Raised Pavement Marker (RPM) Assessment Using Highway Speed Mobile Retroreflectivity Technology

Contract Number: BE715

Final Report

Submitted to:
Project Manager: Charles Holzschuher, P.E.
State Pavement Evaluation Engineer
Florida Department of Transportation
5007 N.E. 39th Avenue Gainesville, FL 32609
(352) 955-6341
Email: Charles.Holzschuher@dot.state.fl.us

Submitted by:
Principal Investigator: James H. Fletcher, Ph.D.
University of Florida
Mechanical & Aero Engineering
PO Box 116300
Gainesville, FL 32611-6300
(904) 620-1844

Co-Principal Investigator: William Lear, Ph.D.
University of Florida
Mechanical & Aero Engineering
PO Box 116300
Gainesville, FL 32611-6300
(352) 392-7572

Research Engineers: Alexander Oracheff and Ali Shahin
University of North Florida
Mechanical Engineering
1 UNF Dr.
Jacksonville, FL 32224
(352) 955-6336
Email: Alex.Oracheff@dot.state.fl.us

April 2021

DISCLAIMER

The opinions, findings, and conclusions expressed in this publication are those of the author(s) and not necessarily those of the Florida Department of Transportation or the U.S. Department of Transportation.

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

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Raised Pavement Marker (RPM) Assessment Using Highway Speed Mobile Retroreflectivity Technology		5. Report Date April 2021
		6. Performing Organization Code
7. Author(s) Alexander Oracheff, Ali Shahin, Dr. James H. Fletcher, and Dr. William Lear		8. Performing Organization Report No.
9. Performing Organization Name and Address University of North Florida 1 UNF Drive Jacksonville, FL 32224		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. BE715
12. Sponsoring Agency Name and Address Florida Department of Transportation 605 Suwannee Street, MS 30 Tallahassee, FL 32399		13. Type of Report and Period Covered Final Report March 2019 – April 2021
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

The focus of this study was to configure a Laserlux G7 mobile retroreflectivity unit (MRU) to accurately and repeatably detect and measure the retroreflectivity of in-service raised pavement markers (RPMs). At this time, the Florida Department of Transportation (FDOT) assesses the quality of in-service RPMs as part of a visual inspection.

Currently, the FDOT State Materials Office collects 25,000 lane miles of line-stripe pavement marking (PM) retroreflectivity data each year using MRUs. Since these MRUs were designed to measure PMs in units of R_L (mcd/m^2/lux), a primary objective of this study was to derive regression equations that correlate the industry standard units for RPMs [R_I (mcd/lux)] and the R_L values collected by the MRU. An additional complexity is that the MRU utilizes a 30-meter measurement geometry related to R_L, and R_I is calculated at a 220-meter measurement geometry.

After executing many research-based experiments, modifications were made to the Laserlux G7 MRU to detect and measure RPM retroreflectivity in terms of R_L. Next, using a 220-meter geometry RPM retroreflectometer, the research team collected reference retroreflectivity readings of in-service RPMs on several roadways throughout Northeast and Central Florida. The modified MRU was then used to capture R_L measurements on the same RPMs so that the research team could evaluate a relationship between R_L and R_I. The results show that the modified MRU can effectively be used to assess RPM retroreflectivity in tenth-mile intervals in a highly repeatable manner with an average error in estimated R_I of ±16%.

17. Key Word	18. Distribution Statement		
FDOT, Pavement, Non-Destructive Testing, RPM, MRU, Mobile, Retroreflectivity, Laserlux, Retroreflectometer, Pavement Markings, Gamma Scientific, UNF, UF, RoadVista			
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 98	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

EXECUTIVE SUMMARY

Raised pavement markers (RPMs) are traffic safety control devices that are installed on roadways to delineate lanes. The condition of an RPM is assessed primarily by its retroreflectivity. Retroreflection is the process in which light is returned in the opposite direction of the source light path, which makes the entrance and exit light paths almost parallel. This property is often maintained over wide variations of the direction of incident radiation. Currently, the Florida Department of Transportation (FDOT) assesses the quality of in-service RPMs as part of a visual inspection procedure. Due to the subjectivity of visual inspections and the inability to perform them on a large scale, the FDOT desires a method of detecting and quantifying RPM retroreflectivity on a network level. A prospective solution was to modify an existing vehicle-mounted mobile retroreflectivity unit (MRU) used for assessing line-stripe pavement markings (PMs) to also analyze RPMs.

Currently, the FDOT State Materials Office collects 25,000 lane miles of line-stripe PM retroreflectivity data each year using Laserlux G7 MRUs. Since these MRUs were designed to measure PMs in units of retroreflected luminance [R_L (mcd/m^2/lux)], a primary objective of this study was to derive regression equations that correlate the industry standard units of luminous intensity [R_I (mcd/lux)] for RPMs and the R_L values collected by an MRU. An additional complexity is that the MRU utilizes a 30-meter measurement geometry related to R_L, and R_I is calculated at a 220-meter measurement geometry.

The 220-meter RPM handheld retroreflectometer, which measures in R_I, used in this study was the Zehntner ZRP 6030+. The accuracy of the Zehntner handheld device was validated on a series of RPM samples in a photometric range. Comparing retroreflectivity measurements from the handheld to those from the photometric range indicated an average measurement error of ±6.6%. As a result, subsequent testing used measurements produced by the Zehntner handheld (R_I) as a “ground-truth” for comparisons with MRU readings (R_L).

After executing many research-based experiments, modifications were made to the Laserlux G7 MRU to detect and measure RPM retroreflectivity in terms of R_L. Next, using the Zehntner RPM retroreflectometer, the research team collected reference retroreflectivity readings of in-service RPMs on several roadways throughout Northeast and Central Florida. The modified MRU was then used to capture R_L measurements on the same RPMs to evaluate a relationship between R_L and R_I. The results show that the modified MRU can effectively be used to assess RPM retroreflectivity in tenth-mile intervals in a highly repeatable manner with an average error in estimated R_I of ±16%. Additionally, data processing software was designed to summarize information extracted from the MRU produced RPM files. Within the output of this data processing software are estimated R_I values and three classifications that classify each tenth-mile reading as “LOW”, “MID”, or “HIGH”. Overall, utilizing the modified MRU for statewide RPM assessments is a significant improvement from the current process of visual assessments and allows maintenance personnel to quantify RPM quality on a network level.

TABLE OF CONTENTS

List of Figures

LIST OF TABLES

CHAPTER 1 - INTRODUCTION

Raised pavement markers (RPMs) are traffic safety control devices that are installed on roadways to delineate lanes. The condition of an RPM is assessed primarily by its retroreflectivity. Retroreflection is the process in which light is returned in the opposite direction of the source light path, which makes the entrance and exit light paths almost parallel. This property is often maintained over wide variations of the direction of incident radiation. Currently, the Florida Department of Transportation (FDOT) assesses the quality of in-service RPMs as part of a visual inspection procedure. Due to the subjectivity of visual inspections and the inability to perform them on a large scale, the FDOT desires a method of detecting and quantifying RPM retroreflectivity on a network-level. A prospective solution was to modify an existing vehicle-mounted mobile retroreflectivity unit (MRU) used for assessing line-stripe pavement markings (PMs) to also analyze RPMs. Figure 1-1 shown below contains images of an RPM and a PM.

Figure 1-1. Class B RPM commonly found in Florida (left). Centerline PM (right).

MRUs are primarily used for measuring the retroreflectivity of PMs and ignore RPMs through data filtering. This is done in an effort to prevent unwanted influence on PM retroreflectivity data. In recent years, MRU technology has greatly increased its data sampling rate, which could potentially count in-place RPMs and measure their retroreflectivity. This information would be recorded separately from the PM data, thus providing a way to assess network-level RPM retroreflectivity at highway speeds.

Previous studies conducted on RPMs addressed installation standards, cost effectiveness, safety, and in-lab RPM retroreflectivity standard evaluations [1, 2, 3, 4]. However, there have been minimal assessments of in-service retroreflectivity, especially retroreflectivity measurements using highway-speed mobile technology.

This project includes examining the feasibility of network-level RPM retroreflectivity assessments, development of equipment and software, determination of measurement precision, and survey protocols for implementing RPM data onto the Pavement Marking Management System (PMMS). The PMMS is an online database hosted by the FDOT that contains 25,000 miles of PM retroreflectivity data collected each year as part of an annual survey. This database was established to improve the efficiency of statewide PM maintenance.

CHAPTER 2 - LITERATURE REVIEW

EXISTING STANDARDS

Currently there are no definitive standards or values for RPM retroreflectivity analysis using highway speed mobile reflectometers. The current RPM standards have focused on instrumentation measurement geometry for stationary field testing with portable handheld devices. These standards also prescribe the RPM orientation geometry and minimum values of retroreflectance for sufficient road safety [5, 8]. As for PM retroreflectivity, there are currently standard test methods for both MRU and portable handheld assessments [6, 7].

The FDOT's retroreflectivity assessment method for new RPMs is through random sample testing in a photometric range. The coefficient of luminous intensity, R_I, values measured in the photometric range are to be compared to the minimum acceptable retroreflectivity values as defined in ASTM D4280 [8]. Table 2-1 represents the minimum acceptable coefficient of luminous intensity, R_I values, for RPM retroreflectivity. Maintenance personnel check if the RPM is visible using a halogen light (replicating vehicle headlights) directed at them from a set distance of at least 250 feet. Since these on-road assessments are conducted as a visual inspection, it is subjective to each maintenance personnel. According to the Federal Highway Administration (FHWA) RPM guidelines, another criterion for Florida RPM maintenance is to replace RPMs in sections where eight or more consecutive markers are missing [9].

Table 2-1. ASTM D4280 minimum acceptable R_I values for new RPMs [8].

Entrance Angle Component β2	Observation Angle α	Minimum Value R_I, mcd/lx				
		White	Yellow	Red	Green	Blue
0°	0.2°	279	167	70	93	26
+20°/–20°	0.2°	112	67	28	37	10
Entrance Angle Component β2	Observation Angle α	Minimum Value R_I, cd/fc				
		White	Yellow	Red	Green	Blue
0°	0.2°	3.0	1.8	0.75	1.0	0.28
+20°/–20°	0.2°	1.2	0.72	0.30	0.4	0.11

According to the FDOT Maintenance Rating Program (MRP), 70% of markers on a given roadway are functional (reflective), and no more than 100 feet of continuous centerline or lane line is without a reflective marker. The evaluation for each test section is as follows [11]:

- Daytime: Check to make sure the correct number of markers are installed. Count all the markers that should be present, based on RPM placement specifications. Then count the number of missing markers. Determine the percentage of markers missing by dividing the number missing by the total number that should be present.
- Nighttime: RPMs shall be visible and reflective at night with low beam headlights. Determine if the markers are reflective at night for a distance of 528 feet. Two lane roadways shall be evaluated from both directions.
- No more than 100 feet of continuous centerline or lane line should be without an RPM.
- If RPMs are required on edge lines, they should be rated.
- At least 70% of the required markers should be functional (reflective) at a distance of 528 feet.
- Designed breaks in pavement lines (crossovers, intersections) shall not be included in the 100 feet.

RPMs fail to meet MRP standards if any of the following exist [11]:

- More than 30% of the required raised pavement markers are missing.
- More than 30% of the required markers are not functional (reflective) at an observation distance of 528 feet.
- More than 100 continuous feet of centerline or lane line is without an RPM.
- If the raised pavement markers are installed incorrectly, such as being imbedded into the pavement or rotated more than 20˚ in any direction.

Currently, there are no national guidelines for when to replace an RPM. As of now, no individual state replaces markers based on measured retroreflectivity values. Instead, they use visual inspections for missing or poorly functioning RPMs. According to the FHWA RPM guidelines, several states use their own different criteria to determine the "effectiveness" of RPMs and when to replace them [9]:

- California RPMs are replaced when two or more consecutive markers are missing.
- Texas RPMs are replaced when 50% or more markers are missing within one mile.
- Massachusetts replaces only reflective lens if casting is intact.
- Michigan replaces only reflective lens if casting is intact.
- New Jersey replaces only reflective lens if casting is intact.
- Massachusetts snow-plowable RPMs (SRPMs) are replaced when 30 percent or more markers are missing on a roadway.
- New Jersey uses visual inspection to determine if RPMs need to be replaced.
- Pennsylvania uses visual inspection to determine if RPMs need to be replaced.
- South Carolina, North Carolina, Alabama, Mississippi, Florida, and many other states replace RPMs periodically every 18-24 months regardless their in-service assessment.

The Texas Department of Transportation (TxDOT) is one of the leading active state highway agencies in RPM assessments. TxDOT mentions in roadway specification 6021 that the department uses the following visual evaluations to assess the performance of in-service RPMs:

Retroreflectivity of RPMs: TxDOT will perform night retroreflectivity evaluations using a passenger vehicle with the headlights set on low beam. The RPMs within the range of the headlights must appear reflective. Exceptions are to be made where road geometry affects RPM visibility. The evaluation may include a video recording to be used for additional review [10].

- At 80-ft spacing, a minimum of 4 RPMs must be retroreflective.
- At 40-ft spacing, a minimum of 8 RPMs must be retroreflective.

Missing RPMs: TxDOT will perform visual evaluations to determine if RPMs are missing [10].

ASTM, ASHTO and FHWA published test methods for measuring PM and RPM retroreflectance. The current national standard test methods and guidelines regarding PMs and RPMs are as follows:

- ASTM D4280 – “Standard Specification for Extended Life Type, Non-plowable, Raised Retroreflective Pavement Markers” [8].
- ASTM E1710 – “Standard Test Method for Measurement of Retroreflective Pavement Marking Materials with CEN-Prescribed Geometry Using a Portable Retroreflectometer” [6].

- ASTM E1696 – "Standard Test Method for Field Measurement of Raised Retroreflective Pavement Markers Using a Portable Retroreflectometer" [5].
- AASHTO TP 111-14 – "Standard Method of Test for Measuring Retroreflectivity of Pavement Marking Materials Using a Mobile Retroreflectivity Unit" [7].
- FHWA-RD-97-152 – "Guidelines for the Use of Raised Pavement Markers."

A thorough review of relevant standards and published literature were completed with the purpose of reviewing methods, determining values previously researched and tested for assessing RPM retroreflectivity using highway speed mobile retroreflectometer, and to understand lessons learned from previous attempts. It was concluded that no reliable correlation has been established between mobile testing data and the handheld or photometric range testing data.

An important factor within the standards are the optical angles which defines the geometric setup. There are the following three main angles: α (observation angle), β_1 (entrance angle 1) and β_2 (entrance angle 2). The observation angle is the angle between the illumination axis and the observation axis. The entrance angle 1 is the angle of vertical rotation between the illuminating axis and the datum axis. Finally, entrance angle 2 is the angle of horizontal rotation between the illuminating axis and the retroreflector axis. For the standard 220-meter RPM geometry, α is 0.2°, β_1 is 0°, and β_2 is 0°.

ASTM D4280 discusses the laboratory photometer retroreflectivity testing standards for RPM coefficient of luminous intensity (R_I) values pertaining to the 220-meter measurement geometry [8]. The standard mentions that the angular aperture of the source and angular aperture of the receiver shall each be no larger than 0.1°. Angular aperture of the retroreflective elements shall be no larger than 0.02°. If the retroreflective elements are no larger than 0.21 in (5.3 mm) in diameter, suggested test dimensions are at a 50-foot (15.2-m) distance, 1.0-inch (25.4-mm) diameter receptor, and 1.0-inch (25.4-mm) diameter source. Other test distances are acceptable, provided that the stated angular aperture requirements are met, and that the marker subtends no more than 1° at the source [8]. These angles are shown schematically in Figures 2-1 and 2-2.

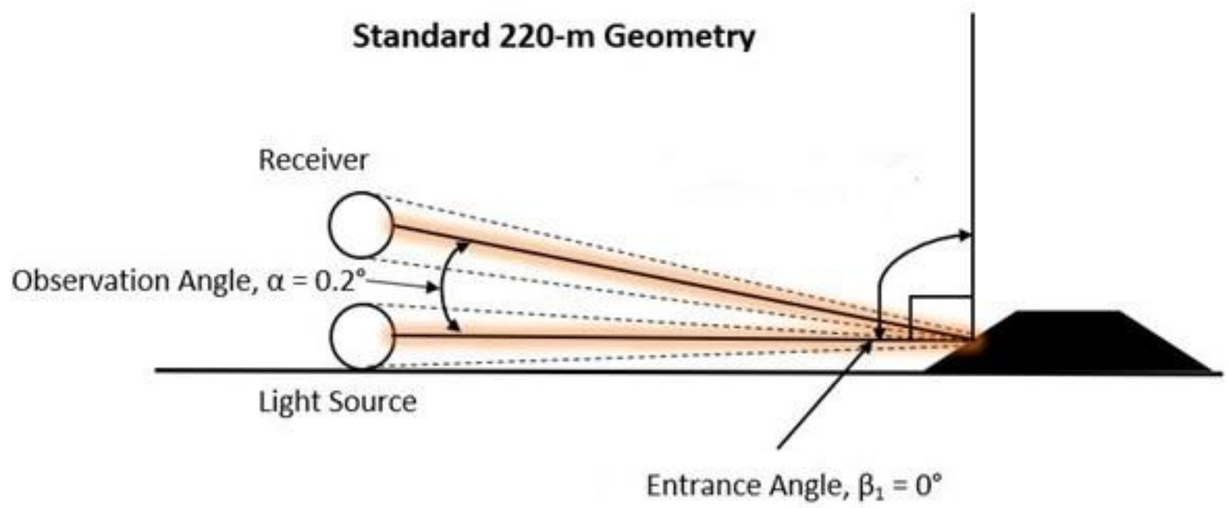


Figure 2-1. Optical angles for R_I measurements on RPMs using the 220-meter geometry [8].

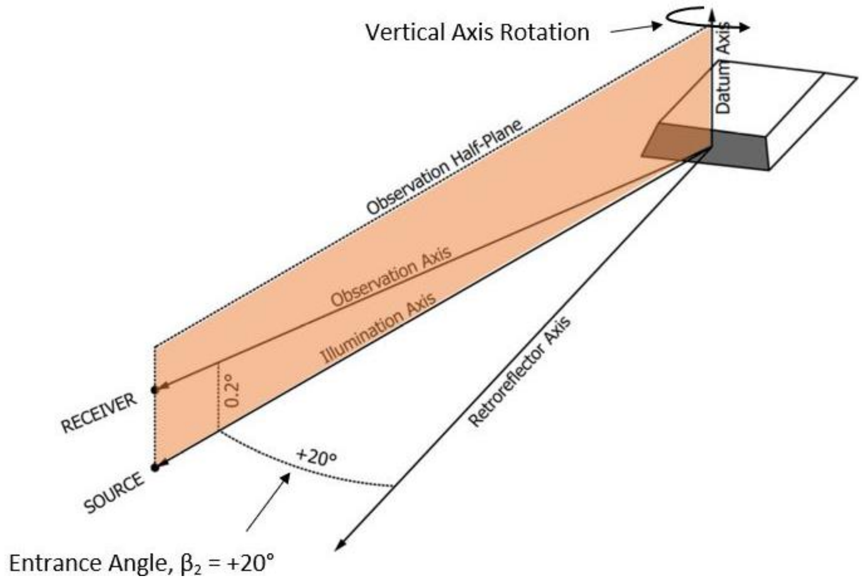


Figure 2-2. Optical angles for the standard 220-meter geometry with +20° rotation [8].

ASTM E1710 discusses the 30-meter portable reflectometer testing standards for measuring the retroreflectivity of PMs [6]. This test method involves the use of commercial portable retroreflectometers for determining the coefficient of retroreflected luminance (R_L) of horizontal coating materials used in PMs. For the measurement geometry, this standard test method states that the light source and receiver may be either at optical infinity or at a finite distance from the measurement area, and they shall be separated from each other by a distance corresponding to an observation angle (α) of 1.05° ± 0.02°. The entrance angle (β) of the retroreflectometer shall be 88.76° ± 0.02° with respect to the entrance aperture plane. This entrance angle produces a co-entrance angle (β_c) of 1.24° ± 0.02° relative to the source and ground. The presentation angle of the retroreflectometer shall be 0° and shall be stated in the instrument specifications. See Figure 2-3 for an illustration of the optics geometry [6].

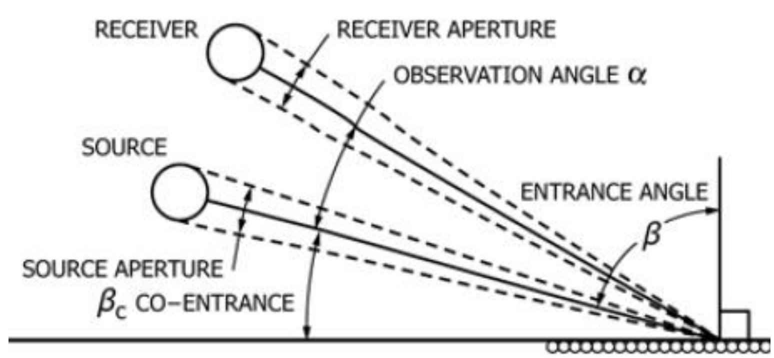


Figure 2-3. Retroreflectometer 30-meter standard optical geometry for R_L measurements [6].

ASTM E1696 discusses the standard test method for field measurement of RPMs using a portable retroreflectometer [5]. The term “portable retroreflectometer” refers to a handheld instrument that can be placed over a raised retroreflective pavement marker to measure R_I using the prescribed 220-meter geometry. This test method involves the use of commercial portable retroreflectometers for determining the coefficient of luminous intensity of pavement markers.

As shown in Figure 2-4, the retroreflector center is located on the surface of the effective retroreflectivity area, centered both vertically and horizontally]. The retroreflector axis extends parallel to the road surface from the retroreflector center. The datum axis extends vertically from the road surface plane starting at the retroreflector center [5].

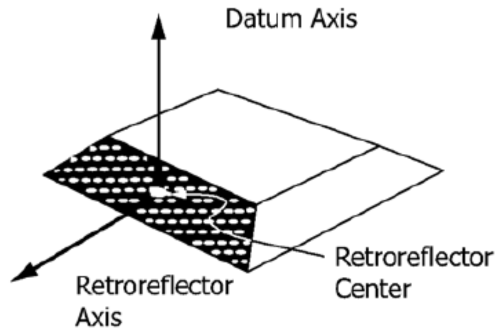


Figure 2-4. Location of the corresponding axes for use in RPM retroreflectivity [5].

ASTM E1696 goes on to describe the relevant optical angles; entrance angle component β_1 shall be between −2° and 0° and entrance angle component β_2 shall be 0° ± 2° [5]. Unless otherwise specified by the user, the observation angle shall be 0.2° ± 0.01°. If a device with collimating lens or mirror is used, the angle setup differs [5]. Geometry for collimating type reflectometers shown in Figure 2-5. This test method's geometry for R_I measurement is considered a setup to imitate a visual observation of the RPM when illuminated by a tungsten filament light source such as a car headlight at approximately 220 meters for cars or 440 meters for trucks [5].

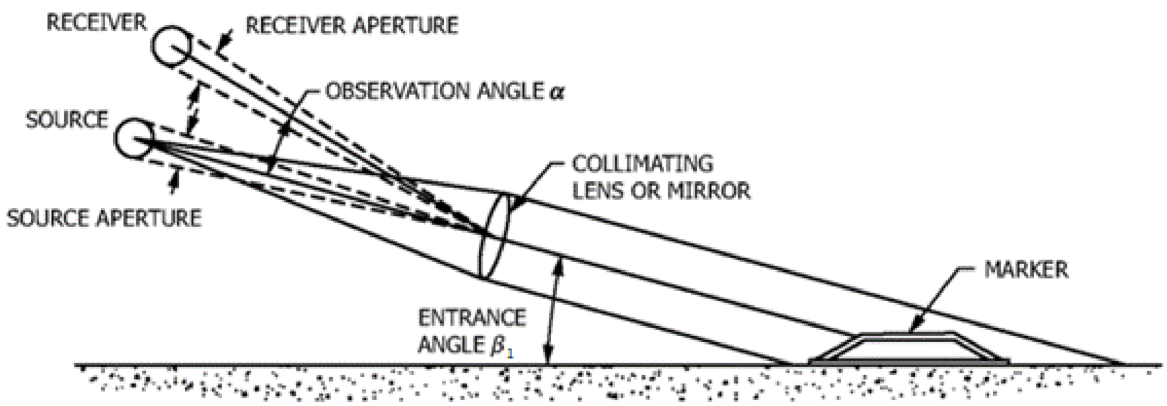


Figure 2-5. Angles and apertures for collimating type portable retroreflectometer for RPMs [5].

AASHTO TP 111-14 discusses a test method that covers measurement of the retroreflective properties of dry, horizontal pavement marking materials, using a vehicle mounted mobile retroreflectivity unit (MRU) operated at posted roadway speeds and a prescribed measurement geometry. The prescribed 30-meter geometry corresponds to the European Committee for Standardization (CEN) geometry and is the standard geometry adopted by ASTM E1710 [7]. The angles specified for the 30-meter geometry, as shown in Figure 2-6, for measuring R_L are as follows [7]:

- The entrance angle (β) is fixed at 88.76° [co-entrance angle (β_c) 1.24°].
- The observation angle (α) is fixed at 1.05°.

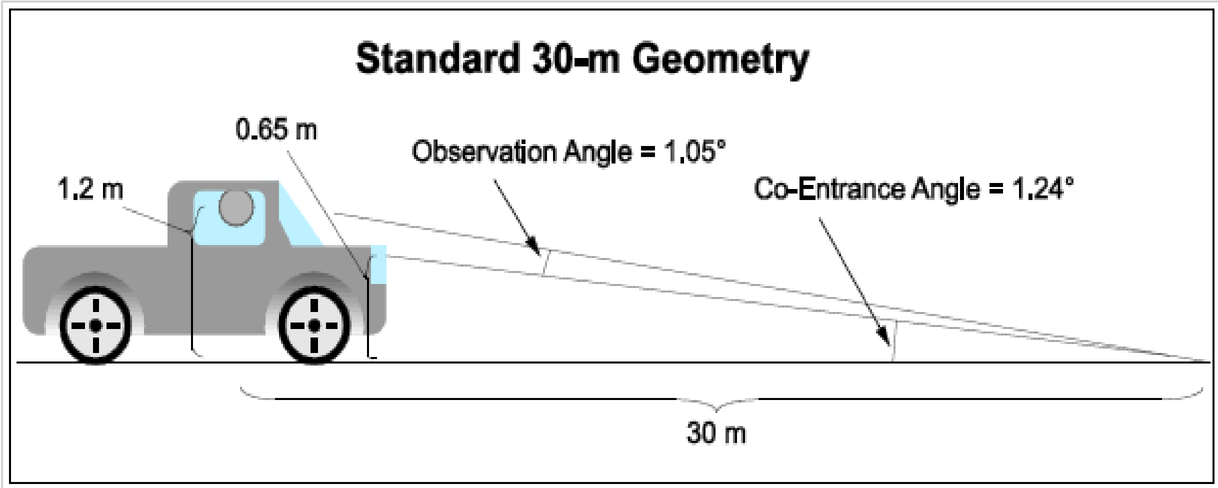


Figure 2-6. Standard 30-meter geometry as specified in ASTM E1710 [7].

Calibration is a very important process. The reflectometer needs to be calibrated to conform to the 30-meter geometry. In addition, the distance measuring instrument (DMI) is also to be calibrated monthly with an error tolerance of ±3.0 feet per mile or less. The MRU calibration equipment should be verified by the manufacturer at least once a year. The equipment must be capable of measuring retroreflectivity of PMs ranging from 75 to 1200 R_L (mcd/m^2/lux) [7].

Vehicle speed relative to the stripe type being assessed are important factors. For continuous edge and center lines, the MRU may be operated at a speed up to 60 mph. To ensure sufficient data is collected, it is recommended to not exceed 60 mph when testing. A minimum of 30 data points should be collected every 0.1 miles for the data to be considered reliable. For skip lines that are not continuous, the MRU may be required to travel at a lower speed to obtain a minimum of 30 data points per 0.1 miles. For precision, two factors to be considered [7]:

- Repeatability, as the difference between two properly conducted retroreflectivity tests using the same MRU on the same pavement marking test section should not exceed 10% at a 95% confidence level.
- Reproducibility, as the difference between two properly conducted retroreflectivity tests using different MRUs on the same pavement marking test section should not exceed 15% at a 95% confidence level.

The MRU described in this method is a RoadVista Laserlux G6. The G6 (6th generation) may be operated at a speed up to 60 mph as mentioned, but the new G7 (7th generation) unit can operate at a speed up to 70 mph. This is due to the higher sampling rate of the G7 being 400 Hz compared to the 20 Hz sampling rate of the G6. This upgrade allows for better precision and resolution at a higher speed, as well as achieving the minimum resolution requirement for the test method. In addition, the G7 integrated a better background filtering system allowing for less signal influence from solar light.

FHWA-RD-97-152 discusses guidelines for the use of RPMs, which includes the retroreflectivity of the RPMs. These guidelines address multiple characteristics for RPM use. These characteristics are as follows:

- General Delineation Requirements
- RPM Location
- RPM Color
- RPM Placement
- RPM Spacing in Traffic Zones
- RPM Spacing in Construction Zones
- RPM Type
- RPM Application and Maintenance
- RPM Reflectivity

Of the characteristics listed above, RPM reflectivity was a main topic of the review. The guidelines stated that "there are no current standard for minimum RPM reflectivity on the basis of how much information the driver requires for controlled driving performance" [7]. The report brings up multiple issues with determining the brightness of the RPM. For example, establishing a minimum preview distance for the average driver must account for the increased processing time and decreased discrimination ability of older drivers. Also, establishing the appropriate level of contrast to optimize driver performance must account for ambient lighting, weather conditions, headlight glare, and additional complexities produced by the surroundings.

The guidelines go on to state that "The Roadway Delineation Practices Handbook" discusses these issues and establishes a criterion of 100 R_L ($mcd/m^2/lux$) as the minimum retroreflectivity for PMs on dry roads [7]. The guidelines also include the following statements regarding roadway delineation visibility requirements:

- Drivers over 65 may require four times as much light to see relative to a 39–year–old [9].
- Older drivers adopt less flexible searching strategies [9].
- Driver perception and reaction time continually increases with age [9].
- Recommendations were made to double the value of luminance contrast to account for older or impaired drivers [9].
- Two seconds of preview time are required for short–range guidance and a minimum of three seconds are required for long–range guidance. At 25 mph (40 km/h), delineation must be visible at a minimum of 110 feet (34 m) ahead. At 55 mph (90 km/h), delineation must be seen at least 250 feet (76 m) ahead [9].
- Optimal contrast levels and the required reflectivity of RPMs to allow for processing at a higher level must account for conditions (such as fog, rain, dew, glare) that could change the required minimum contrast achieved in clear, dry weather [9].

EXISTING LITERATURE

As previously mentioned, there has been minimal research focused on highway speed MRU technology for RPM assessments. The topic was covered by the University of Maryland in 2003, Texas A&M in 2017 and 2018, and addressed indirectly by the University of North Florida (UNF) and the FDOT on optimizing mobile retroreflectivity units (MRUs) for line-stripe pavement markings (PMs) [1,2,3,4]. The following section provides brief summaries regarding the research involved in each one of these aforementioned studies.

University of Maryland [1]

This research aimed to compare the accuracy and productivity of using the Laserlux 30-meter geometry MRU to measure the retroreflectivity snow-plowable RPMs (SRPMs). These measurements captured with the MRU in R_L were compared to R_I measurements produced by a Gamma Scientific 1200SP RPM handheld retroreflectometer. Moreover, since there were no known statewide records of retroreflectivity data, another objective was to collect "benchmark" PM and RPM retroreflectivity data for the state of Maryland. The measurements were performed on the Capital and Baltimore Beltway in Maryland to determine if this type of data can be used in a management system and provide guidance in the selection of PM materials for Maryland State Highway Administration [1].

For the handheld reflectometer testing, each manufacturer installed 40 SRPMs (10 groups of 4) on each test section. There was a space of approximately 50 feet maintained between each different manufacturer's SRPMs. In this research, four SRPMs were placed between each skip line to reduce the total length of the study site. SRPMs were installed in the same order and with the same spacing at both sites. Figure 2-7 shows the typical layout of a section of test deck [1].

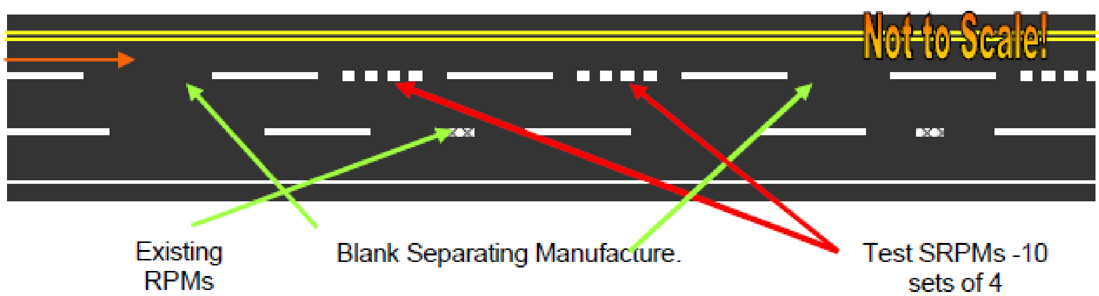


Figure 2-7. RPM test deck section [1].

Retroreflectivity readings were collected using two Model 1200SP Retroreflectometers (Figure 2-8), manufactured by Gamma Scientific of San Diego, California. According to this report, one device had been used previously for a study completed by the Ohio Department of Transportation; the second device was new for this study [1].

Figure 2-8. Gamma Scientific 1200SP RPM portable reflectometer [1].

As for the RPM retroreflectivity measurement at highway speeds, an MRU made for PM retroreflectivity measurements was used. All retroreflectivity readings were done using a RoadVista Laserlux 30-meter geometry MRU, which has an accuracy of ±15% relative to handheld measurements. The MRU was calibrated a minimum of once per day and the reference devices measurements were taken with a Delta LTL 2000 handheld retroreflectometer with an accuracy of ±5% relative to photometric range measurements [1].

The continuous line retroreflectivity data was based on station intervals with average measurements recorded every 528 feet by DMI including the exact route, direction, line type, color, and start and stop distance. A video of the data collection process with retroreflectivity data overlay and a corresponding videotape log was created. The videotapes with their corresponding data overlay provided real time documentation of weather conditions at the time of measurement. The mobile RPM retroreflectivity measurements were compared to those measurements taken by the RPM 1200 handheld retroreflectometer [1].

Figure 2-9 illustrates the layout of the MD 100 RPM test site used for measuring the retroreflectivity of RPMs with the Laserlux MRU. Four RPMs were installed between each skip line. The test location contained a total of seven sections with 40 RPMs in each section. Each section of 40 RPMs was assigned a site number. The RPMs were installed approximately eight feet apart within each of the seven sites. There was a 100-foot gap between each of the seven test sites [1].

