# Macrotexture Assessment of Florida Pavements

## Contract Number: BE711

## Final Report

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## METRIC CONVERSION CHART

| Symbol | When you know | Multiply by | To find | Symbol |
|---|---|---|---|---|
| | | Length | | |
| in. | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | Area | | |
| $in^2$ | square inches | 645.2 | square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.093 | square meters | $m^2$ |
| $yd^2$ | square yard | 0.836 | square meters | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | square kilometers | $km^2$ |
| | | Volume | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| $ft^3$ | cubic feet | 0.028 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | cubic meters | $m^3$ |
| | | Mass | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams | Mg |
| | | Temperature | | |
| °F | Fahrenheit | $\frac{5}{9}(F-32)$ | Celsius | °C |
| | | Illumination | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | $\frac{\text{candela}}{m^2}$ | $\frac{cd}{m^2}$ |
| | | Stress/Pressure | | |
| lbf | poundforce | 4.45 | newtons | N |
| $\frac{lbf}{in^2}$ (or psi) | $\frac{\text{poundforce}}{\text{square inch}}$ | 6.89 | kilopascals | kPa |

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16. Abstract

Regular statewide macrotexture assessments are important for identifying hydroplane safety concerns on roadways. Traditionally, vehicle-mounted point-laser devices have been used by the Florida Department of Transportation (FDOT) State Materials Office to measure network-level macrotexture in accordance with the ASTM E1845 test standard. These point-laser systems are capable of accurately measuring mean profile depth (macrotexture) on flexible pavement; however, the point-laser system fails to completely capture the surface characteristics of rigid pavement, whose longitudinal texture is anisotropic. To overcome this limitation, two line-laser systems were purchased by the State Materials Office which have the capability of producing a nearly continuous three-dimensional (3-D) texture profile along the surface of a roadway.

Preliminary testing carried out by the State Materials Office had shown that the line-laser system was producing mean profile depth values that did not correlate well with accepted reference values. Therefore, the University of North Florida developed a more comprehensive and systematic research plan to validate and implement a vehicle-mounted line-laser system into future network-level macrotexture assessments.

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# EXECUTIVE SUMMARY

When water has nowhere to escape from the surface of a roadway, it can disrupt the tire-to-pavement adhesion of a travelling vehicle and lead to hydroplaning. Pavement macrotexture provides the pathways for water to drain, which allows for the necessary grip between tire and pavement. Macrotexture, which is quantified by the FDOT in terms of mean profile depth (MPD), is analyzed by the State Materials Office using a high-speed point-laser mounted along the driver side wheel path of a friction testing vehicle. The FDOT uses point-lasers to determine MPD values that correspond to the precise location a locked-wheel friction test.

While the point-laser is capable of accurately measuring MPD on flexible pavement, the system fails to capture the anisotropic (measurements in different directions produce different values) texturing of rigid pavement, such as longitudinally-ground (LGD) concrete. A prospective solution to this issue was to utilize a vehicle-mounted line-laser that collects texture data in a three-dimensional (3D) manner, as opposed to the two-dimensional (2D) collection of a point-laser. The three dimensions in which the line-laser collects texture data are transversely along the length of the laser spectrum, longitudinally in the direction of vehicle travel, and vertically as height measurements.

As a result, two line-laser systems were purchased by the State Materials Office from pavement equipment specialists, International Cybernetics (ICC), and installed on two friction testing vehicles. The line-laser itself was developed by LMI Technologies and is identified as the Gocator-2342-3B-12. After receiving the line-laser systems from ICC, the devices had shown poor correlation with accepted MPD values on both flexible and rigid pavement. This discovery was the conclusion of a texture device harmonization study conducted by the State Materials Office in 2018.

Since then, the University of North Florida (UNF) research team has developed and executed a research-based approach in configuring the line-laser system to accurately assess pavement macrotexture on a network-level. This was done by configuring and optimizing the line-laser collection parameters through a series of static and dynamic tests on inactive roadways. Once it was determined that the line-laser was accurately capturing MPD in a controlled setting, the precision and accuracy of the system were further validated on both flexible and rigid pavement through a statewide macrotexture assessment.

Currently, the updated line-laser system produces MPD values that are highly correlated with accepted reference values on both flexible and rigid pavement in both a repeatable and reproducible manner. As a result, the UNF research team recommends implementing this line-laser system into production. Utilizing the updated line-laser system will allow the FDOT to accurately assess the macrotexture of Florida’s longitudinally-ground concrete roadways at highway speeds.

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# CHAPTER 1 – INTRODUCTION

On average, weather-related events cause approximately 1.2 million vehicle crashes within the United States every year. Of these weather-related crashes, 70% occurred on wet pavement and resulted in approximately 4,050 fatalities [1]. When water cannot escape from the surface of pavement, it can disrupt the tire-to-pavement adhesion and lead to hydroplaning. Pavement macrotexture provides the pathways for water to drain, allowing the necessary grip between tire and pavement. Macrotexture is the primary indicator of wet-weather skid resistance, splash and spray, and tire/road interaction noise [2]. All these characteristics play an important role in safety while driving on the road.

Macrotexture is defined as pavement surface profile features with a wavelength between 0.5 and 50 millimeters. Figure 1-1 shows a schematic illustrating the distinction between macrotexture and microtexture, where the latter is due to small scale features below 0.5 millimeters [3]. While there are several terms used to quantify pavement macrotexture, the FDOT quantifies macrotexture in terms of MPD. MPD, as defined by ASTM E1845 "Standard Practice for Calculating Pavement Macrotexture Mean Profile Depth," is the average of all mean segment depths (MSD) within a test section [4]. As shown in Figure 1-2, MSD is a two-dimensional height measurement that is calculated using a 100-millimeter baseline divided into two equal segments. The highest peak of each segment is determined, and the difference between the average of the two peaks and the average profile height of the sample is the MSD [3, 5]. When determining the MPD of a test section, it is ideal to take a continuous profile over the entire length of the test section if possible [4].

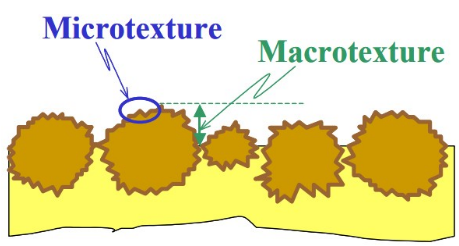



Figure 1-1. Macrotexture and microtexture illustration [3].

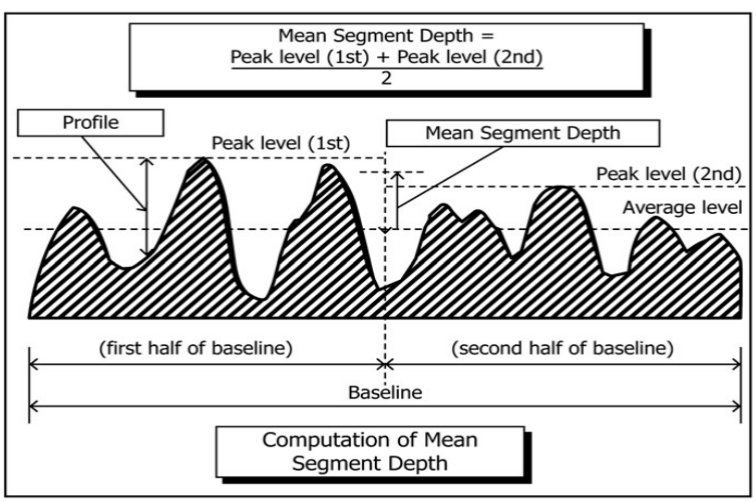



Figure 1-2. MSD calculation diagram [4].

Higher levels of macrotexture are preferable for the wet-weather performance of pavement. As speed increases, macrotexture is the predominant road characteristic that accounts for wet-skid resistance. Figure 1-3 displays a diagram of the influence that texture has on various road characteristics. Static and visual macrotexture measurement methods, such as the sand-patch method, are superseded by high-speed measurements due to the difficulty associated with measuring large pavement areas. With the significance that wet-skid resistance has on road safety, regular high-speed macrotexture assessments should be implemented to help reduce weather-related vehicle accidents [6].

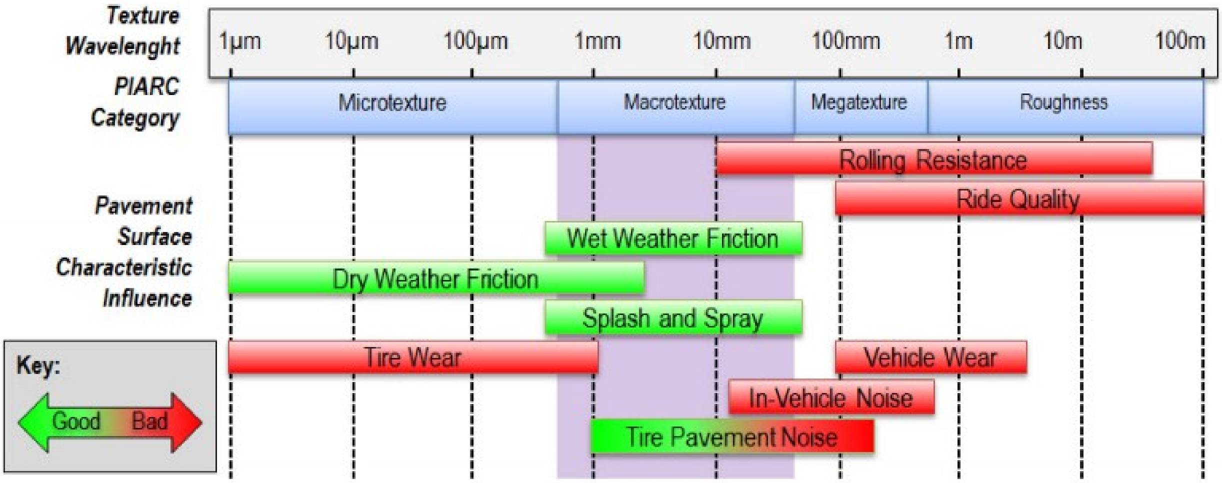



Figure 1-3. Texture and road characteristic relationships [6].

## PROBLEM STATEMENT

The primary objective of this research project is to validate and implement a vehicle-mounted line laser system for network-level macrotexture measurement. For the system to be capable of network-level data collection, a vehicle-mounted, contactless laser measurement device is required to be used at highway speeds without obstructing traffic. Previous studies conducted by the State Materials Office have shown successful high-speed texture data collection on flexible pavement using point-lasers. These studies were considered successful based on a high correlation in MPD measurements between the point-laser and the circular track meter (CTM) reference device. However, on rigid pavement, the point-laser was unable to accurately capture the texture profile due to its anisotropic texturing. In Florida, rigid pavement, such as concrete, undergoes a longitudinal diamond grinding process to establish skid-resistance and rainwater runoffs. Since point-lasers are 2-D measurement devices (one dimension is in the travel direction and the other dimension contains vertical height measurements), they are only capable of measuring isotropic or homogenous texture profiles. Therefore, a 3-D measurement device capable of measuring in the transverse direction, such as a line-laser, was determined to be a potential solution to this issue.

# CHAPTER 2 – LITERATURE REVIEW

## MACROTEXTURE MEASUREMENT METHODS AND DEVICES

### *Sand Patch Method*

The sand patch method is a volumetric approach to measuring pavement macrotexture in accordance with ASTM E965, "Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique." The tools required to perform this method are a known volume of sand or ASTM E965 compliant glass beads, a measuring device (tape measurer or ruler), a brush, and a hard rubber-faced spreading disk. The measurement process begins by clearing the pavement area of any debris using a brush and ensuring that the sample section is free of cracks. Next, a known volume of sand or glass beads is poured onto the road surface. At the FDOT, the volume of sand or glass beads used in sand-patch testing is either 24.58 milliliters for dense-graded surfaces or 49.16 milliliters for open-graded surfaces. From there, the sand or beads are distributed evenly across the pavement using the spreading disk to form a circle. This is done until the surface depressions are filled to the level of the pavement peaks. Finally, the diameter of the circle is measured at four different locations while rotating approximately 45 degrees between each measurement. The diameter used in the MTD calculation is the average of the measured diameters. The formula used to measure MTD is shown below in Equation 2-1.

$$MTD = \frac{4*V}{\pi*D^2} \text{ (Equation 2-1)}$$

In this equation, $V$ denotes the known initial volume of the sand or glass beads and $D$ is the average patch diameter. In this method of testing, the sand or glass beads are only to be used once and should not be recycled [7, 8]. Figure 2-1 shows an FDOT employee performing the sand patch test.

Figure 2-1. Sand patch testing.

While the sand-patch method is relatively simple to perform, the results of the testing are predominately based on the operator. Studies have shown that MTD values produced through this method generally have low levels of reproducibility [9].

*Circular Track Meter (CTM)*

A CTM is a static measurement device used for macrotexture profiling [9]. It uses a charged coupled device (CCD) laser displacement sensor to accumulate MPD and root mean square (RMS) measurements [10, 11]. The CTM measures the pavement profile along a circular track with a 284-millimeter diameter. The circumference of the circular track is divided into eight equally sized segments labeled A through H [10]. The MPD and RMS values are calculated for each individual segment, as well as the entire sample. Figure 2-2 shows the track path of a CTM and the eight segments used in its measurements. As specified by ASTM E2157 "Standard Test Method for Measuring Pavement Macrotexture Properties Using the Circular Track Meter," when using a CTM to analyze texture, the pavement surface should be dry, clear of any debris, and a homogenous test section that is free of unique features, such as cracks or joints [12].

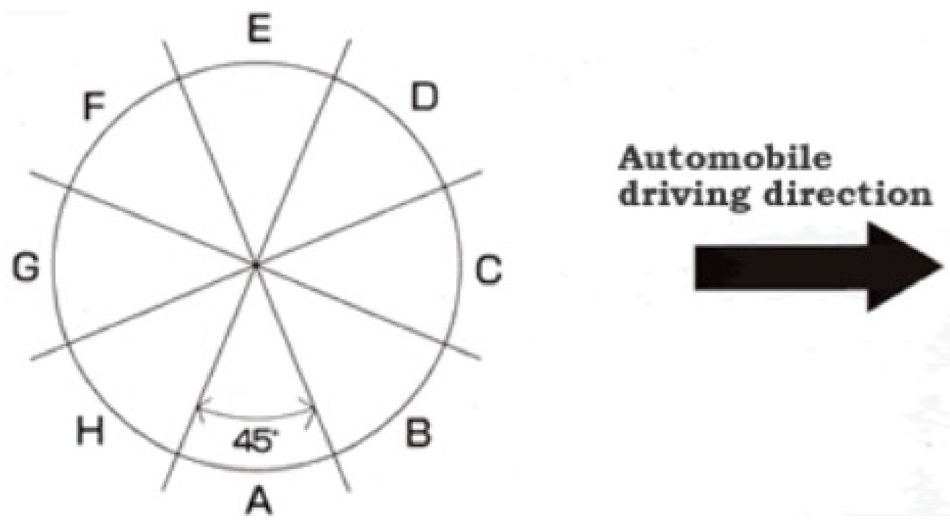
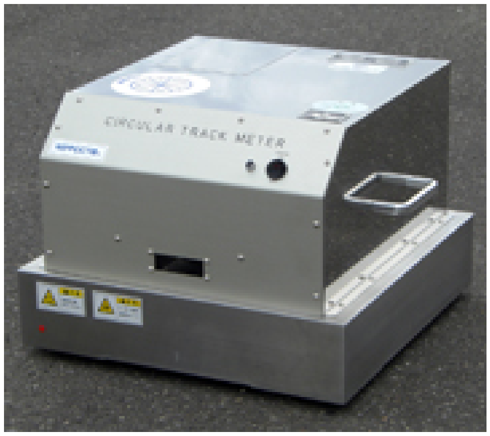



Figure 2-2. CTM measurement track and segments [11].

A commonly used CTM was developed by Nippo Sangyo Company, Limited. This device meets the CTM requirements stated in ASTM E2157, and is used by the FDOT State Materials Office. This CTM has a laser spot diameter of 70 micrometers and a resolution of three micrometers. It takes 1,024 samples per revolution at a tangential velocity of six meters per minute which results in a total measurement time of approximately 45 seconds. As seen in Figure 2-3, the laser displacement sensor is mounted on a rotating arm 80 millimeters above the pavement's surface. It is a portable device weighing approximately 13 kilograms that can be powered using a 12V DC automobile battery. The macrotexture measurement data is collected through the provided software on a notebook computer which records the MPD and RMS of the macrotexture profiles [11, 12]. A shortcoming of the CTM is that it is a static measurement method. Therefore, it is beneficial for producing reference or project-level data, but it cannot be used for network-level assessments.



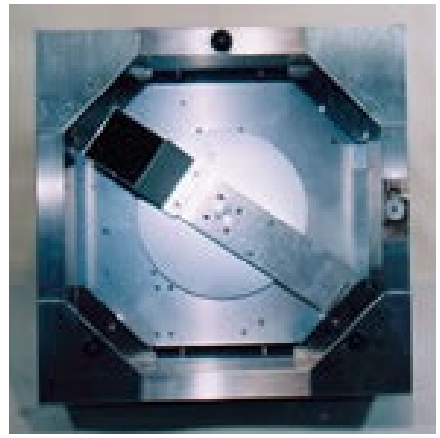



Figure 2-3. Nippo Sangyo CTM (left). Underside of the CTM (right) [11].

### *High-Speed Laser-Based Measurement Devices*

High-speed laser-based measurement devices analyze macrotexture through optical triangulation using a laser light source and a CCD laser sensor. These devices take contactless measurements at highway speeds (45-70 mph) without obstructing traffic. Point-lasers, also known as spot-lasers, are currently the most commonly used device for high-speed texture analysis. However, line-laser technology has been growing in popularity with an emphasis on 3-D mapping of pavement surfaces [13, 14]. Point-lasers develop a 2-D surface profile by emitting light that is reflected off the pavement's surface and captured by a light sensor. Triangulation through common trigonometric functions is used to determine the distance between the laser and the pavement surface profile. Line-lasers operate in a similar fashion, but the laser is spread through optics into a light sheet that shines on a line along the pavement surface. A line of texture heights is then triangulated and measured using a sensor with hundreds of measurement rows. This is the functionality that allows for nearly continuous 3-D data collection during high-speed system-wide surveys. Figure 2-4 shows a component diagram of the laser-based measurement systems, and Figure 2-5 is an example of line-laser system [14-16].

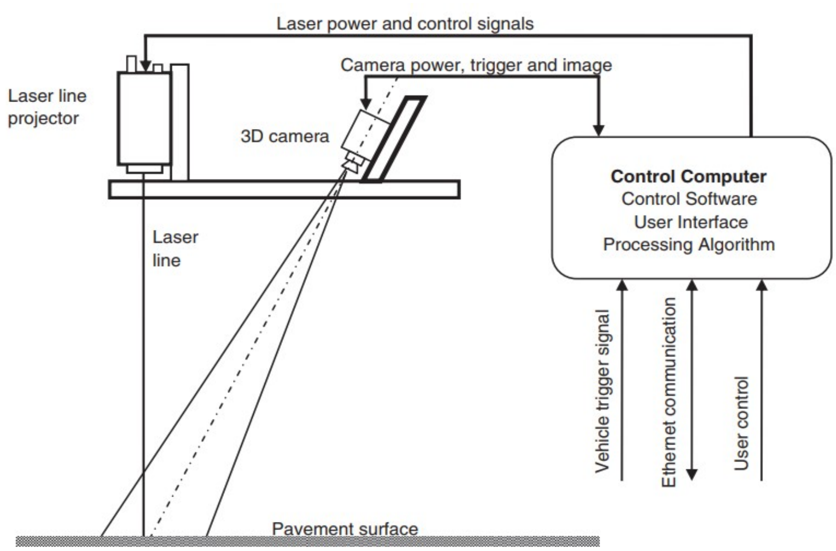



Figure 2-4. Laser-based measurement system diagram [16].

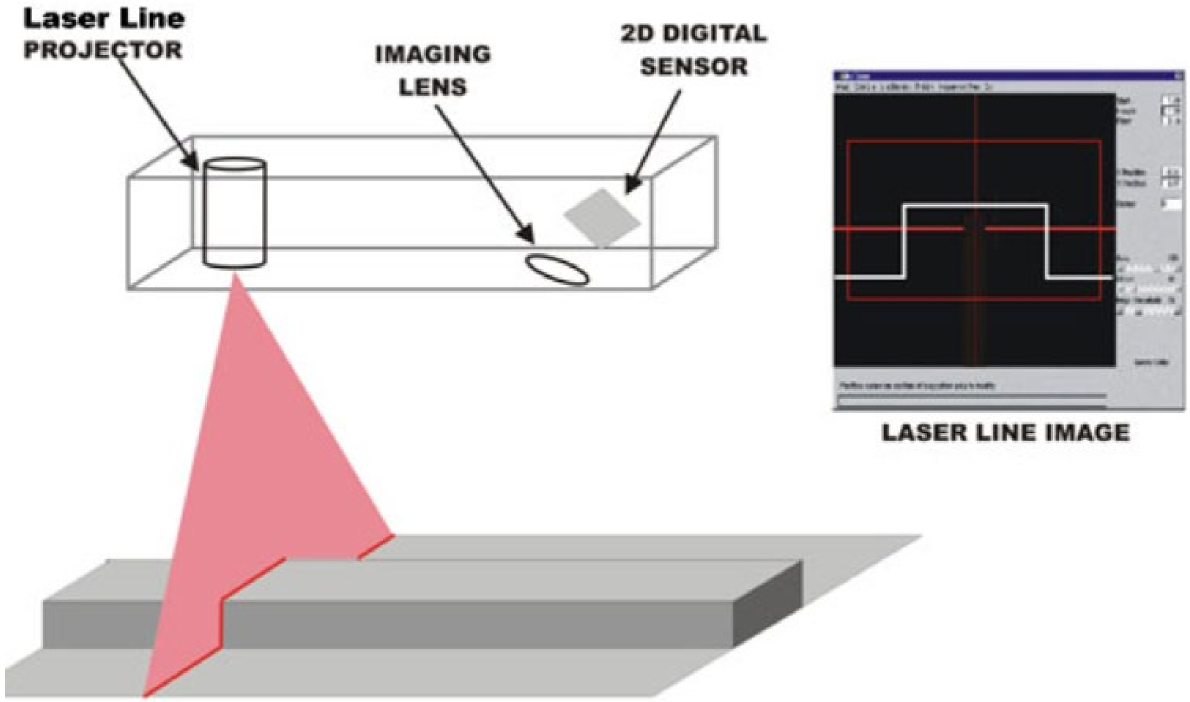



Figure 2-5. LMI Technologies line-laser diagram [28].

These systems are typically mounted on the lower part of a vehicle in either the front or the rear. Their positioning is either aligned with the vehicle's longitudinal axis or along the vehicle wheel path [14]. The sampling frequency of a point-laser sensor is normally between 32 kHz to 64 kHz, while line-laser sensors operate at a much lower frequency typically between 2.5 kHz to 10 kHz [14-16]. Appropriate sampling rates of the lasers are crucial to macrotexture measurement. When the sampling rate is too high, higher signal noise occurs. When the sampling rate is too low, the pavement profile may be misrepresented [2].

## Comparing Various Laser-Based Texture Measurement Devices

### *A Practical Approach to Measuring and Reporting Friction and Macro-Texture at Variable Test Speeds [17]*

In 2008, the Florida Department of Transportation (FDOT) conducted an experiment to measure friction and macrotexture at various speeds (30, 40, and 50 mph). Macrotexture was analyzed by acquiring data with a high-speed point-laser measurement device. The measurements collected with the laser device were used to calculate MPD values of the pavement test sections. The high-speed point-laser device used in this experiment was a 64 kHz LMI Technologies Selcom Optocator that adhered to the requirements of ASTM E1845. The laser device was positioned along the driver-side vehicle wheel path. Testing was conducted on a variety of pavement types to replicate the wide range of state roadways in Florida. [17]. Figure 2-6 shows the test vehicle and the high-speed laser measurement device.


Figure 2-6. Test vehicle (left). Point-laser measurement device (right) [17].

The test sections consisted of three open-grade hot mix asphalt (HMA) sections (Sites 2, 3 and 6), five dense-grade HMA sections (Sites 1, 4, 5, 7 and 8), and two Portland Cement Concrete (PCC) sections (Sites 9 and 10). Ten high-speed macrotexture measurements were collected at each test speed (30, 40 and 50 mph) for each test section. The MPD values acquired using the high-speed laser device were compared against the MPD and MTD reference values collected using a CTM and the sand-patch method, respectively. The reference data was collected in accordance with the ASTM E2157 and ASTM E965 test standards [17].

The MPD values produced by the point-laser generally had a strong correlation with those from the CTM. However, the MPD measurements taken by the high-speed laser at Site 10, the longitudinally ground PCC surface, failed to correlate well with the reference measurements. Also, as seen in Table 2-1, the mean profile height measurements collected by the high-speed laser device did not significantly vary (± 1.0%) between the different test speeds [17]. Figure 2-7 displays a graph comparing the MPD values produced by the high-speed laser and the CTM at each test section. Table 2-2 contains additional information about the test sites.

Table 2-1. Summary of high-speed point-laser measurements at various speeds [17].

| **Speed** | **30 mph** | **40 mph** | **50 mph** | **Avg. Diff.** |
|---|---|---|---|---|
| **Mean (mm)** | 0.794 | 0.800 | 0.810 | ± 1.0% |
| **Std. Deviation (mm)** | 0.593 | 0.582 | 0.547 | ± 0.0081 |
| **95% Conf. Int. (mm)** | ± 0.368 | ± 0.361 | ± 0.339 | ± 0.0091 |

Table 2-2. Site information [17].

| **Site ID** | **Surface** | **Aggregate** | **Mix Design** | **Roadway** |
|---|---|---|---|---|
| 1 | FC 12.5 M | Granite | SPM 06-4852B | 26050000 |
| 2 | FC 5 | Limestone | QA 00-9506A | 26050000 |
| 3 | FC 5 | Granite | LD 02-2523A | 26050000 |
| 4 | FC 9.5 | Granite | SP 04-3068A | 26005000 |
| 5 | FC 9.5 M | Granite | SPM 05-4408A | 26070000 |
| 6 | FC 5 M | Granite | SPM 07-5509A | 26010000 |
| 7 | FC 12.5 | Limestone | SP 02-1920A | 28030001 |
| 8 | FC 12.5 M | Limestone | SPM 06-4609C | 70011000 |
| 9 | Burlap Drag | PCC | - | 79060000 |
| 10 | Long Grind | PCC | - | 79060000 |

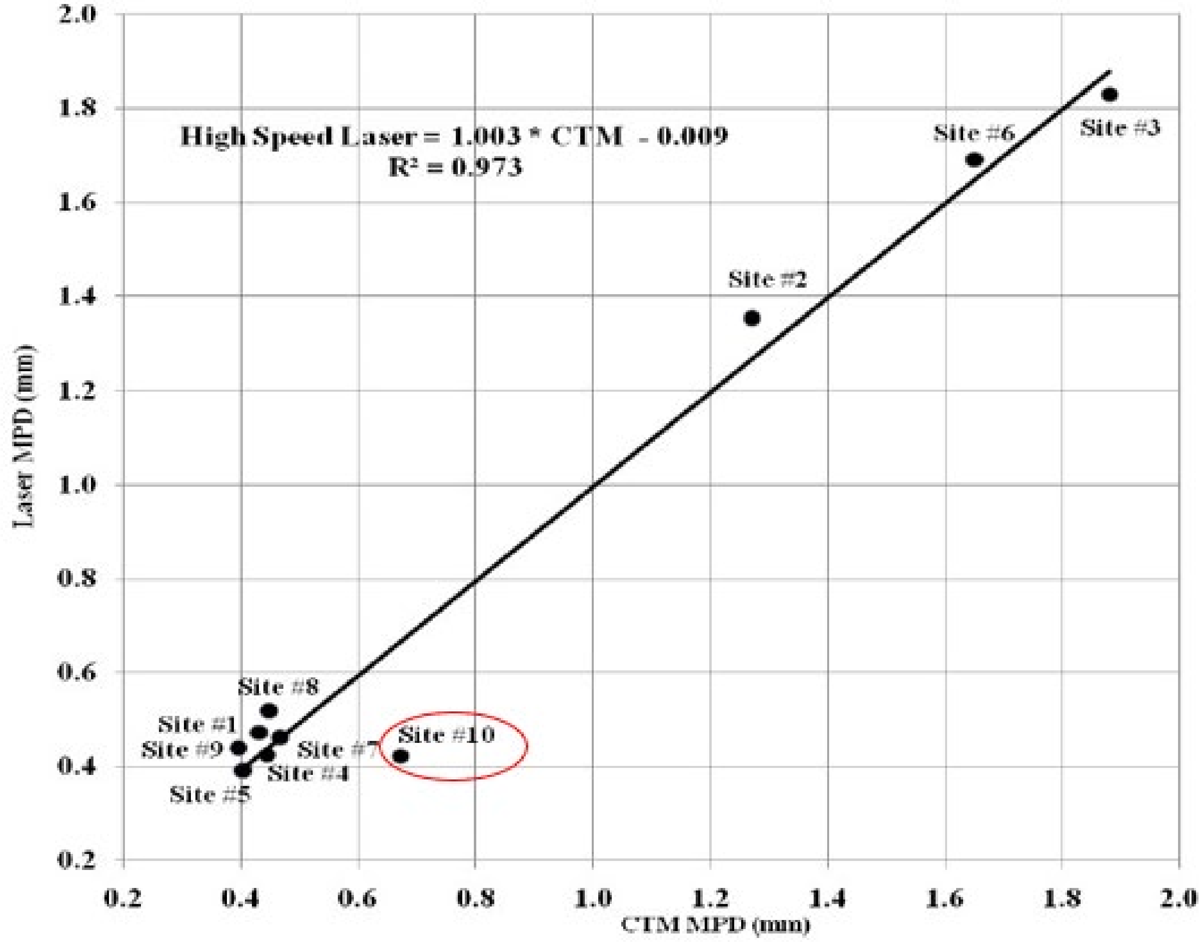



Figure 2-7. High-speed laser device vs. CTM MPD values at 40 mph [17].

***Development of Texture Measurement System Based on Continuous Profiles from a Three-Dimensional Scanning System [16]***

In 2010, a team at the Texas Department of Transportation designed and tested a system called VTexture based on 3-D measurements using laser triangulation. The system used a line-laser containing a beam that was 0.25 millimeters wide and 500 millimeters long. It used a high-speed 3-D digital camera with line-laser processing capabilities to record measurements. The VTexture system was capable of recording height measurements with a resolution of 10 micrometers. The camera would trigger every 53.34 millimeters (2 inches) of travel distance and record a 2,048-point surface profile over the length of the line-laser. The unit was mounted on the rear towing hitch of a vehicle with a standoff distance of 380 millimeters (15 inches) above the pavement surface. Two line-laser orientations were tested as show in Figure 2-8; longitudinal measurements along the centerline of the vehicle, and transverse measurements perpendicular to the vehicle's motion of travel along the wheel path. MPD measurements and other road parameters were calculated according to the ASTM E1845 standard [16].

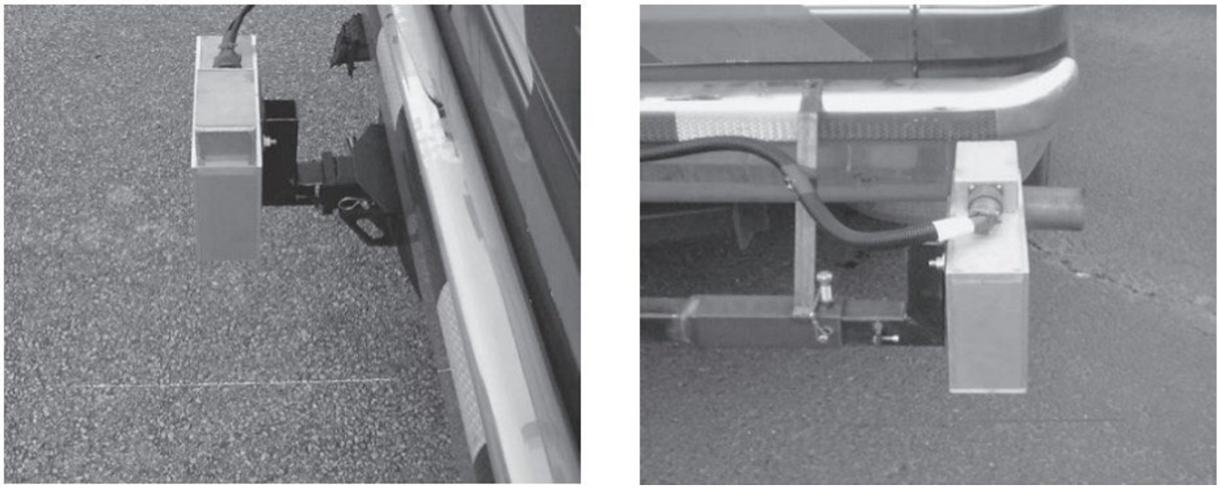


Figure 2-8. VTexture system longitudinal scan (left). Transverse scan (right) [16].

During development of the VTexture system, it was discovered that sensor exposure time was the main cause for MPD values to vary with speed. Sensor exposure time refers to the period an optical sensor opens to receive reflected light from the pavement surface. The appropriate exposure time is determined based on the reflectivity of the pavement surface, the intensity of the laser light, and the sensitivity of the sensor. For example, low-reflective surfaces, low-power lasers, and low-sensitivity sensors are all reasons to increase exposure time so that the laser sensor can accumulate enough light for accurate measurements. Using the VTexture system while assessing the appropriate exposure time can allow for accurate and repeatable network-level data collection between 0 and 70 mph vehicle travel speeds. Based on this study, it was determined that the system exposure time should not exceed 20 microseconds for network-level data collection at varying speeds [16].

***Comparison of Surface Macrotexture Measurement Methods [18]***

In 2012, a study was conducted at the Ohio State University where three laser-based measurement systems were analyzed: LMI Technologies Selcom Optocator 2008-180/390 point-laser profiler, Nippo Sangyo CTM, and Ames Engineering 3-D laser texture scanner. The various laser-based measurement methods were compared with reference data acquired through the sand patch method. Since the laser-based systems use software that calculates MPD, the MPD values were transformed into estimated texture depth (ETD) values to use for comparison. ETD is a converted volumetric value that allows for comparisons with MTD values produced by the sand-patch method. Based on ASTM standards, the equation for calculating the ETD of the laser profile scanner, and the laser texture scanner is shown in Equation 2-2. Equation 2-3 shows the ETD formula using MPD values produced by the CTM [18].

$$ETD = 0\ .2 + 0.8 * MPD \quad \text{(Equation 2-2)}$$

$$ETD = 0\ .069 + 0.947 * MPD \quad \text{(Equation 2-3)}$$

The LMI Technologies point-laser profiler had a sampling rate of 62.5 kHz with a resolution of 45 microns. To simulate this system driving over a road, the laser had a standoff distance of 390 millimeters (15 inches) away from a spinning sample which was connected to a 7,500 RPM metal grinder. This test bench simulated a vehicle driving at 25 mph. Figure 2-9 shows the laser profiler test setup. The CTM uses a point-laser with a spot size of 70 micrometers and a resolution of three micrometers. Since the test samples were 304 millimeters in diameter, the CTM took measurements at a diameter of 284 millimeters. The Ames laser texture scanner provides a 3-D rendering of samples in an area that is 101.6 millimeters long and 76.2 millimeters wide with a capacity of 1,200 lines. Like the CTM, the laser texture scanner has a limited scan area [18].

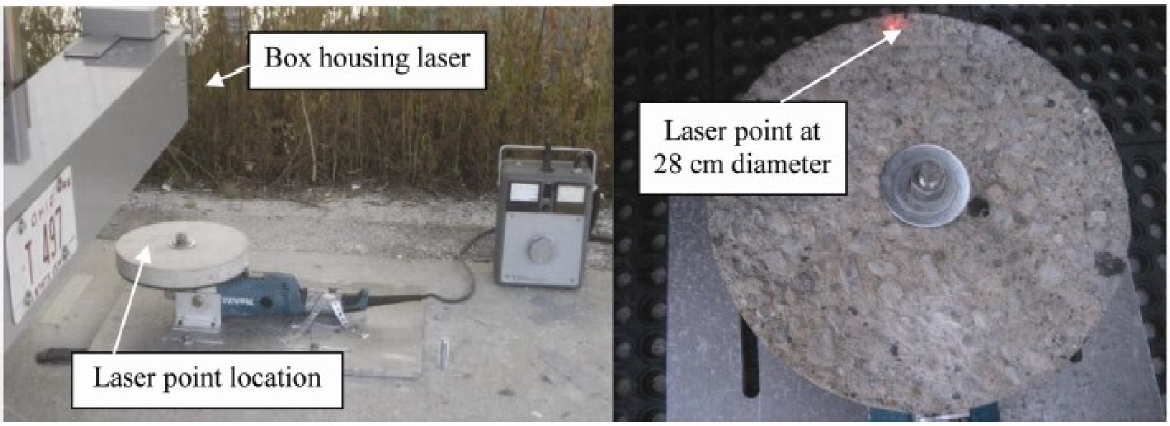



Figure 2-9. LMI Technologies point-laser profiler test bench [18].

When compared to the CTM and the laser profiler, the laser texture scanner provided ETD values closest to the MTD values of the reference data. The average difference between the ETD and the MTD values provided by the sand patch testing were 28% for the Ames laser texture scanner, 36% for the Dynatest laser profiler, and 37% for the CTM [18]. Figures 2-10 and 2-11 show the relationship between MTD values collected through the sand patch method compared to values from the LMI Technologies laser profiler and Ames laser texture scanner, respectively.

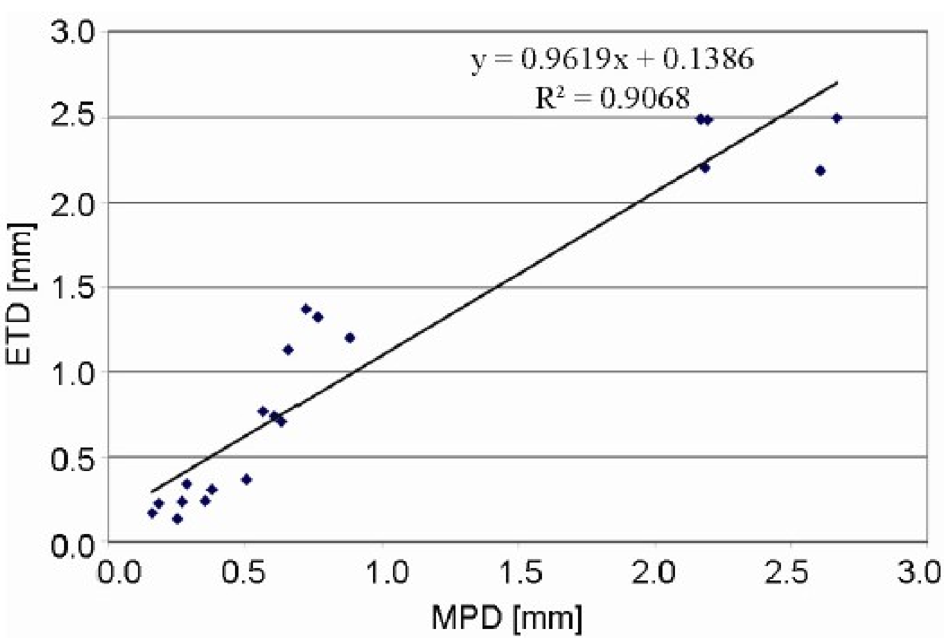



Figure 2-10. Sand patch ETD values vs. MPD values from the laser profiler [18].

