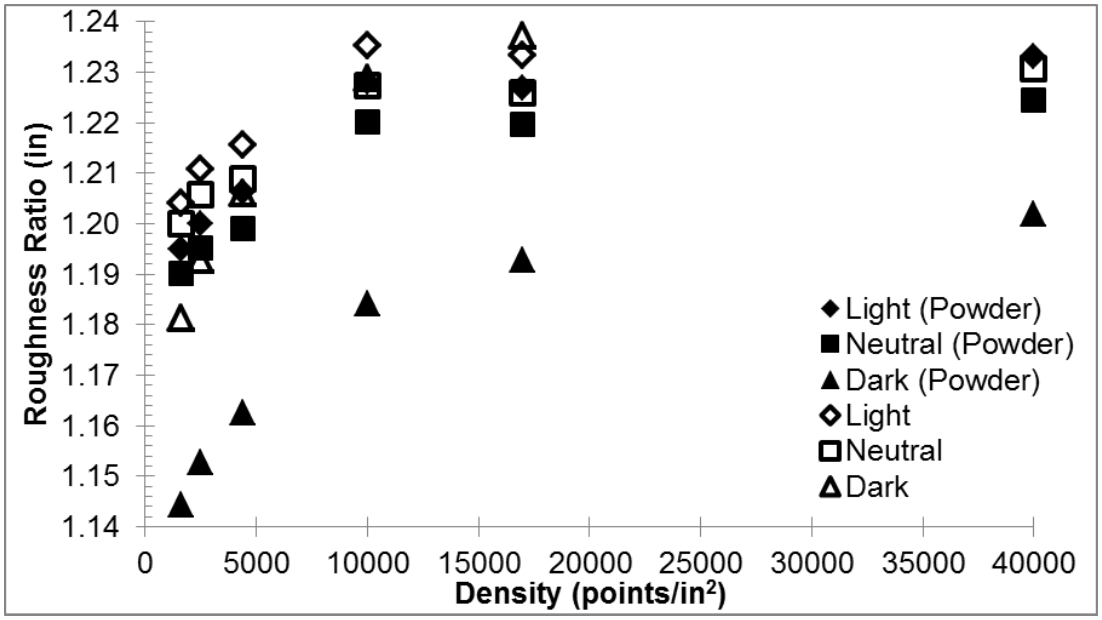


Figure 4.2: Sample 2 roughness ratio versus density for samples with and without powder for light, neutral, and dark surface settings at a distance of 6.5 in from the scanner and increasing point density

From the plot, 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 10,000-40,000 points/in^2. 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 a sufficient scan images, these images had many areas of missing data and therefore did not provide a proper roughness 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 roughness on a flat surface was calculated to be between 0.06-0.07 in and the RMSH was 0.00-0.01 in. Table 4.3 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 roughness at increased densities.

The texture calculations of the ratio and WPER 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.

Table 4.3: Comparison of roughness calculation methods on a test sample with powder

Scan No.	Ratio (in)	RMSH (in)	WPER (in)
L1_L	1.1167	0.0640	0.5470
L2_L	1.1321	0.0629	0.5512
L3_L	1.1533	0.0630	0.5552
L4_L	1.1750	0.0642	0.5580
L5_L	1.1850	0.0640	0.5635
L6_L	1.1895	0.0639	0.5622
Avg (StDev)	1.1586 (0.0297)	0.0637 (0.0006)	0.5562 (0.0064)
L1_N	1.1105	0.0633	0.5404
L2_N	1.1235	0.0623	0.5440
L3_N	1.1391	0.0627	0.5494
L4_N	1.1593	0.0637	0.5488
L5_N	1.1669	0.0637	0.5540
L6_N	1.1695	0.0637	0.5547
Avg (StDev)	1.1448 (0.0244)	0.0632 (0.0006)	0.5485 (0.0056)
L1_D	1.1153	0.0640	0.5439
L2_D	1.1306	0.0628	0.5469
L3_D	1.1508	0.0630	0.5509
L4_D	1.1819	0.0644	0.5561
L5_D	1.1963	0.0643	0.5576
L6_D	1.2018	0.0643	0.5587
Avg (StDev)	1.1628 (0.0359)	0.0638 (0.0007)	0.5523 (0.0061)

