Advanced Methods for Mobile Retro-reflectivity Measurement on Pavement Marking

Final Project Report

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HIGHWAYS FOR LIFE
Accelerating Innovation for the American Driving Experience.

U.S. Department of Transportation
Federal Highway Administration

FORWARD

- Purpose: This report provides an overview of the development of a mobile retroreflectivity unit for pavement marking measurement.
- Content summary: This document details system capabilities and test results of a mobile data collection system for pavement marking. It describes an accurate, repeatable and reliable machine and methodology that will benefit transportation agencies and the motoring public they serve.
- Interested audience: Pavement marking engineers, highway officials, municipality officials.
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16. Abstract

The purpose of this project was to demonstrate the capture of pavement marking retroreflectivity measurement data—regardless of various environmental, marking and road condition issues—to allow transportation agencies to make timely and appropriate decisions in managing their pavement marking assets. The MRU described in this proposal addresses each of the three most challenging technical issues (motion, environmental conditions, and stability) and provides a solution to increase measurement efficiency.

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While driving, drivers cannot react appropriately to what they cannot see. In adverse conditions, whether rain, snow, fog or simply darkness, clear visibility of road markings is essential to the safety of all drivers. Leetron Vision has developed a new, innovative, mobile measurement technology designed to provide consistent, high-fidelity testing of pavement marking reflectivity—known as retroreflectivity—for DOTs nationwide. Moreover, this technology is available at a significant savings of time, labor and cost. The core of this innovation is Leetron's proprietary Mobile Retroreflectivity Unit (MRU), using real-time laser tracking technology maintained in constant visual contact with road markings to provide a new level of reliability and accuracy.

The aim of this project was to meet the needs of transportation agencies to expeditiously capture accurate pavement marking retroreflectivity measurement data—regardless of various environmental, marking and road condition issues—to allow these agencies to make timely and appropriate decisions in managing their pavement marking assets. The MRU described in this proposal addresses each of the three most challenging technical issues (motion, environmental conditions, and stability) and provides a solution for significant increases in measurement efficiency.

Leetron Vision was formed with the single focus of building a total solution for mobile retroreflectivity data collection. The first successful prototype unit was built in 2012 with funding from the Innovation Deserving Exploratory Analysis (IDEA) program, which is part of the National Cooperative Highway Research Program (NCHRP). After achieving promising initial results from this prototype, a production version of the system was built and tested in 2015 with support from Federal Highway Administration's Highways for LIFE Technology (HfL) Partnerships Program. This is the final report compiled from that partnership.

As detailed in the report, a comprehensive solution required a new approach. Leetron Vision's design approach was implemented by examining all of the conditions that could affect mobile measurement and then formulating a solution with built-in capability to handle those conditions. This approach led to the development of a new "variable geometry" measurement technology.

Later, this report explains the new technology, lists the steps taken in building the system, describes in detail the testing protocol and discusses the results achieved under any conditions that may occur in mobile retroreflectivity measurement.

In the process of finalizing the product from a prototype, a number of refinement cycles were incorporated in the testing to ensure that the unit remained capable of handling conditions in real-world settings. Extensive road testing and refinements helped develop a robust commercial-ready system (see Figure 1 above). The system includes an easy to use graphic user interface system and an integrated data management system.

The final work of the HFL project involved an independent evaluation by the Texas A&M Transportation Institute (TTI). TTI's independent evaluation of the Leetron System was designed to evaluate the accuracy and repeatability of the Leetron System. Working with FHWA and TTI, the testing plan design also evaluated the Leetron System's ability to overcome challenges encountered by mobile retro measurement. The goal was to make the Leetron MRU the most capable, reliable, and efficient MRU available. Table 1 below, based on the TTI report (Table 5.1), is a summary of test results from Appendix E of test result on the open road test.

Factor Tested	Impact [1,2]	Notes [1]
Retroreflectivity Level	Not practically significant	In most cases the differences were not statistically significant.
Marking Color	Not practically significant	In most cases the differences were not statistically significant.
Line Type	Not practically significant	In most cases the differences were not statistically significant.
Road Surface Type	No indication that road surface type had an impact	
Data Collection Speed	Not statistically significant	
Drive position Sensitivity	Not statistically significant	
RRPM Presence	Not statistically significant*	*After final RRPM adjustments were made to the system.
Ambient Light	Not practically significant	In most cases the differences were not statistically significant. Some results were impacted by rain on the day between test runs.
Repeatability of Measurements	Not statistically significant	Less than 2% difference in mean values between repeat runs

Table 1 TTI report: Open Road Summary of Test Result

[1] Statistical significance determined at a 95% confidence level (or equivalently at a 5% significance level).
[2] Practical significance if difference exceeded 15% of the mean retroreflectivity.

The independent verification testing conducted at TTI evaluated the Leetron System's ability to collect accurate data under a variety of challenging conditions. The results indicate that Leetron MRU is capable of producing reliable pavement marking retroreflectivity data under challenging conditions which will help transportation agencies optimize re-marking schedules and better manage their pavement marking assets.

As transportation agencies are adopting more data-driven decision-making processes to manage pavement markings, reliable R_L data becomes essential to the success of this process. Recent research from Kentucky[1] shows that it is not necessary to re-stripe many roads annually. The report indicates that nearly half of those stripes had passed acceptability levels after even two years. With the high level of accuracy in measure afforded by the MRU, DOTs is able to manage the performance of markings in a more cost effective manner while delivering drivers what they need for safe driving at night.

Prior to entering the technology partnership with FHWA on this project, the Leetron MRU was a promising innovation that could benefit by working with transportation agencies. As a result of this partnership project, a new product was built and thoroughly tested under real-world conditions to demonstrate commercially-readiness. The results of the comprehensive testing demonstrate Leetron Vision's MRU using "variable geometry" technology is capable of accurately measuring pavement marking retroreflectivty under a broad range of real-world conditions. Combined with the measurement repeatability and ease of operation, Leetron Vision is prepared to introduce the Leetron Vision MRU into the market and support transportation agencies address the challenge of rapidly collecting accurate retroreflectivity data.

[1] Eric R. Green, Kenneth R. Agent. Evaluation of Pavement Marking Performance. www.ktc.uky.edu/Reports/KTC_08_21_SPR_330_07_2I.pdf

Introduction and Overview

1.1 Introduction

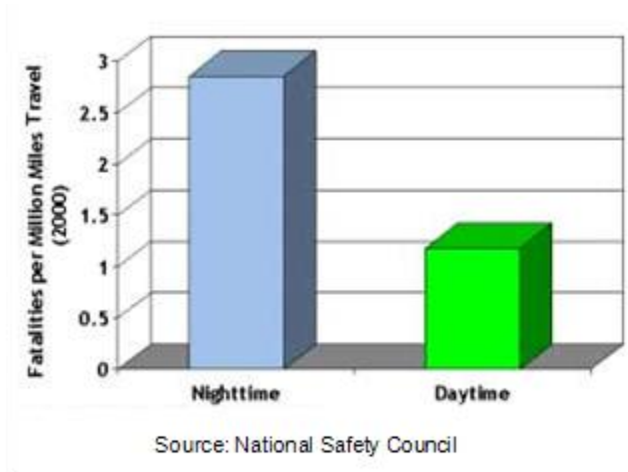

Figure 2 Nighttime vs. Daytime Fatality Comparison

According the National Safety Council, [1] only a quarter of travel in the United States occurs after dark; however, this results in about half of all traffic fatalities (see Figure 2 for comparison). Longitudinal pavement markings are an important traffic control roadway feature and, when they are adequately retroreflective, they are critical for aiding night-time driving, especially for aging drivers.

Retroreflective properties of pavement markings deteriorate over time and highway agencies are challenged to manage the performance of pavement marking retroreflectivity. Some agencies use fixed repainting schedules; however, with advancements in technology for efficiently and accurately measuring retroreflectivity, highway agencies can collect data and plan the replacement of markings based on performance.

DOTs are looking to innovation as a means to reduce costs while maintaining the level of service to the public and applying asset management strategies to managing pavement marking program. In order to accomplish these goals they are increasingly using MRUs as a cost-effective method of collecting pavement marking retroreflectivity performance information on a system-wide scale.

[1] Mass Interchange 2010 http://baystateroads.eot.state.ma.us/newsletters/2010%20Fall_Winter.pdf

Retroreflectivity can be explained as projecting a light toward a pavement marking and then measuring how much light is returned toward the light source. The measurement of pavement marking retroreflectivity is accomplished by carefully controlling the distance and angle at which a light source is projected and the measurement of the amount of light returning to toward the source. While there are many factors that could affect the MRU performance, motion of the vehicle platform is one of the greatest challenges as illustrated in Figure 3.