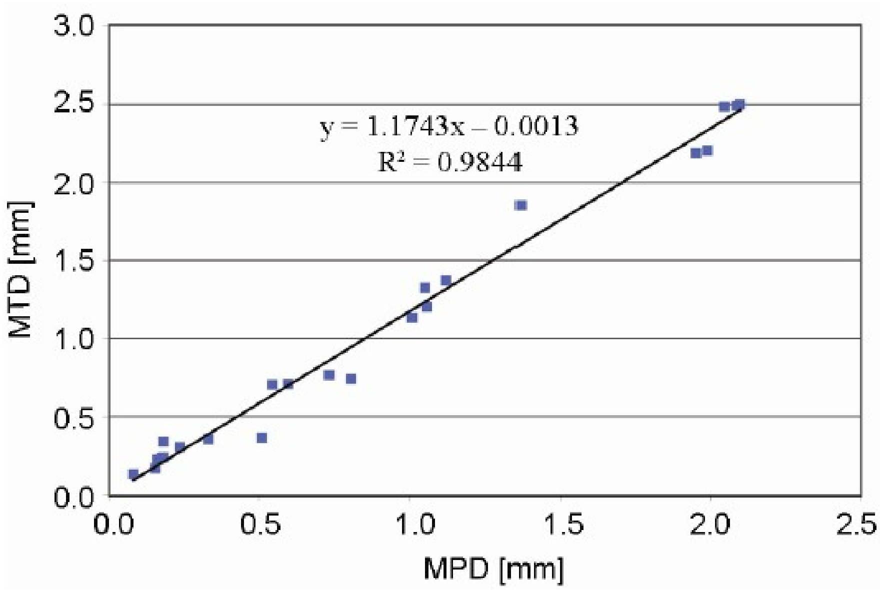
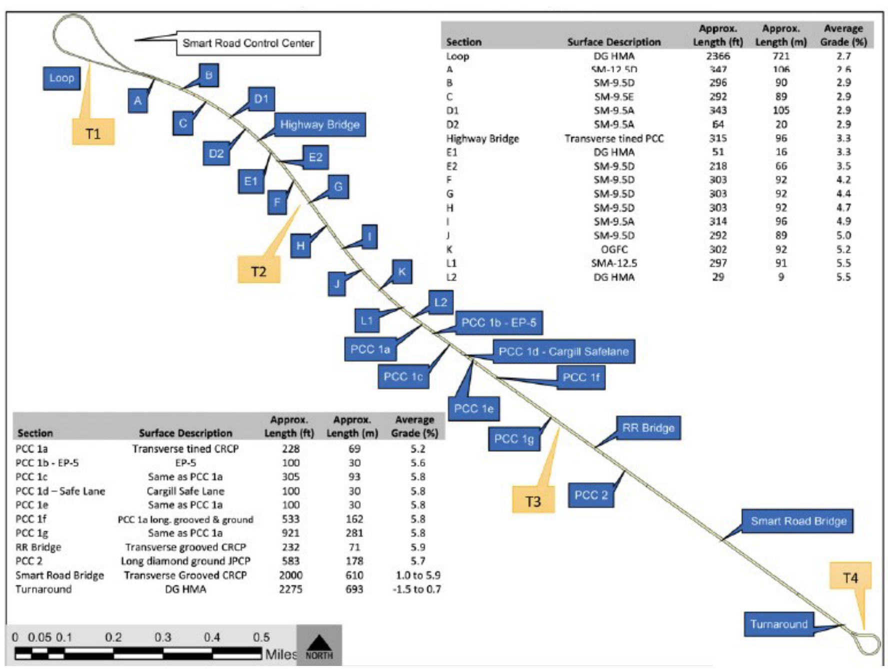



Figure 2-11. Sand patch MTD values vs. MPD values from Ames laser texture scanner [18].

***Evaluation of Variability of Macrotexture Measurement with Different Laser-Based Devices [19]***

In 2015, a study was conducted at the 2.2-mile Virginia Smart Road test track located at the Virginia Tech Transportation Institute in Blacksburg, Virginia. The experiment compared the variability in measurements between a CTM and a high-speed laser measurement device. For reference measurements, ten evenly spaced measurements were taken with the CTM along the left-hand wheel path of each test section. Next, ten 50-mph collection runs were conducted in each test section using a high-speed point-laser device. Figure 2-12 shows the various test sections throughout the Virginia Smart Road.




| Section | Surface Description | Approx. Length (ft) | Approx. Length (m) | Average Grade (%) |
|---|---|---|---|---|
| Loop | DG HMA | 2366 | 721 | 2.7 |
| A | SM-12.5D | 347 | 106 | 2.6 |
| B | SM-9.5D | 296 | 90 | 2.9 |
| C | SM-9.5E | 292 | 89 | 2.9 |
| D1 | SM-9.5A | 343 | 105 | 2.9 |
| D2 | SM-9.5A | 64 | 20 | 2.9 |
| Highway Bridge | Transverse tined PCC | 315 | 96 | 3.3 |
| E1 | DG HMA | 51 | 16 | 3.3 |
| E2 | SM-9.5D | 218 | 66 | 3.5 |
| F | SM-9.5D | 303 | 92 | 4.2 |
| G | SM-9.5D | 303 | 92 | 4.4 |
| H | SM-9.5D | 303 | 92 | 4.7 |
| I | SM-9.5A | 314 | 96 | 4.9 |
| J | SM-9.5D | 292 | 89 | 5.0 |
| K | OGFC | 302 | 92 | 5.2 |
| L1 | SMA-12.5 | 297 | 91 | 5.5 |
| L2 | DG HMA | 29 | 9 | 5.5 |

| Section | Surface Description | Approx. Length (ft) | Approx. Length (m) | Average Grade (%) |
|---|---|---|---|---|
| PCC 1a | Transverse tined CRCP | 228 | 69 | 5.2 |
| PCC 1b - EP-5 | EP-5 | 100 | 30 | 5.6 |
| PCC 1c | Same as PCC 1a | 305 | 93 | 5.8 |
| PCC 1d – Safe Lane | Cargill Safe Lane | 100 | 30 | 5.8 |
| PCC 1e | Same as PCC 1a | 100 | 30 | 5.8 |
| PCC 1f | PCC 1a long. grooved & ground | 533 | 162 | 5.8 |
| PCC 1g | Same as PCC 1a | 921 | 281 | 5.8 |
| RR Bridge | Transverse grooved CRCP | 232 | 71 | 5.9 |
| PCC 2 | Long diamond ground JPCP | 583 | 178 | 5.7 |
| Smart Road Bridge | Transverse Grooved CRCP | 2000 | 610 | 1.0 to 5.9 |
| Turnaround | DG HMA | 2275 | 693 | -1.5 to 0.7 |

Figure 2-12. Virginia Smart Road sections and surfaces [19].

The point-laser laser had a spot diameter of 0.2 millimeters and sampling frequency of 64 kHz. Previous MTD values collected through the sand patch method were used as reference data to verify the measurement accuracy. The presence of outlier data or data spikes are common in profiles collected by high-speed laser devices; therefore, these invalid data points are replaced by linear interpolation of neighboring values. If the percentage of invalid data points exceeded 20% for a test section, the measurements were removed from the profile. For the high-speed laser device, one MPD value was generated per 100 millimeters of pavement. The ETD for the high-speed laser device was calculated using Equation 2-4 [19].

$$ETD = 0.8 * MPD + 0.2 \quad \text{(Equation 2-4)}$$

The testing provided a poor correlation between MTD and ETD values using the data provided by the CTM and the high-speed laser measurement device. As a recommendation, a new method of measuring ETD was suggested to remove unwanted data noise and invalid sensor readings. The suggested method is the "square weight" ETD shown below in Equation 2-5 [19].

$$ETD_{sw} = \frac{\sum_{i=1}^{n} MPD_i * L_i^2}{\sum_{i=1}^{n} L_i^2} \quad \text{(Equation 2-5)}$$

In Equation 2-5 above, $MPD_i$ represents the mean profile depth within a series of profiles that corresponds to a specific profile length ($L_i$). Figure 2-13 below provides a schematic of this method with illustrations for the variables in Equation 2-5.

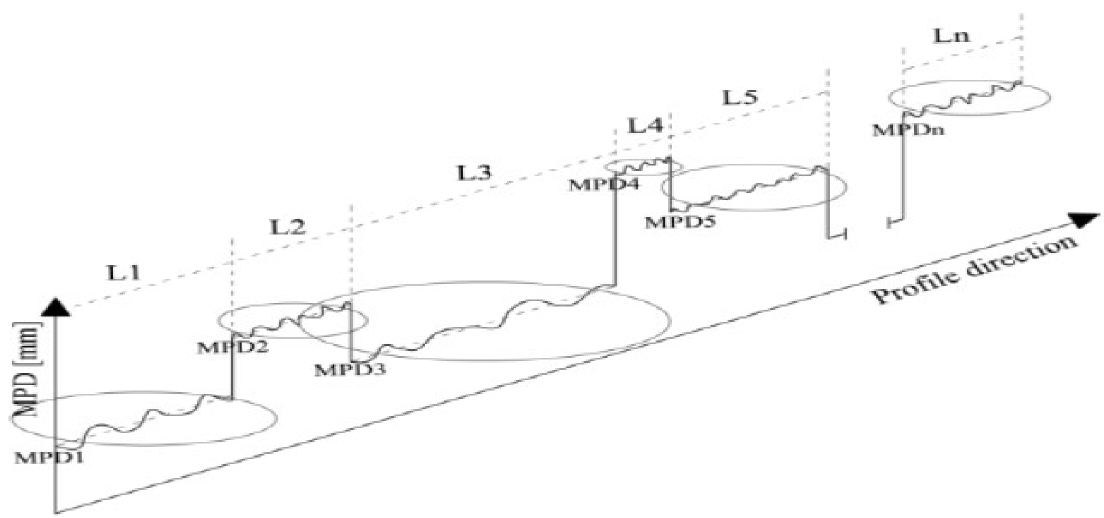



Figure 2-13. Square weight estimated texture depth ($ETD_{sw}$) schematic [19].

However, in a similar study presented at the 9th International Conference on Managing Pavement Assets in May 2015, removing these erroneous data spikes in high-speed MPD measurements resulted in a high correlation with CTM measurements. Figure 2-14 shows a clear depiction of the data spikes which are caused by outlier measurements. This testing was also conducted on the Virginia Smart Road and compared high-speed single-spot laser (HSSL) MPD measurements to those acquired using a CTM. Six measurements were taken along a wheel path at six different test sections and were followed by five test runs at 50 mph with the point-laser along the same wheel path and sections. As seen in Figure 2-15, a histogram was developed using the raw data from the laser measurements, and a combination of Gaussian and Laplace distributions were used to identify and remove the data spikes. Next, a 2.5-millimeter low-pass filter was applied to the data and the MPD values were calculated. The outcome of this outlier removal resulted in a mean MPD value measured by the high-speed device that was "essentially the same" as the value calculated by the CTM [20].

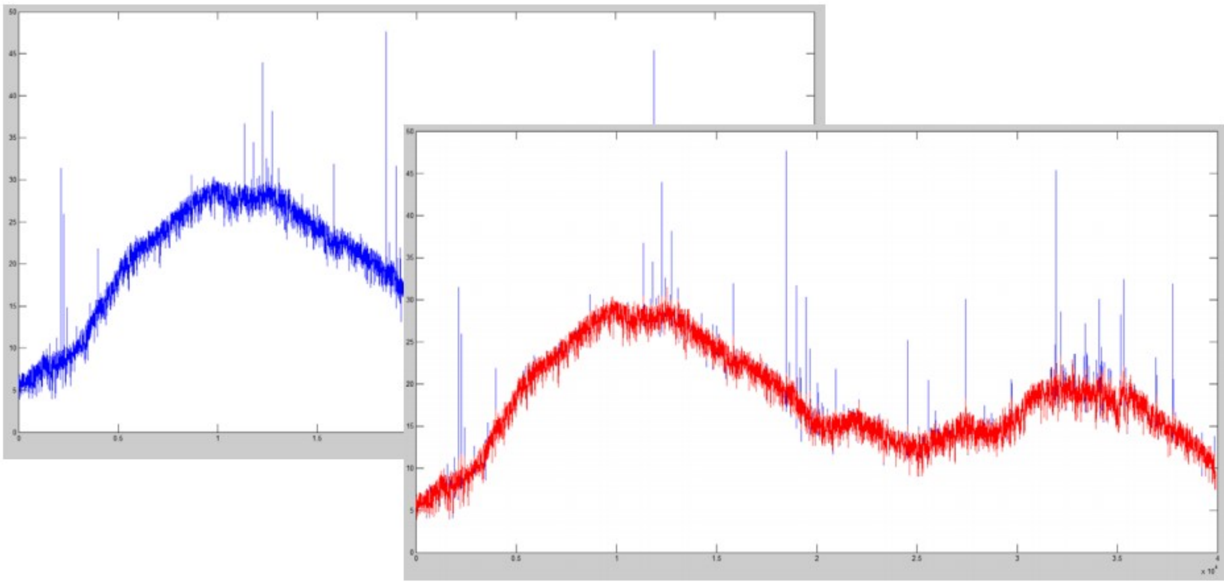


Figure 2-14. High-speed laser profile measurements with data spikes [20].

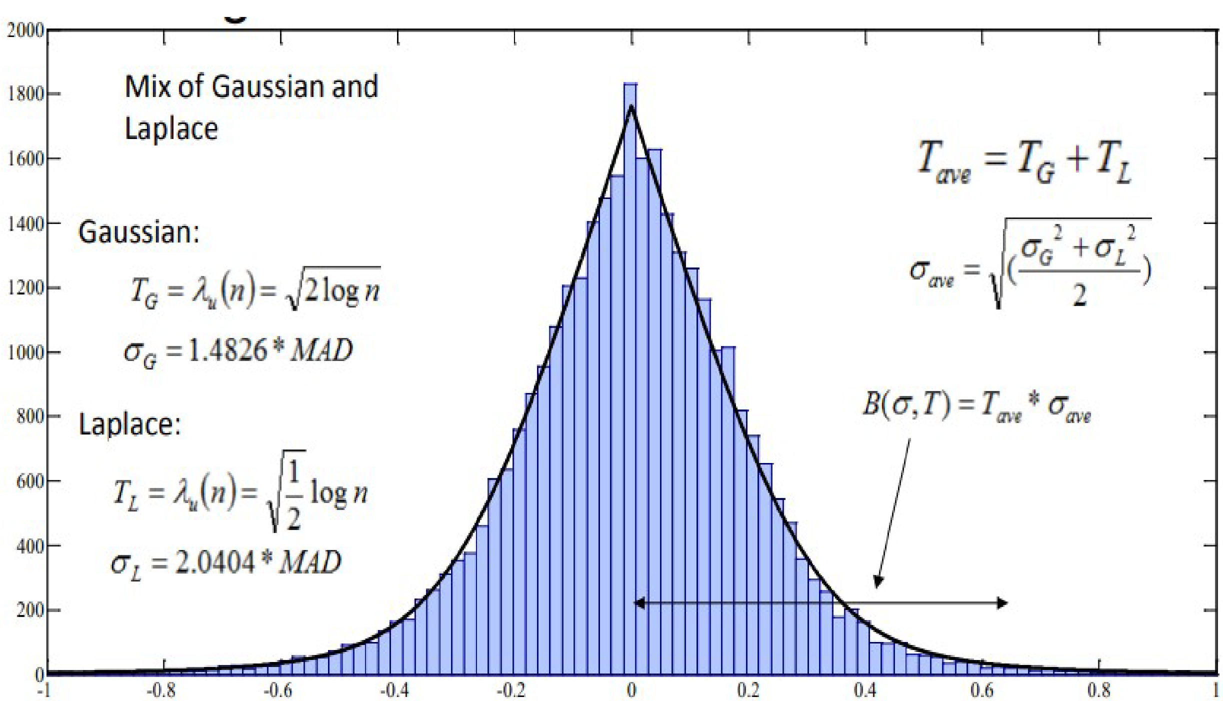



Figure 2-15. Histogram with Gaussian/Laplace distribution for spike removal [20].

*Design and Verification of a Laser-Based Device for Pavement Macrotexture Measurement [21]*

In 2010, a laser-based system used to measure macrotexture was developed at the Wuhan University of Technology in Wuhan, China. The laser-based system contained a high-precision laser range finder (LRF), an optical-electrical rotary encoder (OERE), an ECU, a power supply, a laptop for data acquisition, and a three-wheel cart. The device operates in a way comparable to a traditional CTM. The LRF had a vertical resolution of at least 0.05 millimeters and a range of no less than 20 millimeters with a sampling frequency of 32 kHz. The OERE was used to measure the travel distance of the cart with high precision. A program was developed in MATLAB and Visual C++ to use for data acquisition and storage. The data acquired contained the pavement profile heights, the positions of measuring points, and the characteristic values [21].

To test the accuracy of the system, ten 330-foot pavement sections were analyzed. Each 330-foot section was separated into five equal length subsections. The reference data was collected through the sand-patch method which calculates MTD values. Since the laser-based system measures MPD, Equation 2-6 was used to convert MPD to ETD.

$$ETD = 0.247 + 0.785 * MPD \text{ (Equation 2-6)}$$

When compared to the reference data, the laser-based system data provided a root-mean-square error of 0.0782 and an $R^2$ of 0.95. The $R^2$ represented an acceptable fit for this experiment. The entire manufacturing cost of the device was less than $15,000 USD with the LRF accounting for 70% of the total cost. The device is shown below in Figure 2-16 [21].

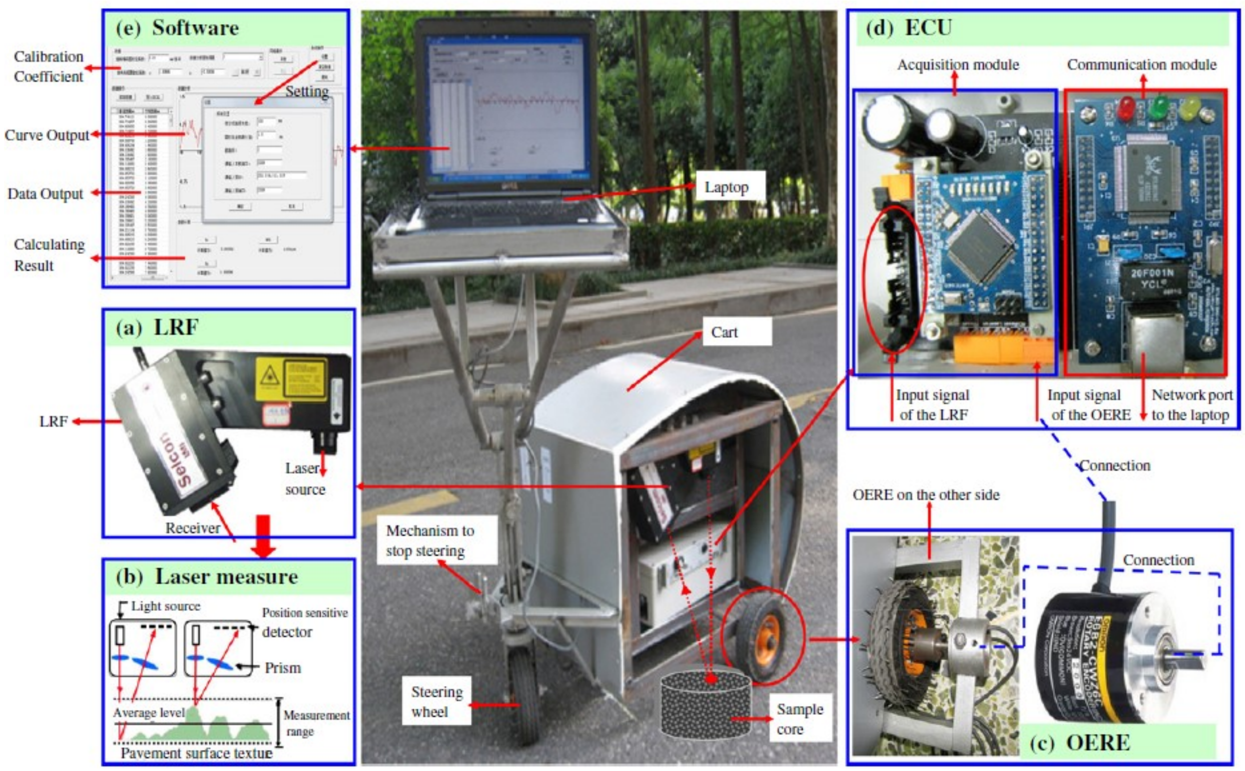



Figure 2-16. Macrotexture measurement device [21].

## ACCURACY AND REPEATABILITY OF LASER-BASED DEVICES

### *Repeatability and Agreement of Various High-Speed Macrotexture Measurement Devices [24]*

In 2019, a study was conducted on the 2.2-mile Virginia Smart Road test track located at the Virginia Tech Transportation Institute in Blacksburg, Virginia. Five high-speed macrotexture measurement devices were compared and analyzed. The term "high-speed" is designated to the vehicle mounted laser-based system traveling at 55 mph. The testing included high-speed (55 mph), various constant speeds, and variable speed which included accelerating and decelerating. Device ID's 1 – 4 were single-spot lasers and Device 5 was a line-laser. MPD was chosen as the parameter to quantify macrotexture. Table 2-3 shows the device specifications of each laser in the experiment [22].

Table 2-3. Specifications for laser measurement devices [22].

| Device ID | Laser Type | Make | Sampling Frequency (kHz) | Raw Data Spatial Interval (mm) | Vertical Resolution ( ± mm) |
|---|---|---|---|---|---|
| 1 | Single Spot | Acuity (custom) | 100 | 0.25 | 0.020 |
| 2 | Single Spot | Limab SR TexRough | 32 | 1 | 0.010 |
| 3 | Single Spot | LMI Gocator 1300 series | 32 | 0.9 | 0.049 |
| 4 | Single Spot | Acuity (custom) | 100 | 0.5 | 0.020 |
| 5 | Line Laser | LMI Gocator | 5 | 0.3 (transverse)<br>25 (longitudinal) | 0.015 to 0.040 |
| 15 | Single Spot | LMI Opticator | 62.4 | 0.25 | 0.045 |

Given the large scope of data acquired by line-lasers, Device 5, the line-laser device, required a large amount of raw data outliers to be removed from the data set for MPD calculations. This outlier data was typically along the edges of the laser's footprint. For every 100 millimeters (3.9 inches) of travel, MPD calculations were made transverse to the travel direction [22].

As shown in Equation 2-7 below, the coefficient of repeatability, $r$, was derived from the mean-square error (MSE) of multiple runs of same device on the same pavement section.

$$r = 1.96 * \sqrt{2} * \sigma_{\text{SD}} \quad \text{(Equation 2-7)}$$

For Device 5, $r$ was determined to be 0.085 millimeters after five runs on the same test section. It was determined that acceleration influences the data acquired by the line-laser. However, in the wide range of data collected, it did not have a significant impact on repeatability. The limits of agreement (LOA) analysis between the line-laser and single-spot lasers had shown low agreement in MPD values. This was determined to be caused by the line-laser measuring the longitudinal texturing of concrete pavement which the single-spot lasers cannot measure. In contrast, the LOA improved significantly (by more than 50%) when comparing the line-laser to other single-spot lasers on asphalt surfaces. [22].

### *Evaluating Non-Contacting Macrotexture Laser Displacement Device Accuracy at Highway Speeds [23]*

In 2019, an experiment was conducted on the Virginia Smart Road to assess the accuracy of several different laser-based measurement devices and determine if speed and sensor exposure time were significant factors in these measurements. An LMI Technologies Gocator 2342 line-laser was mounted in two different orientations, parallel and perpendicular to the vehicle's direction of travel, to be tested for MPD measurement accuracy. The line-laser had a sampling frequency of 5 kHz and a vertical resolution of 0.015 - 0.040 millimeters. The testing consisted of a 6061-aluminum plate with six different sections of grooves with various wavelengths. MPD values were to be measured at highway speeds (25, 45, and 65 mph). Shown below in Figure 2-17 are the two orientations of the aluminum reference plate and the line-laser [23].

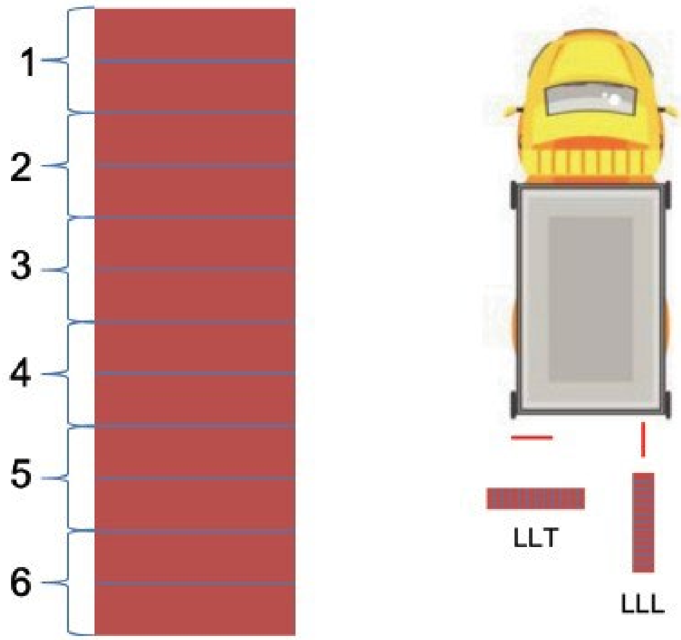



Figure 2-17. Aluminum reference plate (left). Test orientations (right) [23].

The reference data was collected using a Keyence LJ-V7200 line-laser in a controlled lab setting. Another variable in the testing was the exposure time of the line-laser (short, medium, long, and auto). As speed and exposure time increased, the macrotexture profile accuracy degraded. The line laser mounted perpendicular to the vehicle's direction of travel did not accurately reproduce the section of the plate with the smallest waveform and had the largest MPD variability on the other sections. Aside from the perpendicularly mounted line-laser, the vehicle speed and exposure times did not bring the measurement values outside the ± 0.1-millimeter tolerance established for this experiment [23].

***Evaluation of the Repeatability and Reproducibility of Network-Level Pavement Macrotexture Measuring Device [24]***

In 2017, a study was conducted at Virginia Tech to evaluate the repeatability and reproducibility of network-level pavement macrotexture measuring devices. Two high-speed macrotexture measuring devices were used where one was mounted on a Sideways-Force Coefficient Routine Investigation Machine (SCRIM) system and the other on a portable Ames system. The laser-based sensor mounted on the SCRIM system measures macrotexture and friction and records MPD data in 1-meter (3.3-foot) increments. The SCRIM system records raw data every 0.1-meter while traveling at a speed of 30 to 50 mph. It alerts the user when MPD is outside the range of 0.5 – 3.0 millimeters. The Ames 8300 Survey Pro High-Speed Profiler uses high-speed laser sensors mounted at either the front and/or rear end of a vehicle to record macrotexture and profile. This system uses an LMI Technologies Selcom Optocator 2008-180/390 texture sensor rated at 62.5 kHz to provide data readings while traveling between 25 to 65 mph. To provide accurate data readings the laser sensor was mounted within 7.09 inches of the pavement's surface. This system collects and stores data using proprietary software [24].

The data collected using the two different high-speed measurement devices were compared against data acquired using a CTM. All three systems used software to compute and record the MPD of the pavement. The two high-speed systems used the average MSD measurements over a 1-meter (3.3-foot) length, but 10-meter (330-foot) lengths of pavement were also analyzed to find patterns within the acquired data. Using the average MPD of each section, the repeatability of the two high-speed systems was just over 0.1 millimeters. After removing the data on an outlier specimen, the $R^2$ value between the Ames and the CTM data was determined to 0.959 which shows strong correlation. With the same outlier data removed, the $R^2$ value between the SCRIM and the CTM data was determined to be 0.916. The SCRIM system produced consistently lower MPD values when compared those acquired by the CTM [24].

### PROCESSING TEXTURE DATA

#### *Removing Outliers From 3-D Macrotexture Data by Controlling the False Discovery Rate [25]*

Given the large amount of data readings produced by 3-D laser-based measurement devices, removing erroneous data and outlier measurements in post-processing has an important role in macrotexture analysis. When referring to a 3-D laser-based macrotexture measurement device, the three dimensions include the width of the line-laser beam, the longitudinal length the laser travels, and the surface texture heights. Erroneous data readings in both the positive and negative directions are common in these devices. Highly reflective surfaces can cause the laser light to reflect in an unpredictable manner which leads to erroneous data readings. These erroneous data readings can also be caused by extreme light diffusion through an aggregate. The data outliers are removed by setting a threshold of acceptable values in the data acquisition software. This threshold is difficult to determine considering the varying macrotexture readings of aggregates and cements. The false discovery rate (FDR) was the method chosen to determine the appropriate threshold. Unlike a fixed threshold, the FDR procedure accounts for the number of observations and the presence of outliers when producing an acceptable threshold. Figure 2-18 displays a flowchart of the algorithm developed to handle outlier data using the FDR method. Once outliers are identified, they are replaced by interpolation of neighboring values. In this experiment, the outliers were set to zero since this was the mean of the flattened data set. The equipment used in this experiment were an Ames Engineering Laser Texture Scanner 9300 (for 3-D pavement profiling) and a Nippo Sangyo CTM for reference data. Controlling FDR was determined to be a highly effective method for removing outlier data by constantly adapting to the dataset being analyzed [25].

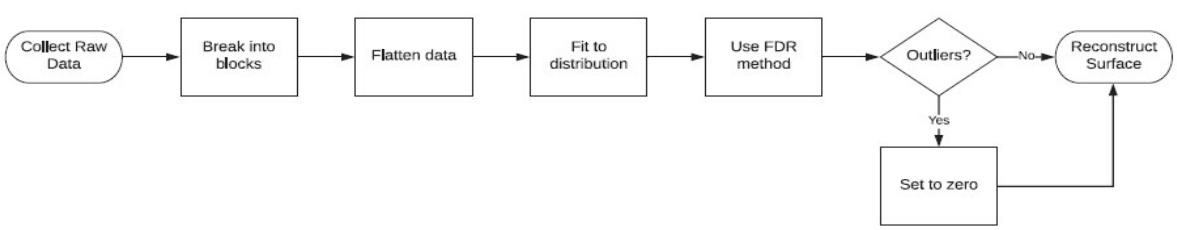



Figure 2-18. Flowchart of outlier removal algorithm [25].

## SURVEY OF U.S. TRANSPORTATION AGENCIES ON MACROTEXTURE

A survey of several state agencies was conducted by phone regarding experiences with high-speed network-level and project-level macrotexture data collection:

- Texas – While performing network-level pavement friction data, macrotexture data from a high-speed 3-D texture laser was acquired. The data has not yet been processed and analyzed for accuracy. The Texas DOT has developed an in-house, line-laser based 3-D texture measurement device with good accuracy and high repeatability for project-level analysis (VTexture system).
- Virginia – Virginia DOT has done no network-level macrotexture data collection. International Cybernetics (ICC) performs project-level pavement smoothness testing to acquire international roughness index (IRI) measurements. A strong correlation in IRI values between the point- and line-lasers for road smoothness measurements has been shown. Results had shown IRI values within one inch per mile between the two devices.
- South Carolina – South Carolina DOT has begun collecting network-level macrotexture data this year (Jan. 2019). Using Gocator line-lasers, macrotexture measurements along vehicle wheel path have been collected. The data has not been processed yet, therefore, no insight on the accuracy or shortcomings of the data collection process was provided.
- Alabama – Alabama DOT has collected 2-D network-level macrotexture data using point-lasers, but do not necessarily use the data. Due to insufficient funds to perform macrotexture analysis, texture measurement is completed in conjunction with network-level friction testing. It is planned to start collecting 3-D profiles with Gocator line-lasers, but currently do not find the need to implement testing at this moment.
- Iowa – Currently, the Iowa DOT is not collecting macrotexture data. A Gocator line-laser is used for IRI measurements when testing for smoothness. Although no formal research-based testing has been performed, the Iowa DOT has seen satisfactory results in the repeatability of multiple line-laser tests for IRI measurements. The lasers are not mounted perfectly transverse to the vehicle and are slightly angled to capture various road features. This arrangement has allowed for acceptable IRI measurements within the agency.

In 2019, a study was conducted at Virginia Tech where surveys were collected of state agencies to determine their macrotexture measurement equipment, frequency, and uses. Of the 28 states that participated in the surveys about network-level macrotexture data collection, five states indicated that the available technology was not yet mature enough, 11 commented on the process being cost deterrent, and 12 states mentioned a lack of human resources to pursue collecting macrotexture data outside of the project-level basis. Also, the majority of those surveyed stated that they only collected macrotexture data while profiling the pavement. Several other states mentioned macrotexture data was only collected during friction testing. The most common device used for states that conducted network-level high-speed measurements was the point-laser, and for project-level cases a circular track meter (CTM) was used. The study stated that only one state (not identified) reported that they use line-lasers for network-level and project-level macrotexture data collection [2].

## FDOT Macrotexture Measurement Gap Analysis

The current network-level macrotexture measurement process performed by the FDOT State Materials Office includes using a vehicle-mounted high-speed point-laser while traveling at highway speeds. Previous FDOT studies had shown close correlation between high-speed point-laser measurements and measurements from a CTM on flexible pavement [28, 29]. In a 2017 FDOT macrotexture measurement experiment, the testing showed that the point-laser does not accurately measure rigid pavement, such as concrete, at highway speeds. The testing included an LMI Technologies Selcom Optocator point-laser, with a sampling frequency of 64 kHz, mounted along the wheel path of a test vehicle. The texture measurements were done in conjunction with lock-wheel friction testing during this experiment. An image of the test vehicle and point-laser are shown in Figure 2-19 [26].

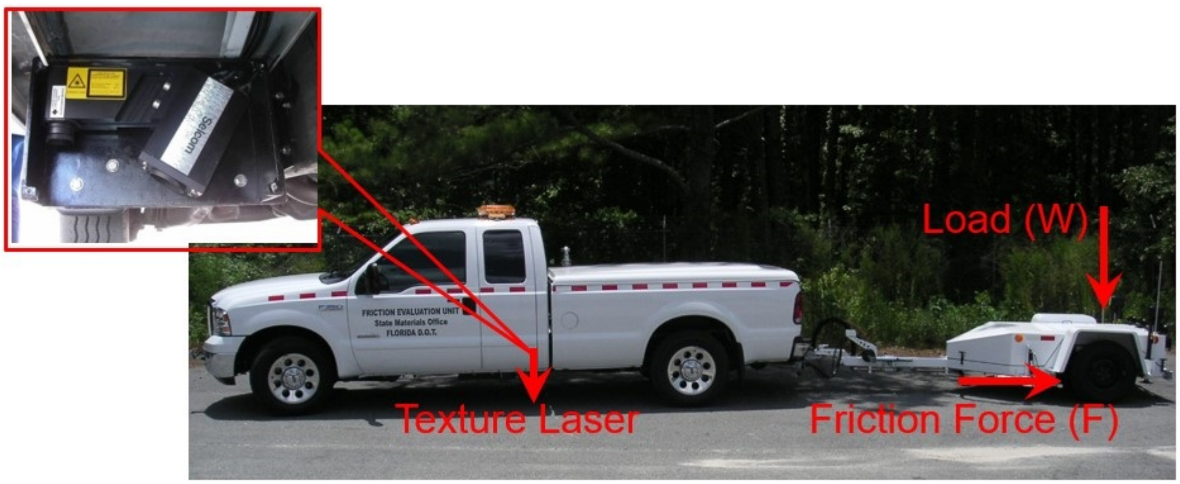



Figure 2-19. High-speed point-laser mounted to test vehicle [26].

According to the graph seen in Figure 2-20, MPD measurements produced by the point-laser on rigid surfaces had poor correlation with the reference MPD values calculated by the Nippo Sangyo CTM. The rigid surfaces the graph is referring to in this experiment are concrete roads with longitudinal texturing [26]. Concrete roads undergo a texturing process, normally either tining or diamond grinding, to produce macrotexture [28]. All tining and diamond grinding processes are done longitudinal to the direction of traffic travel, unless otherwise requested by a project leader [28, 29]. Point-lasers are unable to measure concrete pavement because its texture varies depending on the direction of the measurements (longitudinal or transverse). This is because a point-laser measures one dimension as the travel distance along the pavement surface and measures the second dimension as texture elevation. As a result, while surveying a concrete road longitudinally, a 2-D profile produced by a point-laser misrepresents the true concrete pavement texture [28]. Figure 2-21 shows an image of concrete pavement after longitudinal diamond grinding. Since a line-laser takes 3-D measurements using a transverse laser light orientation, it can possibly overcome this limitation. This is because the width of the laser light produced by the line-laser can accurately capture the longitudinal texturing of concrete.

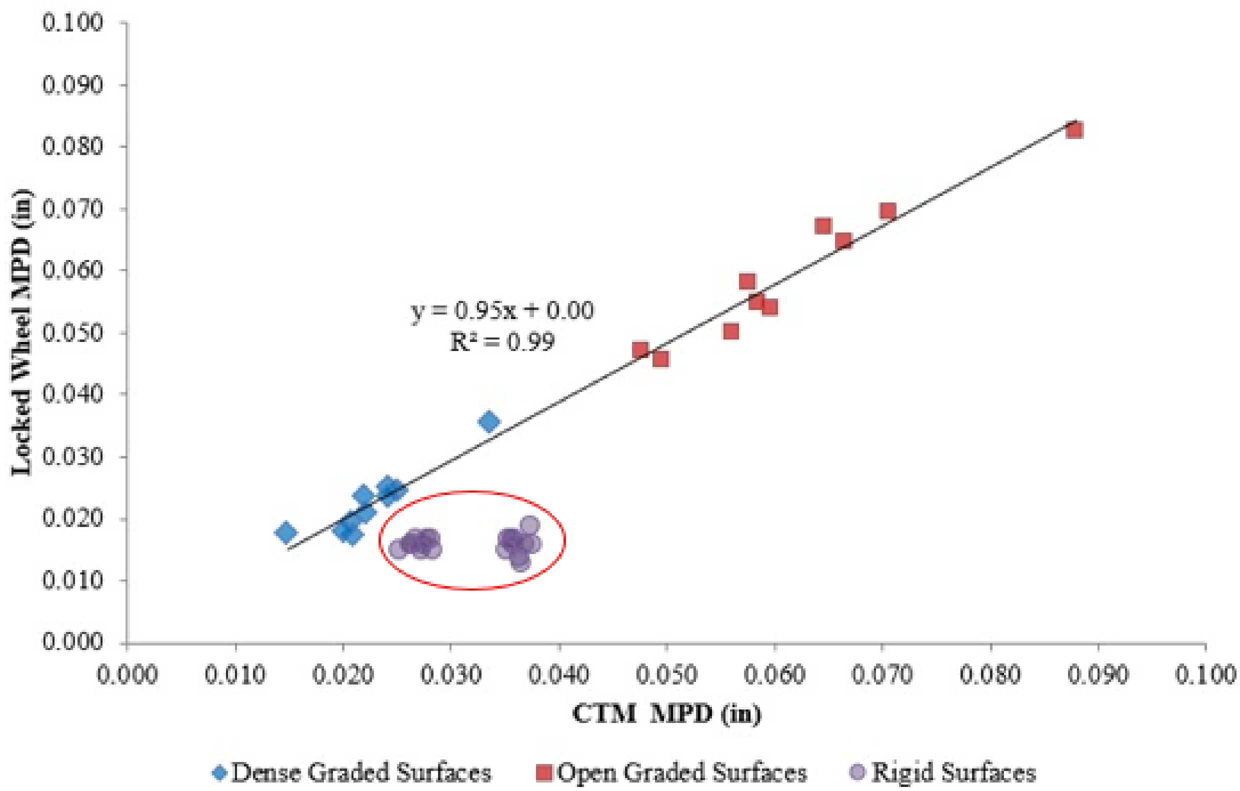



Figure 2-20. Point-laser MPD measurements vs. CTM reference MPD values [26].

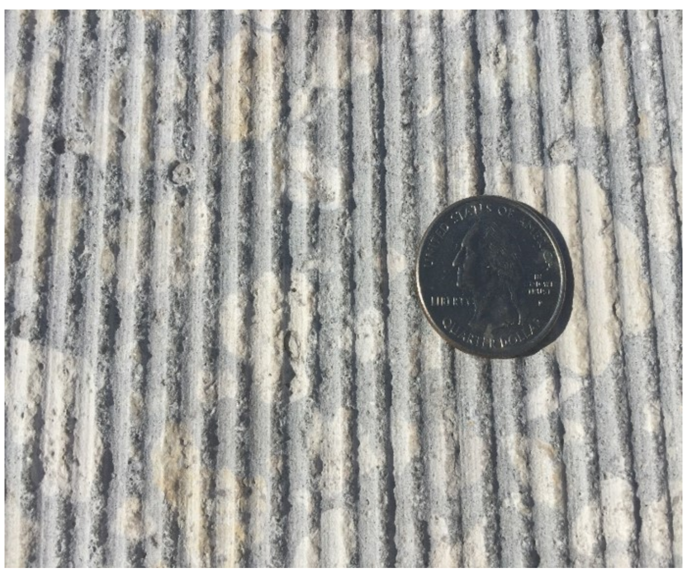


Figure 2-21. Diamond ground concrete road [26].

Another limitation of the point-laser systems arises when the laser is projected onto a rough surface. The laser light is typically scattered in an unpredictable manner due to pavement surface irregularities. As the pavement surface becomes rougher, its specular light reflectivity property decreases, and the scattering effect increases [14]. An image of this scattering effect is shown below in Figure 2-22. An advantage of using a line-laser system is that the numerous data points it acquires from every profile reading greatly exceeds the number of data points from a point-laser. Since MPD measurements are dependent on the average height values of each sample, acquiring a large amount of data points per sample reduces the influence of inaccurate measurements caused by scattered laser light or outlier readings. Figure 2-23 shows a comparison between point-, wide-spot, and line-laser light footprints projected onto a surface [4].

