REPEATABILITY AND REPRODUCIBILITY OF MOBILE RETROREFLECTIVITY UNITS
FOR MEASUREMENT OF PAVEMENT MARKINGS

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The Florida Department of Transportation (FDOT) has historically used a combination of handheld devices and visual surveys to evaluate the retroreflectivity of pavement markings. However, visual surveys have the inherent limitations of operator bias while the use of a handheld device is slow, labor intensive, and presents safety hazards. Many highway agencies have recognized that a Mobile Retroreflectivity Unit (MRU) may be a safer and a more efficient alternative to the handheld retroreflectometers. Since the measurement process relies on the operator-driven instrument, a level of uncertainty is always a concern in evaluating pavement markings with the MRU. This research is aimed at assessing the precision and bias of the MRU while using the handheld retroreflectometer as a reference device. A total of ten 1.0 mile long field sites were selected to include various pavement surface types and pavement marking materials (paints and thermoplastics). The results indicated that, when compared to the handheld retroreflectometers, the MRU demonstrated no statistical differences or bias at a 95 percent confidence level for the retroreflectivity values ranging between 200 and 800 mcd/m²/lux. In addition, it was determined that the retroreflectivity values from two properly conducted tests using a single MRU on the same pavement marking should not differ by more than 7.8 percent and when different MRUs are used on the same pavement marking, the retroreflectivity values should not differ more than 13.3 percent. This paper presents a description of the testing program, the data collection effort, and the subsequent analyses and findings.
INTRODUCTION

Retroreflectivity of pavement marking is one of the key factors for night time visibility, safety, and comfort to those traveling on the state highway network. For this reason, the level of retroreflectance provided by the pavement marking needs to be monitored accurately and maintained appropriately. In recognition of the importance of the pavement marking retroreflectivity, the Federal Highway Administration (FHWA) released their Docket number FHWA-2009-0139 in April, 2010 which proposed that the Manual on Uniform Traffic Control Devices (MUTCD) include standards, guidance, options, and supporting information needed for maintaining the minimum levels of pavement marking retroreflectivity (1). As a result, the proposed revisions to the MUTCD including the minimum levels of pavement marking retroreflectivity has been designated as Revision 1 to the 2009 Edition of the MUTCD (2).

Historically, the Florida Department of Transportation (FDOT) has used a combination of handheld retroreflectometers and visual surveys to evaluate the retroreflectivity of pavement markings. However, the disadvantage of the handheld units is that the data can only be collected at discrete locations. In addition, testing with the handheld devices is labor intensive and presents potentially hazardous to the operator and to the traveling public as testing requires maintenance of traffic. Furthermore, visual surveys have the inherent limitations of operator bias due to subjective opinions which make quantifying retroreflectance near impossible.

The Mobile Retroreflectivity Unit (MRU) was developed to measure retroreflectivity of pavement markings continuously at highway speeds. Due to its improved safety and efficiency, MRU has been recognized by many highway agencies as an appealing alternative to the handheld retroreflectometers. The primary benefit of the MRU is that it offers a more efficient and objective means for obtaining the inventory data needed for maintaining the minimum level of pavement marking retroreflectivity provided in the MUTCD.

BACKGROUND

FDOT, with technical support provided by the University of North Florida (UNF), initiated a program to first evaluate and optimize the MRU performance followed by a comprehensive implementation plan for the MRU as an alternative for evaluating pavement marking retroreflectance.

Evaluation Process

The first step in the evaluation process was to complete a literature review, including a comprehensive discussion with most of the MRU users in the United States. There was a wide variety of experiences, but most users were limited in the implementation due to shortcomings with the device (3). Many of the MRU users reported calibrating the MRU often (up to 20 times a day) in order to achieve reliable results. Other operators discussed efforts to maintain the “30 meter geometry” which is critical to accurate MRU measurement. Road conditions (hills, curves, etc.), changes in vehicle conditions (driver, fuel level, etc.), and vehicle dynamics (pitch, roll, acceleration/deceleration, etc.) were all identified as culprits resulting in difficulty in obtaining accurate and repeatable MRU measurement (3, 4).