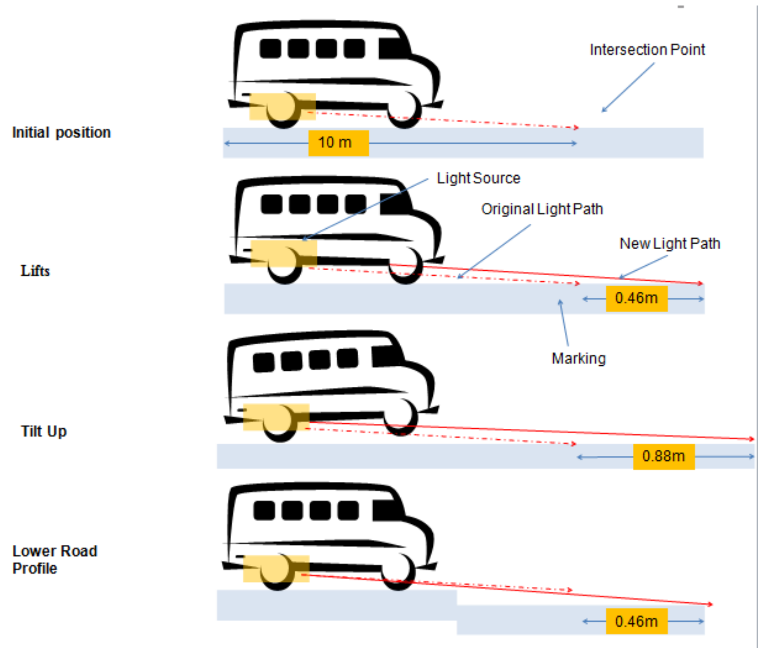

Figure 3 Motion Effects on MRUs Performance

To solve the motion issue, Leetron developed a new "variable geometry" measurement technology that is detailed in Appendix C. The basic idea is to build a measurement system with the ability to follow markings as the vehicle travels at highway speed. With this configuration, the light source and measurement target will stay on a calibrated target point regardless of bounce, tilt or sway from driving.

1.2 System Overview

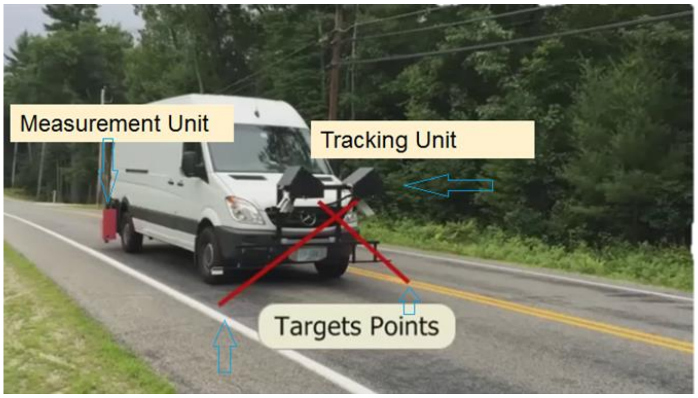

Figure 4 Leetron MRU Overview

The Leetron System consists of measurement units, tracking units, and target points (see Appendix A for details). As shown in Figure 4, a laser light from the measurement unit targets a point on the pavement marking and keeps it there with the tracking unit's automated aiming-correction techniques, and it does so while the vehicle travels at normal highway speeds. With the laser and the measurement camera locked on the target regardless of external motion influences, the system eliminates measurement variations introduced by the vehicle motion and variance in the road profile. This feedback system allows the measurement camera to produce the measurement result by converting the amount of light retroreflective from the pavement marking to a retroreflectivity value.

Key features of the Leetron MRU are:

- Use of "variable geometry" technology to improve accuracy and repeatability by minimizing or compensating for the effects of motion on the measurement results.
- Designed to handle even the most challenging conditions.
- A stable measurement system (see Appendix B: Stability for detail) with thermal control to provide consistent measurement.
- Self-calibration was designed to be quick and efficient.
- User interface is designed for easy use to minimize distraction and allow the operator to *concentrate on driving*.
- Data management system helps operators to spend more time on data collection and less time on managing the data by streamlining the data transfer through wireless communication, the analysis, visualization and reporting.

2. Project Tasks

The HfL project required specific tasks to be conducted which are covered in this section.

2.1 Cycle of Testing and Refinement

Activities associated with this task included evaluation testing and system modifications to improve its ability to handle various road and environmental conditions. Some of the specific efforts focused on the following:

- **Tracking System:** The tracking system was improved to minimize the effects of motion.
- **Sunlight Effect:** Incorporated a robust method to compensate for the influence of oncoming sunlight during hours where the sun is low on the horizon.
- **Auto Calibration Option:** Addition of an auto-calibration option used to improve the measurement consistency.
- **Analytic Tools:** Added software analytic tools for real-time evaluation and debugging of each critical system component to assure system performance. This assists the operator in identifying and correcting any component issues, and supports ongoing system improvements.
- **Contrast of the Pavement Surface:** Concrete surfaces present lower contrast between the pavement marking and pavement surface. New software functions on the sub-system were incorporated to overcome these optical challenges.
- **Broken longitudinal markings:** Broken longitudinal markings or intermittent markings create unique tracking and measurement challenges. Leetron uses dual and coexisting methodologies for tracking both solid and intermittent lines.
- **Retroreflective Raised Pavement Markers (RRPM):** These RRPMs often maintain a far higher coefficient of retroreflection than the marking it supplements. To overcome the challenges RRPMs present, Leetron developed algorithms to detect and remove RRPM from collected data.
- **Low Retroreflectivity:** Refined the system to increase the ability to measure under low retroreflectivity conditions. Refinements designed to increase the contrast between the pavement and marking help to target the marking location so the system can continue to track and measure markings with low retroreflectivity.
- **Horizontal Curves:** the system was fine-tuned to continuously track and measure under smaller radius horizontal curve conditions.
- **Larger Bounce:** While the system was able to handle motion (cause by vehicle vibration and uneven profile of road surface), there would be a point where the bounce was too large (For example, a bump on the road) for the tracking system to handle. This condition

would cause variation on measurement. To solve this issue, new software functions were added to detect the large bounce condition and remove those measurement points.

- **Lane position:** Ideally, the system would be driven at the center of a lane at all times maintaining equal lateral distance between the system and edge of lanes on both sides. But because drivers cannot maintain precise lane position the system was refined to accommodate lateral shifting within the lane.
- **Stripe Location Identification:** Redesigned the stripe location identification system to increase its ability to find stripes under sunlight and dark conditions.
- **Voice Command:** Added voice commands control (See Appendix D for details).
- **Power and Thermal management:** The electrical power system was upgraded with larger capacity. A temperature controls unit was added to keep the measurement components at the desire temperature. Also, a recovery method was added to deal with overheating issues.
- **Measurement Unit Safety Feature:** Naturally the tracking and measurement systems are placed closely to the pavement surface and when necessary the hydraulic system allows the operator to adjust the system height in order to lift the hardware out of harm's way if needed.

2.2 System User Interface

To control data collection on both the driver and passenger side while driving, a new user interface program was needed. This user interface required the ability to control and monitor the data collection on both sides of the vehicle. Since the Leetron MRU was designed to be operated by one person, the interactions between the operator and the user interface program needed to be minimized and simplified. To accomplish this goal, Leetron used the latest software development tools from Microsoft (WCF, WPF and Blend). These provided the functionalities needed for the project.

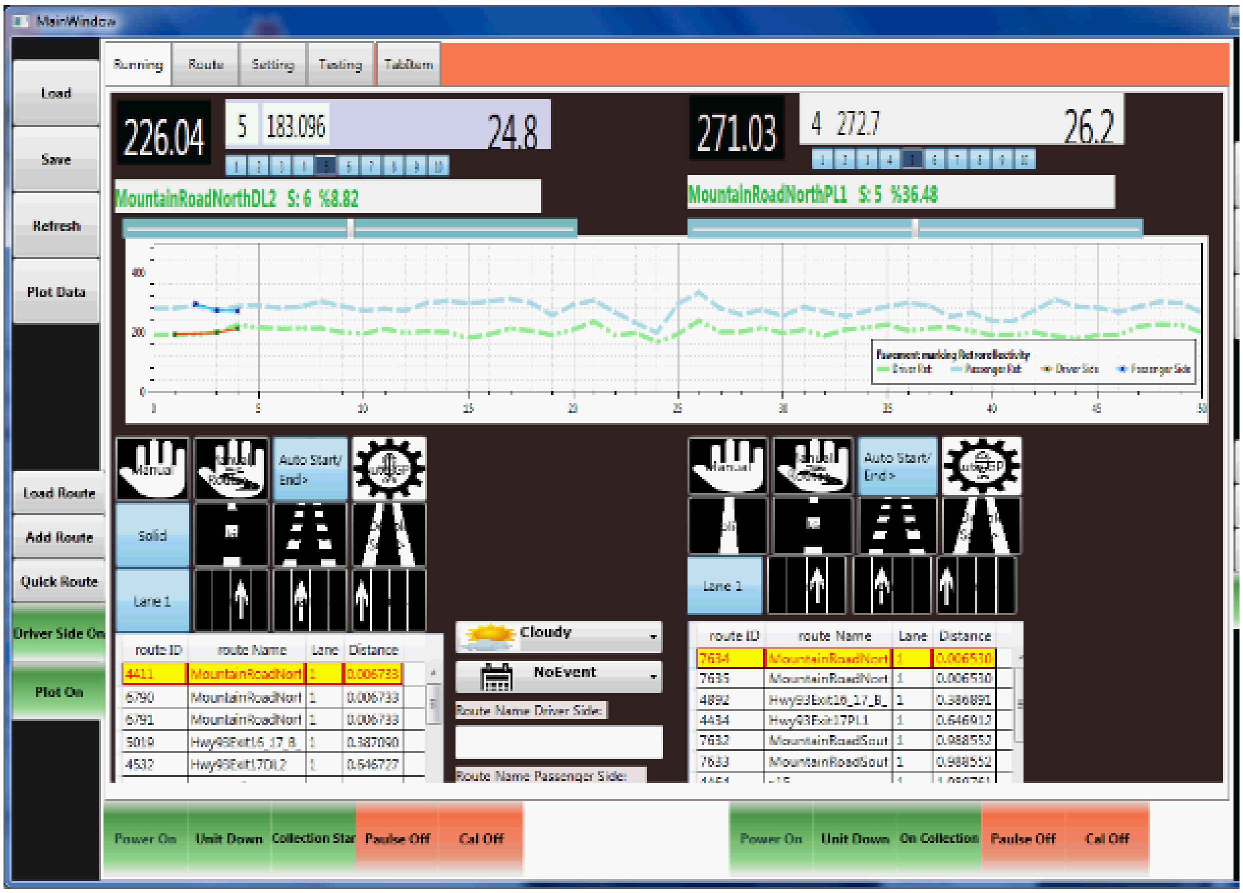

Figure 5 System User Interface Screen

Figure 5 shows the main screen for the user interface. The speech and voice recognition commands feature made it easier for operators to communicate with the system. More detailed functionalities are listed under Appendix D, User Interface.