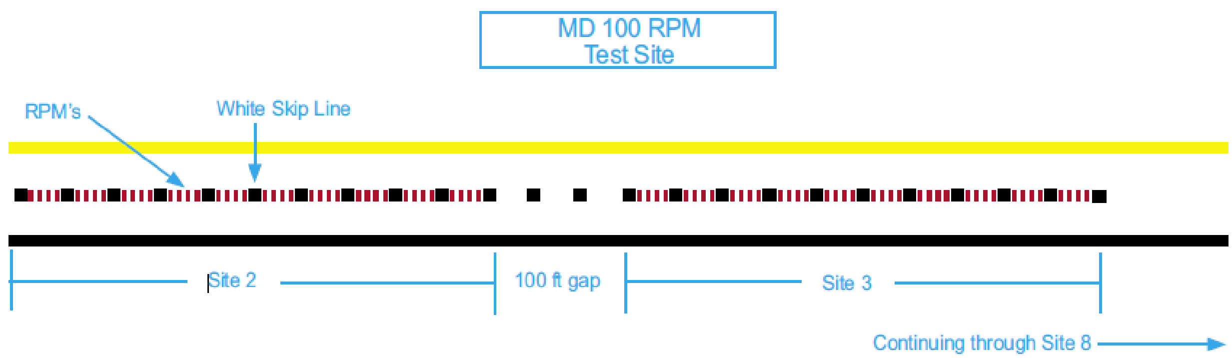


Figure 2-9. Maryland Laserlux RPM test location layout [1].

The major findings from this study were that the retroreflectivity readings collected from the portable handheld device and the MRU do not correlate for the following reasons [1]:

- The geometry used by the two retroreflectometers is different.
- The scanning light source used in the Laserlux may not illuminate the entire surface of each RPM, even at low vehicle speeds.
- The MRU optical system for detecting and measuring RPMs distorts incoming retroreflectivity readings.
- Modifications made to the Laserlux software introduced unknown errors into the retroreflectivity data.

Texas A&M Transportation Institute [2]

The research objective was to provide quantitative means of evaluating new or in-service RPMs. This effort aimed to evaluate RPMs at varying geometries (optical angles), including the standard RPM 220-meter geometry as well as the standard PM 30-meter geometry [2]. Researchers used three data collection setups to implement three different methods. The three setups included a photometric range shown in Figure 2-10, a portable reflectometer shown in Figure 2-11, and a CCD (charge-coupled device) photometer shown in Figure 2-12. The photometric range collected R_I measurements in units of mcd/lux. In addition to the standard measurement, the researchers also incorporated geometries from the portable RPM retroreflectometer and the standard PM geometry (R_L). The factors considered and focused on by the researchers were α and β_1. The entrance angle 2, β_2, was fixed at 0° for all measurements [2]. The standard raised pavement marker geometry was $\alpha = 0.2°$ and $\beta_1 = 0°$. Following the standards, the researchers considered other geometries to compare with the range allowed by the portable retroreflectometer, which were $\alpha = 0.2°$, $\beta_1 = -1°$ and $\alpha = 0.2°$, $\beta_1 = -2°$. An additional geometry to compare with the PM geometry was also incorporated: $\alpha = 1.05°$, $\beta_1 = 1.24°$ [2].

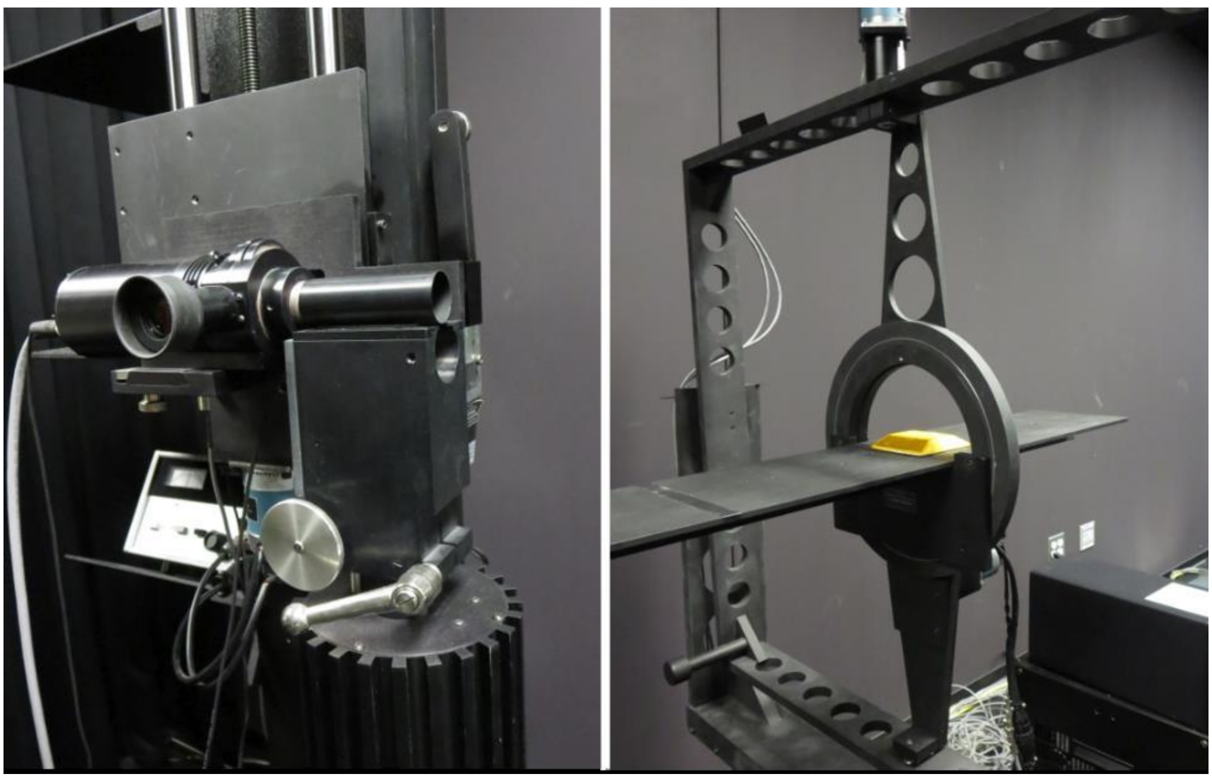


Figure 2-10. Photometric range data collection setup [2].

The portable RPM retroreflectometer was used to collect R_I in units of mcd/lux for all RPMs evaluated in the photometric range. The portable retroreflectometer test was performed in a lab environment. The device was designed with a standard geometry of $\alpha = 0.2°$, $\beta_1 = 0°$. As with the photometric range, β_2 was fixed at 0° for all measurements.

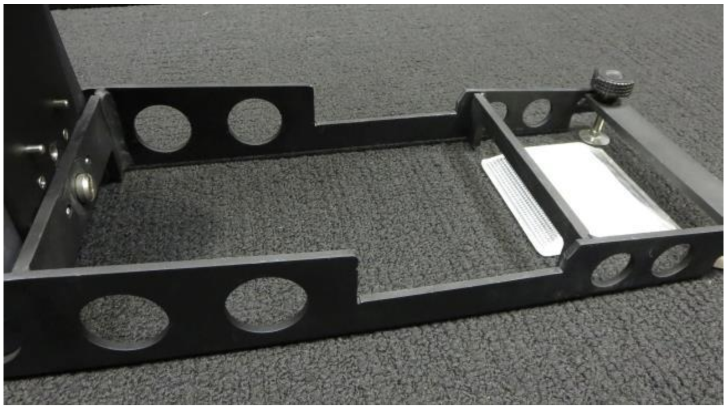


Figure 2-11. Portable reflectometer data collection setup [2].

The inconsistency of the measurements with the portable unit was a cause for concern. Researchers aimed for measurement variation of less than 10%, but in some cases the variation was greater than 40%. One reason was for this large variation was stated to be due to the different types of markers being tested. Since the device was calibrated to one type of RPM, it produced retroreflectivity measurements that were very close to those from the photometric range. However, RPMs with different types of retroreflectors other than the one used for calibration produced large measurement variability. This indicates that picking an appropriate calibration marker is necessary and vital for accurate data collection.

The CCD photometer was used to collect luminance data in units of mcd/m^2. Unlike the other two instruments, where R_I data does not consider the area of the marker, these luminance measurements considered the area being evaluated. The researchers wanted to compare the standard marker and marking geometries. The standard 220-meter RPM geometry evaluated was $\alpha = 0.2°$, $\beta_1 = 0°$. The standard 30-meter PM geometry evaluated was $\alpha = 1.05°$, $\beta_1 = 1.24°$. Illuminance (lux) at the face of the RPM was also collected using an illuminance meter so that the quantity of light falling on the marker could be factored into the data analysis [2].

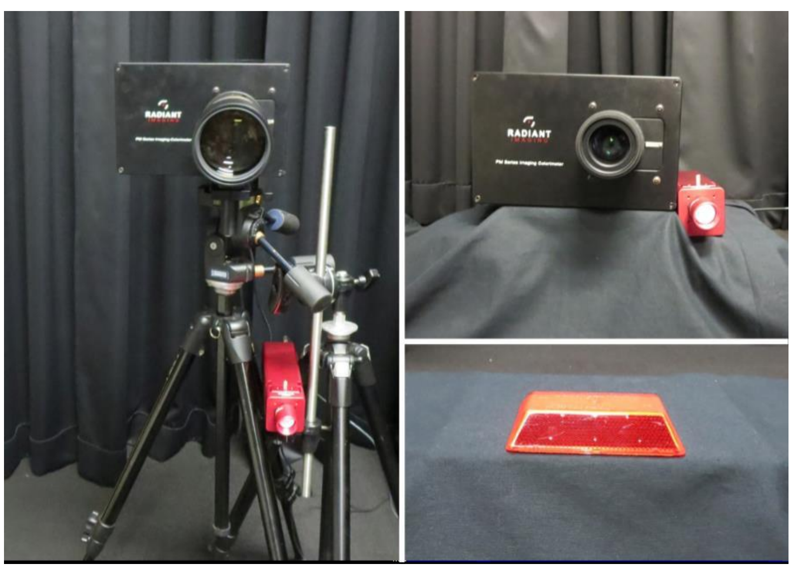


Figure 2-12. CCD photometer data collection setup [2].

The research determined that when the observation angle is held at 0.2° and the entrance angle increases, the coefficient of luminous intensity also increases. This is true for each color and brand of marker for the geometries tested. There is a notable drop in performance when the evaluation geometry was changed from RPM geometry to PM geometry. The PM 30-meter geometry resulted in significant decrease of the data values relative to the RPM 220-meter geometry. The 30-meter geometry data values averaged around 7.8% of the RPM 220-meter geometry data values when using the photometric range. The CCD photometer measurements gathered using pavement marking geometry resulted in data that was an average 6.7% of the value of the RPM geometry. These values being close indicate that the two measurement types are comparable and that the markers can consistently be evaluated using the two geometries [2].

Texas A&M Transportation Institute [3]

This research effort served as a follow-up to previous 2017 study, which was an initial investigation into the impacts of different measurement systems and geometries on evaluating the retroreflectivity of RPMs [2]. The 2018 study aimed to explore how two devices (a portable retroreflectometer and an MRU) measure retroreflectivity levels of in-service markers. One goal was to evaluate if MRUs can aid in maintenance decisions for determining when RPMs should be replaced [3]. The portable retroreflectometer shown in Figure 2-13 was used to obtain R_I (mcd/lux) readings on RPMs. The measured markers were installed at a closed course test area, a county-maintained road test area, and a wet testing in the TTI Visibility Lab [3].

Figure 2-13. Portable reflectometer setup [2].

The MRU shown in Figure 2-14 recorded RPM retroreflectivity in units of R_L ($mcd/m^2/lux$). The MRU system was designed to evaluate the retroreflectivity of line-stripe PMs. The research noted that little work has been done to determine if the mobile data that is collected on markers is useful or how it correlates with standard marker evaluation techniques. The software that controlled the retroreflectometer allowed researchers to filter data greater than a specified value to a separate file, which was where high retroreflectivity values were recorded. RPM R_L values tend to be in the tens of thousands, much greater than typical line striping [< 1000 R_L ($mcd/m^2/lux$)] [3].

Figure 2-14. Laserlux G7 MRU setup [3].

For the researchers to properly analyze the RPM data, it needed to be processed to separate retroreflectivity of RPMs from PMs. Some PMs on the roads have values from 400-750 R_L ($mcd/m^2/lux$), which are close in range to some RPMs and needed to be removed from the RPM data file. Moreover, averaging out repeat hits on the same RPM was necessary due to the speed of data collection. The researchers decided that when multiple hits were recorded for a marker, hits less than 1000 R_L ($mcd/m^2/lux$) would be ignored because the laser most likely only hit a portion of the marker. For the remaining multiple hit RPMs, the R_L values were averaged to obtain a single value. Next, using the coordinate system to make sure the markers lined up, the markers were matched to their corresponding marker numbers from the portable data [3].

Finally, the multiple runs were averaged together to generate average values for each marker. Once the mobile data was collected and synthesized it was determined that most markers had values around 9000 R_L ($mcd/m^2/lux$). Figure 2-15 provides the average data for each marker from the closed course test area [3].

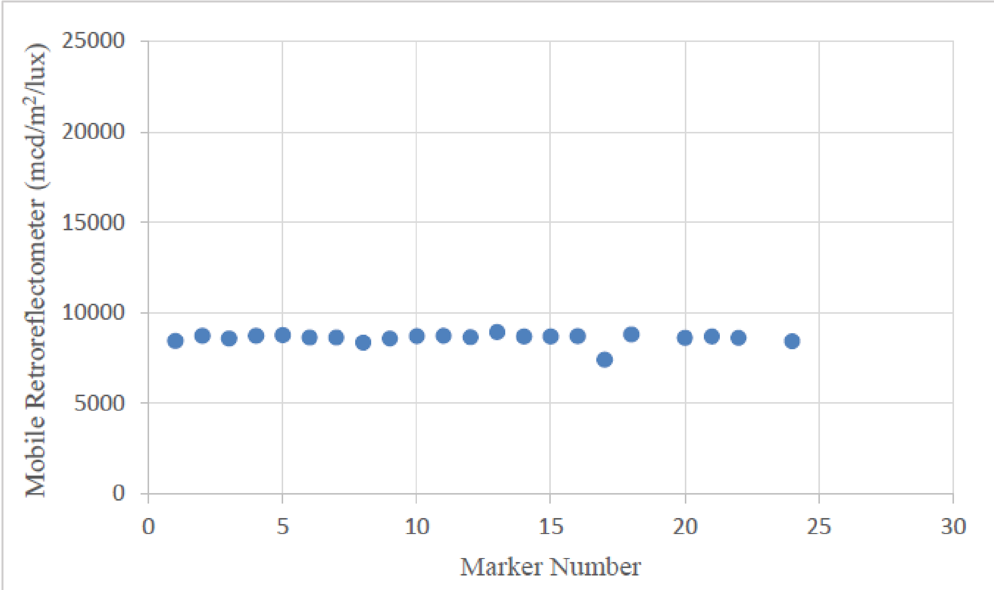


Figure 2-15. MRU R_L readings on RPMs using a 20-mW laser strength [3].

It was determined that the laser strength was too intense to show retroreflectivity variations due to over saturation of the retroreflectometers photodetector. The laser strength was lowered from 20 mW to 8 mW and additional data was collected. The new data was processed using the original set of procedures. Figure 2-16 provides the average data for each marker from closed course test area 2 with reduced laser power. The data from Figure 2-16 was more realistic, which made for a better comparison to the portable data given the range of values that were measured using the portable retroreflectometer. However, it is apparent that with lower laser strength, not all the RPMs registered values during the evaluation. During the lower laser power experiment the experiment, 15 of the 24 markers were detected compared to all 24 being detected at full laser strength [3].

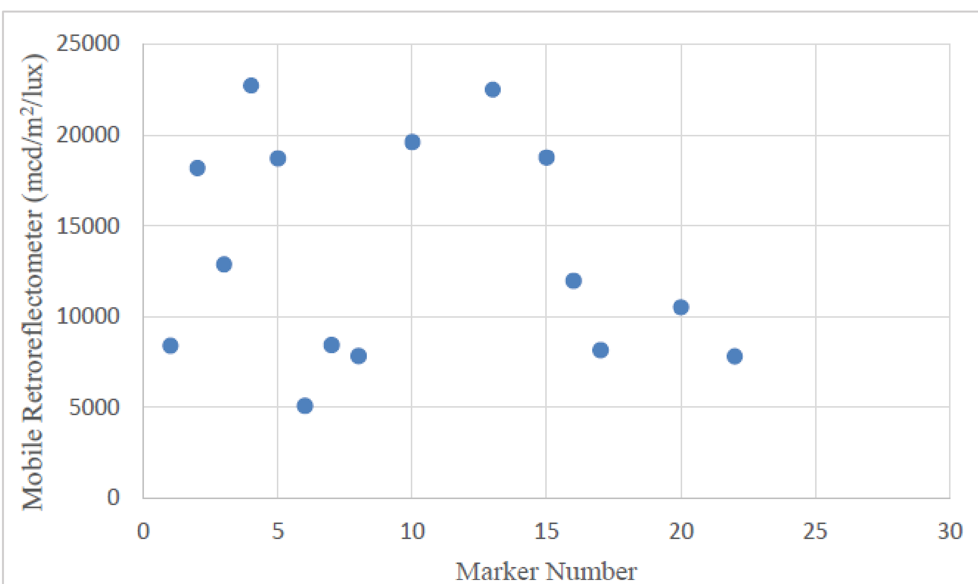


Figure 2-16. MRU R_L readings on RPMs using an 8-mW laser strength [3].

It was determined that the MRU can record R_L values for PMs and RPMs simultaneously. However, the researchers determined that the MRU retroreflectivity values for the RPMs do not correlate well with the portable RPM retroreflectometer. To account for what appeared to be oversaturation of the MRU photodetector, the researchers lowered the laser output power to reduce the signal. This resulted in a larger range of retroreflectivity values, but the data still did not correlate with the portable RPM retroreflectometer. The lower laser strength also resulted in a decrease in RPM detection rate from approximately 95% to 60%. When observing the portable retroreflectivity values of individual markers, researchers found a large R_I difference when evaluating the two faces of the double-sided markers. Both new and in-service markers showed directional differences [3].

FDOT and University of North Florida [4]

This multi-year study was focused primarily on developing data processing algorithms to improve the performance of the Gamma Scientific G7 MRU in assessing PM retroreflectivity. Initial evaluation and optimization of the technology focused on improving the hardware. For example, a cooling system was integrated into existing MRU design to tightly control its operating temperature. Additionally, new calibration materials were tested and selected to establish an optimized, robust calibration process. Most recently, this study focused on data processing algorithms and factors affecting retroreflectivity data collection with the MRU [4]. The identified factors on the repeatability and reliability of the data were as follows:

- Signal Characteristics:
    a. Low Stripe Reflectivity
    b. RPM Signal Filtering
    c. Excessive R_L Signal from surrounding markings like stop lines
- Algorithm Based Optimization for:
    a. Scan Bounding
    b. Lateral Wander Correlation
- On-Road Debugging for:
    a. Power Supply Inconsistency
    b. Background light effects
    c. Voltage Offset
    d. Spinning Mirror Assembly Effects

Researchers concluded that one of the signal characteristics found was an RPM signal. For the purpose of that research, it was crucial to filter out any detected RPM signal or even a partial RPM signal. These RPM signals cause interference with pavement marking readings [4]. As the laser light hits an RPM during its sweep, the system would capture a saturated voltage signal. This is saturation was due to exceeding the maximum photodetector voltage, as the RPM is a highly reflective surface [4]. The saturation is shown in Figure 2-17. The impact of the RPM retroreflectivity was eliminated from the data set by establishing a maximum voltage level threshold. Whenever the signal rises above the threshold, the data was flagged as an RPM reading and removed from the data set.

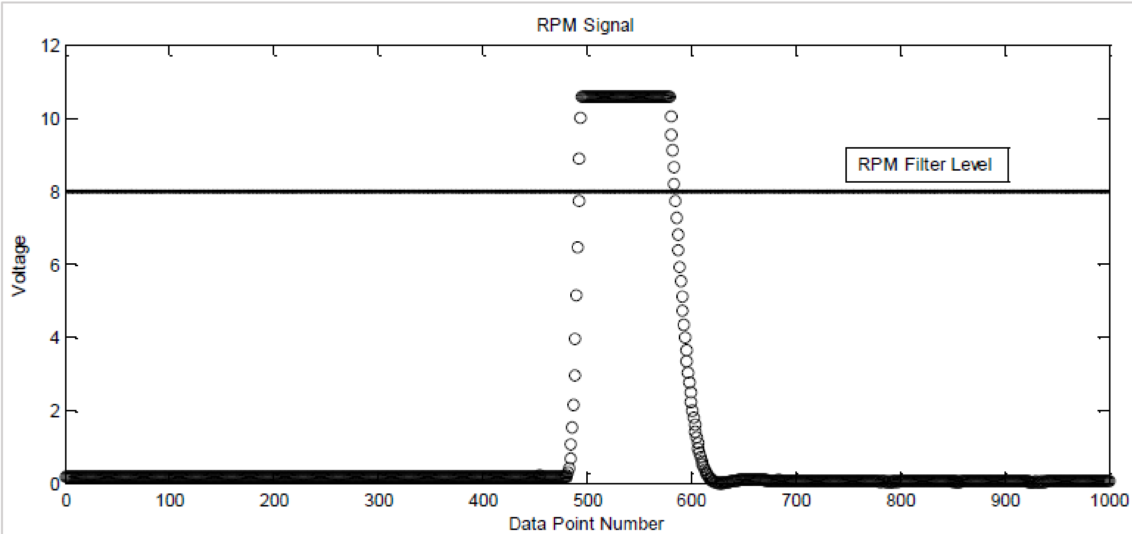


Figure 2-17. Example of an RPM voltage signal [4].

Partial RPM hits were detected during the one-meter-wide laser sweep. The MRU response when the laser light partially hits the RPM is similar to a very thin stripe without having a high voltage response, as shown in Figure 2-18. This erroneous data was identified and removed by setting a minimum line-stripe width, which is normally six inches wide in Florida.

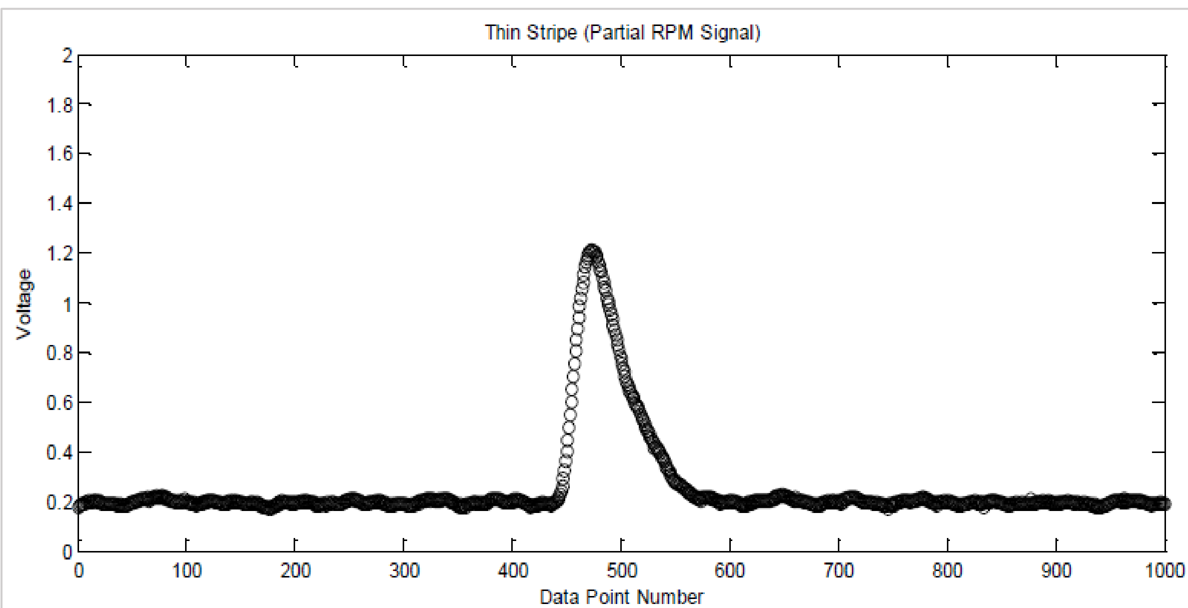


Figure 2-18. Thin stripe signal due to partial RPM reading [4].

In conclusion, a new software application called the Florida Retroreflectivity Software (FRS) was successfully developed that provides complete MRU control as well as providing an easy-to-use operator interface. Substantial testing was conducted to characterize the MRU response towards line-stripes. Additionally, algorithms were developed to ensure that only data that is truly representative of the stripe is used to evaluate its retroreflectivity [4].

The FRS software provides much more data to the investigators than the vendor-supplied software. As a result, it was determined that data collected under conditions of variable ambient light conditions showed vertical shifting between runs and was characterized with inferior repeatability. The background R_L readings correlate to the vertical shifting, and such background R_L is due to a combination of pavement R_L and background solar light. The MRU is designed to mitigate the effect of background solar light using internal interference filters in the MRU hardware, but testing showed that hardware performance is insufficient to achieve improved levels of repeatability under ambient light conditions. Additionally, the quality of interference filters degrades with age. Further testing is needed to characterize this degradation effect [4].

RPM Reflectivity Measurement Definitions

RPM retroreflectivity is measured or calculated in values of coefficient of luminous intensity, R_I, or coefficient of retroreflected luminance, R_L. These two values differ slightly where the R_L accounts for the illuminated area where R_I does not. We can acquire R_L values using the photometric range and the MRU, while R_I values are acquired using the photometric range and the handheld portable reflectometers. The following equations represent the values and terms affiliated with reflectance and retroreflectance:

$$Luminous\ Intensity = 1\ Candelas\ (cd), 1\ milli - Candelas\ (mcd)$$

$$Luminous\ Flux = 1\ Lumens\ (lm)$$

$$Luminance = \frac{Luminous\ Intensity}{Area}\left(\frac{mcd}{m^2}\right)$$

$$Illuminance\ (Lighting\ level\ on\ a\ surface) = \frac{Luminous\ Flux}{Area}\left(\frac{lm}{m^2}\right) or\ (lux)$$

Coefficient of Luminous Intensity, R_I*:* The ratio of the luminous intensity (I) of the retroreflector in the direction of observation to the illuminance (E) at the retroreflector on a plane perpendicular to the direction of the incident light, expressed in candelas per lux (cd/lux) [5].

$$R_I = \frac{Luminous\ Intensity}{Illuminance}\left(\frac{mcd}{lux}\right)$$

Coefficient of Retroreflected Luminance, R_L: The ratio of the luminance, L, of a projected surface to the normal illuminance, E', at the surface on a plane normal to the incident light, expressed in candelas per square meter per lux (cd/m^2/lux). Because of the low luminance of pavement markings, the units used commonly are millicandelas per square meter per lux (mcd/m^2/lux) [6].

$$R_L = \frac{Luminance}{Illuminance}\left(\frac{mcd}{m^2}\right)(lux)^{-1} or\ \left(\frac{mcd}{lm}\right)$$

HIGH-SPEED RPM RETROREFLECTIVITY GAP ANALYSIS

There are no studies in the published literature that detail network-level experience with implementing high-speed assessments of RPM retroreflectivity. The limited number of studies that utilized MRU technology to assess RPMs reported that identification of RPMs was possible [1, 2, 3, 4]. The resulting MRU-measured retroreflectance, however, did not align other measurement techniques such as handheld measurements [2, 3, 4]. The difference in retroreflectance measurements is thought to be, in part, due to different geometries being employed to acquire measurements (MRU 30-meter versus RPM handheld 220-meter).

To properly evaluate MRU technology for RPM assessments, hardware designed specifically for RPM measurement is required. There are many options, such as installation of a second laser sub-assembly optimized for RPM measurement by modifying the existing hardware currently used for PM evaluations. There are many trade-offs ranging from cost to maintaining the ability to measure color.

Given the varying geometries of the different measurement techniques, it is not expected that assessments of RPM retroreflectance will perfectly align between different technologies [2, 3, 4]. Rather, as part of this study, there will be a concentrated effort to develop correlations between the different measurement techniques to facilitate comparisons. At the heart of this comparison effort is the underlying repeatability and reproducibility of the different measurement techniques. The level of repeatability will directly relate to the uncertainty of the correlations. As a result, early and on-going efforts will be placed on studies to quantify and improve the repeatability of the RPM-focused MRU.

Once laboratory testing has been sufficiently completed, on-road effects will need to be analyzed. These effects, for the most part, are well understood by the project team for MRU pavement marking assessment and have been shown to have a significant impact on repeatability and reproducibility. Some of these effects include but are not limited to:

- Vehicle-related issues (acceleration/deceleration, changing fuel levels, etc.)
- Road effects (bumps, turns, changing ambient conditions such as ambient light levels)
- MRU hardware sensitivities (lane wander, operating temperature, etc.)
- RPM installation tolerances (levelness, angle to direction of motion, etc.)

Data processing algorithms will need to be developed. Impact of partial RPM hits, hits on multiple RPMs (closely installed RPMs), and multiple hits on the same RPM are examples of situations that will need to be identified in the MRU response. Algorithms developed will ensure the processed data represents a true system response related to the RPM retroreflectance performance. Finally, further investigation of the distance measuring system (DMI) will be required. The on-road accuracy of the DMI will determine the MRU ability to properly identify closely installed RPMs.

CHAPTER 3 - TEST PLAN

OVERVIEW

Current RPM retroreflectivity assessment practices include using static devices, such as the photometric range or handheld devices. These devices, based on present standards, utilize a long-range 220-meter measurement geometry. For a highway-speed mobile device, such long-range geometry is not practical given issues with vehicle dynamics, road conditions, RPMs shading each other, multiple hits on the same RPM, etc. The existing MRU technology utilizes a 30-meter geometry to measure PM retroreflectivity, and this study proposes to utilize a similar arrangement to measure RPM retroreflectivity. Correlations were developed between the different devices and corresponding different geometries to make measurement comparisons.

Previous studies showed that the MRU is capable of RPM detection utilizing the standard 30-meter geometry. An important benefit of this arrangement is that a single MRU can concurrently assess both RPM and PM retroreflectivity. No published studies detail network-level experience with high-speed assessment of RPM retroreflectivity. The limited number of studies that utilized MRU technology to assess RPMs reported that identification of RPMs was possible. The resulting MRU-measured retroreflectance, however, did not align with other measurement techniques such as handheld devices. The difference in retroreflectance measurement is thought to be, in large part, due to different geometries being employed to acquire measurements.

For proper RPM assessment using MRU technology, hardware designed specifically for RPM measurement is required. One of the early goals of the project team was to work closely with Gamma Scientific (MRU original equipment manufacturer) to develop such equipment. The project team decided that based on the many trade-offs (cost, ability to measure color, etc.), a current Laserlux G7 MRU would be modified to measure both RPM and PM retroreflectivity. As a result, testing ensured the quality of the PM retroreflectivity measurement.

Given the varying geometries of the different measurement techniques, MRU assessment of RPM retroreflectance was not expected to perfectly align with different technologies. Thus, there was a concentrated effort to develop correlations between the different measurement techniques to facilitate comparisons. At the heart of this comparison is the underlying repeatability of the different measurement techniques as the level of repeatability directly relates to the uncertainty of the correlations. As a result, early and on-going efforts to quantify and improve the repeatability of the RPM-focused MRU occurred.

TEST PLAN APPROACH

Based on the above-mentioned challenges, the test plan focused on RPM retroreflectivity assessment using both geometries. This project included five measurement devices that utilize the two geometries. The five devices included the following: the photometric range, two portable devices [one for PM measurements (30-meter geometry) and one for RPM measurements (220-meter geometry)], the modified Laserlux G7 MRU, and one unmodified Laserlux G7 MRU. Table 3-1 lists each device and the corresponding locations for testing each device. The two measurement geometries analyzed were the 30-meter geometry (referred to as PM geometry) and 220-meter geometry (RPM geometry). Figures 3-1 to 3-4 show diagrams pertaining to these measurement geometries. Testing occurred at the following four locations:

1. FDOT photometric test lab: Static measurement of RPM retroreflectivity for both geometries.
2. FDOT MRU calibration bay: Static measurements using handhelds and incorporating both geometries and MRUs.
3. FDOT Williston Airport Test Track: Both handheld and mobile RPM assessment under isolated, controlled conditions
4. Precision Test Sites: Approximately 10 test sites, including five from the PM precision test, to allow for assessment of the MRU technology under road conditions.

Table 3-1. Proposed test locations.

Apparatus	Test Location			
	Photometric Test Lab	MRU Calibration Bay	Williston Airport Test Track	Precision Test Sites
Photometric Range	X			
Retroreflectometer (30-m)		X	X	
Retroreflectometer (220-m)		X	X	
Modified G7 MRU		X	X	X
Unmodified G7 MRU		X		

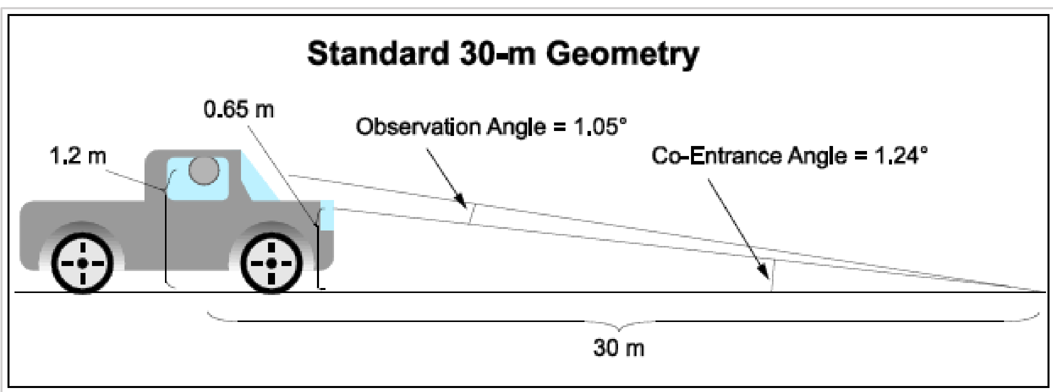


Figure 3-1. PM optical angles for the standard 30-meter measurement geometry.

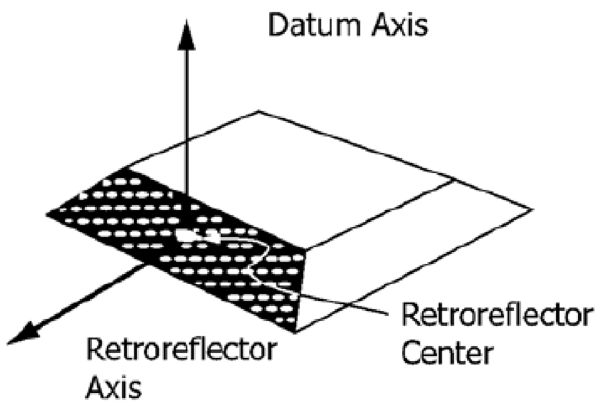


Figure 3-2. RPM retroreflective surface axes.