MRU Optimization

The initial effort was to develop and implement mitigation strategies to improve the MRU performance. For example, early testing showed that measurements taken within a short period of time were repeatable, but over a course of a day the results varied significantly. It was determined the MRU had a significant temperature sensitivity, specifically the interference filters used to eliminate background lighting. To
mitigate this issue, a thermoelectric cooler was installed to maintain the operating temperature and temperature compensation was added to the software (5).

Through testing, it became clear that the critical step in order to obtain accurate MRU measurement was the calibration process. The consistency of the field data and the accuracy of the MRU measurements are highly dependent on the procedure and the material used for its calibration. Calibration standards, consisting of a short section of beaded line striping are similar material to pavement markings but are very difficult to accurately measure (6, 7, 8, 9). Much effort has been spent to improve and optimize the calibration procedure and alternative calibration tools (6, 7).

**Precision and Bias of MRU**

FDOT has been researching the implementation of the MRU for evaluating pavement markings. The benefits of implementing the MRU to evaluate line-marking retroreflectivity include optimization of maintenance efforts, evaluation of construction techniques and new products, and improvement of the overall safety of the driving public. The preliminary goals of the implementation plan include utilizing the MRU to identify pavement markings that are approaching the minimum allowable retroreflectivity, monitoring retroreflective characteristics of various materials/applications of pavement markings, and providing inventory for maintenance to assess restriping strategies.

However, in order for FDOT to survey the statewide pavement markings, it was necessary to have multiple MRUs and operators available. Due to the operator subjectivity and the computational components involved with retroreflective measurements, assessing the precision of the MRU became critical as part of the implementation effort. Hence, FDOT conducted a study in 2010 to assess the precision of the MRU in terms of repeatability, but this preliminary effort was limited to a single MRU (10). The follow up study, which is the basis of this paper, was initiated to assess the precision of the MRU in terms of repeatability and reproducibility for pavement marking retroreflectivity. Handheld retroreflectometers were used as a reference device in assessing the MRU’s precision. This paper documents the test protocols, results, and findings of the study.

**OBJECTIVES**

The primary objective of this study was to assess the precision and bias of the MRU for determining the retroreflective characteristics of in-service pavement markings in Florida. The precision of the MRU was expressed in terms of repeatability and reproducibility while the bias was evaluated using the handheld retroreflectometer as a reference device.

**RETROREFLECTANCE**

Retroreflectivity of pavement markings and traffic signs is an important part of roadway guidance and safety, especially at night. Pavement markings reflect light from the vehicle’s headlamps back to the operator’s eyes. This process is called Retroreflectance (R<sub>e</sub>), and is quantified as the ratio of the luminance (or brightness) of an object as detected by a sensor to the illuminance of the object by a light source and is expressed in units of millicandela per meter squared per lux (mcd/m<sup>2</sup>/lux). Pavement markings typically provide retroreflectivity through the application of small glass spheres (commonly called beads) that are partially embedded into the pavement marking material. This allows incoming light from the vehicle headlamps to reflect back to the origin of the light source, as illustrated in Figure 1.
Pavement markings can consist of various materials such as paints, thermoplastics and tapes, many using the application of glass beads that can vary in size as well. Obtaining a single $R_L$ value for a pavement marking using the handheld retroreflectometer or the MRU can be difficult due to factors that influence the amount of retroreflectivity produced by glass beads such as the dispersion in a non-uniform pattern, embedment depth, refraction index, size, clarity, and roundness. In addition, climate conditions such as rain, fog, snow, ultraviolet light and heat can all affect retroreflective properties (11).