2.3 Data Management Software

The data management system was designed to handle the system which continuously collects massive amounts of data and then reduce down to a format needed by the user. In additional to the basic measurement data, route data management, additional features such as maps and automatic graph generation of collected data were developed to give the user the information needed most. Figure 6 shows an overview of the database.

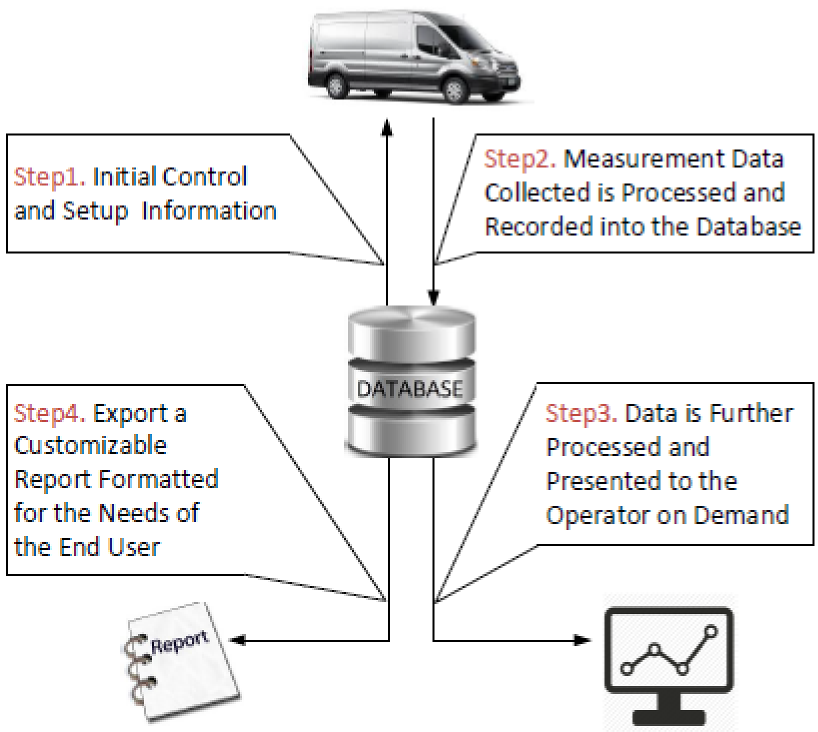

Figure 6 Data Management System Overview

The Leetron System incorporates several connectivity options which make customization of the user interface and data base systems customizable and remote technical support by Leetron Vision possible. As the end users accumulates operation experience with the Leetron System, it is important for this capability of integrating further alterations and improvements to be made available in order to meet future challenges and user needs. More details of functionalities are listed under Appendix D, Database Management.

2.4 Passenger Side Upgrade

This activity involved installing a commercial-ready product on a new van as well as additional improvements and refinements.

New Unit Built: One of the issues identified early on with the prototype unit was ground clearance. The measurement unit was too close to the ground based on the original vehicle size and dimensions and presented the possibility that road contact and damage to the unit could occur. Therefore, Leetron Vision determined that a "Sprinter" van with a longer wheelbase (distance between the front and rear axles) was best suited to alleviate this concern. The Sprinter has plenty of cargo space to allow the system equipment to be mounted inside with plenty of room for the user to work. After the new van was purchased, a new mounting system including a hydraulic lift system was designed and a second tracking and measurement unit for the passenger side was assembled and installed.

Waterproofing the system: Rain and moisture intrusion can wreak havoc on any electronic system that is not shielded. Custom protection was designed and constructed to protect the tracking and measurement components from the elements.

Additional Refinements:

- **Measurement Processing:** The software that tracks and determines the placement of measurement points into a section/interval is complex. The software uses a superior multi-thread method, thus facilitating efficient processing of the continuous data stream that becomes the logic required for the systems measurement control.
- **Hardware Ground Noises:** Electrical ground noise was noted as introducing system measurement variations in the system. Proper grounding of the electrical components eliminated these ground noise issues.
- **System Reliability:** A primary goal for this stage of the project was to assemble and install a reliable production unit. The emphasis was in mitigating potential issues during the key data collection process. These processes are done in both hardware and software. For the hardware, it is important that each component in the system be able to resist such influences as the ongoing effects of vibration and temperature variation. An evaluation of each component in the system that could be influenced by such effects was done and those components judged wanting were replaced with more robust types. Regarding the software, the primary goal was to eliminate software bugs that caused system lock.

3. System Performance Evaluation

The goal for performing the system performance evaluation was to evaluate each of the following four categories: measurement capability; measurement efficiency; user interface; and data system management and user functionality. The following subsection will discuss each category in more details. Section 3.1 was based on results from a FDOT test conducted in 2014 and Section 3.2 will be based on Independent System Performance Evaluation test results conducted by the Texas A&M Transportation Institute (TTI) in 2015.

3.1 Measurement Capability

The most challenging aspect of mobile data collection facing the industry is to produce consistent results for the various road and environmental conditions. To demonstrate the capabilities of the Leetron System, FHWA and the FDOT designed a comprehensive test plan to determine the repeatability and accuracy of the Leetron MRU as compared to the handheld retroreflectometer under a variety of environmental and site-related conditions. Testing was conducted over a two-week period with the assistance of FDOT in September, 2014. The following discussion describes the design goals, the test methodology and the results.

In order to evaluate the Leetron MRU's ability to accurately measure R_L of pavement markings, FHWA defined the test criteria that covered a full range of conditions. The testing involved collecting measurements from nine different one-mile sites.

The reference measurements involved using three handheld retroreflectometers with each collecting data from 100 locations for each site. Traffic control was provided by FDOT for each of the nine sites which consisted of: three site groups including 3 sites of solid yellow markings, three white broken and three yellow broken marking sites. Each site within each group was selected in order to measure a representative marking within the group of low, medium and high *RL* values typically present on roadways.

Both asphalt and concrete road surfaces were included, as well as horizontal curves, "bumpy" road surfaces, open-graded and dense graded pavement roadway characteristics. The Pavement Marking (PM) types consisted of thermoplastics, polyurea and waterborne paint. Two of the solid yellow sites were "audible" markings (more on effects audible to retroreflectivity measurement later). Additionally, the test sites were to be measured under conditions of sunny, cloudy and night to determine the impact of ambient light.

Table 2 Florida Test Routes Details shows the summary of the nine sites:

Site	Line Type	Retro Level	Posted Speed Limit	Pavement Surface Type	Road Condition Type	Pavement Marking Type	Comments	AADT	Lanes	Beginning Latitude & Longitude	Ending Latitude & Longitude
1	Yellow Solid	Low	55	Asphalt	H Curve'			22500	4	29.913686, -81.393203	29.914867, -81.376573
2		Medium	65	Concrete	S+B	Thermo	Audible	13300	4	29.073421, -81.249826	29.083410, -81.237844
3		High	65	Asphalt	F+S	Thermo	Audible	7300	4	29.783654, -82.167412	29.773251, -82.156961
4	White Broke	Low	65	Asphalt	H Curve		RN 3.13	11100	4	29.556264, -82.096684	29.570259, -82.092054
5		Medium	55	Asphalt	F+S	Polyurea		28377	4	29.148213, -82.071157	29.156364, -82.084825
6		High	65	Asphalt	H Curve'			9700	4	29.734038, -82.140983	29.748589, -82.141002
7	Yellow Broken	Low	60	Asphalt	F+S			4100	2	29.499443, -81.484511	29.509921, -81.496005
8		Medium	60	Concrete	F+S			6351	2	29.754970, -82.356596	29.740633, -82.353799
9		High	60	Asphalt	F+S			2000	2	29.184602, -83.014977	29.193991, -83.002343

Table 2 Florida Test Routes Details

The test results were divided into 0.02 mile interval and 0.1 mile interval as shown in Table 3. 0.02 is the based interval unit used for this test and the 0.1 mile interval is the typical reporting unit for MRU. Typically, the smaller interval has higher variations between MRU and handhold. The source of higher variation is mainly due to is measurement difference between the two methods will amplify by the small intervals.

The system performance was evaluated against the following variables:

Repeatability: Many factors can affect a MRU’s ability to capture accurate results, and these factors also can affect the ability to consistently collect accurate readings. With the continuous measurement rate of 4500 lines per second and the ability to adjust the camera and light source aiming at the stripe at the rate of 80 times a second, Leetron system is able to overcome typical factors that cause repeatability errors. The average repeatability error on the FDOT road test was 5.7% at 0.02 interval and 2.9% at 0.1 mile interval as shown in Table 3.