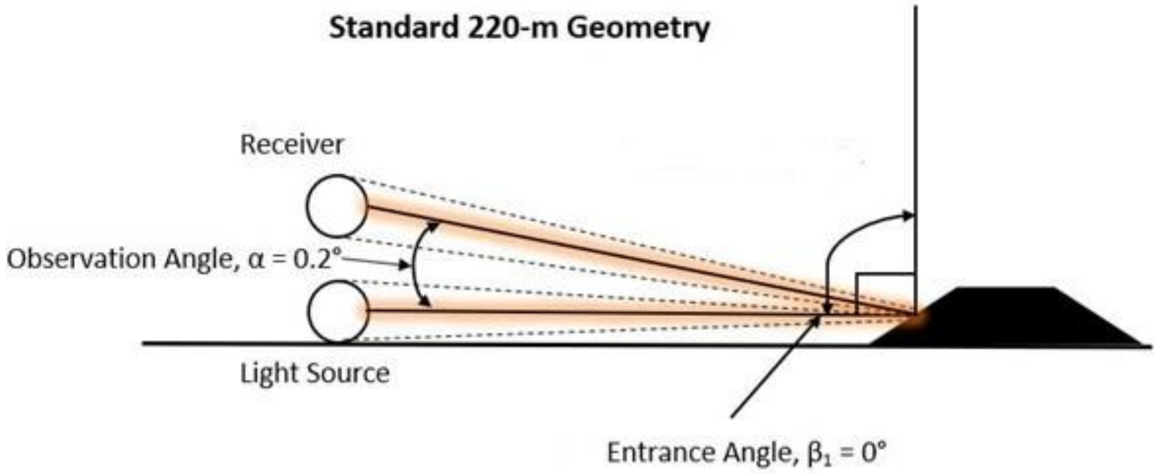


Figure 3-3. RPM optical angles for the standard 220-meter measurement geometry.

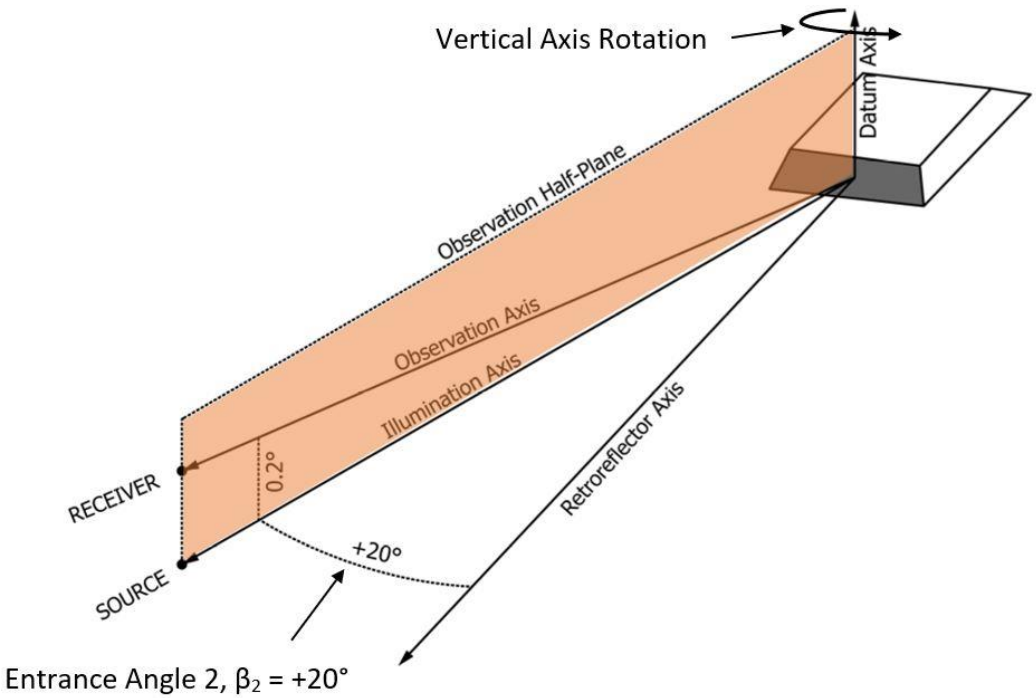


Figure 3-4. RPM optical angles for the standard 220-meter geometry and a 20° rotation.

For the RPM 220-meter geometry, there are three main angles: α (observation angle), β_1 (entrance angle 1), and β_2 (entrance angle 2). The observation angle is the angle between the illumination axis and the observation axis. Entrance angle 1, shown in Figure 3-3, is the angle of vertical tilt between the illuminating axis and the datum axis. Entrance angle 2, shown in Figure 3-4, is the angle of horizontal rotation between the illuminating axis and the retroreflector axis. For the 30-meter PM geometry, the co-entrance angle (β_c) is denoted as entrance angle 1 (β_1) when referring to the 220-meter geometry angle nomenclature. Table 3-2 shows the optical angle configurations for each standard geometry.

Table 3-2. Optical angle configurations for the standard measurement geometries.

Geometric Standard	Optical Angle Configurations		
	Observation, α	Entrance Angle 1, β_1	Entrance Angle 2, β_2
Standard PM 30-m	1.05°	1.24°	0°
Standard RPM 220-m	0.2°	0°	0°
Standard RPM 220-m w/ Horizontal Tilt	0.2°	0°	-20°
Standard RPM 220-m w/ Max. β_1 Tolerance	0.2°	-2°	0°
Standard RPM 220-m w/ Horizontal Tilt & Max. β_1 Tolerance	0.2°	-2°	-20°

Standardized Tests

The standardized tests utilized existing instrumentations configured to current standards. For the RPM geometry tests, the photometric range configured to standard RPM optical angles and the RPM portable retroreflectometer acquired retroreflectivity values. For the PM geometry, the photometric range configured to standard PM optical angles and the PM portable reflectometer acquired retroreflectivity values.

Developmental Tests

The existing MRU was to be modified to measure the higher retroreflectance of RPMs. Thus, the modified MRU underwent extensive static and mobile testing to evaluate and optimize measurement of RPM retroreflectivity. Quantification of the MRU response to RPMs ensued to develop appropriate data processing algorithms and ensure the assessment of only quality data. Sensitivities of the new device to highway conditions (turns, bumps, etc.), vehicle dynamics (speed, acceleration/deceleration), ambient conditions (light levels, temperature, etc.) were also evaluated.

The MRU has three channels capable of holding three laser sub-assemblies. Usually, three channels are utilized for color detection, which is an add-on option. At this point, the FDOT does not utilize the color detection option. A second laser sub-assembly was incorporated into the first iteration of the modified MRU to have a total of two laser sub-assemblies. The first laser sub-assembly was the same as used in existing MRUs capable of measuring PMs only. By incorporating the second laser sub-assembly for RPM measurements, a direct comparison between the modified laser sub-assembly used for RPM and PM assessment and the nominal PM-assessment laser sub-assembly could occur. As a result, any impact of the modifications on PM measurements can be directly quantified. It is not expected that future modified MRUs will include the second laser sub-assembly. Table 3-3 lists the measurement geometries associated with each testing apparatus.

Table 3-3. Measurement apparatus and their corresponding geometry.

Measurement Apparatus	Geometric Test	
	Standard PM 30-meter	Standard RPM 220-meter
Photometric Range	X	X
Portable Retroreflectometers	X	X
Modified G7 MRU	X	
Unmodified G7 MRU	X	

Repeatability Test

Repeatability testing of each device, using the standard precision test methods, occurred. For the photometric range and the handheld retroreflectometers, three measurements of eight random RPM samples were conducted with each device under both the 30-meter and 220-meter geometries. The MRU precision tests occurred at nine defined test sites with each measured three times. The sites included four from existing MRU PM test sites and five newly defined test sites. The newly defined test sites included different RPM manufacturers. Precision testing of both RPMs and PMs measurement by the modified MRU also occur.

Data Analysis

The first goal of the data analysis was to determine correlations between the different measurement geometries. This included correlations between measurements of the same device but different geometries; for example, the photometric range RPM retroreflectance measurement with 30-meter geometry versus 220-meter geometry. It also included correlation development between different devices, including the two different geometry-based handheld devices. Most importantly, correlations were developed between the modified MRU (30-meter geometry) and existing RPM measurements (220-meter photometric range and 220-meter handheld device).

The second goal was to evaluate any impact of the MRU modification on PM retroreflectivity measurements. RPM retroreflectivity [up to 50,000 R_L (mcd/m^2/lux)] is much higher than typical pavement marking [< 1000 R_L (mcd/m^2/lux)]. Note that measurement of RPMs mainly focused on R_I values (mcd/lux), as the RPM is considered a point source of retroreflectance rather than a large area as in line-stripe PM calculations.

TEST DESCRIPTION

As mentioned above, testing incorporated four devices. Each apparatus was unique in its setup, configuration, and data collection process. The existing devices (photometric range and handheld devices) were calibrated according to manufacturer specifications. For the modified MRU, development of a calibration procedure for RPM measurement needed to occur. To ensure testing was useful to the FDOT, the selected RPM models were from the FDOT Approved Product List (APL). An assortment of brand new, used but still functional, and used non-functional RPMs were employed.

RPM Models

The RPM models shown below (pictures from FDOT specification manual 706 - Raised Pavement Markers and Bituminous Adhesive) were used for this project. These Class B RPMs are the most commonly used RPMs on Florida roadways. The RPM samples were labeled according to the sample number, RPM type, and RPM condition. For example, 1-1W is sample 1, Type 1, white reflective surface, new condition. While 2-2Y/U is sample 2, Type 2, yellow reflective surface, used condition. The following RPM models shown in Figures 3-5 to 3-7 were chosen from the APL for testing.

Figure 3-5. Yellow two-way reflector, Type 1.

Figure 3-6. White/red two-way, two color reflector, Type 2.

Figure 3-7. Yellow one-way reflector, Type 3.

Photometric Range Test

The photometric range is the most flexible setup for standard retroreflectivity tests. The testing utilized the FDOT's 940D RoadVista photometric range built by Gamma Scientific which is capable of both 30-meter and 220-meter measurement geometries. The testing accounted for vertical and horizontal tilts in order to observe the effect that these optical angles have on the retroreflectivity readings. In this testing, retroreflectance was measured in R_I and R_L units. Each sample had three measurements using each variation of optical angles for to check for repeatability and accuracy. Figures 3-8 and 3-9 show the photometric range equipment.

Figure 3-8. RoadVista 940D photometric range apparatus [12].

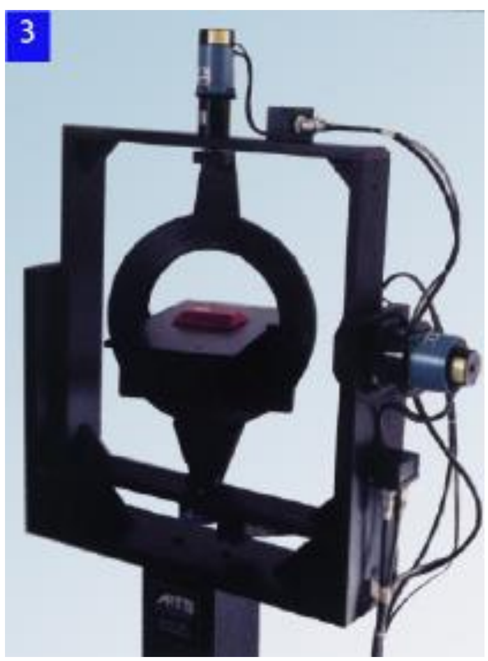


Figure 3-9. RPM setup on the goniometer in the photometric range [12].

Portable Retroreflectometer Test

The portable retroreflectometer testing utilized one RoadVista PM handheld retroreflectometers and one RPM handheld made by Zehntner. For the RPM 220-meter geometry, the Zehntner ZRP 6030+ was used. The Zehntner device outputs retroreflectivity measurements in R_I (mcd/lux). As for the PM 30-meter geometry, the RoadVista Stripe Master 2 was used, which outputs retroreflectivity in R_L (mcd/m^2/lux). These devices are shown in Figures 3-10 and 3-11.

Figure 3-10. Zehntner ZRP 6030+ 220-meter geometry handheld RPM retroreflectometer [12].

Figure 3-11. RoadVista Stripe Master 2 30-meter geometry line-stripe retroreflectometer [12].

Modified MRU Validation Test

The hardware validation tests initially took place in the MRU calibration bay. The test bench in the calibration bay utilizes a 1/5th scale of the 30-meter measurement geometry while maintaining the same optical angles listed in the standard. These tests evaluated MRU performance in a controlled environment to ensure that the MRU was capable of measuring the high R_L values associated with RPMs. The testing also defined the MRU signal response to RPM retroreflectivity. Measurement of PM retroreflectivity occurred for comparisons between the modified MRU and the unmodified FDOT MRU. This was done to ensure the validity of the modified MRU PM readings and that the modifications did not affect the PM measurements.

The FDOT Williston Airport test track was also used for this study. The ¾ mile roadway is located within the Williston Airport boundary, and as such, is gated with limited access. The test track allowed for testing different vehicle conditions (such as speed) and different RPM configurations (such as distance between RPM installations). Back-to-back repeat testing of the two laser sub-assemblies (one nominal and one modified for RPM measurement) was able to occur without traffic disruption.

Development of the data processing algorithms also occurred during this testing. These algorithms eliminated the impact of low-quality data, such as partial hits on an RPM, from the data set. Mitigations to external factors (such as ambient light levels) and internal factors (such as vehicle wander) were also implemented. Continual improvement of the performance of the modified MRU was the goal of algorithm development.

A series of precision tests also occurred during this study. Similar to the testing performed for existing FDOT MRUs, these tests occurred at nine test sites in the Gainesville area. Precision estimates were determined for both PMs and RPMs with the modified MRU. To achieve repeatable and reproducible measurements between different MRUs, the FDOT designated multiple field sites to verify the precision of MRU measurements. The test sections consisted of various pavement markings. The range of PM retroreflectivity for these test sections was from 100 to 800 R_L (mcd/m^2/lux). The modified MRU performed three repeat runs at each test section at the posed roadway speeds. The results of the modified MRU at each test section were expected differ by no more than ±10.0% for repeatability and ±15.0% for reproducibility when compared reference data [13]. Figure 3-12 shows the MRU test vehicle.

Figure 3-12. FDOT G7 MRU and the test vehicle.

TEST PLAN SCHEDULE

The test plan included a comprehensive study for RPM assessments including detection and retroreflectivity evaluations. The defined tests also facilitated the development of comparison correlations of different testing devices and the corresponding differences in geometries. As well, quantifying and minimizing the impact of MRU modifications on PM retroreflectivity measurement was planned to occur. The resulting information, including precision values, allowed for development of a successful implementation plan for network-level RPM assessments. Shown below in Figure 3-13 is a Gantt chart showing the test plan timeline.

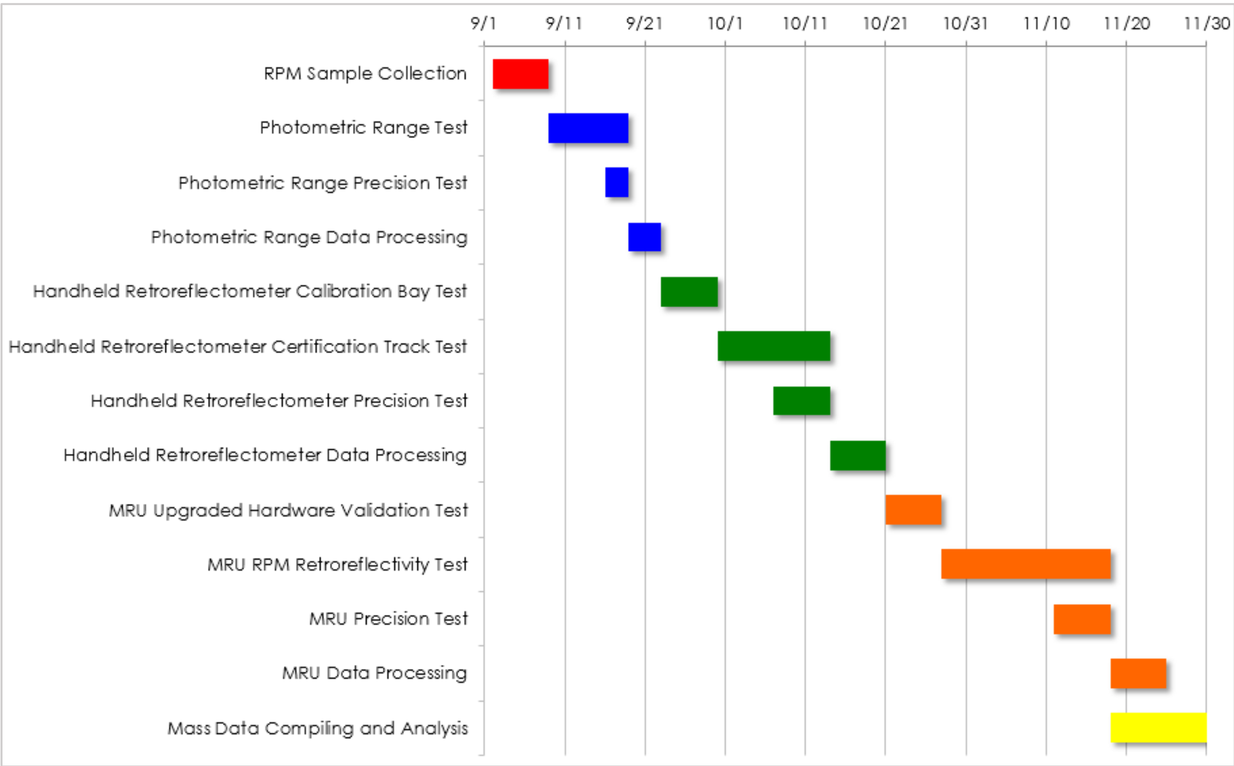


Figure 3-13. Test plan Gantt chart.

CHAPTER 4 - MODIFIED MRU EXPERIMENTAL TESTING

OVERVIEW

Based on the test plan established in the previous chapter, the testing focused on RPM retroreflectivity assessment using both geometries. Per Task 3 agreement, the research team evaluated the data acquisition software and data processing algorithm while working together with Gamma Scientific (original equipment manufacturer). The research team provided recommendations to the manufacturer for modifying the test equipment, algorithms, and software to ensure that the RPM data collected by the MRU are comparable to reference equipment such as handheld retroreflectometer and lab-based photometric range. A precision test was conducted to assess repeatability and accuracy for all apparatuses used in this study.

PHOTOMETRIC RANGE TEST

Tests were executed using the FDOT's 940D RoadVista photometric range built by Gamma Scientific, involving both 30-meter and 220-meter geometries. The testing accounted for vertical tilts and horizontal rotations in order to observe the effect that changes to the optical angles have on retroreflectivity readings. According to the test plan, retroreflectance was to be measured in R_I (mcd/lux) and R_L (mcd/m^2/lux) units, where R_I is the retroreflectance of a surface without accounting for its area (point source) and R_L accounts for surface area. Each sample had three non-consecutive measurements for each set of optical angles to assess measurement precision. Figure 4-1 shows the photometric range equipment.

Figure 4-1. RoadVista 940D photometric range equipment [12].

The RPM retroreflectivity measurements collected from the photometric range test were used as reference data. This assumption was based on the photometric range being a certified apparatus with standard testing methods already being implemented. A variety of angle combinations were used. As mentioned in the optical angles section, (β_1, α, β_2) were set to (0°, 0.2°, 0°) for the 220-meter geometry, and (1.24°, 1.05°,0°) for the 30-meter geometry. The vertical tilt applied according to the ASTM D4280 standard was -2° for β_1, and the horizontal rotation was -20°. The 30-meter geometry accounted for a horizontal rotation of -20°.

The sensitivity to variations in horizontal angle and vertical angle were assessed independently. Using the ASTM standard testing method, RPMs were assessed using the 220-meter geometry. Two scenarios were applied, first a 20° horizontal rotation then a 2° vertical tilt. For the 20° horizontal rotation, the values obtained in Figures 4-2 and 4-3 averaged approximately 56% of the 220-meter geometry 0° rotation value.

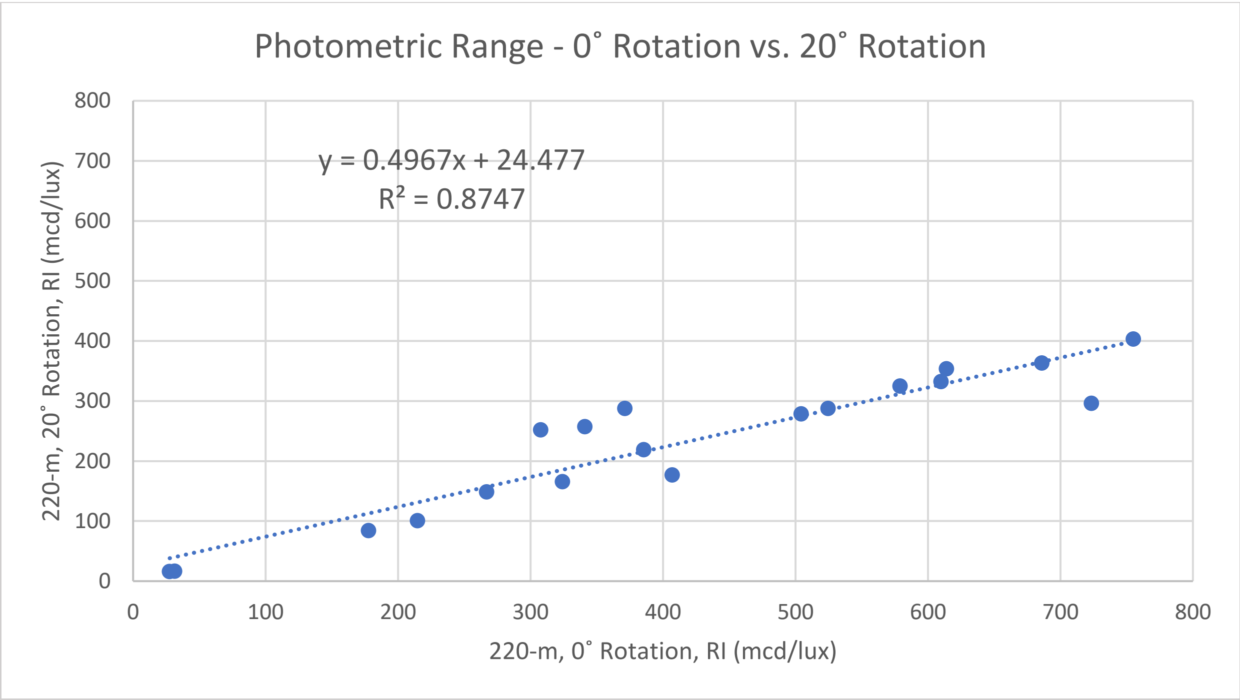


Figure 4-2. Rotated vs. non-rotated RPM R_I Values.

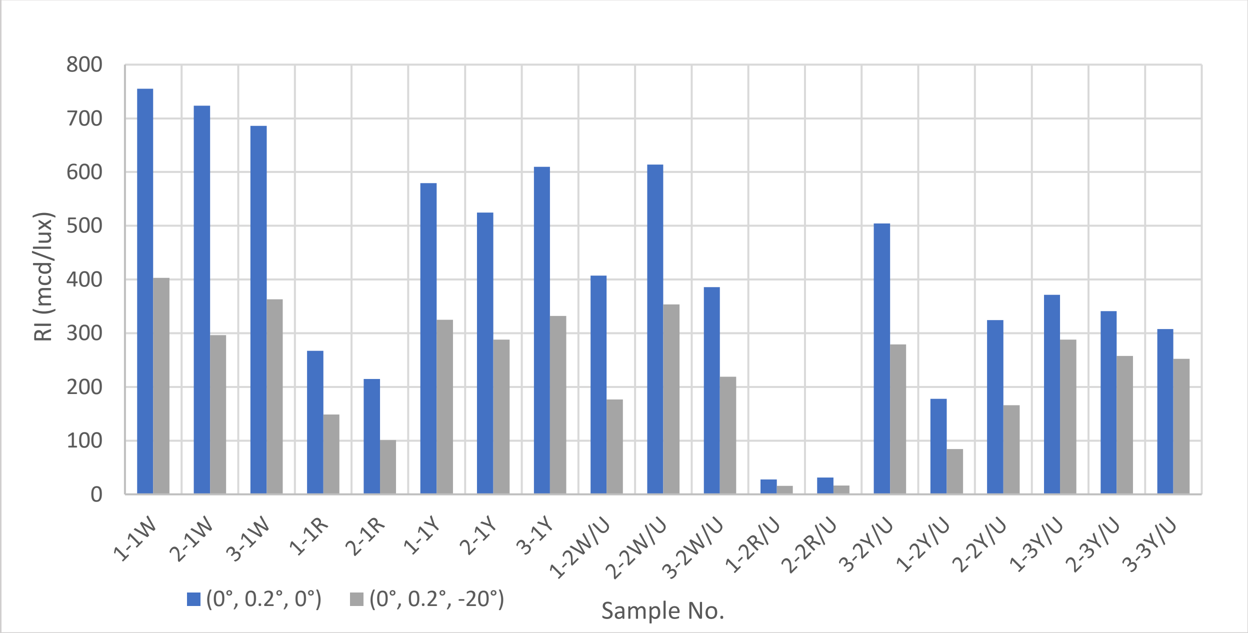


Figure 4-3. RPM R_I values trend for 220-meter geometry at 0° and 20° rotation.

As for the 2° vertical tilt, the values obtained in Figures 4-4 and 4-5 averaged approximately 106% of the 220-meter geometry 0° tilt value. Overall, these tilted and non-tilted measurements had strong agreement with each other, indicating a minimal effect on measurements by the 2° vertical tilt.

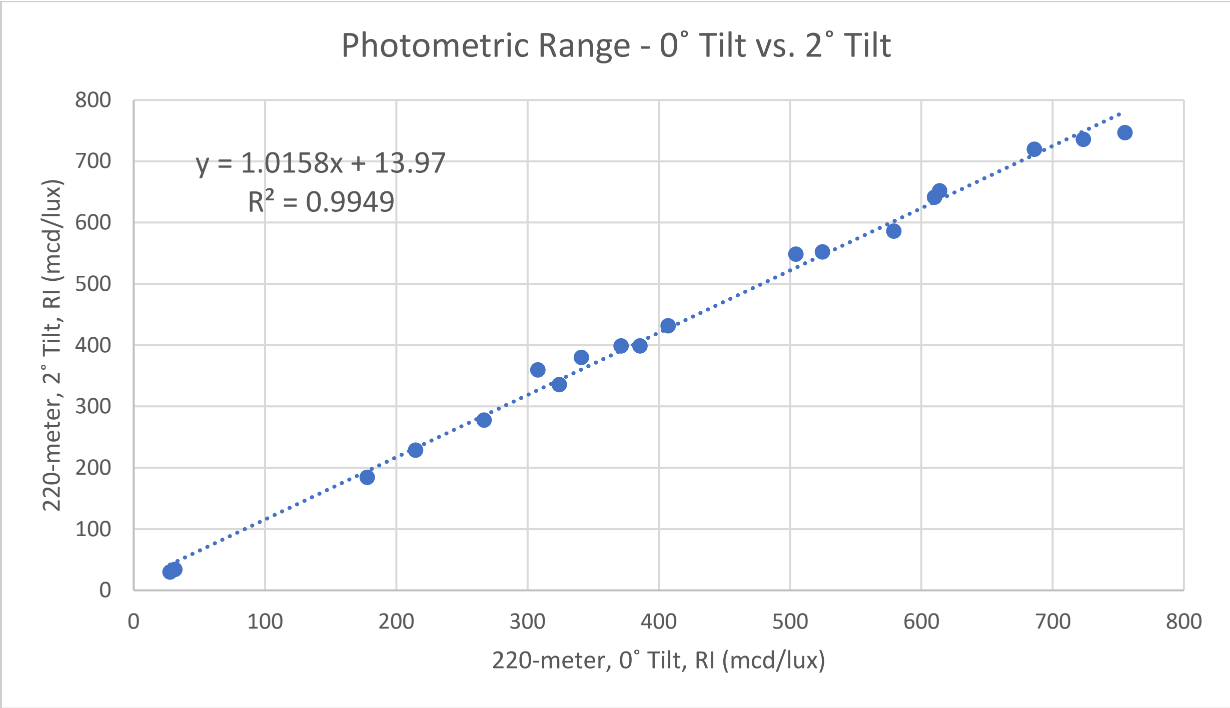


Figure 4-4. Tilted vs. non-tilted RPM R_I values.

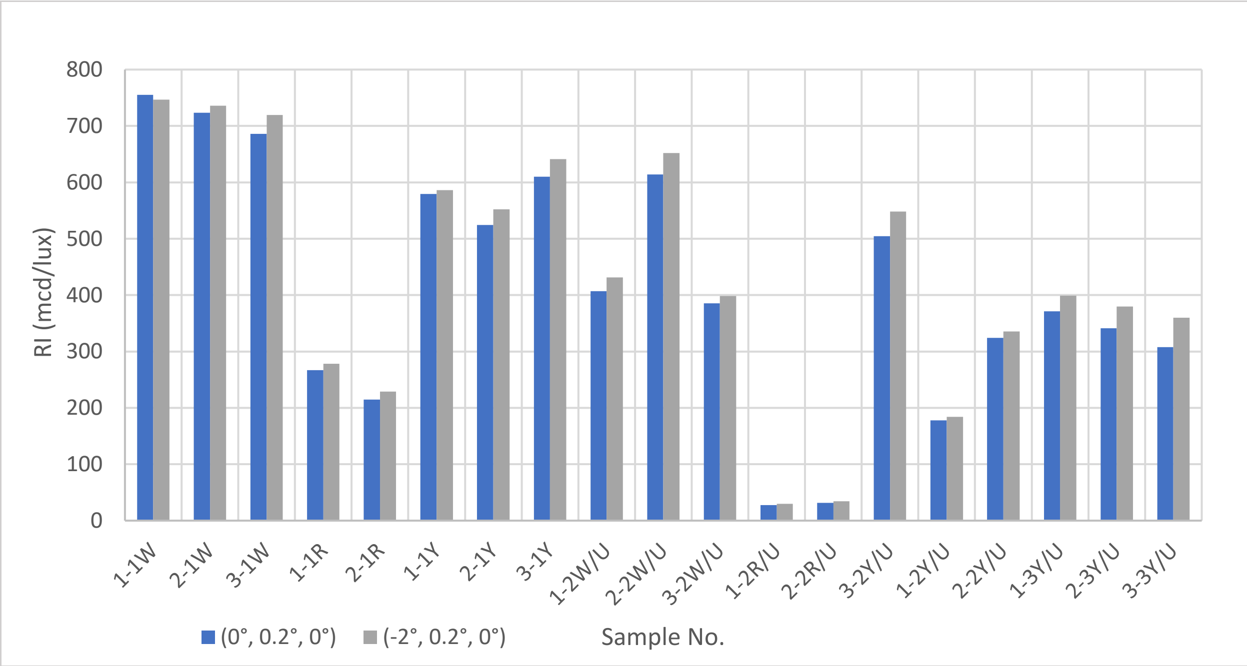


Figure 4-5. RPM R_I values trend for 220-meter geometry at 0° and 2° vertical tilt.

For the 30-meter geometry, retroreflectivity measurements averaged approximately 9% of the 220-meter geometry value. On the other hand, the correlation was at 70% and trends were different to some extent, with a low linearity depending on R^2. These results are shown below in Figure 4-6 and Figure 4-7.

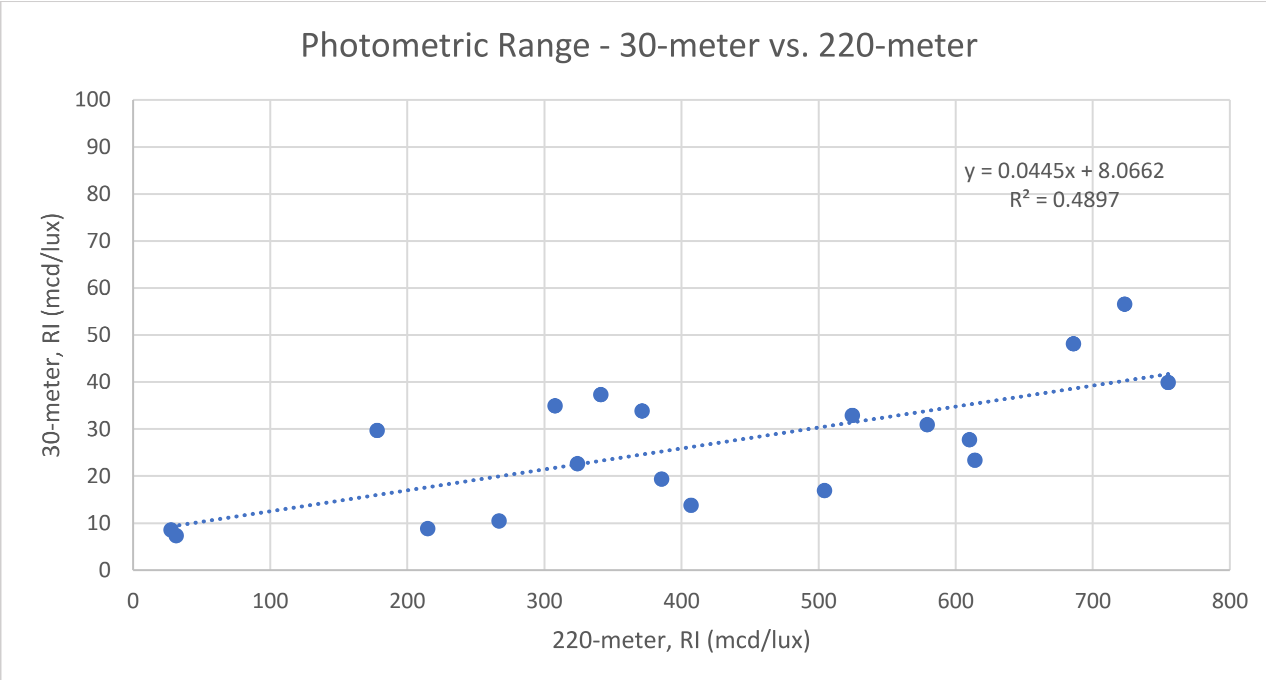


Figure 4-6. 30-meter vs. 220-meter RPM R_I values.