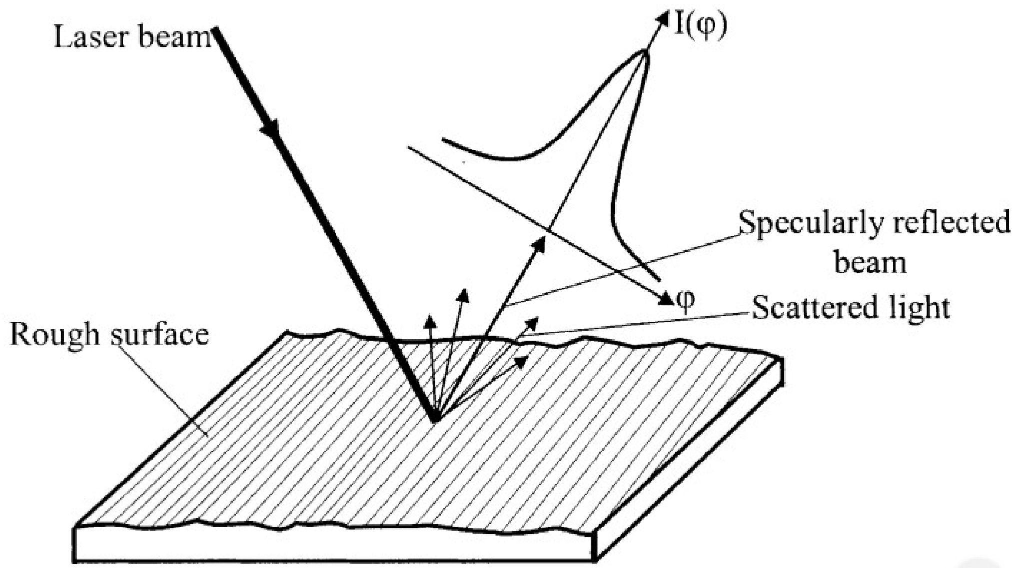



Figure 2-22. Laser light scattering effect on a rough surface [14].

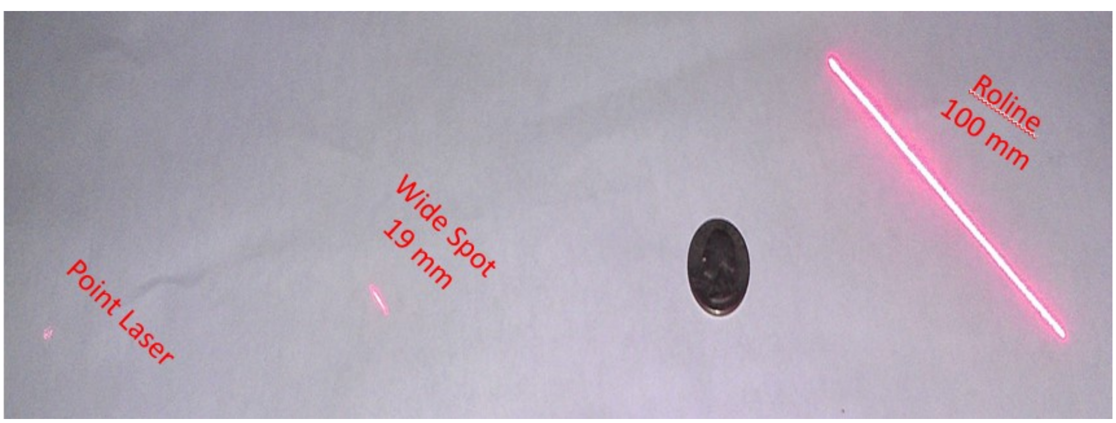



Figure 2-23. Point-laser, wide-spot, and line-laser (Roline) footprint comparison [26].

While line-lasers are a potential solution to the aforementioned issues, further research and testing is required to implement line-lasers into network-level macrotexture analysis. Based on data acquired from a 2018 FDOT experiment comparing point-laser measurements to line-laser measurements, there is a clear distinction between the measurements of the two lasers. As seen in Figures 2-24, 2-25, and 2-26, the measurements between the point-laser and line-laser do not correlate well on either flexible or rigid pavement. As previously shown in Figure 2-3, since measurements from the point-laser have good correlation with the CTM on flexible pavement, it could be concluded that the erroneous measurements were with the line-laser. Discrepancies between line-laser and point-laser systems were also shown in the 2019 Virginia Tech study [22].

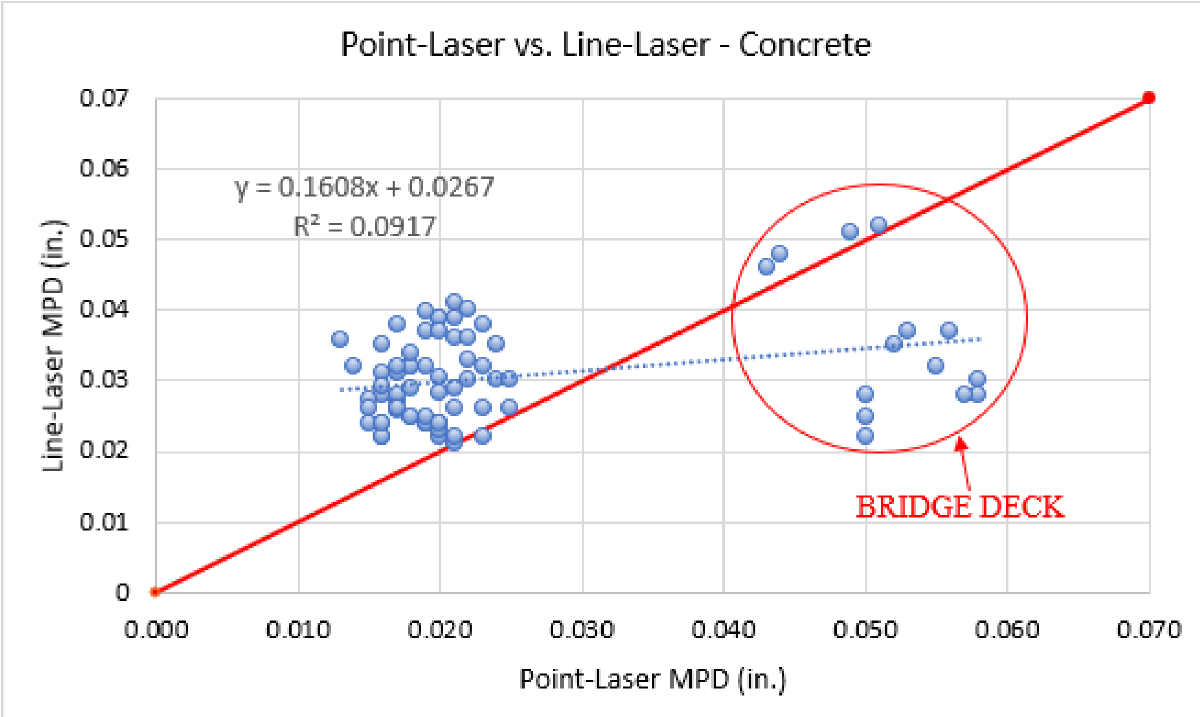



Figure 2-24. Point-laser vs. line-laser measurements on concrete.

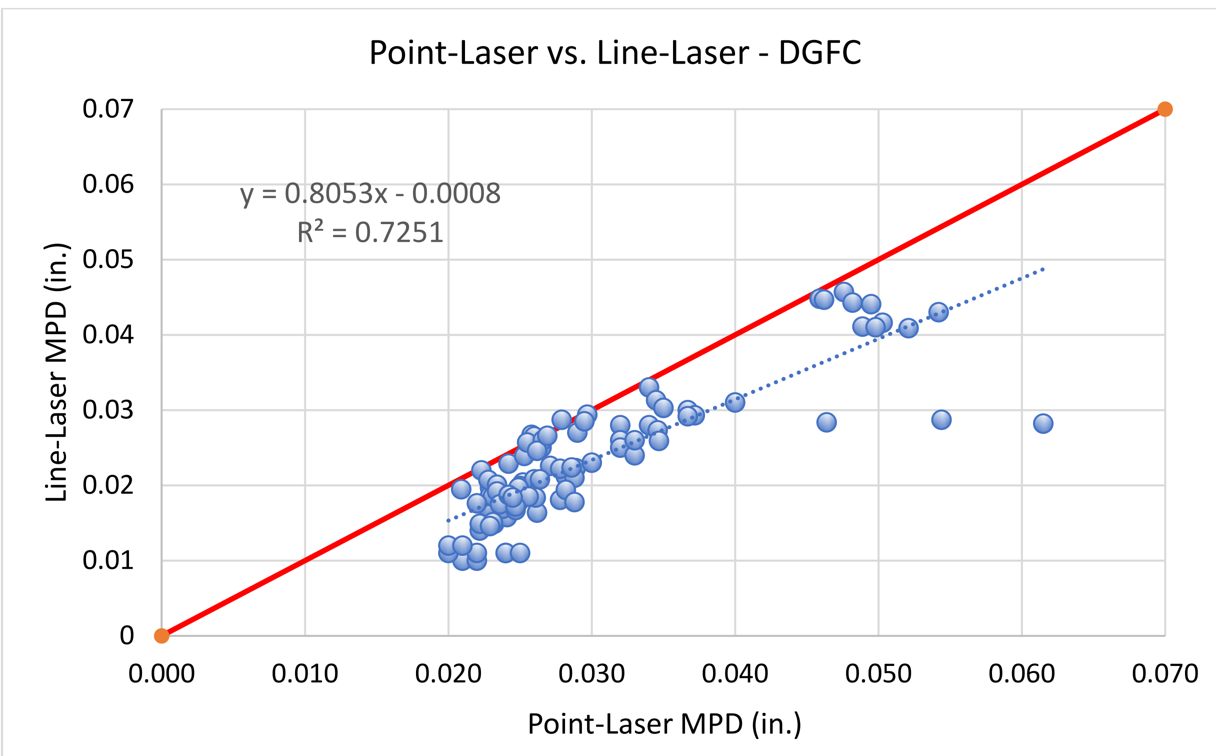



Figure 2-25. Point-laser vs. line-laser measurements on dense-grade asphalt.

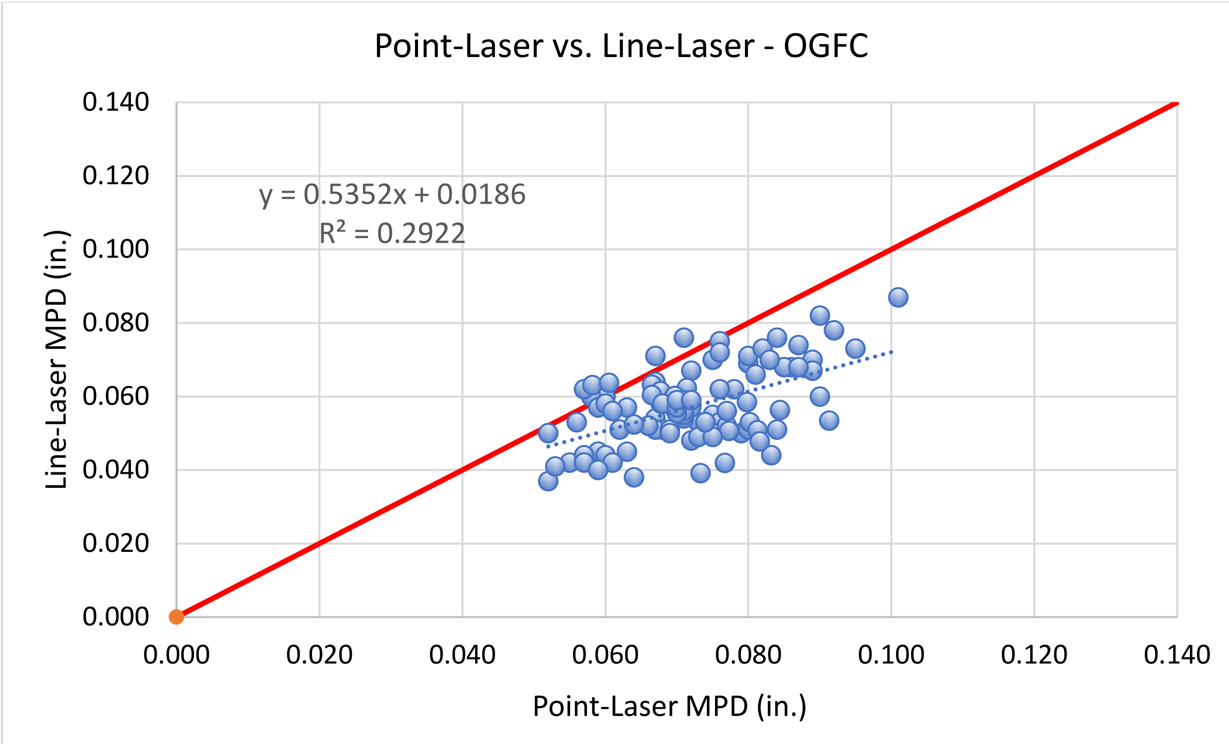



Figure 2-26. Point-laser vs. line-laser measurements on open-grade asphalt.

The methodology involved with implementing line-lasers into high-speed network-level macrotexture measurement has not been successfully demonstrated within the available published literature. The Texas DOT, however, has indicated that the VTexture equipment that they developed in-house is capable of network-level measurement [17]. Different studies indicate varying levels of accuracy related to line-laser measurement of macrotexture, and testing has shown improvement of line-laser data with post processing, such as removing outlier data [27]. Further research, which is a focus of this study, is required to improve the line-laser system with respect to laser positioning, exposure time, data processing algorithms, and outlier measurement removal process. Once the performance of line-laser system has been enhanced, a comprehensive study of different texture reference devices (CTM, FTM, and TM2) and high-speed measurement devices (point-laser and line-laser) will commence to determine the path towards improved network-level macrotexture measurement.

# CHAPTER 3 – TEST PLAN

Currently, the FDOT has an LMI Technologies Gocator-2342-3B-12 line-laser mounted along the driver-side wheel path of two of their friction evaluation vehicles. These line-laser systems were equipped to the FDOT owned Ford F-350's by pavement equipment specialists, International Cybernetics (ICC). One laser is mounted underneath the vehicle along the driver-side wheel path at an angle of approximately 30° relative to the x-axis of the vehicle and the other laser is mounted at 45°. The line-laser is mounted at an angle as opposed to perfectly transverse with the vehicle to capture periodic texturing along the x-direction. Figure 3-1 shows a diagram of the line-laser mounting orientation and the vehicle datum axes.

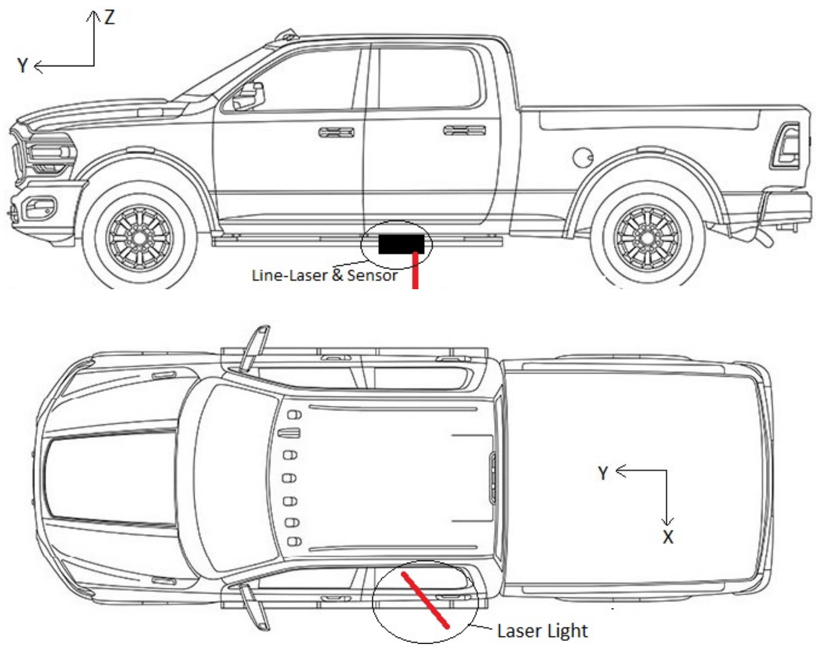



Figure 3-1. Profile view and overhead view of the test vehicle (not shown to scale) [30].

After the line-laser captures raw height measurements, the data is processed using a program developed by ICC to calculate MPD. An overview this program is as follows:

1) Drop-out points in the z-direction (uncaptured height values) are identified and replaced through interpolation of neighboring values.

2) Raw z-axis data points are sorted according to their respective x- value within the profile.

3) Length of the scan is checked (ASTM E1845 requires 100 millimeters of data points with point spacing ≤ 1 millimeter for MPD calculations), and the best 100-millimeter range index is identified [4].

4) Slope suppression is applied to the profile and an interquartile range (IQR) is determined.

5) Outlier Removal Process: If a height measurement is greater than or equal to three times the IQR, it is removed and replaced through the interpolation of neighboring values.

6) The data points along the x-axis are then resampled to 0.1-millimeter spaced intervals.

7) Lowpass filtering corresponding to the specifications listed in ASTM E1845 is applied.

8) The data profile is then cropped to 100 millimeters based on the index previously identified, and the mean segment depth (MSD) of the profile is determined.

9) MPD is determined by taking the average of all MSD values of every profile in the test section.

As shown in previous FDOT line-laser precision studies, the current system is unable to adequately depict macrotexture profiles on either flexible or rigid pavements. As previously discussed, resultant MPD values from these line-laser precision studies had low correlation with both point-laser data and reference data captured by the CTM. Based on the specifications of the line-laser itself, it was assumed that the current line-laser could achieve the desired project goals. Therefore, the issue of erroneous MPD measurements with the line-laser was determined to lie within the current system configuration or the post-processing program.

### TEST LOCATIONS

Testing was conducted by the UNF research team in three stages. The first stage consisted of static testing, the second stage included dynamic accuracy testing on flexible pavements, and the third stage included repeatability testing on flexible and rigid pavement. For the first stage, static testing was conducted at the FDOT State Materials Office. Once static testing was complete, the second stage began with dynamic testing at the Williston Municipal Airport test track. The test track consists of a one-lane road approximately 3,800 feet in length with a turnaround at each end. Roughly half of the test track is open-grade pavement, and the remaining half is dense-grade. The test track is also closed to the public; therefore, it required no maintenance of traffic (MOT) to conduct testing. Figure 3-2 shows the Williston Municipal Airport test track.


Figure 3-2. Williston Municipal Airport test track.

The third stage was conducted at the Williston Municipal Airport test track and a previously used FDOT test site containing concrete pavement. The selected concrete test site was used in an FDOT texture harmonization study in 2018 and is located along State Road 9B (SR 9B) in Jacksonville, Florida. The test section consisted of approximately 2,500 feet of LGD concrete. To check the line-laser accuracy, MOT was established to take reference measurements. As done in the 2018 study, the testing was conducted in the left-hand wheel path of southbound lane three starting at Milepost 3. The test site contained five subsections which were evenly spaced 500 feet apart. Figure 3-3 shows images of the test site.


Figure 3-3. SR-9B Test Site.

## TEST EQUIPMENT

### *Line-Laser*

The initial focus of the testing was to configure the line-laser so that it can accurately collect reproducible texture data. A specifications table for the line-laser used in this experiment is shown below in Table 3-1. The table also includes a few of the configurable parameters within the Gocator Web interface. The Gocator Web interface is accessible via ethernet communication using the test vehicle computer. From the Web interface, the user can configure the line-laser sensor settings in real-time. The interface also has a feature where the user can view the returned line-laser light within an x- and z-coordinate system. Figure 3-4 shows an image of the line-laser with a diagram of its laser light [Field of View (FOV), Far End (FE), Close End (CE), Measurement Range (MR), Clearance Distance (CD)], and Figure 3-5 shows an image of the Gocator Web interface.

Table 3-1. Line-laser specifications [31].

| | |
|---|---|
| **Make and Model** | LMI Technologies Gocator 2342-3B-12 |
| **Scan Rate** | Up to 5,000 Hz |
| **Field of View (FOV)** | 64 mm – 140 mm |
| **Points per Profile** | 1,280 |
| **Resolution (X)** | 0.095 mm – 0.170 mm |
| **Resolution (Z)** | 0.015 mm – 0.040 mm |
| **Laser Class** | 3B (< 500 mW) |

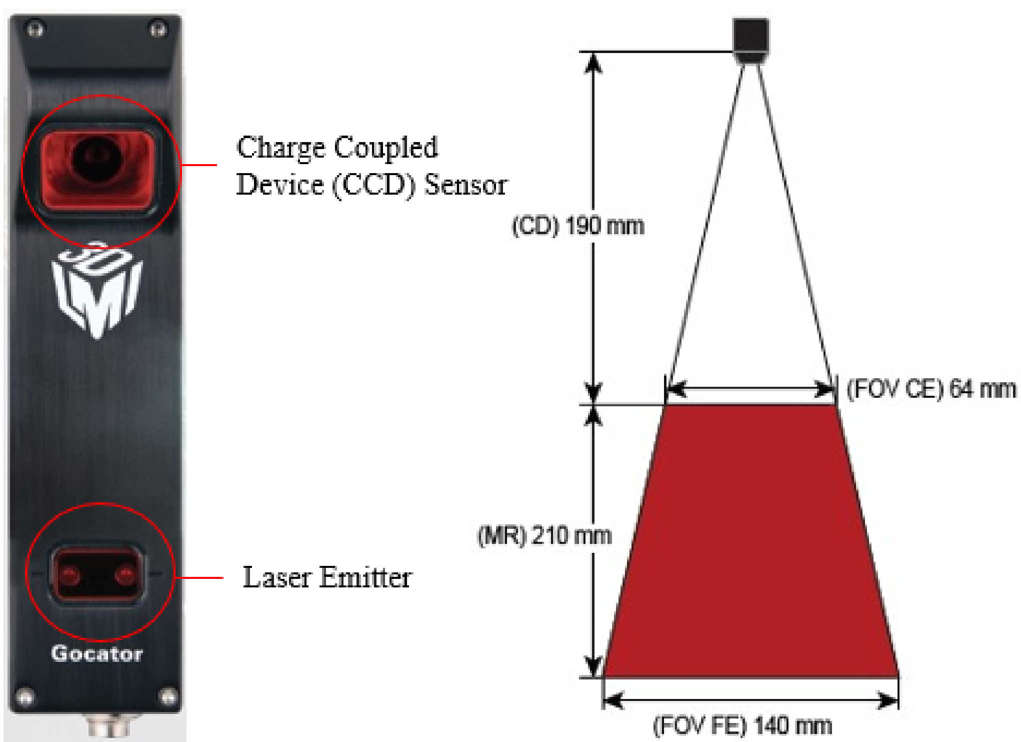



Figure 3-4. LMI Technologies line-laser (left). The laser light diagram (right) [32].


Figure 3-5. Gocator Web interface with a profile view of the line-laser [31].

### *Test Vehicle*

The test vehicle used in this experiment was an FDOT-owned pavement friction testing unit. The primary use of this vehicle is to perform locked-wheel skid-testing, where the vehicle collects texture data via a point-laser during lockups. However, the test vehicle is also equipped with a Gocator line-laser to collect texture data which can be used as a standalone system. An image of the test vehicle is shown below in Figure 3-6.


Figure 3-6. FDOT pavement friction testing unit with line-laser.

***Circular Track Meter (CTM)***

To test the accuracy of the line-laser, reference measurements with accepted reference devices were required. The CTM used by the FDOT was developed by Nippo Sangyo Inc. and was the primary reference device for this project. The CTM is a static measurement device that has been widely accepted for producing accurate measurements of pavement macrotexture. Comparisons between MPD values computed by the CTM and MTD values produced from sand-patch testing have shown a high-correlation with each other. Another advantage of the CTM is that it has an ASTM testing standard (ASTM E2157). Table 3-2 shows a few relevant specifications of the Nippo Sangyo CTM and Figure 3-7 shows the device.

Table 3-2. CTM specifications [11].

| | |
|---|---|
| **Make and Model** | Nippo Sangyo CTM |
| **Scan Time** | Approx. 45 seconds |
| **Measurement Radius** | 142 mm |
| **Points per Profile** | 1,024 |
| **Point Spacing Interval** | 0.87 mm (± 0.05 mm) |
| **Resolution (Z)** | 3 µm |


Figure 3-7. Nippo Sangyo circular track meter.

*Fast Texture Meter (FTM)*

The FTM is a static reference device developed by ICC. It is a high-resolution texture measurement device that produces MPD calculations in accordance with ASTM E1845 [33]. The FTM produces a high-resolution pavement analysis using all the available data points in a texture profile and a low resolution CTM-equivalent MPD value using 1,024 data points. Some specifications of the FTM are shown below in Table 3-3. Through a previous study conducted by the FDOT State Materials Office, the CTM-equivalent (low-resolution) MPD values produced by the FTM were nearly identical to those produced by the CTM. However, the high-resolution MPD values produced by the FTM had shown a 5-10% difference in MPD calculations when compared to those produced by the CTM. Figure 3-8 shows a graph comparing MPD values from the FTM and CTM and Figure 3-9 shows the FTM device. Comparisons between high-speed devices, the CTM, and the FTM were conducted.

Table 3-3. FTM specifications [33].

| | |
|---|---|
| **Make and Model** | International Cybernetics FTM |
| **Scan Time** | 9.75 seconds |
| **Measurement Radius** | 159 mm |
| **Points per Profile** | 9,410 (± 6) |
| **Point Spacing Interval** | 0.053 mm |
| **Resolution (Z)** | 0.01 mm |

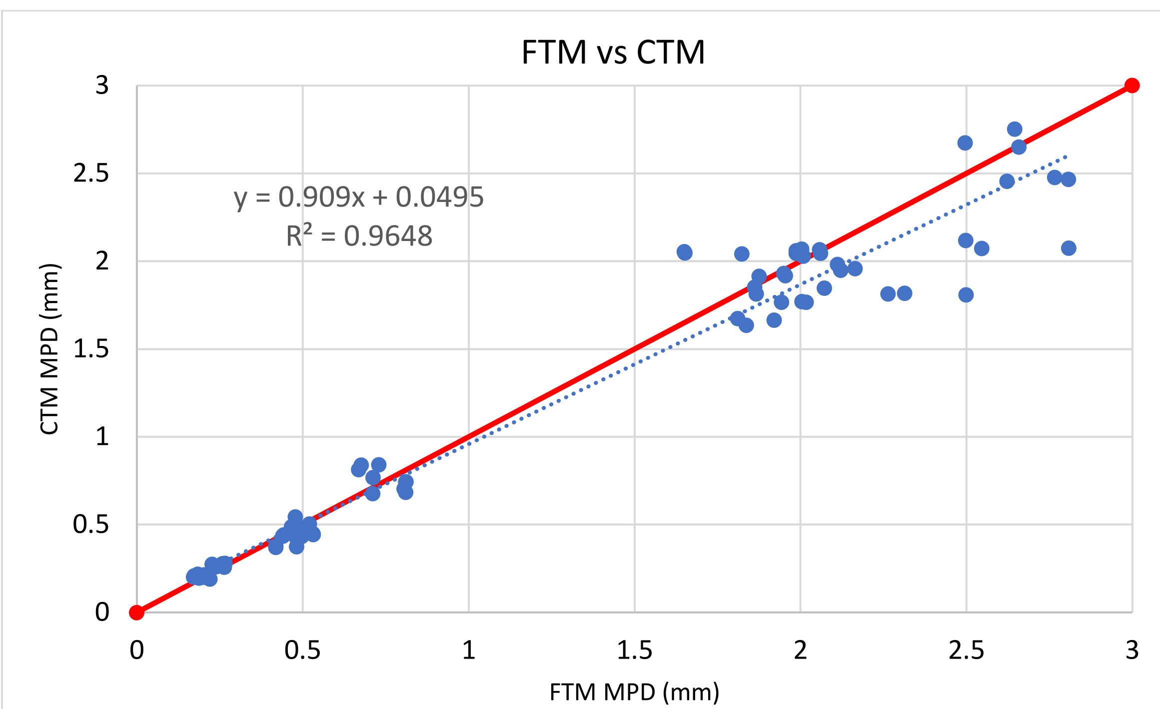



Figure 3-8. FTM vs. CTM comparison study.


Figure 3-9. Fast texture meter (FTM).

***Texture Meter 2 (TM2)***

The Texture Meter 2 (TM2) is a dynamic macrotexture measurement device developed by WDM. The device contains a line-laser mounted transverse to the travel direction and emits a 100-millimeter-wide laser profile. The device operator collects texture data in either 10-meter (33-foot) or 50-meter (164-foot) intervals at an ideal walking speed of approximately two mph. However, using the "TM View" program provided by WDM, the operator can measure MPD values in shorter intervals. The sampling interval of the TM2 can be set from 2 to 5-millimeters (0.08 to 0.20-inches) of travel. For example, if the sampling interval is set to 5 millimeters (0.2 inches), a 10-meter (33-foot) test section will contain 2,000 measurement profiles. The height measurement resolution is stated to be less than 0.05 millimeters [34]. Testing will include a comparison study of the accuracy of the TM2 as a reference device relative to the CTM and FTM. Figure 3-10 shows an image of the TM2.

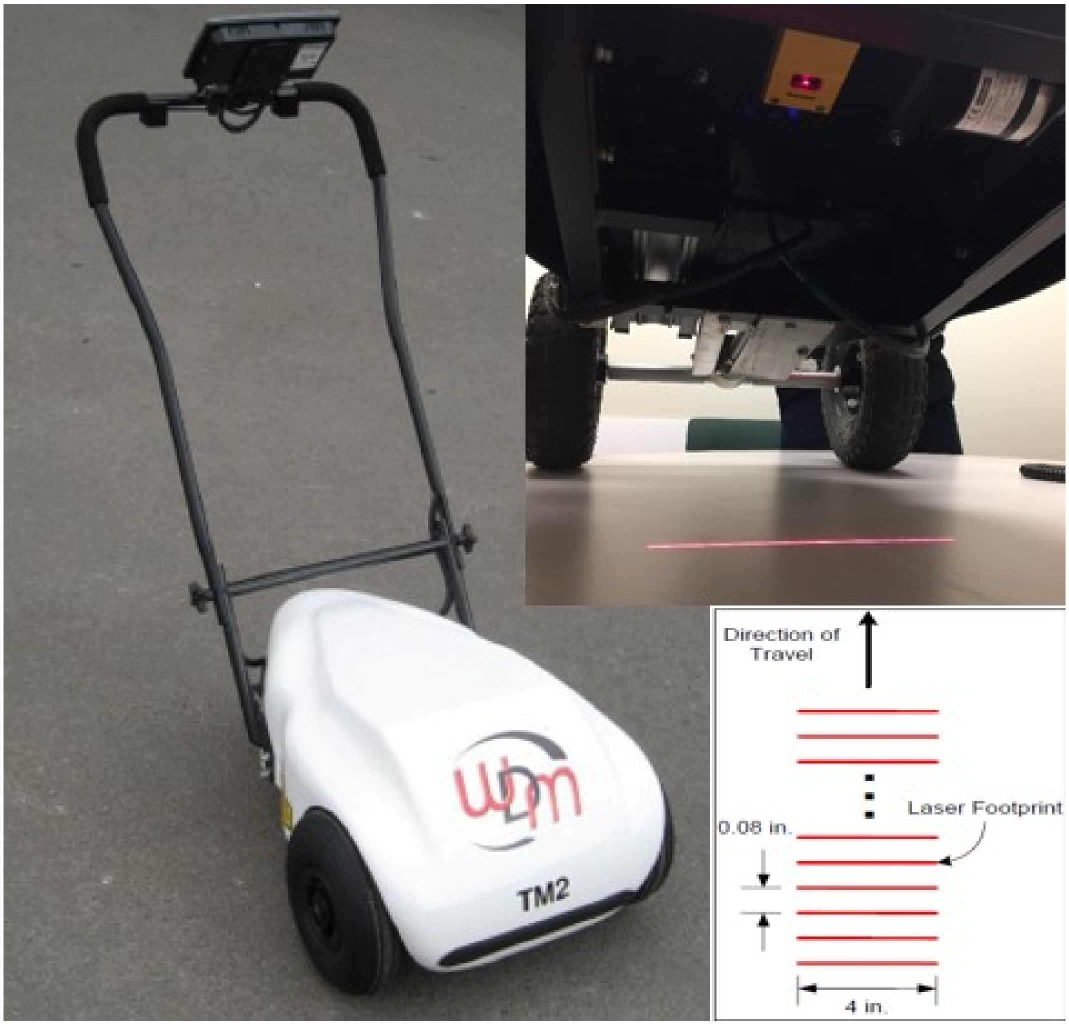


Figure 3-10. Texture meter 2 (TM2) [26].

### *Texture Reference Plate*

When determining pavement's macrotexture, the true MPD value is unknown. As a result, accuracy testing with high-speed measurement devices on pavement has shown to be difficult. Therefore, the UNF research team designed and developed a texture reference plate with known dimensions and geometry. The material used for the reference plate is a 6061-aluminum alloy. The dimensions of the plate were constrained to the maximum cutting parameters of a computer numeric control (CNC) Haas Mini-Mill located in the UNF Fabrication Lab. The plate dimensions are 292 millimeters wide, by 406 millimeters long, and a thickness of 12.7 millimeters. These dimensions account for the measurement radius of the CTM, which was used as a reference device. The texture of the plate replicates longitudinal diamond ground concrete with slot depths of 1.5 millimeters. After machining, the plate was coated with flat-finish gray primer to replicate the reflectivity properties of pavement. Figure 3-11 shows the completed texture reference plate, and Figure 3-12 shows a diagram of the plate's geometry.


Figure 3-11. UNF research team texture reference plate.

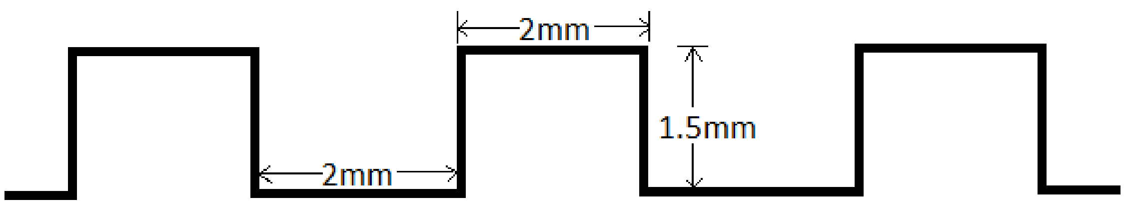



Figure 3-12. Texture reference plate geometry.

The purpose of this texture reference plate was to check the line-laser's measurement accuracy during static and dynamic testing. To verify the uniformity of the reference plate post-machining, a member of the UNF research team took 20 evenly spaced depth measurements along the center of the plate using digital calipers. The resulting average depth of cut for the reference plate was 1.498 millimeters. Since the slots are two millimeters wide with 2-millimeter spacing between slots, the average depth of the reference plate is half this value, or 0.748 millimeters. The measurements were separated into three 100-millimeter profiles and the average MPD of the plate was calculated. Next, the plate was measured using the CTM eight times with five relocations totaling 40 MPD measurements. Table 3-4 shows the results of the plate measurements.

Table 3-4. Texture reference plate MPD values.

| Attribute | Texture Reference Plate | % Difference from Design MPD |
|---|---|---|
| **Design MPD** | 0.750 mm | N/A |
| **Caliper Measured MPD** | 0.753 mm | 0.4% |
| **CTM Measured MPD** | 0.769 mm | 2.5% |

### *Pavement Samples*

For static testing, the FDOT had pavement samples available to the UNF research team for testing purposes. These samples were used for optimizing sensor exposure time based on the absorptivity and reflectivity of various pavement types. They were also used for determining the effect that ambient light has on measurement accuracy. The samples were placed underneath the line-laser with the vehicle parked in the FDOT calibration bay. From there, the returned laser-light intensity and the number of available data points for each sample were analyzed. An image of these pavement samples is shown below in Figure 3-13.


Figure 3-13. FDOT pavement samples.

## TEST APPROACH AND METHODOLOGY

The initial focus of the testing process was to optimize the line-laser configuration settings. As previously stated, this process was conducted in three stages which included static testing, dynamic testing, and precision testing. After optimizing the configuration settings to where the device would output accurate raw height measurements, the UNF research team began analyzing the post-processing program. To begin, optimizing the line-laser configuration settings was conducted as follows:

### *Static Testing*

1) **Sensor Exposure Time:** Sensor exposure time refers to the amount of time the electronic shutter of a sensor remains open to receive reflected laser light [2]. The UNF research team analyzed the effect that exposure time has on various pavement types. For dark objects, longer exposure times are required to receive adequate triangulated laser light from the object's surface, and the opposite is true for light-colored objects. Also, when an exposure time is too long for a certain pavement type, the reflected light intensity will be oversaturated. Since the line-laser determines height measurements by taking the center of mass of reflected light, oversaturated return light distorts the measurement accuracy [35]. Therefore, a range of exposure times that accounts for various pavement types needed to be determined. This included optimizing the current range of 20 to 200 μs based on the absorptivity and reflectivity of the pavement samples. Determining an optimized range of exposure times reduces saturation of returned laser light and provides an optimal number of data points for MPD calculations.
   **Test Procedure:** The testing involved placing a single pavement sample under the line-laser with the test vehicle parked in the FDOT calibration bay. Using the LMI Technologies Gocator Web interface, the UNF research team analyzed the laser-light intensity via an exposure map in "Video Mode" and the corresponding number of available data points collected by the sensor in "Profile Mode." The optimum exposure time for a given pavement type is the value where a maximum number of data points in the profile are captured while minimizing the presence of visible outliers in the interface.

2) **Ambient Light Effect:** According to previous studies, there is a relationship between ambient light intensity, the color of the scanned surface, and laser scanning quality. Ambient light has been shown to cause erroneous data readings on certain 3D laser scanners, such as line-lasers [36]. As stated in an LMI Technologies Gocator training video, at low exposure times (< 400 μs) the laser sensor is "relatively immune" to ambient light [33]. Therefore, the UNF research team conducted an experiment to verify whether ambient light has an effect on MPD calculations.
   **Test Procedure:** Testing was conducted in the FDOT State Materials Office calibration bay. Like the static exposure time test, laser-light intensity and the corresponding data points were analyzed via the Gocator Web interface in both "Video Mode" and "Profile Mode," respectively. The testing included analyzing height measurements on the UNF texture reference plate in direct sunlight and while completely shaded. The raw height measurements were recorded and averaged per 100-millimeter profile and compared between the two configurations. If ambient light influences the measurement quality, the previously established exposure range would be intermittently reduced until the discrepancy is removed.

3) **Reference Measurements:** Historically, the CTM has been a widely accepted reference device for macrotexture measurements. Although the "true" MPD of a roadway is unknown, the FDOT utilizes the CTM to produce accurate MPD values when conducting field assessments. In addition, the ASTM E2157 test method was developed to guide users in operating the device. As a result, the UNF research team utilized the CTM for reference measurements when assessing the accuracy of the update line-laser system. **Test Procedure:** Testing was conducted at a test track provided to the FDOT located the at Williston Municipal Airport. The test track was marked with traffic cones to designate 330-foot sections on both pavement types. Using the CTM, sixteen evenly spaced measurements were taken within each 330-foot section and averaged to find the overall MPD of the test section. The average MPD of the two sections on each pavement type was considered the overall test section average.

4) **X-Resolution:** According to the Gocator user manual, x-resolution refers to the distance between each measurement point along the length of the laser line [31]. This term is also commonly referred to as "point-spacing interval." From previous testing conducted by the UNF research team, the average number of data points in each 100-millimeter profile is 404 given the current configuration. This equates to an x-resolution of approximately 0.24 millimeters. In this configuration, "Uniform Spacing" is disabled. Therefore, the x-resolution is passively produced based on the clearance distance between the laser light on the surface and the sensor. A diagram illustrating x-resolution is shown in Figure 3-14. When the line-laser has "Uniform Spacing" mode enabled, the user can manually select the x-resolution accounting for up to 1,280 data points per profile. Figure 3-15 shows x-resolution while in "Uniform Spacing" mode. A comparison study between the current x-resolution setting and several other configurations was conducted. This comparison study determined how x-resolution affects MPD calculations.
   **Test Procedure:** Testing will be conducted in the FDOT State Materials Office calibration bay. Using the texture reference plate developed by the UNF research team, measurements will be taken under several different x-resolution settings. The first test will be the current configuration with "Uniform Spacing" disabled and 1/2 sub-sampling. Sub-sampling allows the user to reduce the number of data points (e.g., ½ sub-sampling reduces the number of data points by half) and allow for faster processing speeds within the Gocator's CPU. The next test will also have "Uniform Spacing" disabled, but without sub-sampling. Finally, the remainder of the testing will have "Uniform Spacing" enabled and test the following x-resolutions (millimeters): 0.1, 0.25, 0.5, 0.75, and 1.0. The average MPD will be calculated at each resolution setting and will be compared against the design MPD value. From there, the UNF research team will analyze the effect x-resolution has on measurement accuracy and determine the most appropriate setting.

