

Evaluation of the Repeatability and Reproducibility of Network-Level
Pavement Macrotexture Measuring Devices

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ABSTRACT

The purpose of this thesis was to assess the repeatability and reproducibility of two high-speed macrotexture measuring systems. The first portion of the study collected macrotexture measurements using the two high-speed systems on the Virginia Smart Road facility and validated the reproducibility of the mean profile depth (MPD) measurements with reference CT Meter measurements. The various data sets were then compared with each other. The objective was to determine whether the two systems are collecting repeatable and reproducible data.

The analysis showed that the two high-speed systems investigated have good repeatability (approximately 0.11 mm) when measuring the average MPD of the sections investigated. The two systems produce measurements that are highly correlated with the reference ones obtained with the CT Meter. While the Ames systems, with the data processed using the Virginia Tech filter, measures MPD values that are very close to those of the CT Meter, with a virtually zero systematic bias, the SCRIM measure slightly lower readings. The differences are thought to be due to the filtering of the data used by the SCRIM processing software to eliminate dropout and spikes in the laser measurements

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GENERAL AUDIENCE ABSTRACT

The researched compared two different devices used to record data for a surface property of pavement, macrotexture. The macrotexture is a measure of the spaces in between the particles making up the surface of the asphalt. This property is linked to the level of friction on the roadways affecting safety. The readings from each of the devices were validated through a reference device in order to insure they were obtaining reliable results on the Virginia Smart Road. The repeatability and reproducibility of each of the devices was examined to determine whether the two systems were collecting repeatable and reproducible data.

It was determined the two devices had good repeatability and were highly correlated with the reference device. The first device called the Ames system obtained measurements very close to those of the reference device, with a virtually zero systematic bias. The second device called the SCRIM system obtained measurements close to the reference device but slightly lower. Through the comparisons and data analysis, an equation permitting users to convert readings from the SCRIM to Ames system and vice versa was computed. Because one device obtains slightly higher readings than the other, this equation is very important in order to have comparable results.

CONTENTS

Abbreviations.....	vi
List of Tables	vii
List of Figures.....	viii
Chapter 1: Introduction.....	1
Problem Statement.....	2
Objective.....	2
Significance/ Contribution	2
Overview.....	3
Chapter 2: Literature Review.....	4
Uses of Macrotexture.....	4
Macrotexture Measurement	4
Macrotexture Characterization Parameters.....	4
“Static” Macrotexture Measuring Devices.....	6
High-Speed Macrotexture Measuring Devices.....	6
High-Speed Macrotexture Devices Used in This Thesis	7
Data Processing.....	8
Past Equipment Comparisons	10
Conclusions of the Literature Review.....	12
Chapter 3: Research Approach	13
Data Collection and Pre-Processing.....	13
Data Analysis.....	15
Descriptive Statistics.....	15
Limits of Agreement Analysis	16
Orthogonal Regression Analysis.....	18
Chapter 4: Results.....	19
Reference Measurements.....	19
Qualitative Comparisons.....	20
Repeatability	22
Reproducibility	22
Orthogonal Regression Analysis.....	28
Discussion.....	31
Chapter 5: Summary, Findings, and Conclusions.....	32
Summary.....	32

Main Findings of the Research	32
Conclusions.....	32
Recommendations.....	33
References.....	34

ABBREVIATIONS

MTD – Mean Texture Depth

PMS – Pavement Management Systems

MPD – Macrotexture Mean Profile Depth

CT Meter – Circular Track Meter

SCRIM – Sideways-Force Coefficient Routine Investigation Machine

ASCE - American Society of Civil Engineers

SMTD - Sensor-Measured Texture Depth

FHWA - Federal Highway Administration

DOT – Department of Transportation

TDOT - Texas Department of Transportation

GGD - General Gaussian Distributions

FDR - False Discovery Rate

LOA – Limits of Agreement

Anova – Analysis of Variance

MS – Mean Square

LIST OF TABLES

Table 1. Lengths of Virginia Smart Road sections recorded in meters.....	15
Table 2. CT Meter MPD means and standard deviations for examined pavement sections	19
Table 3. High-Speed Macrotexture measurements	20
Table 4. ANOVA test results	22
Table 5. Repeatability (mm) for the average sectional MPD.....	22
Table 6. Limit of Agreement Boundary Results: Concrete 4 Removed	27
Table 7. Ames and CT Meter orthogonal regression analysis results (Concrete 4 removed)	28
Table 8. SCRIM and CT Meter orthogonal regression analysis results (Concrete 4 removed).....	29
Table 9. SCRIM and Ames orthogonal regression analysis results: Concrete 4 removed.....	30

LIST OF FIGURES

Figure 1. Method for computing the mean segment depth (Pulugurtha et al 2012)	5
Figure 2. The CT Meter	6
Figure 3. The SCRIM system	7
Figure 4. The Ames system	8
Figure 5. Test site layout.....	14
Figure 6. Comparison of MPD profiles	17
Figure 7. Standard deviation of the CT Meter MPD measurements vs. the CT Meter MPD means	19
(a) Figure 8. Comparison of Ames and SCRIM 1-meter data	
(b) 21	
Figure 9. Standard deviation vs. mean for the high-speed systems: (a) Ames, (b) SCRIM	21
Figure 10. Ames vs. CT Meter comparisons	23
Figure 11. SCRIM vs. CT Meter comparisons	24
Figure 12. Limits of agreement with upper and lower bounds for the Ames system and the CT Meter (Concrete 4 removed)	25
Figure 13. Limits of agreement with upper and lower bounds for the SCRIM system and the CT Meter (Concrete 4 removed)	25
Figure 14. SCRIM and Ames comparisons: Concrete 4 removed	26
Figure 15. Limits of agreement with upper and lower bounds for the SCRIM and Ames MPD differences	27
Figure 16. Ames and CT Meter orthogonal regression analysis: Concrete 4 removed.....	28
Figure 17. SCRIM and CT Meter orthogonal regression analysis: Concrete 4 removed	29
Figure 18. SCRIM and Ames orthogonal regression analysis: Concrete 4 removed.....	30

CHAPTER 1: INTRODUCTION

Pavement macrotexture is an important pavement surface property that affects many vehicle-pavement interactions, including friction, splash and spray generation, and tire/road noise, among other aspects. While many pavement characteristics are important to road safety, tire pavement friction is particularly important for drivers when they need to react quickly. The frictional forces between the pavement and the vehicle's tires help drivers maintain control of the vehicle in instances where sudden emergency maneuvers are needed. However, the level of friction generated between a tire and the road changes with the speed of the vehicle, and pavement macrotexture is the main road surface characteristic that affects this change (Fulop et al. 2000).

Both macrotexture and microtexture influence the available friction and consequently the crash risk on the roadways. Macrotexture is the spaces between the aggregate comprising the surface of the pavement. Microtexture describes the asperities in the aggregates. This is the voids and divots found on the surface of a piece of aggregate (Rezaei et al. n. d.).

In wet pavement conditions, macrotexture plays a key role in providing channels for the water to escape from under the tire. With high macrotexture, there are larger crevices in the pavement where the rain water can drain into. With low macrotexture, the holes get filled quicker and water lays on the surface of the pavement, reducing the contact between the tire and the road and consequently the friction. Therefore, if the macrotexture is low and the pavement is wet, a vehicle will need more time and a longer distance to slow down or come to a complete stop (Pulugurtha et al. 2012).

Due to pavement texture's influence on safety, highway agencies are starting to monitor the macrotexture of the roadways at the network level. Therefore, there is a need to standardize the way macrotexture data is collected at high speeds. Historically, pavement macrotexture on roads has been measured using the sand patch test. In this test, one must take a 24.6 ml container and fill it with sand. Then, the sand is dumped on the pavement surface and a rubber disk is used to spread the sand in a circular motion. The diameter of the resulting circle is used in an equation to compute the mean texture depth (MTD) (TxDOT 2008). This process is very time consuming and operator-dependent. Current equipment used to measure the macrotexture use high-speed laser sensors. Examples include the Circular Track Meter (CT Meter) and high-speed laser-based systems, such as those found in the Sideways-Force Coefficient Routine Investigation Machine (SCRIM) and Ames systems used in this thesis. The CT Meter is a stationary test while the SCRIM and Ames systems continuously take measurements along the length of the pavement.

Problem Statement

The American Society of Civil Engineers (ASCE) infrastructure report card recently gave our country's roads a D, which indicated poor conditions. ASCE reports that road safety conditions take part in about one-third of the United States traffic-related deaths. To mitigate this problem, significant resources have been invested over the years to "... add... or improve... median barrier systems, and widen... lanes and shoulders..." (ASCE 2013). While this, in conjunction with improvements that have made vehicles safer, has helped reduce the number of crashes and fatalities by 24% from 2005 to 2010, more work needs to be done. Safety can be improved by providing adequate pavement friction. With limited funds, investments must target projects with the most significant impact on the safety for drivers and their passengers.

Past studies (e.g., Flintsch et al. (2003) and Pulugurtha et al. (2012)) concluded that macrotexture is an important road surface property that affects safety, making it a crucial quality to consider in pavement evaluation. Although high-frequency lasers have facilitated the collection of pavement macrotexture at highway speed, available measuring devices do not always result in identical macrotexture values.

Objective

The objective of this thesis is to assess the repeatability and reproducibility of two-high-speed systems used to measure macrotexture, using the static CT Meter measurements as the reference.

Significance/ Contribution

The CT Meter is an advancement to the sand patch test, but this method still takes time and require traffic control. Newer laser-based macrotexture measurement devices can be used in continuous stretches to collect network-level data quicker. This thesis evaluated two high-speed laser-based systems for repeatability and reproducibility. The availability of repeatable and reproducible high-speed macrotexture measurement systems is expected to facilitate, among other things, setting a standard procedure for measuring macrotexture at the network level and defining desired macrotexture levels that can be applied and maintained for roadway safety. Furthermore, if it is proven that the high-speed systems are just as reliable as the CT Meter, the newer systems can be employed. This will increase data collection speed and safety of the data collection personnel and reduce data collection costs.

Overview

Macrottexture is an important pavement surface property to safety. Efforts have been made to help improve road safety, but the budget to maintain the roads is small. This study will assess the repeatability and reproducibility of devices used to measure macrottexture to find the better high-speed laser device to use at network levels, while exposing and improving the defaults in the current data collection procedure. The uses of macrottexture and how those uses help with driver and passenger safety are explained as well as the different devices used to collect macrottexture data and their filters. From there the data collection and processing steps are described in detail with equations. The analysis was used to determine interconversion formulas between the two systems.

CHAPTER 2: LITERATURE REVIEW

This chapters discusses the uses of macrotexture in road safety and the parameters used to characterize macrotexture. Then, it introduces several static and dynamic forms of macrotexture data collection devices, going into detail about the data filtering and presents the results of past device comparisons in order to provide a good background to the methods of this thesis.

Uses of Macrotexture

In 1978, a study completed for the Federal Highway Administration (FHWA) showed that crash rates are impacted by the friction of the pavement. The study found that the crash rate for a road when it is dry is lower than the crash rate for the same road when it is wet, the two rates being related. It also found that pavement macrotexture affects friction and thus, affects the wet-weather crash rate (DOT 1978). Macrotexture becomes more important during rain. Smith and Uddin (2016) showed that when the pavement is wet, the frictional force between the tire and the road decreases. High macrotexture levels provide a higher friction at high speeds, which is needed to help bring a vehicle to a complete stop or decrease the speed of the vehicle at a faster rate during rain. With high macrotexture, the water present on the pavement is evacuated faster from the area between the tire and the pavement, allowing for a larger contact patch and thus higher friction, which help prevent the vehicle from skidding (Flintsch et al. 2012).

Pulugurtha et al. (2012) found that as the macrotexture increased, the percentages of crashes decreased. This result was obtained after accounting for factors such as visual distractions while driving, traffic entering the lane, insufficient visual sight, and the amount of traffic. Their study concluded to reduce the number of crashes, the macrotexture on asphalt pavement should be at least 1.016 mm (0.04 in.) and on concrete pavement at least 2.032 mm (0.08 in.) (Pulugurtha et al. 2012).