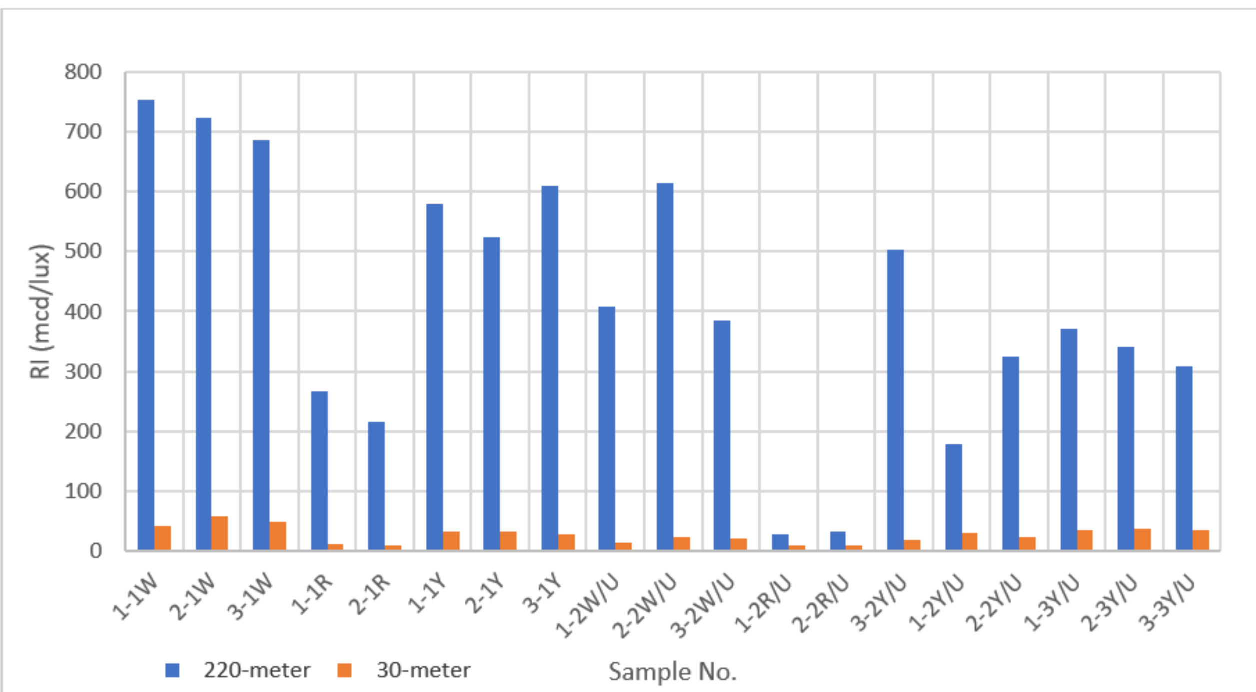


Figure 4-7. RPM R_I values trend for 30-meter and 220-meter geometries.

The repeatability study in the photometric range presented an average coefficient of variation (COV) of only 1.6% using the standard 220-meter geometry. This indicates low measurement variability between measurements of the same sample. Three non-consecutive measurements were acquired for each sample, and the coefficient of variation (COV) was calculated from the three runs average and standard deviation at a 95% confidence interval. It should be noted that the two red RPMs exhibited low R_I values, which introduced a higher COV with any slight difference. Table 4-1 shows the precision data sheet for the photometric range using the standard 220-meter geometry. In addition, the results of the photometric range testing are summarized below:

- The photometric range showed high measurement repeatability using the standard 220-meter measurement geometry with a COV of 1.6%.
- Using the 220-meter geometry, a 20° horizontal rotation causes a 44% drop in the RPM retroreflectivity relative to a non-rotated orientation.
- Using the 220-meter geometry, a 2° vertical tilt causes a 6% rise in the RPM retroreflectivity relative to a 0° tilt.
- Using the 30-meter geometry, the RPM retroreflectivity averaged around 9% of the 220-meter geometry RPM retroreflectivity value.

Table 4-1. Photometric range precision results.

	Test Date	*Unit*				***Variance***	***St. Dev***	***COV***
	9/26/19	mcd/lux				**8**	**3**	**1.6**
Test ID	*Type*	*Run 1*	*Run 2*	*Run 3*	*Average*	*Variance*	*St. Dev*	*COV*
Photometric Range 220-m (0°, 0.2°, 0°)	*1-1W*	758	754	753	755	8	3	0.38
	2-1W	726	722	722	723	7	3	0.37
	3-1W	689	685	684	686	9	3	0.43
	1-1R	270	265	265	267	9	3	1.14
	2-1R	216	214	214	215	1	1	0.48
	1-1Y	582	578	578	579	6	2	0.42
	2-1Y	528	523	523	525	9	3	0.58
	3-1Y	613	608	609	610	6	3	0.42
	1-2W/U	410	405	406	407	9	3	0.72
	2-2W/U	618	612	612	614	10	3	0.52
	3-2W/U	390	384	383	386	14	4	0.98
	1-2R/U	31	26	26	28	8	3	10.44
	2-2R/U	35	30	30	31	8	3	9.27
	3-2Y/U	507	503	503	504	7	3	0.52
	1-2Y/U	181	176	176	178	8	3	1.57
	2-2Y/U	327	323	322	324	8	3	0.89
	1-3Y/U	371	372	371	371	0	1	0.15
	2-3Y/U	344	339	339	341	9	3	0.86
	3-3Y/U	311	306	306	308	9	3	0.97

PORTABLE (HANDHELD) RETROREFLECTOMETER TEST

The portable retroreflectometer tests utilized one RoadVista handheld retroreflectometer and one from Zehntner. For the RPM 220-meter geometry measurements, the Zehntner ZRP 6030+ was used. As for the PM 30-meter geometry measurements, the RoadVista Stripe Master 2 was used. Each RPM sample had three non-consecutive measurements for the precision study and the average of the three measurements were used as the final RPM retroreflectivity value.

During preliminary testing, the 30-meter geometry handheld failed to achieve a proper quantitative RPM retroreflectivity measurement. It is believed to have been the result of oversaturation in the device's photodetector from the high retroreflectivity signal of RPMs. Therefore, the RoadVista Stripe Master 2 did not qualify for this test. The Zehntner 220-meter geometry handheld on the other hand demonstrated promising results. The same RPM samples from the photometric range test were laid down on a flat pavement surface and a series of measurements were acquired. Table 4-2 shows the data sheet and precision analysis for the Zehntner ZRP 6030+ handheld device. Three non-consecutive measurements were acquired for each sample and the coefficient of variation (COV) was determined.

Table 4-2. Zehntner ZRP 6030+ retroreflectivity and precision data from 19 RPM samples.

		Test Date	*Unit*			***Variance***	***St. Dev***	***COV***
		9/23/19	mcd/lux			**17**	**4**	**1.0**
Test ID	*Type*	*Run 1*	*Run 2*	*Run 3*	*Average*	*Variance*	*St. Dev*	*COV*
ZRP 6030+ Handheld	*1-1W*	660	667	678	668	82	9	1.36
	2-1W	650	656	657	654	14	4	0.58
	3-1W	642	644	643	643	1	1	0.16
	1-1R	254	256	253	254	2	2	0.60
	2-1R	228	225	228	227	3	2	0.76
	1-1Y	559	560	556	558	4	2	0.37
	2-1Y	534	543	532	536	34	6	1.09
	3-1Y	569	568	575	571	14	4	0.66
	1-2W/U	408	399	398	402	30	6	1.37
	2-2W/U	600	600	601	600	0	1	0.10
	3-2W/U	432	433	431	432	1	1	0.23
	1-2R/U	29	28	29	29	0	1	2.01
	2-2R/U	32	32	31	32	0	1	1.82
	1-2Y/U	552	555	555	554	3	2	0.31
	2-2Y/U	201	201	197	200	5	2	1.16
	3-2Y/U	311	309	314	311	6	3	0.81
	1-3Y/U	414	398	405	406	64	8	1.98
	2-3Y/U	392	391	384	389	19	4	1.12
	3-3Y/U	286	285	295	289	30	6	1.91

These results had an average difference of 0.8%, repeatability COV of 1.0%, and reproducibility between the handheld and the photometric range of 5.3%. The average error between the handheld and photometric range was ±6.6%. According to the above results, the handheld falls within the FDOT's acceptable repeatability and reproducibility COV values of 10% and 15%, respectively. These results indicate that this device produces accurate retroreflectivity measurements on RPMs will be useful for reference data. Figure 4-8 shows data plotted to demonstrate the correlation between the photometric range data and the handheld ZRP 6030+ device. The two devices show a high correlation with an R^2 of 0.9751.

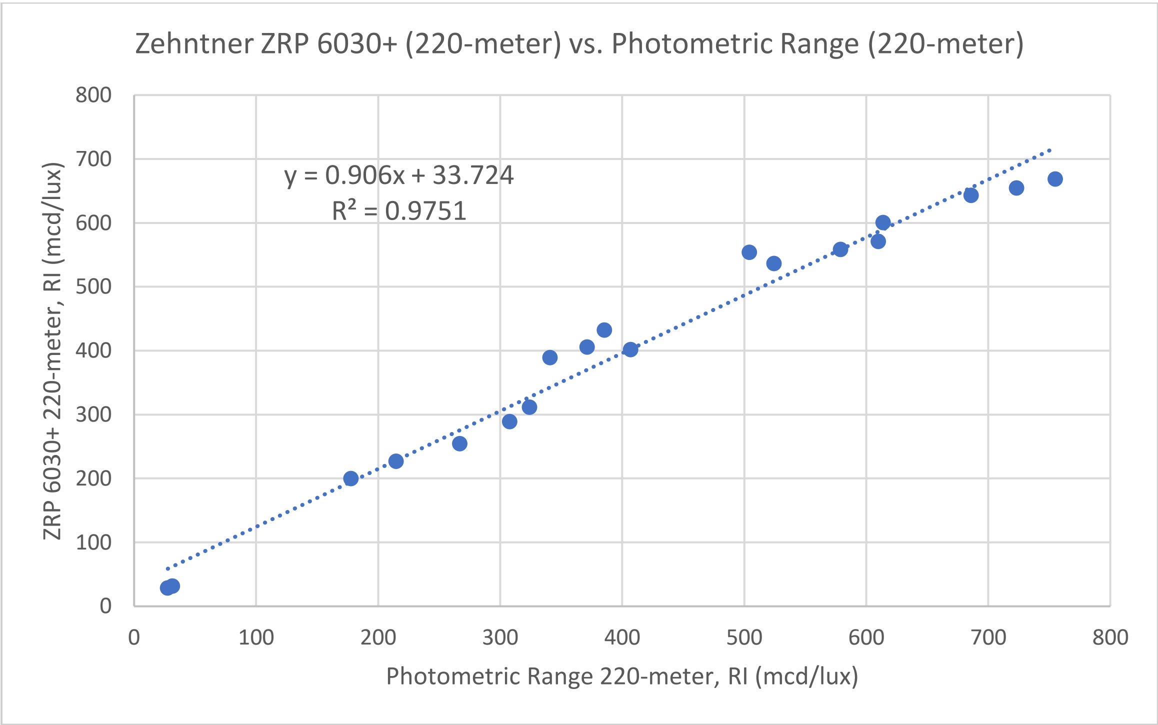


Figure 4-8. ZRP 6030+ vs. photometric range R_I values plot.

After completion of a series of tests with the portable retroreflectometers, the following is concluded:

- The striping retroreflectometer, the RoadVista Stripe Master 2, failed to measure RPM retroreflectivity due to oversaturation of the photodetector.
- The 220-meter geometry Zehntner ZRP 6030+ showed promising repeatability and reproducibility with the photometric range having COVs of 1.0% and 5.3%, respectively.
- The ZRP 6030+ obtained a 99.86% correlation with the photometric range 220-meter geometry test, with almost a direct linearity based on an R^2 value of 0.9751. The resulting average percent error between the two devices was ±6.6%.

MODIFIED MRU TEST

The MRU underwent a series of tests at the following three locations:

- FDOT MRU Calibration Bay: a controlled lab environment that replicates a the 30-meter geometry setup.
- FDOT Williston Airport Test Track: mobile (dynamic) RPM assessment on roads with no traffic, and variable conditions such as RPM placement and retroreflectivity values.
- FDOT Precision Test Sites: an on-road testing environment with no control over placement or retroreflectivity values.

Modified MRU Line-Stripe PM Precision Tests

The modified unit for these experiments was a Laserlux G7 MRU identified as LZ1017. The LZ1017 MRU is equipped with two channels, channel 0 (modified channel) and channel 1 (standard channel identical to the unmodified LZ1030). The hardware validation tests initially took place in the MRU calibration bay followed by the local precision test sites. The test bench within the calibration bay utilizes a 1/5th scale of the standard 30-meter geometry while maintaining the standard optical angles. These tests aimed to evaluate the modified MRU performance in a controlled environment, such as the calibration bay, to ensure the capability of the MRU to measure the higher RPM R_L values. The testing also aimed to define the MRU signal response to RPM retroreflectivity. Measurement of PM retroreflectivity occurred for a comparison between the modified MRU (LZ1017) and the unmodified FDOT MRU (LZ1030). This is to ensure the validity of the modified MRU PM readings, and that the modifications did not affect the PM R_L value measurements.

Initially LZ1017 was calibrated using the Gamma Scientific calibration plate, which had predetermined assigned values of 294 and 306 R_L (mcd/m^2/lux) for channels 0 and 1, respectively. The modified MRU had 7-mW laser power instead of the standard 20-mW for the FDOT boxes. The concept behind reducing the laser power on the modified unit was to avoid photodetector saturation previously seen with the 30-meter handheld retroreflectometer. Circuitry gains were adjusted accordingly by the manufacturer.

For RPM readings, channel 0 (modified) was able to detect RPMs with a wide range of R_L readings from 20,000 to 100,000 R_L (mcd/m^2/lux) showing a promising variation of R_L values relative to the photometric range readings. However, channel 1 (unmodified) could not achieve accurate readings, since all RPM samples saturated around a constant value of 10,000 R_L (mcd/m^2/lux).

For PM readings in the calibration bay and at the precision sites, LZ1017 showed a significant difference in the readings when compared to LZ1030 and the pooled historical data. For reference, the pooled historical data is a 6-month moving average of accepted retroreflectivity readings at each of the five precision sites. Figures 4-9 and 4-10 shown below contain precision results for sites 1 and 2. Both channels 0 and 1 were used to measure line-striping retroreflectivity at each site. The repeatability and reproducibility (between LZ1017 and historical pooled data) did not pass with precision COV thresholds acceptable by the FDOT, which are 10% and 15%, respectively. Channel 0 read higher values while channel 1 read lower values relative to the other MRUs

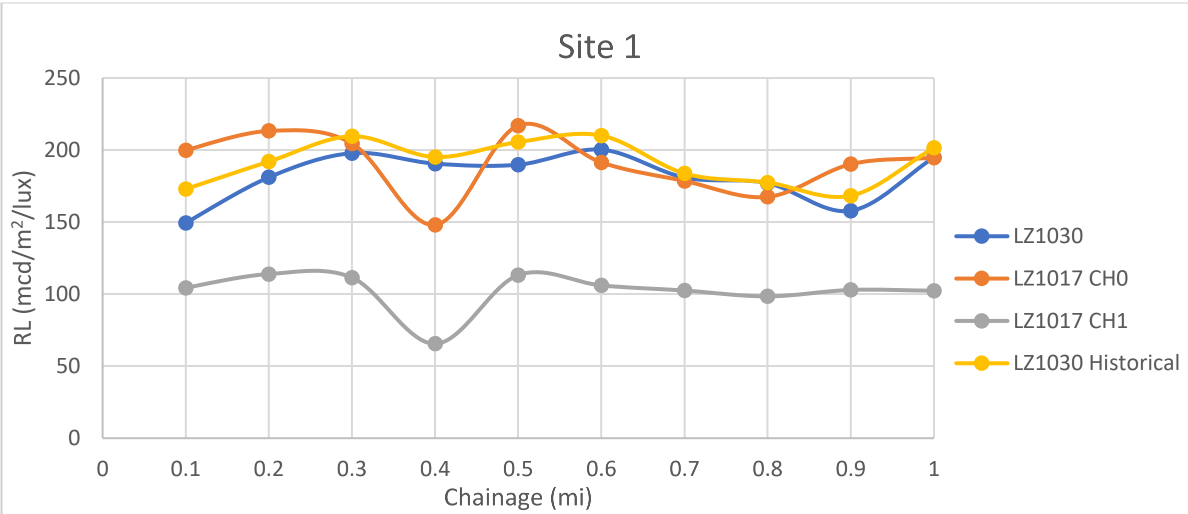


Figure 4-9. Precision site 1 LZ1017 channel 0, channel 1, and historical data plot.

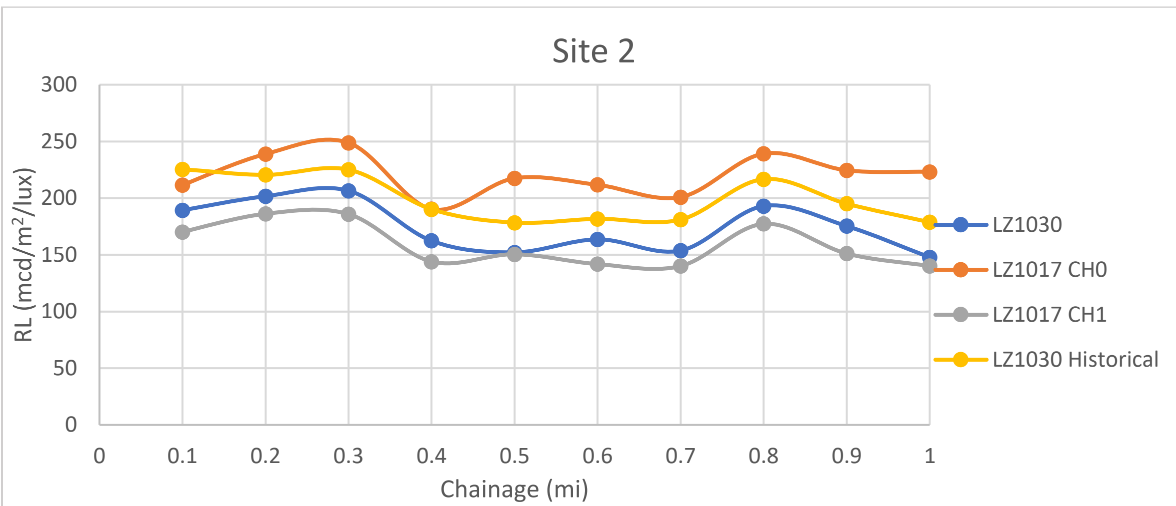


Figure 4-10. Precision site 2 LZ1017 channel 0, channel 1, and historical data plot.

Moreover, the LZ1017 did not pass the FDOT accuracy test or lateral test. The accuracy test is executed by reading a set of stripes identified by the FDOT with known R_L values then calculating the average percent difference of the readings. For an MRU to pass this test, its average percent difference should be less than 10%. The LZ1017 achieved a 15% and 19% difference for channels 0 and 1, respectively.

The research team then investigated using the FDOT MRU calibration method. The calibration procedure was performed using the ceramic standard which measured 161 R_L (mcd/m^2/lux) according to the FDOT's photometric range measurements. The new calibration values assigned to the Gamma Scientific calibration block were 314 and 344 R_L for channel 0 and channel 1, respectively. Next, the team decided to run a full precision test and compare values with the FDOT MRU historical data for the precision test sites. This time the repeatability and reproducibility values passed the FDOT standards. Channel 0 had a COV of 6.4% for repeatability and a COV of 8.4% for reproducibility. Channel 1 had a COV of 5.5% for repeatability and 15.6% for reproducibility.

While the reproducibility for channel 1 was outside of the maximum COV value of 15%, the research team went ahead with line-stripe testing at the five precision sites. Channels 0 and 1 were both activated and ran simultaneously at each site. Each channel was collecting line-stripe PM data for evaluation. Figures 4-11 to 4-20 compare the measurement results of LZ1017 (Test 1, 2, and 3) to the pooled historical averages (QA1, QA2, and QA3).

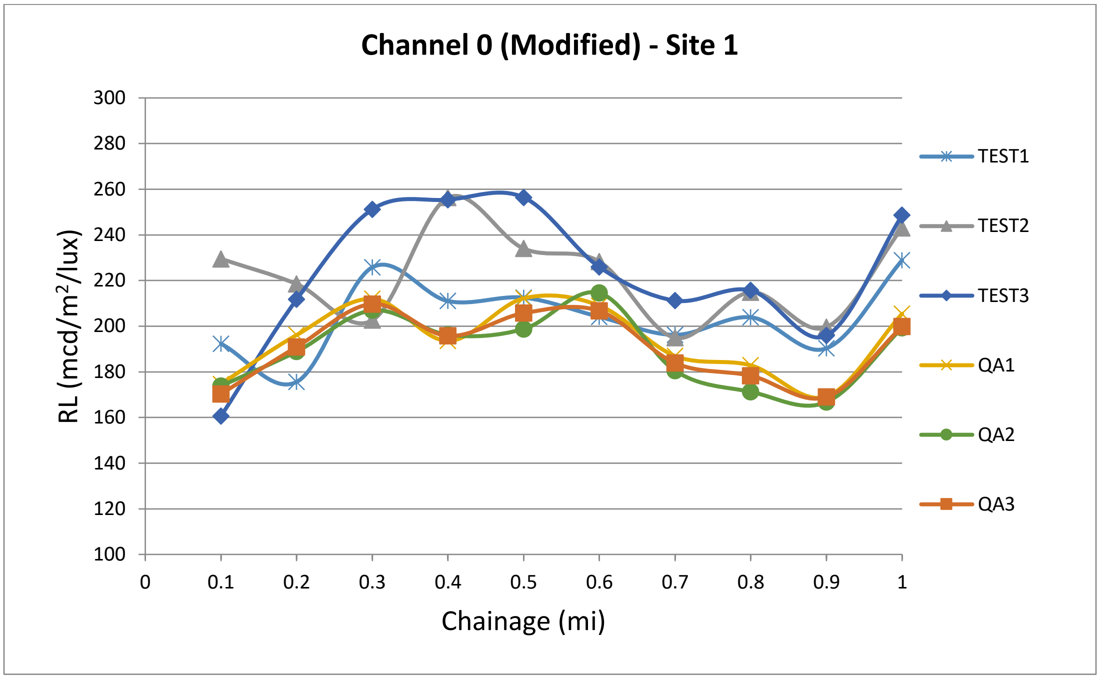


Figure 4-11. Precision site 1 LZ1017 channel 0 and historical data plot.

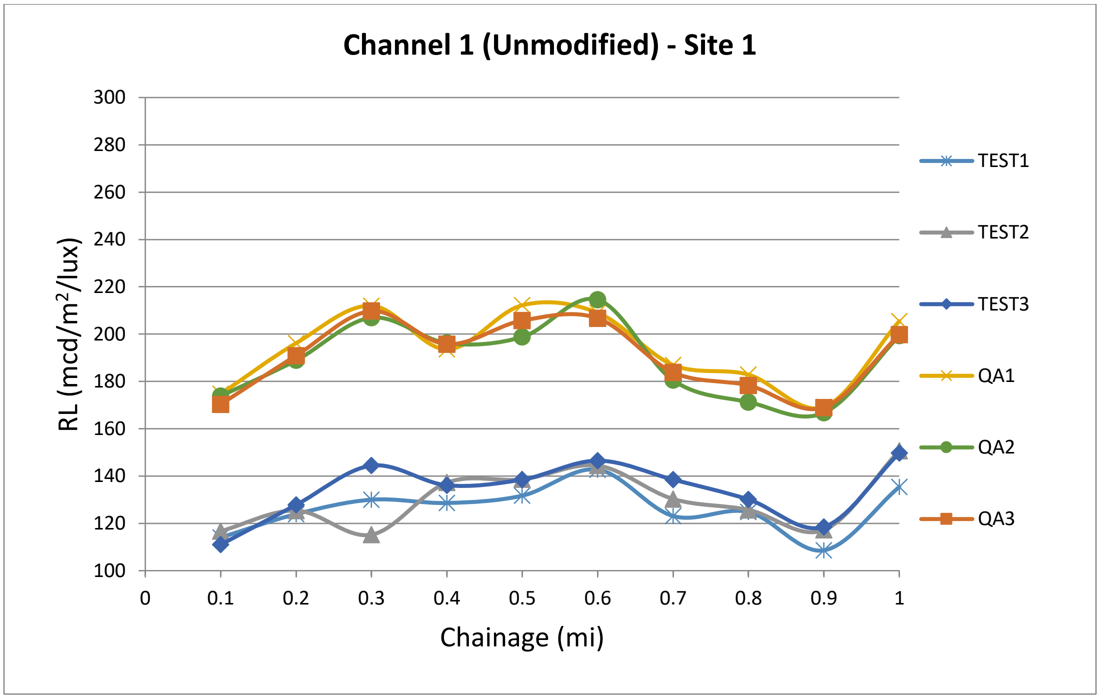


Figure 4-12. Precision site 1 LZ1017 channel 1 and historical data plot.

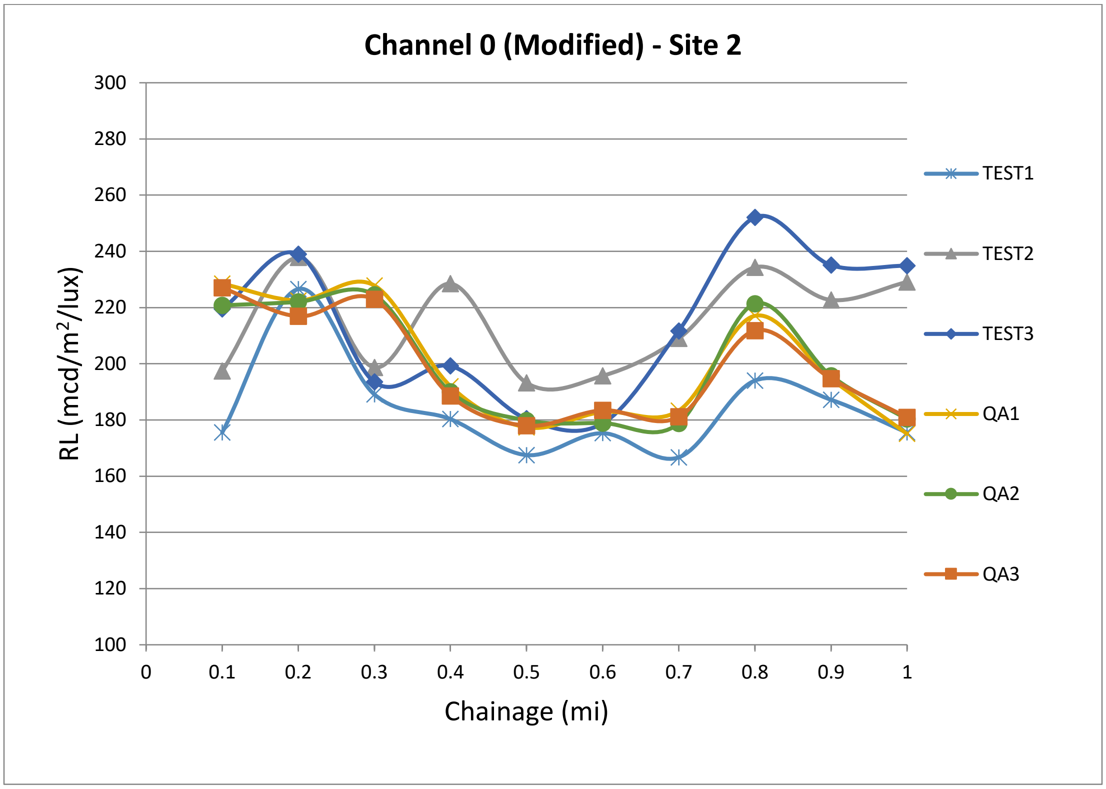


Figure 4-13. Precision site 2 LZ1017 channel 0 and historical data plot.

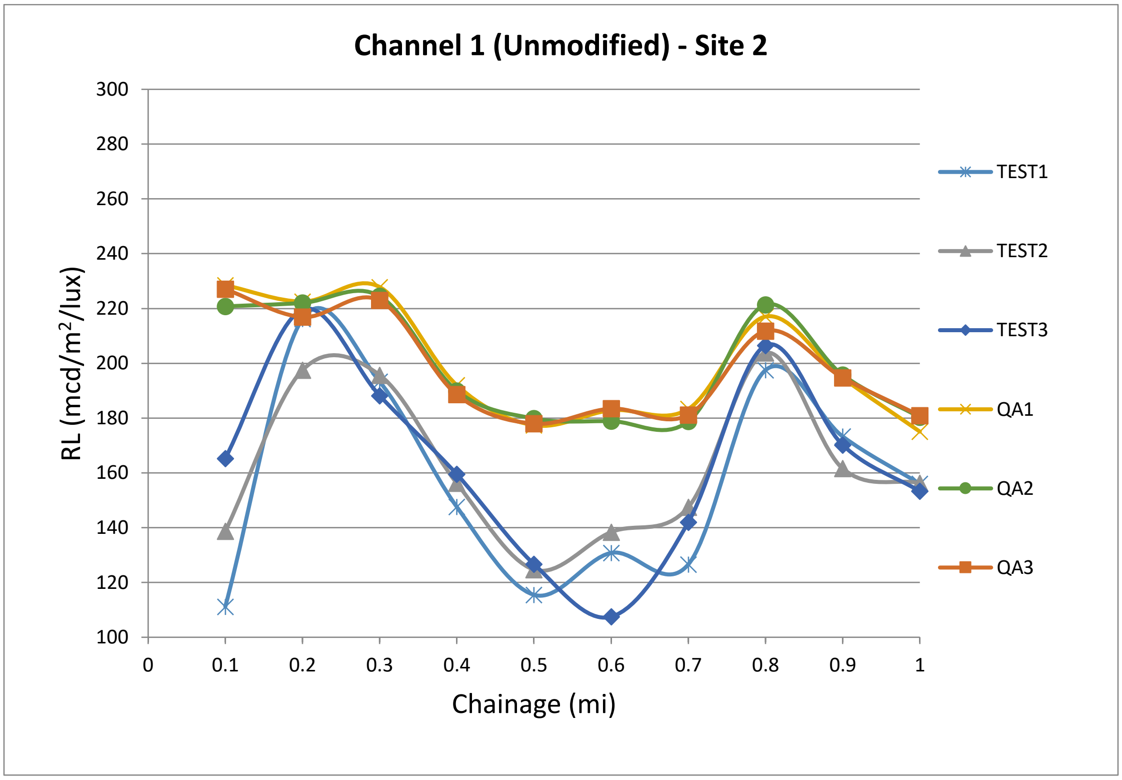


Figure 4-14. Precision site 2 LZ1017 channel 1 and historical data plot.

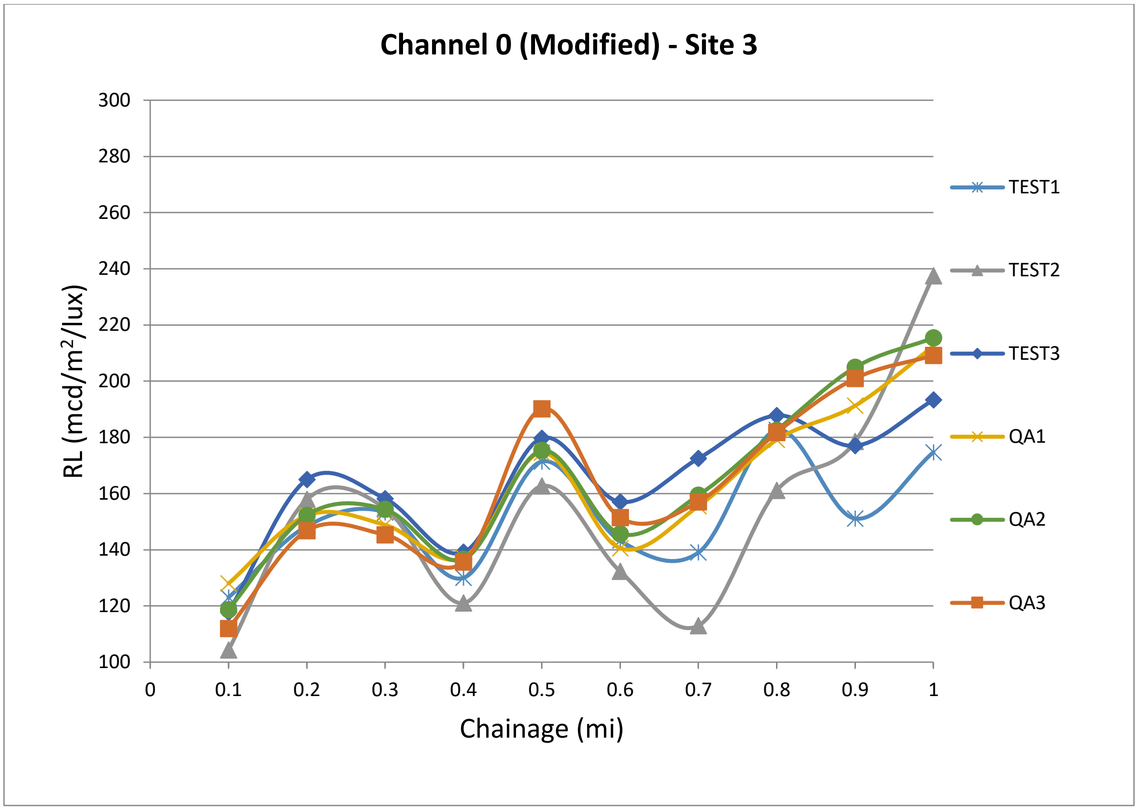


Figure 4-15. Precision site 3 LZ1017 channel 0 and historical data plot.

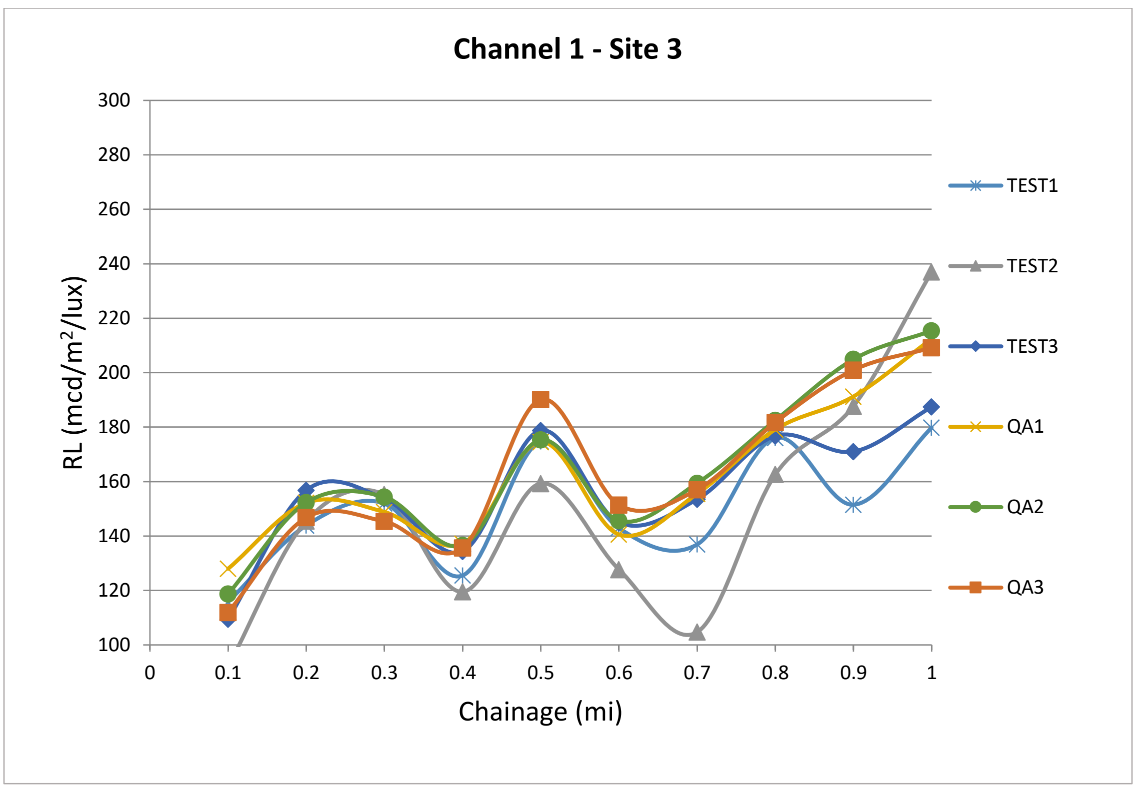


Figure 4-16. Precision site 3 LZ1017 channel 1 and historical data plot.