Leetron Mobile Unit Florida Test Result Summary				
	Interval 0.02 mile		Interval 0.1 mile	
	Repeatability	Accuracy	Repeatabil	Accuracy
Site #	Mobile	HandHeld Vs Mobile	Mobile	HandHeld Vs Mobile
1	5.82%	11.71%	3.68%	4.44%
2	2.85%	9.87%	1.56%	1.56%
3	4.99%	27.08%	3.16%	23.76%
4	6.33%	8.13%	2.91%	4.31%
5	6.56%	11.79%	3.85%	9.63%
6	5.76%	9.09%	3.55%	5.73%
7	4.85%	9.72%	2.04%	8.14%
8	5.56%	8.36%	3.63%	6.39%
9	3.78%	6.27%	1.74%	2.70%
Average *	5.17%	9.29%	2.90%	5.91%
Note: *	Site #2 & # 3 is not included in the average calculation HandHeld Vs Mobile due to audible stripes.			

Table 3 Florida Road Test Result

These repeatability error values are considered low which indicates that the Leetron MRU is highly repeatable. Figure 7 represents the repeatability test results for one of the tested sites.

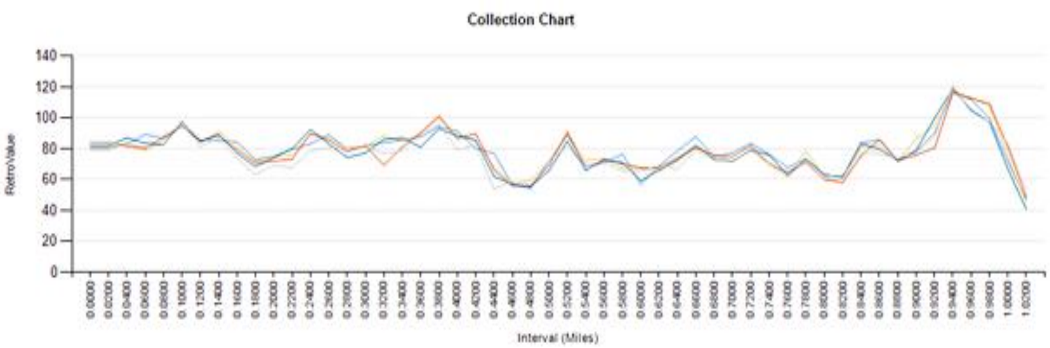

Figure 7 Sample Graph on Repeatability Result

Operating Speed: The operating speed of an MRU while collecting measurement data can impact the ability to collect accurate and repeatable results. Different speeds may affect the number of measurement points in a section and, depending on the measurement technology, adversely affect measurement results. The Leetron MRU collects 4,500 measurements per second and based on the data collected operating speed was not identified as an issue. The effect of varying operating speed was tested using speeds ranging from 35 m/h to 65 m/h. No notable difference in repeatability and accuracy was identified indicating that the Leetron MRU is not sensitive to traveling speed.

Pavement Surface Type: The effect of different pavement surface type was evaluated for influence on the MRU measurement. The Leetron MRU's technology used for tracking and measurement controls the light source in such a manner as to continuously track and measure only the pavement marking. This helps to avoid interaction with the pavement surface which could affect measurement performance. Two pavement types – concrete (sites 2 and 8) and asphalt (remaining sites) were evaluated for higher repeatability variations when grouping the results by the surface types. The results shown in Table 4 indicate low and similar repeatability errors as compared to handheld tests, and therefore imply that pavement surface types do not affect R_L measurement on the Leetron MRU.

Leetron MRU Test Result Summary					
		Interval 0.1 mile		Category Average	
	By Pavement	Repeatal	Accuracy	Repeatal	Accuracy
Site #	Surface Type	Mobile	HandHeld Vs Mobile		
2	Concrete	1.56%	6.23%		
8		3.63%	6.39%	2.59%	6.31%
1	Asphalt	3.68%	4.44%		
4		2.91%	4.31%		
5		3.85%	9.63%		
6		3.55%	5.73%		
7		2.04%	8.14%		
9		1.74%	2.70%	2.96%	5.83%

Table 4 Test Results Grouped by Pavement Surface Type

Environmental Conditions: External and/or ambient illumination such as sunlight and headlights from other vehicles may influence MRU measurements. The amount of influence may be limited by the ability of the MRU to adapt and overcome these conditions. The Leetron MRU is utilizes optical filters as well as an automatic compensation procedure to reduce or eliminate the influence of outside illumination.

To evaluate the Leetron MRU under varying ambient light conditions, all sites were measured under sunny, cloudy and night conditions. If the mean values or variance of the test results vary when grouped by the different ambient lighting conditions, it is likely that these inconsistencies were in part due to the changing ambient light conditions. There were no significant indications noted in the results and therefore is concluded that Leetron MRU is not sensitive to environmental conditions.

Pavement Marking Material Type: Different pavement marking (PM) materials could affect MRU measurements if the material properties affect the ability to target and measure the retroreflectivity. The test sites consisted of water based paint (site 1 and 4), thermoplastic (site 2, 3, 6, 7, 8, 9) and polyurea (site 5). In the event that PM types do affect the MRU readings, it is expected that the test results for accuracy measurement when comparing between the hand-held and MRU would be higher. Since road test results grouped by water-based paint, polyurea and thermoplastic (as shown in Table 5) do not show higher accuracy errors, this indicates that the Leetron MRU is not sensitive to these pavement marking material type.

Leetron MRU Test Result Summary					
		Interval 0.1 mile		Category Average	
		Repeatak	Accuracy	Repeatak	Accuracy
Site #	By Marking Type	Mobile	HandHeld Vs Mobile		
1	water based paint	3.68%	4.44%		
4		2.91%	4.31%		
				3.29%	4.37%
	polyurea				
5		3.63%	6.39%	3.63%	6.39%
2	Thermoplastic	1.56%	6.23%		
6		3.55%	5.73%		
8		0.00%	0.00%		
9		0.00%	0.00%	1.28%	2.99%

Table 5 Florida Results by Pavement Type

Retroreflectivity ranges: Retroreflectivity ranges were evaluated to determine the system's ability to measure R_L at categories identified as low, medium and high levels to cover typical ranges from worn markings reaching the end of their functional life to newly placed markings being evaluated for acceptance. FDOT road tests are summarized based on a low range (below 120), normal (120 to 400) and high (over 400) in Table 6. Comparing the MRU against the hand-held results indicate there is no significant difference in repeatability and accuracy results and therefore indicates that the Leetron MRU is not sensitive to variation in in-situ pavement marking R_L.

Leetron MRU Test Result Summary					
		Interval 0.1 mile		Category Average	
	Retroreflectivity	Repeatability	Accuracy	Repeatability	Accuracy
Site #	Level Category	Mobile	HandHeld Vs Mobile		
1	Low	3.68%	4.44%		
4		2.91%	4.31%		
7		2.04%	8.14%	2.88%	5.63%
2	Medium	1.56%	6.23%		
5		3.85%	9.63%		
8		3.63%	6.39%	3.01%	7.42%
	High				
6		3.55%	5.73%		
9		1.74%	2.70%	2.64%	4.22%

Table 6 Florida Result by Range

Road conditions: Specific road conditions were sought to evaluate the Leetron MRU's ability to accurately track and measure pavement marking retroreflectivity through horizontal curves and rough roadways. Although these conditions usually occur only on small portions of a typical section of measured roadway, they can have a significant impact on when averaged into the overall values used to represent each segment.

Figure 8 Target Point Difference between Typical and Leetron MRU

Horizontal Curve: The Leetron MRU uses a targeting mechanism to locate where the system will measure R_L. Figure 8 illustrates how the Leetron MRU targeting and measurement systems work together to avoid measuring a location projected along the vehicle axis beyond the curve of the road. To test the curved road conditions, three sites (1, 4, and 6) with curved sections were selected as shown on Table 7. Since there is no notable difference in repeatability and accuracy errors, this indicates that the Leetron MRU is not significantly affected by horizontal curvature.

Rough/Bumpy: Traveling on rough and bumpy roads will cause more lift and tilt (see Appendix C for detail). Leetron uses the "variable geometry" technology (see Appendix C for detail) to overcome those motion issues.

One test site (2) with a rough/bumpy road was tested on the FDOT test as shown in Table 7. Since there is no notable difference in repeatability and accuracy errors, this indicates that the Leetron MRU is not affected by rough/bumpy road conditions.

Leetron MRU Test Result Summary					
		Interval 0.1 mile		Category Average	
	By Road	Repeatat	Accuracy	Repeatat	Accuracy
Site #	Condition	Mobile	HandHeld Vs Mobile		
1	Curve	3.68%	4.44%		
4		2.91%	4.31%		
6		3.55%	5.73%	3.38%	4.83%
	Rough/Bumppy				
2		3.63%	6.39%	3.63%	6.39%
5	Normal	3.85%	9.63%		
7		2.04%	8.14%		
8		3.63%	6.39%		
9		1.74%	2.70%	2.81%	6.72%

Table 7 Test Results Grouped by Road Curve, Rough/Bumpy and Normal

Comparison to Hand-Held Retroreflectometers: Mobile accuracy analysis is based on the direct comparison between handheld retroreflectometers calibrated in accordance with ASTM E1710 - 11 and the Leetron System. The average accuracy error on the FDOT road test was 9.29% at a 0.02 mile interval and 5.919% at a 0.1 mile interval as shown in Table 3. These results indicate that the Leetron MRU has a high degree of consistent measured R_L as compared to hand-held measurements collected in accordance with the industry prescribed test method standard.

3.2 Additional Measurement Capability with TTI Evaluation

Marking Color: The color (white or yellow) of the marking potentially can influence measurement readings. This evaluation was conducted to determine if the system has the ability to repeatedly measure both colors accurately. The TTI report provided a detailed analysis of line color under the section titled “open road test”. The analysis concluded that line color does not seem to affect the accuracy of the measurement.