TESTING EQUIPMENT

The equipment used in this study included two MRUs and three handheld retroreflectometers, owned by FDOT. The handheld and mobile retroreflectometers measure the retroreflectance by applying the “30 meter geometry” described in ASTM E 1710 (12). The 30 meter geometry consists of the following assumptions: a typical passenger vehicle headlamp height of 0.65 m (2.1 ft.), a driver eye height of 1.2 m (3.9 ft.), and a distance of 30 m (98 ft.) between the headlamps and the ground-based retroreflectance target. In order to reduce the size of the measuring device, the MRU uses a 1/3rd scale of the 30 meter geometry, as shown in Figure 2. The geometry of the handheld retroreflectometer corresponds to a much smaller scale.
Handheld Retroreflectometer

The handheld devices used for this study were one Road Vista StripeMaster and two Delta LTL-X retroreflectometers, all conforming to ASTM E 1710 and are shown in Figure 3. The device outputs a digital readout of the measured retroreflectivity to the nearest 1 mcd/m²/lux. The handheld retroreflectometers have supports that are approximately 10.0 cm (4 inches) wide for better stability positioned on the pavement marking and when placed down, are centered in the pavement marking.

Mobile Retroreflectivity Unit

The two MRUs used in this study were both Road Vista Laserlux retroreflectometers mounted on full-size passenger vans equipped with all the mechanical and electrical power supplies for evaluating pavement markings. In addition, the vehicles include a data acquisition system for collecting and storing information. A distance-measuring instrument (DMI) is provided to determine the position along the roadway. The longitudinal distance measurement is critical in associating the precise location for each
0.16 km (0.1 mile), the interval at which the MRU is reporting the data. One of the MRUs used in the study is shown in Figure 4.

**FIGURE 4** FDOT's Mobile Retroreflectivity Unit

The MRU is equipped with a 10 mW Helium Neon (HeNe) laser to provide a controlled light source with a wavelength of 632.8 nm (0.025 mils) (13). The other principal sub-system is the photodetector which is a device that houses a silicon photodiode to convert the retroreflected light into an electrical signal and an amplifier that magnifies the low-level signal to a measurable level (5). Interference filters are utilized to filter out light of wavelengths other than the laser light as the reflected light may consist of wavelengths resulting from other sources such as sunlight, street lighting, vehicle headlamps, etc. A double-sided mirror rotates at 10 Hz and collects the data at a rate of 200 samples/scan, creating a scan width of up to 1.1 m (3.6 ft.) wide as the laser and the photodetector sweep the pavement marking (13). Other mirrors are utilized to re-direct the light to achieve the reduced 30 meter geometry. Figure 5 is a schematic of the internal components of the retroreflectometer unit and the path of the laser light (11).

**FIGURE 5** Internal components and laser path of retroreflectometer
The MRU is a sensitive instrument and the precision of the MRU measurements is highly dependent on the calibration of the equipment. It is important that accurate geometry and an appropriate calibration panel be used during MRU calibration to reduce uncertainty in pavement marking measurements. Any errors introduced during the calibration process will be transferred to errors in pavement marking evaluation. To ensure precise measurement, calibration of the MRU was performed in close proximity to the pavement marking test section, as shown in Figure 6.

![FIGURE 6 Calibration of FDOT’s Mobile Retroreflectivity Unit in the field](image)

The goal of the calibration process is to standardize the MRU by scanning a calibration panel of which the $R_L$ value is known. The consistency of the calibration panel is crucial to the success of the MRU calibration and should result in reproducible calibration factors. Since there is no standard procedure broadly accepted for the calibration and operation of the MRU, FDOT has researched and implemented a new calibration panel that has provided more reproducible calibrations. The new calibration panel used by FDOT is a 152 mm (6 inches) wide black reflective vinyl with a $R_L$ of 895 mcd/m$^2$/lux. A picture of the new calibration panel is shown in Figure 7. For this study, the aforementioned retroreflective panel was consistently used to calibrate the MRU prior to any data collection.
DATA COLLECTION

Ten 1.6 km (1.0 mile) test sections with various pavement surface types (open and dense graded) and pavement marking materials (paints and thermoplastics) were selected within Alachua County, Florida. The test sites were selected to avoid breaks in the pavement marking and to minimize roadway geometric variables such as inclines, declines, and curves. All tests were performed on the 152 mm (6 in.) wide white edge-line. Prior to testing, the beginning and ending limits of the test sections were clearly identified to ensure an accurate point of reference between all MRU tests.