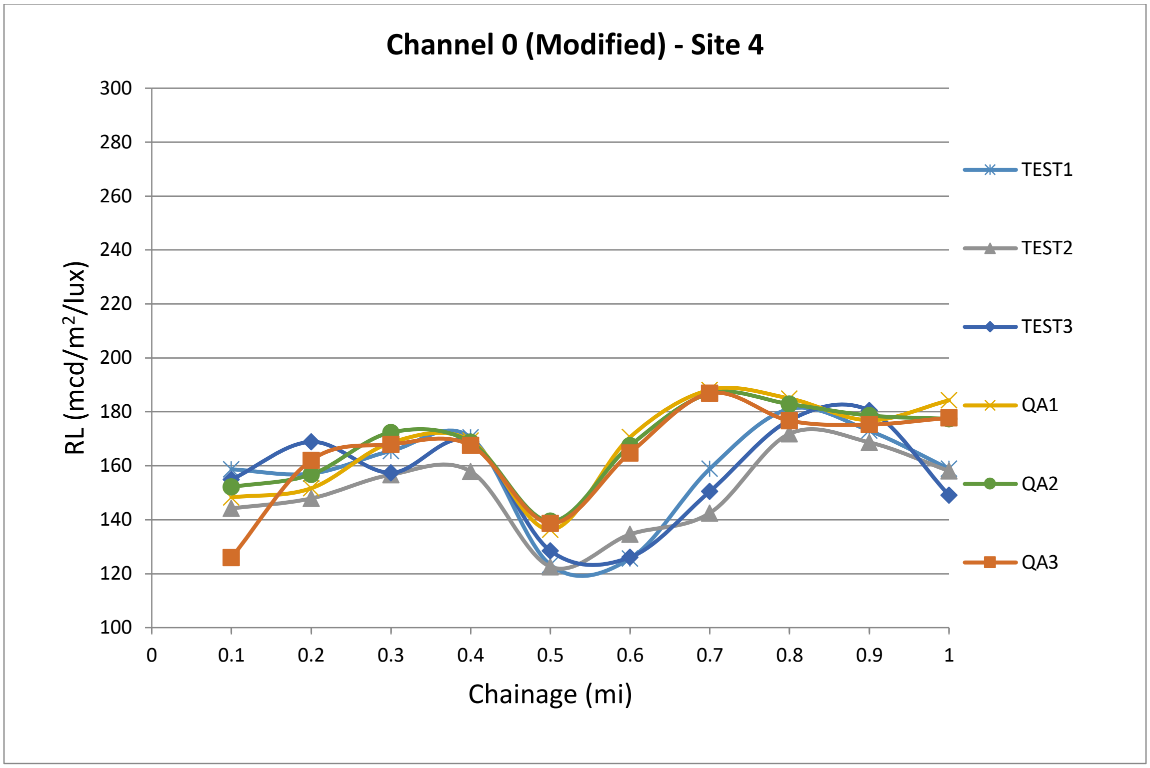


Figure 4-17. Precision site 4 LZ1017 channel 0 and historical data plot.

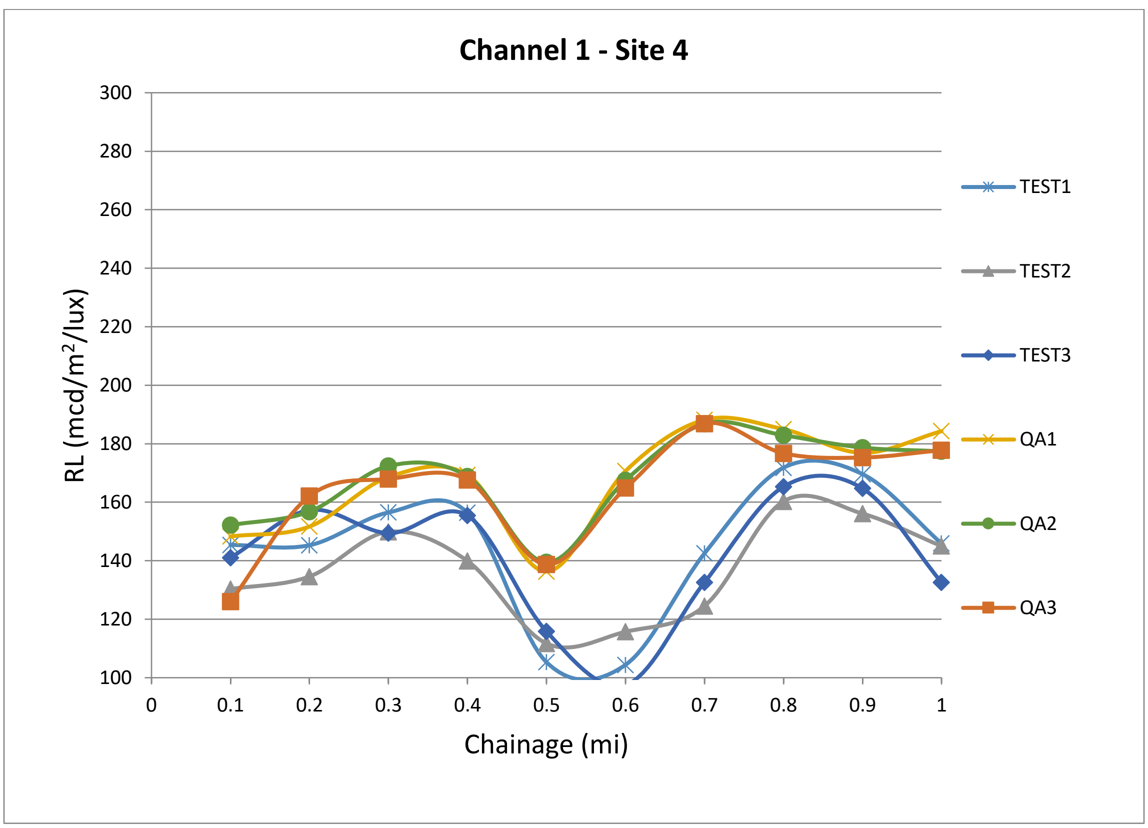


Figure 4-18. Precision site 4 LZ1017 channel 1 and historical data plot.

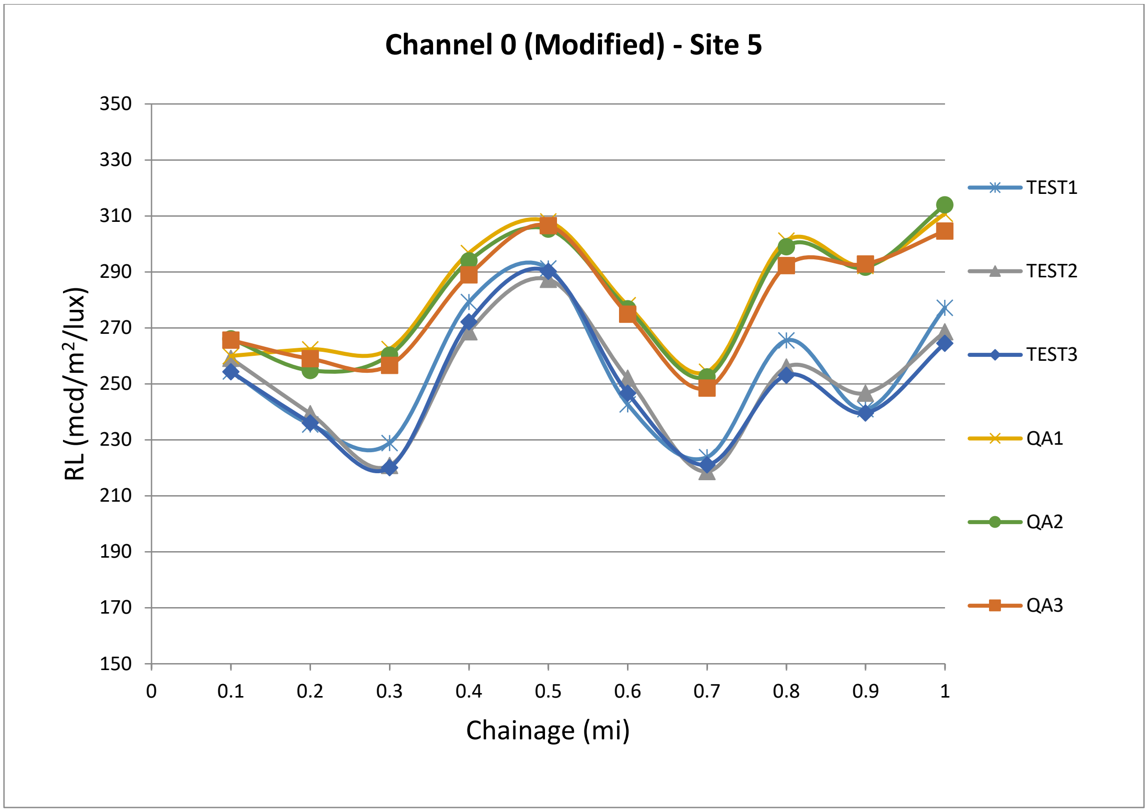


Figure 4-19. Precision site 5 LZ1017 channel 0 and historical data plot.

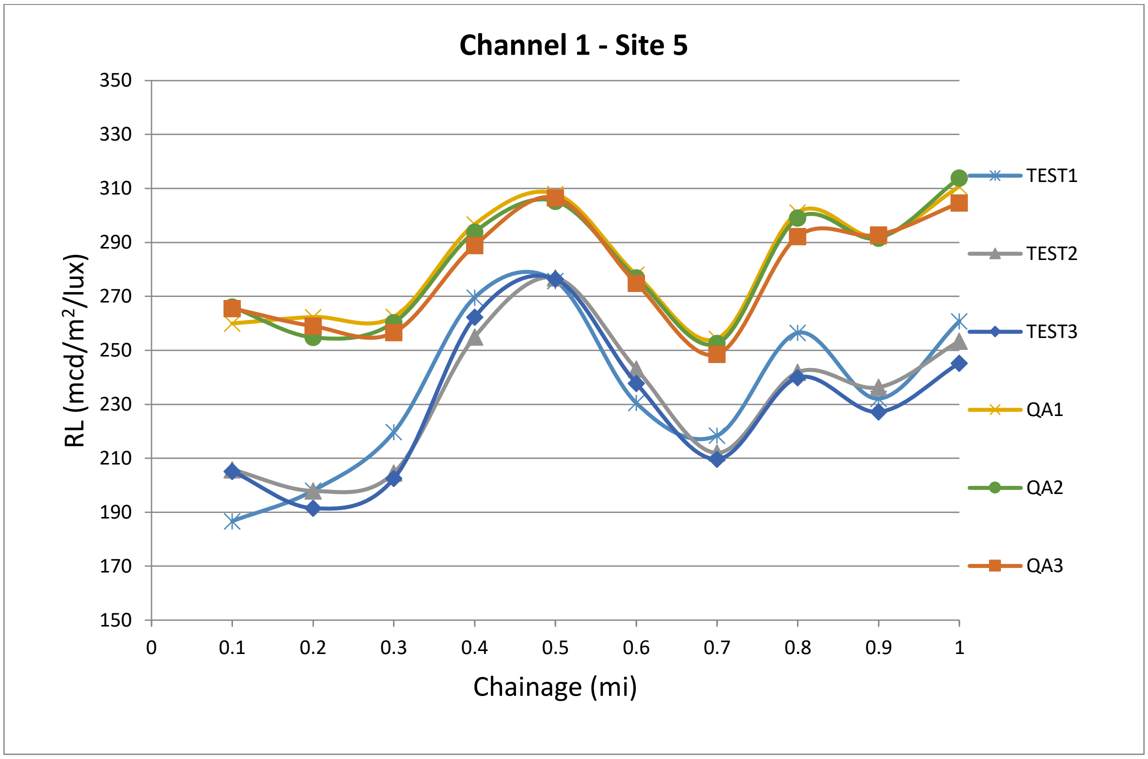


Figure 4-20. Precision site 5 LZ1017 channel 1 and historical data plot.

After completion of a series of tests with the LZ1017 modified MRU for line-stripe PMs the following is concluded:

- The modified channel 0 is capable of measuring striping retroreflectivity with an acceptable repeatability and reproducibility, achieving COV values of 6.4% and 8.4%, respectively.
- There is no interference between PM and RPM readings using the LZ1017 using channel 0 as a stand-alone system.
- Using both channel 0 and 1 simultaneously caused interference with PM readings on channel 1.
- The LZ1017 passed the FDOT quality assurance test, which included accuracy, lateral, and dynamic alignment tests using channel 0.

Modified MRU RPM Detection and Retroreflectivity

The FDOT Williston Airport test track was used for this study, shown in Figure 4-21. The ¾ mile roadway is located within the Williston Airport boundary, and as such, is gated with limited access. The test track allowed testing under various vehicle conditions (such as speed) and RPM configurations (such as distance between RPM installations). Back-to-back identical testing of the two laser sub-assemblies (one nominal and one modified for RPM measurement) occurred without traffic disruption, an advantage of a closed track.

Figure 4-21. Modified MRU setup at the Williston Airport test track.

For this testing, 13 RPM samples were used at the Williston test track to determine the RPM detection under various conditions. First, the RPM was placed solely without any surrounding retroreflective materials. Then to determine any interference in the readings due to PMs, the RPM was placed next to an edge line and the average of three runs were compared to another average of three runs without the RPMs next to an edge line. The results indicated no discernable interference in RPM retroreflectivity measurements caused by PMs. Results for PM interference are shown in Table 4-3.

Table 4-3. Data representing the PM interference with RPM readings

Site	*RPM Spacing*	*Type*	*Chainage*	RPM	RPM next to edge line
Williston Airport Test Track	*40 ft.*	*New & Used White/Yellow*	*1*	68,870	67,427
			2	39,158	38,307
			3	39,465	40,859
			4	31,009	25,824
			5	120,165	121,325
			6	117,842	117,309
			7	119,739	124,181
			8	118,868	117,428
			9	117,462	117,424
			10	122,388	121,790
			11	118,399	113,870
			12	119,408	118,092
			13	122,033	121,317

Next, in accordance with the FDOT specifications for roadway RPM placement, nine RPM samples were placed 40 feet apart at the test track. Three or more runs were executed for each setup to identify the performance under the previously mentioned conditions. The LZ1017 MRU did not demonstrate any interferences between RPMs and PMs or between both channels 0 and 1. However, the device did produce multiple readings for each RPM, where a single RPM would register two or more R_L measurements. Table 4-4 shows RPM detection relative to vehicle speed (MOD meaning channel 1 turned off). The data shows multiple hits of the same RPM in most cases as the number of RPMs registered exceeded the actual number of RPMs placed.

Table 4-4. RPM detection test (nine RPMs) at the Williston Airport test track.

Run File Name	RPM Placement	Vehicle Speed (mph)	RPMs Detected
MULTIPLE_F08	9 RPMs placed 40 ft. apart	Acc. 26-43	9
MULTIPLE_F07		10	37
MULTIPLE_F06		8	24
MULTIPLE_F05		3	94
MULTIPLE_F04		33	14
MULTIPLE_F03		53	12
MULTIPLE_F02		22	22
MULTIPLE_F01		54	15
MULTIPLE_F00		59	12
MULTIPLE_MOD_F00		60	9
MULTIPLE_MOD_F01_1		58	16
MULTIPLE_MOD_F01_2		49	15

The multiple RPM detection issue was communicated to the Gamma Scientific team. The RPM R_L registry algorithm was reviewed for possible bugs along with exploring a hardware upgrade that could help with detection at higher speeds. Meanwhile, further tests were conducted by the research team to pinpoint the technical difficulty that was preventing higher speed detection. After hardware specification, algorithm analysis, and raw data analysis, it was discovered that the hardware and physics of the LZ1017 satisfy higher speed detection and that the algorithm had a bug that prevented the MRU from registering the proper peak signal average. Based on the test results above, it was concluded that a new algorithm needed to be developed for smarter RPM detection and registration.

Working with Gamma Scientific, firmware v1.318 was delivered and testing could resume. A setting was added to set the distance at which the MRU should wait after an RPM is registered before registering another. This setting was labeled RPMD and was set to a default value of 0.1 meters. Another parameter added in this firmware was the search distance that the MRU should travel to collect retroreflectivity readings. This setting was labeled RPMV and was set to a default value of 0.1 meters. The standard channel (channel 1) was to be completely turned off to provide the modified (RPM) channel with 100% CPU usage instead of 50%.

The detection issue was narrowed down to a factor in the software that could be potentially blocking an RPM registry. The research team set a test plan to check if the stripe width restriction could be the reason. The stripe width range was changed from 2 to 20 inches (minimum and maximum) to 0.1 to 20 inches wide. The Williston Airport test track was tested again with a collection of 13 RPMs: nine new and four used RPMs (high and low retroreflectivity). The results showed proper detection and R_L readings with good precision.

Table 4-5 shows the detection results using the latest firmware, v1.318. The results showed that the number of RPMs detected with the updated stripe width range (0.1 to 20 inches) was consistently 13 out of 13. As a result, it was confirmed that this stripe width range was the optimal setting. The results shown in Table 4-5 below contains the different stripe width configurations that were tested. The testing included placing 13 RPMs spaced 40 feet apart at the Williston Airport test track and using the modified channel 0 on the MRU for detection.

Table 4-5. RPM detection test using upgraded firmware (v1.318).

Run File Name	RPM Placement	Width Range (in)	Vehicle Speed (mph)	RPMs Detected
MULTIPLE_65MPH_F01	13 RPMs placed 40 ft. apart	2-20	65	10
MULTIPLE_65MPH_F02		2-20	65	12
MULTIPLE_65MPH_F03		2-20	65	11
MULTIPLE_65MPH_F04		0.1-20	65	13
MULTIPLE_65MPH_F05		0.1-20	65	13
MULTIPLE_65MPH_F06		0.1-20	65	13
MULTIPLE_65MPH_F07		2-25	65	11
MULTIPLE_65MPH_F08		2-25	65	12
MULTIPLE_65MPH_F09		2-25	65	12
MULTIPLE_65MPH_F10		0.1-25	65	13
MULTIPLE_65MPH_F11		0.1-25	65	13
MULTIPLE_65MPH_F12		0.1-25	65	13
MULTIPLE_65MPH_F13		0.1-20	65	13
MULTIPLE_65MPH_F14		0.1-20	65	13
MULTIPLE_65MPH_F15		0.1-20	65	13

Finally, it was concluded that the RPM width recognized by the MRU at high R_L readings is narrower than that of line-striping as the detection rate was proper with a minimum width of 0.1 inches. Hence, the stripe width range was preventing the MRU from registering any R_L reading that has a width less than two inches, in addition to any partial hit due to mild misalignment or brief interruptions of the signal. Additionally, Table 4-6 shows the detection results from subsequent testing using firmware v1.318. The data shows that the RPMs detected were consistently 13 out of 13. The optimal firmware parameters used were RPMD of 0.1 meters, RPMV of 0.1 meters, stripe width range of 0.1 to 20 inches. Figure 4-22 shows a graph for the three non-consecutive runs with width range setting of 0.1 to 20 inches. The data shows good repeatability and proper detection for all RPM samples across the three runs.

Table 4-6. Final RPM detection test using firmware v1.318.

Run File Name	RPM Placement	Vehicle Speed (MPH)	RPMs Detected
MULTIPLE_65MPH_F16	13 RPMs placed 40 ft. apart	65	13
MULTIPLE_65MPH_F17		65	13
MULTIPLE_65MPH_F18		65	13
MULTIPLE_65MPH_F19		65	13
MULTIPLE_65MPH_F20		65	13
MULTIPLE_65MPH_F21		65	13
MULTIPLE_65MPH_F22		65	13
MULTIPLE_65MPH_F23		65	13
MULTIPLE_65MPH_F24		65	13

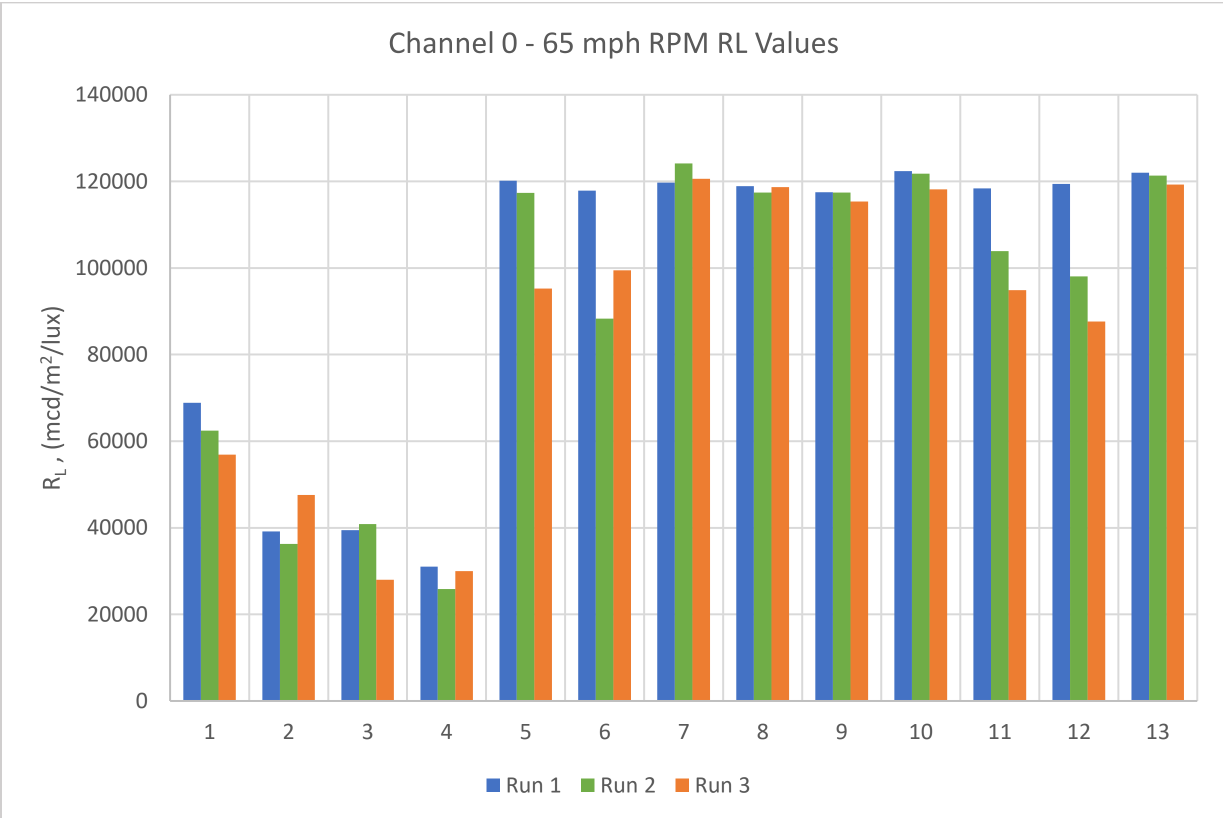


Figure 4-22. RPM retroreflectivity values on the 13 RPMs used for detection.

Additionally, Table 4-7 shows the R_L precision analysis for the data shown in Figure 4-22. The data shows the three runs with width range setting of 0.1 to 20 inches. The values show good repeatability with a COV value of 8.8%, which satisfies the minimum repeatability requirements established by the FDOT.

Table 4-7. Precision data on the 13 RPMs used for detection testing.

	Test Date				*Unit*		***Variance***	***St. Dev***	***COV***
	2/7/19				**LZ1017**		**73,448,662**	**8,570**	**8.8**
Site	*RPM No.*	*Run 1*	*Run 2*	*Run 3*	*Avg.*		*Variance*	*St. Dev*	*COV*
Williston Airport Test Track	*1*	68,870	62,427	56,867	62,721		36,081,658	6,007	10
	2	39,158	36,307	47,611	41,025		34,563,882	5,879	14
	3	39,465	40,859	28,020	36,114		49,627,581	7,045	20
	4	31,009	25,824	30,010	28,947		7,566,533	2,751	10
	5	120,165	117,325	95,212	110,900		186,606,757	13,660	12
	6	117,842	88,309	99,474	101,875		222,371,286	14,912	15
	7	119,739	124,181	120,624	121,515		5,527,984	2,351	2
	8	118,868	117,428	118,705	118,333		621,092	788	1
	9	117,462	117,424	115,332	116,739		1,486,018	1,219	1
	10	122,388	121,790	118,148	120,776		5,266,137	2,295	2
	11	118,399	103,870	94,904	105,724		140,591,327	11,857	11
	12	119,408	98,092	87,619	101,706		262,429,144	16,200	16
	13	122,033	121,317	119,247	120,865		2,093,199	1,447	1

After completion of a series of tests with the MRU for the RPMs using the modified channel (channel 0), the following is concluded:

- Using the proper firmware settings, the LZ1017 is capable of RPM detection, with almost a 100% detection rate at speeds up to 65 MPH.
- The LZ1017 demonstrated a proper repeatability for RPM retroreflectivity readings, with a COV value of 8.8% at a closed-course test track.
- Proper firmware settings include RPMD set to 0.1 meters, RPMV set to 0.1 meters, and stripe width range set from 0.1 to 20 inches.
- The MRU is capable of proper RPM detection and PM retroreflectivity readings using channel 0 as a stand-alone system.
- Running both channel 0 and 1 simultaneously produced PM measurement interference.

CONCLUSIONS

A series of tests were performed to evaluate and compare three retroreflectivity measurement devices. These devices included the photometric range, a 220-meter geometry RPM handheld, and a 30-meter geometry MRU. Testing was performed under controlled laboratory conditions, on a closed test track at the Williston Airport, and at designated locations on public roadways. The primary objectives were to evaluate the viability of using the MRU to detect and quantify RPM retroreflectivity at highway speeds using 30-meter measurement geometry.

For the precision study, the Gamma Scientific photometric range and the Zehntner ZRP 6030+ had passing repeatability results according the FDOT precision standards. The Gamma Scientific LZ1017 MRU passed both the repeatability and reproducibility according to the FDOT precision standards for PM retroreflectivity readings. The handheld ZRP 6030+ appears to hold high potential within the maintenance program as part of RPM retroreflectivity evaluation. This conclusion is based on the high correlation and very low percent difference between the device measurements and that of the photometric range.

A series of tests were performed with the LZ1017 MRU, which was equipped with two independent channels to allow side-by-side retroreflectivity comparisons. The modified channel was identical to the standard channel in current use for line-striping measurement, except that the laser power was reduced to avoid saturation of the detector by RPMs. The objective was to see whether the modified channel could detect both line striping and RPMs, thereby increasing efficiency of network evaluation. Tests were conducted using a wide range of RPM types and conditions, at various speeds up to 65 MPH. The key conclusions from these tests are:

- Using the proper firmware settings, the LZ1017 is capable of RPM detection, with almost a 100% detection rate at speeds up to 65 MPH.
- The LZ1017 MRU modification allowed the photodetector to accurately detect the RPM retroreflectivity while avoiding saturation.
- Promising LZ1017 results were obtained regarding R_L value variation for a wide range of RPM types and conditions, with a COV value of 8.8%.
- The LZ1017 modified channel 0 performed better than the standard channel and passed FDOT repeatability and reproducibility standard for PMs.
- The LZ1017 modified channel 0 repeatability of 6.4%, and a reproducibility relative to the existing FDOT MRUs of 8.4% for line-stripe PMs.
- The LZ1017 modified channel 0 is capable of an RPM retroreflectivity readings with a repeatability COV of 8.8% at high speeds up to 65 MPH.
- The LZ1017 modified channel (channel 0) is capable of performing both PM and RPM measurements simultaneously without interference.
- The LZ1017 modified channel 0 does not demonstrate the photodetector saturation issues that occurred with channel 1 while measuring the high R_L values of RPMs.

CHAPTER 5 - MODIFIED MRU VALIDATION TESTING

OVERVIEW

The two primary objectives of this task order were to validate the modified Laserlux G7 MRU's ability to count Class B raised pavement markers (RPMs) and to harmonize the retroreflected luminance values [R_L – (mcd/m^2/lux)] produced by the MRU with coefficient of luminous intensity [R_I – (mcd/lux)] values produced by a handheld RPM retroreflectometer. The handheld reference device used in this study was a Zehntner ZRP 6030+. In Task 3, R_I values produced by the Zehntner device had shown very strong agreement with R_I values measured in the photometric range on the same RPM samples with an average error of ±6.6%. Based on those results, the research team determined that this device would be suitable for reference measurements in field testing. Figures 5-1 and 5-2 show images of the MRU test vehicle and reference device, respectively.

Figure 5-1. High-speed testing vehicle equipped with the modified MRU device.

Figure 5-2. Collecting reference data with the Zehntner handheld device.

Field testing was conducted at nine sites in close proximity to the SMO with varying wear of both pavement and RPMs. All nine of the sites listed in Table 5-1 were used for RPM detection, or counting, analysis. Of these nine sites, four were used for R_L versus R_I retroreflectivity comparisons (26020000, 26130000, 265805000, and 72120000). In the sites listed in Table 5-1, four were yellow center lines, and five were white skip lines. Utilizing both center line and skip line test sections allowed for the collection of both white and yellow RPMs to ensure measurement consistency regardless of color. Table 5-1 lists the test site details and Figure 5-3 shows a map of their approximate locations.

Table 5-1. One-mile RPM test sites.

Roadway ID	Lane	Location	RPM Color	Speed (mph)	BMP	EMP
26020000	R1SL	SR 20	White	55	8.55	9.55
26050000	R1SL	SR 331	White	55	6.13	7.13
26060000	L1SL	SR 200	White	65	9.95	8.95
26080000	L1SL	SR 20	White	65	8.25	7.25
26130000	RCL	SR 26	Yellow	55	3.70	4.70
26580500	RCL	CR 1474	Yellow	55	2.53	3.53
28050000	RCL	SR 230	Yellow	60	2.37	3.37
34010000	L1SL	SR 55	White	65	15.79	14.79
72120000	RCL	SR 228	Yellow	55	4.13	5.13

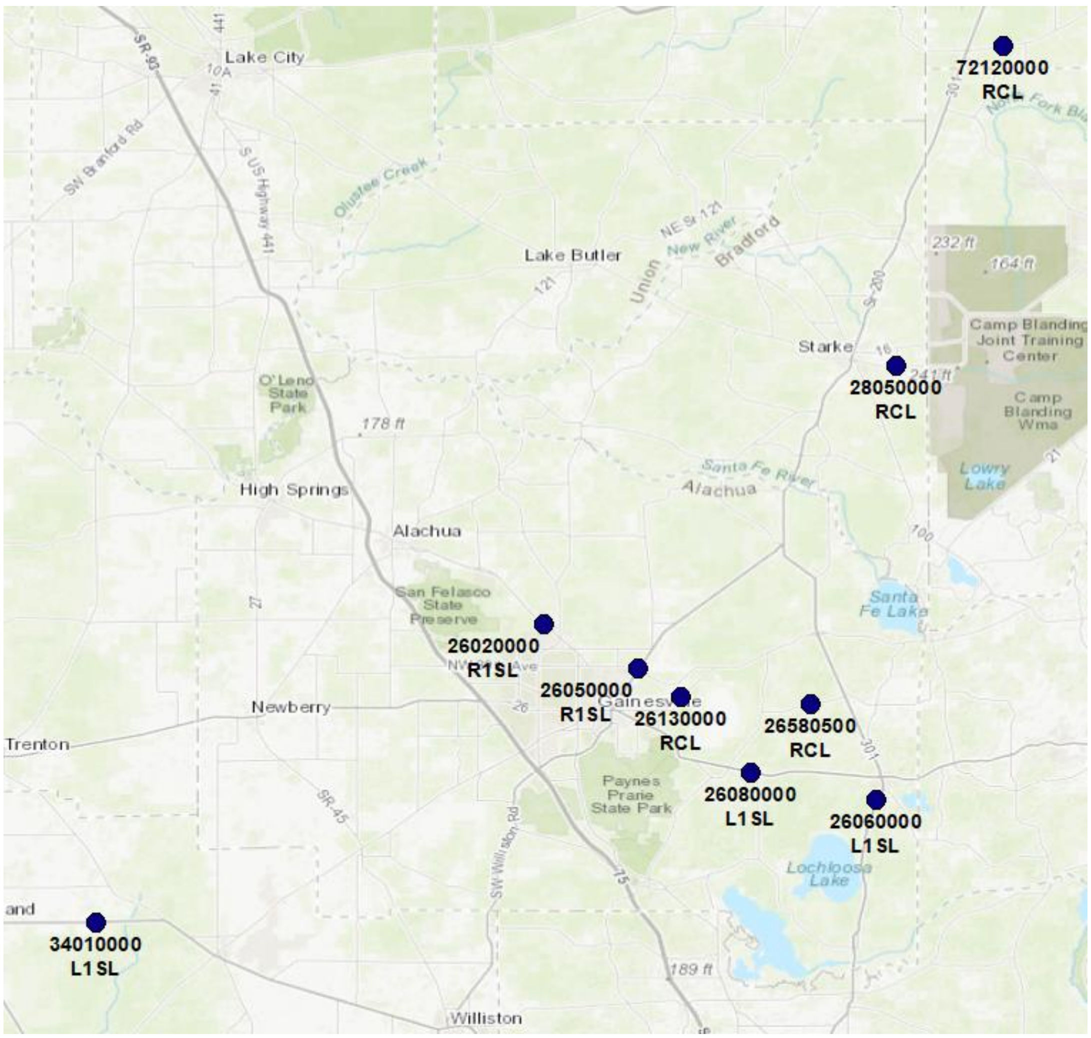


Figure 5-3. Test site map.

MRU MODIFICATION

At this point in the study, the LZ1030 unit was outfitted with a second channel (channel 0) which was modified to contain the same parameters, firmware, and hardware as the LZ1017 unit. The following testing used the modified LZ1030 MRU. Initially, testing was conducted using an emitted MRU laser power of seven milliwatts (mW). This value was originally selected in an effort to minimize measurement saturation at high levels of retroreflectivity. However, it was later determined that an issue with the device's software pertaining to peak signal detection may have been contributing to measurement saturation. As a result, firmware version 1.318 was delivered by the original equipment manufacturer, Laserlux, to the research team for testing. Using the 7-mW configuration, field testing had shown that this laser power did not produce the desired levels of repeatability. In addition, using the preliminary R_L to R_I regression equations, the 7-mW configuration had an average error of 34% when comparing estimated R_I values to R_I values measured by the handheld reference device.

It was observed that increasing the laser emission power produced a more focused laser spectrum, which is desirable for this application due to the inherent variability in retroreflectivity across an RPM in both the vertical and horizontal directions. As a result, the research team decided to utilize a 20-mW laser power, which is the standard laser power used in production pavement marking MRUs at the FDOT. Static testing within the MRU calibration bay had shown that the 20-mW configuration was producing a more linear trend when comparing R_L values to the handheld measured R_I values on 12 new RPMs. Additionally, these static measurements had higher repeatability when compared to the 7-mW configuration. For these reasons, the remainder of the project utilized a 20-mW laser emission power. Figure 5-4 shows a visual comparison between the two laser powers. Figures 5-5 and 5-6 show the static test results on 12 new RPMs.