Macrotexture Measurement

Macrotexture Characterization Parameters

The MPD is currently the parameter most used in the U.S. for characterizing macrotexture. The equipment used for data collection takes a continuous stream of very closely-spaced pavement surface elevations in 100 mm increments and has with a laser with a footprint of 1 mm or less. For data processing, the 100 mm increments are divided in two 50 mm sub-segments. In each sub-segment, the height of the highest peak of the pavement surface is found and then the average of all measurements in the 100 mm increment is subtracted from the highest peak height of the 50-mm half (Figure 1). The average of the two resulting values from the 50 mm halves is then reported as the MPD value of the 100-mm section (ASTM International n.d.(a)).

$$\text{MPD} = \text{Average}(\text{Mean Segment Depth}) = \text{Average}\left(\frac{\text{Peak Level 1} + \text{Peak Level 2}}{2}\right) \quad (1)$$

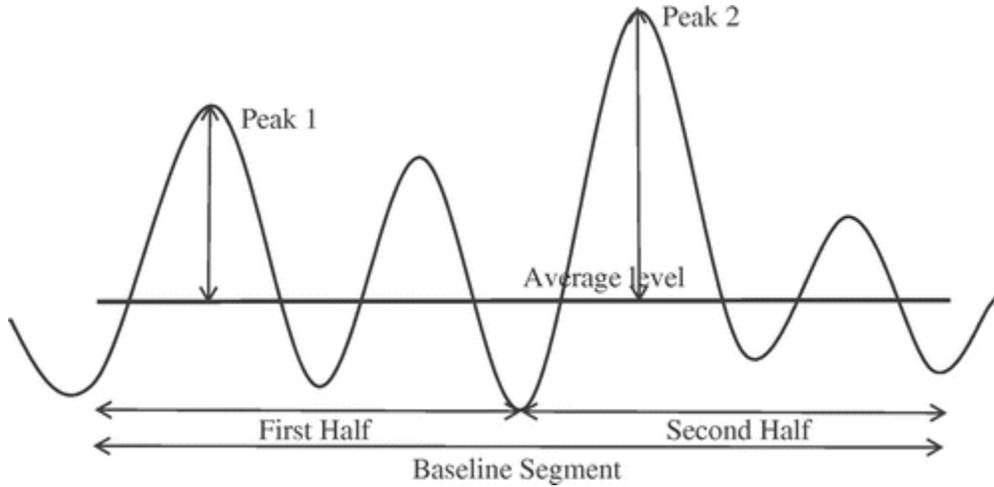


Figure 1. Method for computing the mean segment depth (Pulugurtha et al 2012)

Roe and Sinhal (2005) discussed other parameters used around the world to characterize macrotexture. In their study, the texture depth was reported as a sensor-measured texture depth (SMTD), averaged in 10 meter increments. The SMTD data, along with other characteristics, were monitored and reported at this interval level to provide a fuller picture of the pavement conditions and enhance the interpretation of the friction results without becoming caught up in the small changes of the pavement surface. The SMTD measures the height of the pavement texture by finding the root mean square (RMS) of the texture above and below the average level seen in Figure 1. This parameter represents the standard deviation of the texture profile measurements, examining the pavement in 2-D (Liu et al. 2016). The actual computational method for computing SMTD is the following (Freitas et al. 2015):

$$\text{SMTD} = \sqrt{\frac{\sum_{i=1}^n (y_i - y_e)^2}{n}} \quad (2)$$

Where y_i = laser height measurement at laser measurement i

n = number of laser measurements (odd)

y_e = curve obtained by quadratic least square regression = $a + bx + cx^2$

x = distance between measurements

a, b, c = curve parameters

The MPD, in contrast, measures the mean of only the height above the average level. The laser devices typically record the average measurements every 1 meter, but allow the user to report in 10 meter increments. Viner et al. (2006) found the following relationship between the SMTD and the MPD:

$$\text{MPD} = 1.42 \times \text{SMTD}^{0.840} \quad (3)$$

“Static” Macrotexture Measuring Devices

The CT Meter (**Error! Reference source not found.**) is a recognized standard device used to measure the pavement macrotexture in the U.S. and has mostly replaced the sand patch test. The CT Meter is placed on the pavement and an arm with an attached laser sensor rotates in a circle and collects elevation data at regularly spaced 0.87 mm intervals. The device software divides the measurements into 8 sectors labeled A through H and reports the computed MPD and Root Mean Square (RMS) for each sector, as well as the average of the readings taken around the circumference (ASTM International n. d.(b)). This device is a widely accepted test method for measuring macrotexture in the transportation engineering community. Other static devices include the sand patch test as described in the introduction, Ames Engineering Scanner, ZScanner 800, and the Outflow Meter.



Figure 2. The CT Meter

High-Speed Macrotexture Measuring Devices

High-speed devices use laser-based sensors to collect a high-resolution profile of the pavement surface and determine the macrotexture at higher speeds. These systems can be easily installed on a vehicle to collect data at regular traveling speeds (Ames n.d.). High-speed macrotexture measuring devices include the Dynatest Laser Profiler, Ames system, and SCRIM system. The Dynatest Laser Profiler uses a Selcom Optocator 2008-180/390 laser that can measure up to 7.09 inches away with a sampling rate of 62.5 kHz at a 45-micron resolution. (Fisco 2009).

High-Speed Macrotexture Devices Used in This Thesis

This thesis compared two available high-speed macrotexture measuring devices, one mounted on a SCRIM system and a portable Ames system. The SCRIM system (Figure 3) is a multi-function pavement evaluation system that can measure the pavement macrotexture and friction, along with GPS location, road geometry (gradient, cross-slope, and curvature) and front video to provide supplemental information on the area of interest.



Figure 3. The SCRIM system

The laser-based system mounted on the SCRIM system (referred to as SCRIM system in the rest of the thesis) records processed MPD data at 1-meter increments to complement wet skidding resistance measurements. The SCRIM system typically collects data within a 50 to 80 km/h range (30 to 50 mph), and the data is post-processed on a computer (WDM n. d.(b)). Specifically, for the MPD measurements, the SCRIM system alerts the user when the MPD reading is outside a range of 0.5 to 3.0 mm. When the readings are outside of this range, the screen turns red (Griffin and Ali 2015). The system records the raw data every 100 mm or 0.1 meters, but it can report the results at longer averaging intervals (WDM 2015). The steps on how to process and analyze this data are described in the following chapter.

The Ames 8300 Survey Pro High Speed Profiler is a portable system that simultaneously collects macrotexture and profile data using high-speed laser sensors that can be mounted on the back and/or front end of a vehicle. The system also has a GPS, forward facing camera, temperature gauge, speed gauge, distance monitor, and a battery power reader (Ames 2015). The system uses a LMI-Selcom Optocator 2008-180/390 texture sensor rated at 62.5 kHz (Olmedo et al. 2015) and is set up to operate between 25

and 65 mph. To provide good readings, the sensor has to be located within 180-mm from the pavement surface (Ames, n. d.).



Figure 4. The Ames system

Data Processing

The SCRIM system incorporates an internal filter that automatically processes the measurements before the MPD is calculated (WDM n. d.(a)). The Ames system collects and stores its data using proprietary software on a laptop. The raw pavement profile data typically include outliers because of spikes or drop-off in the laser measurements (Mogrovejo et al 2015). To identify and remove these bad measurements, the Ames software incorporates several filtering options. The details on how this works are described following.

The Ames software processes the pavement elevations and calculates the MPD value (Ames n. d.). This system includes two filters to pre-process the data, before the MPD is calculated, and to remove

possible outliers, drop-offs, and spikes in the data. The software offers three options: no filter, three-point filter, or Virginia Tech filter. The three-point filter uses the following rules to sort through the data:

$$\text{if } |z(i+1) + z(i-1)| < .5 \text{ mm} \quad (4)$$

$$\text{and } \left| \left(\frac{z(i+1) + z(i-1)}{2} \right) - z(i) \right| > .25 \text{ mm} \quad (5)$$

$$\text{then replace } z(i) \text{ with } (z(i+1) + z(i-1))/2 \quad (6)$$

where $z(i)$ is the data reading at distance i

The Virginia Tech filter identifies and removes more of the outlying spikes using a statistically based approach (Ames 2015), but it does take more time to process the data. The Virginia Tech filter was applied for the data analysis in this thesis. This filter uses the General Gaussian Distributions (GGD), presented in equation 6, to find the best distribution to represent each examined data set.

$$p(x) = \frac{\beta}{2\alpha\Gamma(\frac{1}{\beta})} \exp\left(-\frac{|x-\mu|}{\alpha}\right)^\beta \quad (7)$$

Where β = shape parameter
 α = scale parameter related to variance
 Γ = gamma function
 μ = location parameter

The shape parameter that best fits the 90th to 97th percentiles of the data is selected. These percentiles were chosen because as the percentages increase, the fit of the distribution to the data increases; however, the number of outliers included in the analysis also increases. This is because the tail ends of the distribution become more and more specific to the data as the percentage increases and less specific to the data at the percentage decreases. Therefore, the top most percentiles are not considered because at higher percentages the tail ends of the distribution would be changing to better fit data points in the tail which could be outliers. The low percentages would begin to remove too many good data points. The 97th percentile would adjust for up to 3% outlying data (Mogrovejo 2015).

The Virginia Tech filter then uses the False Discovery Rate (FDR) of Benjamini and Hochberg (1995) to identify the threshold used to identify outliers. In this method, the threshold applied changes to fit the circumstances, while other methods such as the Bonferroni and 2-sigma do not. FDR controls the ratio of falsely identified spikes to all identified spikes (Mogrovejo 2015). The FDR procedure is outlined below:

1. Given n measurements of which n_o are not spikes and $1 - n_o$ are spikes, using the determined distribution of texture measurements, calculate the p-value of all n measurements
2. Reorder the p-values in increasing order

$$(p_1 \leq \dots \leq p_i \leq \dots \leq p_n) \quad (8)$$

3. Select a q value at which to control the FDR (e.g. 0.01, 0.05, or 0.1)
4. Let k be the maximum I such that:

$$p_i \leq \frac{i}{n} q \quad (9)$$

5. Spikes are identified as all measurements whose p-value is $\leq p_k$

After the spikes are removed, the MPD values are computed according to the ASTM E1845-09 standard using a 2.5 mm moving average and reported at every 1 meter (Mogrovejo 2015).

Past Equipment Comparisons

In 1992, the Permanent International Association of Road Congress performed one of the first international macrotexture comparison studies. The study compared and tried to harmonize 14 macrotexture measuring devices, in addition to many friction measuring devices. It was determined that MPD would be the designated macrotexture characterization parameter because it had the best repeatability amongst the devices in use (Wambold et al. 1995). Europe also performed several other follow-up studies involving pavement texture measurements and the harmonization of the measurements from different devices. In the US, the Annual NASA Tire/Runway Friction Workshops focused on friction measurements but also compared macrotexture devices (Yager 2005).

Flintsch et al, (2003) compared macrotexture measurements obtained with a CT Meter, sand patch test, and a laser inertial profiler. The study found that the CT Meter and sand patch measurements were highly correlated with an R^2 value of 0.943. The laser inertial profiler and sand patch results also had good correlation as well, but with an R^2 value slightly lower at 0.884.

Fisco (2009) examined and compared macrotexture measurements using the sand patch test, Dynatest laser profiler, Ames laser texture scanner, and CT Meter at several locations in Ohio. The study found inconsistencies between the measurements and concluded that that the laser profiler underestimated the sand patch test's MTD, the Ames laser texture scanner predicted the MTD with a high correlation to the sand patch test, and the CT Meter could predict the MTD but not as well as the Ames laser scanner (Fisco 2009).

Aktas et al. (2011) compared macrotexture measurements obtained with the outflow meter ASTM STP 583, and the Transit New Zealand TNZ T/3 sand circle (a version of the sand patch) macrotexture measurements. The comparison was performed over a period of 3 years on 23 different asphalt and concrete pavement sections. The study found that the measurements did not agree for all texture ranges. It recommended to use the outflow meter for macrotexture smaller than 0.79 mm, the sand patch method for macrotexture greater than 1.26 mm, and either methods for macrotexture between 0.79 and 1.26 mm, using MTD as the designated parameter. For low levels of macrotexture, the sand used in the sand patch method will continuously spread over the pavement surface making it hard to get a uniform circle. The outflow meter does not seal tightly with the pavement surface in the presence of high macrotexture, making the test water flow out too quickly to obtain a good measurement.