Marking Pattern: Marking Pattern (solid or intermittent) determines if the system has the ability to measure accurately on both solid and intermittent markings. Intermittent markings pose many challenges for MRUs due to the gaps between the markings and others are relative to the technology used. This evaluation regimen was performed to determine whether the Leetron System’s measurements are affected which would be confirmed by higher variations in repeatability for this type of marking. The TTI report provided a detailed analysis of line color under the section titled “open road test”. The analysis concluded that marking pattern does not seem to affect the accuracy of the measurement.

Measurement Unit: Both the driver side and passenger side measurement unit results were tested against each other to determine the ability for each unit to reproduce the other’s results. The TTI report provided detailed analysis under the section titled “runway test”. Both the driver’s side system and passenger’s side system were used to evaluate the same markings. The analysis of test results concluded that the variation in measurement results between both units is not statistically significant.

Lane Lateral Position: This evaluation evaluates whether the position of the van in the lane and the subsequent variation distance between the marking and tracking/measurement instruments are affected by the lateral position of the Leetron System within a lane. The TTI report provided a detailed analysis of the driving position in the section titled “open road test”. The analysis of the test result concluded that the drive position is not statistically significant.

Retro-reflective Raised Pavement Marker (RRPM): The system uses a number of criteria to separate RRPM from the data. During the TTI Runway Testing, issues relating to the ability for the Leetron System to collect accurate pavement marking R_L values were identified due to the presence of RRPMs. Leetron was able to make some software modification to solve the issue prior to the open road testing (that includes RRPMs on some of the markings tested) and the issue was resolved. 8 out of 18 test sections on the open road are with RRPMs, TTI report concluded the presence of RRPM’s did not impact the open road testing.

Special Pavement Surface Condition: As shown in Figure 9, the pavement surface color at the middle of the road has a lighter color appearance from the adjacent pavement surface. This condition may occur when an agency places a new coat of asphalt is placed without covering the edges of each lane to retain the existing pavement markings and thus save money. This results in a color variation between the old pavement (lighter) and newer pavement (darker) and subsequently caused issues for the Leetron systems measurement results during open road test. The Leetron System MRU architecture was designed for flexibility allowing engineers to solve the issue. Road test results on this special road condition from the TTI test (see test results in Appendix E section name nb 47 skip, nb 47 yellow, sb 47 skip, sb 47 yellow on page 46) indicated that the system ultimately was not adversely affected by this special road condition.

Figure 9 Special Road Condition "Silk Road"

3.3 Leetron System Functional Hightlights

To provide more detail on system operation, Appendix D listed the functional highlights in measurement efficiency, user interface, data management and data collection procedures.

4. Independent Contractor Testing

The final evaluation for the Highways for Life "Advanced Methods for Mobile Retroreflectivity Measurement on Pavement Marking" was to have an independent qualified laboratory conduct an independent evaluation of the Leetron System for comparing and validating the results of the prior testing. The Texas A&M Transportation Institute was contracted with to conduct the independent testing and provide a detailed, independent report (See Appendix E).

The independent testing included controlled lab testing, controlled field testing on an airfield runway at the TTI facility, and open road field testing. Lab and controlled field testing were done in November 2015 and the open road field testing was completed in January 2016. Leetron engineers worked to resolve the issues discussed previously that include the sun at low angles causing glare from pavement and the influence of retroreflectivity raised pavement marker (RRPM) on the measurement results.

The TTI report confirms that the Leetron System MRU is accurate and highly repeatable; and is capable of handling challenging conditions MRUs may encounter in the real-world environment.

5. Conclusion

Prior to entering the technology partnership with FHWA on this project, the Leetron MRU was a promising innovation that could benefit by working with transportation agencies. As a result of this partnership project, a new, product was built and thoroughly tested under real-world conditions to demonstrate commercially-readiness. The results of the comprehensive testing demonstrate Leetron Vision's MRU using "variable geometry" technology is capable of accurately measuring pavement marking retroreflectivty under a broad range of real-world conditions. Combined with the measurement repeatability and ease of operation, Leetron Vision is prepared to introduce the Leetron Vision MRU into the market and support transportation agencies address the challenge of rapidly collecting accurate retroreflectivity data.

Appendix

Appendix A: System Overview

Leetron's MRU has two identical systems, one on the driver's side and the other on the passenger side. Each system consists of two main units. A measurement unit consists of a laser, image device, and light path adjustment (re-aiming) devices. A tracking unit consists of cameras for location information.

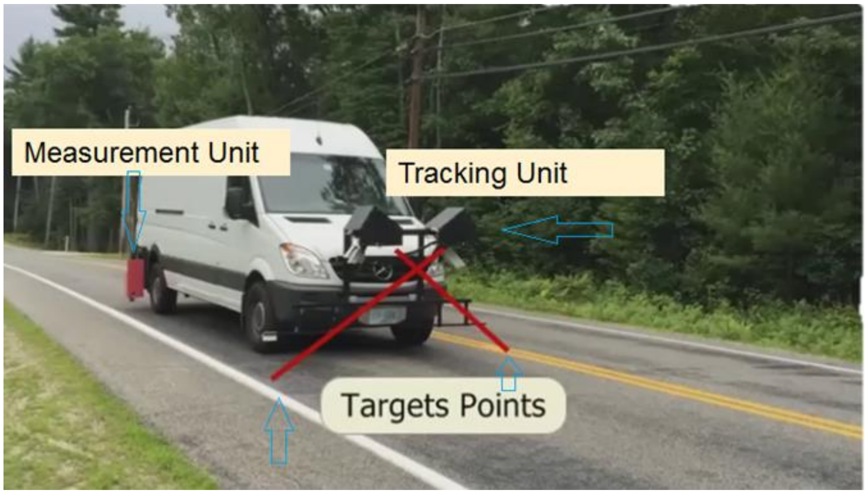

Figure 10 Leetron MRU Overview

There are three steps during measurement. First, a laser from the measurement unit points to the strip target point. Second, the tracking unit identifies the laser and target locations and applies any offsets needed to keep the measurement system aimed at the target. Third, a camera on the measurement unit reads the amount of light returning from the stripe and reports it as a retro-reflectivity value.

How well the Leetron MRU system performs depends on this critical tracking system. To keep up with sway and bounce at highway speeds, the tracking system needs to be fast. We determined that a cycle time of 80 cycles per second (80 Hz) would be fast enough to keep the laser aimed at its target. This means that the MRU acquires an image, processes that image for location information, calculates the needed movement to compensate for positional offset resulting from motions and finally repositions the aim of the light source 80 times per second. With this fast cycle time and robust movement control mechanism, the tracking system is performing significantly better than conventional MRUs.

Appendix B: Technical Challenges

Since Leetron's goal is a total solution for R_L data collection, it is critical to identify the challenges MRUs face. Our investigations into the matter found three main challenges: motion, conditions, and stability.

Motion: During data collection, bounce and tilt will cause higher variations of measurements (see Appendix C, Variable Geometry Technology Concept for more detail). Variations in road profile, wheel path, and rutting and sway from driving will have similar effects as well. Clearly, the combination of these three conditions may have tremendous impacts on R_L measurement. Based on estimates, the range of variation is from 20% to 50%. Therefore, reliable MRU systems must be able to handle motion.

Conditions: Collecting data outdoors at high speeds introduce many new conditions that impact measurement. Common conditions are:

- **Environmental:** Sunlight, darkness, temperature and humidity.
- **Road Conditions:** Pavement material, road profile, road roughness, curves and hills.
- **Stripe Type and Conditions:** Color, R_L Level, stripe type (solid/skip), RPM, rumble strips.
- **Data Collection Conditions:** Travel speed and sway from driving.

It is common for MRUs to calibrate on one condition (e.g. solid stripe on smooth pavement at mid-range retro-reflectivity on a cloudy day) and achieve accurate measurements. However, when conditions change (e.g. the sun came out), the measurements will lose accuracy unless time is taken to recalibrate. Therefore, it is important for MRU designers to consider all these conditions at the beginning of product design. It is equally important to measure performance under all conditions when evaluating MRU performance.

Stability: System stability measures the amount of variation over time – for example, a section of road measured four hours apart with all the conditions remaining the same. If the measurements remain close, the system is stable; if measurements are far apart, the system is unstable. For other measurement systems such as handheld measurement units, system stability is not important; frequent calibration will solve the problem. However, it is an issue with MRUs because it is not practical to recalibrate a system frequently (e.g. hourly).

To build a stable system, Leetron invested much time and work to study the sources of instability and develop solutions to minimize these effects. Key features of the stability system are:

- Selected components with low sensitivity to temperature.
- Sealing of the measurement unit to prevent external influence.
- The measurement unit is environmentally controlled with temperature variation controlled to +/- 1 degree.

One indication of system stability of Leetron's MRU is that the calibration values remain the same for months.

Appendix C: Variable Geometry Technology Concept

Variable Geometry Technology, developed by Leetron, is a new method of measuring retro-reflectivity in mobile applications. The main objective is to remove the technical limitations on mobile data collection.

Measurement Principle

The basic principle for MRUs is the same. First, light from a measurement unit is pointed at the target (stripe); second, glass beads from the stripe bounce the light back to the measurement unit; third, a light sensor from the measurement unit reads the amount of light bounced back.