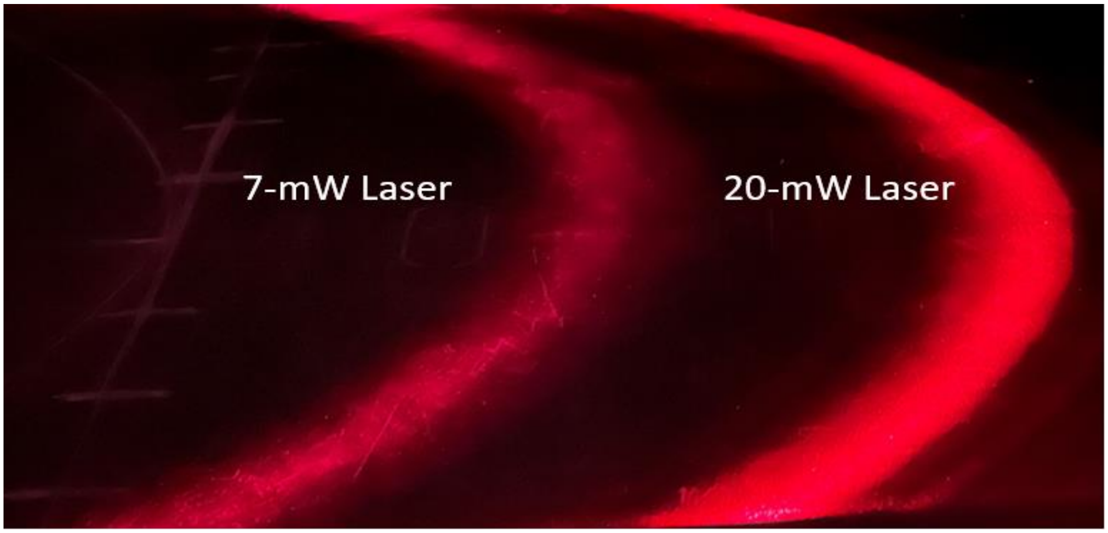


Figure 5-4. Comparing 7-mW laser power to the 20-mW laser power.

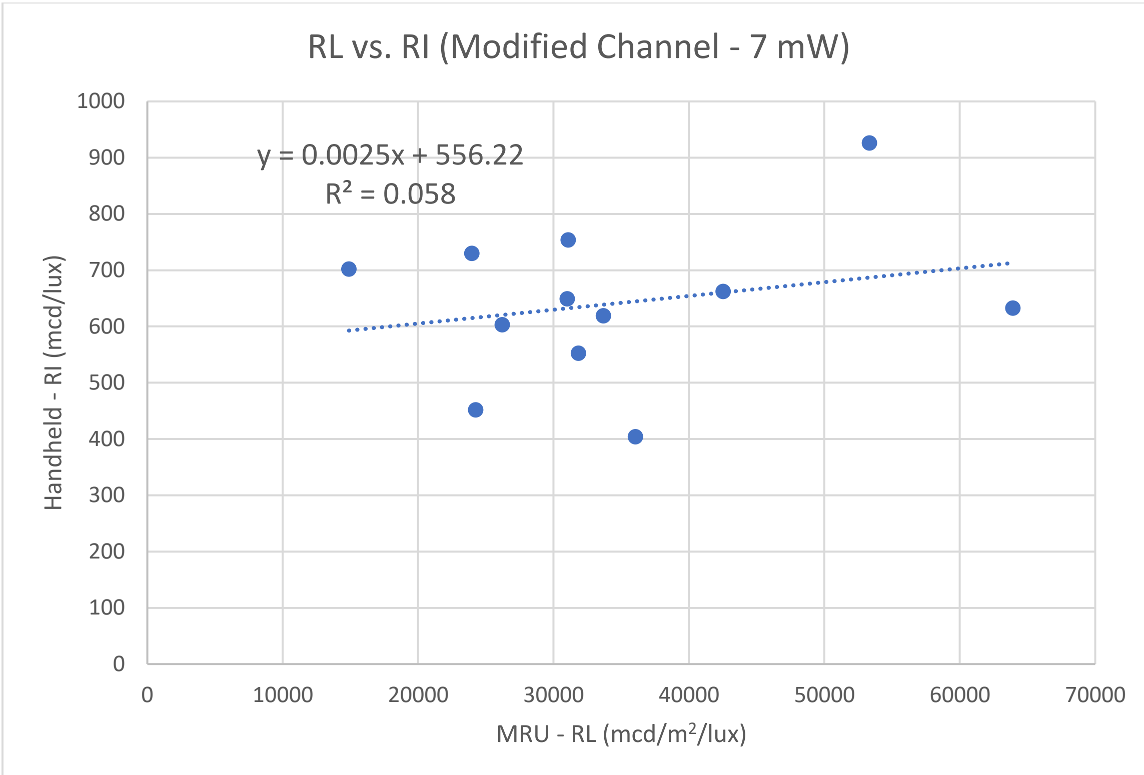


Figure 5-5. Static RPM test results using the 7-mW configuration.

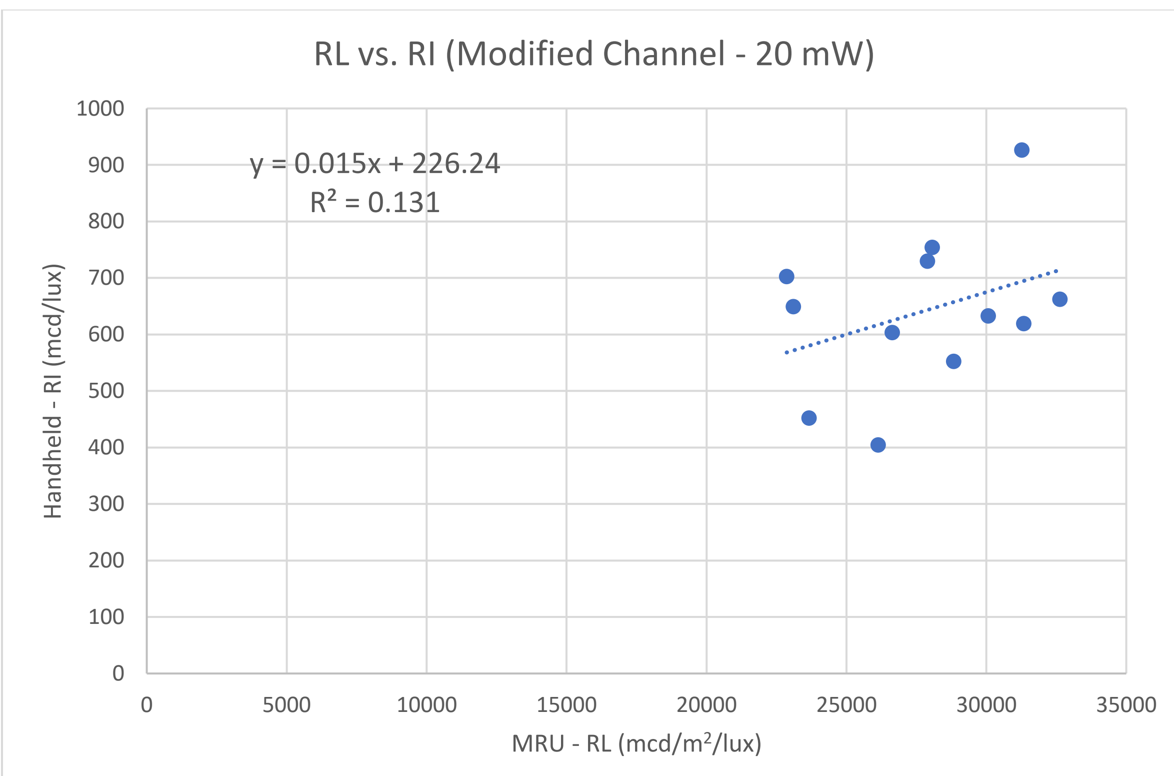


Figure 5-6. Static RPM test results using the 20-mW configuration.

In order to implement the modified MRU into production, it must be capable of accurately collecting both line-stripe and RPM retroreflectivity data, simultaneously. Using the 20-mW configuration, the modified channel on LZ1030 was calibrated to the FDOT ceramic standard, which has an assigned value of 161 R_L as determined in a photometric range. This resulted in a Laserlux calibration plaque value of 202 R_L, which is a device used to perform daily calibrations of the MRU. The modified MRU produced COV values of 3.6% for repeatability and 8.4% for reproducibility when compared to historical averages at the five precision sites. For reference, the FDOT precision acceptance standards at these five sites are 10% for repeatability and 15% for reproducibility.

Once the modified channel was able to pass the FDOT accuracy and precision standards for line-stripe markings (as specified in the Florida Test Method FM 5-600), the unit was taken to three roadways that were included in the 2020 – 2021 line-stripe pavement marking retroreflectivity survey [13]. Data from the annual pavement marking retroreflectivity survey is collected with Laserlux G7 MRUs by an independent contractor. The accuracy of the line-stripe retroreflectivity data referenced on these three roadways was verified by the FDOT quality assurance team using an unmodified MRU (LZ1067). The results are shown below in Figures 5-7, 5-8, and 5-9. In these figures, data from the modified MRU (LZ1030) is represented by the black line, data from the 2020 – 2021 survey is represented by the blue line, and data collected from the unmodified FDOT MRU (LZ1067) is shown in green. The data shown in these graphs from the modified MRU satisfy the FDOT ±75 R_L (mcd/m^2/lux) difference acceptance criteria.

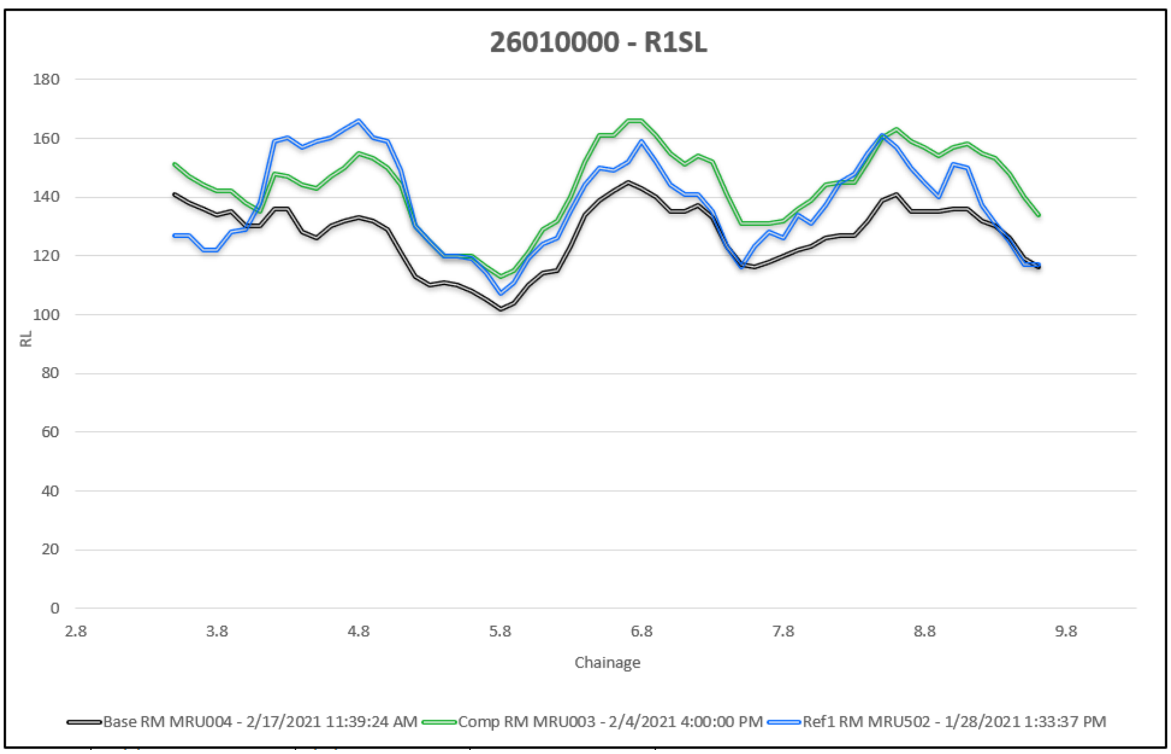


Figure 5-7. 26010000 R1SL line-stripe retroreflectivity comparison.

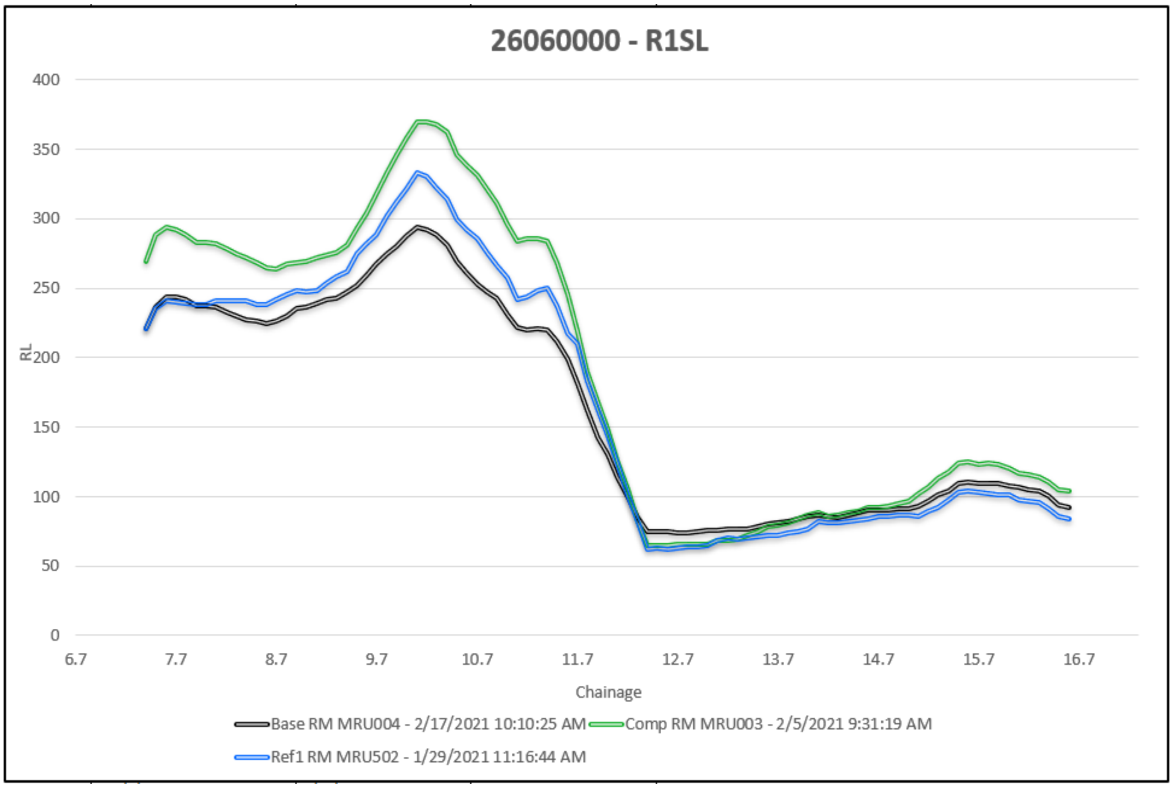


Figure 5-8. 26060000 R1SL line-stripe retroreflectivity comparison.

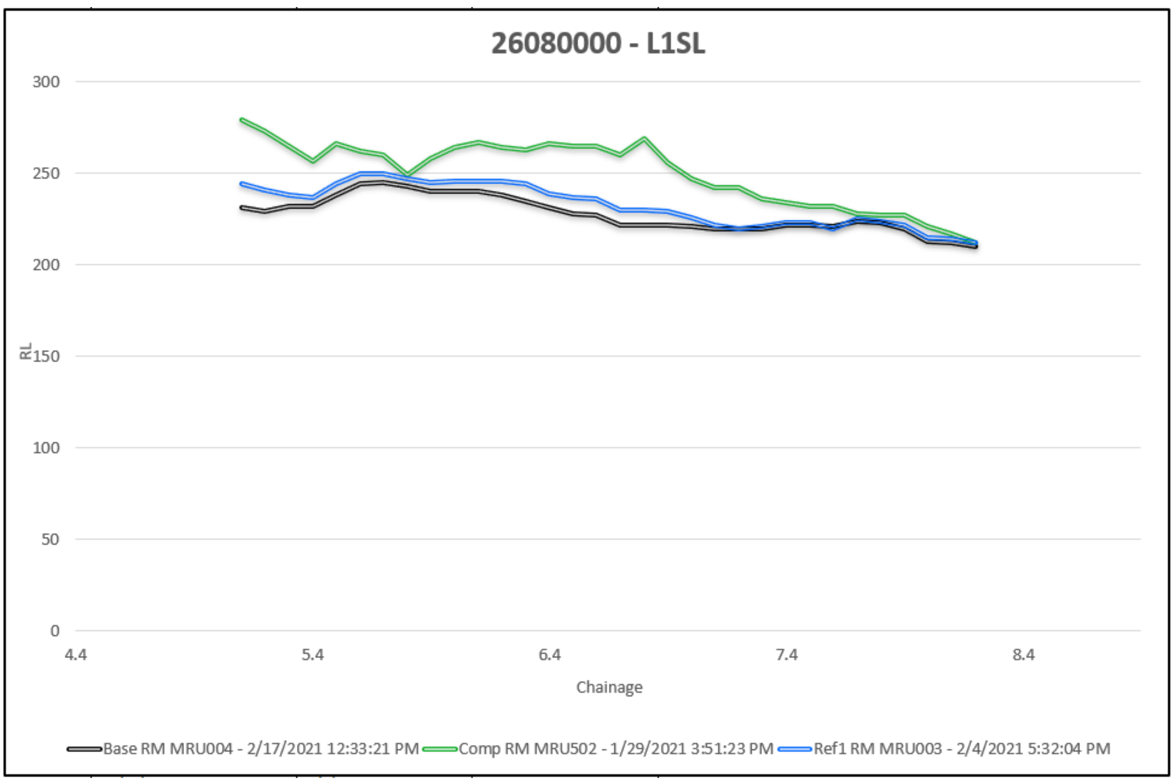


Figure 5-9. 26080000 L1SL line-stripe retroreflectivity comparison.

DATA COLLECTION

Data collection was conducted using a static handheld device for reference measurements and followed by high-speed collection with the LZ1030 modified MRU. The handheld Zehntner ZRP 6030+ measures R_I using a 220-meter collection geometry. The R_I values produced by the handheld device were then compared against R_L values produced by the modified Laserlux G7 MRU. Since an MRU uses the standard CEN-prescribed 30-meter collection geometry for R_L, and the Zehntner uses a 220-meter geometry pertaining to R_I, a focus of this study was to develop regression equations correlating R_L and R_I. The research team determined that these equations would need to be validated at various active roadways throughout northern and central Florida. Since the proposed test sites were on active roadways, maintenance of traffic (MOT) was required to collect the handheld reference data. High-speed data collection was conducted at the posted roadway speeds as listed in Table 5-1.

Reference Data

According to FDOT roadway maintenance standards, the center lines and skip lines of a one-mile roadway (excluding double center lines) should contain 132 evenly spaced RPMs approximately 40 feet apart [11]. However, due to RPMs becoming dislodged over a roadway's lifetime, the exact value for each roadway would differ from the ideal 132 RPMs. With MOT in place, each one-mile section was walked, and three handheld readings were taken for each RPM and averaged to obtain a final R_I value. Additionally, the locations of all missing RPMs were recorded. The number of RPMs manually counted in each test section would be later compared to the number of RPMs detected by the modified MRU during high-speed data collection. Figure 5-10 illustrates typical RPM spacing.

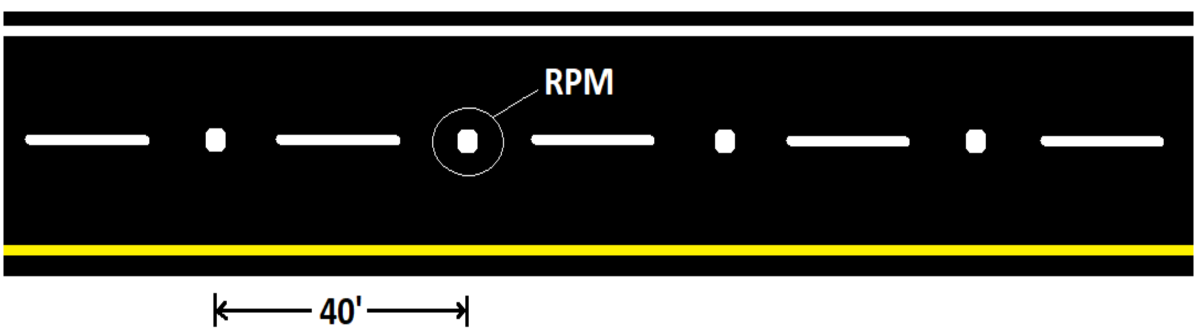


Figure 5-10. RPM locations in a single tenth-mile section.

High-speed Data

After it was verified that the LZ1030 MRU could accurately assess line-stripe markings, RPM data collection began. Three runs were conducted at the posted speed for each test site. Cruise-control was utilized to minimize the effect that vehicle dynamics have on the "auto-leveling" feature of the MRU. Correlating a single R_L value to a specific RPM was shown to be difficult, therefore, it was determined that tenth mile averages would be more effective in comparing the high-speed and handheld retroreflectivity values. Figure 5-11 shown below contains an image of the MRU laser spectrum during a high-speed assessment.

Figure 5-11. MRU laser spectrum during high-speed data collection

RESULTS

The results of this experiment are separated into two main sections. The first section covers the LZ1030 modified MRU's ability to detect, or count, RPMs. The second section pertains to identifying a relationship between the R_L values collected by the modified MRU and R_I values produced by the handheld device. Regression equations were developed based on this relationship to transform R_L values into estimated R_I values, which are the accepted industry standard units for RPM retroreflectivity.

RPM Count Data

The modified MRU's ability to count RPMs was quantified by comparing the actual number of RPMs in a test section to the number of RPMs detected by the MRU. Each of the test sites listed below were one mile in length. The accuracy column was calculated by comparing the average number of RPMs detected after three passes to the actual number of RPMs present. The results of the high-speed RPM count using the modified MRU are shown in Table 5-2.

Table 5-2. RPM detection results produced by the modified MRU.

Roadway ID	Lane	Run 1	Run 2	Run 3	Average	Actual	Accuracy
26020000	R1SL	120	116	116	117	120	98%
26050000	R1SL	119	120	115	118	122	97%
26060000	L1SL	131	131	130	131	131	100%
26080000	L1SL	136	138	134	136	132	97%
26130000	RCL	125	125	126	125	127	98%
26850500	RCL	67	72	69	69	73	95%
28050000	RCL	124	130	127	127	126	99%
34010000	L1SL	131	134	132	132	132	100%
72120000	RCL	121	122	123	122	124	98%
						Average	**98%**

Roadways 28050000 and 72120000 contained centerlines that varied between single- and double-stripe markings. On 72120000 the MRU was able to detect RPMs with 98% accuracy and on 28050000 the detection accuracy was 99%. While the modified MRU is able to detect two RPMs in the same longitudinal location, this requires the operator to be positioned close enough to the centerline so that both RPMs are within the 3.3-foot (1-meter) wide laser spectrum. For reference, a single-stripe line contains 132 RPMs per mile with 40-foot spacing. Double-stripe pavement markings contain 264 RPMs per mile, with two RPMs placed side-by-side and 40-foot spacing. An image illustrating this roadway characteristic is shown below in Figure 5-12.

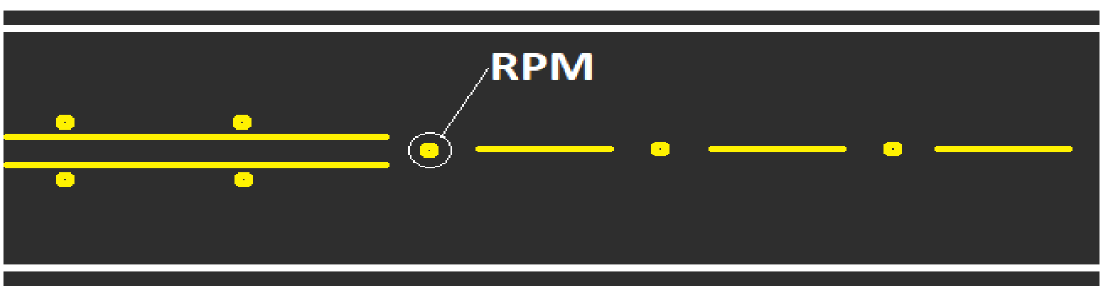


Figure 5-12. Example of centerline varying between single- and double-striping.

For roadway 26850500, there were 54 missing RPMs. Additionally, several RPMs on this roadway produced R_I (mcd/lux) values of zero, and the rest had shown severe signs of wear. These factors may have prevented the MRU from detecting certain RPMs that were present but produced little-to-no retroreflectivity. The research team recognizes that this county roadway was an irregularity, and state roadways typically have higher maintenance standards. However, the lower limit for detection accuracy on this single-stripe roadway was shown to be 95%. Considering all nine roadways, the average RPM detection accuracy was determined to be 98%.

R_L and R_I Comparisons

The purpose of this testing was to determine a relationship between R_L values produced by a 30-meter geometry MRU and R_I values produced by a 220-meter geometry handheld Zehntner ZRP 6030+. To accomplish this, handheld reference measurements were collected on RPMs at six of the nine roadways shown in Table 5-1. However, two of the roadways were repaved before high-speed collection, leaving four roadways for R_L versus R_I comparisons (26020000, 26130000, 265805000, and 72120000). For each of the four, one-mile roadways, the data gathered from each device was averaged in tenth-mile intervals for comparison.

The LZ1030 unit was used for in-field RPM detection and retroreflectivity estimates. For high-speed testing, three passes were made at each site using the modified MRU channel (channel 0). Preliminary testing had shown that operating the modified channel and unmodified channel simultaneously caused interference between the two channels. The result would be periodic uncaptured retroreflectivity data for both RPMs and line-stripe markings. Therefore, the modified channel was utilized to measure both line-stripe and RPM retroreflectivity, simultaneously. The three passes made at each of these one-mile test sites were combined to determine the average RPM R_L values in tenth-mile intervals. The datasets were then graphed on R_L versus R_I scatter plots to identify the relationship between these two measurement units.

Preliminary analysis showed two distinct trends in the data plot between RPMs with low retroreflectivity and those with mid/high retroreflectivity. As a result, it was determined that the most effective relationship between R_L and R_I would be derived by determining two regression equations. Based on the test results, it was determined that the threshold that delineates low and mid/high retroreflectivity was approximately 10,000 R_L. Additionally, new RPMs with retroreflectivity values in the 300 to 500 R_I (mcd/lux) range produced MRU measurements between 30,000 and 50,000 R_L. Therefore, the "mid" condition RPMs were between 10,000 and 30,000 R_L. Figure 5-13 shows a graph containing data from all four roadways to show the delineation between "LOW," "MID," and "HIGH" ranges of retroreflectivity.

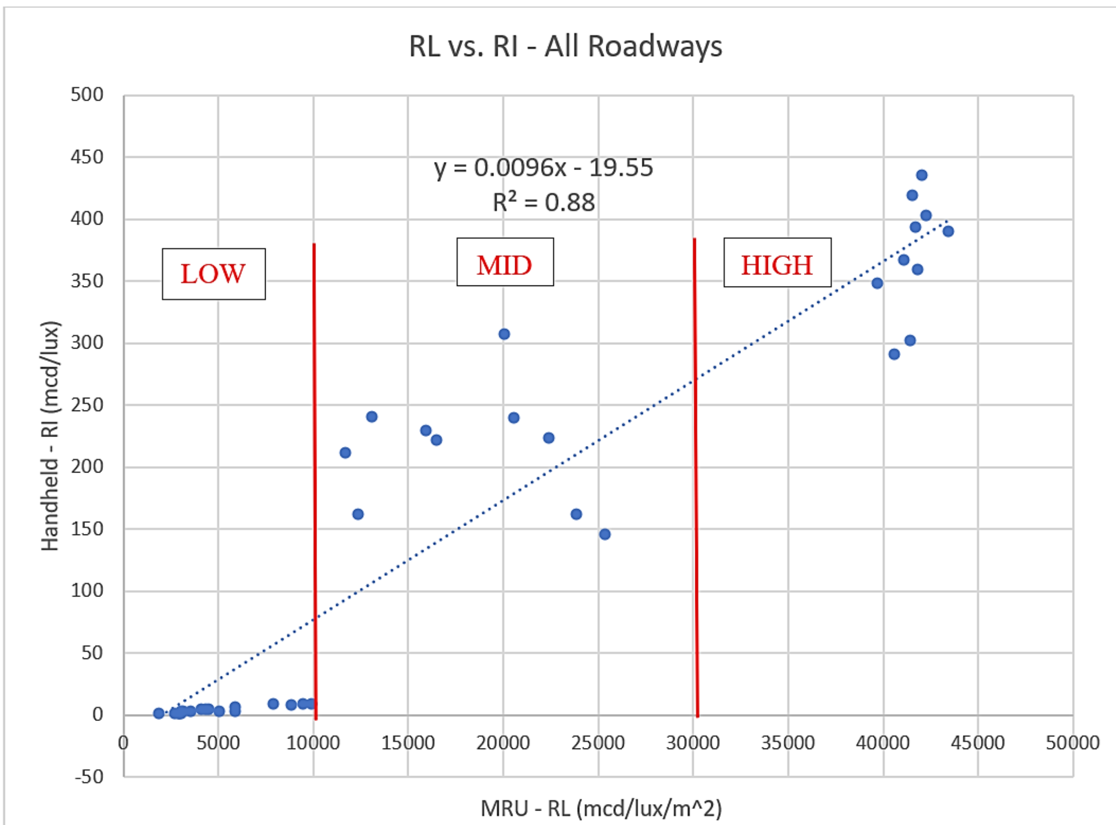


Figure 5-13. Graph comparing R_L and R_I values at the four one-mile test sites.

To provide a visual representation of the “LOW,” “MID,” and “HIGH” classifications, the images in Figures 5-14, 5-15, and 5-16 show RPMs with information regarding their respective retroreflectivity measurements. These values were produced on a static test bench within a controlled environment. These measurements correspond with the quality and retroreflectivity of RPMs observed during field testing.

Figure 5-14. Low retroreflectivity RPMs with MRU readings below 10,000 R_L.

Figure 5-15. Mid retroreflectivity RPMs with MRU readings between 10,000 and 30,000 R_L.

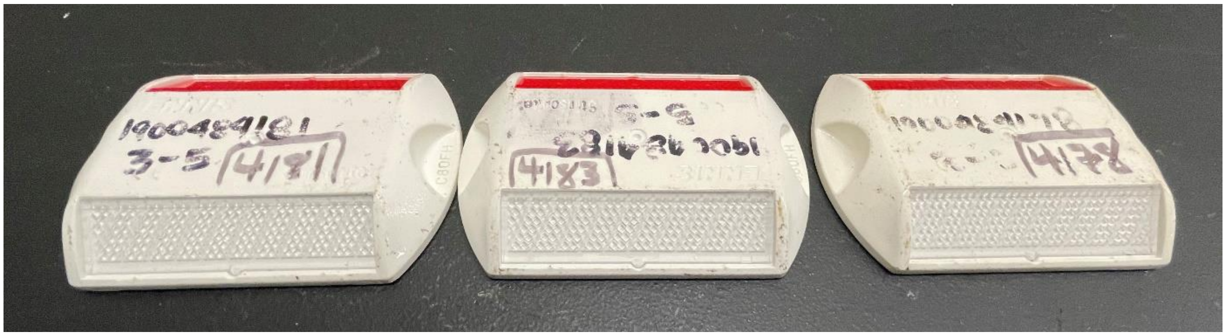


Figure 5-16. High retroreflectivity RPMs with MRU readings greater than 30,000 R_L.

The two roadways that made up the low retroreflectivity sites were 26020000 and 26580500, where RPMs were between 0 and 10 R_I (mcd/lux). For reference purposes, it was observed that RPMs measuring 0 or 1 R_I (mcd/lux) with the handheld device produced MRU measurements of approximately 1,500 to 2,000 R_L. The RPMs at these roadways had signs of severe wear and damage to their reflective windows. Therefore, RPMs within the 0 to 10,000 R_L range are considered to be in poor condition and in need of replacement. Figure 5-17 shown below illustrates the R_L and R_I relationship for the low range RPM values. Additionally, the resulting regression equation for RPMs in poor condition is shown as Equation 1.

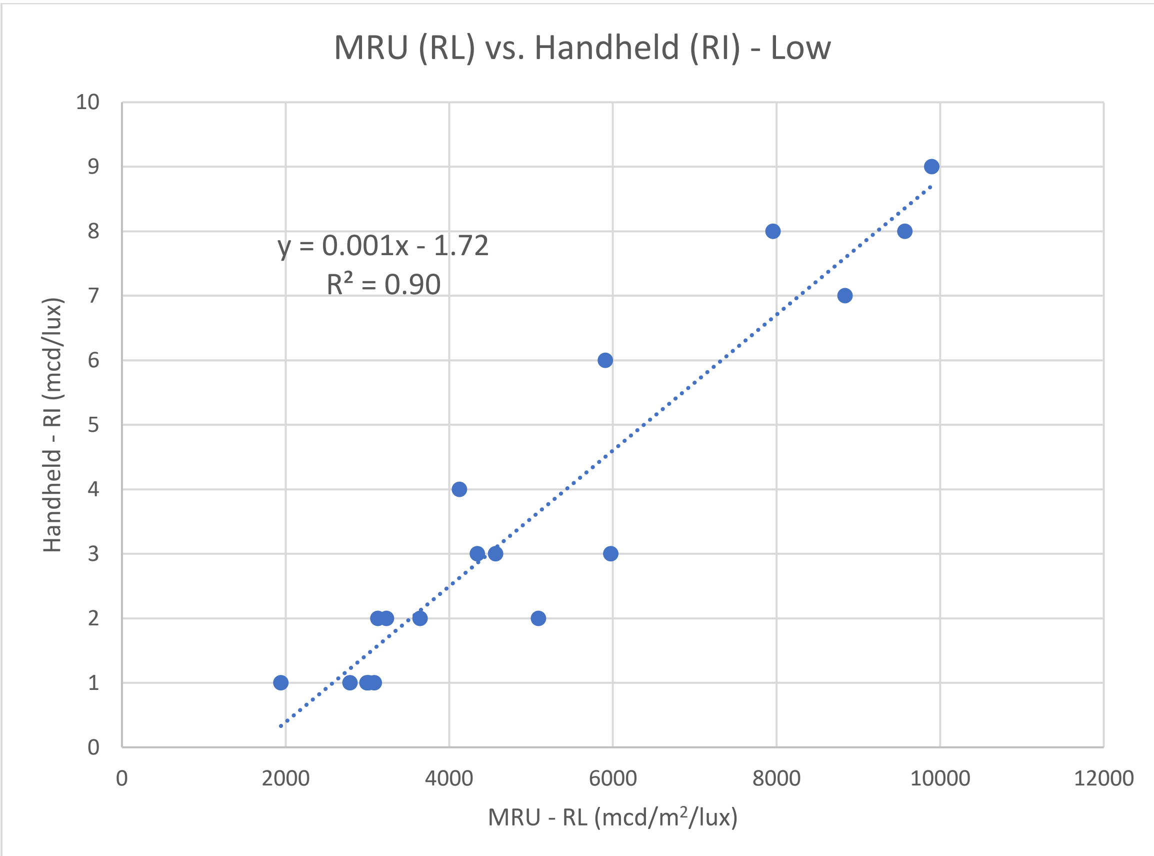


Figure 5-17. R_L vs. R_I at the low retroreflectivity RPM test sites.

$$R_{I,Estimated,Low} = 0.001 * R_L - 1.72 \text{ (Equation 1)}$$

Equation 1 shown above is used for converting R_L to estimated R_I for low retroreflective RPMs (< 10,000 R_L). By comparing the handheld R_I values to the estimated R_I values, the average error for the low RPM retroreflectivity relationship was determined to be ±18%.