Perera and Wiser (2013) compared an Ames system using a LMI-Selcom Optocator 2008-180/390 high-speed sensor with the CT Meter and Ames Engineering Scanner. The study considered 3 sections of interest, two asphalt sections and one chip seal, and the researchers conducted 6 repeated runs on each section. They computed the percent difference in MPD for each section, for each device, for each wheel path. The study recommended that there is a need for a better method to verify the reproducibility of the instruments and recommended the incorporation of a spike detection algorithm.

Mogrovejo et al. (2014) tried a method to help remove spike from macrotexture data collection using the MPD parameter. The high-speed laser device filtering approach was validated using CT Meter measurements taken in the same location as the high-speed laser device. The study concluded that where they placed the CT Meter for testing did not matter as long as it was within the test section. Therefore, it did not matter if the device was placed on or off the wheel path. However, the test site used did not have a lot of traffic.

D'Apuzzo et al. (2015) compared a high-speed laser device against the CT Meter. A preliminary analysis confirmed the need to apply filters to remove invalid measurements from the data sets. The researchers applied a filtering system with a moving window concept and the “ETD square weight evaluation based sectioning procedure.” The ETD square weight procedure obtains a macrotexture estimate by converting 2D MPD values into volumetric macrotexture estimates using the following equation:

$$\text{ETD square weight} = \frac{\sum_{i=1}^n \text{MPD}_i \cdot L_i^2}{\sum_{i=1}^n L_i^2} \quad (10)$$

After the filtering process, researchers performed a student t-test and a Fisher test. The preliminary results suggested that the CT Meter and the high-speed laser device measurements agreed satisfactorily

after applying the filtering, and thus the high-speed sensors can be used to measure the MPD of pavement surfaces (D'Apuzzo et al. 2015).

Kováč et al (2015) compared a Profilograph GE device, which collects continuous measurements, and a ZScanner 800, which takes three-dimensional stationary measurements. The macrotexture parameter chosen to use for comparison was MPD. They found there was a high correlation between the two devices MPD measurements with an R^2 value of 0.981. They did find, however, that the ZScanner 800 did take a lot more time to collect the data, making it less practical for a network level use.

Olmedo et al. (2015) investigated how to collect macrotexture data on a network scale using an Ames system. A Model 8300 profile/texture device with a LMI-Selcom Optocator 2008-180/390 sensor was mounted on a Ford E150 XLT Wagon. The researchers compared the mean, high, and low MPD readings between each examined pavement type, along with the section's standard deviation. Various number of runs were collected for each section. They investigated the difference between readings for various pavement types, surface conditions, climatic regions, traffic load levels, and overlays. The study identified which pavement type or condition resulted in the highest and lowest MPD readings. The study concluded that the higher MPD readings occur on open graded friction courses (OGFC), chip seals, course graded AC pavements, and non-freeze zone sections.

Conclusions of the Literature Review

The CT Meter and Ames Engineering Scanner seem to be good reference devices for measuring pavement surface macrotexture as both correlate well with the tradition sand patch tests. Past comparisons provided mixed results with the high-speed systems but in general agree MPD is the most used macrotexture characterization parameter and that filters are needed to remove bad laser measurements (Perera and Wisser 2013).

CHAPTER 3: RESEARCH APPROACH

This chapter provides details on the data collection, pre-processing and analysis. It provides descriptive statistics for the tested pavement section for each device, uses a limits of agreement analysis to determine the repeatability and reproducibility of the data and orthogonal regression analysis to determine interconversion formulas.

Data Collection and Pre-Processing

Macrottexture data was collected on 8 asphalt pavement sections and 2 concrete pavement sections at the Virginia Smart Road using two high-speed profilers and the CT Meter. The data was processed to compute a continuous MPD profile. The measurements from the different test files were aligned for the 10 sections of interest and then compared using descriptive statistics, box-plots, limits of agreement, and orthogonal regression analysis to assess the repeatability, and reproducibility of the high-speed devices. VTTI representatives collected data with the SCRIM system in June of 2015 and with the Ames system in December of 2015. The CT Meter data was collected in May of 2016. This difference in collection times is not expected to have a significant effect on the macrottexture measurements, but it could be a possible source of variation between the measurements. The three systems include software to compute and report the pavement MPD.

The Virginia Smart Road includes 18 different sections, with asphalt and concrete pavements, along with several bridges and 2 special treatments applied on concrete pavements for winter maintenance studies. The EP-5 treatment is an epoxy-based surface treatment that uses a combination of angular grained silica sand and basalt (Sprinkle et al. 2009). The Cargill Safe Lane system is a trademarked product. Ten sections with different level of macrottexture were selected for the study and measured with the static reference device. These sections are analyzed in this thesis. To prepare the Smart Road for data collection, the starting point along the test direction of each pavement section was marked off.

The CT Meter measurements were obtained on the wheel path. Four to seven CT Meter measurements were taken on each section. As explained earlier, the CT meter takes 8 readings around the circumference the sensor makes. The 8 readings and the averages in each location were recorded.

The high-speed macrottexture measuring devices collected data for the entire road. The data was saved then processed to compute MPD and exported into excel files for analysis. Using manual markers recorded by the operator in the SCRIM data sets, the start of the first section was found within each data set. The lengths of the sections identified in Figure 5 and summarized in Table 1, were used to mark the beginning and end of each section in the excel file.

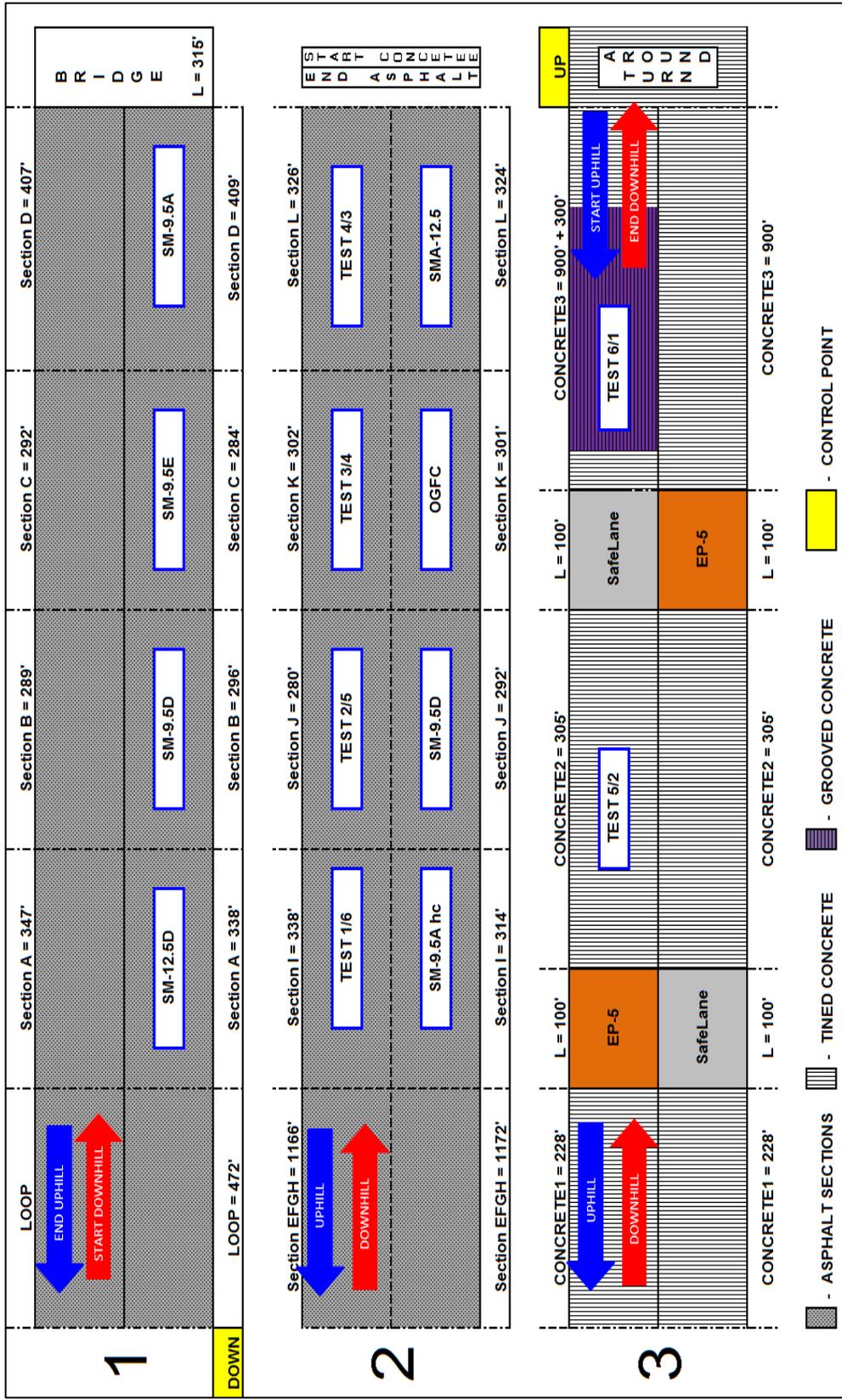


Figure 5. Test site layout

Table 1. Lengths of Virginia Smart Road sections recorded in meters

Sections	Length in the Uphill Direction (m)
Sect PCC5 (Tined)	279
Sect PCC4 (Grooved)	158
Sect PCC3 (Tined)	30
Cargill Safe Lane	30
Sect PCC2 (Tined)	93
EP-5	30
Sect PCC1 (Tined)	70
Sect L	99
Sect K	92
Sect J	85
Sect I	103
Sect H-E	355
Bridge	96
Sect D	124
Sect C	89
Sect B	88
Sect A	106

Minor adjustments were made visually to align the macrotexture profiles and fine-tune the position of the markers. The start and end of the sections can be noted by sudden changes in the trends through a drop or jump. For example, the Cargill Safe Lane section was adjusted by 1 meter to start at 244 meters. After identifying the start and end of each of the sections, the first and last two data entries were removed (approximately 2 m or 6.6 ft.) from the sectional data set to compensate for small misalignment of the successive measurements.

Data Analysis

The data for the two high-speed systems were analyzed using the average of the measurements over a 1-meter length. Longer data averaging increments (e.g., 10 m) were also used to better observe pattern or similarity between the two data streams.

Descriptive Statistics

The first step in the data analysis was to calculate the mean and standard deviations of the measurements collected from each device for each of the 10 analyzed pavement sections. In order to observe general trends in the data, measurements for the high-speed systems were plotted along the

traveled distance. Two runs from the Ames system were discarded because of laser sensor malfunctioning.

To find the start of the pavement sections in the Ames data files, the plots for the SCRIM and Ames systems were overlaid. A small data alignment was necessary because the Ames data did not have a GPS location or data markers incorporated. The measurements of the Ames system were shifted to match the general trends in the data and align the various profiles with each other. The SCRIM system's sections were known because the start of each sections was marked in the data. In addition, the start of the sections could be confirmed with video feed. Only one run from each system was used to match the distance parameter for the two data systems. Using the marked sections, the SCRIM and Ames profiles were adjusted as depicted in Figure 6.

An analysis of the data variability within each section was performed. For each of the systems under consideration, the following statistics were calculated and used to prepare box plots for each pavement section using the standard equations as in Ott and Longnecker's textbook (2016).