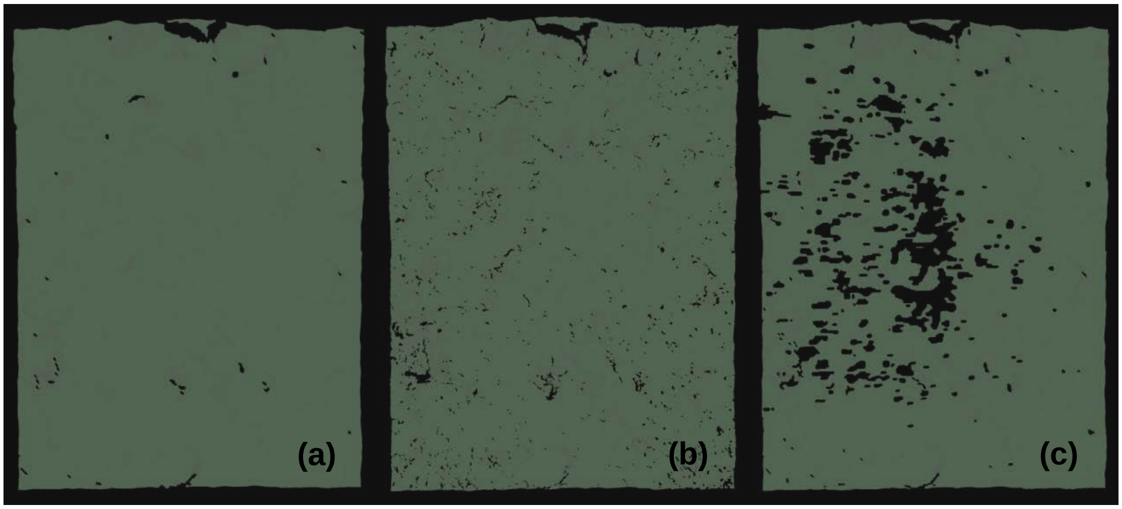


Figure 4.3: Sample test scan images at a 6.5 in distance with powder (a) good (neutral, 1,600 points/in^2), (b) fair (light, 17,000 points/in^2), (c) poor (dark, 2,500 points/in^2)

The sample lab test images were used to choose 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, image c in Figure 4.3. Despite pavement being a dark surface, the dark settings on the scanner generally did not provide usable images. The dark surface provided a poor return of the 3D laser scanner. With large gaps in the data, poor scans provide an inaccurate pavement texture measurement. Scan settings were chosen 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.

Rough or broken pavement will produce occlusions and holes in the scan image such as the holes seen at the top of the scans in Figure 4.3.

4.4.2 Pavement Testing

The pavement testing was completed using the same 3D laser scanner settings for pavement surfaces of each predominant aggregate size tested (¼, ½, ¾ in). The settings for each scan number are presented in Table 4.2. 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. 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 4.4. The changes in texture calculations are more clearly distinguished in Figure 4.4 and Figure 4.5.

Table 4.4: Roughness calculation results for field pavement testing

		Roughness Ratio			WPER (in)			RMSH (in)		
	Scan / Size	0.25 in	0.50 in	0.75 in	0.25 in	0.50 in	0.75 in	0.25 in	0.50 in	0.75 in
No Powder	F1	1.0613	1.0468	1.1573	0.1923	0.1369	0.2364	0.0279	0.0166	0.0322
	F2	1.1115	1.0944	1.1997	0.2117	0.1518	0.2409	0.0289	0.0181	0.0329
	F3	1.0643	1.0515	1.1611	0.1980	0.1366	0.2360	0.0285	0.0174	0.0326
	F4	1.0717	1.0739	1.1670	0.2048	0.1433	0.2323	0.0287	0.0175	0.0326
	F5	1.0330	1.0275	1.1135	0.2852	0.1754	0.2652	0.0414	0.0316	0.0387
	F6	1.0333	1.0483	1.0869	0.2579	0.2305	0.3967	0.0527	0.0647	0.0653
Powder	F7	1.0406	1.0421	1.0828	0.2142	0.2246	0.4258	0.0756	0.1514	0.0655
	F8	1.0296	1.0264	1.1047	0.2427	0.1793	0.2683	0.0357	0.0308	0.0386
	F9	1.0281	1.0229	1.1042	0.2486	0.1925	0.2716	0.0358	0.0285	0.0386
	F10	1.0610	1.0496	1.1601	0.1926	0.1429	0.2387	0.0286	0.0186	0.0325
	F11	1.0566	1.0737	1.1539	0.1943	0.1577	0.2390	0.0289	0.0195	0.0323
	F12	1.0860	1.0459	1.1827	0.2009	0.1430	0.2439	0.0296	0.0186	0.0329
	AVG	1.0564	1.0502	1.1395	0.2203	0.1679	0.2746	0.0369	0.0361	0.0396
	STDEV	0.0254	0.0213	0.0391	0.0307	0.0331	0.0655	0.0143	0.0387	0.0124