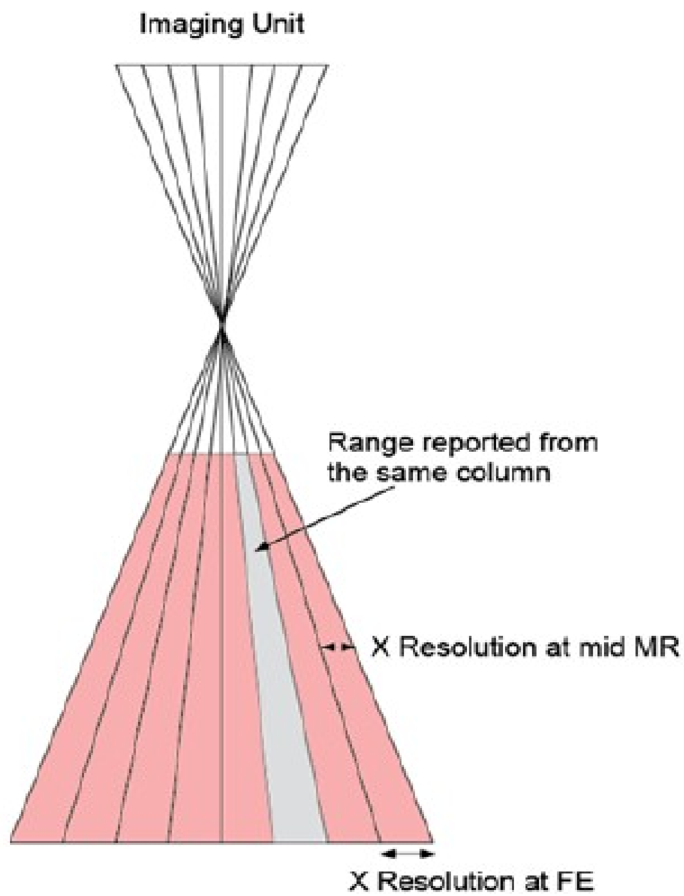



Figure 3-14. X-resolution for the line-laser [31].

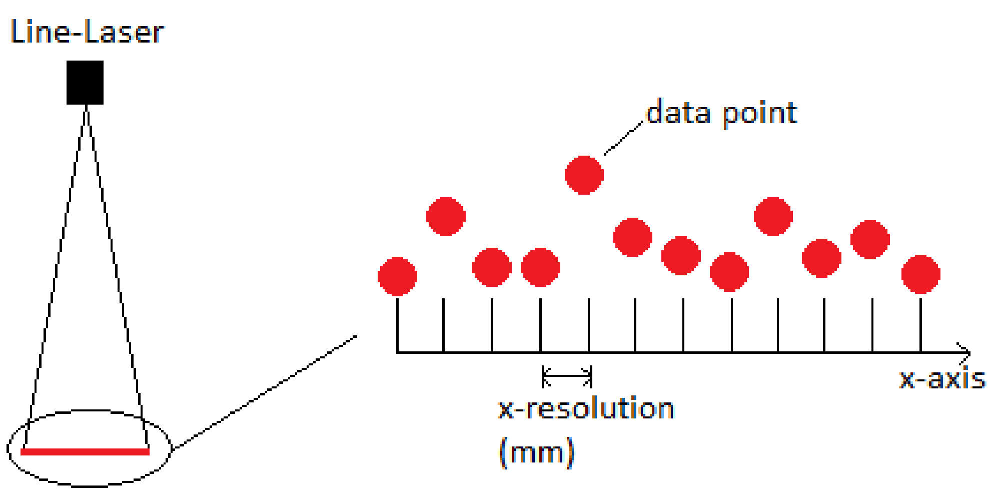



Figure 3-15. Diagram displaying x-resolution in “Uniform Spacing” mode.

*Dynamic Testing*

1) **Sensor Exposure Time:** As previously stated, longer exposure times at highway speeds have shown an "averaging effect" on macrotexture profiles. This effect blurs pavement features when the sensor is moving at high speeds and results in underestimated MPD measurements [36]. The UNF research team analyzed the relationship between exposure time, vehicle speed, and measurement accuracy.
   **Test Procedure:** Testing was conducted at the Williston Municipal Airport test track. The testing included acquiring measurements with the line-laser at several constant highway speeds and various exposure times. The MPD for each exposure setting will be calculated and recorded. There will be three separate exposure settings to be tested: dynamic range, multiple fixed exposures, and single exposure. The dynamic range and multiple fixed exposure times to be tested were determined in static exposure testing. The dynamic range consisted of the lower and upper limits of the exposure times determined using the FDOT pavement samples. The multiple fixed exposure times will consist of the optimal exposure time for open-grade friction course (OGFC), dense-grade friction course (DGFC), and concrete also determined in static testing. The single exposure portion of testing consisted of one exposure time (160 µs) to analyze the "averaging" effect at various test speeds. The optimal exposure setting was determined based on the system's ability to calculate MPD values closest to those from reference devices.

2) **Sampling Rate:** According to ASTM E1845, a minimum requirement of 10 evenly spaced profiles per 100 meters (330-foot) of test section shall be used when determining pavement MPD [4]. This requirement is easily achievable given a vehicle speed of 60 mph with a sampling rate of 3 Hz will capture at least 11 profiles per 100 meters (330-foot). However, given various periodic road characteristics such as tining or grooving, higher sampling rates are required to account for these characteristics in the texture profile. Also, since MPD values are calculated by taking the average of every MSD in the test section, the UNF research team analyzed the effect that the number of scan profiles per test section has on MPD [35].
   **Test Procedure:** Testing was conducted at the Williston Municipal Airport test track. The test track was marked with traffic cones to designate 330-foot sections on both pavement types. Data previously collected with the CTM was used as a reference for accuracy. Beginning with the current sampling rate of 20 Hz, the test vehicle collected texture data at a constant speed of 40 mph within the two 330-foot test sections. The sampling rate was increased and tested up until the maximum possible value. Considering the processing power of the line-laser system, 1,440 Hz was the maximum sampling rate when utilizing the maximum z-resolution, or height precision. With this information, the UNF research team analyzed the effect sampling rate has on MPD calculations.

3) **Precision:** Testing was conducted to check the measurement repeatability of the updated line-laser system. The measurement repeatability refers to the system's ability to produce the same MPD results on a certain test section given multiple test runs. Assuming the test parameters remained constant for each test run, the UNF research team calculated any standard deviation ($\sigma_{SD}$) from the mean ($\bar{x}$) MPD value to calculate the coefficient of variation, $COV$. The equation for COV is shown below in Equation 3-1 and is expressed as a percentage [22].

$$COV = \sigma_{SD}/\bar{x} \text{ (Equation 3-1)}$$

**Test Procedure:** Testing was conducted at the Williston Municipal Airport test track and a designated test section located on SR 9B. The beginning and end points at each test section were marked with reflective tape, and evenly spaced reference measurements were taken with each device. The OGFC and DGFC sections were 1,000 feet long and tested at constant speeds (40, 50, and 60 mph) to determine the measurement repeatability in intervals of 50, 100, 200, and 250 ft. The LGD concrete site at SR 9B was 2,500 feet long and contained five evenly spaced 500-foot subsections. Using the updated line-laser system, three high-speed runs were conducted at each test site.

### DATA PROCESSING AND PROGRAM ANALYSIS

After data collection was completed, the data was processed using a program developed by ICC. Comparisons were made between manually calculated MPD values from raw height data and those produced by ICC's post-processing program. If the post-processing program caused MPD values to diverge from reference values produced by the CTM, the UNF research team were to perform further analysis of the program in communication with ICC. If the program causes the MPD measurements to converge towards the reference MPD values, the UNF research team would then determine if any area of the program should be optimized.

In the event of an issue within the post-processing program was discovered, the UNF research team would conduct further analysis of the program as follows:

1) The Team would focus on the robustness of the algorithm regarding its ability to handle very large datasets.
2) Comparisons would be made between MPD calculations using raw height measurements and those with a lowpass filter applied per ASTM E1845 specifications [4].
3) The outlier removal and replacement method would also be analyzed. It was proposed by ICC to input synthetic outliers into datasets to determine the processing algorithm's ability to identify and remove said outliers.
4) Testing would also determine the program's ability to ignore "false" outliers as well. False outliers are true values that are incorrectly identified as outliers and removed.
5) Analysis of alternative outlier replacement methods (i.e., False Discovery Rate) would be considered and tested.

### Test Plan Schedule and Gantt Chart

The test plan schedule for optimizing the line-laser system is shown below in Table 3-5. Additionally, a Gantt Chart is shown in Figure 3-16 to illustrate the testing timeline.

Table 3-5. Test plan schedule.

| Test Type | Test Parameter | Start Date | End Date | Total Days |
|---|---|---|---|---|
| Static | Sensor Exposure Time & Ambient Light Effect | 10/01/19 | 10/07/19 | 6 |
| Static | Reference Data | 10/07/19 | 10/14/19 | 7 |
| Static | X-Resolution | 10/14/19 | 10/28/19 | 14 |
| Dynamic | Sensor Exposure Time | 10/21/19 | 11/04/19 | 14 |
| Dynamic | Sampling Rate | 10/28/19 | 11/11/19 | 14 |
| Dynamic | Ambient Light Effect | 11/04/19 | 11/18/19 | 14 |
| N/A | Data Processing & Program Analysis | 11/11/19 | 12/02/19 | 21 |
| Dynamic | Accuracy and Repeatability | 11/18/19 | 12/09/19 | 21 |

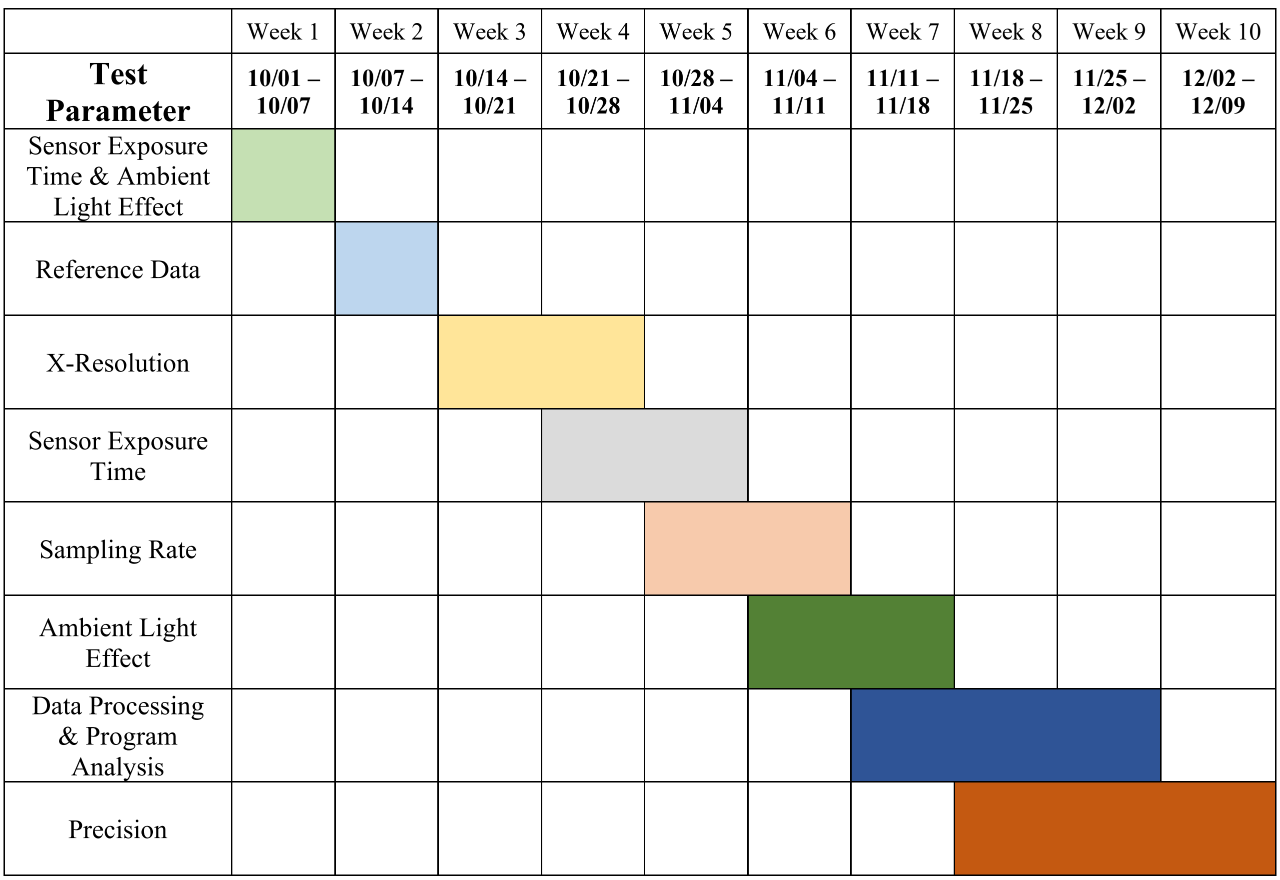



Figure 3-16. Test plan Gantt Chart.

# CHAPTER 4 – OPTIMIZING THE LINE-LASER PARAMETERS

## STATIC TESTING

Static testing was conducted at the FDOT State Materials Office. The testing included optimizing the sensor exposure time, analyzing the effect ambient light has on measurements, comparing various x-resolutions (point spacing interval), and analyzing static measurement repeatability. These parameters were tested using the vehicle-mounted LMI Technologies Gocator-2342-3B-12 line-laser in the State Materials Office commercial vehicle lot. The line-laser was mounted along the driver's side wheel path at a 45-degree angle relative to the transverse axis of the vehicle. The vehicle used for testing was an FDOT Friction Evaluation Unit (Ford F-350) also identified as Unit 10. Figure 4-1 shows the test vehicle.

Figure 4-1. Test vehicle (Unit 10).

### *Texture Reference Plate Measurements*

To begin, measurements of the texture reference plate developed by the UNF research team were taken using various devices. To analyze device measurement accuracy, the texture reference plate was created to establish a "ground-truth" texture MPD. The texture design of the plate replicates longitudinal diamond ground concrete with 2-millimeter-wide slots, slot depths of 1.5 millimeters, and 2-millimeter spacing between slots. The initial measurements shown below in Table 4-1 were taken with reference devices as well as the Gocator line-laser under its original configuration.

Table 4-1. Initial texture reference plate measurements.

| Device | MPD (mm) | % Error from Design |
|---|---|---|
| Design | 0.75 | N/A |
| Circular Texture Meter (CTM) | 0.77 | 2.5% |
| Fast Texture Meter (FTM) | 0.89 | 18.3% |
| FTM – CTM Equivalent | 0.79 | 5.3% |
| Gocator Line-Laser Raw (Unprocessed) | 0.82 | 9.3% |
| Gocator Line-Laser Processed (MDR Pro) | 0.87 | 16.1% |

As shown above, the design MPD of the texture reference plate is 0.75 millimeters. The device that produced an MPD value closest to that of the design was the CTM with 2.5% error. Based on the results of this test, the CTM MPD value was used as an acceptable reference value in subsequent testing. Also seen in the table above, the MPD values produced by the line-laser, both from raw measurements and post-processed through ICC software, were overestimated by 9.3% and 16.1%, respectively. As a result, the UNF research team began investigating the current configuration settings of the line-laser and the ICC processing algorithm. Figure 4-2 shows the line-laser on the texture reference plate during static measurements.

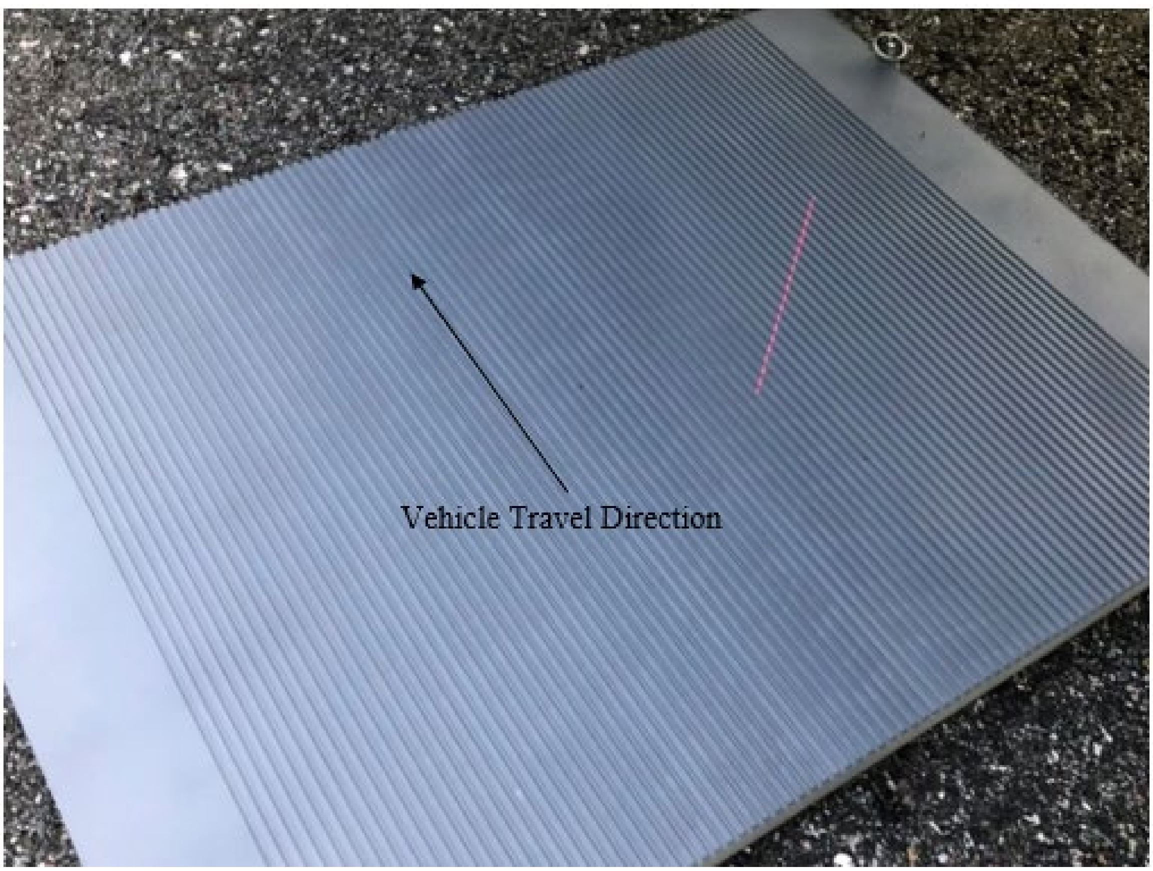



Figure 4-2. UNF texture reference plate.

### *Sensor Exposure Time*

The ideal sensor exposure time varies based on the pavement type being analyzed. More specifically, the exposure time required to receive a desirable amount of reflected laser light depends on the reflectivity properties of the pavement. For example, dark-colored surfaces require longer exposure times to receive reflected laser light compared to light-colored surfaces. However, if the exposure time is too long (overexposed), the reflected light will be oversaturated. Since height measurements from the line-laser are produced by data points along the center of mass of reflected light on a surface, an oversaturated profile causes overestimated height measurements and unwanted noise in the dataset. If the sensor is underexposed for the selected pavement type, the electronic shutter of the sensor will not remain open long enough to capture reflected light which causes dropout points in the dataset. Figure 4-3 shows images from the Gocator Web interface for the line-laser when an exposure time is too long (overexposed). Figure 4-4 shows images of the interface if the exposure time is optimized for a specified pavement type. The images on the left are from the previously mentioned "Video Mode" and the images on the right are from the "Profile Mode."

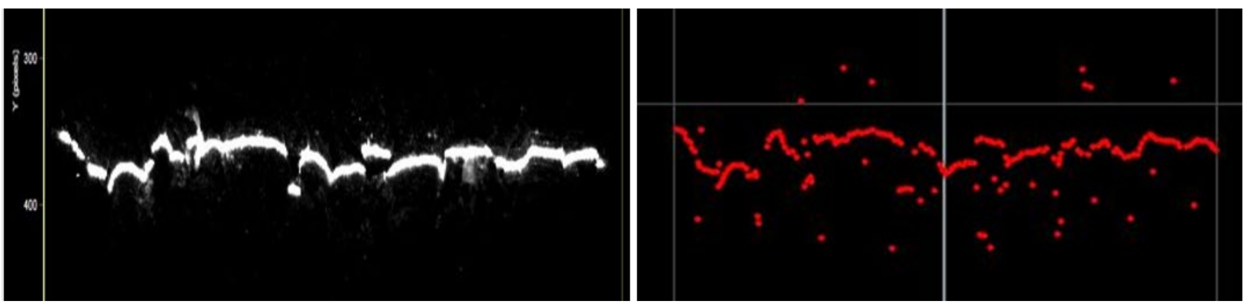



Figure 4-3. Light intensity map (left). Data points captured by the sensor (right) – 200 μs.

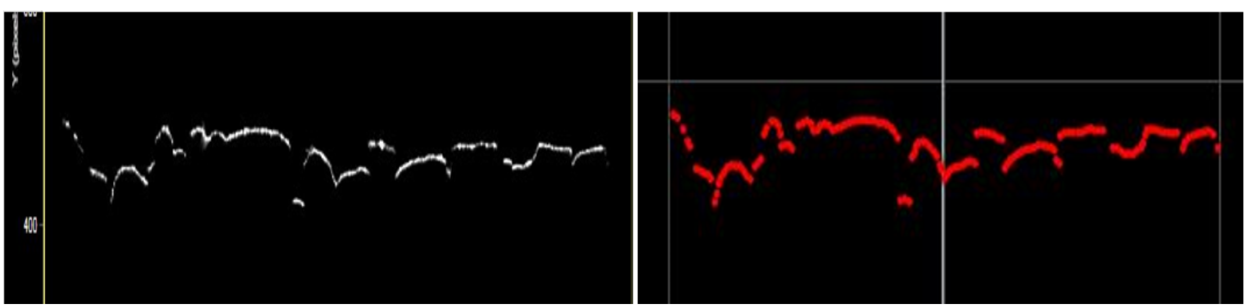



Figure 4-4. Light intensity map (left). Data points captured by the sensor (right) – 65 μs.

Using various pavement samples provided by the FDOT, optimizing the sensor exposure time was conducted with samples both in direct sunlight and while shaded from the sun via a canopy tent. The pavement samples used in the experiment contained two open-grade friction course (OGFC) samples, two dense-grade friction course (DGFC) samples, and one concrete sample. Images of these samples taken during the exposure test are shown below in Figure 4-5. To begin, an initial exposure time was determined using the "Auto-Select" feature within the Gocator Web interface while the pavement sample was in direct sunlight. The "Auto-Select" feature determines the best-fit exposure time based on unknown factors within the system's internal programming. From there, the exposure time was manually adjusted in increments of five microseconds while viewing the light intensity map in "Video Mode" and the availability of data points in “Scan Mode.” Once oversaturation was removed, the optimal exposure time was recorded, and the process was repeated with the pavement sample completely shaded. In every case, the optimized exposure time was the same for the sample in direct sunlight and while shaded. Table 4-2 shows the results of the static exposure optimization testing.

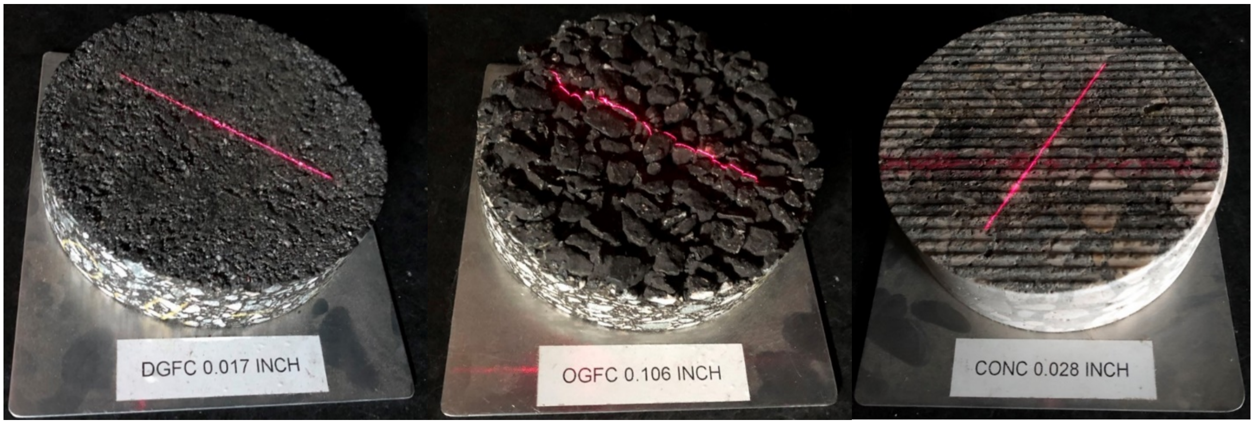



Figure 4-5. Pavement samples used in the static exposure time optimization experiment.

Table 4-2. Sensor exposure time test results.

| Pavement Sample | Direct Sunlight - Ideal Exposure Time (μs) | No Sunlight - Ideal Exposure Time (μs) |
|---|---|---|
| **DGFC #1 (0.017” MPD)** | 40 | 40 |
| **DGFC #2 (0.033” MPD)** | 40 | 40 |
| **OGFC #1 (0.065” MPD)** | 70 | 70 |
| **OGFC #2 (0.106” MPD)** | 60 | 60 |
| **Concrete (0.028” MPD)** | 25 | 25 |

In the original configuration of the line-laser, the exposure time was set as a dynamic range from 20 to 200 microseconds. Based on the results shown above, the upper limit of the dynamic range would allow the sensor to reach an overexposed state. This overexposed state creates a greater potential to capture outliers and unwanted noise. Another issue with the upper limit of the dynamic range being too high is that, at high speeds, it can create an “averaging effect” on profiles and result in underestimated MPD values, but this topic will be discussed in further detail in the “Dynamic Testing” section. It is recognized by the UNF research team that conclusions derived from this experiment are based on the reflectivity properties of the test samples. To compensate, the ideal dynamic range was determined to be 20 microseconds to 80 microseconds to account for roadways that are outside the scope this testing.

### *Ambient Light Effect*

Resembling the sensor exposure time testing, the ambient light effect testing included collecting data on the previously used pavement samples in both direct sunlight and while completely shaded. Using the previously determined ideal exposure time for each sample, one pavement sample would be placed under the line-laser and approximately 60 measurement scans would be taken. Next, the average height for each 100-millimeter scan would be determined, and the overall average height for the test sample was calculated. Without moving the pavement sample, the canopy tent would be placed near the test vehicle to completely shade the sample from sunlight. From there, the average height of the sample would be determined, and the sunlight versus no sunlight values were compared. The process was then repeated for each pavement sample. The results of this test are shown below in Table 4-3.

Table 4-3. Ambient light effect test results.

| Pavement Sample | Avg. Height Sun (mm) | Avg. Height No Sun (mm) | Test Exposure Time (µs) | Difference (mm) |
|---|---|---|---|---|
| **DGFC #1 (0.017" MPD)** | -0.349 | -0.474 | 40 | 0.125 |
| **DGFC #2 (0.033" MPD)** | -0.648 | -0.638 | 40 | 0.010 |
| **OGFC #1 (0.065" MPD)** | 0.604 | 0.558 | 70 | 0.046 |
| **OGFC #2 (0.106" MPD)** | 0.229 | 0.240 | 60 | 0.011 |
| **Concrete (0.028" MPD)** | -0.721 | -0.738 | 25 | 0.017 |

For most of the test samples, ambient light had little effect on the measurement quality of the line-laser. However, on DGFC #1, the difference in average height between the sunlight versus no sunlight configurations was 0.125 millimeters. Since the measurements shown above were raw, unfiltered measurements, the discrepancy may be attributed to high frequency components such as noise and transients within the data. Also, pavements with low MPD values, like the DGFC #1 sample in this test, have texture wavelengths that are shorter than those with high MPD values. Because of this, the laser-based system taking measurements must be very precise. Since these measurements were taken with the unoptimized system, this discrepancy could exist as a result of the one-half sub-sampling in the z-direction, which reduces measurement precision by half and allows for a larger influence of noise at short wavelengths. This test was completed in the early stages of the project, and it has since then been determined that ambient light did not have an effect on MPD calculations.

### *X-Resolution (Point Spacing Interval)*

To establish a coordinate system for the line-laser, the x-axis is along the width of the projected laser line, the z-axis is normal to the pavement and contains height measurements, and the y-axis is in the vehicle's travel direction. The line-laser has two primary configurations regarding x-resolution, the first being "Non-Uniform Spacing" and the second being "Uniform Spacing". Non-uniform spacing passively establishes an x-resolution based on the clearance distance between the line-laser and the surface. Within the non-uniform spacing setting, there are options for "No Sub-Sampling", "1/2 Sub-Sampling", and "1/4 Sub-Sampling". Given that every camera column contains a single data point (height measurement), sub-sampling refers to the fraction of camera columns to be recorded and stored in the profile. For example, under the "1/2

Sub-Sampling" configuration, every second data point will be used in the measurement profile. Uniform spacing allows the user to select an x-resolution by specifying the desired point-spacing in millimeters, and the system produces a profile using evenly spaced data points based on that input value [32]. For example, given a profile width of 100 millimeters, an x-resolution of 0.5 millimeters will produce 200 evenly spaced data points. An example of how x-resolution is established in non-uniform spacing mode is shown in Figure 4-6 and an example of x-resolution in uniform-spacing mode is shown in Figure 4-7.

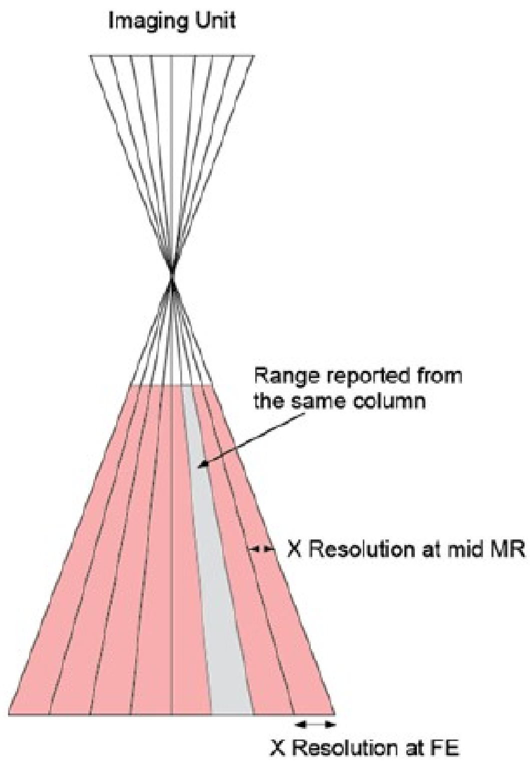



Figure 4-6. X-resolution with "Non-Uniform Spacing" enabled [32].

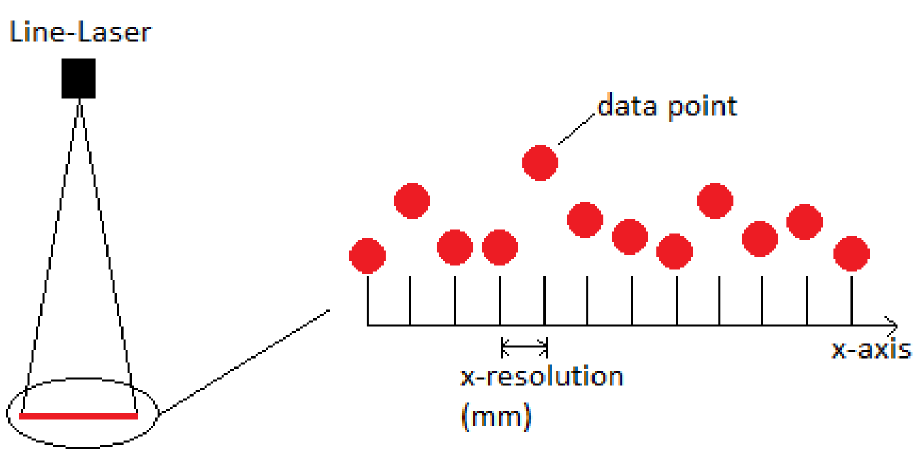



Figure 4-7. X-resolution with "Uniform Spacing" enabled.

Using the texture reference plate as a test surface, several x-resolutions were compared using both “Uniform Spacing” and “Non-Uniform Spacing” configurations. The original resolution settings for the line-laser system had non-uniform spacing enabled with ½ sub-sampling in both the x- and z-directions. For this test, the raw height measurements were used to calculate the MPD at each resolution setting. The unprocessed results of the static resolution testing are shown below in Table 4-4. As previously mentioned, the design MPD for the texture reference plate was 0.75 millimeters and the CTM MPD was 0.77 millimeters.

Table 4-4. Static resolution test results.

| **Setting** | **Resolution (mm)** | **Number of Data Points** | **Reference Plate Raw MPD (mm)** | **% Difference from Design** |
|---|---|---|---|---|
| Uniform Spacing Disabled | ½ Sub-Sampling X & Z (Initial Setting) | 404 | 0.819 | 8.4% |
| | ½ Sub-Sampling X & No Sub-Sampling Z | 404 | 0.783 | 4.4% |
| | ¼ Sub-Sampling X & No Sub-Sampling Z | 203 | 0.775 | 3.2% |
| | No Sub-Sampling in X or Z directions (Max Resolution) | 808 | 0.790 | 5.1% |
| Uniform Spacing Enabled | 1.0 | 101 | 0.752 | 0.3% |
| | 0.75 | 134 | 0.767 | 2.2% |
| | 0.5 | 201 | 0.775 | 3.2% |
| | 0.25 | 402 | 0.788 | 4.8% |
| | 0.1 | 1,004 | 0.795 | 5.7% |

Comparing the initial resolution setting to those from testing, ½ sub-sampling in the z-direction negatively affected measurements and produced an MPD furthest from the design value. Sub-sampling in the z-direction reduces the accuracy of height measurements by utilizing only a fraction of the available data columns in the z-direction and, therefore, decreasing the number of potential height values. An initial observation would reveal that the 1-millimeter spacing produced an MPD value closest to the design MPD. However, ASTM E1845 states that the maximum sampling interval between measurement points should not exceed one millimeter [4]. Due to the inherent nature of laser-based measurement devices having dropout points and outliers, the valid point count in each 100-millimeter profile (maximum of 101 points at 1-millimeter spacing) would be less than 100 and exceed the 1-millimeter resolution requirement. This issue also applies to the 0.75-millimeter uniform spacing with a maximum point count of 134. Another observation is the relationship between MPD and the maximum number of data points being similar in both non-uniform spacing and uniform spacing configurations. Since the ICC post-processing program resamples each profile to 0.1-millimeter spacing, the UNF research team decided to utilize this program feature and further observe the non-uniform spacing configurations (½, ¼, and no sub-sampling in the x-direction) in dynamic testing.

- System Update: Z-resolution updated from “½ Sub-Sampling” to “No Sub Sampling”.

### DYNAMIC TESTING

Building upon the results determined in static testing, dynamic testing was conducted at the Williston Airport Test Track. The test track is a one-lane road approximately 3,800 feet in length consisting of half OGFC and half DGFC. For dynamic testing, the UNF research team collected data using a software utility developed by ICC. The data collection had to be done with ICC software to utilize the ICC data processing program. The processing program handles several processes such as outlier removal, lowpass filtering, slope suppression, and MPD calculations. Two ICC programs were used for comparison during testing. The primary difference between the two programs was the method of lowpass filtering. The original processing program, which will be referred to as Program 1, contained a Butterworth bi-quadratic lowpass filter. The recently developed processing program, which will be referred to as Program 2, contained a Savitzky-Golay convolution lowpass filter. Lowpass filtering is a process required by the ASTM E1845 to remove high-frequency components within the texture profile such as the influence of noise and transients [4].

#### *Williston Airport Reference Measurements*

To begin, a 330-foot test section was marked with traffic cones on both the OGFC and DGFC portions of the test track. Within each of these 330-foot test sections, 16 evenly spaced reference measurements were taken with the CTM. The CTM measurements were taken along the driver-side wheel path. The results from reference measurements are shown below in Table 4-5. Figure 4-8 illustrates the CTM locations at the Williston Airport Test Track.

Table 4-5. Williston Airport Test Track CTM reference data.

| | **DGFC – 100m Test Section** | **OGFC – 100m Test Section** |
|---|---|---|
| **Location Number** | **Average MPD (mm)** | |
| **#1** | 0.44 | 1.66 |
| **#2** | 0.39 | 1.62 |
| **#3** | 0.45 | 1.94 |
| **#4** | 0.43 | 2.17 |
| **#5** | 0.50 | 1.83 |
| **#6** | 0.51 | 1.75 |
| **#7** | 0.47 | 1.72 |
| **#8** | 0.55 | 2.07 |
| **#9** | 0.40 | 1.92 |
| **#10** | 0.48 | 1.78 |
| **#11** | 0.37 | 1.83 |
| **#12** | 0.46 | 1.77 |
| **#13** | 0.44 | 2.06 |
| **#14** | 0.44 | 1.92 |
| **#15** | 0.42 | 1.68 |
| **#16** | 0.41 | 1.57 |
| **Overall MPD Avg.** | **0.448** | **1.831** |

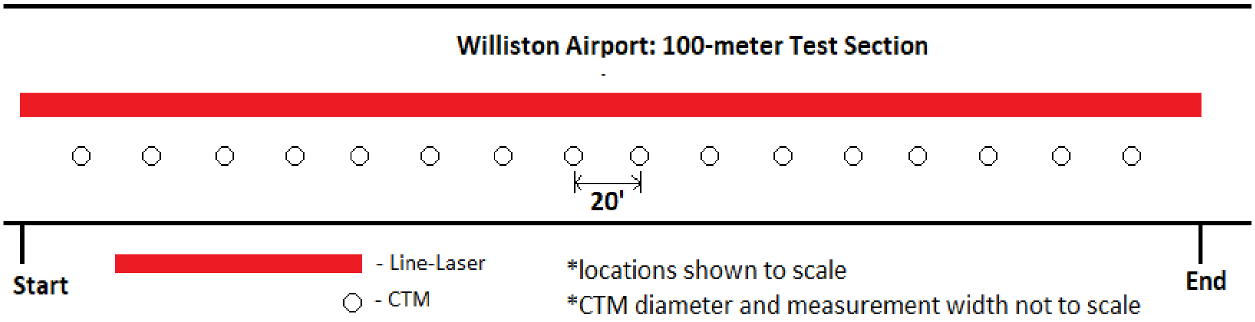



Figure 4-8. Williston Airport test section measurement locations.

When determining the MPD of a roadway, section 6.1.2 of ASTM E1845 states that it is sufficient to obtain 16 evenly spaced measurement locations regardless of the test section length [4]. Given this information, the UNF research team utilized the overall MPD average for each test section to use for comparison with the line-laser measurements. Figure 4-9 shows an image of the CTM at the Williston test track.


Figure 4-9. CTM measurement at Williston Airport.

***Sensor Exposure Time***

Further testing of the sensor exposure time was conducted in dynamic testing. This was done to analyze the "averaging effect" caused by elongated measurements at highway speeds as shown in Figure 4-10. These elongated measurements are dependent on the amount of time the sensor's electronic shutter remains open to receive reflected light (exposure time). For example, at a speed of 40 mph with an exposure time of 50 microseconds, the return spot-width of each data point will be elongated by 0.894 millimeters of travel during each scan. Therefore, the dynamic exposure time testing was used to analyze this effect and how it applies to MPD.

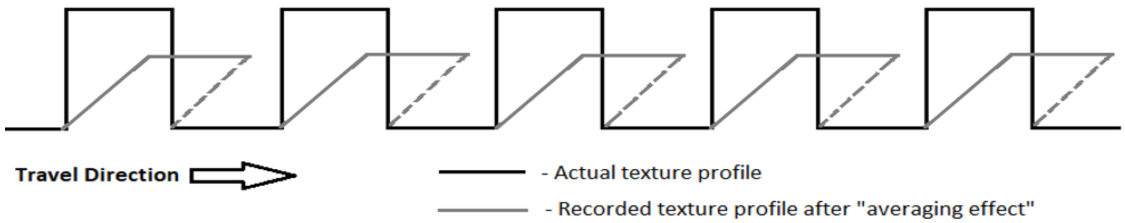



Figure 4-10. Averaging effect produced in dynamic testing.

The testing was conducted on the 330-foot OGFC and DGFC test sections at the Williston Airport Test Track. Three exposure time configurations were tested at 20, 40, and 60 mph. The first configuration consisted of the dynamic range setting previously established in static testing (20 to 80 µs). Using the dynamic range feature, the line-laser system finds the most suitable exposure time within a specified range based on the reflectivity properties of a surface. The second configuration was the multiple exposure setting. When multiple exposures are enabled, the user can specify up to five fixed exposure times and allow the system to determine which exposure is most suitable for the surface being analyzed. For this configuration, one exposure time was set for the three different pavement types. The exposure times were 20 µs for LGD concrete, 50 µs for DGFC, and 80 µs for OGFC. This was done to see if the system would apply the correct exposure time corresponding to the DGFC and OGFC pavements. The third configuration was a fixed single exposure. To enhance and observe the "averaging effect," the single exposure was set to 160 µs. Table 4-6 shown below contains the results of the dynamic exposure testing.