Limits of Agreement Analysis

A limits of agreement analysis (LOA) (Bland and Altman 1986) was conducted to compare the Ames to the CT Meter, the SCRIM to the CT Meter, and the Ames to the SCRIM. The LOA takes into consideration "...the variability across individuals of the true quantity being measured, the variability of each individual's average values about overall average for that method, ..., and the variability of repeated measurements about the average for an individual" (Bland and Altman, 2007). One of the goals of the analysis is to compute the LOA boundaries to find the average difference between measurement systems data collection. The plus and minus 1.96 standard deviation to the mean was used to computed the 95% confidence range for the difference in MPD readings between two measurement systems. It should be noted that this method assumes that the measurements are independent of each other. The method used for this study followed the steps outlined in Bland and Altman (2007):

- a) Find the average and variance of the average section MPD measurements for devices 1 and 2 (s_1^2 and s_2^2) and the variance of the difference between the two devices (s_D^2).
- b) Calculate the corrected variance using the following equation:

$$s_c = \sqrt{s_D^2 + (f_1)s_1^2 + (f_2)s_2^2} \quad (21)$$

Where

$$f_i = 1 - \frac{1}{m_i} \quad (22)$$

m_i = number of runs for device i

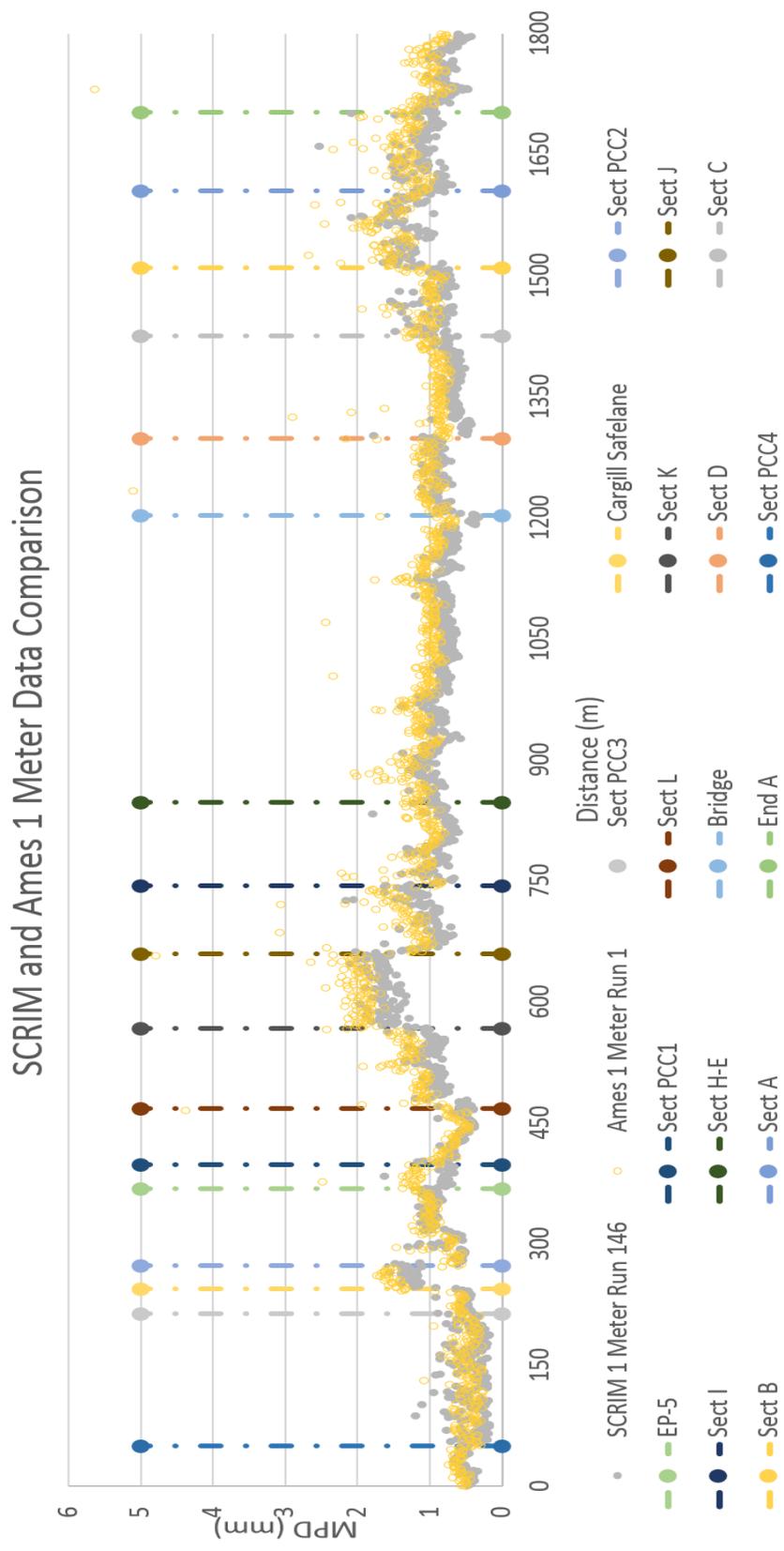


Figure 6. Comparison of MPD profiles

- c) Calculate the limits of agreement bounds for the 95% confidence range:

$$LOA = 1.96*s_c \quad (23)$$

- d) Compute the upper and lower limits as the average difference plus or minus the LOA.

The repeatability and reproducibility for each of the devices was determined using the Anova results from above and a LOA. Here repeatability is the measurement that describes the variation in repeated measurements performed on the same subject under the same conditions. The reproducibility is the measurements that describes the variation in measurements obtained in varying conditions. The repeatability was computed twice for each system, using the within group variance for all pavement section and removing the section Concrete 4 because it has a longitudinally textured finishing that is difficult to measure with point lasers. The equation used is the following (Bartlett and Frost 2008):

$$\text{Repeatability} = \text{Repeatability Factor} * \sigma_i = 1.96 * \sqrt{2} * \sigma_i \quad (24)$$

Orthogonal Regression Analysis

The final portion of the analysis consisted of an orthogonal regression analysis. This analysis considers that both the predictor and response variable have measurement error. The error variance ratio is computed by dividing the error variance for the response variable by the error variance for the predictor. The analysis use an error variance ratio of 1. This means that the error variance in the two systems being compared is assumed the same and the orthogonal regression line it will reduce the residuals both device the same (Minitab 2017(a)). If this assumption is correct, the fit using the orthogonal distances produced unbiased estimates of the regression parameters, unlike the ordinary least squares regression which would be biased. The orthogonal regression minimizes the distance from each point to the best fit (Minitab 2016). Minitab (2017 (b)) was used to find the best fit and confidence intervals for the intercept and slope. The following equation is used to calculate the value for each separate residual (Minitab 2017(a)):

$$\hat{V}_t = Y_t - \hat{\beta}_0 - X_t \hat{\beta}_1 \quad (25)$$

Where $Y_t = t^{\text{th}}$ response value

$\hat{\beta}_0 =$ intercept

$X_t = t^{\text{th}}$ predictor value

$\hat{\beta}_1 =$ slope

CHAPTER 4: RESULTS

This chapter presents the results of the analysis. It presents descriptive statistics for the three systems, the results of synchronizing the data streams, and the comparisons done to assess the repeatability and reproducibility of the two high-speed macrotexture measuring devices.

Reference Measurements

As mentioned before, CT Meter measurements were used as reference for verifying the reproducibility of the high-speed devices. The CT Meter records individual measurements over 8 arcs, which were considered as independent measurements for the statistical analysis. With 4 measurement sets collected, this provided a total of 32 MPD readings. Table 2 summarizes the CT Meter measurements. Figure 6 shows that the standard deviation seems to be independent of the mean MPD.

Table 2. CT Meter MPD means and standard deviations for examined pavement sections

Section	Tests	Sample Size	Mean (mm)	Standard Deviation (mm)
Section PCC4 (Grooved)	4	32	2.06	0.14
Section PCC3 (Tined)	4	32	1.30	0.21
Section L	4	32	1.22	0.12
Section K	4	32	1.07	0.07
Section J	4	32	0.88	0.06
Section I	4	32	1.04	0.07
Section D	4	32	1.62	0.13
Section C	4	32	1.43	0.16
Section B	4	32	0.79	0.20
Section A	4	32	1.67	0.09

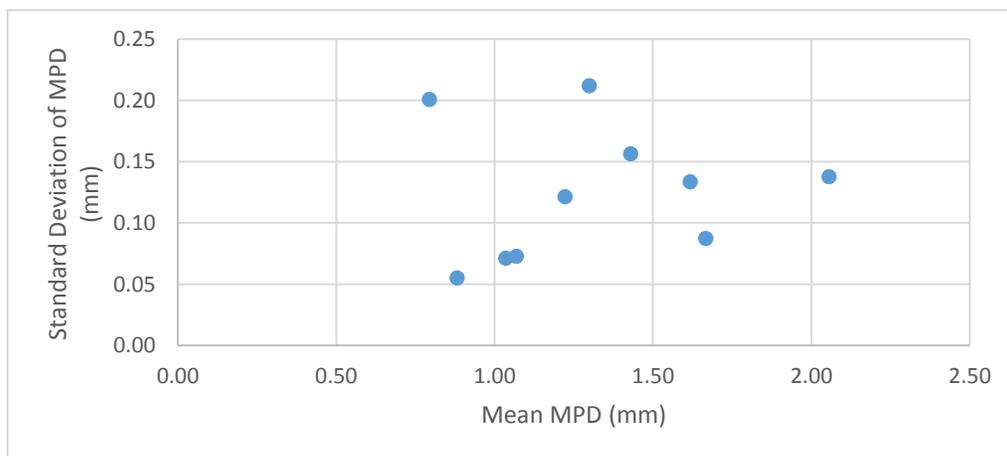


Figure 7. Standard deviation of the CT Meter MPD measurements vs. the CT Meter MPD means

Qualitative Comparisons

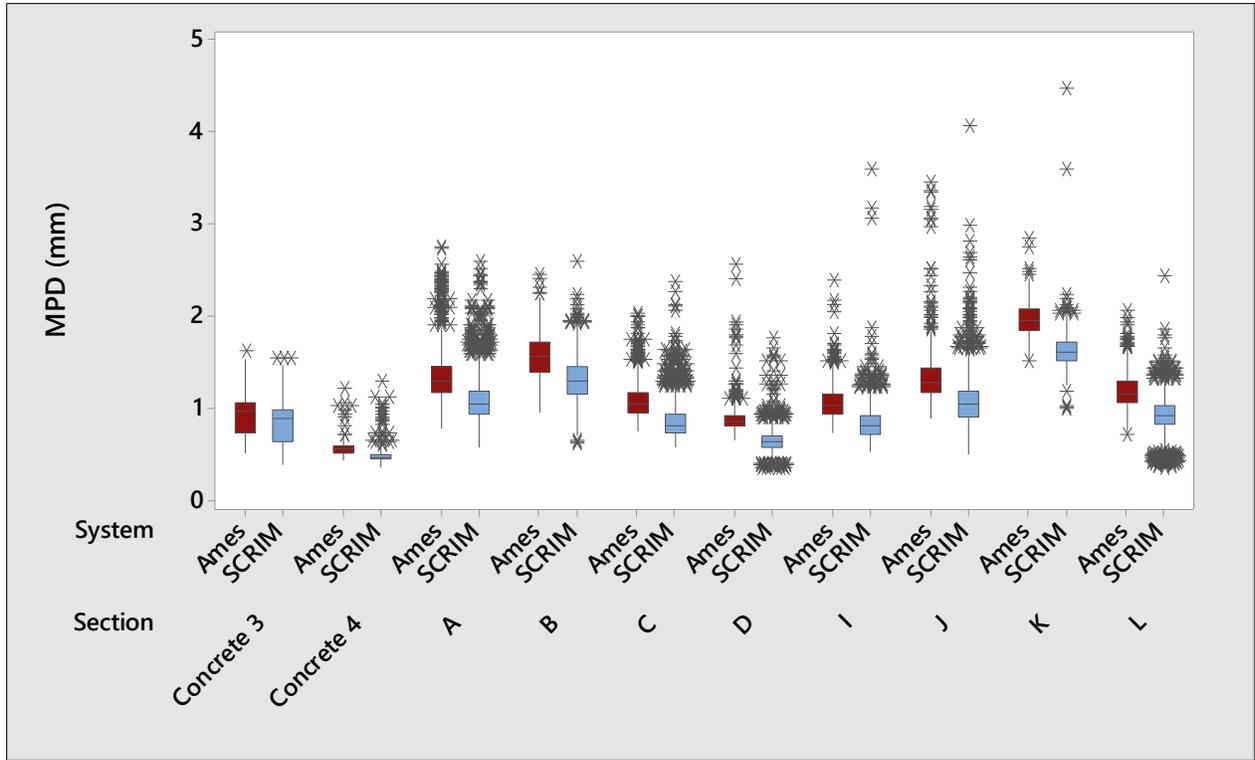
Table 3 summarizes the descriptive statistics for measurements taken with the high-speed systems. Figure 6 compared the data measurements along the length of the road (only one run from each).