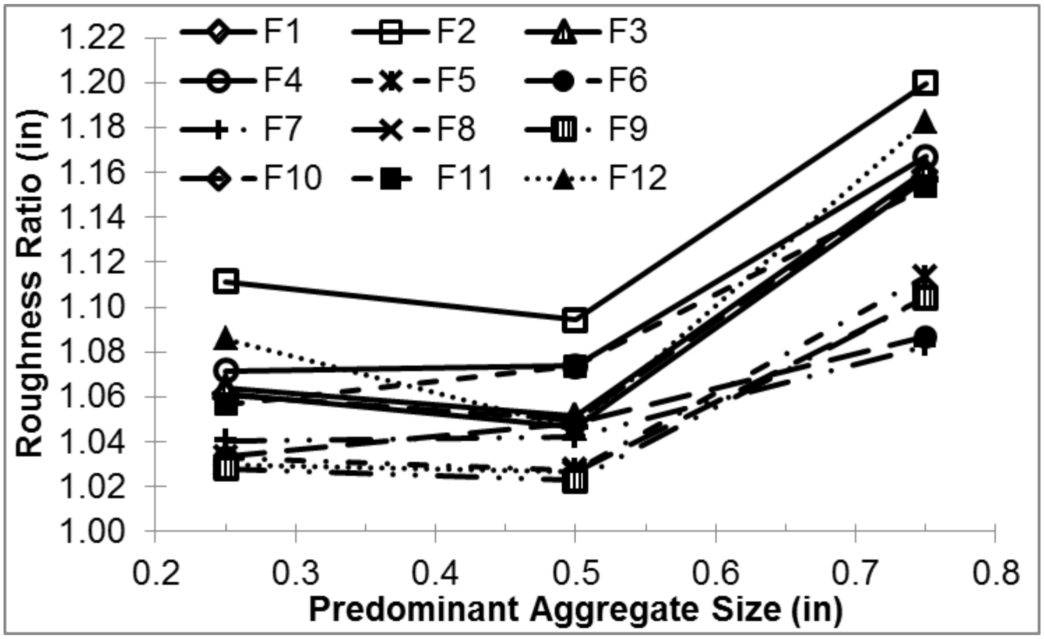


Figure 4.4: Roughness ratio results from in-field pavement testing

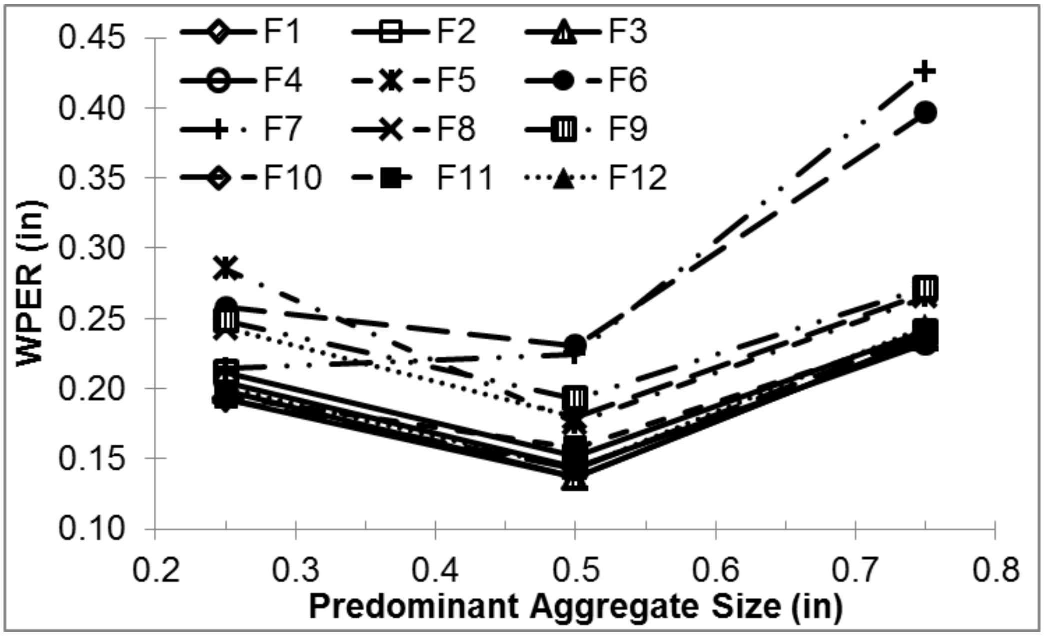


Figure 4.5: WPER results from in-field pavement testing

As expected, the larger aggregate size of ¾ in resulted in increased roughness calculations. However, it is interesting to note that the ¼ in aggregate pavement was slightly rougher than the ½ in 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. The roughness ratio calculations show that the average texture for the ¼ and ½ in 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 (0.05 in). These differences show the impact of the various texture calculation methods, the roughness ratio show the same trends but not the same magnitudes. However, these methods are not able to be directly compared.

Table 4.5: Settings and roughness results from the most complete 3D laser scan images

Aggregate Size	Optimal Settings				Roughness		
	Exposure	Density (points/in^2)	Distance (in)	Powder	Ratio	WPER (in)	RMSH (in)
1/4 inch	Neutral	2500	6.5	No	1.0643	0.1980	0.0285
1/4 inch	Light	2500	6.5	Yes	1.0610	0.1926	0.0286
1/2 inch	Neutral	2500	6.5	No	1.0515	0.1366	0.0174
1/2 inch	Light	2500	6.5	Yes	1.0496	0.1429	0.0186
1/2 inch	Neutral	2500	6.5	Yes	1.0737	0.1577	0.0195
3/4 inch	Neutral	2500	17	No	1.1135	0.2652	0.0387
3/4 inch	Light	2500	17	Yes	1.1047	0.2683	0.0386

The scans in Table 4.5 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 ¾ in aggregate size but the macro setting had fewer holes for the ¼ in and ½ in aggregates. The optimal scan setting without powder was neutral, but with powder was light. Overall, the 2,500 points/in^2 density setting produced the best images for scan analysis.

Unlike the roughness results from the sample testing, the use of powder on the pavement testing did not always result in a lower roughness. 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.

4.5 CONCLUSION

The micron resolution 3D laser scanner was able to measure the texture 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” setting on the 3D laser scanner did not provide a complete image of the pavement surface, with several, large data gaps. The light surface color 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. The texture increased when powder was applied to pavements with a predominant aggregate size of ¾ in.

Predominant aggregate size plays an important role in the texture of the pavement surface. The larger aggregate size of ¾ in 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 roughness. It is interesting to note that in general the ¼ in aggregate pavement is rougher than the ½ in pavement.

Further research may provide insight on the reasoning for ¼ in aggregate pavement being rougher than ½ in 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.

4.6 ACKNOWLEDGMENTS

This project was performed with funding from the Oregon Department of Transportation (Project #SPR-744). A thank you is extended to Keith Williams for building the scanner mount.

5 CONCRETE LITERATURE REVIEW

5.1 INTRODUCTION

The measurement of roughness on portland cement concrete (PCC) pavements is being transitioned from PI to IRI in many states. 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 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 5.1. However, the studies also discuss whether the roughness of the pavement needs to be measured so quickly after completion. Particularly since settlement processes from the highway placement will take time to complete.

Figure 5.1: Example of a light weight inertial profiler (from 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.