Three handheld retroreflectometers were initially used to measure the retroreflectivity every 36.6 m (120 ft.), resulting in 44 measurements over the 1.6 km (1.0 mile) distance. At each site, the three handheld devices were calibrated and used to measure the retroreflectivity of the pavement marking. The resulting measurements were then averaged for each 0.16 km (0.10 mile) section for direct comparison with the MRU data output. The longitudinal distance between each test was measured using a digital measuring wheel with a 2.5 mm (0.1 in.) resolution.

Once the handheld measurements were completed, each MRU performed three repeat runs over each test section. The MRUs were aligned in the center of the edge-line and the vehicle wander was minimized to ± 6 inches from the center of the pavement marking. In addition, the same operators were utilized throughout the series of tests and each operated the same MRU. The number of data scans taken by the MRU depends on the travelling speed of the vehicle. On average, FDOT’s MRUs collect approximately 145 scans per 0.16 km (0.1 mile), when traveled at a speed of 80 km/h (50 mph). The MRUs were calibrated prior to taking measurements at each test site. The MRU data was averaged for every 0.16 km (0.1 mile) segment, producing 10 averaged retroreflectivity values per site.

For the test program, a total of 440 retroreflective measurements were collected for each of the three handheld retroreflectometers. For each of the two MRUs, three runs were performed at each of the ten sites, resulting in a total of 600 average retroreflectivity MRU measurements.

PRECISION AND BIAS ESTIMATES

Accuracy and precision are two of the most important criteria for the usefulness of any reliable testing device. ASTM E 177 indicates that the accuracy is typically stated in terms of bias which is defined as the difference of the measured values and the accepted reference value \( \Delta \). It also states that the precision is typically stated in terms of repeatability (within MRU precision) or reproducibility (between MRUs precision).

ASTM C 670 specifies that the existence of bias should be determined by comparing the \( t \) statistic calculated from the difference between the reference and the estimated values to the critical \( t \) statistic, \( t_{\text{crit}} \), for a given confidence level \( (1.5) \). For the evaluation of the MRU, the \( t \) statistic was calculated based on the difference between the MRU measurements and the reference handheld retroreflectometers.

In addition, ASTM C 670 states that an “acceptable difference between two test measurements” or the “difference two-sigma limit” \( (d_{2S}) \), can be selected as an appropriate index of precision. The \( d_{2S} \) index for a 95 percent confidence level can be calculated by multiplying the appropriate standard deviation or coefficient of variation (COV) by \( 2 \sqrt{5} \). \( (15) \). The appropriate standard deviation and coefficient of variation (COV) are those that represent the within and between unit variation due to the multiple MRU measurements made by two operators and two units. In this study, the above statistics were first obtained for each segment, and then pooled to result in an overall estimate of the within unit
(repeatability) and between unit (reproducibility) variation as outlined in ASTM C 802 (16). The precision statement was then determined based on the pooled statistics. The MRU data as well as the analysis and the resulting precision statements are presented in the subsequent sections.

STATISTICAL ANALYSIS

The range and variation in data collected with the three handheld retroreflectometers and two MRUs for each test section are illustrated in Figure 8. Based on the measurements of both devices, the magnitude ranged from 151 to 834 mcd/m$^2$/lux.

FIGURE 8  Range of the Retroreflective Data.
The retroreflectivity values for the handheld retroreflectometers were compared to the MRUs and are illustrated in Figure 9. Statistical analysis was also performed to assess the precision of the MRU in terms of bias defined as the systematic error that contributes to the difference between the mean of the MRU and the accepted reference measurement, which in this case is the average of the handheld measurements. A matched-pairs t-test was conducted to test the significance in the mean difference between manual and automated faulting measurements (15). The \( t \) and \( t_{\text{crit}} \) statistics were calculated as 1.4 and 2.0, respectively. Because the calculated \( t \) statistic falls inside of the \( \pm t_{\text{crit}} \) range, it can be concluded that the MRU does not exhibit bias when compared to the handheld devices.