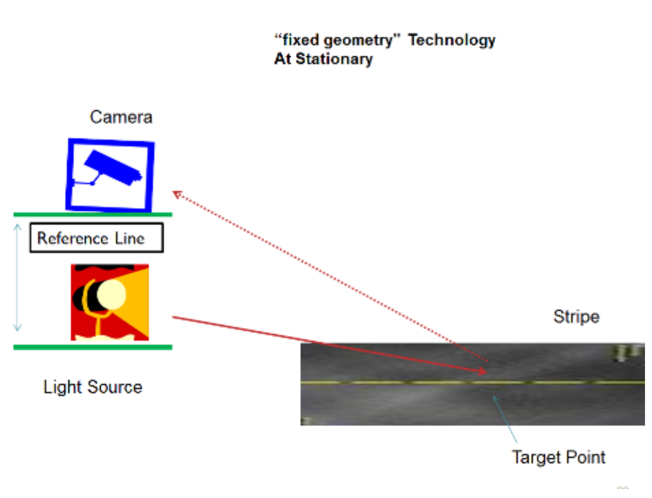

Figure 11 "Fixed geometry" Technology at Stationary

"Fixed Geometry" technology

For "fixed geometry" technology, motion will cause variation in measurement. Figure 11 shows the main measurement components under stationary conditions. As the system travels, there will be bounce, as shown in Figure 12. The sequence of events is as follows:

1. The light source and camera move up as the unit bounces up.
2. The path of the light source will move farther from the original target point.
3. The path of the camera will move up as well. However, it does not move at the same rate as the light source, due to the angle's variation.

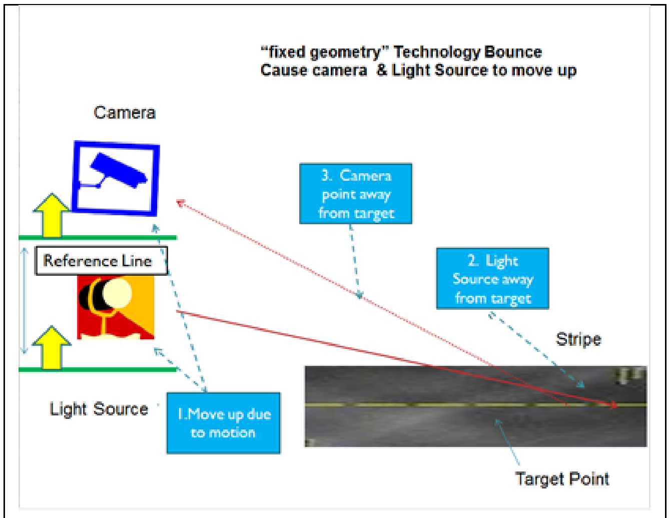

Figure 12 "Fixed Geometry" Technology with Bounce

With the light source and camera pointed away from the target point, the MRU will generate variation in measurements. The amount of variation is based on the bounce, tilt and road profile. The range of variation can extend from 20% to 50%. To compensate for this variation, existing MRUs use averaging, filtering, or other methods to minimize the effects. While there is no study that has been done on the effectiveness of those methods, it is known that those methods are inconsistent.

“Variable Geometry” technology

The Leetron design team understood that in order to build a solid system, a solution was needed to handle the variations introduced by motion. Variability of the sensor position relative to the target is unavoidable in practical driving conditions, being caused by the aforementioned factors. All efforts to control and minimize motion will, at best, create only a marginal improvement in variance. Even if the movement is controlled, the road profile variation will still need to be addressed. The solution developed by Leetron is “Variable Geometry Technology”. This innovation points the laser at the center of pavement marking and continually adjusts the aim to keep it on target. By keeping the laser a consistent distance from the road surface, the variables and their effects on the measurements are minimized. As a result, the retro-reflectivity measurements are independent of the motion and road profile variation.

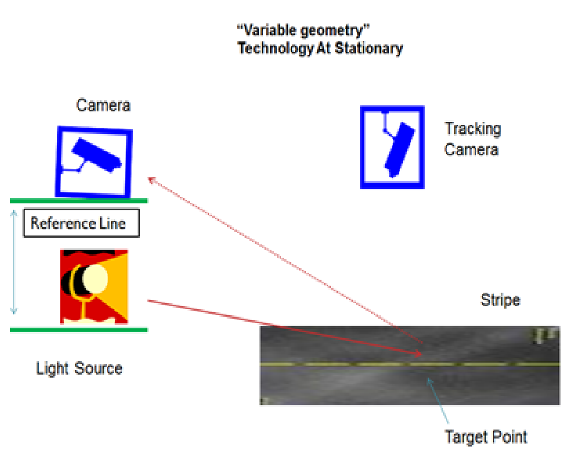

Figure 13 “Variable Geometry” Technology at stationary

As illustrated in Figure 13, a tracking camera is added to the system; also, the light source and camera are adjustable. As the system travels, there will be bounce, as shown in Figure 14. The sequence of events is as follows:

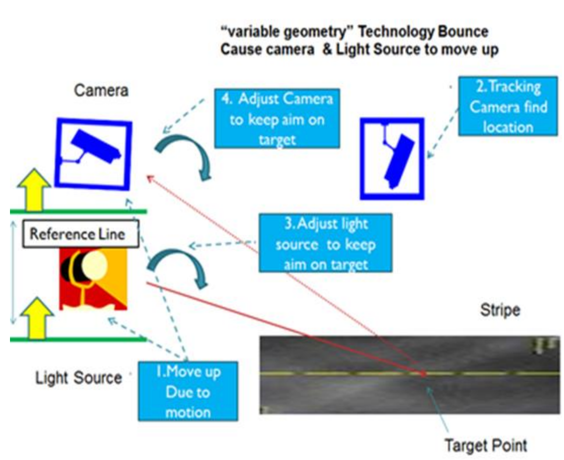

Figure 14 “Variable Geometry” Technology with Bounce

1. Light source and camera move up as the unit bounces up.
2. The tracking camera detects the unit moving up.
3. The tracking system will adjust the light source to keep it aimed at the target.
4. The tracking system will adjust the camera to keep it aimed at the target as well.

With a high tracking rate, the tracking system is able to keep both the light source and camera pointed at the target on stripe regardless of bounce, tilt, or road profile variations.

Appendix D: Leetron System functional Highlight

Measurement Efficiency

The measurement efficiency describes the amount of effort used in collecting data. The Leetron MRU was designed with measurement efficiency in mind and explored opportunities to maximize data collection efficiency in measurement rate, calibration and measurement procedures. Key factors include:

Measurement Rate: The Leetron MRU was designed to drive at the center of the lane, which allows a measurement unit mounted on the driver and passenger side of the vehicle and measures two lines simultaneously. Measuring two lines at the same time allows for more efficient data collection, reduced driving mileage and increase productivity. For instance, in order to measure both center and edge line longitudinal markings along a 10-mile section of a two-lane roadway, using a MRU mounted to only one side of a vehicle, a MRU will mount the unit on the driver's side and calibrate the system, travel 10 miles to measure the center line, turn around and travel 10 miles back to the original location. Then the unit would be moved to the passenger side, recalibrated, and travel another 10 miles to measure the passenger side. The Leetron MRU will perform calibration automatically and drive 10 miles to measure the driver and the passenger side simultaneously. As a result, the Leetron will travel only 10 miles instead of 30 to measure the same distance and also will eliminate the time-consuming remounting and recalibration procedures.

Auto Calibration: The Leetron MRU was designed with an automatic calibration procedure that minimizes downtime and maximizes data collection. With the calibration targets permanently mounted at the front of the vehicle, the calibration can be performed while stationary or in motion. The procedure will be performed before and after data collection on a route. The calibration results are stored in the database for future analysis.

User Interface

The user interface is designed for an operator to control the two measuring systems and to monitor the results. The main features are:

Voice Communication: The user interface uses voice commands or a touchscreen to operate the system. It communicates the system's status and measurement results to the operator through voice as well as by a graphical display. This creates fewer distractions for the driver and thus a safer operating environment.

Real-time Result: Measurement results are communicated to the operator through voice and graphical displays with past results available for comparison. This allows the operator to better monitor the measurement results.

Mobile Broadband: The Leetron MRU uses mobile broadband to allow remote communication during data collection. This capability allows collected data to transfer to an office directly and thereby also allows full control of the data coordination and monitoring and provides real time interaction with the operator to allow engineers to debug issues remotely to minimize downtime.

Auto Route Start/End: Typically, the operator of a conventional MRU needs to slow down to look for starting mile posts to manually start the data collection and must do the same at the end of a section. This practice is not safe, since the operator needs to slow down to find the particular start/end locations. This also takes time and the starting and ending locations are not consistent. Leetron's MRU uses pre-entered GPS locations to automate this process. It eliminates a task the operator would otherwise have to perform and allows the operator to concentrate on driving.

Real Time Graphical Display: In addition to communicating the current section measurement value through voice and display, the Leetron MRU provides a real-time graphical display with current and past results, as shown in Figure 15. For example, the light green line represents the route value collected from last year and the red line presents the result from the current measurements. The operator is able to view the difference in measurement between current and past results in real time. This feature allows the operator to react to any abnormal conditions immediately.