5.2 FACTORS AFFECTING IRI

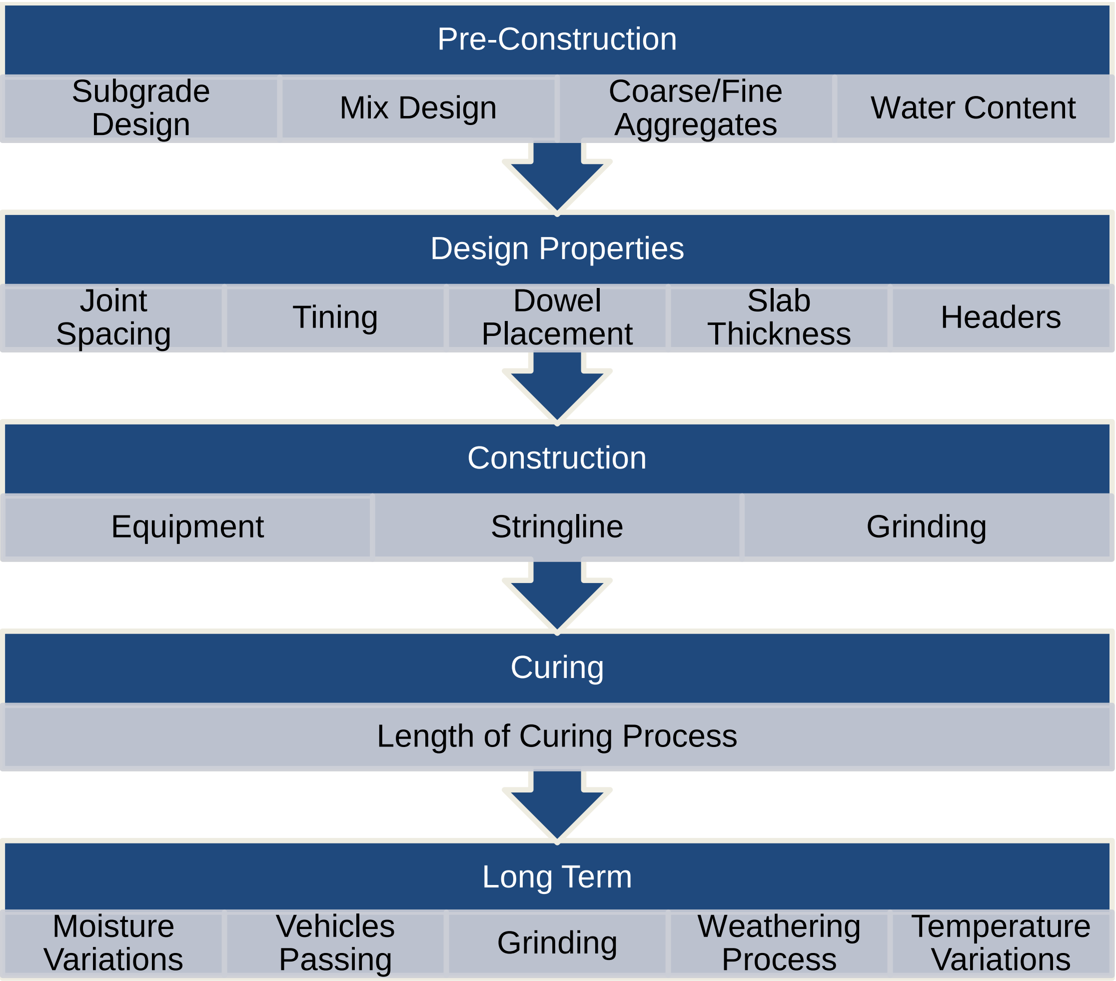


Figure 5.2: PCC pavement design and construction factors affecting IRI

Construction factors (Figure 5.2) 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.

5.2.1 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).

5.2.2 Construction Factors

During construction of PCC pavements stringlines, headers, and dowel bars 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).

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 25 ft. 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.

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. 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 sub base will increase the lifetime of the pavement since the surface will remain smoother for longer (Akhter *et al*. 2004). The sub base 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).

5.2.3 Post Construction

Following the construction of PCC pavements, the surface may experience 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.

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.

5.2.4 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).

5.3 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 concrete becomes raised above the surface of the depth is larger than allowable, the IRI will increase.

5.4 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).

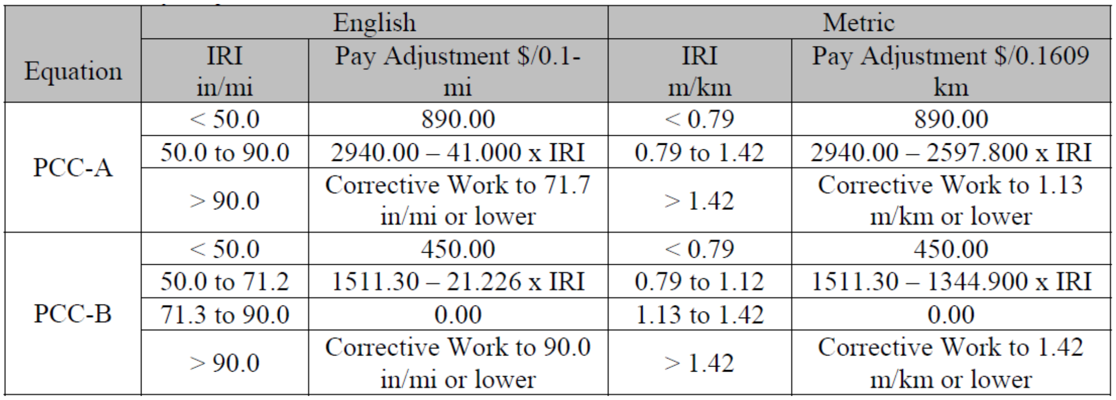
The study from the FHWA also determined that the IRI can be measured at any time within the first few months of paving completion (Perera *et al*. 2005). The benefit of measuring the IRI immediately is that any problems can be identified and fixed. This is advantageous since the study concluded that 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 at the end of each day of construction (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.