![Handheld retroreflectometer vs. MRU](image)

**FIGURE 9 Handheld retroreflectometer vs. MRU**

ASTM C 802 also states that the form of the precision statement should be determined based on the relationship between the average and the standard deviation of the measurements (16). In order to determine if the repeatability and reproducibility of the MRU are dependent on the level of retroreflectance, the pooled standard deviation and coefficient of variance (COV) were plotted against the average retroreflectivity values and are shown Figures 10 and 11, respectively. As indicated by the slope of the linear regression lines being much less than 1.0 and close to zero, there is no direct relationship between the variability of the collected data and the magnitude of the retroreflectivity values. This indicates that both the repeatability and reproducibility statements could be drawn independent of the retroreflectivity values considered herein.

\[
y = 0.96x + 7.01 \\
R^2 = 0.80
\]
y = 0.02x + 0.82
R² = 0.32

y = 0.01x + 12.75
R² = 0.03

FIGURE 10 Standard deviation vs. average retroreflectivity
In addition, the pooled variance, standard deviations, COV, d2s, and d2s% were calculated from the data for the repeatability and reproducibility assessments of the MRU. A summary of the results is shown in Table 1. The table shows that the overall pooled standard deviations of the retroreflectivity for the MRU were calculated to be 12.0 mcd/m²/lux (within MRU) and 18.8 mcd/m²/lux (between MRUs), respectively.

FIGURE 11 Coefficient of variation vs. average retroreflectivity
Based on the results provided above, bias and precision statements for both the handheld retroreflectometers and MRU are established in the following section.

**BIAS AND PRECISION STATEMENT FOR THE MRU**

In accordance with the methodology described in ASTM C-670 (15), the results from FDOT MRUs were compared with reference values from handheld retroreflectometers and no statistically significant bias was found.

The overall pooled results of two properly conducted retroreflectivity tests using the same MRU on the same pavement marking test section should not differ by more than 7.8% (34.0 mcd/m$^2$/lux for the ten sites tested for this study) at a 95 percent confidence level for retroreflectivity values ranging between 200 and 800 mcd/m$^2$/lux.

The overall pooled results of two properly conducted retroreflectivity tests using different MRUs on the same pavement marking test section should not differ by more than 13.3% (53.0 mcd/m$^2$/lux for the ten sites tested for this study) at a 95 percent confidence level for retroreflectivity values ranging between 200 and 800 mcd/m$^2$/lux.

**CONCLUSIONS**

The present study was aimed at establishing the precision statement of the Mobile Retroreflectometer Unit (MRU) for pavement marking retroreflectivity. For the precision and bias of the MRU, ten test sections were selected to perform retroreflective measurements using the average results of three handheld retroreflectometers as reference, in accordance with ASTM E-1710 (12). The results of two MRUs were used as the basis for evaluating the repeatability and reproducibility of the MRU.

The average pavement marking retroreflectivity for the test sections ranged from 200 to 800 mcd/m$^2$/lux. The MRU showed no statistically significant bias indicating that the device produces similar retroreflectance measurements as the handheld retroreflectometer. The overall pooled standard deviation for the retroreflectivity for the MRU was determined to be 12.0 mcd/m$^2$/lux (within MRU) and 18.8 mcd/m$^2$/lux (between MRUs). Also, the overall pooled coefficient of variance for the retroreflectivity for the MRU was determined to be 2.8% (within MRU) and 4.7% (between MRUs). Therefore, the results of two properly conducted retroreflectivity tests using the same MRU on the same pavement marking test section should not differ by more than 7.8 percent at a 95 percent confidence level when using the same MRU. In addition, the results of two properly conducted retroreflectivity tests using two different MRUs on the same pavement marking test section should not differ by more than 13.3 percent at a 95 percent confidence level.
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DISCLAIMER

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REFERENCES