Table 4-6. Dynamic sensor exposure time test results with ¼ sub-sampling.

| Exposure Time | Speed | DGFC MPD (mm) | OGFC MPD (mm) |
|---|---|---|---|
| **Dynamic Range (20 - 80 µs)** | **20 MPH** | 0.445 | 1.849 |
| | **40 MPH** | 0.426 | 1.717 |
| | **60 MPH** | 0.418 | 1.761 |
| **Multiple (20; 50; 80 µs)** | **20 MPH** | 0.417 | 1.635 |
| | **40 MPH** | 0.391 | 1.603 |
| | **60 MPH** | 0.383 | 1.684 |
| **Single (Long: 160 µs)** | **20 MPH** | 0.443 | 1.735 |
| | **40 MPH** | 0.378 | 1.608 |
| | **60 MPH** | 0.361 | 1.556 |
| **CTM Reference MPD (mm)** | | **0.448** | **1.831** |

For the test results shown above, the sampling rate was kept at the original setting of 20 Hz and the x-resolution was set to ¼ sub-sampling. The data was processed using Program 1 containing the Butterworth lowpass filter. Looking at the results of the single exposure setting, a decreasing trend in MPD is shown relative to increasing speed on both pavement types. This confirms the relationship between vehicle speed, exposure time, and measurement accuracy. To overcome this relationship, the UNF research team decided to utilize the ½ and no sub-sampling configurations for subsequent testing in place of the ¼ sub-sampling. This was done based on the MPD values produced during static testing under these configurations being inherently higher. Since the results of the "dynamic range" configuration were closer to the accepted CTM MPD values when compared to the "multiple" configuration, subsequent testing was conducted using the dynamic exposure range of 20 to 80 microseconds.

- System Update: The optimal exposure setting was determined to be a range of 20 – 80 μs.

***Sampling Rate***

The sampling rate for the line-laser system refers to the number of scanned profiles collected each second. The original configuration contained a 20 Hz sampling rate which, at 60 mph, equates to one profile collected every 4.4 feet of travel. Since CTM reference measurements were taken every 20 feet in each test section, and the measurement diameter of the CTM is 11.2 inches, the initial sampling rate to be analyzed was 100 Hz [11]. This equates to one profile captured every 0.88 feet of travel at 60 mph, and it was done to ensure at least one measurement profile would be captured within the vicinity of each CTM measurement on the test track. Considering that MPD calculations are based on the average of all MSD values in a test section, higher sampling rates would theoretically provide a more accurate representation of the actual MPD. However, too high of a sampling rate can induce signal noise and distort measurement accuracy [35]. Also, high sampling rates produce large data files which are limited to the memory capacity of the on-board computer. These factors were all considered in the development of the sampling rate test procedure. As previously stated, the sampling rate testing also served as a comparison study between no sub-sampling and ½ sub-sampling x-resolution settings. The ½ sub-sampling results are shown below in Table 4-7.

Table 4-7. Sampling rate test results with ½ sub-sampling and processed with Program 1.

| Sampling Rate | Speed | DGFC MPD (mm) | DGFC - % Error from CTM | OGFC MPD (mm) | OGFC - % Error from CTM |
|---|---|---|---|---|---|
| 100 Hz | 20 MPH | 0.452 | 0.9% | 1.822 | -0.5% |
| | 40 MPH | 0.440 | -1.8% | 1.884 | 2.9% |
| | 60 MPH | 0.440 | -1.8% | 1.836 | 0.3% |
| 200 Hz | 20 MPH | 0.444 | -0.9% | 1.760 | -3.9% |
| | 40 MPH | 0.439 | -2.0% | 1.890 | 3.2% |
| | 60 MPH | 0.436 | -2.7% | 1.756 | -4.1% |
| 1,410 Hz (Max) | 20 MPH | 0.458 | 2.2% | 1.787 | -2.4% |
| | 40 MPH | 0.442 | -1.3% | 1.751 | -4.4% |
| | 60 MPH | 0.435 | -2.9% | 1.730 | -5.5% |
| **CTM Reference MPD** | | **0.448** | **-** | **1.831** | **-** |

Under the ½ sub-sampling configuration, Table 4-7 shows relatively consistent MPD values regardless of the given sampling rate. The standard deviations between all MPD values in each test section were 0.007 millimeters for DGFC and 0.055 millimeters for OGFC. Also, given the current resolution setting and sampling rates above, the measurement deviation due to increasing speed (as seen ¼ sub-sampling dynamic exposure testing) was greatly alleviated. Additionally, using the ½ sub-sampling configuration, the system had strong agreement with the reference MPD values produced by the CTM. The greatest differences in MPD between the line-laser and CTM were 2.9% on DGFC and 5.5% on OGFC indicating that the line-laser is producing accurate results. The results with no sub-sampling are shown below in Table 4-8.

Table 4-8. Sampling rate test results with no sub-sampling and processed with Program 1.

| Sampling Rate | Speed | DGFC Processed MPD (mm) | DGFC - % Error from CTM | OGFC Processed MPD (mm) | OGFC - % Error from CTM |
|---|---|---|---|---|---|
| **100 Hz** | **20 MPH** | 0.547 | 22.1% | 1.861 | 1.6% |
| | **40 MPH** | 0.517 | 15.4% | 1.833 | 0.1% |
| | **60 MPH** | 0.545 | 21.7% | 1.738 | -5.1% |
| **200 Hz** | **20 MPH** | 0.514 | 14.7% | 1.900 | 3.8% |
| | **40 MPH** | 0.531 | 18.5% | 1.860 | 1.6% |
| | **60 MPH** | 0.500 | 11.6% | 1.768 | -3.4% |
| **1,410 Hz (Max)** | **20 MPH** | 0.566 | 26.3% | 1.866 | 1.9% |
| | **40 MPH** | 0.518 | 15.6% | 1.876 | 2.5% |
| | **60 MPH** | 0.503 | 12.3% | 1.805 | -1.4% |
| **CTM Reference MPD** | | **0.448** | **-** | **1.831** | **-** |

Based on the results in Table 4-7 and 4-8, there is no indication that MPD significantly varies between the initial and tested sampling rates (20 to 1,410 Hz). Since macrotexture has shown to be generally uniform along the length of a roadway, increasing the number of measurement profiles past 20 Hz does not have a significant effect on MPD calculations. Therefore, at the request of the project manager, the sampling rate would remain at 20 Hz to minimize the macrotexture file sizes. Additionally, Table 4-8 shows that the percent error values relative to reference measurements on DGFC are larger compared to those in the ½ sub-sampling configuration (similar error on OGFC). Also, the MPD values shown in Table 4-8 are nearly all overestimated and show larger variation with speed on DGFC compared to those in Table 4-7. The overall standard deviations between MPD values in each test section were 0.021 millimeters for DGFC and 0.051 millimeters for OGFC. One can speculate based on the standard deviations that the no sub-sampling option potentially produces less repeatable results on DGFC when compared to ½ sub-sampling shown in Table 4-7.

- System Update: Sampling rate and x-resolution unchanged (20 Hz and ½ sub-sampling).

Based on the results above, the configuration settings to be implemented are as follows:

- Exposure: Dynamic Range (20 µs – 80 µs)
- X-Resolution: Non-Uniform Spacing with ½ Sub-Sampling
- Z-Resolution: No Sub-Sampling
- Sampling Rate: 20 Hz

### PRECISION TESTING

Precision testing was conducted at the Williston Airport test track and at SR 9B in Jacksonville, Florida to assess the repeatability of the line-laser system. A 1,000-foot test section was designated on both the OGFC and DGFC portions of the Williston test track. At SR 9B, the LGD concrete test site consisted of five consecutive 500-foot sections. In addition to precision, this testing allowed the UNF research team to assess the accuracy of the line-laser on concrete. All high-speed data collection was completed using the optimized system parameters as determined in previous testing. The repeatability of the system was evaluated by calculating the COV (Equation 3-1) between three runs.

For the OGFC and DGFC test sections, various levels of precision were determined by comparing MPD values in 50-ft, 100-ft, 200-ft, and 250-ft intervals at several test speeds. However, since the concrete section was located on an active roadway, testing was conducted at 60 mph and the collection procedure only allowed for comparisons in roughly 250-foot intervals. The results of the precision testing are shown below in Tables 4-9 and 4-10. Graphs illustrating these results on each pavement type at 60 mph are shown in Figures 4-11 to 4-19.

Table 4-9. Line-laser COV on OGFC and DGFC at the Williston test track.

| | **50 FT** | | **100 FT** | | **200 FT** | | **250 FT** | |
|---|---|---|---|---|---|---|---|---|
| | **OGFC** | **DGFC** | **OGFC** | **OGFC** | **DGFC** | **OGFC** | **OGFC** | **DGFC** |
| **40 mph** | 7.1% | 6.1% | 4.7% | 7.1% | 6.1% | 4.7% | 2.9% | 2.0% |
| **50 mph** | 7.9% | 5.7% | 5.0% | 7.9% | 5.7% | 5.0% | 3.0% | 2.3% |
| **60 mph** | 5.7% | 5.9% | 4.0% | 5.7% | 5.9% | 4.0% | 2.2% | 2.2% |

Table 4-10. Line-laser COV and MPD comparison on LGD concrete at SR-9B (60 mph).

| | |
|---|---|
| **COV (250 FT)** | 8.1% |
| **Line-Laser MPD (mm)** | 0.59 |
| **CTM MPD (mm)** | 0.64 |
| **Difference in MPD** | 7.5% |

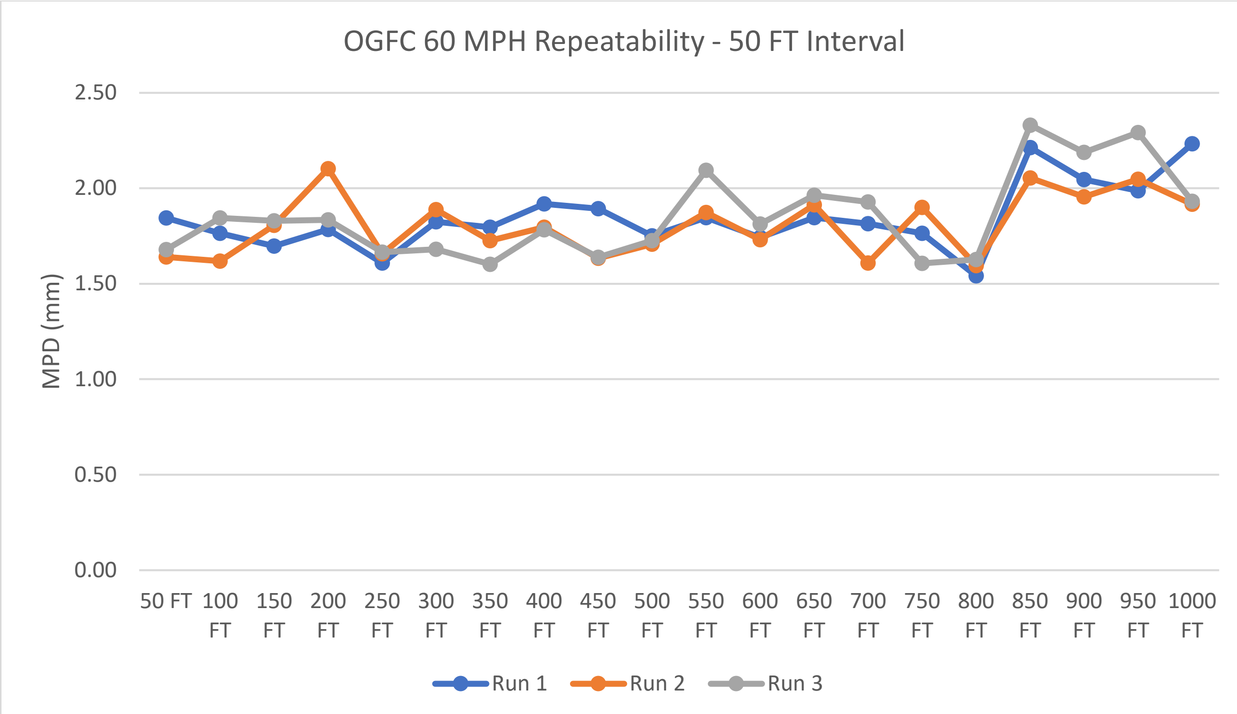



Figure 4-11. Precision results in 50-foot intervals on OGFC at 60 mph.

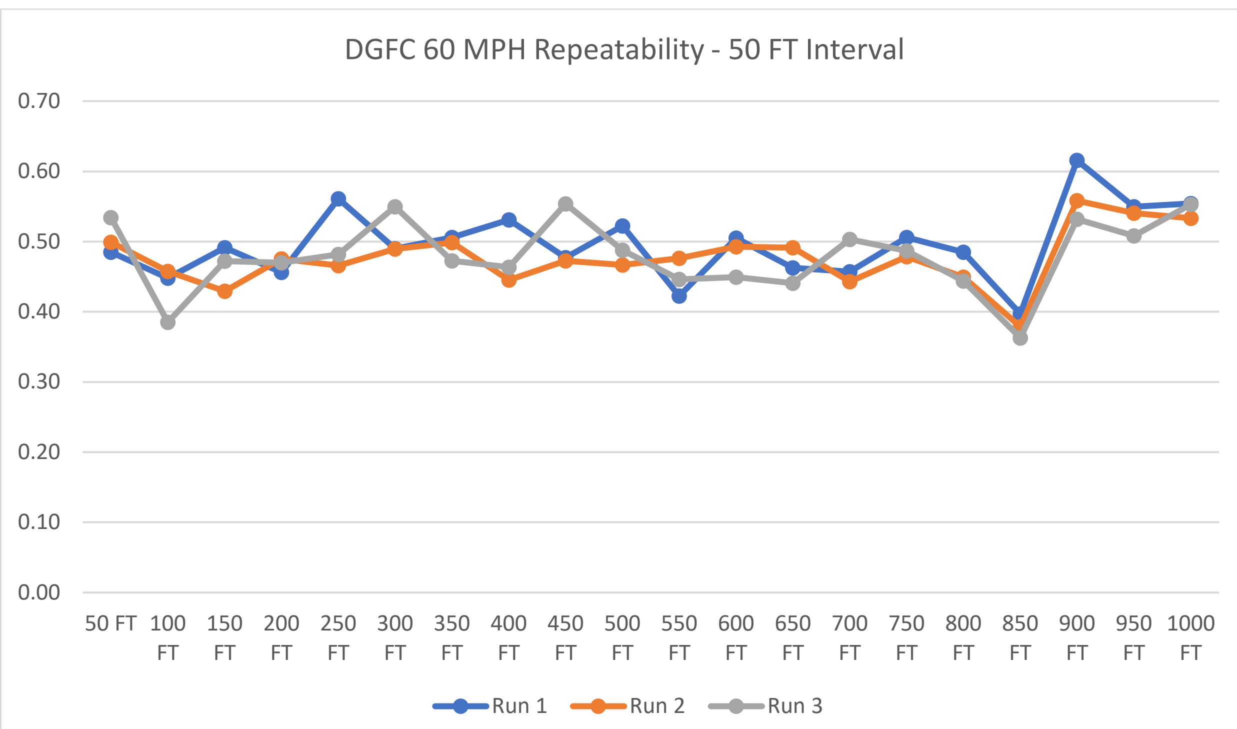



Figure 4-12. Precision results in 50-foot intervals on DGFC at 60 mph.

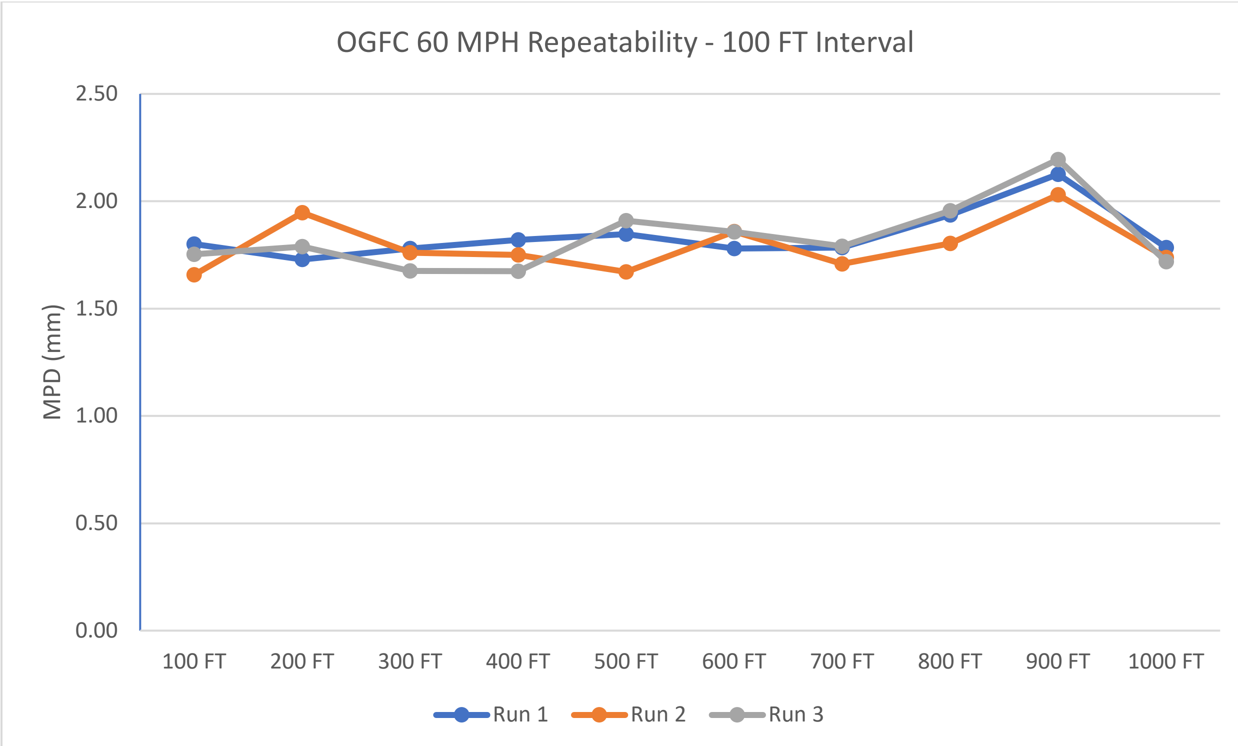



Figure 4-13. Precision results in 100-foot intervals on OGFC at 60 mph.

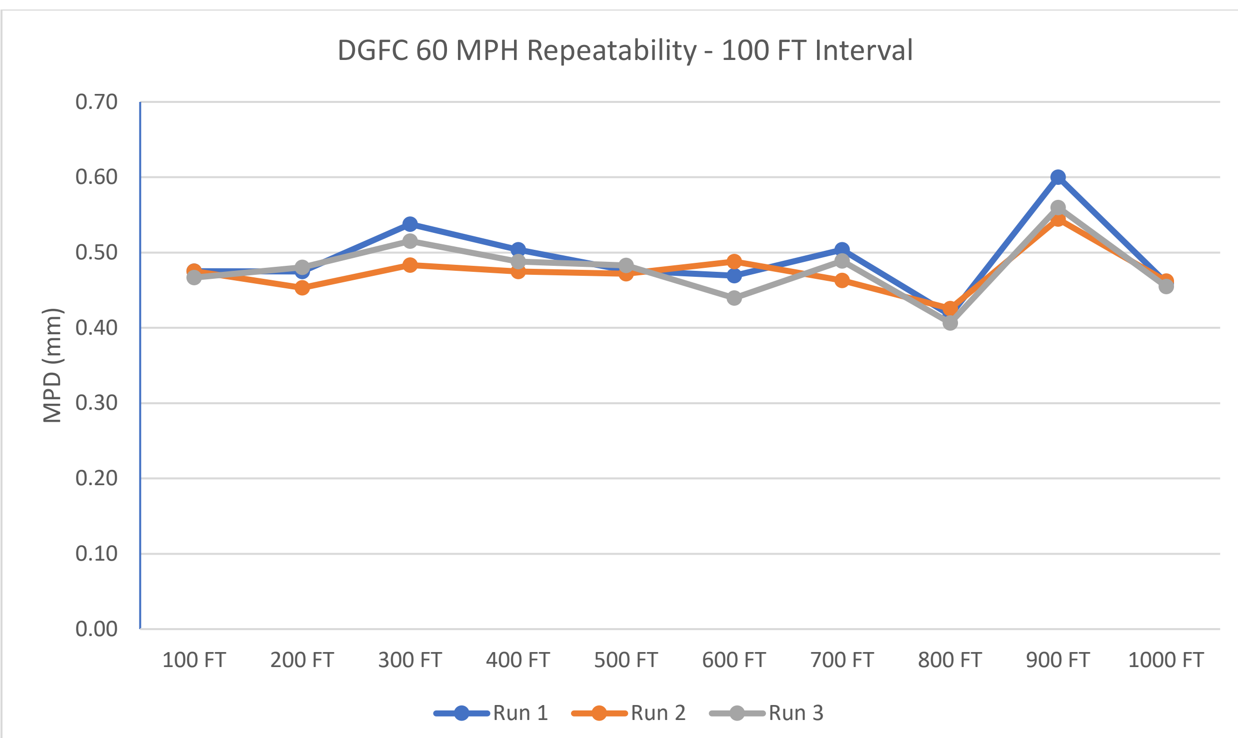



Figure 4-14. Precision results in 100-foot intervals on DGFC at 60 mph.

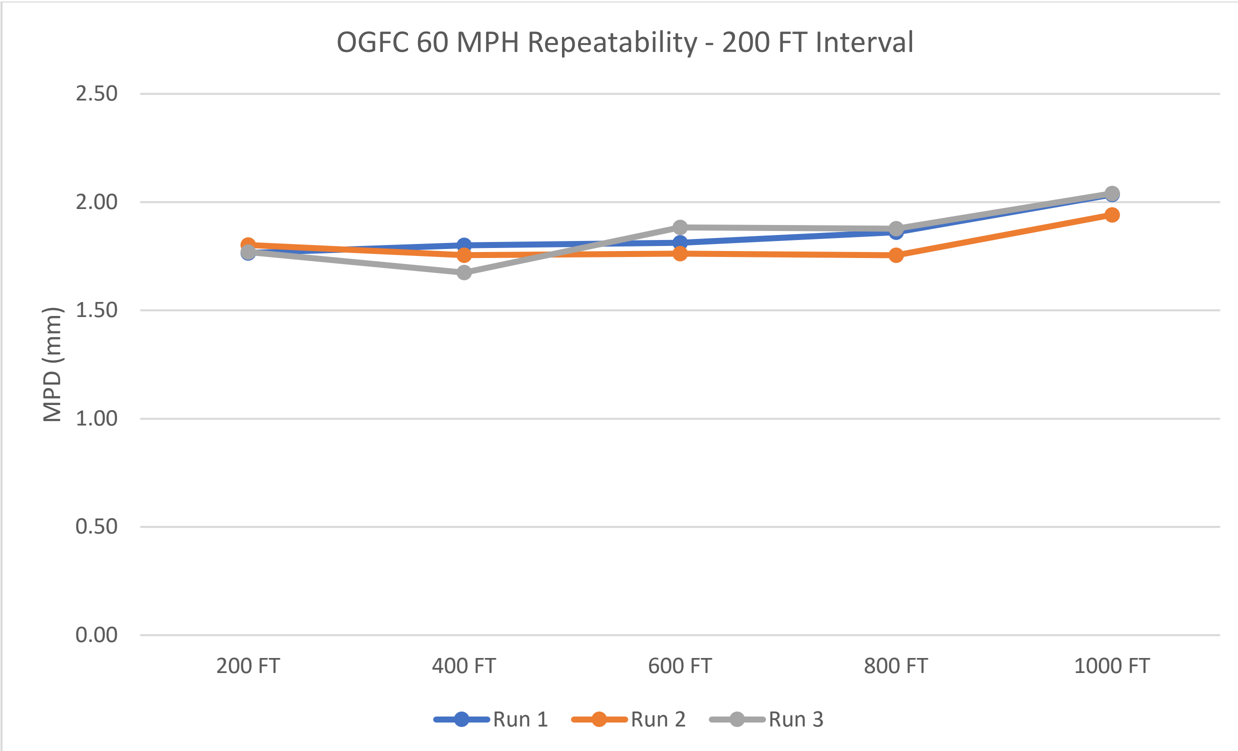



Figure 4-15. Precision results in 200-foot intervals on OGFC at 60 mph.

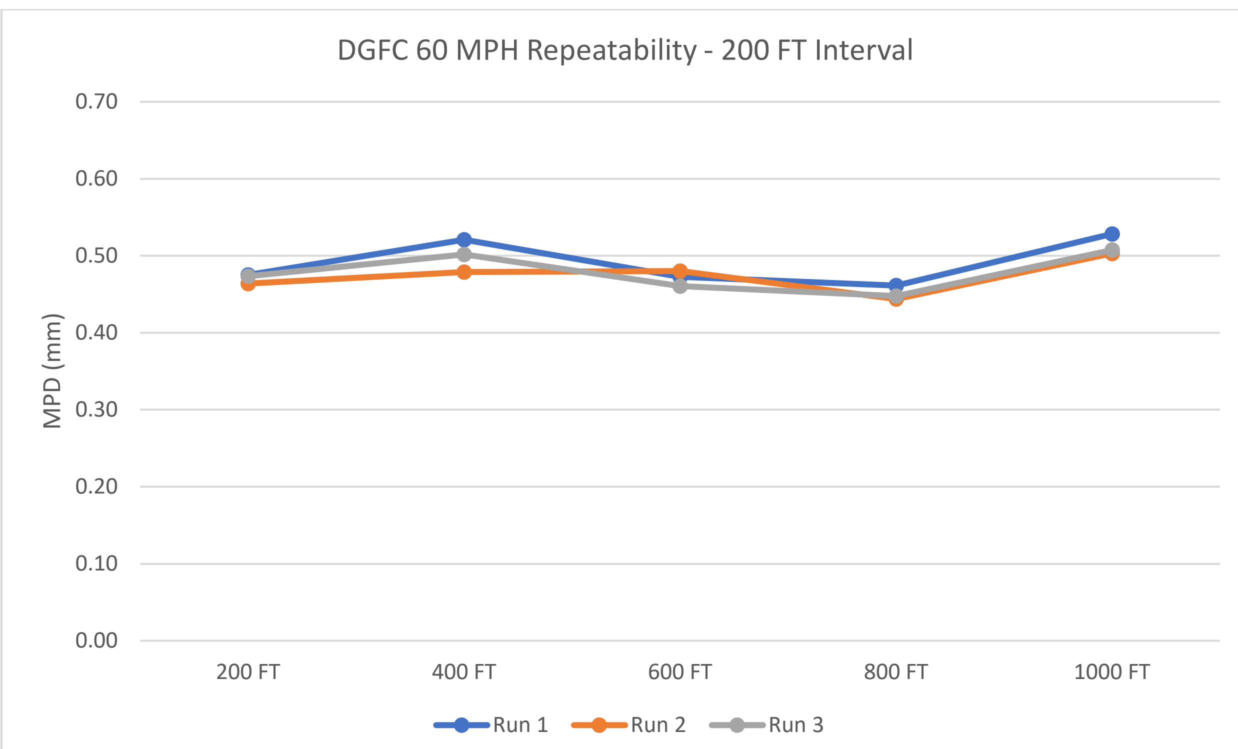



Figure 4-16. Precision results in 200-foot intervals on DGFC at 60 mph.

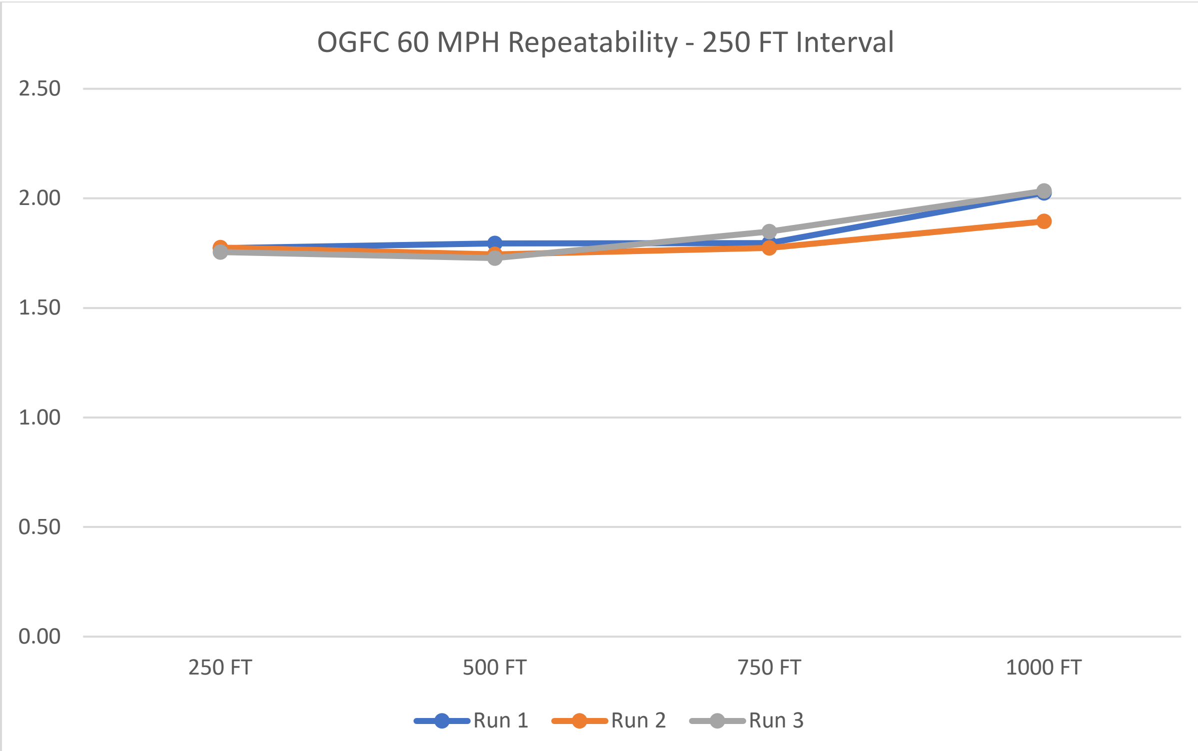



Figure 4-17. Precision results in 250-foot intervals on OGFC at 60 mph.

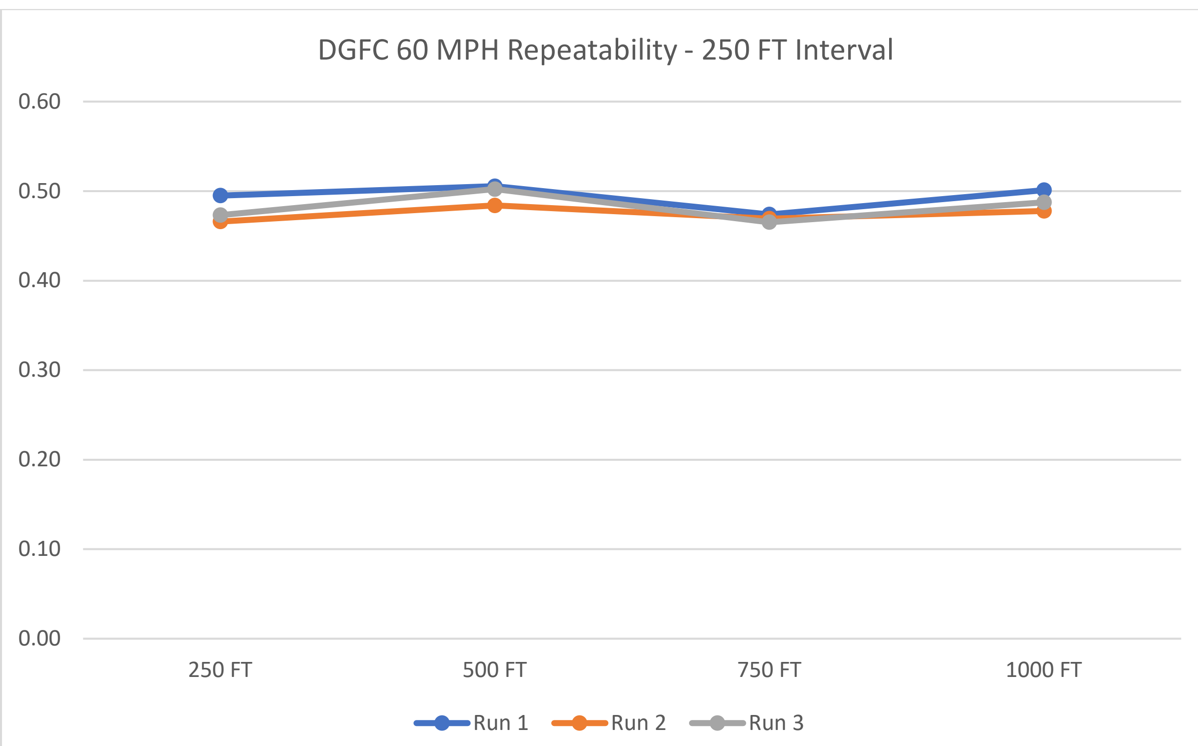



Figure 4-18. Precision results in 250-foot intervals on DGFC at 60 mph.

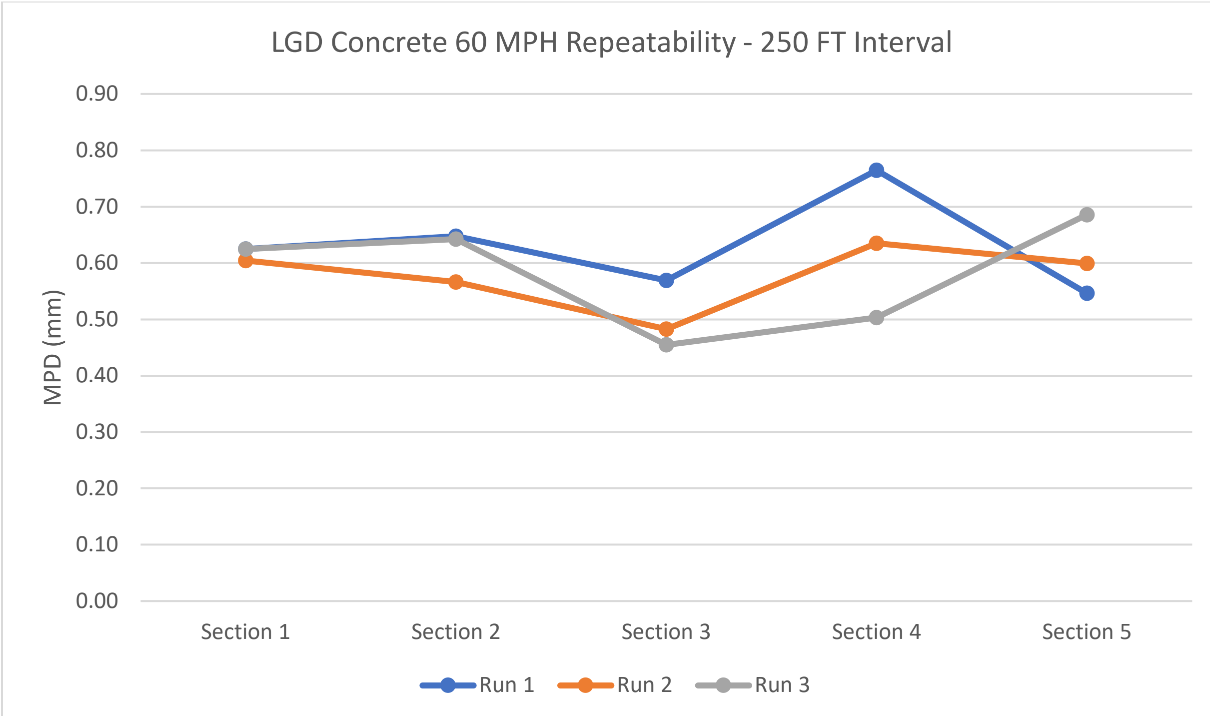



Figure 4-19. Precision results in 250-foot intervals on LGD concrete at 60 mph.

Based on the results above, the updated line-laser system can produce repeatable results in segments as small as 100 feet on OGFC and DGFC. At this level of precision, the highest COV between three separate runs was shown to be 5.0% which occurred on the OGFC test section. On LGD concrete, the system was shown to have a COV of 8.1% while travelling at 60 mph. In addition, when comparing the reference MPD from the CTM to MPD produced by the line-laser, the average difference was 7.5% between the five subsections. With these results, the UNF research team proceeded into subsequent testing with the updated line-laser system.

### TEXTURE PROCESSING PROGRAM ANALYSIS

The primary function of the original data processing program was to calculate an MPD value that correlates to the location of a locked-wheel skid test in an area of interest. The algorithm contained a fixed lowpass filtering method that complied with the parameters stated in ASTM E1845 [4]. As previously stated, the dynamic testing conducted in Phase I compared two filtering methods (Butterworth and Savitsky-Golay) in separate versions of the processing program. While the testing only evaluated MPD results on OGFC and DGFC pavement, it was determined by the UNF research team that the Butterworth filter was the most suitable option.

Working with the software developers at ICC, it was proposed to create a user interface containing several versions of the Butterworth lowpass filter. Each version maintained the 2.5-millimeter pass and 5-millimeter stop bands as required by ASTM E1845, the primary difference in the alternative versions was the stop band (2.5 mm) attenuation magnitude. The three alternate versions of the Butterworth filter contain attenuation values of -3 dB, -6 dB, and -8 dB per octave. The user interface also contains the Savitsky-Golay lowpass filter. Figure 4-20 shows an image of the texture processing options in the new program.

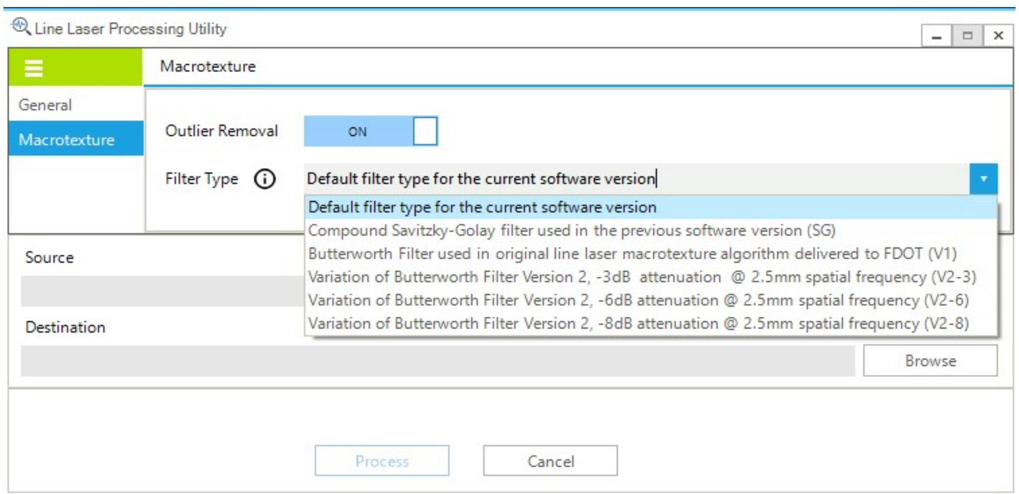



Figure 4-20. Texture processing program showing various lowpass filter versions.

Another feature of the new processing program is the ability to trim large binary files produced by the line-laser system. The current system collects texture data as soon as the vehicle DMI is activated. This results in large file sizes containing unneeded data during the collection process. To remove this unneeded data from the on-board computer, the program trims the binary files to contain only texture data collected during a locked-wheel skid test. This is made possible by correlating the event information located in the skid files produced by MDR Pro to texture measurements within the binary file.

Utilizing the new features of the processing program, the UNF research team reprocessed the data from nine sites collected during the 2018 harmonization study. Previously, the MPD values produced by the line-laser system were underestimated on every pavement type that was tested. Every available filter in the new processing program was analyzed to see their effect on MPD. The results of reprocessing this data had shown only slight increases in MPD. Therefore, it was determined by the UNF research team that the bulk of the measurement errors were due to incorrect system parameters within the line-laser.

# CHAPTER 5 – DEVICE HARMONIZATION AND PRECISION TESTING

The purpose of this testing was to harmonize the recently updated line-laser with the existing point-laser and determine precision estimates for each system. The study was conducted at 15 of the 30 sites previously analyzed in the 2018 texture harmonization study [39]. These 15 sites were chosen based on their proximity to the State Materials Office and are in Districts 2 and 5. These test sites include five open-grade, five dense-grade, and five LGD concrete roadways. Each test site also contained five subsections to further analyze the repeatability and accuracy of the line-laser system. The subsections were evenly spaced approximately 500 feet apart. Table 5-1 shown below lists the harmonization test sites and roadway information.