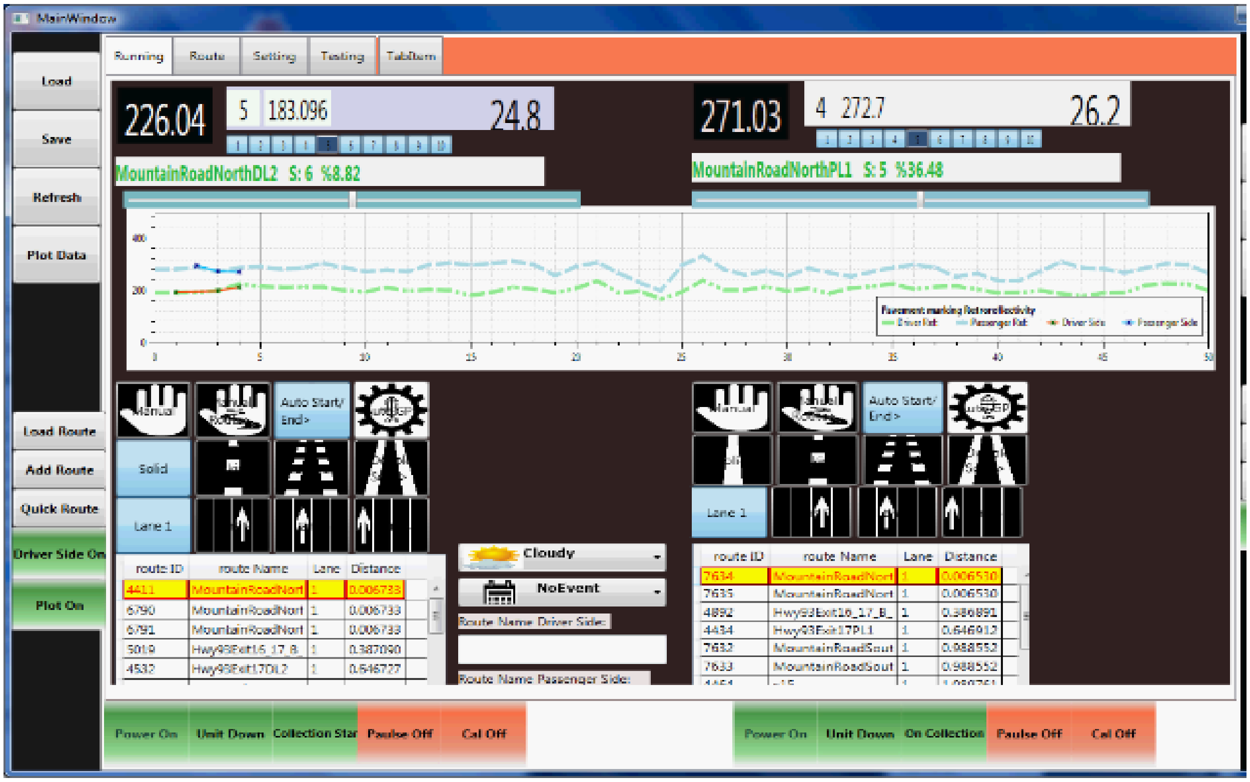

Figure 15 User Interface Screen with real-time result display

Data Management

The data management system is a central communication point between the customer and the MRU. The objective is to streamline the process of gathering route information, communicate with the MRU, analyze collected data and transfer the results to the customer. It allows the user to spend more time on collecting data and less time on managing data. The five main steps are listed on Figure 6 and discussed in more details as follows:

Step 1: Data Entry: The information relative to routes is entered in this step. The goal is to minimize the data entry during data collection by entering the data off-line. Typical route information includes route name, starts /end GPS locations, lane number and stripe type.

Step 2: Export data to the MRU: Routes selected to collect data are exported to the MRU system through mobile broadband or USB memory stick.

Step 3: Return collected data: Collected routes are sent back to the data management system from the MRU through mobile broadband or USB memory stick.

Step 4: View and Analyze Results: The last step before sending the data to the customer is to review the data integrity to detect missing or inaccurate data. Tools provided to accomplish this task are graphic representation of data as shown in Figure 16; comparison to past data (e.g. last year); and map location of the route as shown in Figure 17. Also, the system provides functions to build a list of finished and outstanding routes to assist on route scheduling.

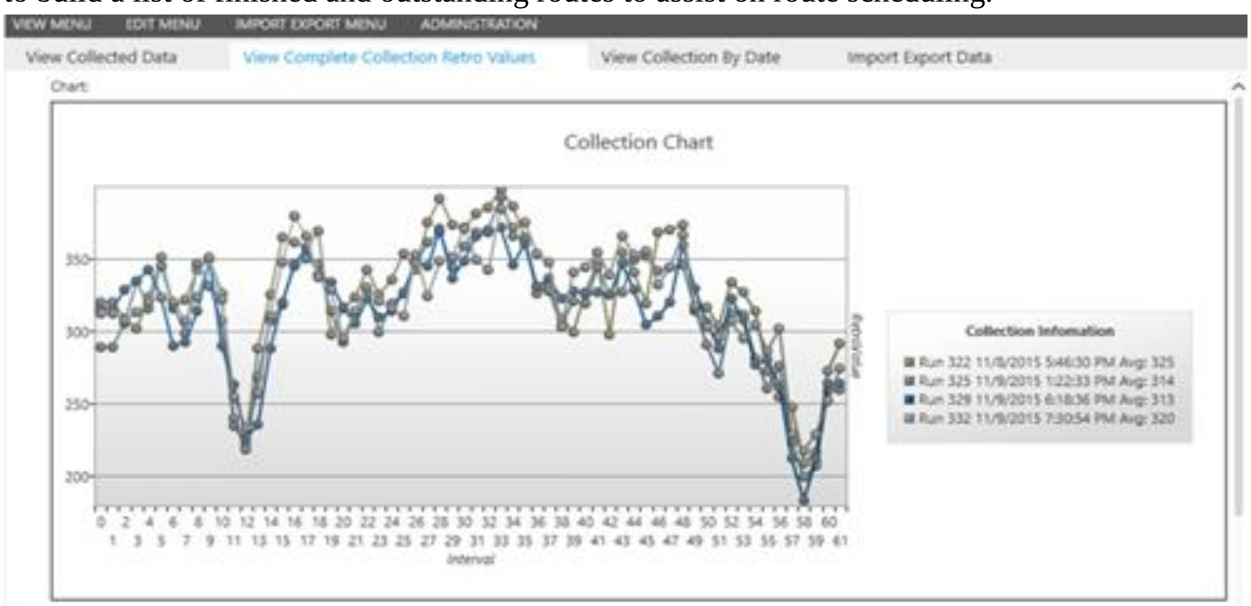

Figure 16 Route Result Graphic

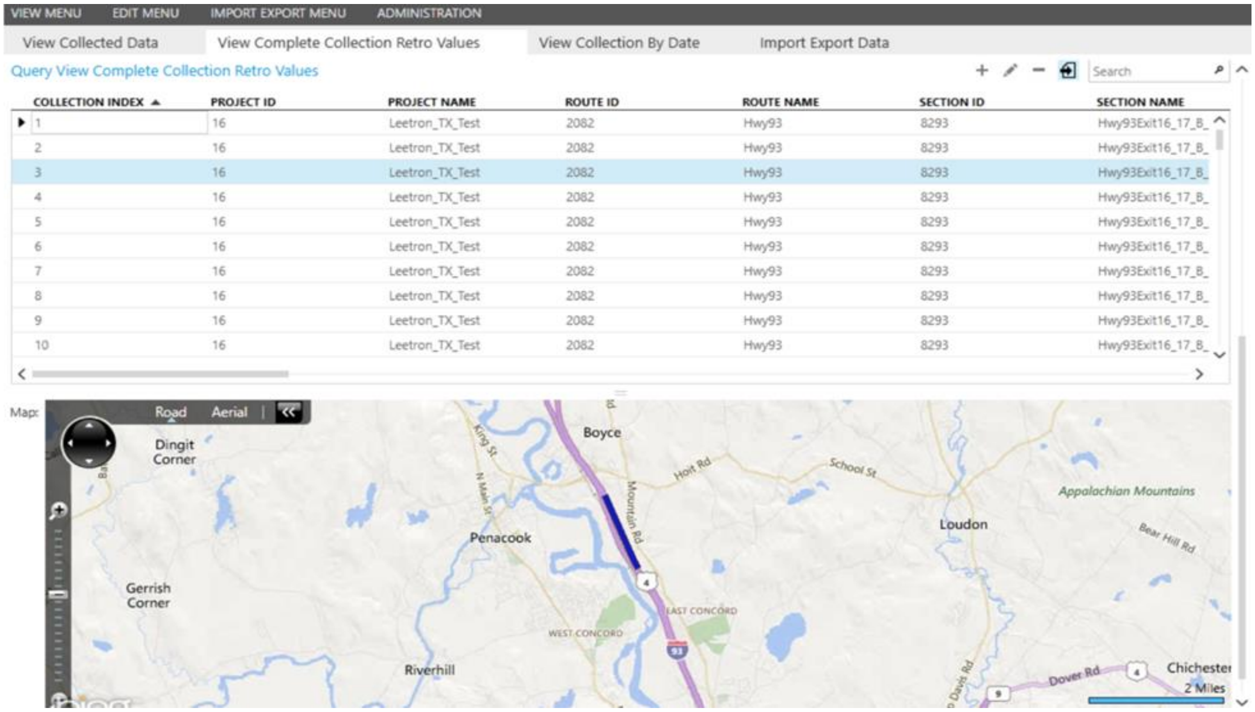

Figure 17 Route in Map

Step 5: Report: The final step is to generate a custom report in a format based on the customer's specifications as shown in Figure 18. Normally the customer uses the report to import the collected data into their system.