Once the relationship was established for the low range R_L values, the same process was performed on the mid/high retroreflective RPM values (> 10,000 R_L). Similar to the low range, the handheld R_I values were averaged on a tenth mile basis to compare with the tenth mile averaged MRU R_L values. After plotting the corresponding values together for each roadway, as shown in Figure 5-18, a relationship could be determined. Additionally, the regression equation pertaining to the mid/high retroreflectivity RPMs is shown by Equation 2.

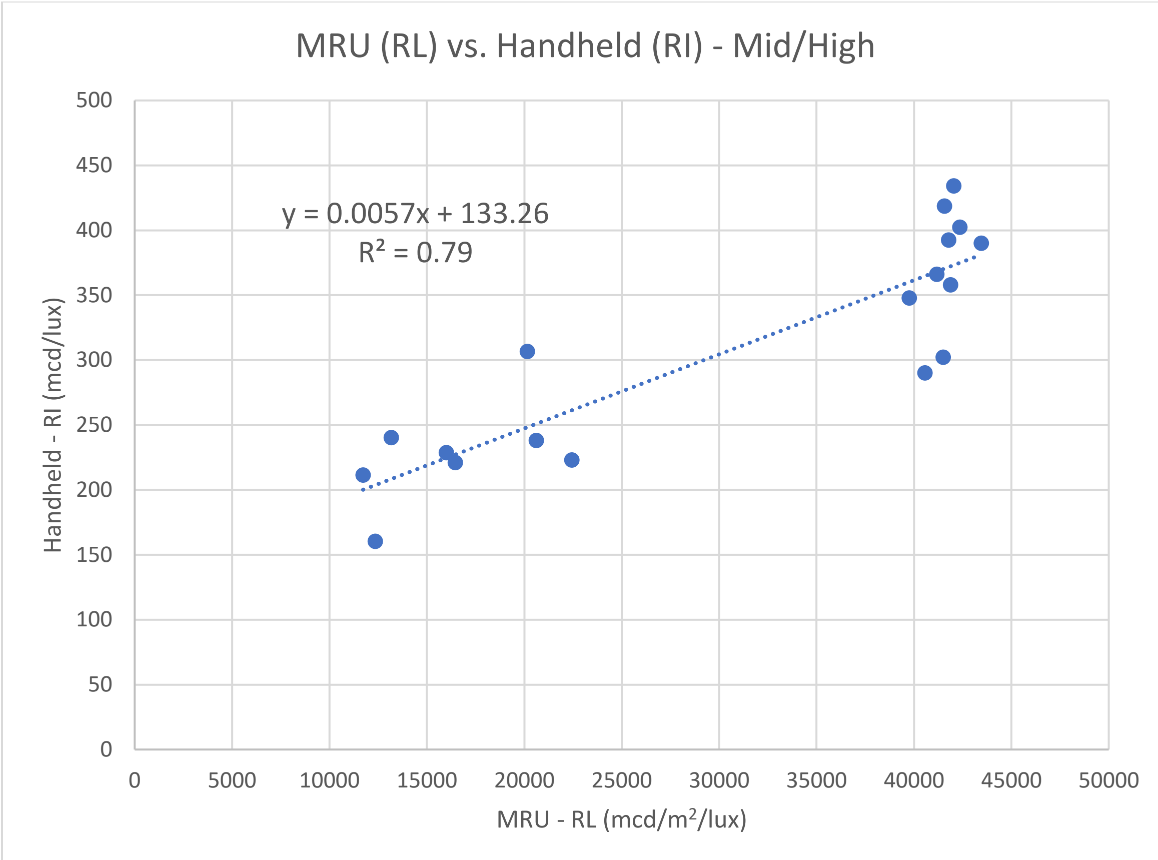


Figure 5-18. R_L vs. R_I at the mid/high retroreflectivity RPM test sites.

$$R_{I,Estimated,High} = 0.0057 * R_L + 133.26 \text{ (Equation 2)}$$

Equation 2 shown above is used for converting R_L to estimated R_I for mid and high retroreflective RPMs (> 10,000 R_L). Comparing the handheld R_I values to the estimated R_I values, the average error for the high RPM retroreflectivity relationship was determined to be ±15% on a tenth mile basis. Combining all datasets, the average percent error in estimated R_I values for all test sections was determined to be ±16%.

RPM Processing Utility

To aid in the MRU data analysis, a processing utility was created in Microsoft Excel to better interpret the high-speed MRU data. High-speed RPM data can be imported into the program to summarize a multitude of values, such as the number of RPMs per tenth mile and mile, the average R_L values per tenth mile, the number of instances and locations with more than 100 feet of missing RPMs (typically two or more), and the estimated RPM R_I values per tenth mile. The average R_L values pertaining to each tenth-mile section contain a "status" that classifies each tenth mile of RPMs as "LOW," "MID," or "HIGH" based on the previously mentioned thresholds. These three classifications are for reference purposes and do not necessarily describe the actual retroreflectivity of RPMs. Additionally, the processing utility applies the appropriate regression equations to determine an estimated R_I value in units of mcd/lux. Figures 5-19 and 5-20 show the front panel of the RPM processing utility.

26130000_LCL_W_F02_2021-02-25_1	
Total Number of RPMs	1080
Roadway Length (Miles)	8.0
Average # of RPMs Per Mile	135
Instances of 100ft Missing RPMs:	0
Average Estimated Ri	367
# of Tenth Mile "LOW"	0

Import RPM Data

Tenth Mile	#RPMs	Avg. RL	Estimated Ri	Status
10.9	12	41873	372	HIGH
10.8	15	43807	383	HIGH
10.7	13	39078	356	HIGH
10.6	14	37578	347	HIGH
10.5	14	41813	372	HIGH
10.4	18	39429	358	HIGH
10.3	13	38934	355	HIGH
10.2	13	42751	377	HIGH
10.1	12	42035	373	HIGH
10.0	14	40940	367	HIGH
9.9	13	45489	393	HIGH
9.8	11	43186	379	HIGH
9.7	14	43670	382	HIGH

Figure 5-19. Front panel of Excel processing utility.

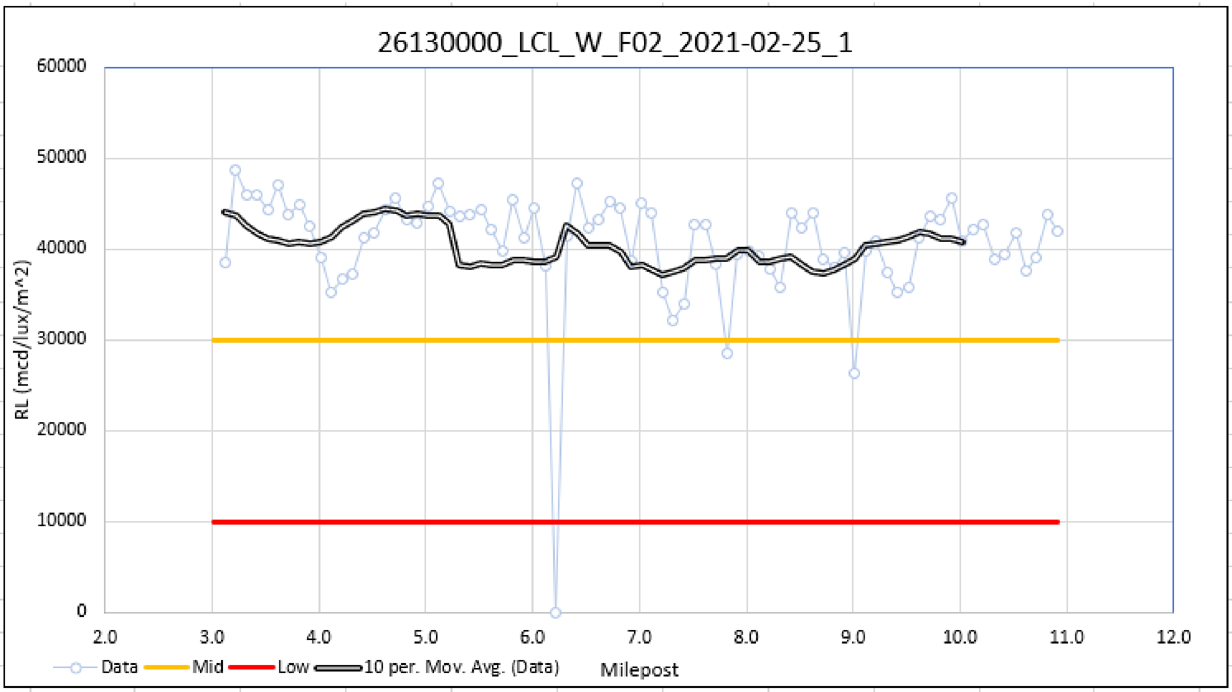


Figure 5-20. Graph produced by the processing utility showing RPM retroreflectivity.

To analyze the high-speed RPM data, the user would click “Import RPM Data” button and locate the data to be assessed. Once the data has been loaded, the “Summary Page” will populate with the output of the data analysis. In addition to the summary tables, a graph showing RPM R_L along the roadway is also produced. The graph in Figure 5-20 shows average R_L values for each tenth mile interval and a running-mile-average trend line for the entire roadway. The red line on the graph represents the threshold for the “LOW” criteria at 10,000 R_L and the yellow line separates the “MID” and “HIGH” classifications at 30,000 R_L.

Precision Results

Precision testing was conducted at four test sites in close proximity to the FDOT State Materials Office. The precision estimates were produced using two modified MRU's and two different operators that performed RPM assessments on the same day. One operator used a modified MRU from the original equipment manufacturer, Laserlux, which was identified as the LZ1017 unit. The other operator used the FDOT LZ1030 modified MRU. Both MRUs utilized the same modified collection parameters. With one vehicle following the other, the operators performed three passes at each test location to establish both repeatability and reproducibility estimates for RPM detection and retroreflectivity.

The repeatability and reproducibility of the system were quantified in terms of coefficient of variation (COV), which is the standard deviation divided by the mean evaluated at a 95% confidence interval and represented as a percentage. In the results below, the standard deviation pertains to the variation between three runs through each tenth-mile subsection. Each roadway was tested at the posted speed pertaining to that roadway as shown in Table 5-3. Figure 5-21 shows the retroreflectivity results between the two devices where each data point represents a tenth-mile section. Additionally, Tables 5-4 and 5-5 display the precision estimates.

Table 5-3. Precision testing locations.

Roadway ID	Location	Lane	RPM Color	Speed (mph)	BMP	EMP	Length
26050000	SR 24	R1SL	White	65	7.42	16.74	9.3 mi
26060000	SR 200	L1SL	White	55	26.27	20.82	5.5 mi
26130000	SR 26	LCL	Yellow	50	10.92	3.00	7.9 mi
26005000	SR 222	R1SL	White	45	0.00	10.50	10.5 mi

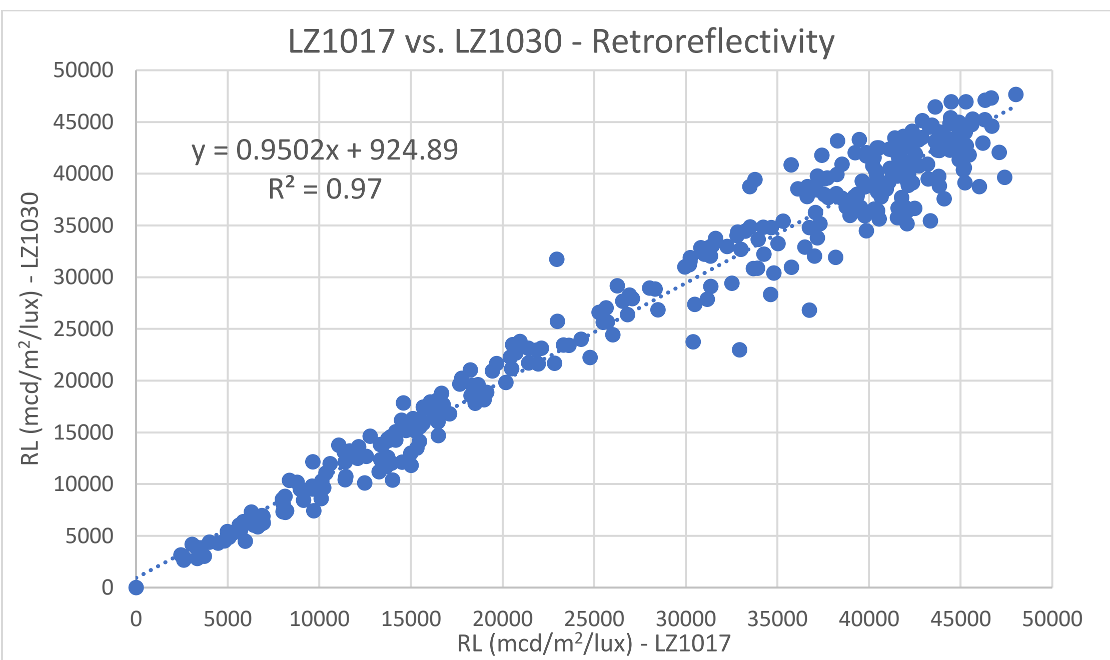


Figure 5-21. Comparing R_L values between the LZ1017 and LZ1030 modified MRUs.

Table 5-4. Precision results for RPM detection in tenth-mile intervals.

Roadway ID	Std. Dev. Repeatability	COV Repeatability	Std. Dev. Reproducibility	COV Reproducibility
26050000	0.8	4.9%	0.9	5.6%
26060000	0.7	5.5%	0.8	6.2%
26130000	1.1	6.8%	1.7	9.5%
26005000	1.4	8.2%	1.7	9.9%
Overall	**1.1**	**6.5%**	**1.4**	**7.9%**

Table 5-5. Precision results using for RPM retroreflectivity in tenth-mile intervals.

Roadway ID	Std. Dev. Repeatability	COV Repeatability	Std. Dev. Reproducibility	COV Reproducibility
26050000	1,910	7.2%	2,052	8.5%
26060000	3,818	10.0%	4,901	12.6%
26130000	2,747	5.8%	2,976	6.5%
26005000	2,040	9.6%	2,768	11.8%
Overall	**2,446**	**7.7%**	**2,698**	**9.1%**

As shown in the tables and figure above, both modified MRUs can measure the retroreflectivity of RPMs in a highly repeatable and reproducible manner. In Figure 5-21 shown above, an R^2 value of 0.97 indicates strong agreement in the tenth mile R_L values produced by each device. Additionally, the COV acceptance thresholds for line-stripe pavement marking retroreflectivity at the State Materials Office are ±10% for repeatability, and ±15% for reproducibility. The information in Tables 5-4 and 5-5 show that the modified MRU falls comfortably within these acceptance thresholds for both RPM detection and retroreflectivity. On a tenth-mile basis, the modified MRU can detect RPMs with a repeatability COV of 6.5% and reproducibility COV of 7.9%. Similarly, the modified MRU can measure retroreflectivity with a repeatability COV of 7.7% and reproducibility COV of 9.1%.

Conclusions

Regarding the MRU's ability to detect RPMs, the high-speed count strongly agreed with the actual number of RPMs on both a tenth mile and one-mile basis. Based on the results of the testing, the modified MRU's ability to count RPMs was found to have an average accuracy of 98%. This detection value represents the average detection accuracy on both single- and double-stripe roadways, which includes both yellow and white Class B RPMs.

The second portion of testing dealt with the relationship between the MRU measured R_L values and the handheld R_I values. It was determined that using a single regression equation to convert R_L to R_I produced a large amount of error for values less than 10,000 R_L [roughly corresponds to 0 to 10 R_I (mcd/lux)]. As a result, two regression equations were derived with one equation pertaining to R_L values under 10,000 ("low") and the other equation for values at or above 10,000 ("mid/high"). Using these two regression equations, the average error between estimated R_I values and the actual R_I values was ±16%. Additionally, the research team established criterion that classifies RPMs as "LOW," "MID," or "HIGH" and are reported in tenth mile intervals using the processing utility. The "LOW" classification represents RPM values below 10,000 R_L. The "MID" classification limits were set from 10,001 to 30,000 R_L, and any data reading higher than 30,000 R_L is classified as "HIGH." Based on several roadways in this study, new Class B RPMs produced retroreflectivity values between 30,000 and 50,000 R_L.

To obtain precision estimates, the RPM detection data and retroreflectivity data were averaged in tenth-mile intervals. For RPM detection, the results had shown average COV values of 6.5% and 7.9% for repeatability and reproducibility, respectively. For retroreflectivity, the precision results had shown COV values of 7.7% and 9.1% for repeatability and reproducibility, respectively. These results indicate that the modified MRU can accurately and repeatably detect and measure the retroreflectivity of RPMs in a way that meets the precision standards specified by the FDOT (±10% for repeatability and ±15% for reproducibility). Overall, utilizing the modified MRU for statewide RPM assessments is a significant improvement from the current process of visual assessments and allows maintenance personnel to quantify RPM quality on a network-level.

CHAPTER 6 - IMPLEMENTATION PLAN

OVERVIEW

Currently, statewide raised pavement marking (RPM) assessments are performed as a visual inspection and/or through random spot-checks with handheld retroreflectivity devices. The issue with the current method of RPM evaluation is the inconsistent nature of visual inspections and the lack of established industry standards regarding network-level retroreflectivity assessments. A prospective solution to this problem was to modify an existing mobile retroreflectivity unit (MRU) to count and measure the retroreflectivity of RPMs at highway speeds. Currently, two modified MRU devices (LZ1017 and LZ1030) possess the capability of counting and measuring the retroreflectivity of RPMs while maintaining its ability to assess the retroreflectivity of line-stripe pavement markings.

OPERATIONAL PROCEDURE

Operating the modified MRU remains very similar to the current procedure for assessing line-stipe pavement markings. When possible, data collection should occur with the vehicle traveling at a constant speed to minimize measurement variations caused by braking and acceleration. Using the Road Vista Laserlux software for data collection, the modified MRU collects both line-stripe and RPM retroreflectivity data simultaneously.

To ensure data collection occurs as intended, several parameters should be verified on the Laserlux user interface. The first parameter, the RPM threshold, indicates the highest value that the device will use for line-stripe retroreflectivity calculations. Any retroreflectivity values received by the MRU that exceed this threshold will be used for RPM retroreflectivity calculations. An optimal value for the RPM retroreflectivity threshold was determined to be 1200 R_L, which remains unchanged from the current MRU systems.

Another parameter that is critical to RPM data collection was the change from double-stripe collection to single-stripe collection. Prior to this study, the operators would always utilize double-stripe collection mode to account for the retroreflectivity of double-stripe centerlines. However, when operating in single-stripe mode, testing had shown no noticeable impact to line-stripe retroreflectivity data at several double-centerline test sites. Furthermore, single-stripe mode must be enabled to accurately detect RPMs. Testing had shown that utilizing double-stripe mode induced many duplicate RPM readings. Figure 6-1 shows the results comparing single- and double-stripe mode on a roadway that contains a double-stripe centerline. In the figure shown below, data collected with the modified LZ1030 MRU is shown in black and the data shown in green was collected with LZ1030 prior to modifications. Figure 6-2 shows the aforementioned collection parameters on the Laserlux interface.

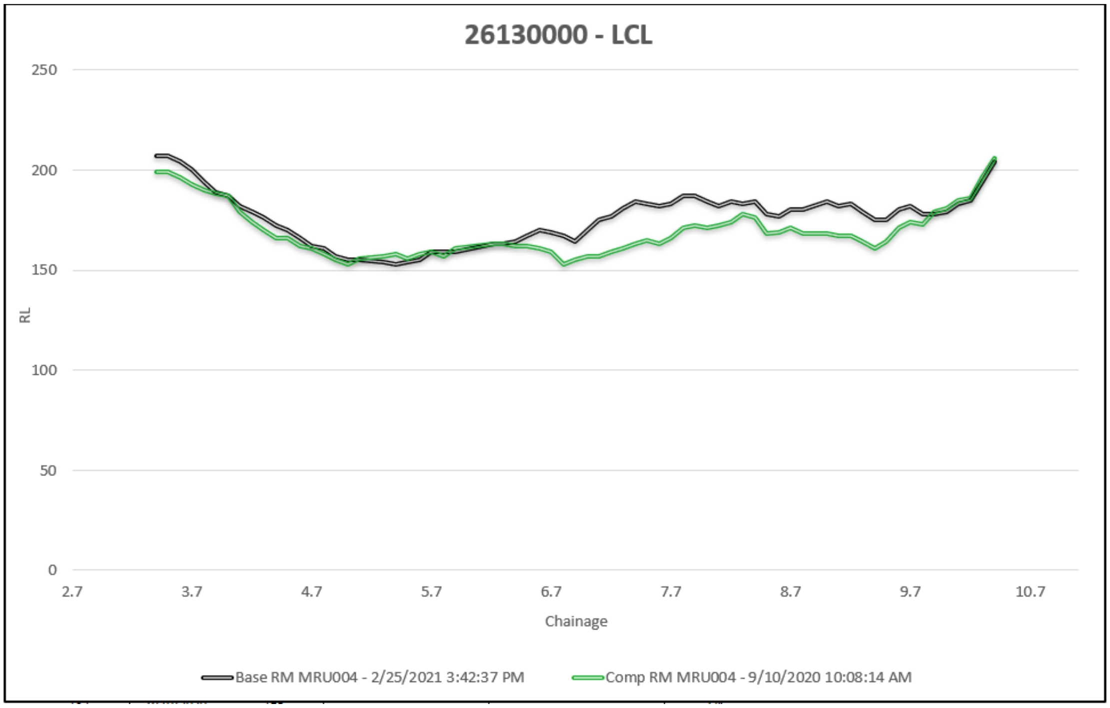


Figure 6-1. Single- vs. double-stripe collection mode.

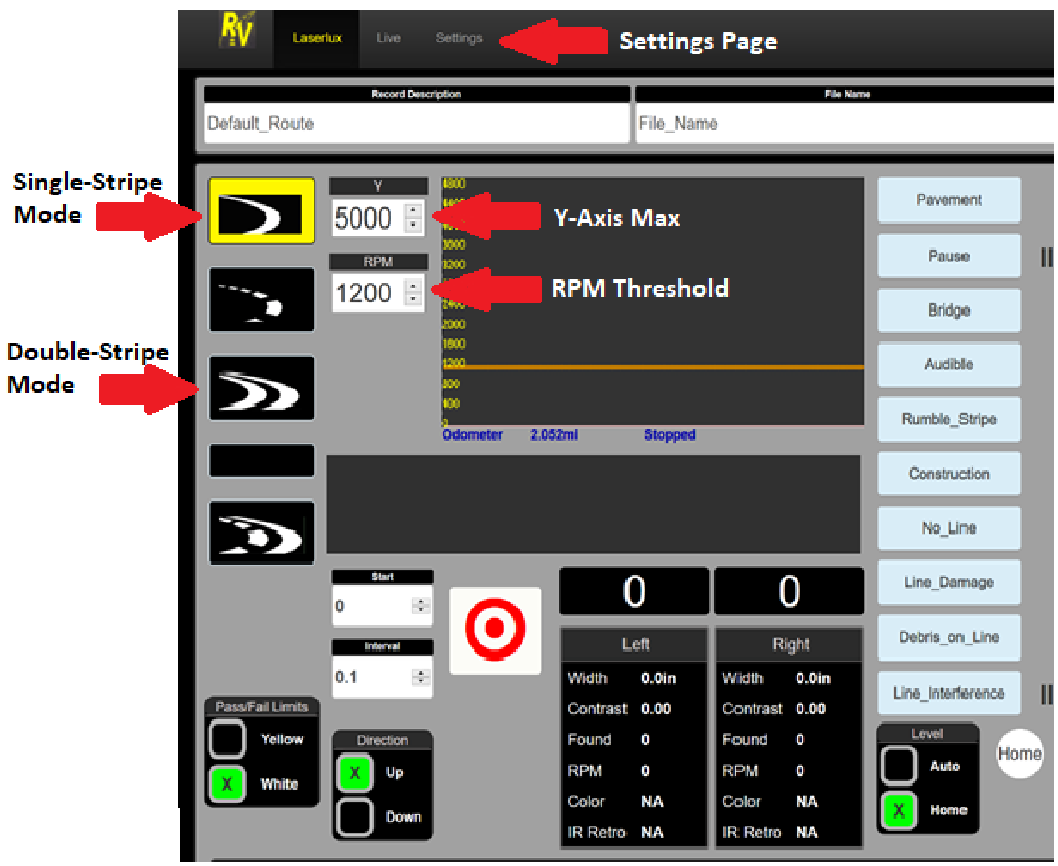


Figure 6-2. Laserlux data collection user interface.

Additionally, the minimum stripe width found on the "Settings" page should be adjusted to 0.1 inches and the maximum stripe width should remain at 20 inches. Reducing the minimum stripe width to 0.1 inches greatly improved the accuracy of RPM detection. Figure 6-3 shows the stripe width data collection parameters.

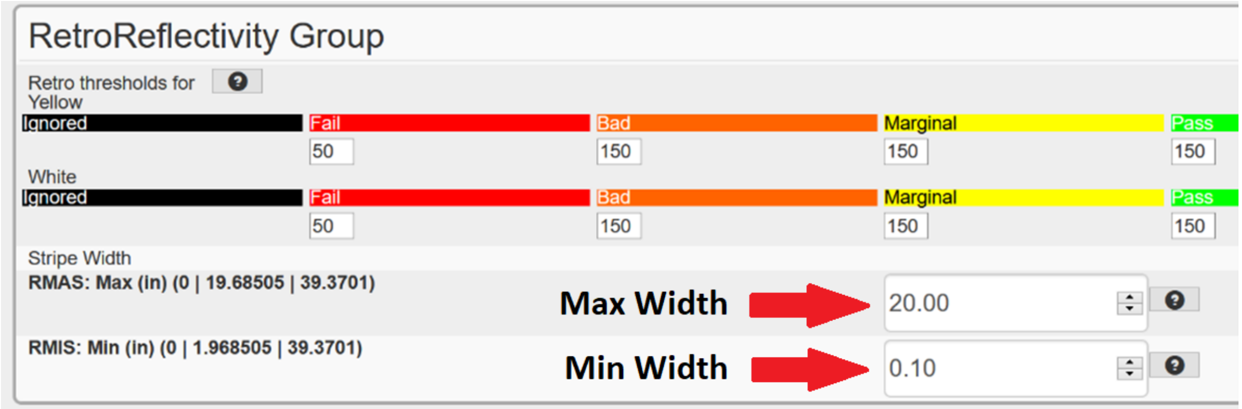


Figure 6-3. Minimum and maximum stripe width thresholds found on the settings page.

Data Processing Procedure

After RPM data is collected, it should be processed using a program created in Microsoft Excel called "RPM_Processing_Utility_v1.3.xlsm". This program was designed to summarize information extracted from the Laserlux produced RPM files (the filenames containing RPM information end with "_RPM.csv"). The program analyzes the user input RPM data file and outputs several values, such as: total number of RPMs, number of RPMs per mile, number of instances with successively missing RPMs (> 100 ft of roadway with missing RPMs), the tenth mile average R_L value, and estimated R_I values. Figures 6-4 and 6-5 display the front-panel of the processing program. Instructions on how to process RPM data are shown in Appendix A.

26130000_LCL_W_F01_2020-12-30_1	
Total Number of RPMs	1072
Roadway Length (Miles)	7.9
Average # of RPMs Per Mile	136
Instances of 100ft Missing RPMs:	0
Average Converted Ri	399
# of Tenth Mile "LOW"	0

Import RPM Data

Tenth Mile	#RPMs	Avg. RL	Converted Ri	Status
10.9	13	59566	417	HIGH
10.8	14	51720	362	HIGH
10.7	14	58205	407	HIGH
10.6	13	54128	379	HIGH
10.5	13	57860	405	HIGH
10.4	17	41811	293	HIGH
10.3	13	45253	317	HIGH
10.2	13	57188	400	HIGH
10.1	12	48942	343	HIGH
10.0	13	49715	348	HIGH
9.9	13	56998	399	HIGH
9.8	13	58262	408	HIGH
9.7	13	55318	387	HIGH

Figure 6-4. RPM processing program front panel.

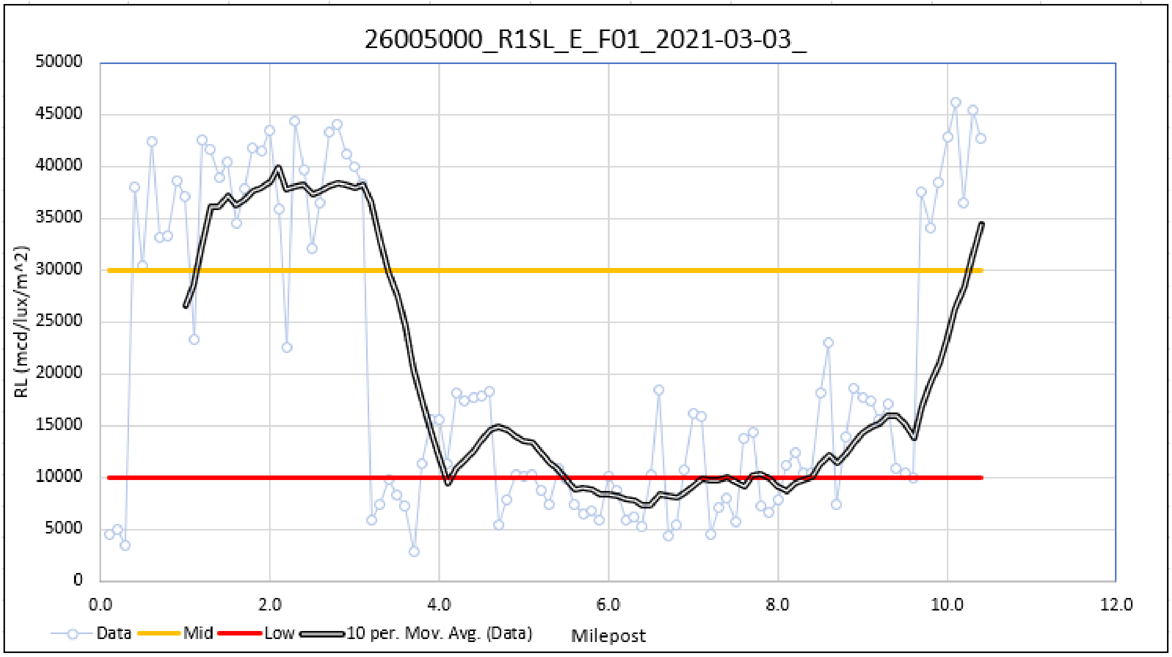


Figure 6-5. RPM retroreflectivity graph produced by the processing program.

Calibration Procedure

The calibration method for the modified MRU device is the same as the current calibration process for unmodified MRU devices. Since the modified MRU device still must accurately measure line-stripe data, the laser must be calibrated using the same ceramic block and process. Refer to section 5.1 in the "FDOT Operations Manual G7" for a more detailed procedure for calibrating the modified MRU device.

Device Verification

In conjunction with the bimonthly line-stripe pavement marking precision testing, the modified MRU device should undergo field site verification to ensure it is accurately counting and measuring RPM retroreflectivity. The verification process requires an additional one-mile test site (26130000 RCL). In addition to a manual count of the RPMs at roadway 26130000 RCL, this site also contains handheld retroreflectivity measurements using the Zehntner ZRP 6030+ reference device.

Three consecutive runs must be conducted at the test site, and the average RPM count for the three runs will be compared to the actual number of RPMs to determine the accuracy. To pass the verification test, the average RPM count must have an accuracy of at least 98% relative to the actual count (127 ± 2 RPMs for 26130000 RCL). In addition, detection repeatability can be quantified in terms of COV where the maximum value for detection repeatability is 10%. Detection repeatability is assessed in tenth-mile intervals.

In addition to verifying the MRU's RPM detection ability, the operator can verify that the device is accurately measuring retroreflectivity using the same data from 26130000 RCL. The average estimated R_I value for the entire roadway and all three runs will be compared against the average R_I value produced by the handheld reference device. The minimum passing accuracy for retroreflectivity is 90.0% [370 ± 35 R_I (mcd/lux) for 26130000 RCL]. In addition, the maximum COV for retroreflectivity repeatability is 10%. Retroreflectivity repeatability is assessed in tenth-mile intervals.

The verification process can be checked and easily summarized using the RPM processing program. Each run must be individually imported into the program using the "Import RPM Data" button and saved using the "Save Data for RPM Precision Results" button. If the device is functioning properly, the accuracy and COV cells for both criteria will be highlighted green. If the device does not meet the accuracy and precision minimum requirements, the cells will be highlighted red. This process is explained further in Appendix B. Figure 6-6 shows an image of the precision results within the processing program and Figure 6-7 shows the test site.

RPM Detection - Repeatability (26130000 RCL)

Chainage	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	Accuracy
Run1	11	12	11	12	13	13	14	13	13	13	
Run2	11	12	10	13	13	13	13	13	14	13	98.7%
Run3	11	12	11	12	13	14	13	14	13	13	
COV	0%	0%	5%	5%	0%	4%	4%	4%	4%	0%	2.7%

RPM Retroreflectivity (Ri) - Repeatability (26130000 RCL)

Chainage	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	Accuracy
Run1	382	384	368	360	369	381	371	386	369	366	
Run2	357	381	373	354	381	376	373	360	368	381	99.9%
Run3	365	378	383	365	367	362	371	365	356	363	
COV	4%	1%	2%	2%	2%	3%	0%	4%	2%	3%	2.1%

Figure 6-6. Precision results section of the RPM processing program.

Figure 6-7. 26130000 RCL RPM measurement verification site.

PARAMETER CONFIGURATION

As previously mentioned, the modified MRU device uses the same Road Vista Laserlux collection software as the current MRU devices. However, additional parameters have been added to the software through an updated firmware (v1.318), and experimental testing by the research team determined the optimal values for these additional parameters. The two primary additional parameters are the "RPM Suppression Distance," RPMD, and the "RPM Maximum Value Search Distance," RPMV. The RPMD parameter changes the distance that the MRU software will wait after identifying an RPM before identifying another. This parameter prevents the "double counting" previously encountered during testing. The RPMV value changes the distance with which the MRU software will look for the maximum value of retroreflectivity. This maximum retroreflectivity value is what is recorded by the Laserlux software, so this parameter edits the distance with which the MRU software will look for the highest retroreflectivity value pertaining to each RPM. After extensive testing, the optimal value for both parameters was found to be 0.1 meters. Additionally, ensure that the "Stripe Threshold" (RSBT) is set to 0.25. This setting is typically 0.5 on unmodified MRUs. This setting determines the percentage of the peak retroreflectivity to be used for determining the edge of a line-stripe or RPM. Information on how to adjust these altered parameters can be found in Appendix C.