Table 3. High-Speed Macrotexture measurements

Section	Ames Results			SCRIM Results		
	Runs	Mean (mm)	Standard Deviation (mm)	Runs	Mean (mm)	Standard Deviation (mm)
Section PCC4 (Grooved)	9	1.575	0.042	15	1.323	0.035
Section PCC3 (Tined)	9	1.378	0.064	15	1.118	0.061
Section L	9	1.105	0.048	15	0.881	0.036
Section K	9	0.888	0.012	15	0.653	0.011
Section J	9	1.075	0.030	15	0.853	0.021
Section I	9	1.345	0.025	15	1.102	0.058
Section D	9	1.974	0.019	15	1.632	0.023
Section C	9	1.200	0.042	15	0.935	0.027
Section B	9	0.931	0.032	15	0.831	0.059
Section A	9	0.426	0.019	15	0.455	0.032
Average			0.033			0.036

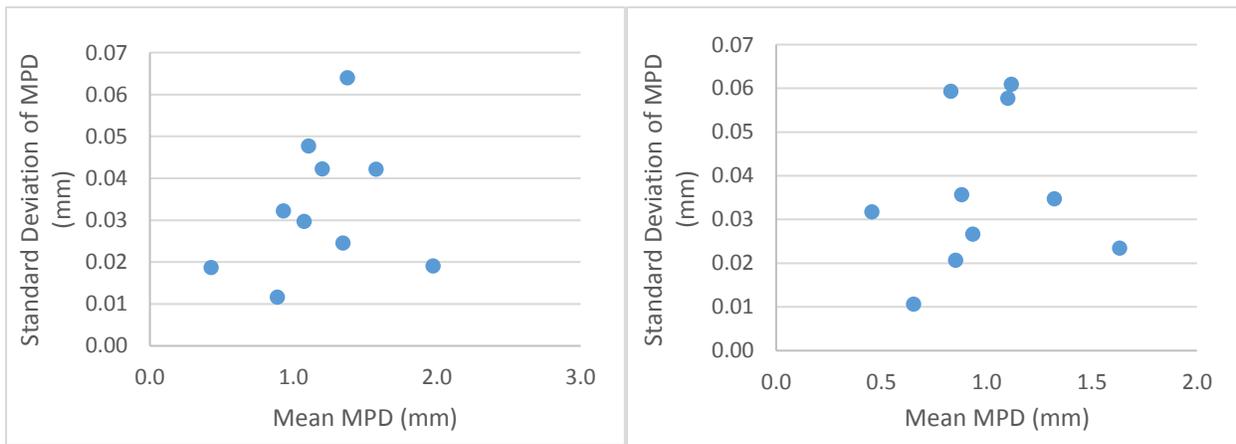
It should be noted that CT Meter standard deviations results in Table 2 for each section are higher than those in Table 3 for the Ames and SCRIM system. This can be explained because the values for the Ames and SCRIM systems correspond to the variation between the averages of all the readings taken over the entirety of each section in one run. For example, Section I is 103 m long and thus there were 1030 readings taken each run. The CT Meter data, however, only had 8 readings in each location and collect data on 4 locations.

Figure 8 shows a box-plot for the measurements taken by the two devices on the sections investigated. The two devices seem to produce similar trends but the AMES system produces higher mean MPD values than the SCRIM. For some sections, the means seem to be closer together than others. For instance, the Concrete 4 section's means are very close together as compared to the rest of the sectional means. In addition, for Concrete 4, looking at the placement of the mean within the interquartile range, there tends to be more high readings, while the rest of the sections' median tends to be in the middle of the interquartile range. This may be caused by the longitudinal grooves present in this section.



(a) Figure 8. Comparison of Ames and SCRIM 1-meter data
(b)

Figure 9 compares the standard deviations for the averages of the various sections measured with the two high-speed systems. The standard deviation ranges from 0.01 to 0.06 suggesting that the average section MPD measurements are quite repeatable. For example, 95% of the data is within 0.02 mm from the mean according to the lower standard deviation, and within 0.12 mm from the mean according to the higher standard deviation. The repeatability is further discussed in the next section.



(b)

(b)

Figure 9. Standard deviation vs. mean for the high-speed systems: (a) Ames, (b) SCRIM

Figure 9 shows the high and low data points also are spread throughout varying mean MPD values. Therefore, the variance seems to be independent from the mean MPD.

Repeatability

The repeatability of the systems measures how well systems obtain the same measurements under the same conditions. The LOA Anova tests summarized in Table 4 were used to obtain the repeatability based on the within group variability. The results were summarized in Table 5 with the Concrete 4 section included and with it removed.

Table 4. ANOVA test results

	Ames ANOVA test results for the variance between runs			Results for the variance between runs with Concrete 4 removed		
Source of Variation	SS	df	MS	SS	df	MS
Between Groups	14.260	9	1.584	8.428	8	1.054
Within Groups	0.107	80	0.00133	0.104	72	0.00144
Total	14.367	89		8.532	80	
	SCRIM ANOVA test results for the variance between runs			Results for the variance between runs with Concrete 4 removed		
Source of Variation	SS	df	MS	SS	df	MS
Between Groups	15.135	9	1.682	10.571	8	1.321
Within Groups	0.222	140	0.00159	0.208	126	0.00165
Total	15.357	149		10.779	134	

Table 5. Repeatability (mm) for the average sectional MPD

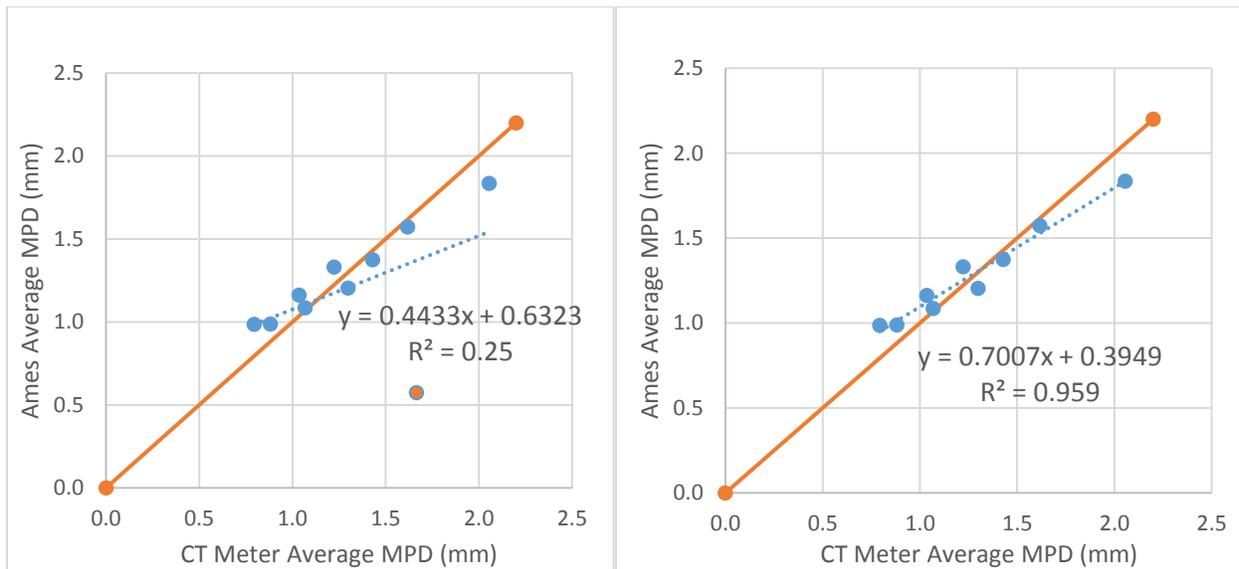
Ames		SCRIM	
All sections	Concrete 4 removed	All sections	Concrete 4 removed
0.101	0.105	0.110	0.113

Both systems can measure the average section MPD with a repeatability of just over 0.1 mm. The result that the repeatability does not improve by removing the Concrete 4 was unexpected. It was thought that the repeatability would improve due to the difficulties in measuring longitudinally-textured pavements.

Reproducibility

The reproducibility of the high-speed systems against the reference device was checked to find how well the results could be reproduced from one system to another. This too is an important factor to consider if the systems were to be used in PMS.

Figure 10 compares the Ames system measurements with the reference CT Meter measurements. The orange line represents the line of equality. The linear regression of Ames MPD as a function of CT Meter MPD is presented in blue. In Figure 10(a), the linear regression resulted in an R^2 value of 0.25 suggesting the correlation of the CT Meter MPD measurements by the Ames system is very poor. However, the point highlighted in orange represent the longitudinally ground and Concrete 4 section and is clearly very influential in the regression. Single spot lasers such as the Ames system are not adequate to measure surfaces having longitudinal grooves. When the laser is picking up a reading it could be in the carved out portion of the pavement for several meters, but then it could start picking up a reading on the risen portion of the pavement, making it hard to obtain a true and accurate representation of the profile. The Concrete 4 section was removed and the results are shown in Figure 10(b). In this case the linear regression results in a coefficient of determination, R^2 , of 0.959, indicating very high correlation between the 2 measurements.



(a) All Section

(b) Concrete 4 removed

Figure 10. Ames vs. CT Meter comparisons

(a) All Section

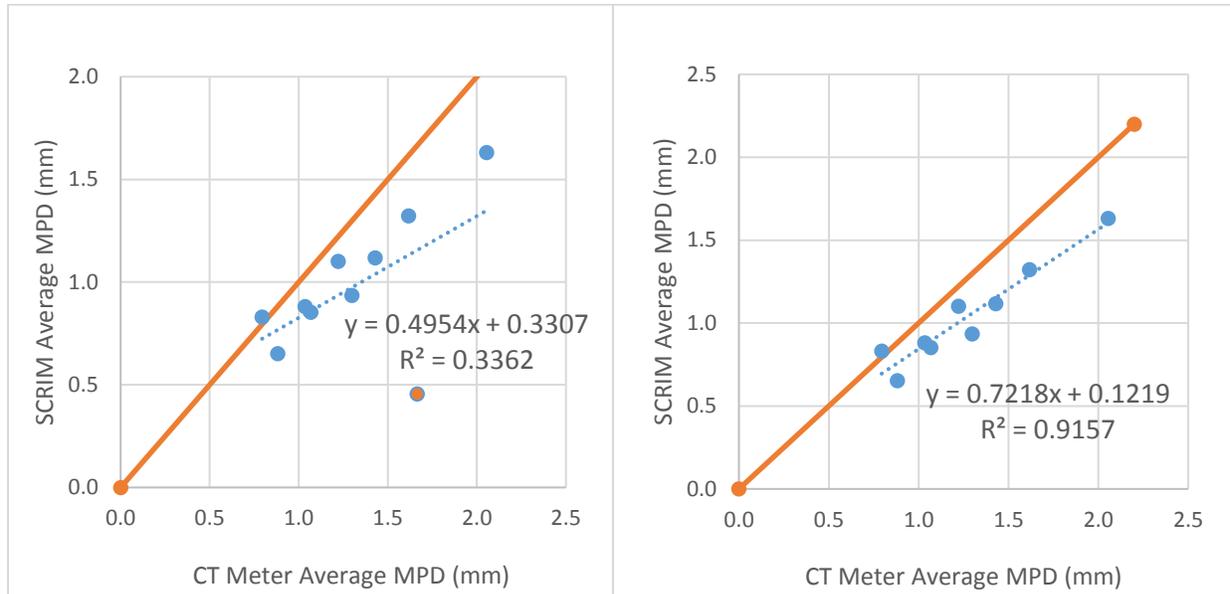
(b) Concrete 4 remove

Figure 11 compares the SCIRM and CT Meter measurements, Figure 11(a) shows a trendline with an R^2 value of 0.3362, affected again by the longitudinally ground, Concrete 4 section (highlighted in orange). (a) All Section

(b) Concrete 4 remove

Figure 11(b) shows the results with the Concrete 4 section removed, which results in an R^2 value of 0.916. The figure also shows that SCIRM system produce consistently lower MPD measurements than

the CT Meter measurements. Overall, the results suggest that the SCRIM system can reproduce the results of the CT Meter if a conversion equation is determined.