Table 5-1. Harmonization sites.

| Pavement Type | Project ID | Surface | Location | Speed | BMP | EMP | Lane | Material |
|---|---|---|---|---|---|---|---|---|
| **OGFC - 1** | 26060000 | FC-5M | SR 200 | 55 MPH | 27.00 | 27.54 | NBTL | Granite |
| **OGFC - 2** | 26050000 | FC-5 | SR 24 | 65 MPH | 12.15 | 12.54 | NBPL | Limestone |
| **OGFC - 3** | 26010000 | FC-5M | US 441 | 65 MPH | 1.10 | 1.70 | SBPL | Granite |
| **OGFC - 4** | 28010000 | FC-5 | SR 200/US 301 | 65 MPH | 3.01 | 3.58 | SBTL | Limestone |
| **OGFC - 5** | 73010000 | FC-5AW | SR5 | 65 MPH | 1.41 | 2.00 | NBTL | Limestone |
| **DGFC - 1** | 27010000 | FC-125MR | SR 10 | 60 MPH | 15.00 | 15.60 | SBTL | Limestone |
| **DGFC - 2** | 29040000 | FC-12.5 | SR 25/SR 100 | 60 MPH | 3.30 | 3.87 | NB | Granite |
| **DGFC - 3** | 39020000 | FC-125MR | SR 121 | 60 MPH | 10.59 | 11.79 | NB | Granite |
| **DGFC - 4** | 27010000 | FC-125MR | SR 10 | 60 MPH | 13.3 | 13.9 | EBTL | Limestone |
| **DGFC - 5** | 28030001 | FC-12.5 | SR 16 | 60 MPH | 6.94 | 7.47 | WBTL | Limestone |
| **Concrete - 1** | 72002027 | LGD | SR 9B | 60 MPH | 3.00 | 3.54 | SBL3 | NA |
| **Concrete - 2** | 79110000 | LGD | SR 400 | 70 MPH | 17.01 | 17.70 | NBL3 | NA |
| **Concrete - 3** | 79060000 | LGD | SR 600/US 92 | 65 MPH | 7.72 | 8.30 | EBL2 | NA |
| **Concrete - 4** | 79060000 | BD | SR 600/US 92 | 65 MPH | 8.3 | 7.7 | WBL2 | NA |
| **Concrete - 5** | 72120000 | LGD | SR 228 | 60 MPH | 4.11 | 4.71 | EBTL | NA |

## STATEWIDE DATA COLLECTION

In the 2018 harmonization study, MPD values produced by the point-laser had a strong correlation with those produced by the CTM on flexible pavement [39]. Also, since the CTM is considered a reputable texture reference device, the harmonization effort used the point-laser as a reference device for the open-grade and dense-grade test sections. Using the point-laser as a reference device on the ten flexible pavement sites eliminated the need for MOT in these sections. In addition, since the point-laser is mounted adjacent to the line-laser, data collection was done simultaneously with both devices. However, since current point-laser technology is unable to accurately capture macrotexture on LGD concrete, the remaining test sections required MOT to collect reference measurements. At each of the five concrete sites, reference measurements were taken with the CTM and FTM. Once these reference measurements were completed, high-speed data collection was conducted using both the vehicle-mounted point- and line-laser. Figure 5-1 shows a map of the test sites.

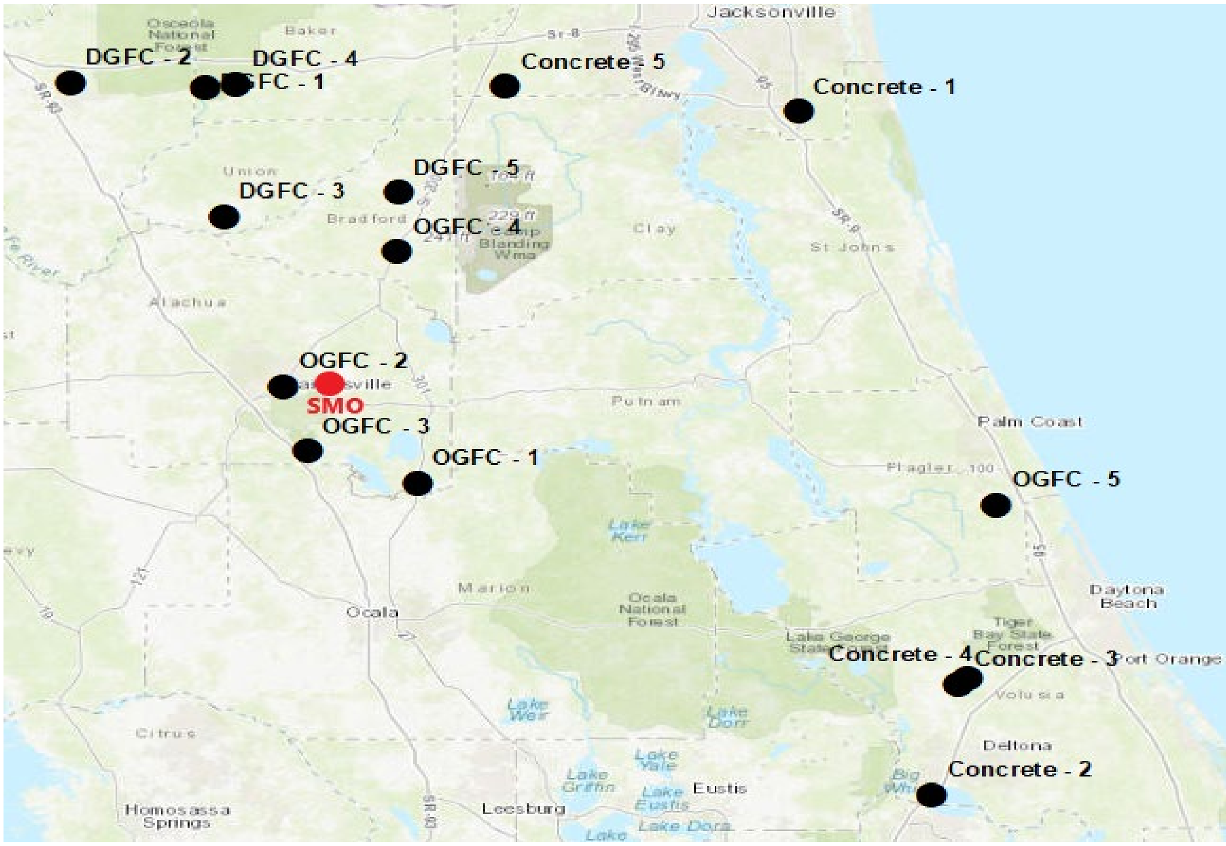



Figure 5-1. Harmonization test locations.

***Reference Devices***

In accordance with ASTM E1845, there were a total of 20 evenly spaced measurement locations using the CTM and FTM at each test site [4]. These measurement locations were positioned along the driver-side wheel path approximately 125 feet apart. Without moving the devices, measurements with the CTM and FTM were repeated three times to obtain an average MPD value for that location. The UNF research team was only able to collect data with the TM2 at one LGD concrete test site due to a software issue at the time of testing. Therefore, the TM2 was excluded in the device comparisons for this study. However, a comparison between the TM2 and line-laser at this site and the collected reference measurements are shown in Appendix B. Table 5-2 shown below further summarizes the data collection process. Figure 5-2 illustrates the measurement locations for each device, and Figures 5-3 and 5-4 show the devices.

Table 5-2. Summary of reference measurements.

| Device | Number of Runs | Number of Locations | Total Measurements per Site |
|---|---|---|---|
| CTM | 3 | 20 | 60 |
| FTM | 3 | 20 | 60 |
| TM2 | 3 | 5 | 15 |

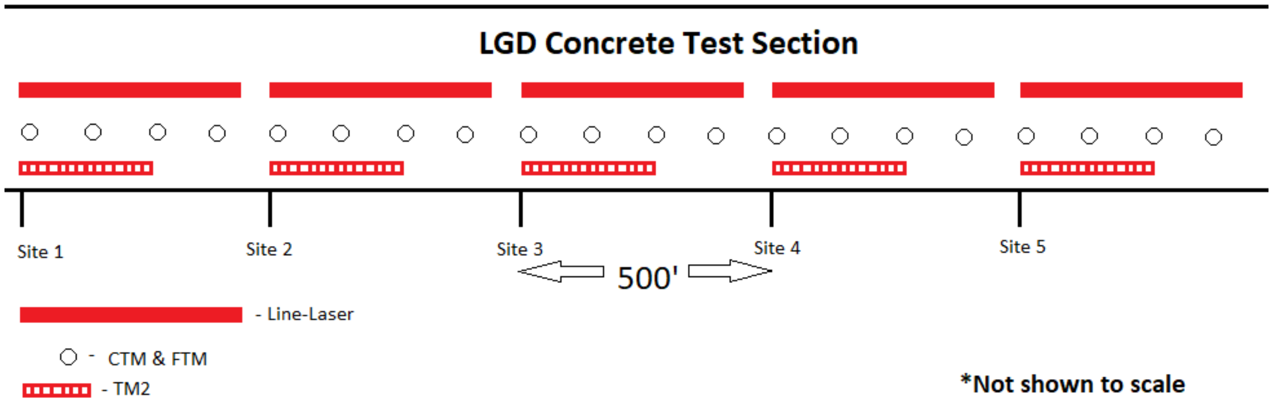



Figure 5-2. Reference measurement locations.


Figure 5-3. CTM at an LGD concrete test site.

Figure 5-4. FTM (left). TM2 (right) at LGD concrete test sites.

### *High-Speed Devices*

For the high-speed devices, four repeat runs were conducted at each test site. Data collection with the line-laser and point-laser was activated by simulating a lock-wheel skid test ("fake" lockup) at an automated sampling interval of 500 feet. The simulation lockup activates the texture lasers for a time interval equivalent to a friction lockup (three seconds) and is repeated every 500 feet totaling five lockups per site. This method allowed the vehicle operators to collect data at the posted speed for each roadway without obstructing traffic flow. Each lockup occurred at the beginning of the five subsections that were designated with reflective tape. The high-speed data collection was conducted using both Unit 12 and Unit 13 to establish reproducibility between two vehicles with two different operators. As a note, Unit 13 was retrofit with the texture equipment from Unit 10, which was the vehicle used during the line-laser optimization testing. Figure 5-5 shows the Unit 12 test vehicle and Table 5-3 summarizes the high-speed data collection.


Figure 5-5. Unit 12 test vehicle (top). Texture laser locations (bottom).

Table 5-3. Summary of high-speed measurements.

| Device | Number of Runs per Vehicle | Number of Locations | Total Lockups per Site |
|---|---|---|---|
| Line-Laser | 4 | 5 | 20 |
| Point-Laser | 4 | 5 | 20 |

Each vehicle contained an LMI Technologies Gocator line-laser mounted along the driver's side wheel path. However, the laser on Unit 12 was mounted 30 degrees from the transverse axis of the vehicle and at 45 degrees on Unit 13. Since concrete roadways in Florida contain longitudinal texture, as opposed to the isotropic texture of asphalt, the harmonization study allowed the UNF research team to analyze the effect, if any, that the line-laser angle has on MPD calculations for concrete. Figure 5-6 displays how the laser angle is measured using Unit 13 on the UNF texture reference plate.

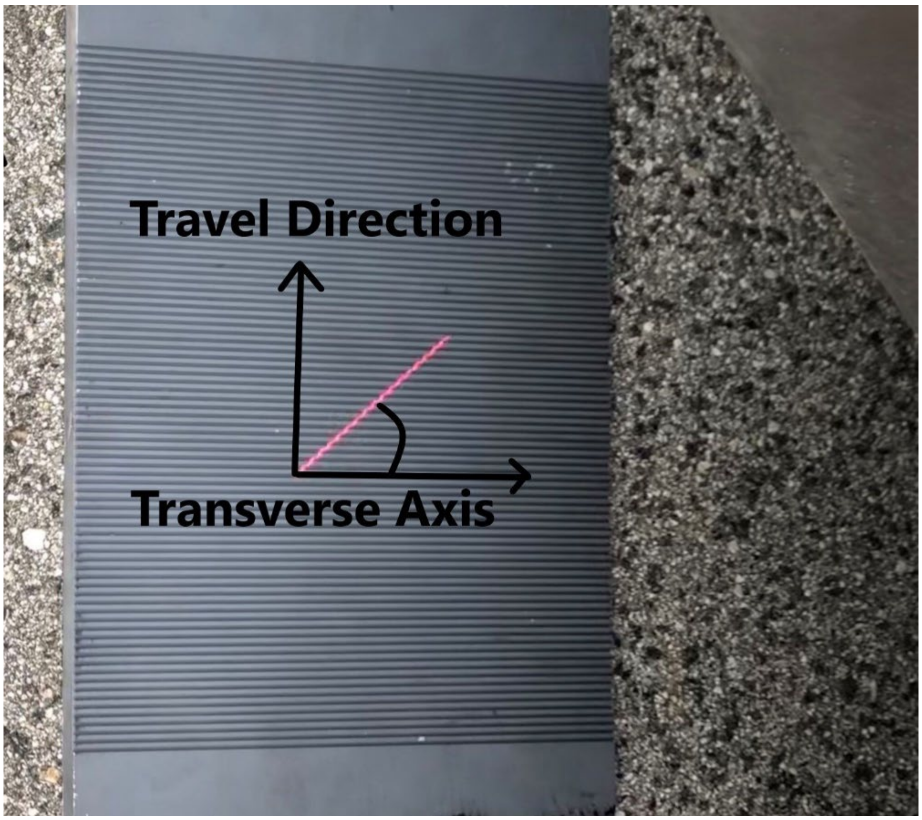



Figure 5-6. Laser angle on the UNF texture reference plate.

**RESULTS**

To eliminate as many variables as possible, the test vehicles traveled together to each test site during sunlight hours to ensure data was being collected under the same environmental conditions. Before leaving, the research engineer ensured that each vehicle contained the optimized settings as determined in previous testing. The optimized settings are also listed in Appendix A. The vehicle operators performed data collection at the posted speed pertaining to each roadway. All data was collected using the MDRPro software, processed with the Butterworth filtering method within the Trimming Utility, and summarized in reports produced by WinSkid. Additional comparisons were made using the Savitsky-Golay filtering method for the concrete sections; However, the results were undesirable compared to the Butterworth filtering method and, therefore, were excluded from this section of the report. Of the four runs conducted at each test site, the best three were selected when carrying out the device comparisons. However, all data pertaining to the harmonization study is shown in summarized tables located in Appendix B.

*Flexible Pavement – OGFC and DGFC*

At the test sites containing flexible pavement, data collection with the point-laser and line-laser occurred simultaneously. Using the MDRPro software developed by ICC, the two lasers were triggered by the operator and programmed to perform a simulation lockup every 500 feet until five lockups were collected. At the OGFC and DGFC test sites, the point-laser was used as a reference device to assess the accuracy of the line-laser. Graphs comparing the MPD values produced by the point and line-laser for each run and subsection on flexible pavement are shown below in Figures 5-7, 5-8, and 5-9. Figure 5-10 shows a comparison between the MPD values produced by Unit 12 and Unit 13.

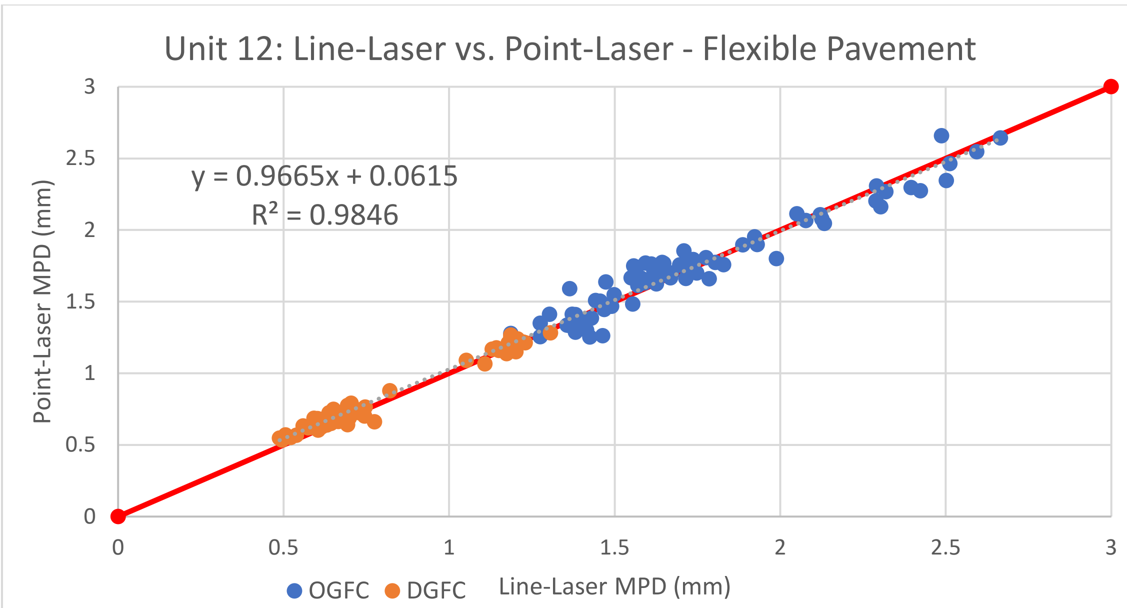



Figure 5-7. Line-laser and point-laser comparison on flexible pavement by Unit 12.

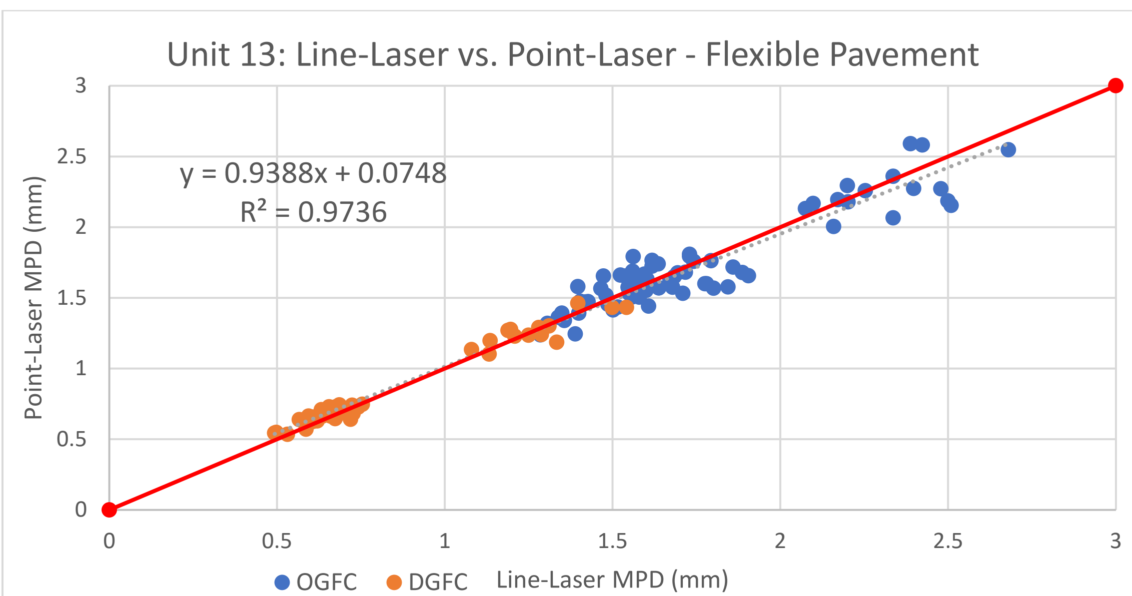



Figure 5-8. Line-laser and point-laser comparison on flexible pavement by Unit 13.

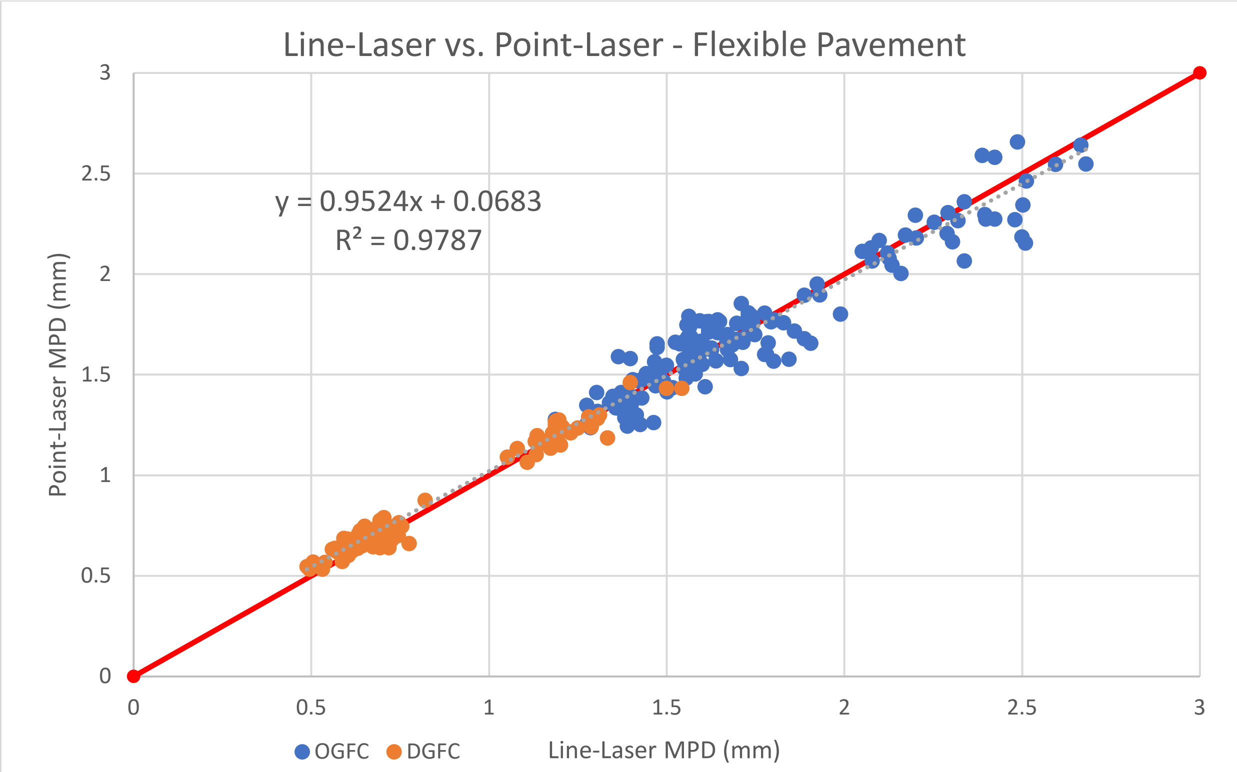



Figure 5-9. Line-laser and point-laser comparison on flexible pavement with both vehicles.

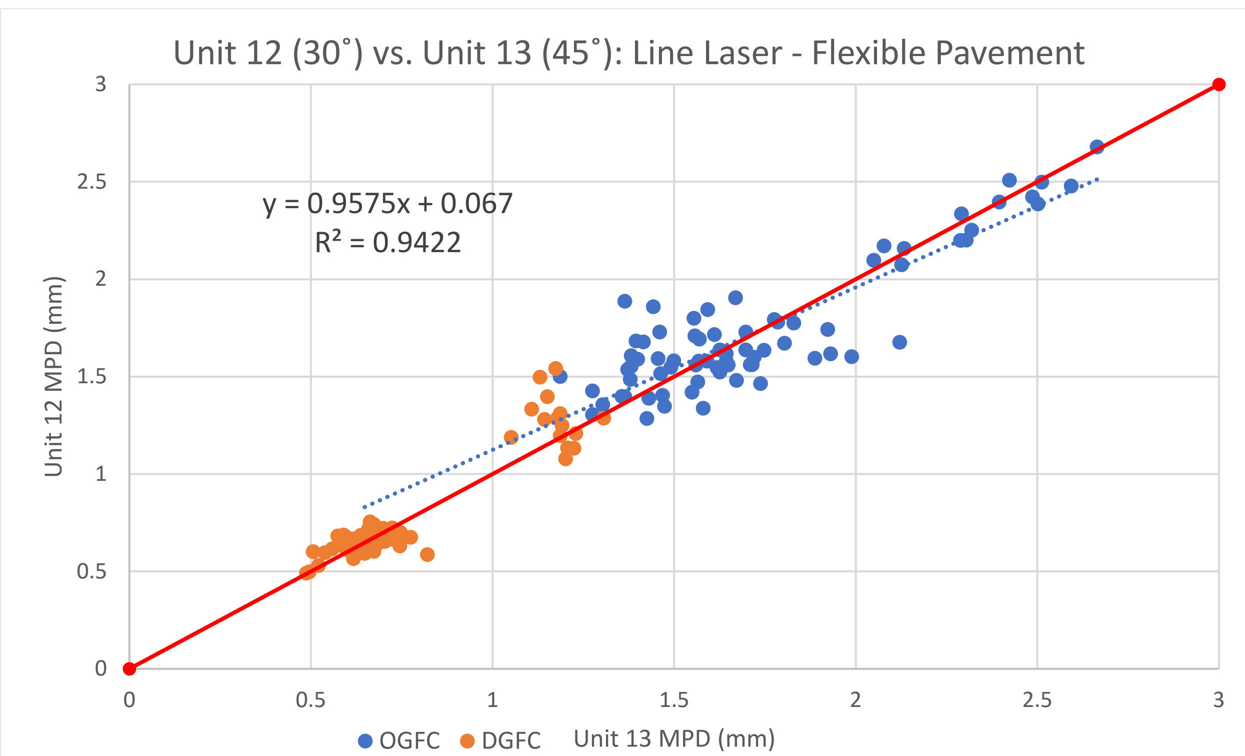



Figure 5-10. Comparison of laser angles on flexible pavement.

Based on the coefficient of determination ($R^2$) values in Figures 5-7 through 5-10 shown above, the updated line-laser system produces measurements that are highly correlated with those from the point-laser on flexible pavement. Furthermore, since the point-laser has shown to produce MPD values that have a strong correlation with those from the CTM, the UNF research team believes that the line-laser is accurately depicting the pavement's macrotexture. Upon further inspection of the results in Figure 5-10, there is no indicator that the laser angle influences measurement accuracy on flexible pavement. This is believed to be a result of the homogenous aggregate distribution in flexible pavement.

***Rigid Pavement – LGD Concrete***

High-speed data collection at the rigid pavement sites was conducted in the same method as completed on flexible pavement. However, device comparisons against the line-laser were made with the CTM, FTM, and TM2, as opposed to the point-laser. This was done because the current point-laser system cannot accurately capture longitudinal texture. Similarly, the MPD values used for comparisons with the CTM and FTM excluded segments A and E which run nearly parallel with the vehicle's direction of travel [11]. Images containing how the segments are denoted on the CTM and FTM are shown in Figure 5-11. Figure 5-12 shows a close-up image of the longitudinal texture on concrete roadways. Figures 5-13 to 5-19 show comparisons between the line-laser, point-laser, CTM, and FTM on concrete.

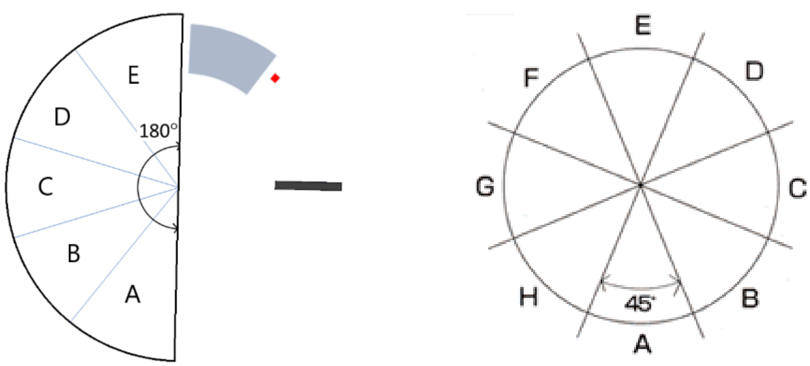



Figure 5-11. FTM segments (left). CTM segments (right) [11].

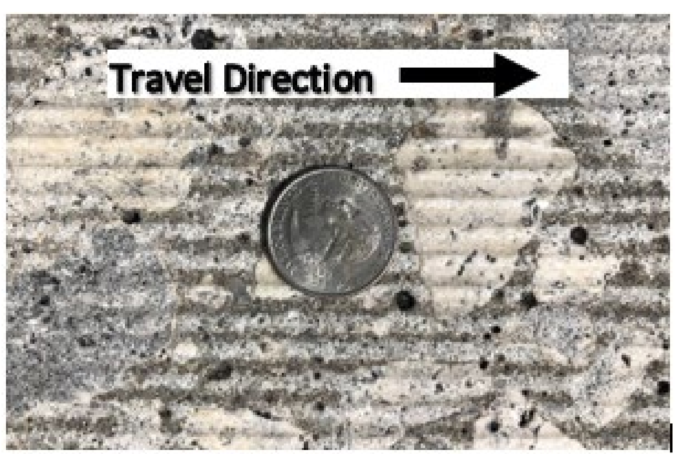



Figure 5-12. Longitudinal texture of concrete roadways in Florida.

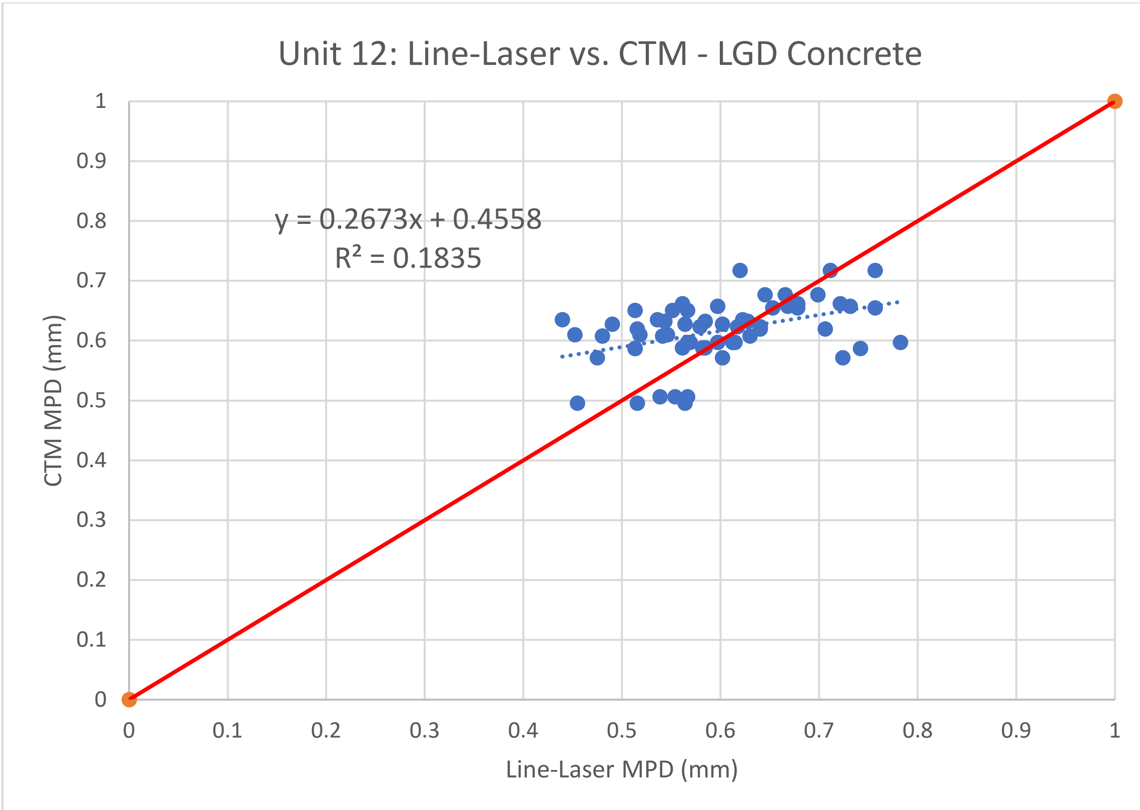



Figure 5-13. Line-laser and CTM comparison on LGD concrete by Unit 12.

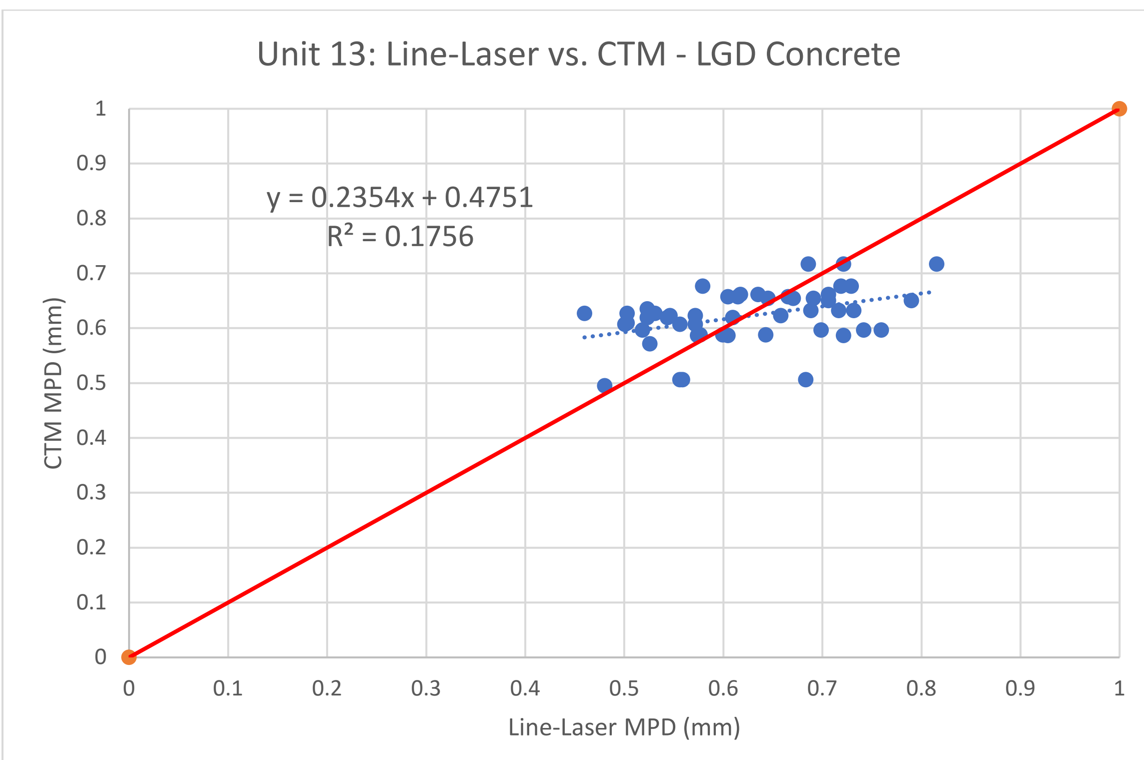



Figure 5-14. Line-laser and CTM comparison on LGD concrete by Unit 13.

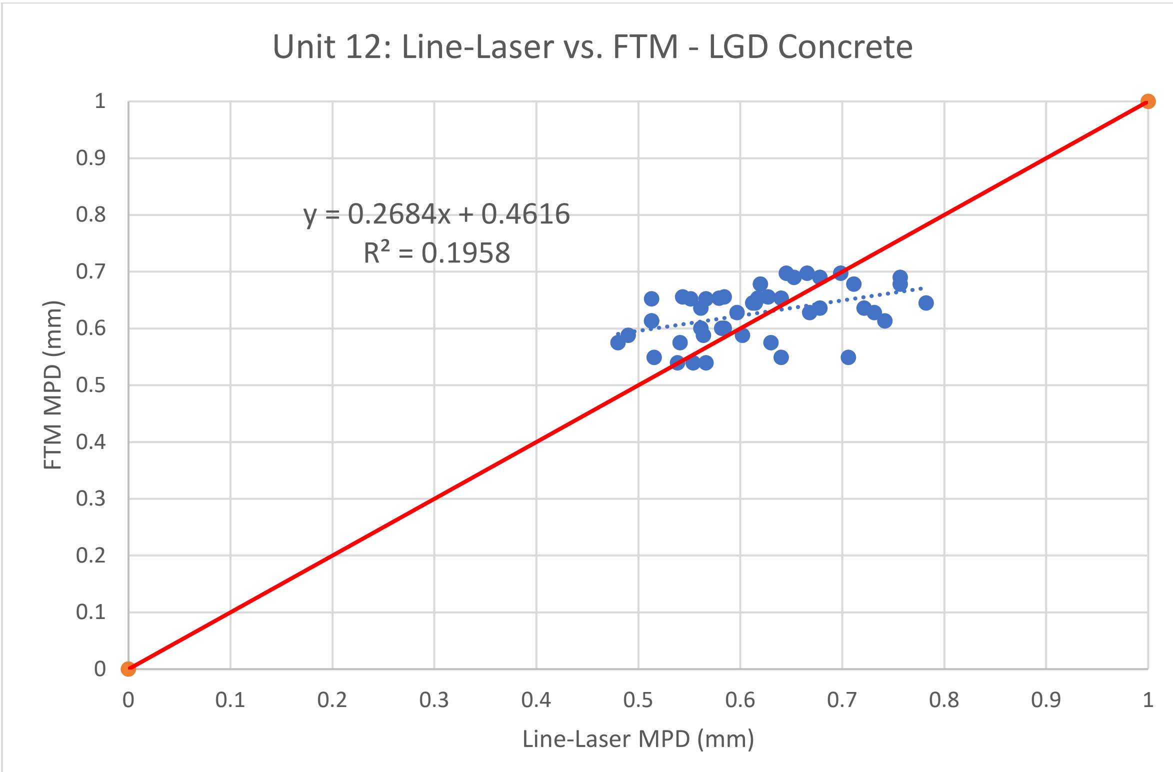



Figure 5-15. Line-laser and FTM comparison on LGD concrete by Unit 12.

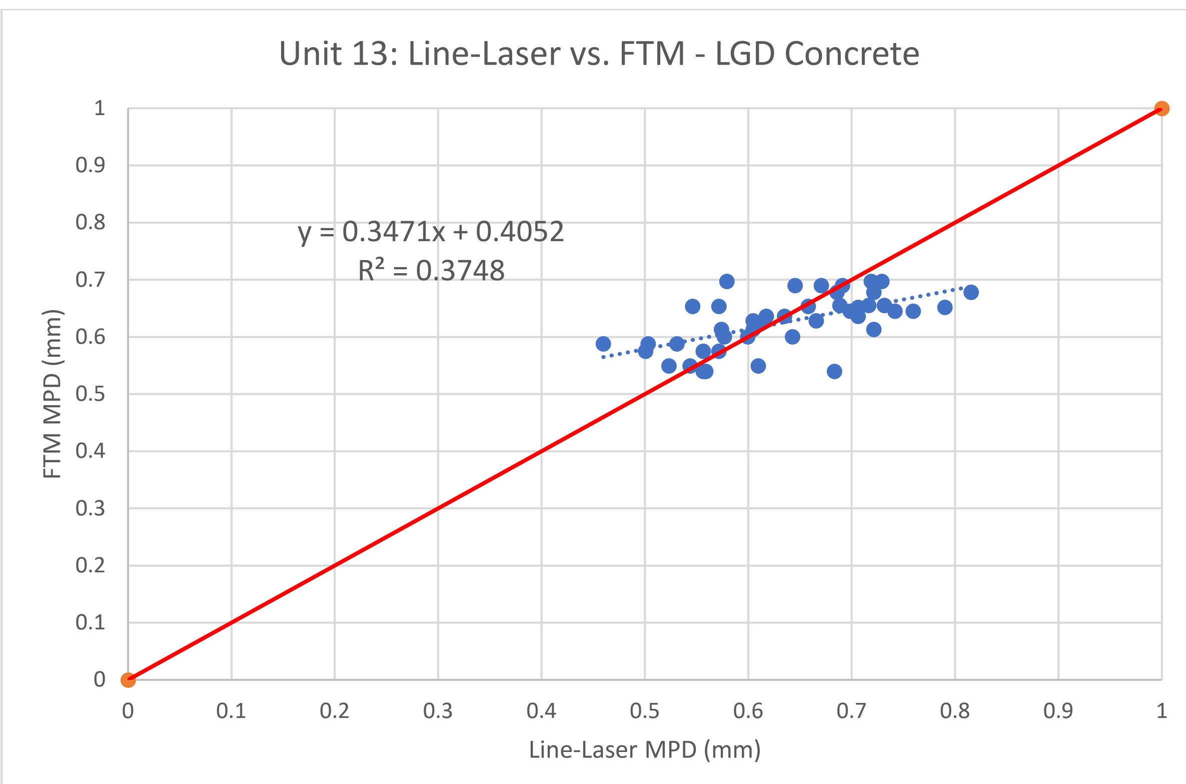



Figure 5-16. Line-laser and FTM comparison on LGD concrete by Unit 13.