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 IRI requirements (Table 5.1).

Table 5.1: 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 (from Wilde and Nordstrom 2010)



Equation	English		Metric	
	IRI in/mi	Pay Adjustment $/0.1-mi	IRI m/km	Pay Adjustment $/0.1609 km
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	0.00	1.13 to 1.42	0.00
	> 90.0	Corrective Work to 90.0 in/mi or lower	> 1.42	Corrective Work to 1.42 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.

5.5 CONCLUSION

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.

6 **CONCLUSION**

This research has effectively studied the use of 3D laser scanning to investigate asphalt pavement roughness. This was studied at a large scale measurement (*e.g.* IRI) and small scale (*e.g.* texture).

Current terrestrial laser scanning systems do not have the ability to provide a reference profile of sufficient accuracy for pavement evaluation due to the limitations of the point spacing. However, it provides the added benefit of collecting data across the entire roadway, enabling it to be used for more post construction quality control analysis. The IRI and cross correlations were successfully determined from the TLS. The optimal sampling interval for filtering TLS data is 5-11 in (note that it should be collected at a denser resolution for use on pavement roughness evaluation). This sampling interval provides profiles with a good correlation to IRI values obtained with common instruments such as inertial profilers, inclinometers, and digital levels. However, TLS has a poor cross correlation to other instruments, which take into account the location of roughness. This data was successfully used to determine the road cross slopes, providing an additional check on the construction quality control for the roadway. Each method of measurement was affected by the same wavelengths showing that TLS is a comparable form of measurement to current methods. The statistical profile elevation comparison also showed that the TLS profiles are comparable with very low RMS values (less than 0.05 in).

Micron resolution 3D laser scanning was studied to determine the effects of aggregate size on pavement roughness. The settings within the 3D laser scanner and the use of powder were tested on lab samples as well as pavement sections. The use of powder is not recommended when investigating roughness as it had a noticeable effect on the measurements. Quality measurements can be obtained without the use of powder using the neutral color with 2,500 points/in^2 density settings. The optimal distance of the scanner to the pavement surface varies with the surface characteristics.

WORKS CITED

AASHTO-M328-10. (2010). "Standard Specification for Inertial Profiler."

AASHTO-R54-10. (2010). "Accepting Pavement Ride Quality When Measured Using Inertial Profiling Systems."

AASHTO-R56-10. (2010). "Certification of Inertial Profiling Systems."

AASHTO-R57-10. (2010). "Operating Inertial Profiling Systems."

Akhter, Mahmuda, Jeffrey Hancock, and Mustaque Hossain. (2004). *A Study of Factors Affecting Roughness Progression on Portland Cement Concrete Pavements in Kansas.* Final Report, Topeka: Kansas Department of Transportation.

Ames Engineering. (2010). <http://www.amesengineering.com/ameshsp.htm> (March 15, 2012).

ASTM-E-1364-95. (2005). "Standard Test Method for Measuring Road Roughness by Static Level Method."

ASTM-E-950. (2009). "Standard Test Method for Measuring the Longitudinal Profile of Traveled Surfaces with an Accelerometer Established Inertial Profiling Reference."

Blair, John A, and Kai K Tam. (2009). "Moving to International Roughness Index Measured by Inertial Profilers for Acceptance of New Asphalt Construction in Ontario." *CUPGA.*

Chang, Jia-Ruey, Kuan-Tsung Chang, and Dar-Hao Chen. (2006). "Application of 3D Laser Scanning on Measuring Pavement Roughness." *Journal of Testing and Evaluation,* 34(2).

FHWA. (2002). “Design, Construction, and Rehabilitation of Continuously Reinforced Concrete Pavements”. <http://www.pooledfund.org/Details/Solicitation/66> (April 8, 2012).