(a) All Section

(b) Concrete 4 remove

Figure 11. SCRIM vs. CT Meter comparisons

The analysis shows that both the Ames and SCRIM system measure MPD values that are highly correlated with those produced by the CT Meter. However, both high-speed systems produce MPD values that are different in magnitude, with the Ames systems producing values very close to the CT Meter and the SCRIM slightly lower values. This is further analyzed in the following section.

Based on the results of the this section, the Concrete 4 section (longitudinally ground and grooved) was removed from the rest of the analysis. In order to check the reproducibility of the high-speed systems against the CT Meter, the difference of the MPD measurements versus the average of the measurement systems’ readings was compiled along with the LOA as seen in Figure 12 for the Ames system. In the graph, the data points graphed are the difference of the average MPD results for each section. Also displayed are two limit bounds. The outer bounds considers the variance for the various runs. The smaller bounds consider the variance for the average of the 9 runs. The results suggest the Ames system (with the Virginia Tech filter) does not show any bias. The difference for the average measurements for the sections is between -0.321 and 0.336 with a 95% level of confidence for the outer bounds and 0.176 and -0.161 for the inner bounds.

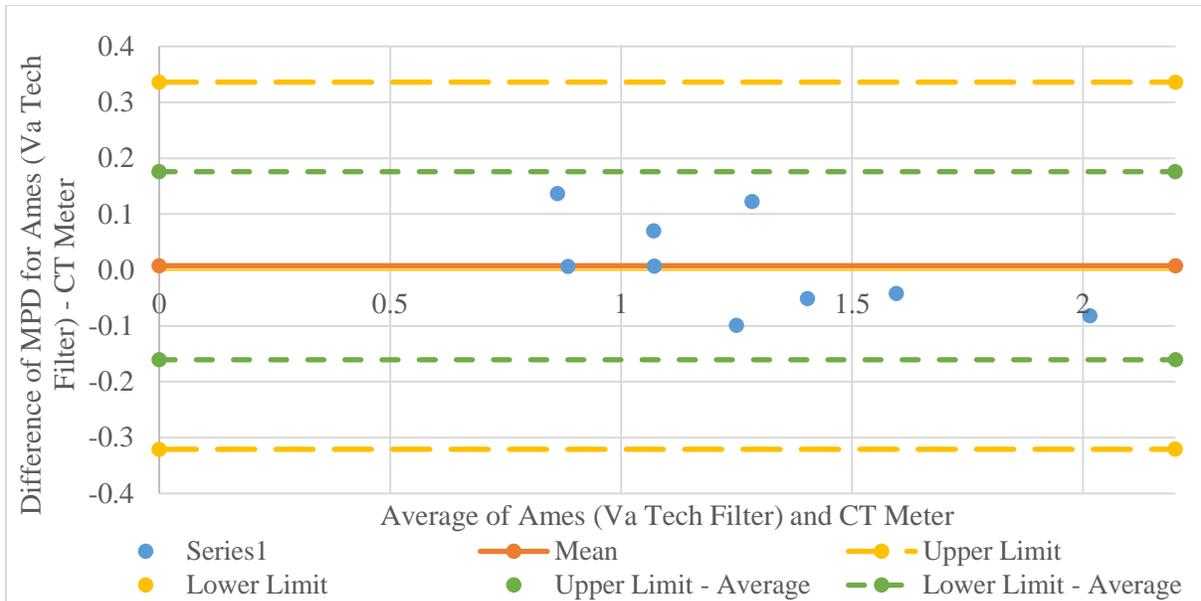


Figure 12. Limits of agreement with upper and lower bounds for the Ames system and the CT Meter (Concrete 4 removed)

Figure 13 confirms that the SCRIM system tends to measure lower MPD values lower than the CT Meter. The limits of agreement for the SCRIM and CT Meter MPD difference suggests that the SCRIM system seems to have an average systematic bias of -0.231 with respect to the CT Meter. This difference is suspected to be due to filtering issues.

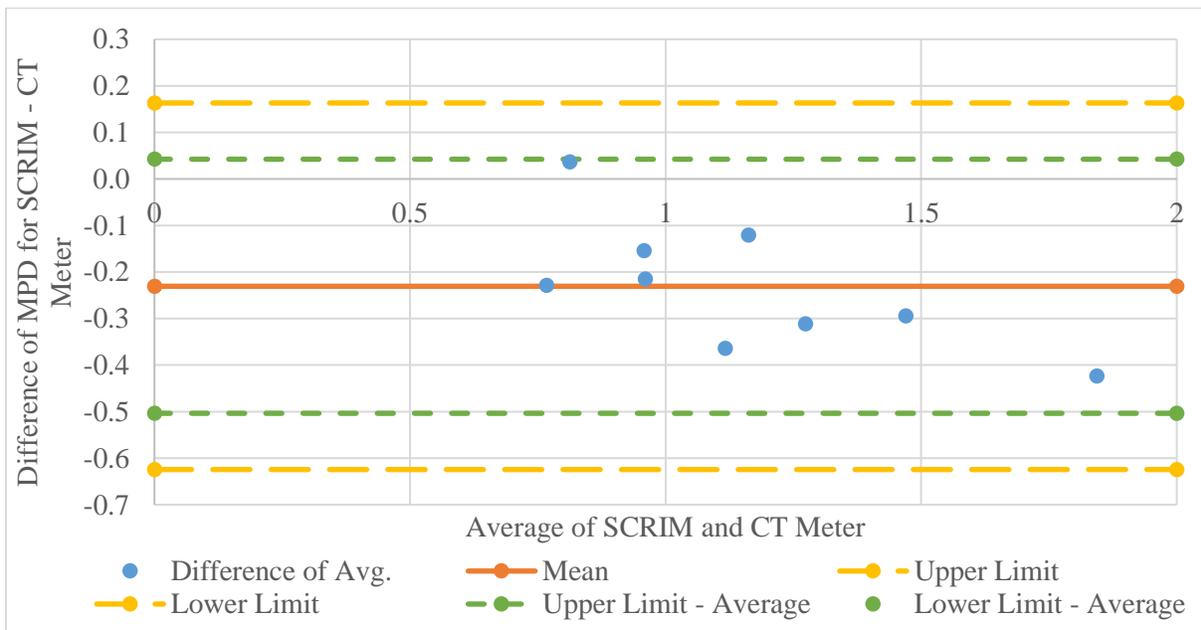


Figure 13. Limits of agreement with upper and lower bounds for the SCRIM system and the CT Meter (Concrete 4 removed)

Figure 14 depicts the relationship between the average Ames and SCRIM measurements. The points hover over the orange equality line remaining parallel; therefore, the difference between the systems stays relatively the same through all measured levels of macrotexture. The linear regression line shows that the Ames system MPD measurements are higher than the SCRIM system's. The two measurements are highly correlated with a coefficient of determination R^2 of 0.97. Figure 14(b) shows an equation with a slope closer to one and an intercept closer to zero.

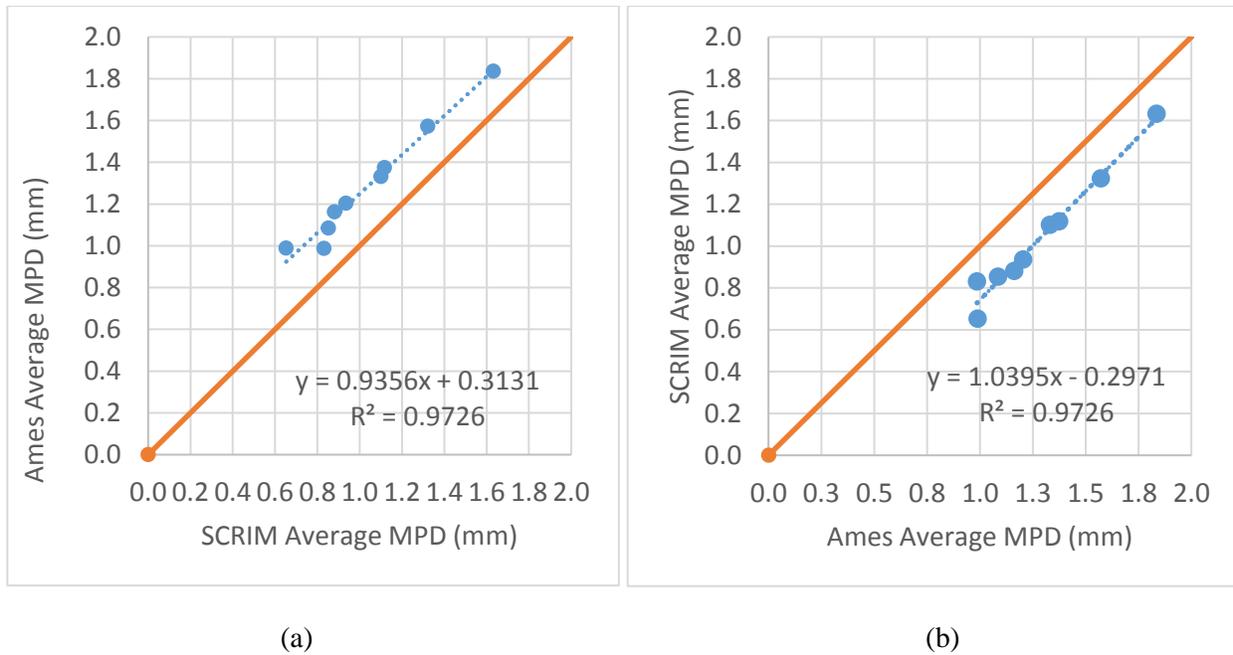


Figure 14. SCRIM and Ames comparisons: Concrete 4 removed

The SCRIM and Ames differences in readings along with the LOA are displayed in Figure 15. The plot confirms that the Ames system records a higher MPD reading than the SCRIM system. The SCRIM measurements are on average 0.24 mm lower than the Ames measurements.

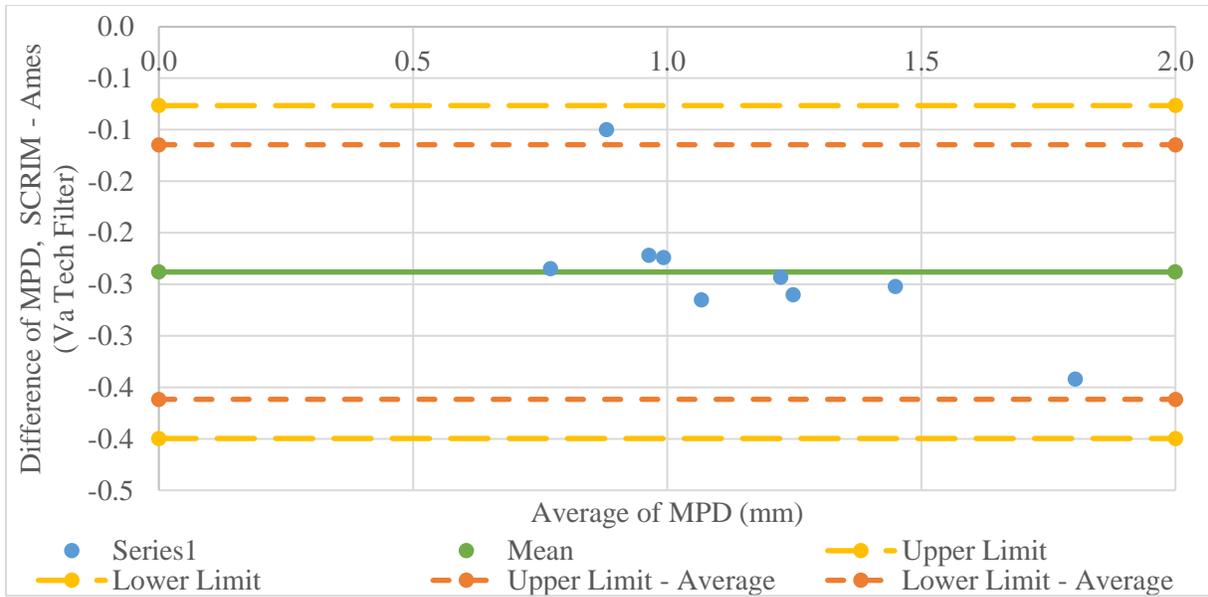


Figure 15. Limits of agreement with upper and lower bounds for the SCRIM and Ames MPD differences

The difference of the SCRIM and Ames readings are always negative. The difference between the two system measurements is highest for Section K, which is an OGFC. The LOA suggest that difference between the SCRIM and Ames MPD measurements will be between -0.077 and -0.400 for the outer bounds and -0.115 and -0.326 for the inner bounds with a 95% of confidence.