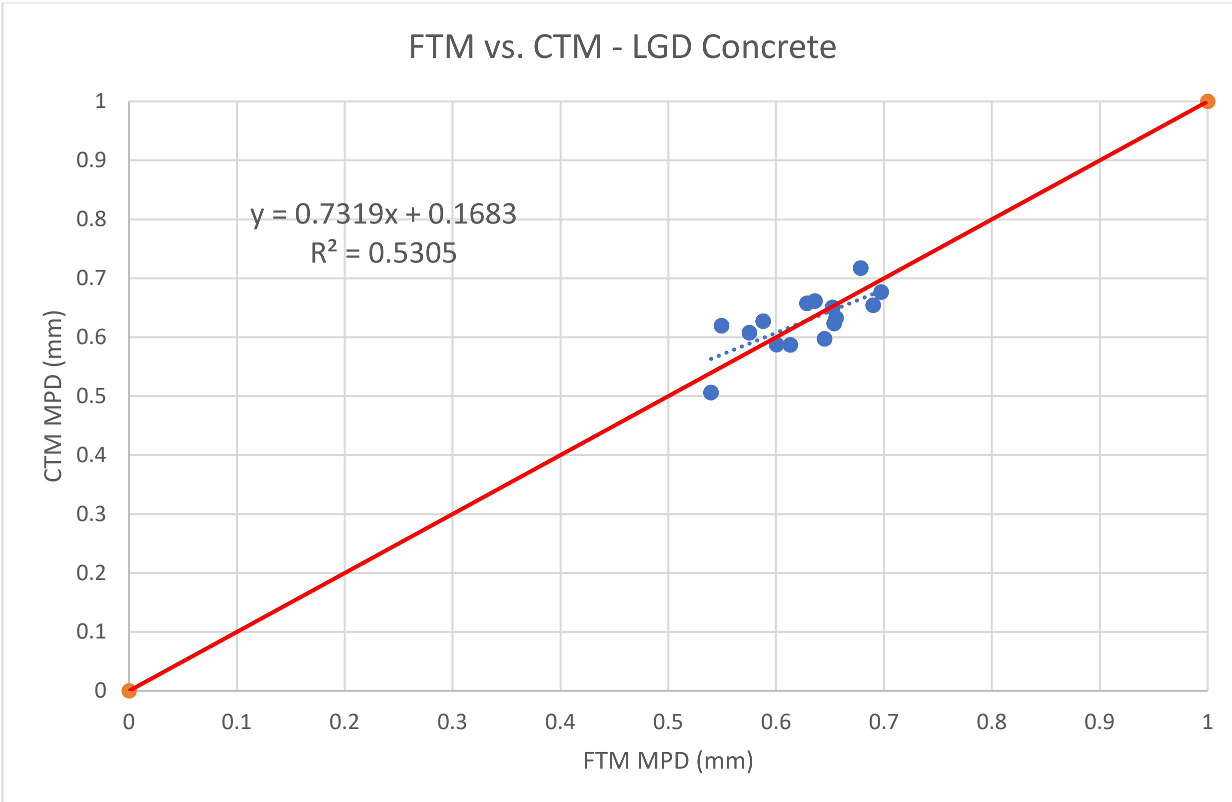



Figure 5-17. CTM and FTM comparison on LGD concrete.

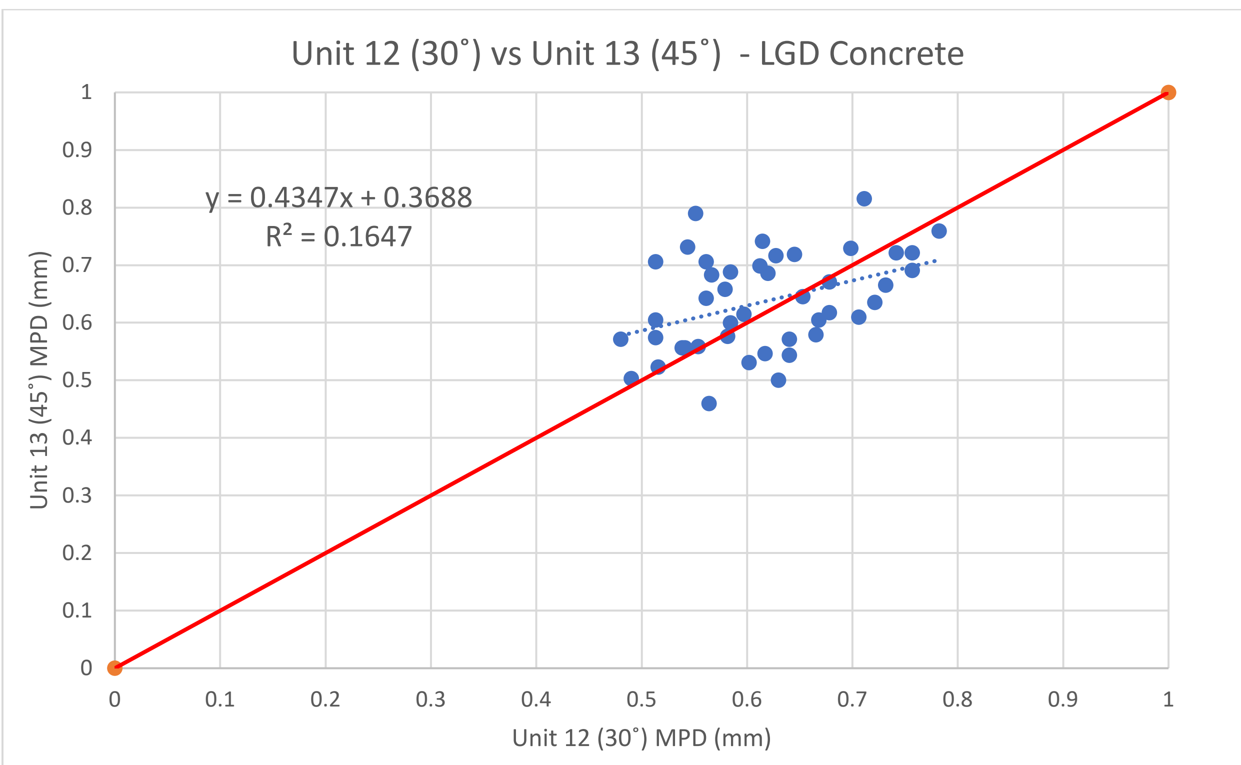



Figure 5-18. Laser angle comparison on LGD concrete.

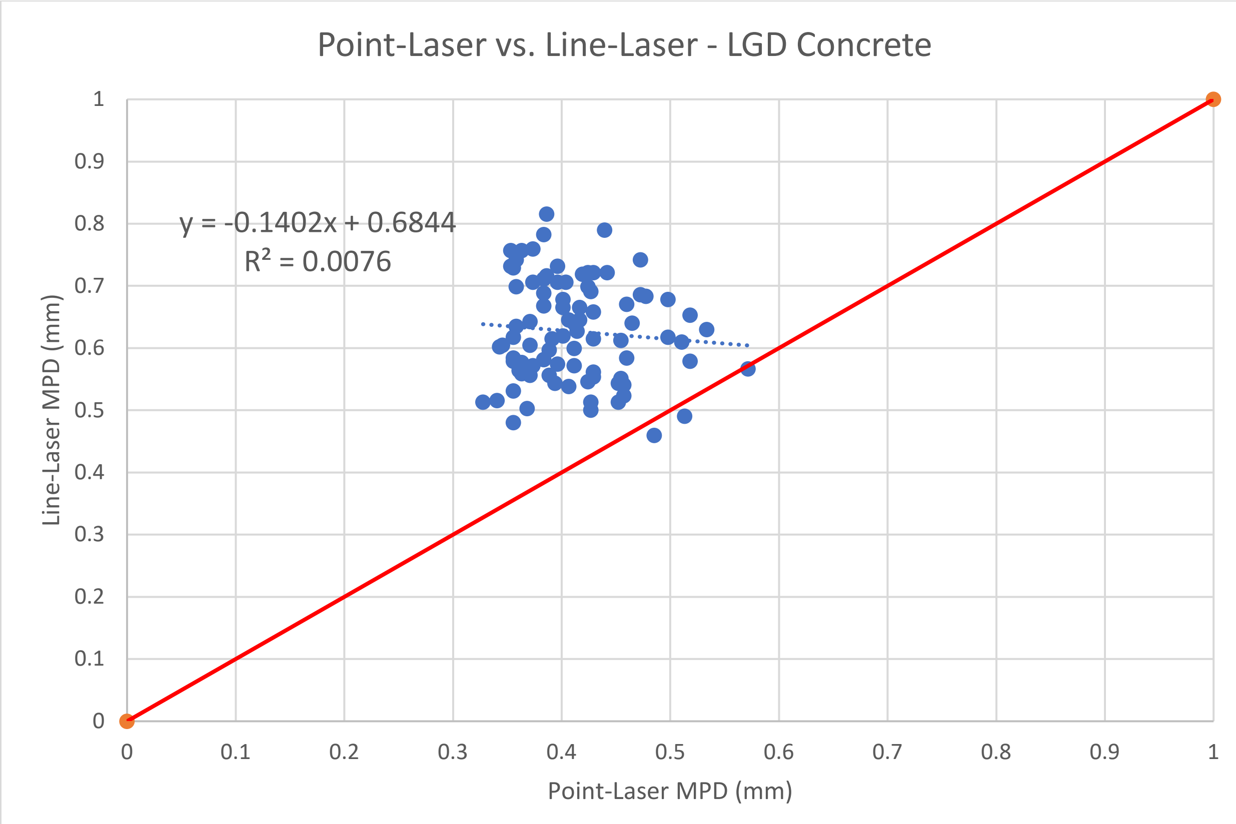



Figure 5-19. Point-laser compared to line-laser on LGD concrete with both vehicles.

In the comparisons shown above, MPD values produced by the line-laser for every run and subsection were compared against the average MPD of the four CTM or FTM locations in each subsection. The results show comparable MPD values between the line-laser and static devices. However, due to the small range of MPD values and several inaccuracies between devices, the $R^2$ is lower than previously shown on flexible pavement. Further inspection of the data had shown an average ± 9.9% and ± 10.8% error between the CTM and line-laser on each subsection for Units 12 and 13, respectively. For comparison, when correlating point-laser MPD to the CTM in the 2018 harmonization study, results had shown differences of 15.5% on OGFC and 18.2% on DGFC between the two devices. In addition, the results above show no direct relationship between laser angle and MPD on LGD concrete.

Since there were no CTM or FTM reference measurements taken at the flexible pavement sites for this study, a comparison between the updated line-laser system and CTM MPD values from the 2018 study is shown in Figure 5-20. In Figure 5-20, the CTM MPD values for concrete were collected during the course of this project. Figure 5-21 shows a comparison between the two vehicles and laser angles on all pavement types.

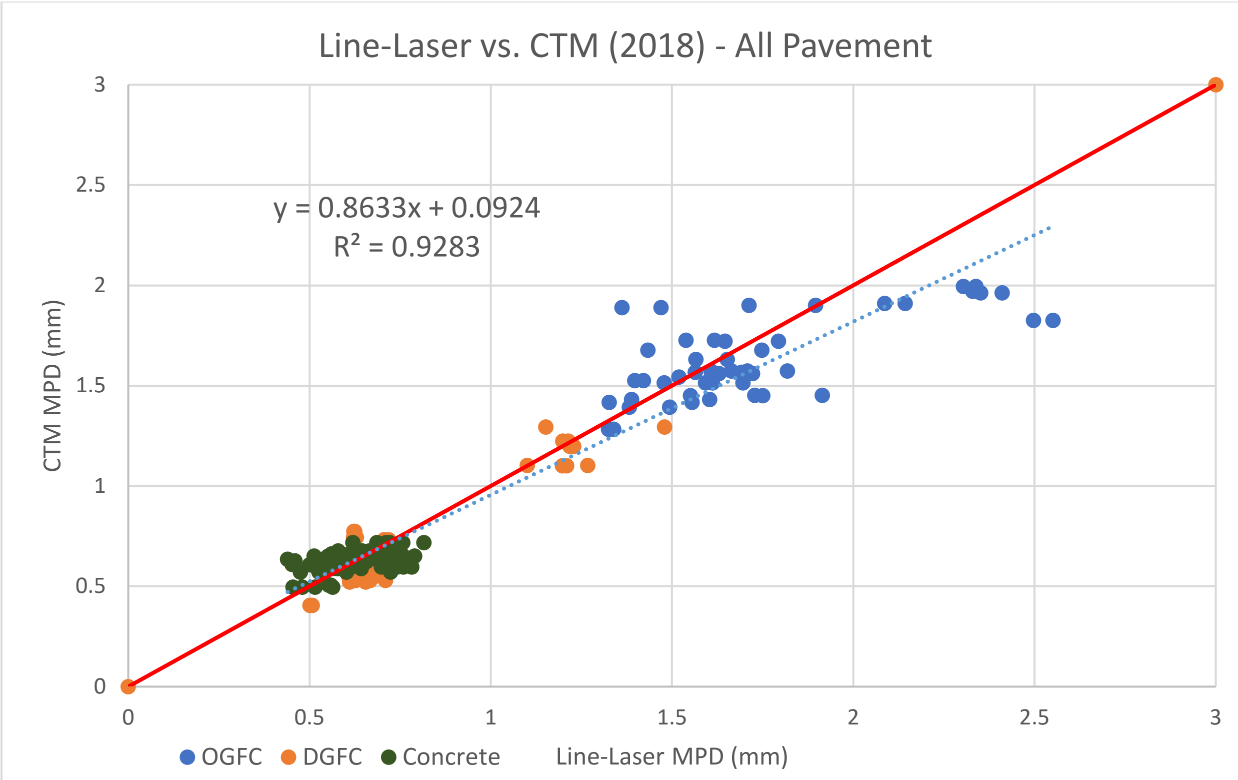



Figure 5-20. Line-laser and CTM MPD comparison on all pavement types with both vehicles.

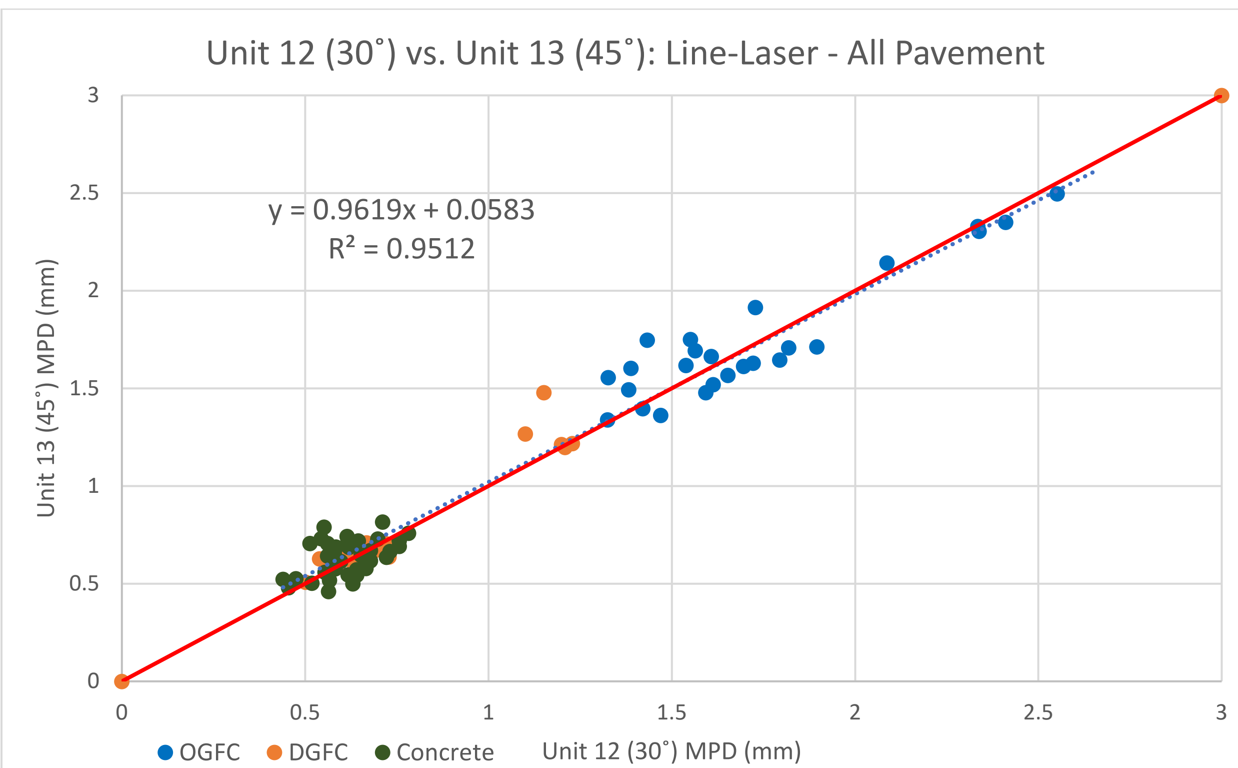



Figure 5-21. Comparing the Unit 12 and Unit 13 line-lasers.

Concrete Site 3 (79060000 EB – SR 600) was removed from the comparisons due to an abnormally high disagreement between the line-laser and CTM. At this site, a one-inch wide, elevated seam in the left-hand wheel path ran longitudinally throughout the test section. This elevated seam, when captured by the CTM, FTM, or line-laser, produced high MPD values relative to the surrounding LGD texture. While this feature was captured with the CTM and FTM at each measurement location, it was only intermittently captured by the line-laser during high-speed testing. As a result, the standard deviations between runs for each subsection were high relative to those at the other LGD concrete test locations. This seam is shown in Figure 5-22.

Figure 5-22. Texture feature in left-hand wheel path at SR-600 EB location.

To harmonize the line-laser with the point-laser, several regression equations were established based on the comparisons shown above. Since the point-laser does not have a perfectly linear relationship with the line-laser, these regression equations are used to transform MPD produced by the point-laser to more closely align with MPD values produced by the line-laser. These equations are summarized in Table 5-4.

Table 5-4. Regression equations for the line-laser and point-laser.

| MPD Between the Line-Laser and the Point-Laser (mm) | |
|---|---|
| OGFC | $MPD_{Line}$ = 0.8918*$MPD_{Point}$ + 0.1854 ($R^2$ = 0.885) |
| DGFC | $MPD_{Line}$ = 0.9351*$MPD_{Point}$ + 0.0731 ($R^2$ = 0.974) |
| LGD Concrete | $MPD_{Line}$ = -0.1402*$MPD_{Point}$ + 0.6844 ($R^2$ = 0.008) |

In addition to the device comparisons, the repeatability and reproducibility of the line-laser were quantified by calculating the repeatability limit (*r*) and the reproducibility limit (*R*). The repeatability and reproducibility limits indicate that 95% of all pairs of test results are expected to differ by no more than these calculated values for either repeatability or reproducibility testing conditions [37]. Equations 5-1 and 5-2 contain formulas for the repeatability and reproducibility limit, respectively. In the equations below, repeatability was calculated using the standard deviation in MPD between three runs for a given subsection (five subsections at each test site). Reproducibility was determined by calculating the standard deviation in MPD between both vehicles for each run and subsection. Tables 5-5 and 5-6 contain the precision results using data from the 15 test sites. The mean and standard deviation values in the tables below are the average of all five test sites for each pavement type.

$$r = 1.96 \times \sqrt{2} \times \sigma_{Repeat.\ Std.\ Dev.} \quad \text{(Equation 5-1)}$$

$$R = 1.96 \times \sqrt{2} \times \sigma_{Reprod.\ Std.\ Dev.} \quad \text{(Equation 5-2)}$$

Table 5-5. Line-laser precision averages for each subsection and pavement type.

| Pavement Type | Mean, $\bar{x}$ (mm) | Repeat. Standard Deviation, $\sigma_{St.\ Dev.}$ (mm) | Reprod. Standard Deviation, $\sigma_{St.\ Dev.}$ (mm) | Repeat. Limit, *r* (mm) | Reprod. Limit, *R* (mm) |
|---|---|---|---|---|---|
| OGFC | 1.74 | 0.13 | 0.15 | 0.36 | 0.43 |
| DGFC | 0.76 | 0.05 | 0.08 | 0.15 | 0.20 |
| Concrete | 0.64 | 0.08 | 0.08 | 0.20 | 0.20 |
| **Combined** | **1.12** | **0.09** | **0.11** | **0.25** | **0.30** |

Table 5-6. Point-laser precision averages for each subsection and pavement type.

| Pavement Type | Mean, $\bar{x}$ (mm) | Repeat. Standard Deviation, $\sigma_{St.\ Dev.}$ (mm) | Reprod. Standard Deviation, $\sigma_{St.\ Dev.}$ (mm) | Repeat. Limit, *r* (mm) | Reprod. Limit, *R* (mm) |
|---|---|---|---|---|---|
| OGFC | 1.73 | 0.10 | 0.13 | 0.30 | 0.36 |
| DGFC | 0.79 | 0.03 | 0.05 | 0.10 | 0.18 |
| Concrete | 0.41 | 0.05 | 0.05 | 0.13 | 0.15 |
| **Combined** | **1.07** | **0.08** | **0.10** | **0.20** | **0.25** |

## CONCLUSIONS

The updated line-laser system produces MPD values in strong agreement with those produced by the current point-laser system on flexible pavement. Given the $R^2$ values shown in Figures 5-7 and 5-8, at a minimum this system can perform the same level of macrotexture analysis that the current point-laser system provides. Additionally, Figures 5-20 and 5-21 show that the two systems are capable of statewide macrotexture analysis with negligible influence related to laser angle or pavement type. When comparing MPD values to those from the CTM, the updated line-laser system is capable of capturing macrotexture on LGD concrete within an average error of ± 10.4% up to 70 mph. Similarly, this system has a slightly stronger correlation with ICC's FTM providing an average MPD difference of ± 9.3% on LGD concrete.

Based on the results above, the optimized line-laser system can produce repeatable results on all pavement types with an average repeatability limit, *r*, of 0.25 millimeters. Additionally, the reproducibility limit, $R$, between two different vehicles and operators was determined to be 0.30 millimeters. These values were determined to be very close to the precision results of the point-laser in the same test sections. In addition, when comparing MPD values to those produced by the CTM, the line-laser had shown an average error of ± 11.2% on all pavement types. When compared to the point-laser on flexible pavement, the average error was determined to be ± 4.9% for Unit 12 and ± 5.4% for Unit 13 . While there was no evidence that the line-laser angle influences MPD, investigation of additional laser orientations is required to derive a conclusion.

Overall, the UNF research team believes that implementing the line-laser system is an improvement to the current macrotexture analysis process. Utilizing the updated line-laser system will allow the FDOT to accurately assess the macrotexture of Florida's longitudinally-ground concrete roadways at highway speeds. Additionally, the robust amount of data collected in each scan of the line-laser is expected to provide a more accurate representation of macrotexture on flexible pavement as well. As a result, the UNF research team recommends utilizing the updated line-laser system in production macrotexture analysis.

# CHAPTER 6 – IMPLEMENTATION PLAN

## OPERATIONAL PROCEDURE

The updated line-laser system was designed to replace the current point-laser system regarding its macrotexture data collection that occurs during friction tests. Therefore, its primary role in field production is to accurately produce an MPD value pertaining the location of a locked-wheel skid test. This operation is performed using ICC's MDRPro data collection software. The friction operators will collect texture data with the line-laser following their current procedure for testing. However, they should ensure certain preparations are completed before starting data collection, which are listed in Appendix A.

## DATA PROCESSING PROCEDURE

Currently, data collected with the line-laser system needs to be trimmed and processed through software developed by ICC. This software will be referred to as the "Processing Utility." Since the line-laser begins collecting data as soon as the operator enters the MDRPro "Run" screen, the Processing Utility removes all data within the binary (.bin) and .csv files that do not correspond to a locked-wheel skid test. This is done by correlating event information located in the MDRPro "Skid Logs," which are automatically generated during collection, to the binary file containing texture measurements. If texture data was collected with "Continuous Collection" enabled as opposed to "Skid Only Collection," the Processing Utility will only keep measurements that were collected with the DMI enabled. In addition to the trimming feature, the Processing Utility allows the operator to select the appropriate lowpass filter, as required by ASTM E1845, that is applied to each texture profile. In the current configuration, line-laser data should be processed using the Version 1 Butterworth Filter. All files should be trimmed and processed through the Utility at the end of each collection day to preserve computer memory. Instructions on how to perform this task are shown below in Appendix B.

## CALIBRATION PROCEDURE

The Gocator line-lasers are delivered pre-calibrated from the manufacturer. However, the sensor should undergo an alignment procedure to compensate for inaccuracies related to its mounted orientation. The manufacturer does not state a recommended alignment frequency, however, the UNF research team recommends that this process is completed in conjunction with the bimonthly friction calibration procedure. The sensor alignment procedure is easily completed within the Gocator Web interface and should be executed on a level surface (i.e., the State Materials Office calibration bay). Instructions on how to perform the alignment procedure are shown below in Appendix C.

## DEVICE VERIFICATION

To ensure the line-laser is accurately producing MPD values, the device should undergo precision testing in conjunction with the bimonthly friction calibration. However, due to the nearest location of a suitable LGD concrete test site, it is recommended that precision testing on concrete is completed every other calibration (every four months) until the FDOT test track on US 301 is completed. Once the test track containing LGD concrete is completed, device verification on all three pavement types (open-grade, dense-grade, and concrete) should occur on a bimonthly basis. It should be noted that this procedure is already implemented as part of the current calibration process at five verification sites containing open-grade and dense-grade pavement. Verifying the line-laser should be conducted in the same manner as was done with the point-laser. This includes five lockups spaced approximately 500 feet apart at each site with the water tank at half capacity and a full fuel tank. The MPD values produced by the line-laser should be within ±10% of historical values or those produced by reference devices.

### PARAMETER CONFIGURATION

The updated line-laser system uses a configuration file containing the optimized parameters as determined by the UNF research team. The line-laser parameters are accessible through a Web-based interface which can be locally accessed through the friction truck's onboard computer. If an operator requires specific adjustments to these parameters, instructions on how to execute this endeavor are shown below in Appendix D.

### HANDLING LEGACY POINT-LASER DATA

Accepted point-laser data stored in a State Materials Office database, also referred to as "legacy data," can be adjusted to provide stronger agreement with data produced by the updated line-laser system using a series of regression equations. As part of Task 4, the UNF research team determined these regression equations between the line-laser and point-laser systems using statewide texture data. Each regression equation pertains to a specific pavement type and should be used accordingly. Since the line-laser and point-laser produce MPD values that strongly agree on flexible pavement, the equations for open-grade and dense-grade only provide a very slight adjustment to point-laser MPD. Therefore, it is not currently necessary to adjust legacy data on flexible pavement using the regression equations below. However, on LGD concrete, legacy MPD values collected with the point-laser should be corrected using its corresponding regression equation. While the accuracy of the converted MPD values will vary, utilizing this equation to convert legacy LGD concrete data provides a more accurate depiction of the pavement's true macrotexture at each site. These regression equations are shown below in Table 6-1.

Table 6-1. Regression equations for comparisons between line-laser and point-laser MPD.

| MPD Between the Line-Laser and the Point-Laser (inches) | |
|---|---|
| OGFC | $MPD_{Line}$ = 0.8918*$MPD_{Point}$ + 0.0073 ($R^2$ = 0.885) |
| DGFC | $MPD_{Line}$ = 0.9351*$MPD_{Point}$ + 0.0029 ($R^2$ = 0.974) |
| LGD Concrete | $MPD_{Line}$ = -0.1402*$MPD_{Point}$ + 0.0269 ($R^2$ = 0.008) |

| MPD Between the Line-Laser and the Point-Laser (millimeters) | |
|---|---|
| OGFC | $MPD_{Line}$ = 0.8918*$MPD_{Point}$ + 0.1854 ($R^2$ = 0.885) |
| DGFC | $MPD_{Line}$ = 0.9351*$MPD_{Point}$ + 0.0731 ($R^2$ = 0.974) |
| LGD Concrete | $MPD_{Line}$ = -0.1402*$MPD_{Point}$ + 0.6844 ($R^2$ = 0.008) |

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# APPENDIX A – OPERATIONAL PROCEDURE

## Operating the Line-Laser

**Step 1.** Clean the line-laser emitter window and sensor window at the beginning of each day using a microfiber cloth. **This is crucial to ensure that data collection is accurate.**


Figure A-1. A dirty line-laser.

**Step 2.** Open the latest version of MDRPro.

**Step 3.** Select the "Hardware Options" tab at the top of the interface.

**Step 4.** Click the "Hardware Setup" button.

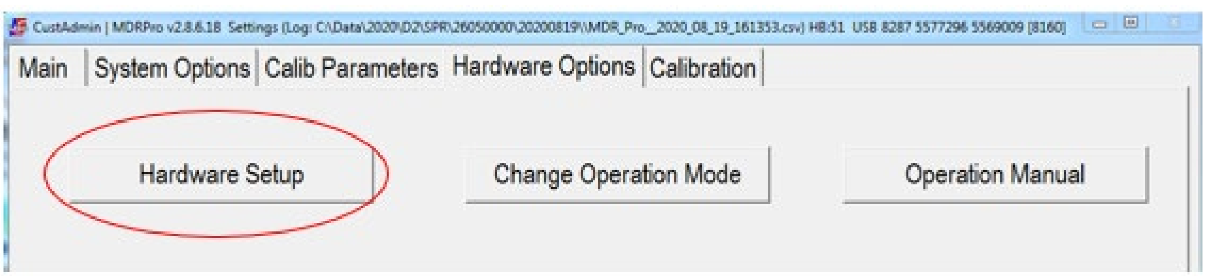



Figure A-2. MDRPro interface.

**Step 5.** Under the "Lasers" tab, click "Laser 2" and ensure that it is enabled.

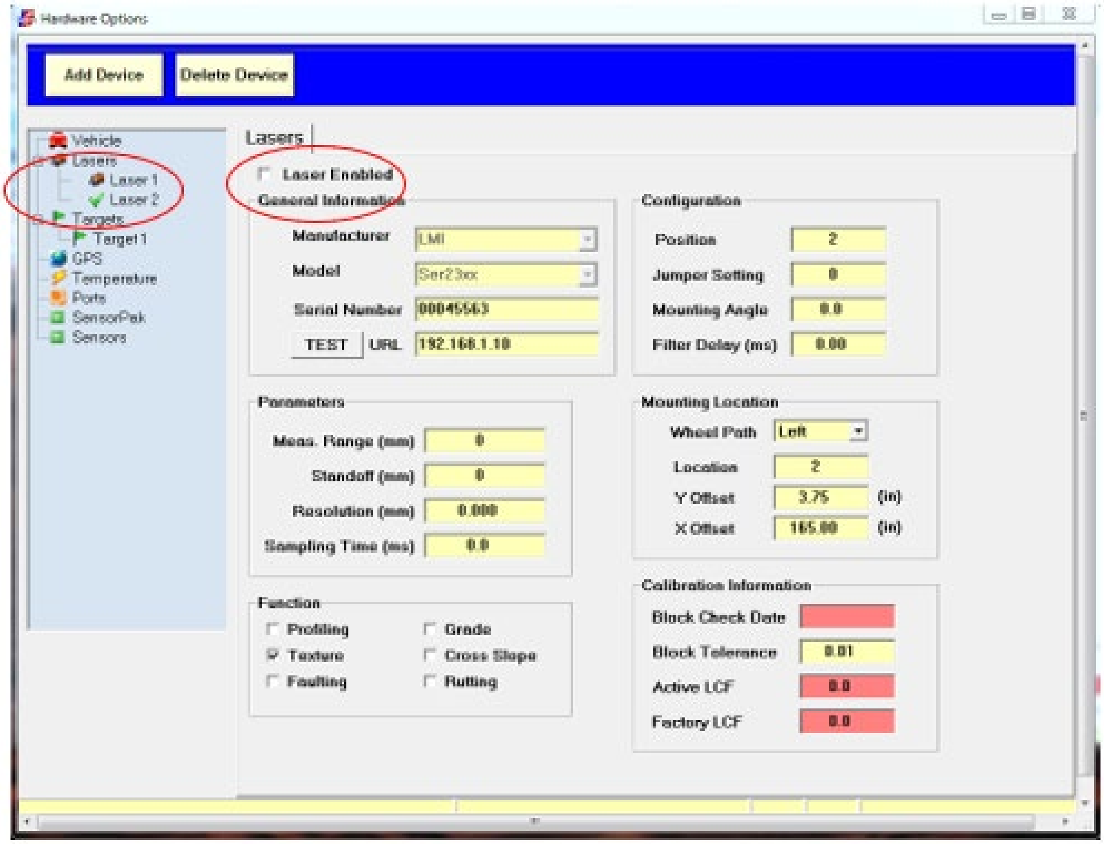



Figure A-3. MDRPro "Hardware Setup" page.

**Step 6.** After ensuring that the laser is enabled, allow the equipment to warmup for at least **30 minutes** before data collection. This will allow for even heat distribution throughout the system and promote high quality data collection.

**Step 7.** Press F9 or the "Collect" button located on the Main page and begin macrotexture analysis (MPD) by initiating locked-wheel skid tests.


Figure A-4. MDRPro "Main" page.

# APPENDIX B – DATA PROCESSING PROCEDURE

## Processing Line-Laser Data

**Step 1.** To use the ICC Processing Utility, the computer must contain the Microsoft C++ Redistributable for Visual Studio 2015-2019 located here.

**Step 2.** Copy the Processing Utility folder onto the computer. **Note:** the executable must remain in the folder containing all other dependent files, as shown below.

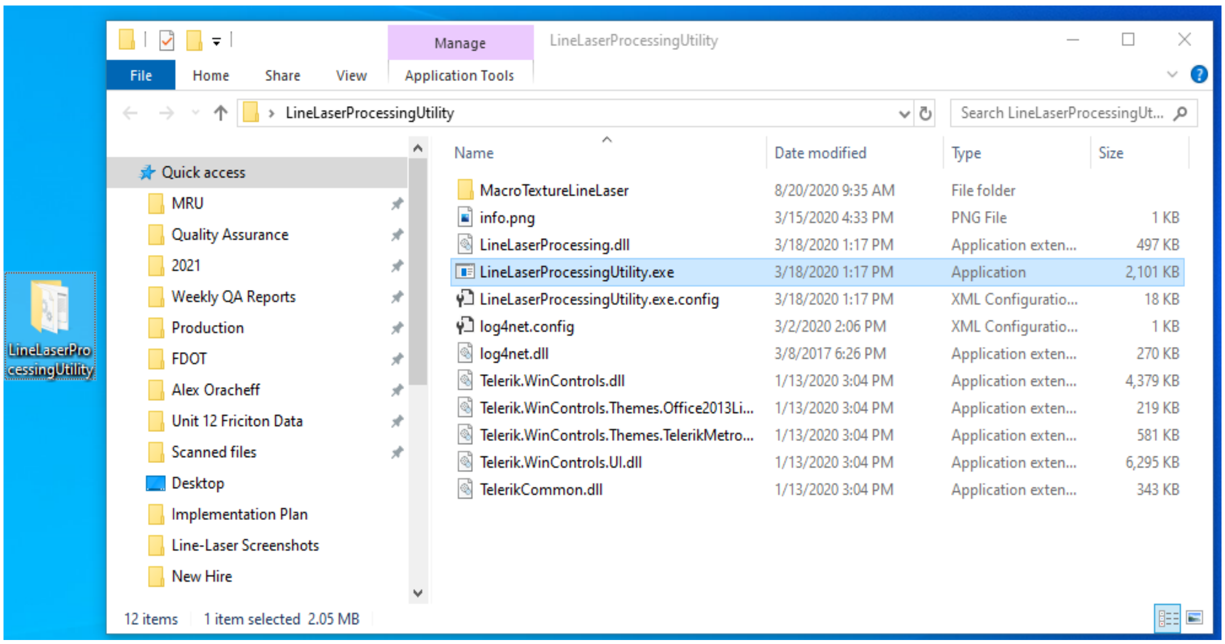



Figure B-1. Accessing ICC's processing utility.

**Step 3.** Run "LineLaserProcessingUtility.exe" as shown above.

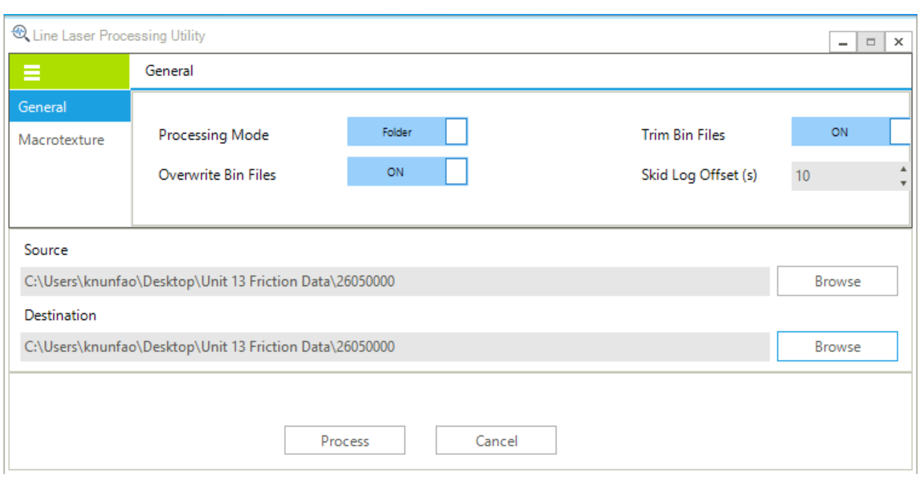



Figure B-2. Processing utility main screen.

**Step 4.** When the Processing Mode is set to "Folder", the utility allows operators to batch process multiple files for a given roadway or individual files when set to "File." Determine whether you would like to process a single file or the entire folder.

**Note:** Although you can process multiple roadways at once, all the processed files will be output to a single location, so it is not recommended to do this.

**Step 5.** Locate the folder/file you wish to be processed under "Source" and insert the same folder/file into the "Destination" location. These will replace the untrimmed files.

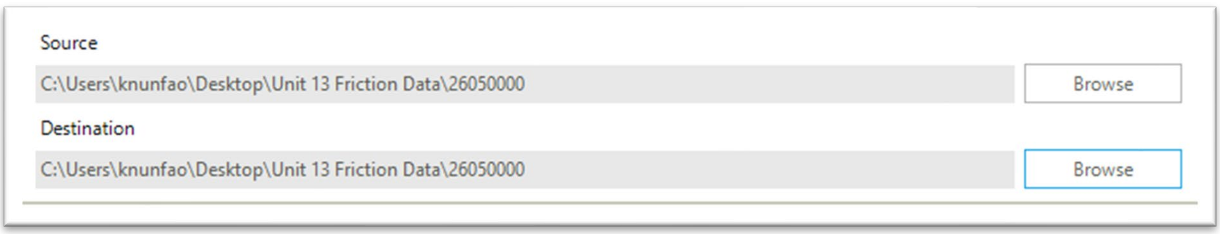



Figure B-3. Choosing the source and destination folders for processing.