Dyer, Stephen A, and Justin S. Dyer. (2008). "Implementation Problems in Inertial Road-Profiling: An Overview." *IEEE International Instrumentation and Measurement Technology Conference,* IEEE, Victoria, Vancouver Island, Canada.

FHWA. (2002). *Pavement Smoothness Index Relationships: Final Report.* McLean, VA: U.S. Department of Transportation Federal Highway Administration.

Haubrock, Soren-Nils, Matthias Kuhnert, Sabine Chabrillat, Andreas Gunter, and Hermann Kaufmann. (2009) "Spatiotemporal variations of soil surface roughness from in-situ laser scanning." *Catena*, 128-139.

Hays, Joshua D. (2006). "Comparison of New Technology for Measuring Ride Quality." Thesis, Auburn University,.

FHWA. (2012). “Improving the Quality of Pavement Profiler Measurement.” <http://www.pooledfund.org/Details/Solicitation/716> (April 8, 2012).

FHWA. (2002). “Interpretation of Road Roughness Profile Data.” <http://www.pooledfund.org/Details/Solicitation/58> (April 8, 2012).

FHWA. (2002). “Investigation of Aggregate Shape Effects on Hot Mix Performance Using an Image Analysis Approach.” <http://www.pooledfund.org/Details/Solicitation/15> (April 8, 2012).

Jaselskis, Edward J, Zhili Gao, and Russell C Walters. (2005). "Improving Transportation Projects Using Laser Scanning." *Journal of Construction Engineering and Management*, 377-384.

Johnson, Wei Hong, and Andrew M. Johnson. "Operational Considerations for Terrestrial Laser Scanner Use in Highway Construction Applications." *Journal of Survey Engineering*, In Press.

Karamihas, Steven M. (2005). *Critical Profiler Accuracy Requirements.* Ann Arbor: University of Michigan Transportation Research Institute.

Karamihas, Steven M. (2004). "Development of cross correlation for objective comparison of profiles." *International Journal of Vehicle Design,* 36(2/3), 173-193.

Kohn, Starr D., Rohan W. Perera, James K. Cable, Steven M. Karamihas, and Mark Swanlund. (2008). "Use of Profile Data to Detect Concrete Paving Problems." *9th International Conference on Concrete Pavements.* San, Francisco, 690-703.

Lee, Mei-Hui, and Chia-Pei Chou. (2010). "Laboratory Method for Inertial Profiler Verification." *Journal of the Chinese Institute of Engineers* 33(4), 617-627.

Mn/DOT. (2011). "Mn/DOT Inertial Profiler Certification Program."

MnRoad. (2012). *Minnesota Department of Transportation.* <http://www.dot.state.mn.us/mnroad/projects/> (April 8, 2012).

ODOT. (2011). "ODOT TM 769: Certification of Inertial Profiler Equipment."

ODOT. (2011). "ODOT TM 772: Determining the International Roughness Index with an Inertial Laser Profiler."

ODOT. (2009). "Supplement 1058 Surface Smoothness Equipment and Operator Requirements."

Olsen, Michael. (2011). “Bin ‘N’ Grid: A simple program for statistical filtering of point cloud data.” *Lidar News,* <http://www.lidarnews.com/content/view/8378/206/> (March 15, 2012).

Olsen, Michael. (2011). “Putting the Pieces Together – Laser Scan Geo-Referencing,” <http://www.lidarnews.com/content/view/8643/136/> (March 15, 2012).

Olsen, Michael, Adam P. Young, and Scott A. Ashford. "TopCAT - Topographical Compartment Analysis Tool to analyze seacliff and beach change in GIS." *Computers & Geosciences*, In Press.

Olsen, Michael, R. Singh, K. Williams, and A. Chin. *Transportation Applications Subchapter, ASPRS LIDAR Manual,* In press.

Perera, R.W., S.D. Kohn, and S. Tayabji. (2005). *Achieving a High Level of Smoothness in Concrete Pavements Without Sacrificing Long-Term Performance.* Final Report, McLean: FHWA.

Sayers, Michael W, and Steven M Karamihas. (1998). "The Little Book of Profiling." The Regent of the University of Michigan.

Schwartz, Charles W, John Andrews, Peter Stephanos, and Dimitrios G. Goulias. (2002). "Laboratory Evaluation of Inertial Profiler Accuracy."