ANNUAL SURVEY IMPLEMENTATION

Currently, the FDOT contracts out annual pavement marking retroreflectivity surveys that consist of approximately 25,000 miles of line-stripe data collection. The line-stripe retroreflectivity data collected during these surveys is subsequently uploaded to an online database called the Pavement Marking Management System (PMMS), which is hosted by the FDOT. The PMMS is available to the public, but its primary function is to inform local district maintenance personnel on the quality of the pavement markings in their area. With the modified MRUs capability of evaluating RPM retroreflectivity, this data can be added into the PMMS.

Of the target mileage planned to be evaluated each year, approximately 12,100 miles are allocated to yellow centerlines (100% of state road centerlines in one direction), 5,300 miles are allocated to white skip lines, 4,500 are for white edge lines, and 3,100 miles are allocated to special requests from the seven district transportation facilities. Table 6-1 shows statistics from the 2020-2021 pavement marking annual survey run log.

Centerline	Skip Line	Edge Line	Special Request	Total
12,100	5,300	4,500	3,100	25,000

Table 6-1. 2020 – 2021 annual retroreflectivity survey target mileage.

Since RPMs are generally located on either centerlines or skip lines, and the modified MRU can evaluate RPMs and line-stripe retroreflectivity simultaneously, the research team recommends maximizing the centerline and skip line (one skip line per roadway) collection of all state roads in one direction. Based on information from the Roadway Characteristics Inventory (RCI) database, there were estimated to be 7,000 miles of multi-lane state roadways (in one direction) where at least one skip line exists. In general, one can expect the retroreflectivity values of both RPMs and line-striping to be similar in both traveling directions. Considering that

RPMs are the primary source of lane delineation during heavy rainfall, this recommendation can improve roadway safety with annual statewide RPM evaluations. As shown in Table 6-2, the additional 1,700 miles of skip line could be supplemented with special request mileage.

Centerline	Skip Line	Edge Line	Special Request	Total
12,100	7,000	4,500	1,400	25,000

Table 6-2. Proposed annual retroreflectivity survey target mileage.

FLORIDA TEST METHOD REVISIONS

Several revisions were made to the FM 5-600 “Florida Test Method for Measuring Retroreflectivity of Pavement Marking Materials Using a Mobile Retroreflectivity Unit” to encompass the collection of RPM data [13]. While the revisions were relatively minor, the most important revision pertains to the requirement that an MRU can measure pavement markings ranging from 75 to 50,000 R_L (mcd/m^2/lux). The precision requirements for RPM retroreflectivity remain the same as for line-stripe pavement markings. This includes maximum COV values of 10% and 15% for repeatability and reproducibility, respectively.

RECOMMENDATIONS

While many of the processes involved with the modified MRU remain unchanged from current processes, there are several recommendations to help ensure that RPM data is usable, accurate, and easily understandable by the end-users. The first recommendation is for the State Materials Office to purchase a 220-meter measurement geometry handheld RPM retroreflectometer. Purchasing a handheld retroreflectometer is useful to maintain accurate reference values at the 26130000 RCL verification site. Also, the device can be used to read RPMs within the calibration bay to use for static retroreflectivity accuracy tests with the MRU. In addition to accuracy testing, a handheld RPM measurement device can be used for spot checking project-level requests as they are received throughout the annual survey. Lastly, through purchasing an RPM retroreflectometer, continuous improvement can be made to the estimated R_I regression equations to further reduce calculation error. This would also allow for optimization of the “LOW”, “MID”, and “HIGH” RPM classification thresholds to more provide more accurate representations of RPM quality.

The next recommendation would be to coordinate with an FDOT software developer to incorporate the RPM processing program into the current MRU line-stripe pavement marking workbook. This would allow operators and engineers to easily verify RPM and line-stripe retroreflectivity data using the same workbook. An additional feature that would need to be incorporated into the processing program for quality assurance (QA) checks on RPM data would be the ability to compare two separate files against each other. This process would essentially be the same as the line-stripe retroreflectivity QA checks, but the acceptance threshold would need to be adjusted. For line-stripe pavement markings, the acceptance threshold between QA and the contractor is ±75 R_L (mcd/m^2/lux) per running mile. A recommended acceptance threshold for two sets of RPM retroreflectivity data is ±5,000 R_L (mcd/m^2/lux), which corresponds to the upper-limit standard deviation between two modified MRUs.

References

[1] E. Stellfox, *Evaluation of Snowplowable, Retroreflective Raised Pavement Markers*, TRID, Maryland State Highway Administration, Baltimore, 2004. trid.trb.org/view/698277.

[2] A. M. Pike, "Lab Based Retroreflectivity Assessment of Raised Retroreflective Pavement Markers," 2017 Transportation Research Board Annual Meeting, Washington D.C., 2017.

[3] A. M. Pike, "Evaluating Retroreflectivity Assessment Techniques for In-Service Raised Retroreflective Pavement Markers," 2018 Transportation Research Board Annual Meeting, Washington D.C., 2018.

[4] F. Colson, J. Sevearance, and J. H. Fletcher, "Optimized Mobile Retroreflectivity Unit Data Processing Algorithms," 2018 Transportation Research Board Annual Meeting, Washington D.C., 2018.

[5] ASTM International, "ASTM E1696-15 Standard Test Method for Field Measurement of Raised Retroreflective Pavement Markers Using a Portable Retroreflectometer," ASTM International, West Conshohocken, PA, 2015. [Online]. Available: https://ewb.ihs.com. [Accessed May 2019].

[6] ASTM International, "ASTM E 1710-11 Standard Test Method for Measurement of Retroreflective Pavement Marking Materials with CEN-Prescribed Geometry Using a Portable Retroreflectometer," ASTM International, West Conshohocken, PA, 2011. [Online]. Available: https://ewb.ihs.com. [Accessed May 2019].

[7] AASHTO, "TP 111-14 (2018) - Standard Method of Test for Measuring Retroreflectivity of Pavement Marking Materials Using a Mobile Retroreflectivity Unit," American Association of State and Highway Transportation Officials, Washington D.C., 2018. [Online]. [Accessed May 2019].

[8] ASTM International, "ASTM D4280-18 Standard Specification for Extended Life Type, Nonplowable, Raised Retroreflective Pavement Markers," ASTM International, West Conshohocken, PA, 2018. [Online]. Available: https://ewb.ihs.com. [Accessed May 2019].

[9] Federal Highway Administration, *Guidelines for the Use of Raised Pavement Markers*, U.S. Department of Transportation, Washington, DC, 2016.

[10] Texas Department of Transportation, *Texas Department of Transportation FTP Server*, Texas Department of Transportation, Austin, TX, November 2014. [Online]. Available: ftp://ftp.dot.state.tx.us/pub/txdot-info/cmd/cserve/specs/2014/spec/ss6021.pdf. [Accessed September 2019].

[11] Florida Department of Transportation, *FDOT Maintenance Rating Program (MRP) 2019 Handbook*, Florida Department of Transportation, Office of Mainenance, Tallahassee, FL, 2019. [Online]. Available: https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/maintenance/rdw/mrp/mrphandbook.pdf?sfvrsn=4ec62676_2. [Accessed September 2019].

[12] RoadVista, *Retroreflectometer*, RoadVista, San Diego, CA, August 2019. [Online]. Available: http://www.roadvista.com/retroreflectometer/. [Accessed August 2019]

[13] Florida Department of Transportation, *Florida Test Method for Measuring Retroreflectivity of Pavement Marking Materials Using a Mobile Retroreflectivity Unit - FM 5-600*, Florida Depatrment of Transportation, State Materials Office, Gainesville, FL, 10 May 2018. [Online]. Available: https://www.fdot.gov/docs/default-source/materials/administration/resources/library/publications/fstm/methods/fm5-600.pdf. [Accessed October 2020].

APPENDIX A – OPERATIONAL PROCEDURE

Operating the Modified MRU

Step 1. Turn the modified MRU device on and connect the tablet to the 5G WiFi corresponding to that device.

Step 2. Once connected, open Firefox browser and enter "192.168.88.11" into the search bar and press "Enter". This action should open the Laserlux program collection page.

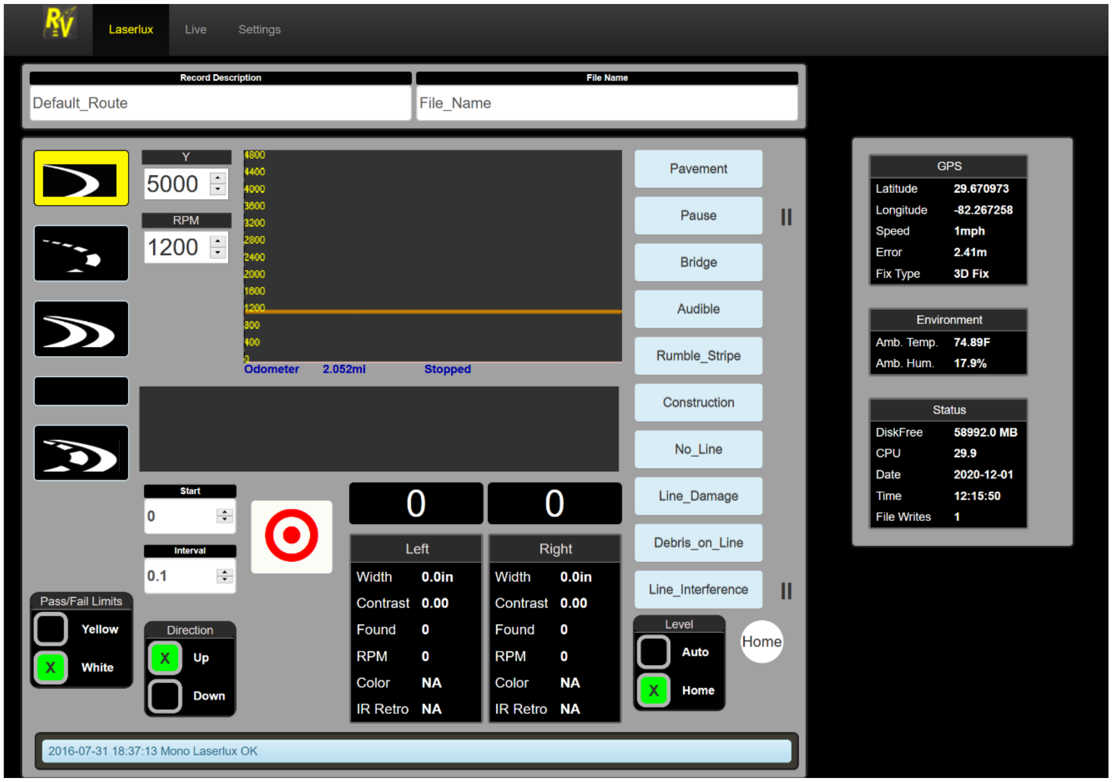


Figure A-1. The front page of the Laserlux data collection program.

Step 3. For effective operation, ensure the device is set to single-stripe collection. This is different from the typical double-stripe collection of the non-modified MRU devices.

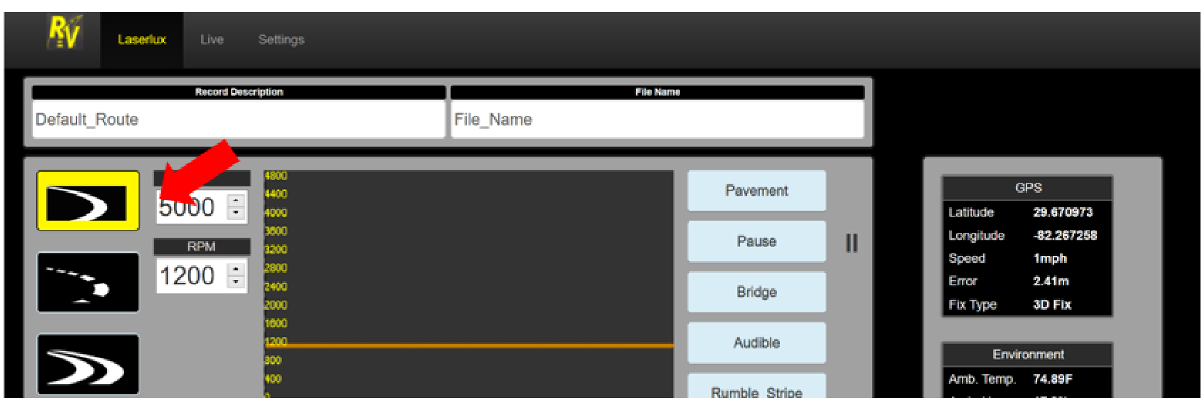


Figure A-2. The arrow indicates the location of stripe selection.

Step 4. Ensure the RPM retroreflectivity threshold is set to 1200 R_L.

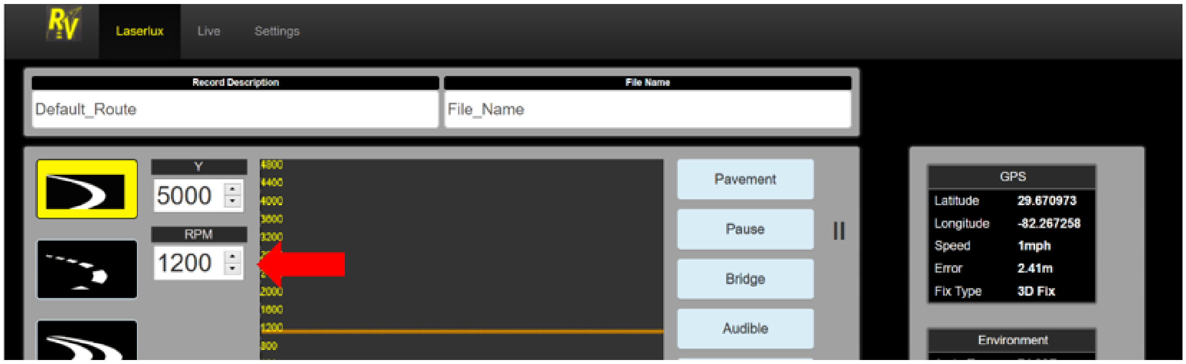


Figure A-3. The arrow indicates the location of RPM threshold.

Step 5. Navigate to the settings panel within this program by clicking on "Settings" in the upper left-hand corner of the screen

Figure A-4. The arrow indicates the location of the settings tab within the Laserlux program.

Step 6. Scroll down to the "Retroreflectivity Group" and check the RMAS maximum and minimum stripe width. The maximum stripe width (RMAS) should be set to 20 inches while the minimum stripe width (RMIS) should be set to 0.1 inches.

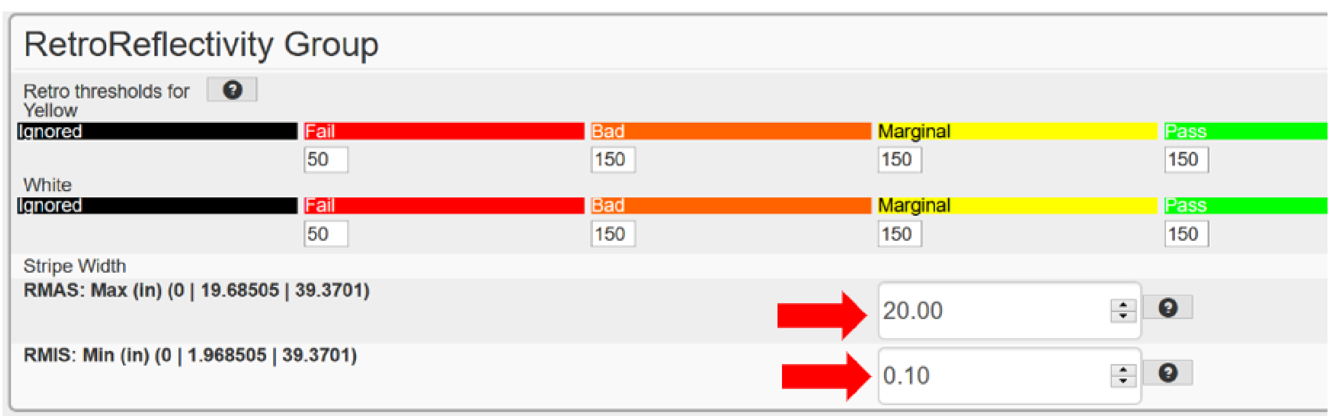


Figure A-5. The arrows indicate the location of the stripe width settings.

Step 7. Once the above parameters have been checked, the operators can initiate data collection in the same manner as with an unmodified MRU while minimizing vehicle dynamics.

APPENDIX B – DATA PROCESSING PROCEDURE

Processing RPM Data

Step 1. Open the macro-enabled excel workbook labeled "RPM_Processing_Utility_v.xx" and ensure the macro content is enabled.

Step 2. On the page labeled "Summary Report," click the button labeled "Import RPM Data." This button will prompt the user to browse from the RPM file to be evaluated.

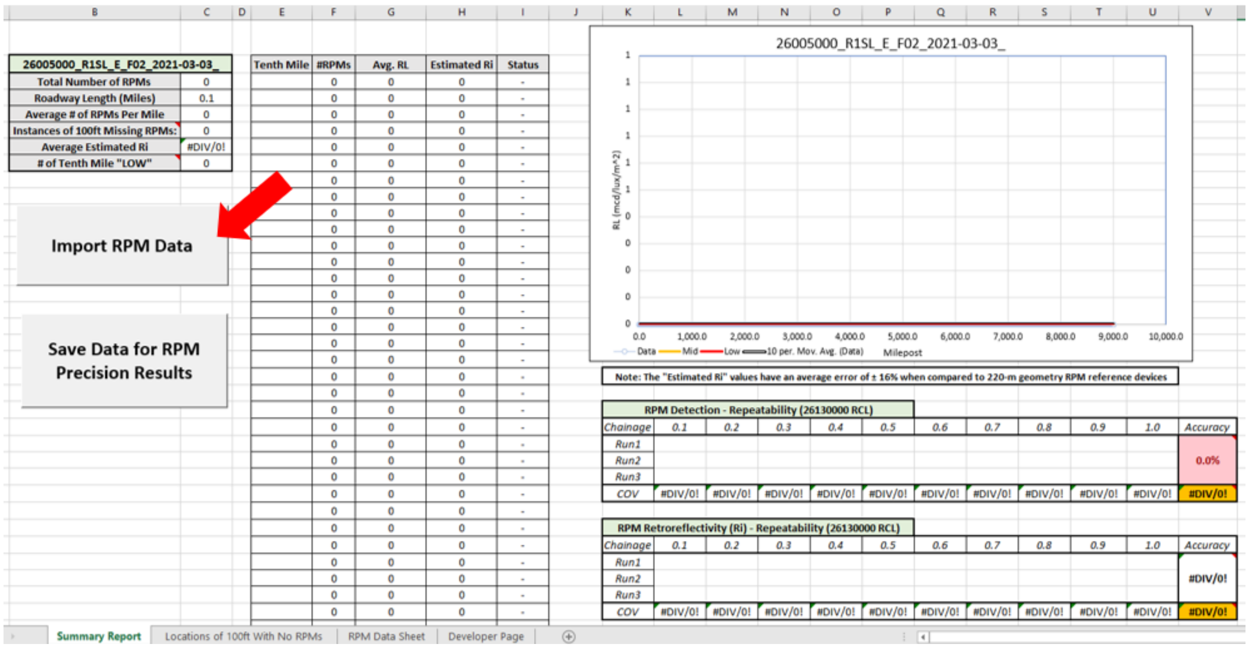


Figure B-1. Processing program front panel prior to loading RPM data.

Step 3. Navigate to the files intended for analysis. For each run, three different files will be recorded by the MRU, two .csv files and one .kml file. For this program, you will upload the file that has "_RPM.csv" after the run intended for analysis.

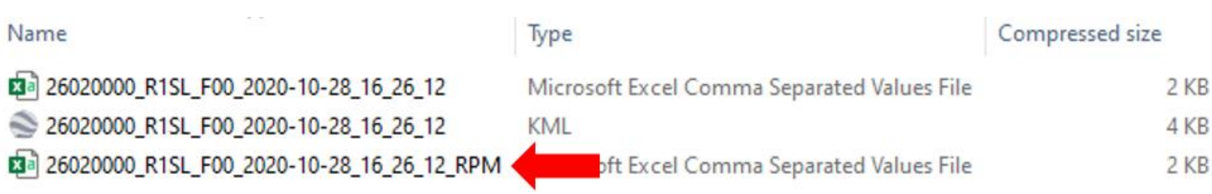
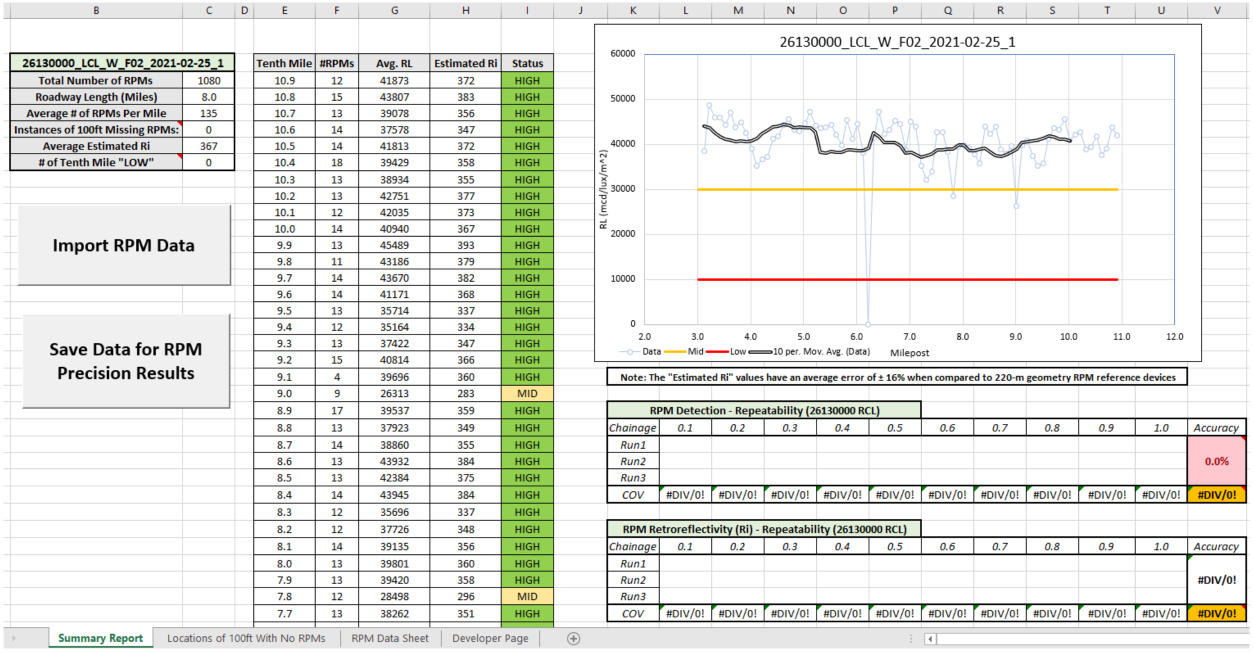


Figure B-2. The RPM data files from the MRU.

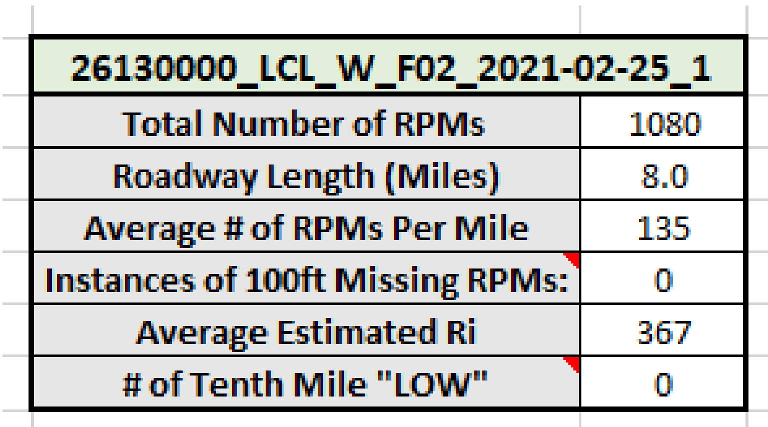
Step 4. Once the intended file has been selected and uploaded into the spreadsheet, the analysis will automatically occur and proceed to populate the data reporting tables.



26130000_LCL_W_F02_2021-02-25_1	
Total Number of RPMs	1080
Roadway Length (Miles)	8.0
Average # of RPMs Per Mile	135
Instances of 100ft Missing RPMs:	0
Average Estimated Ri	367
# of Tenth Mile "LOW"	0

Tenth Mile	#RPMs	Avg. RL	Estimated Ri	Status
10.9	12	41873	372	HIGH
10.8	15	43807	383	HIGH
10.7	13	39078	356	HIGH
10.6	14	37578	347	HIGH
10.5	14	41813	372	HIGH
10.4	18	39429	358	HIGH
10.3	13	38934	355	HIGH
10.2	13	42751	377	HIGH
10.1	12	42035	373	HIGH
10.0	14	40940	367	HIGH
9.9	13	45489	393	HIGH
9.8	11	43186	379	HIGH
9.7	14	43670	382	HIGH
9.6	14	41171	368	HIGH
9.5	13	35714	337	HIGH
9.4	12	35164	334	HIGH
9.3	13	37422	347	HIGH
9.2	15	40814	366	HIGH
9.1	4	39696	360	HIGH
9.0	9	26313	283	MID
8.9	17	39537	359	HIGH
8.8	13	37923	349	HIGH
8.7	14	38860	355	HIGH
8.6	13	43932	384	HIGH
8.5	13	42384	375	HIGH
8.4	14	43945	384	HIGH
8.3	12	35696	337	HIGH
8.2	12	37726	348	HIGH
8.1	14	39135	356	HIGH
8.0	13	39801	360	HIGH
7.9	13	39420	358	HIGH
7.8	12	28498	296	MID
7.7	13	38262	351	HIGH

Figure B-3. Populated "Summary Report" page based on the imported RPM file.



26130000_LCL_W_F02_2021-02-25_1	
Total Number of RPMs	1080
Roadway Length (Miles)	8.0
Average # of RPMs Per Mile	135
Instances of 100ft Missing RPMs:	0
Average Estimated Ri	367
# of Tenth Mile "LOW"	0

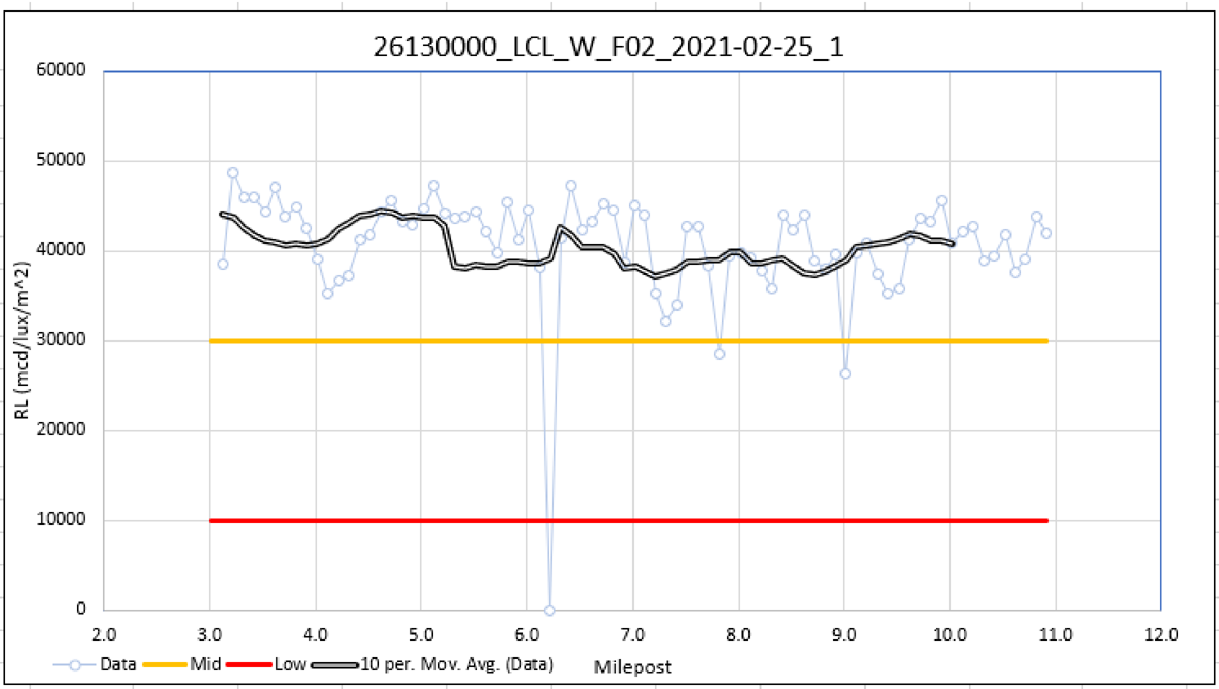
Figure B-4. RPM summary information for the imported RPM file.

Step 5: The information corresponding to each tenth-mile section can be found in the middle table of the summary page. This information includes the number of RPMs, the average R_L value, the estimated R_I value, and the resulting retroreflective classification for that section.

Tenth Mile	#RPMs	Avg. RL	Estimated Ri	Status
10.9	12	41873	372	HIGH
10.8	15	43807	383	HIGH
10.7	13	39078	356	HIGH
10.6	14	37578	347	HIGH
10.5	14	41813	372	HIGH
10.4	18	39429	358	HIGH
10.3	13	38934	355	HIGH
10.2	13	42751	377	HIGH
10.1	12	42035	373	HIGH
10.0	14	40940	367	HIGH
9.9	13	45489	393	HIGH
9.8	11	43186	379	HIGH
9.7	14	43670	382	HIGH
9.6	14	41171	368	HIGH
9.5	13	35714	337	HIGH
9.4	12	35164	334	HIGH
9.3	13	37422	347	HIGH
9.2	15	40814	366	HIGH

Figure B-5. Data summary showing number of RPMs and estimated R_I on a tenth mile basis.

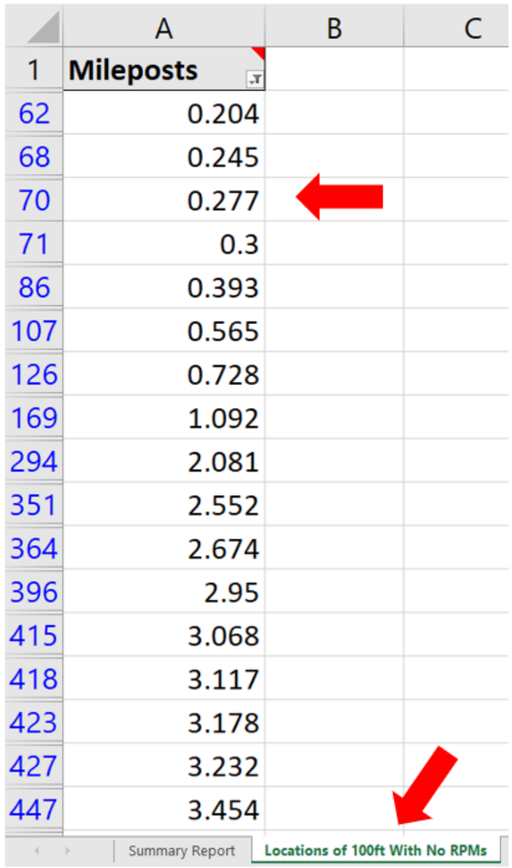
Step 6. The one mile running average and each tenth-mile R_L value for the section can be found in a graph on the right side of the summary page. Additionally, the graph also shows the thresholds for the "LOW", "MID", and "HIGH" retroreflectivity classifications.



Note: The "Estimated Ri" values have an average error of ± 16% when compared to 220-m geometry RPM reference devices

Figure B-6. RPM retroreflectivity graph.

Step 6. Lastly, the roadway sections where more the 100 feet of roadway contain no RPM can be found by navigating to the "Locations of 100ft With No RPMs" page. This page will show you the location of any instances with two or more RPMs missing in a row. This feature is to aid in the replacement of missing RPMs, and it pertains to two-lane centerlines and standard skip lines with the standard 40-foot spacing.



	A	B	C
1	**Mileposts**		
62	0.204		
68	0.245		
70	0.277		
71	0.3		
86	0.393		
107	0.565		
126	0.728		
169	1.092		
294	2.081		
351	2.552		
364	2.674		
396	2.95		
415	3.068		
418	3.117		
423	3.178		
427	3.232		
447	3.454		

Figure B-7. Table showing the approximate locations of two successively missing RPMs.

APPENDIX C – PARAMETER CONFIGURATION

Configuring RPM Analysis Parameters

Step 1. Turn the modified MRU device on and connect the tablet to the 5G WiFi corresponding to that device.

Step 2. Once connected, open Firefox browser and enter "192.168.88.11/settings_eng" into the search bar and press "Enter". This action should open the LaserLux programs engineering settings. The username and password are "admin" and "lanternerouge", respectively.

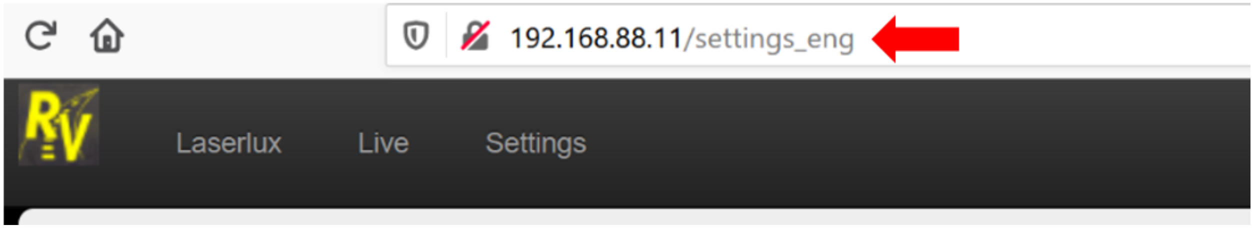


Figure C-1. The arrow indicates the URL entry to access the engineering settings.

Step 3. Scroll to the bottom of the page to the two adjusted parameters: "RPM Suppression Distance" (RPMD), and "RPM Maximum Value Search Distance" (RPMV).

Figure C-2. RPM parameters exclusive to the updated Laserlux firmware (post v1.318).

Step 4. Ensure both identified parameters are set to a value of 0.1. This value was determined by the research team to produce the most accurate RPM detection.

Step 5. Additionally, ensure that the "Stripe Threshold" (RSBT) is set to 0.25. This setting is typically 0.5 on unmodified MRUs. This setting determines the percentage of the peak retroreflectivity to be used for determining the edge of a line-stripe or RPM.

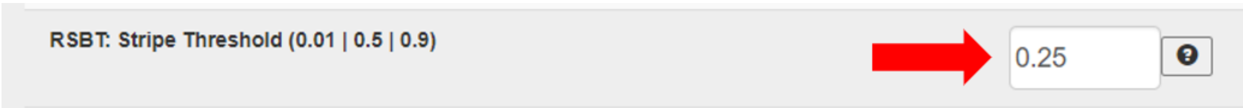


Figure C-3. Stripe threshold parameter found under the engineering settings page.