**Step 6.** Next, click the  symbol in the upper left-hand corner and select "Macrotexture."

**Step 7. Note* The "Default filter type…" is the Butterworth Filter – V1.**

**Step 8.** Select the appropriate lowpass filter (Butterworth V1) in the dropdown menu.

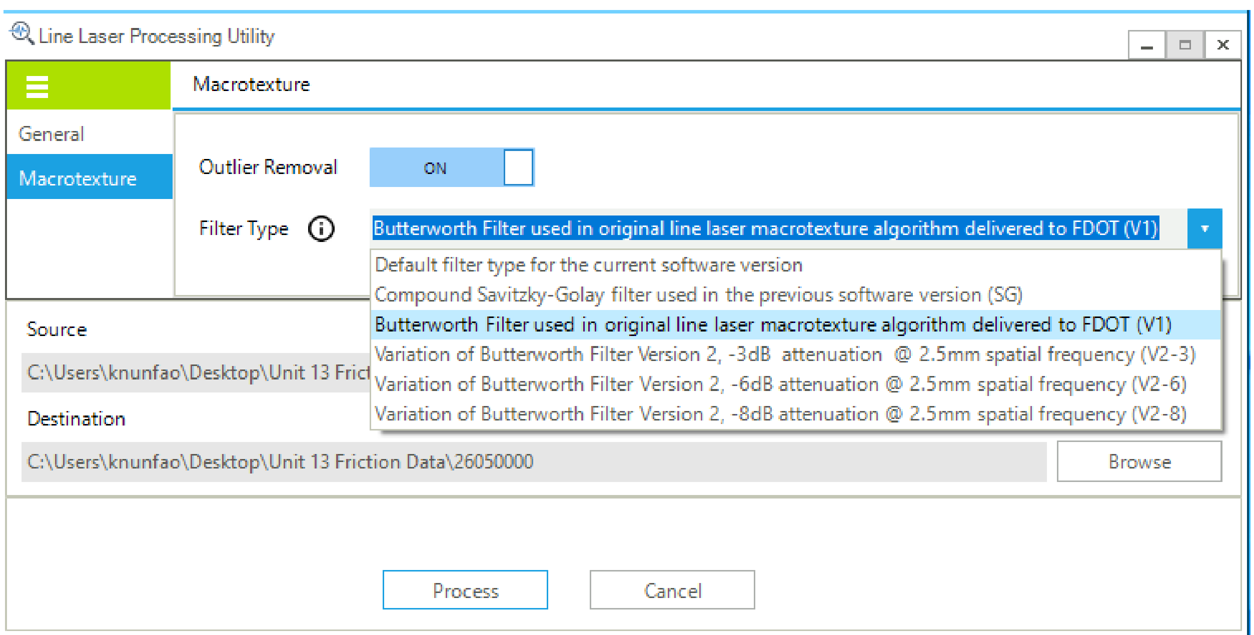
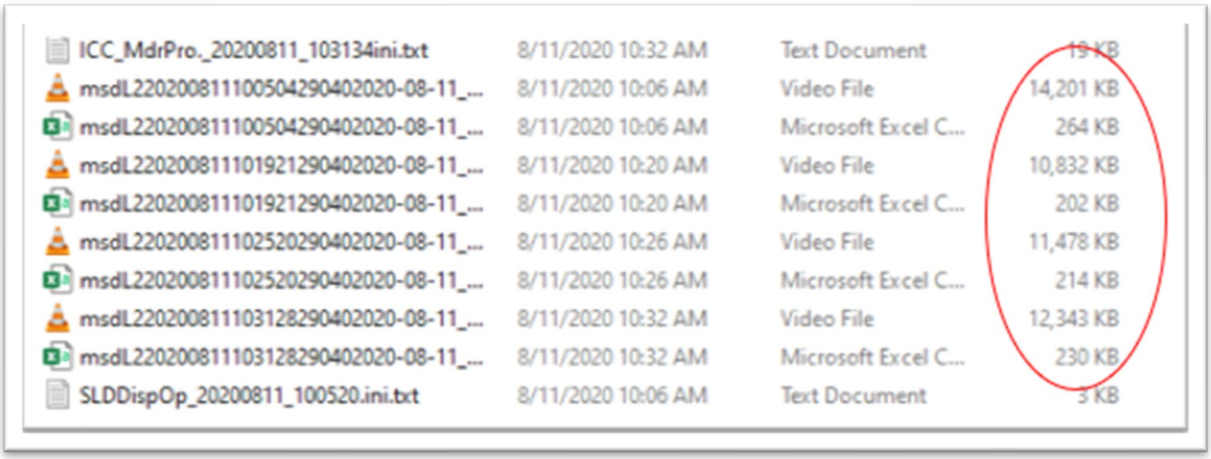


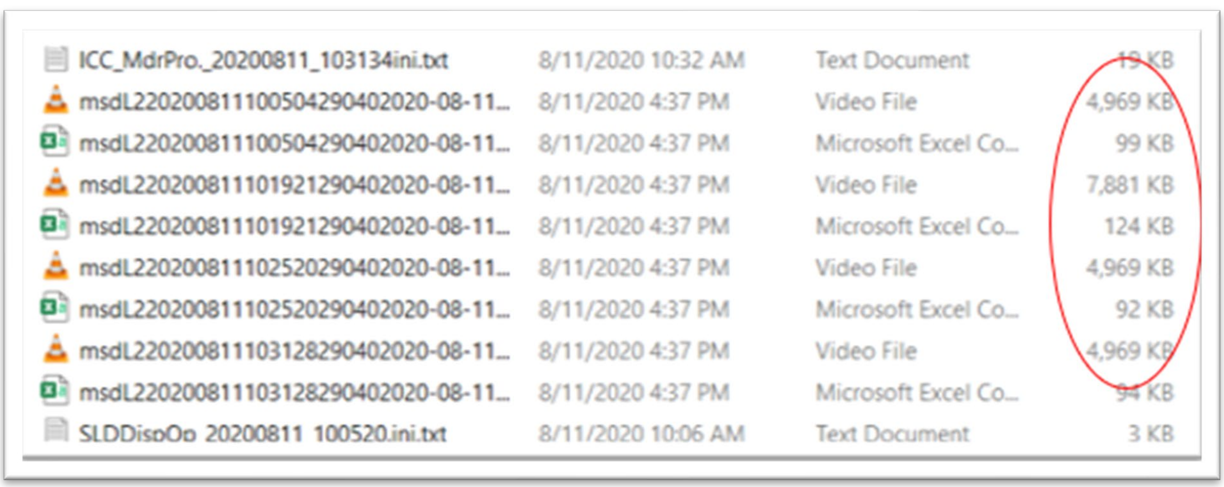

Figure B-4. Selecting the lowpass filter for data processing.

**Step 9.** Finish processing by clicking "Process" at the bottom of the interface. The processed files will be in their designated Destination folder. Proceed to Steps 9 and 10 for instructions on how to output a report summarizing the line-laser data.



| | | | |
|---|---|---|---|
| ICC_MdrPro._20200811_103134ini.txt | 8/11/2020 10:32 AM | Text Document | 19 KB |
| msdL220200811100504290402020-08-11_... | 8/11/2020 10:06 AM | Video File | 14,201 KB |
| msdL220200811100504290402020-08-11_... | 8/11/2020 10:06 AM | Microsoft Excel C... | 264 KB |
| msdL220200811101921290402020-08-11_... | 8/11/2020 10:20 AM | Video File | 10,832 KB |
| msdL220200811101921290402020-08-11_... | 8/11/2020 10:20 AM | Microsoft Excel C... | 202 KB |
| msdL220200811102520290402020-08-11_... | 8/11/2020 10:26 AM | Video File | 11,478 KB |
| msdL220200811102520290402020-08-11_... | 8/11/2020 10:26 AM | Microsoft Excel C... | 214 KB |
| msdL220200811103128290402020-08-11_... | 8/11/2020 10:32 AM | Video File | 12,343 KB |
| msdL220200811103128290402020-08-11_... | 8/11/2020 10:32 AM | Microsoft Excel C... | 230 KB |
| SLDDispOp_20200811_100520.ini.txt | 8/11/2020 10:06 AM | Text Document | 3 KB |

Figure B-5. File size *before* processing the line-laser data.



| | | | |
|---|---|---|---|
| ICC_MdrPro._20200811_103134ini.txt | 8/11/2020 10:32 AM | Text Document | 19 KB |
| msdL220200811100504290402020-08-11... | 8/11/2020 4:37 PM | Video File | 4,969 KB |
| msdL220200811100504290402020-08-11... | 8/11/2020 4:37 PM | Microsoft Excel Co... | 99 KB |
| msdL220200811101921290402020-08-11... | 8/11/2020 4:37 PM | Video File | 7,881 KB |
| msdL220200811101921290402020-08-11... | 8/11/2020 4:37 PM | Microsoft Excel Co... | 124 KB |
| msdL220200811102520290402020-08-11... | 8/11/2020 4:37 PM | Video File | 4,969 KB |
| msdL220200811102520290402020-08-11... | 8/11/2020 4:37 PM | Microsoft Excel Co... | 92 KB |
| msdL220200811103128290402020-08-11... | 8/11/2020 4:37 PM | Video File | 4,969 KB |
| msdL220200811103128290402020-08-11... | 8/11/2020 4:37 PM | Microsoft Excel Co... | 94 KB |
| SLDDispOp_20200811_100520.ini.txt | 8/11/2020 10:06 AM | Text Document | 3 KB |

Figure B-6. File size *after* processing the line-laser data.

# APPENDIX C – CALIBRATION PROCEDURE

## Calibrating the Line-Laser

Each line-laser system arrives precalibrated from the manufacturer. However, it is recommended by the UNF research team to perform a laser alignment with the bimonthly calibration process.

**Step 1.** Top off the vehicle fuel tank and fill the water tank to half capacity.

**Step 2.** Ensure that the vehicle is parked on a level surface (i.e., within the calibration bay).

**Step 3.** Open Google Chrome and type "192.168.1.10" into the search bar. Press "Enter."

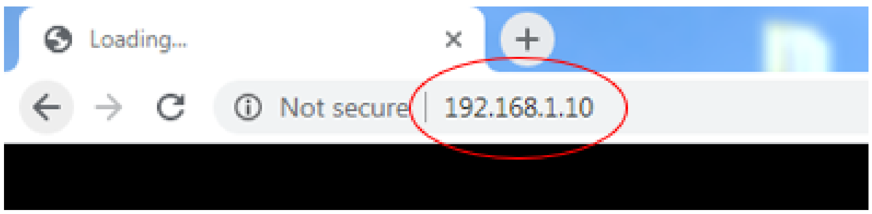



Figure C-1. Accessing the Gocator line-laser Web interface.

**Step 4.** When prompted, click "install the latest version."

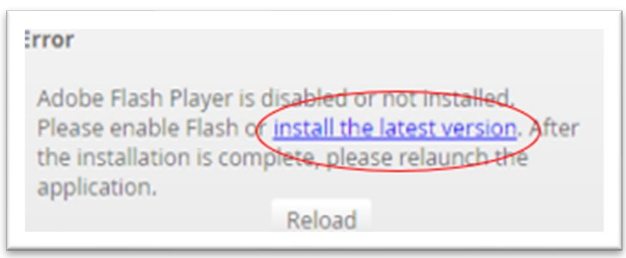



Figure C-2. Adobe Flash Player error.

**Step 5.** The pop-up shown below should appear. When it does, click "Allow."

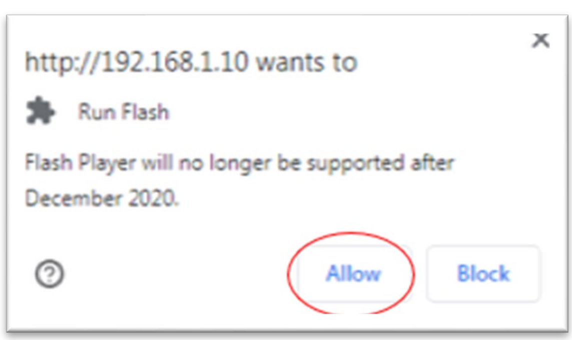



Figure C-3. Bypassing the Adobe Flash Player error.

**Step 6.** At this point, a loading symbol will appear in the center of the screen. In the upper right-hand corner of the page, click the symbol shown below and select “Run Flash this time.” **Note:** The loading symbol will disappear after some time and a pop-up will appear. If this happens, close the page, and begin from Step 1.

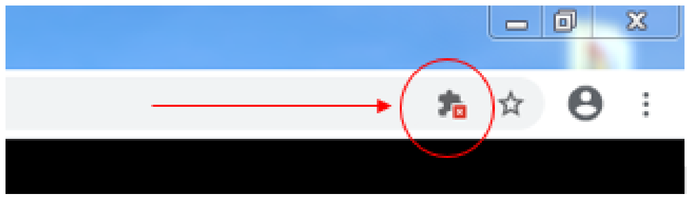


Figure C-4. Bypassing the Adobe Flash Player error.

**Step 7.** Finally, the Gocator interface should appear. In the upper left-hand corner, ensure you have the “Scan” page selected. Under “Scan Mode,” select “Profile”.

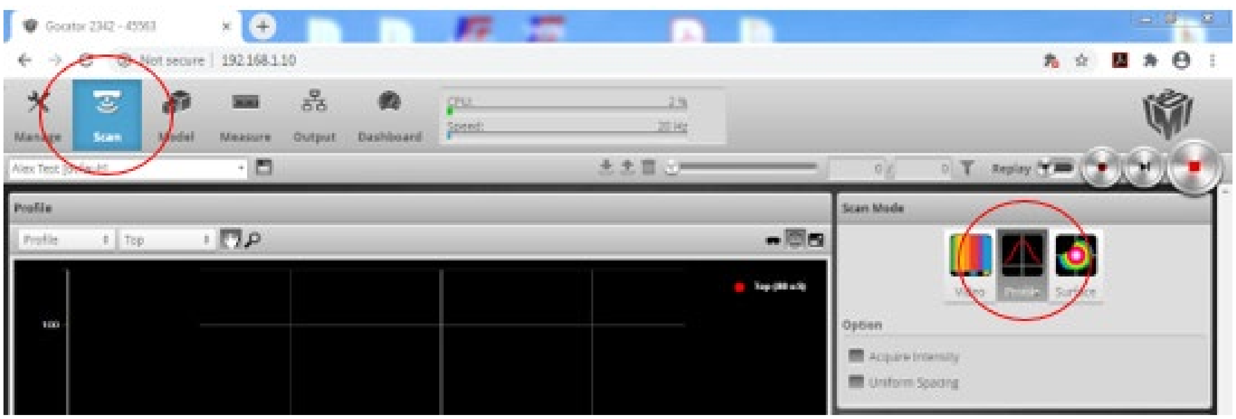



Figure C-5. Accessing the line-laser parameters.

**Step 8.** From there, click the “+” symbol located on the “Alignment” tab and set “Type” to “Stationary” and “Target” to “Flat Surface.”

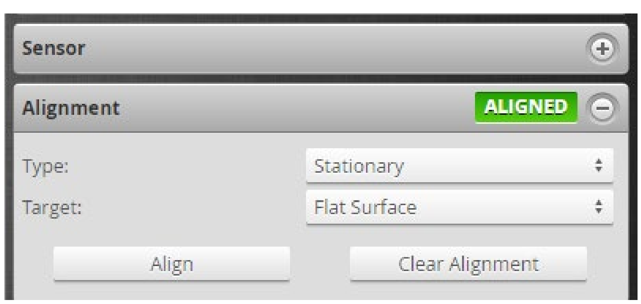



Figure C-6. Setting the correct alignment parameters.

**Step 9.** Click "Align."

**Step 10.** Perform a visual inspection of the laser profile to ensure that the emitted spectrum is level along the x-axis and at "0" on the z-axis. If so, the alignment is complete. If not, reaffirm that the vehicle is on a level surface and click "Align" until completed.

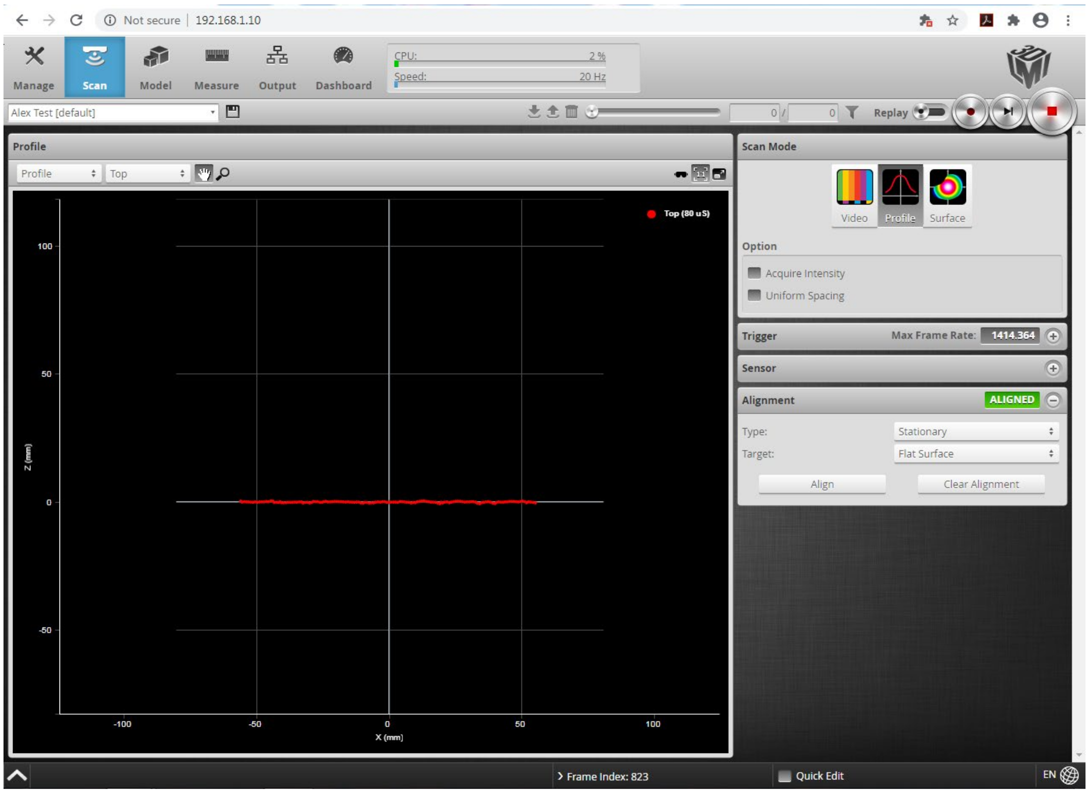



Figure C-7. User interface after a successful alignment.

**Step 11.** Run the verification sites containing open-grade, dense-grade, and LGD concrete pavement. Compare the line-laser MPD values with those from historical data and reference devices. The line-laser MPD values should be within a ±10% difference of the accepted MPD values to pass. If the average difference in MPD for the five lockups exceeds 10% for a given site, clean the line-laser's sensor and emitter windows and begin again at Step 2.

**Step 12.** Once a year, operators should run the line-laser at each verification site with the vehicle's water tank empty, at half capacity, and at full capacity, totaling three runs per site. This will ensure that the laser is accurate at varying heights. MPD values should be within a within a ±10% difference of the accepted MPD values to pass.

# APPENDIX D – PARAMETER CONFIGURATION

## Configuring the Line-Laser Parameters

**Step 1.** Open Google Chrome and type “192.168.1.10” into the search bar. Press “Enter.”

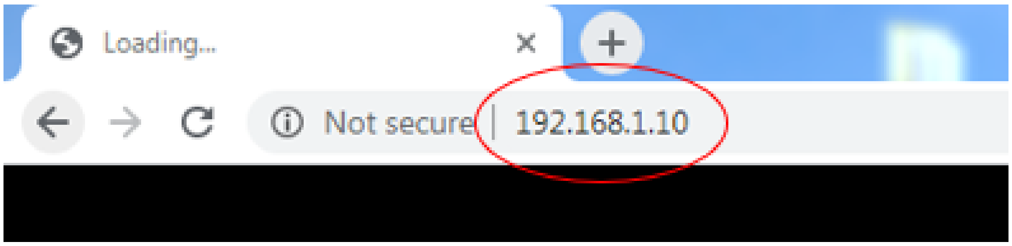



Figure D-1. Accessing the Gocator line-laser Web interface.

**Step 2.** When prompted, click “install the latest version.”

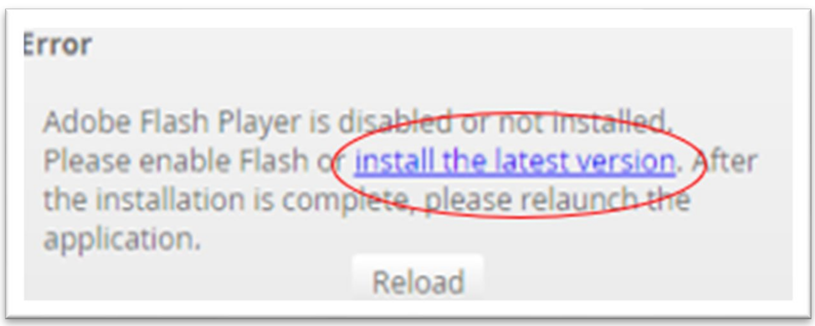



Figure D-2. Adobe Flash Player error.

**Step 3.** The pop-up shown below should appear. When it does, click “Allow.”

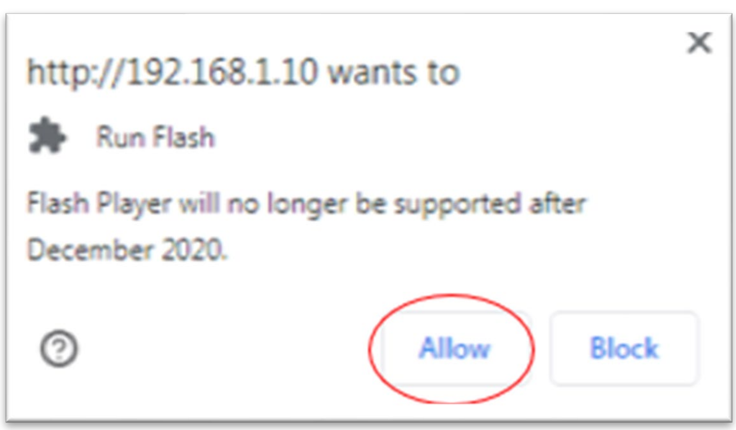



Figure D-3. Bypassing the Adobe Flash Player error.

**Step 4.** At this point, a loading symbol will appear in the center of the screen. In the upper right-hand corner of the page, click the symbol shown below and select "Run Flash this time." **Note:** The loading symbol will disappear after some time and a pop-up will appear. If this happens, close the page, and begin from Step 1.

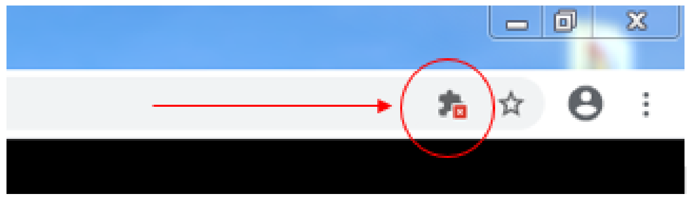


Figure D-4. Bypassing the Adobe Flash Player error.

**Step 5.** Finally, the Gocator interface should appear. In the upper left-hand corner, ensure you have the "Scan" page selected. Under "Scan Mode," select "Profile".

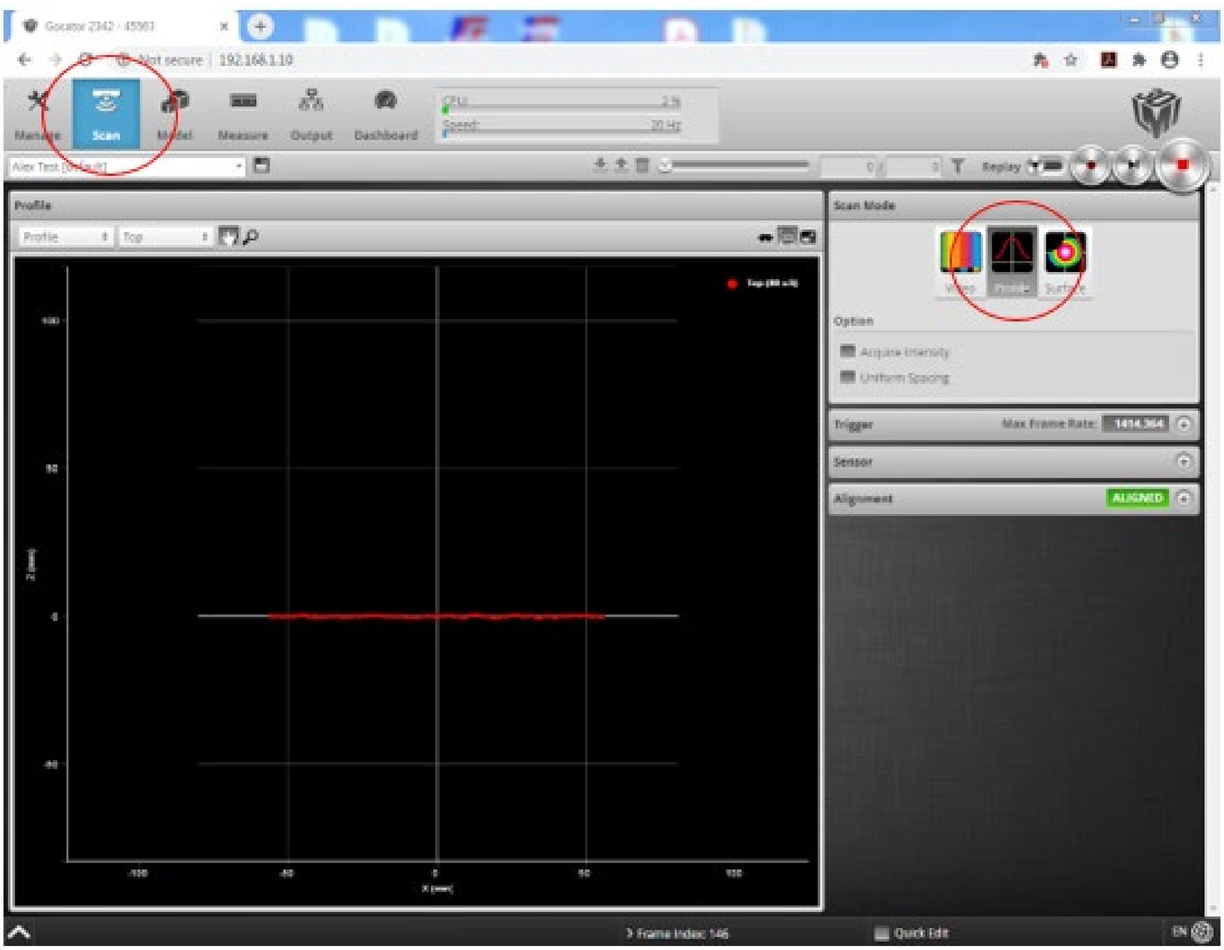



Figure D-5. Accessing the line-laser parameters.

**Step 6.** Clicking the "+" symbol on the "Trigger" tab opens a window where the operator to change the scan frequency of the line-laser. The default setting should be 20 Hz.

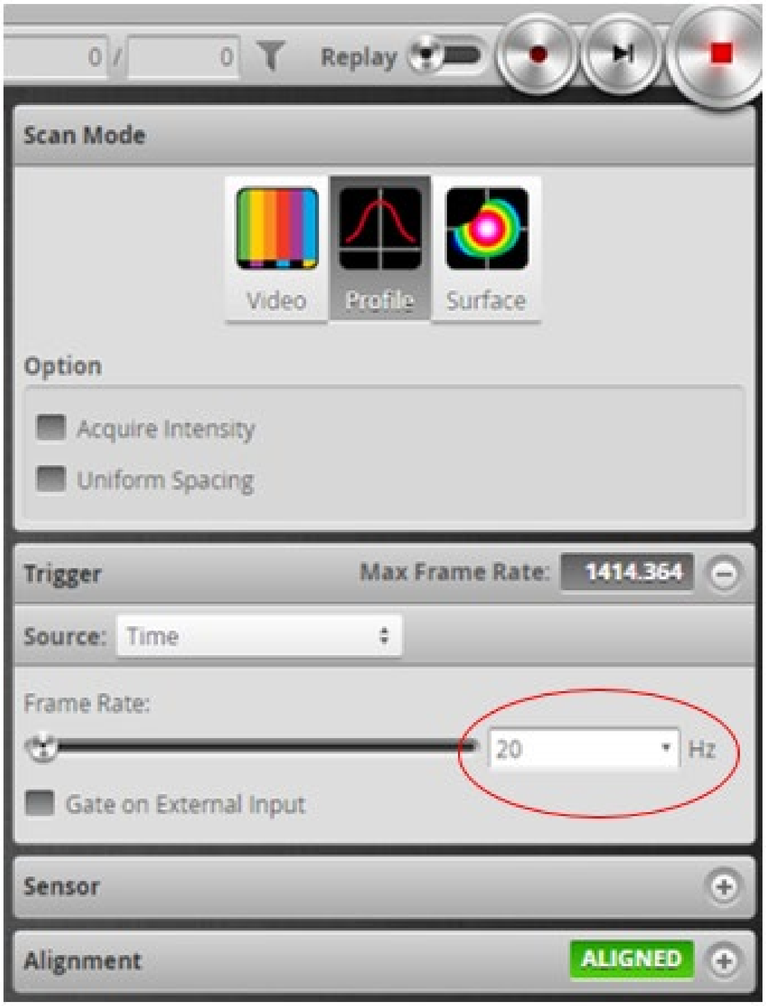



Figure D-6. Adjusting the line-laser scan frequency.

**Step 7.** Clicking the "+" symbol on the "Sensor" tab opens a window where the operator to change the exposure time (Step 8), point-spacing (x-resolution) and measurement precision (z-resolution) (Step 9), tracking window area (Step 10), and other "Advanced" line-laser parameters (Step 11).

**Step 8.** Under the "Exposure" section on the "Sensor" tab, the operator can input a range of exposure times where the line-laser will automatically select a best-fit value based on the pavement color. The default range is 20 to 80 microseconds.

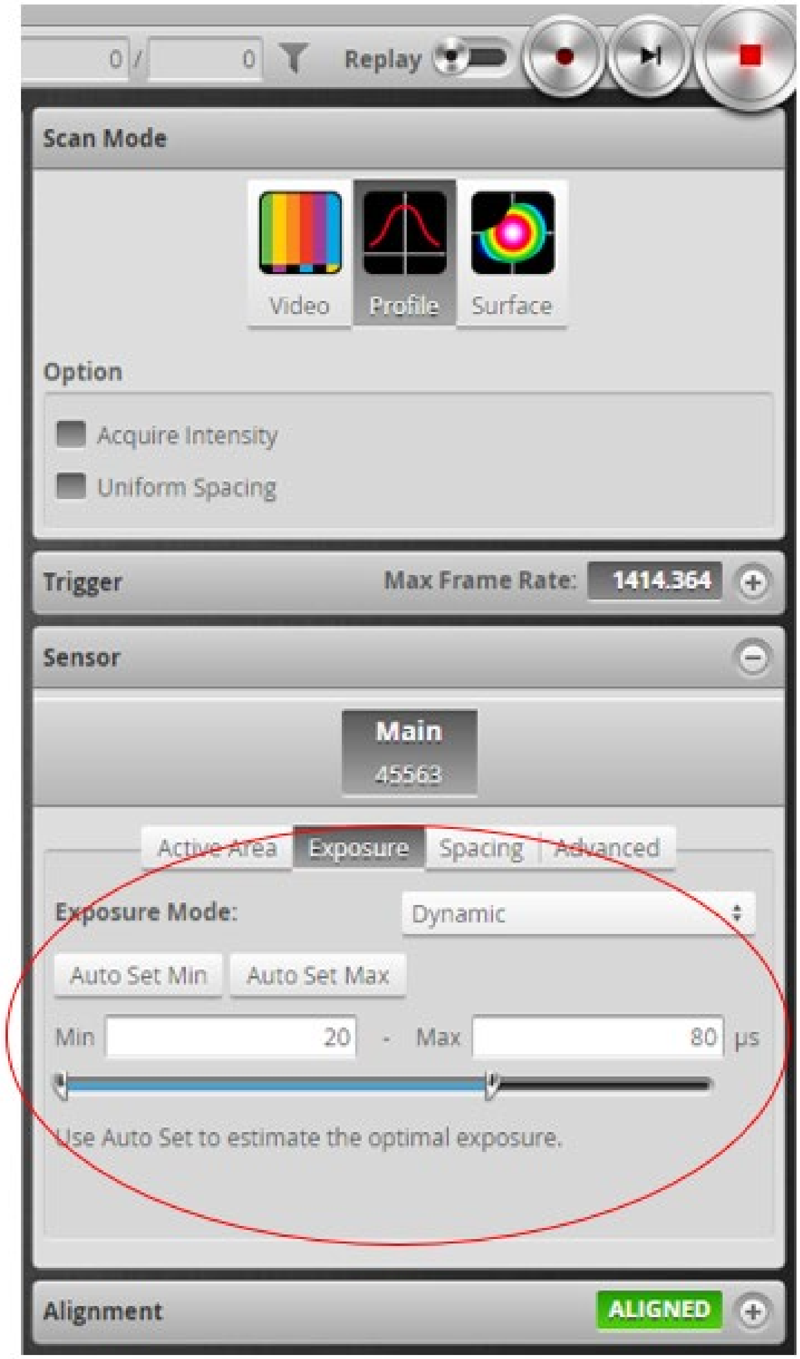



Figure D-7. Adjusting the line-laser exposure time.

**Step 9.** Under the "Spacing" section on the "Sensor" tab, the operator can select a "Sub-Sampling" value pertaining the z-axis or x-axis. Sub-Sampling in the x-direction refers to the fraction of data points that will be used in the mean-segment depth calculation (MSD) for each profile. At a maximum, there can be 1280 points along the length of the laser spectrum. Sub-Sampling in the z-direction refers to the precision of height measurements, where a one-to-one value represents maximum precision. Operating the line-laser at maximum precision reduces the maximum possible scan frequency and limits the device operating speed. The default values are ½ in the x-direction and 1:1 in the z-direction.

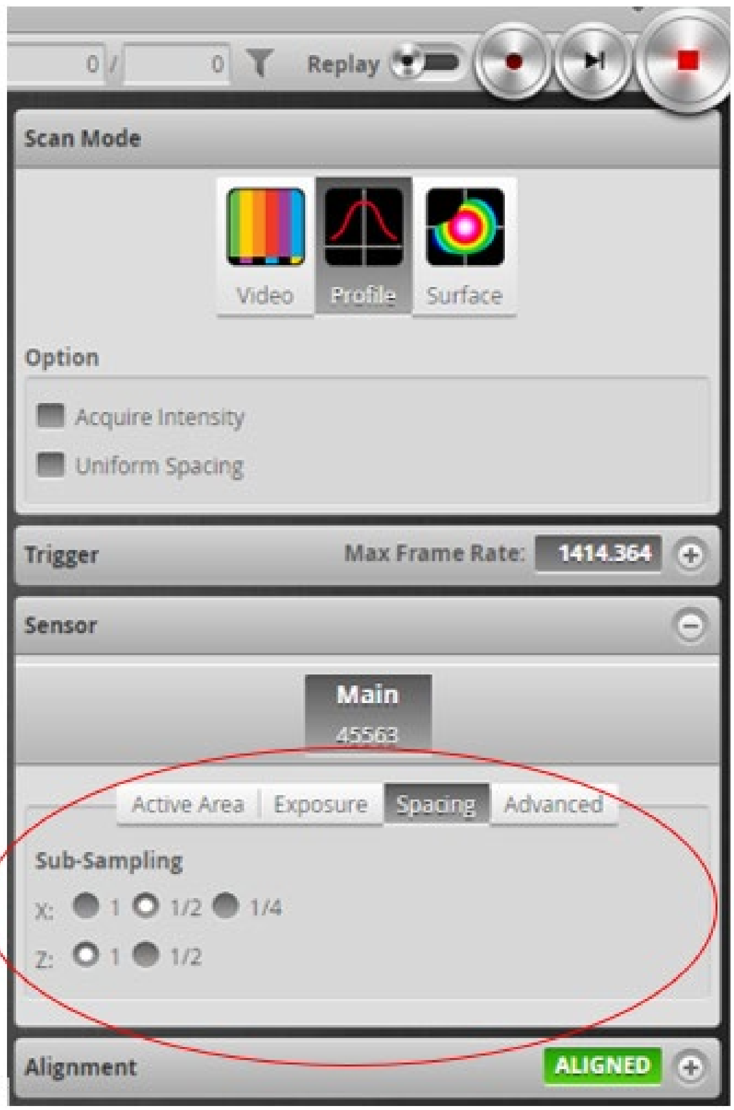



Figure D-8. Adjusting the line-laser exposure time.

**Step 10.** Under the “Active Area” section on the “Sensor” tab, the operator can input the area of the line-laser’s field of view for data collection. The system has a “Tracking Window” feature that searches within the active area for the line-laser’s return light to ensure all measurements are captured. Reducing the active area allows the line-laser to operate at higher scan frequencies. The default parameters are shown below.

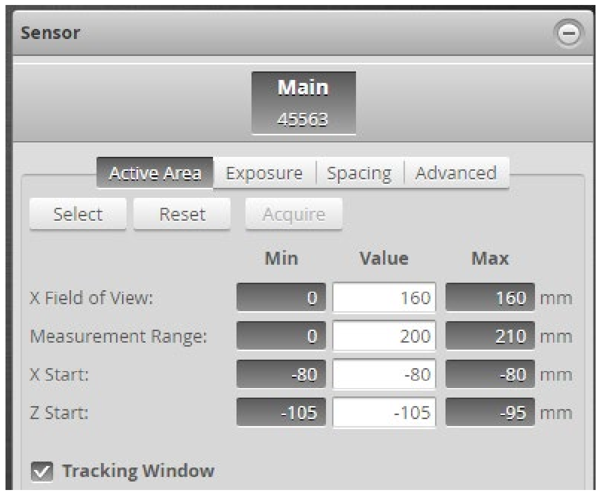



Figure D-9. Active area settings.

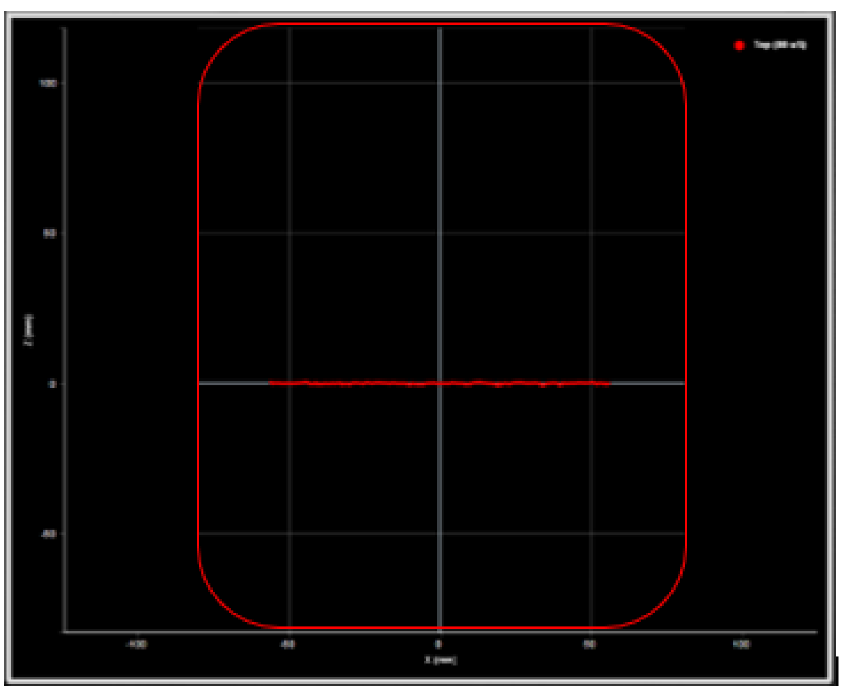


Figure D-10. Example of the active area (tracking window) shown in red.

**Step 11.** Under the "Advanced" section on the "Sensor" tab, there are several configurable parameters pertaining to the line-laser emitter and sensor. The UNF research team determined the most suitable dynamic exposure sensitivity value to be 5. These parameters should remain unchanged unless specified by the Research Engineer.

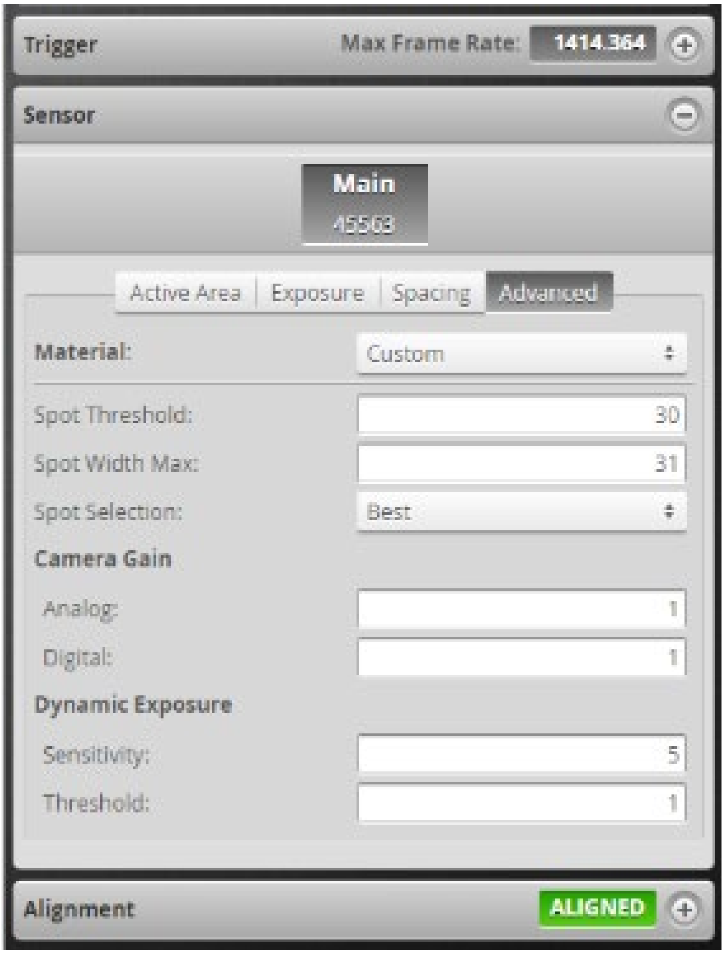



Figure D-11. Advanced settings.

# Appendix E – Optimized Line-Laser Parameters

## Optimized Line-Laser Parameters

- **Exposure:** Dynamic Range (20 μs – 80 μs)
- **X-Resolution:** Non-Uniform Spacing with ½ Sub-Sampling
- **Z-Resolution:** No Sub-Sampling
- **Sampling Rate:** 20 Hz
- **Processing:** Butterworth Lowpass Filter
- **Dynamic Exposure Sensitivity:** 5