Shan, Jie, and Charles K Toth. (2009). *Topographic Laser Ranging and Scanning Principles and Processing.* Boca Raton: CRC Press.

Slattery, Kerry T., Dianne K. Slattery, and James P. Peterson. "Road Construction Earthwork Volume Calculations using 3D Laser Scanning." *Journal of Surveying Engineering*, In Press.

SurPRO. (2011). SurPRO http://www.surpro.com/ (October 12, 2011).

Tex-1001-S. (2008). "Operating Inertial Profilers and Evaluating Pavement Profiles."

The Transtec Group, Inc. (2011). “ProVal.” <http://www.roadprofile.com/> (July 2011).

The Transtec Group, Inc. (2008). “Smooth Pavements.” <http://www.smoothpavements.com/> (July 2011).

Thompkins, Derek, John Tweet, and Lev Khazanovich. (2006). "MnROAD Mainline IRI Data and Lane Ride Quality."

Tutumluer, Erol, Tongyan Pan, and Samuel H. Carpenter. (2005). *Investigation of Aggregate Shape Effects on Hot Mix Perrformance Using an Image Analysis Approach.* Project Report, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Federal Highway Administration.

Vosselman, George, and Hans-Gerd Maas. (2010). *Airborne and Terrestrial Laser Scanning.* Scotland: Whittles Publishing.

Watkins, James. (2010). "Mississippi DOT's MRI Pilot Specification." *Road Profiler Users Group (RPUG).*

Wen, Haifang, and Cynthia Chen. (2007). "Factors Affecting Initial Roughness of Concrete Pavement." *Journal of Performance of Constructed Facilities*, 459-464.

Wilde, W. James. (2007). *Implementation of an International Roughness Index for Mn/DOT Pavement Construction and Rehabilitation.* Final Report, St. Paul: Minnesota Department of Transportation.

Wilde, W. James, and Thomas J. Nordstrom. (2010). *Mn/DOT Combined Smoothness Specification.* Final Report, St. Paul: Minnesota Department of Transportation.

Wilson, Joe. (2010). "WisDOT's Profiler Certification Program." *Road Profiler Users Group (RPUG).*

Yi, Zhang, and Ma Rong-Gui. (2009). "A Study of Pavement Roughness Measurement System Based on Laser Ranger Finder." *International Conference on Image Analysis and Signal Processing (IASP),* 295-299.

Yu, Si-Jie, Sreenivas R Sukumar, Andreas F Koschan, David L Page, and Mongi A Abidi. (2007). "3D reconstruction of road surfaces using an integrated multi-sesory approach." *Optics and Lasers in Engineering*, 808-818.

APPENDICES

APPENDIX A – ELECTRONIC APPENDIX

This disk contains the electronic files and data collected to complete the road profile and pavement micro-texture analyses done by Abby Chin at Oregon State University. Questions regarding the contents of this disk should be directed to Abby Chin at: chinab@onid.orst.edu.

Included are the collected road profiles from an inertial profiler and inclinometer provided by the Oregon Department of Transportation in an ERD file format and as a ProVAL file. The files are clearly marked to distinguish the left and right wheel paths of the road test section in Albany, Oregon. The collected data files from the TLS and rod and level are included on this disk as well. The rod and level data were analyzed to create a continuous profile between setups and can be found in the RodLevel folder. The TLS folder contains the ArcGIS and excel files used to create the profiles as well as the final ERD files.

Also included on this disk are the files used for the pavement micro-texture analysis. The raw data files for the two pavement samples and ¼”, ½”, and ¾” pavement tests are placed in the respective folders. The complete data analysis spreadsheet is included on this disk.

The following page details the specific contents of each folder found on the disk.

Folder Name	Contents
20110615_SurPRO	June Inclinometer ERD Files
20111023_Profiler	October TLS Data and ERD Files
20111120_RodLevel	Rod and Level Data and ERD Files
20111120_SurPRO	November Inclinometer ERD Files
Failed Test	Inertial Profiler ERD Files
Passed Test	Inertial Profiler ERD Files
2011_Albany	Processed Roughness Data
ProVAL	ProVAL Files
20120402_GrafLot	1/4” Pavement Scan Data
20120415_Benton	1/2” Pavement Scan Data
20120416_GrafLot3Q	3/4” Pavement Scan Data
Sample1	Lab Test Sample 1 Data
Sample2	Lab Test Sample 2 Data
2012_PavementTexture	Processed Pavement Texture Analysis Data