Table 6 summarizes the results of the LOA. It shows that the Ames and CT Meter produce very close average section results but the SCRIM measurements produce values approximate 0.23-0.24 mm lower.

Table 6. Limit of Agreement Boundary Results: Concrete 4 Removed

Ames and SCRIM		SCRIM and CT Meter		Ames and CT Meter	
Mean	-0.24	Mean	-0.23	Mean	0.01
Upper Limit	-0.08	Upper Limit	0.04	Upper Limit	0.34
Lower Limit	-0.40	Lower Limit	-0.50	Lower Limit	-0.32
Range	0.32	Range	0.54	Range	0.66

Orthogonal Regression Analysis

For the orthogonal regression analysis, each measurement system was compared against the two others, obtaining the regression equation and the confidence intervals for the intercept and slope. The results for various comparisons are presented in Table 7 through

Table 9 and illustrated in Figure 16 through Figure 18.

Table 7. Ames and CT Meter orthogonal regression analysis results (Concrete 4 removed)

Error Variance Ratio (Ames / CT Meter)		0.0638			
Regression Equation		Ames = 0.156 + 0.883 CT Meter			
Coefficients					
Predictor	Coef.	SE Coef.	Z	P	Approx. 95% CI
Constant	0.15622	0.0836825	1.8668	0.062	(-0.007796, 0.32023)
Ames	0.88261	0.0634930	13.9009	0.000	(0.758165, 1.00705)
Error Variances					
Variable		Variance			
Ames		0.0003181			
CT Meter		0.0049859			

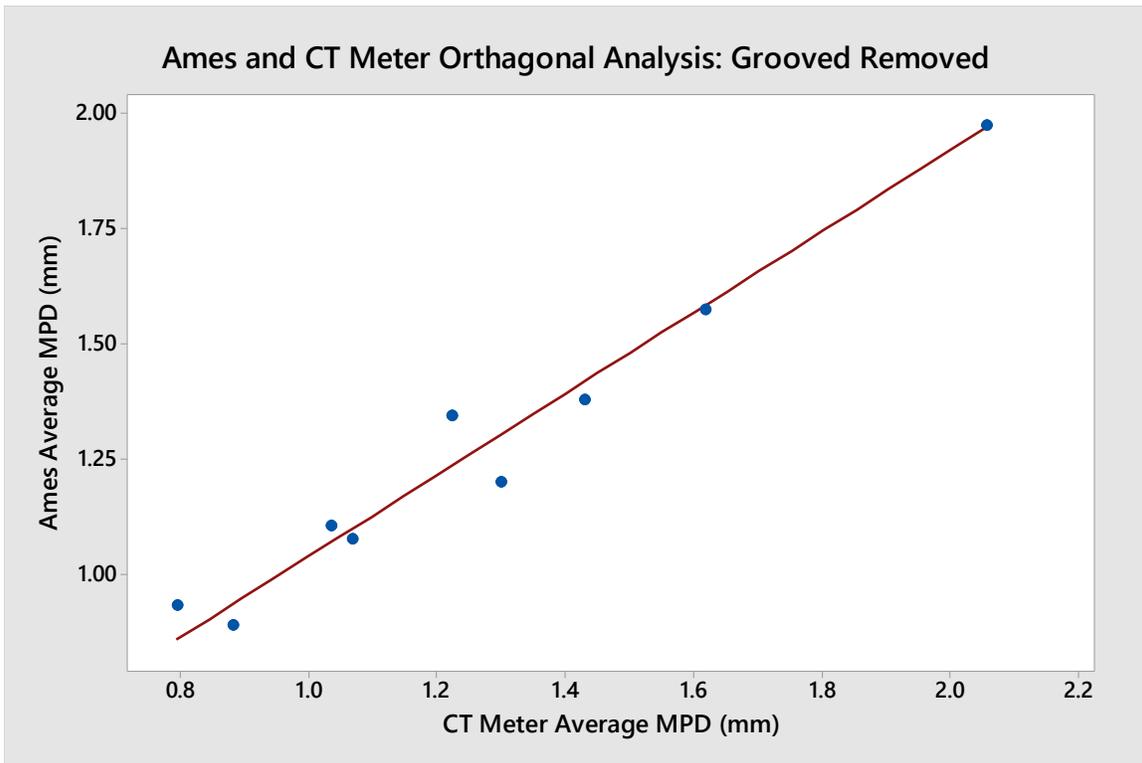


Figure 16. Ames and CT Meter orthogonal regression analysis: Concrete 4 removed

The slope of the equation obtained with orthogonal regression in Table 7 is closer to 1 than the linear regression slope found in Figure 10.

Table 8. SCRIM and CT Meter orthogonal regression analysis results (Concrete 4 removed)

Error Variance Ratio (SCRIM / CT Meter)	0.0556				
Regression Equation	SCRIM = 0.045 + 0.782 CT Meter				
Coefficients					
Predictor	Coef.	SE Coef.	Z	P	Approx. 95% CI
Constant	0.04527	0.118510	0.3820	0.702	(-0.187007, 0.277544)
SCRIM	0.78223	0.090111	8.6808	0.000	(0.605619, 0.958847)
Error Variances					
Variable	Variance				
SCRIM	0.0006654				
CT Meter	0.0119680				

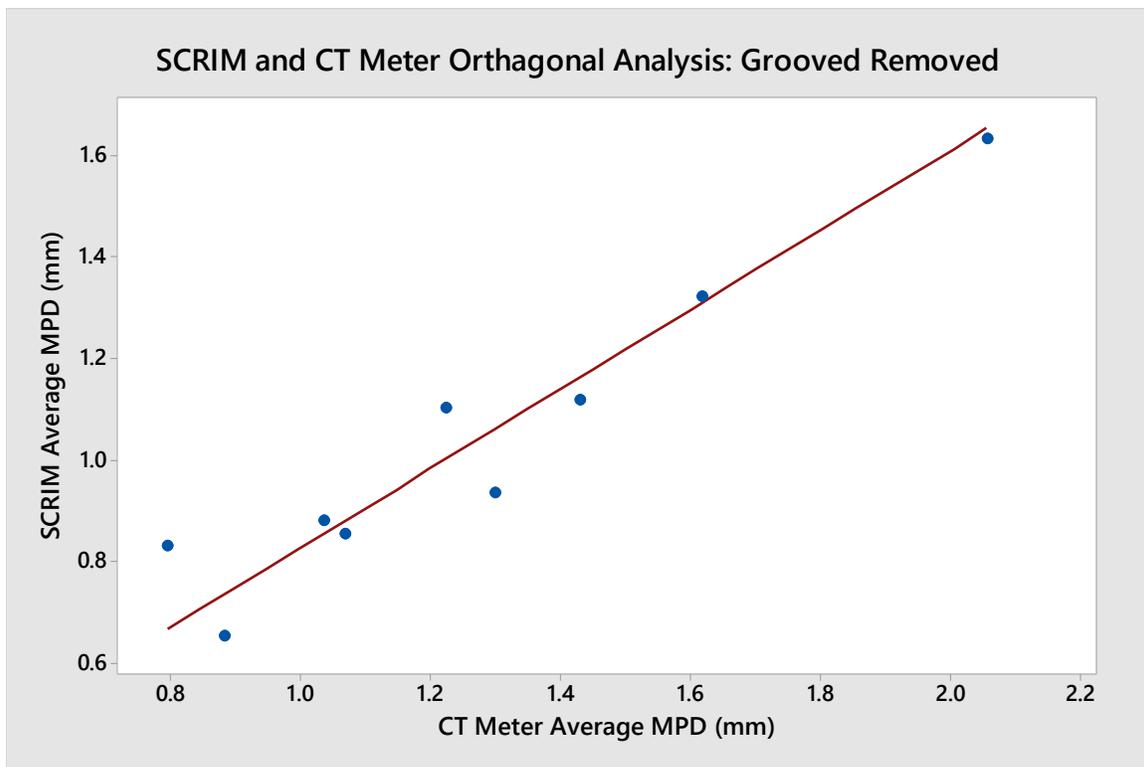


Figure 17. SCRIM and CT Meter orthogonal regression analysis: Concrete 4 removed

Table 9. SCRIM and Ames orthogonal regression analysis results: Concrete 4 removed

Error Variance Ratio (SCRIM / Ames)		1.147			
Regression Equation		SCRIM = - 0.067 + 0.866 Ames			
Coefficients					
Predictor	Coef.	SE Coef.	Z	P	Approx. 95% CI
Constant	-0.06706	0.0595206	-1.1266	0.260	(-0.183717, 0.049600)
Ames	0.86577	0.0452977	19.1129	0.000	(0.776990, 0.954553)
Error Variances					
Variable		Variance			
SCRIM		0.0010043			
Ames		0.0008755			

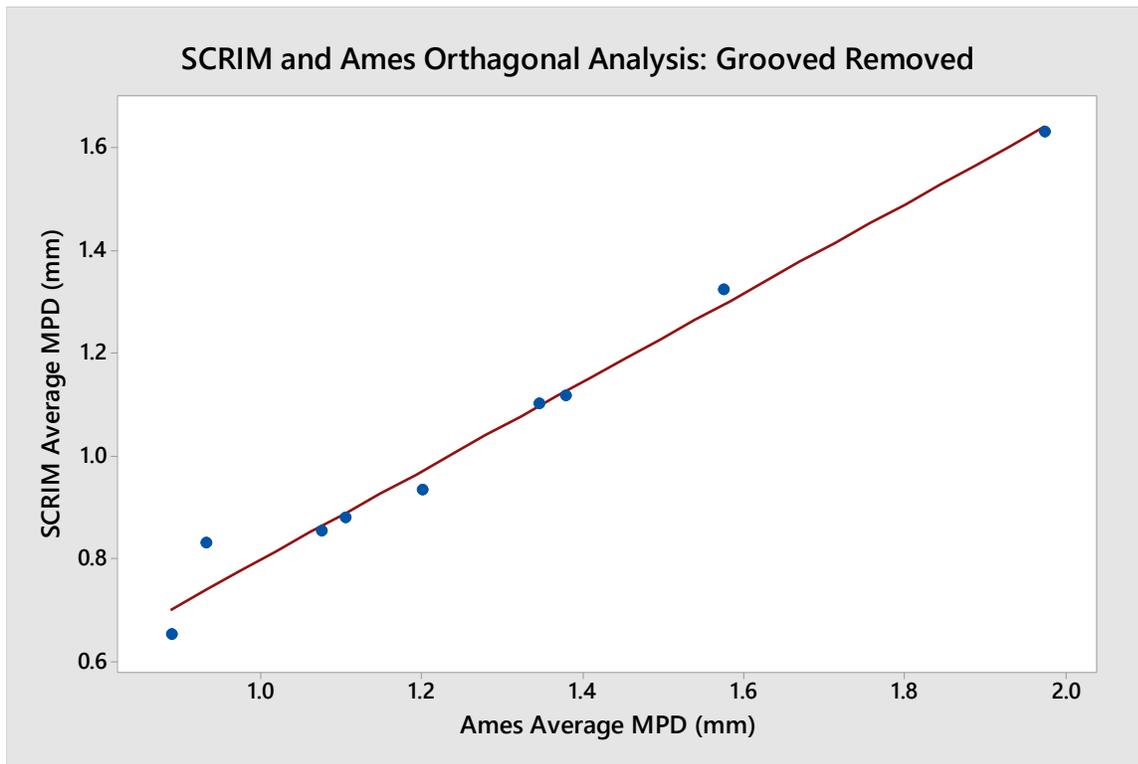


Figure 18. SCRIM and Ames orthogonal regression analysis: Concrete 4 removed

The SCRIM to Ames results comparison suggest that the measurements from the two systems can be interconverted using the equation in

Table 9. The confidence interval for the intercept contain the 0 suggesting that it is not statistically significant at a 95 confidence level.

Discussion

While the Ames system tended to get MPD measurements that are highly correlated with to those obtained with the CT Meter, the SCRIM system tended to get lower computed MPD values than the CT Meter. Possible reasons for the differences between the two systems include:

1. Although the two systems can collect data with a frequency of up to be 64 KHz, the sensor could be sampling with a lower rate.
2. There could also be differences in the data conversion from a time domain to a space domain.
3. Finally, the filter approached used for pre-processing the data is suspected to be the main source of differences.

CHAPTER 5: SUMMARY, FINDINGS, AND CONCLUSIONS

Summary

The thesis compared two high-speed macrotexture measurement devices, Ames and SCRIM, against each other and with the reference CT Meter measurements. The measurements were first aligned and separated into homogenous sections. The data were then filtered and processed using the manufacturers' software to calculate the MPD. Descriptive statistics and box-plots were created to preliminarily compare the results. A LOA analysis was then conducted to help compare the high-speed systems' variability. The results were also used to find the repeatability of the two systems. Finally, the reproducibility between the two high-speed systems was examined through regression analysis.

Main Findings of the Research

Following are some of the main findings of the study.

- 1) Both system showed good repeatability, with an average repeatability of 0.105 mm for the Ames system and 0.113 mm for the SCRIM system.
- 2) The Ames system produced measurements that are closely comparable with those produced by the CT Meter. The mean difference was almost zero with a value of 0.008. The relationship between the Ames and CT Meter can be best described through the following equation:

$$MPD_{Ames} = 0.883(MPD_{CT\ Meter}) + 0.156 \quad (27)$$

- 3) The SCRIM system producing measurements that also correlate very well with the CT Meter but the measurements are consistently lower, showing an average bias of -0.231. The following equations can be used to convert the SCRIM MPD measurements to CT Meter MPD:

$$MPD_{SCRIM} = 0.782(MPD_{CT\ Meter}) + 0.045 \quad (28)$$

- 4) The Ames systems produce measurements that are on average 0.238 mm higher than the SCRIM measurements.
- 5) As expected, both system failed to produce accurate measurements on the longitudinally textured concrete section (Concrete 4).

Conclusions

The analysis showed that the two high-speed systems investigated have good repeatability (approximately 0.11 mm) when measuring the average MPD of the sections investigated. The two systems produce measurements that are highly correlated with the reference ones obtained with the CT

Meter. The Ames systems, with the data processed using the Virginia Tech filter, measures MPD values that are very close to those of the CT Meter, with a virtually zero systematic bias. The SCRIM measures slightly lower readings, with an average value approximately 0.23 mm lower than the CT Meter. The differences are thought to be due to the filtering of the raw pavement elevation measurements to eliminate dropout and spikes in the laser measurements.

Recommendations

Future studies should explore the reasons for the difference in measurements among devices, and whether the type of pavement surface may influence these differences. In particular, a detailed investigation of the various filters applied is needed. Investigation the impact of other operational factors, such as cleanness of the surface, speed of measuring, slope, etc. can also shed some light on the limitations of the laser systems.

The difference is thought to be due to differences in the systems' filtering methods. Therefore, in future research the raw data should be collected and put through the same filtering process. The processed data can be analyzed and possible difference quantified. Other possible contributing factors may include frequency of data collection and the way the data s transformed from the time domain to the space domain.

There is also a need to find an appropriate procedure to measure macrotexture on longitudinally textured section such as those encountered on the Concrete 4 section. As expected, neither of the two systems tested produced accurate results on these types of surfaces.

REFERENCES

- Aktas, B., Gransberg, D. D., Riemer, C., and Pittenger, D. (2011). "Comparative Analysis of Macrotecture Measurement Tests for Pavement Preservation Treatments." *Transportation Research Record*, 2209, 34-40.
- Ames Engineering (2015). *Ames Engineering Profiler Software: Software Version 6.0 User Manual*. Ames Engineering.
- Ames Engineering. n. d. "8300 Survey Pro High Speed Profiler." *Ames Engineering*, <<https://amesengineering.com/products/8300-survey-high-speed-texture-profiler/>> (November 18, 2016).
- ASCE. (2013). "Roads." *2013 report card for America's infrastructure: roads*, <<http://www.infrastructurereportcard.org/a/#p/roads/overview>> (November 11, 2016).
- ASTM International. (n. d.(a)). *Standard practice for calculating pavement macrotecture mean profile depth (Designation: E1845 – 09)*. ASTM International: West Conshohocken, Pennsylvania.
- ASTM International. (n. d.(b)). *Standard test method for measuring pavement macrotecture properties using the circular track meter (Designation: E2157 – 09)*. ASTM International: West Conshohocken, Pennsylvania.
- Bartlett, J. W., and Frocst, C. (2008). "Reliability, repeatability and reproducibility: analysis of measurement error in continuous variables." *Ultrasound Obstet Gynecol*, 31, 466-475.
- Benjamini, Y., and Hochberg, Y. (1995). "Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing." *Journal of the Royal Statistical Society*, 57(1), 289-300.
- Bland, J. M., and Altman, D. G. (2007). *Agreement Between Methods of Measurement with Multiple Observations Per Individual*. Journal of Biopharmaceutical Statistics Volume 15, Taylor and Francis Group: London, UK. 571-582.
- D'Apuzzo, M., Evangelisti, A., Flintsch, G. W., Izeppi, E. de L., Mogrovejo, D. E., and Nicolosi, V. (2015). *Evaluation of Variability of Macrotecture Measurement with Different Laser-Based Devices*. Airfield and Highway Pavements, ASCE.
- Department of Transportation. (1978). *Effectiveness of Alternative Skid Reduction Measures: Vol. II. Benefit-Cost Model*. National Technical Information Service: Springfield, Virginia. 31; 43.
- Fisco, N. R. (2009). *Comparison of Macrotecture Measurement Methods*, Ohio State University.

- Flintsch, G. W., De León, E., McGhee, K. K., and Al-Qadi, I. L. (2003). "Pavement Surface Macrotexture Measurement and Application." *TRB 2003 Annual Meeting*.
- Flintsch, G. W., McGhee, K. K., Leon Izeppi, E., and Najafi, S. (2012). "The Little Book of Tire Pavement Friction." *Pavement Surface Properties Consortium*.
- Freitas, E., Pereira, P., and Domingos, P. (2015) "Analysis of Test Methods for Textured Depth Evaluation Applied in Portugal". *ResearchGate*,
 <https://www.researchgate.net/publication/266353601_Analysis_of_Test_Methods_for_Texture_Depth_Evaluation_Applied_in_Portugal> (July 6, 2017).
- Fulop, I. A., Bogardi, I., Gulyas, A., and Csicsely-Tarpay, M. (2000). "Use of friction and texture in pavement performance modeling." *Journal of Transportation Engineering*, May/June Issue, 243 - 248.
- Griffin, S., and Ali, A. (2015). *SCRIM-S99 Survey Monitor Touch Panel Software User Guide*. W. D. M.
- Kováč, M., Kotek, P., and Decký, M. (2015). "Conventional and Non-Conventional Equipment for Pavement Surface Macrotexture Measuring." *Transactions of the VŠB – Technical University of Ostrava*, 15(1), 1-6.
- Liu, Q., Kavanagh, L., Shalaby, A., and Izevbekhai, B. I. (2016). "Comparison of Pavement Texture Measurements from a Three-Dimensional Profiler and a Circular Track Meter at MnROAD Test Facilities." *Transportation Research Record: Journal of the Transportation Research Board*(2591), pp 121–129.
- Minitab Inc. (2016). "Orthogonal Regression" *Minitab Support*, Minitab Inc., State College, PA.
- Minitab Inc. (2017(a)). "Basic Statistics: Regression" *Minitab StatGuide* (CD-ROM), Minitab Inc., State College, PA.
- Minitab Inc. (2017(b)). "Statistics: Regression: Orthogonal Regression: Example." *Minitab Help* (CD-ROM), Minitab Inc., State College, PA.
- Mogrovejo, D. E., Katicha, S., Flintsch, G. W., and De Leon Izeppi, E. (2014). *Latest Development in the Processing of Pavement Macrotexture Measurements of High Speed Laser Devices*. Virginia Polytechnic Institute and State University: Blacksburg, VA.
- Mogrovejo, D. E. (2015). *Enhancing Pavement Surface Macrotexture Characterization: Chapter 3*. Virginia Polytechnic Institute and State University: Blacksburg, VA. 25-41.

- Olmedo, C., Leal, C., Cimini, G., and Springer, J. (2015). *Initial Results of Pavement Texture Testing in the FHWA-LTPP Program*. Transportation Association of Canada: Charlottetown, PEI.
- Ott, R. L., and Longnecker, M. (2016). *An introduction to statistical methods & data analysis* (7th ed.), Cengage Learning: Boston, MA.
- Perera, R., and Wisner, L. (2013). "Comparison of MPD Values from High-Speed Laser Measurements with MPD From Two Stationary Devices." *RPUG 2013*, San Antonio, TX.
- Pulugurtha, S. S., Kusam, P. R., and Patel, K. J. (2012). "Assessment of the effect of pavement macrotexture on interstate crashes." *Journal of Transportation Engineering (ASCE)*, May Issue, 610 – 617.
- Rasmussen, R. O., Sohaney, R., Wiegand, P., and Harrington, D. (2011). "Measuring and Analyzing Pavement Texture: Concrete Pavement Surface Characteristics Program." *Tech Brief*, January Issue.
- Rezaei, A., Hoyt, D., and Martin, A. E. n. d. "Simple laboratory method for measuring pavement macrotexture: pavement cores and aggregate image measurement system." *Transportation Research Record: Journal of the Transportation Research Board*, No. 2227, 146 – 152.
- Roe, P. G., and Sinhal, R. (2005). *Recent developments to the SCRIM measurement technique in the UK*, TRL Limited: PA.
- Smith, R. H., and Uddin, Waheed. (2016). *A rational theory of tire-pavement friction*. Hindawi Publishing Corporation.
- Sprinkle, M., Roosevelt, D., Flintsch, G., De Leon Izeppi, E., and Mokarem, D. (2009). *Virginia Transportation Research Council Research Report: Evaluation of the Cargill Safe LaneTM Surface Overlay*, Report Number VTRC 09-R8. Virginia Transportation Research Council: Charlottesville, Virginia.
- Texas Department of Transportation. (2008). *Tex-436-A, measuring texture depth by the sand patch method*, Texas Department of Transportation: Austin, Texas.
- Viner, H., Abbott, P., Dunford, A., Dhillon, N., Parsley, L., and Read, C. (2006). *Surface texture measurements on local roads*, TRL Limited: Pennsylvania. Wambold, J., Antle, C., Henry, J., Rado, Z., Descornet, G., Sandberg, U., Gothié, M., and Huschek, S. (1995). "International PIARC Experiment to Compare and Harmonize Skid Resistance and Texture Measurements (Paris: PIARC) Publication n 01.04." PIARC, Paris, France.

WDM. (2015). *SkidVid User Manual*. W. D. M.

WDM. n. d.(a) *RavCon Manual Version 4.26.0*. W. D. M.

WDM. n. d.(b) "SCRIM/ SCRIMTEX." *WDM: Driving innovation for an ever-changing world*,
<<http://www.wdm.co.uk/equipment/scrim-scrimtex>> (September 23, 2016).

Wheatley, M. (2015). "Crossed Gage R&R: How are the Variance Components Calculated?" *The Minitab Blog*, < <http://blog.minitab.com/blog/marilyn-wheatleys-blog/crossed-gage-rr:-how-are-the-variance-components-calculated>> (February 25, 2017).

Yager, T. J. (2005). "An Overview of the Annual NASA Tire/Runway Friction Workshop and Lessons Learned."