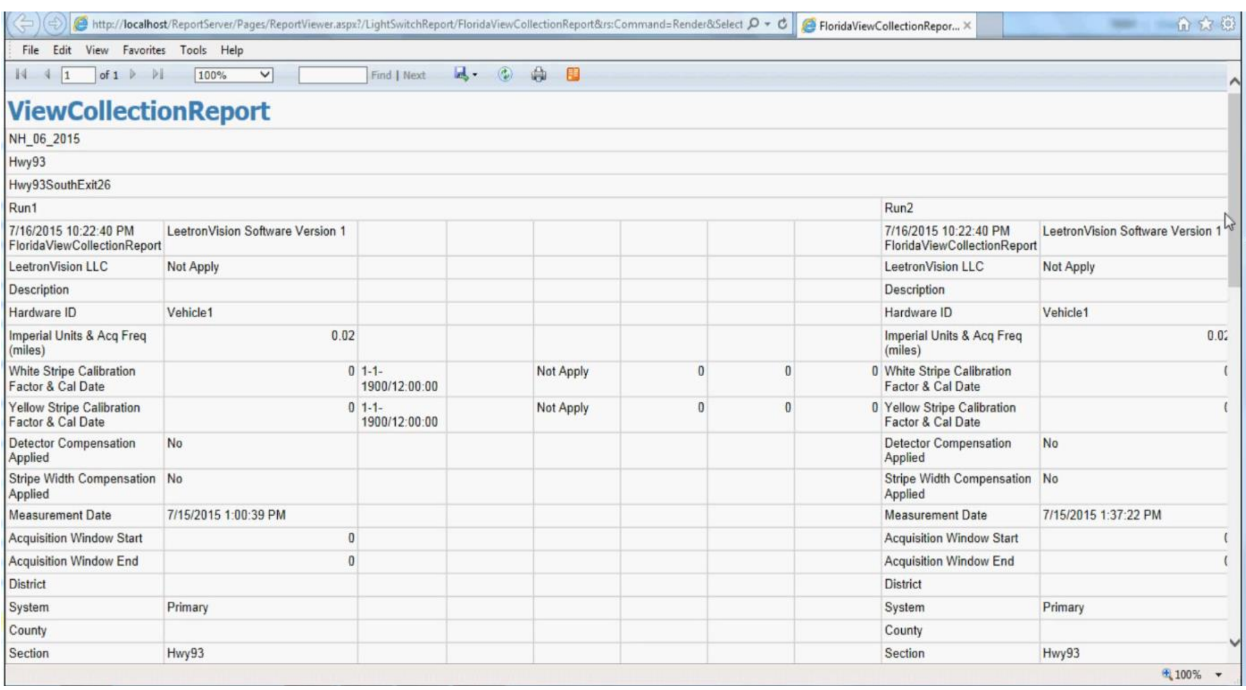

Figure 18 Route Report

Data Collection Procedures

Description of mechanisms for data collection:

The steps in data collection for Leetron MRU are as follows:

1. Enter project and routes information to database.
2. Route information from database is exported to data collection computers through network or by USB memory stick.
3. On the van, the operator starts the system by:
    - turning the system power on;
    - clearing the windows;
    - turning on the environmental controls; and
    - running the automatic calibration procedure.
4. The Leetron system uses GPS to determine the distance to closest section and the operator drives to the location. As the van approaches a section, the system communicates its status through voice and screen messages to the operator. Note: for multiple lanes, the operator will select a lane number by voice command. The auto-calibration procedure will be launched about 300 meters before the route start location is reached.
5. When the van reaches the starting location, the measurement system will start measuring automatically.
6. During data collection, the operator's tasks are to:
    - pause collection on missing stripe areas;
    - enter special events;
    - enter weather conditions; and
    - monitor real-time data collection results.
7. At the end of the route, the system will stop data collection based on GPS location, then launch a calibration procedure and store data collected for the section. A graphical representation of the collected section will be displayed for the operator to review and inspect.
8. The operator drives to the next route and repeats the procedure from step 4 through 7.
9. At the end of the day, all collected data are delivered to the office database system.
10. Reports then will be generated and sent to the customer.

Maintenance:

One maintenance task during data collection is window cleaning. The frequency is based on the road and weather conditions and the calibration value. Typical frequency is twice a day.

Appendix E: Independent Contractor Test By TTI

Please Click TTI Report.

Reference

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Leetron Vision Retroreflectivity Evaluation

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Report Prepared for Leetron Vision

June 2016

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CHAPTER 1:
WORK PLAN

The objective of this project was for the Texas A&M Transportation Institute (TTI) to evaluate the mobile pavement marking retroreflectometer that was being tested by Leetron Vision. The performance measure under evaluation was the measured retroreflectivity, R_L, (mcd/m^2/lux) of a variety of pavement markings under a variety of conditions. The details of the data collection are described in this chapter.

DATA COLLECTION LOCATIONS

All data were collected at or near TTI facilities in Bryan and College Station Texas. Three areas were used for data collection. The first area was inside a large laboratory building where static measurements took place. This building on the Texas A&M University Riverside Campus allowed data to be collected on pavement marking samples in a controlled environment. The second location for data collection was on the runways at the Texas A&M University Riverside Campus. The runways have numerous markings of various retroreflectivity levels and configurations. The runways allowed the researchers to test in a closed course environment where other vehicles would not impact the safety of the data collection team. The third location where data collection took place was on open roads around the Bryan, College Station area. Roadways were selected based on their marking characteristics, road surface type, traffic volume, factors that could influence data collection, and proximity to the other data collection areas.

DATA COLLECTION

Data collection took place in November, 2015 and January, 2016. The initial data collection period consisted of the lab and closed course testing at the TTI Riverside facility. Open road testing was started during this data collection period but was canceled by the operator due to concerns with data quality during the initial test conditions. The second data collection period was used to conduct the open road testing. The Leetron Vision marking assessment system was operated by Terry Lee of Leetron Vision. TTI did not operate the equipment. TTI directed the operator where to collect data, how to name data files, and marked the start and end locations for the data on the open road testing.

Variables Evaluated

The main interest of the testing was to determine how well the Leetron Vision system evaluates the retroreflectivity of pavement markings. There are numerous factors that can impact the ability of a mobile retroreflectometer to repeatedly collect accurate retroreflectivity readings. The researchers developed a list of factors and then developed the testing plan to evaluate the influence of these factors. The variables included in the testing are listed and described below.

- **Retroreflectivity Level:** Evaluate marking across a range of retroreflectivity levels to test the linearity of the detector across a broad range and to test the upper and lower threshold for which the system can accurately collect data.
- **Marking Color:** Evaluate the two main marking colors to make sure the system is not biased by color.
- **Line Type:** Evaluate solid and skip lines to make sure the system can accurately factor out the areas between skip markings.
- **Road Surface:** Evaluate markings on asphalt (dark and faded), concrete, and chip seal surfaces to test the impact of varying the background retroreflectivity and contrast levels.
- **Data Collection Speed:** Evaluate the same marking section at varying speeds to see if the system will produce the same results.
- **Drive Position Sensitivity:** Evaluate the same markings at different positions within the measurement window (width of measurement field for the system) to test the influence of measurements away from the central position.
- **Retroreflective Raised Pavement Marker (RRPM) Impact:** Evaluate similar markings with and without RRPMs to determine if they are appropriately factored out.
- **Ambient Light:** Evaluate markings during the day, at night, and at times when the sun is at low angles causing glare.

- Other factors considered were acquire frequency length, software settings, and temperature sensitivity.

Data Collection Procedures

The data collection at each location required different data collection procedures. The Leetron Vision system consisted of a retroreflectometer mounted on both sides of a van allowing data to be collected on one or two markings during a single pass. All handheld measurements were made with a properly calibrated handheld retroreflectometer. The general methodology at each location is described below.

Lab Testing

The lab testing consisted of evaluating 19 pavement marking samples in various setups. The pavement marking samples were 4 feet long and on thin substrate materials. A description of each pavement marking sample is provided in Appendix A. An initial static test was performed on 19 of the samples. Substrate panels that were the same thickness of the pavement marking samples were placed under each wheel of the test vehicle to ensure the proper geometry was maintained during testing. During each test an individual sample was centered in the center of the measurement area. This was accomplished by using the video output from the system. Once positioned, several measurements were taken and then the next sample was put in place and tested. After the center position was evaluated the samples were shifted to the outer edges of the measurement window, centered and then evaluated. A subset of 5 of the samples were evaluated during the position testing. The markings were positioned approximately 50 centimeters further away from the vehicle than the center position and 40 centimeters closer to the vehicle than the center position. After the readings on the driver side unit were complete the same measurements were taken on the passenger side unit. On the following day the subset of 5 samples and 3 other samples were reevaluated in the center position for the driver side system.

The samples were evaluated with a handheld retroreflectometer 24 times in the center portion of the marking. The measurements were made across the width of the marking and along the middle portion lengthwise. The goal was to get a representative value for the markings where they were evaluated with the Leetron Vision system for comparison purposes.

Runway Testing

The runway testing consisted of evaluating 14 different pavement markings under various conditions. The runway pavement markings were approximately 0.35 miles in length and consisted of both white and yellow, solid and skip line pavement markings. The markings evaluated during the runway testing were typical markings found on roadways. These markings consisted of paint, epoxy, and thermoplastic binders with standard big and small beads. A description of each marking is provided in Table 8. Sections evaluated as NB or SB (northbound or southbound) are the same marking just evaluated in opposite directions. Images of each runway test marking are provided in Appendix B.

Table 8. Runway Marking Information.

Line Name	Line Type	Marking Material	Color	Bead Type
Line 1	Solid	Epoxy	White	Big and Small
Line 2	Skip	Epoxy	Yellow	Big and Small
Line 3	Solid	Epoxy	White	Big and Small
Line 8	Skip	Thermoplastic	White	Small
Line 10	Solid	Paint	Yellow	Small
Line 14	Solid	Thermoplastic	Yellow	Small
Line 15	Skip	Paint	Yellow	Small
Line 16	Skip	Paint	White	Small
Line 17	Solid	Thermoplastic	Yellow	Small
Line 18	Skip	Epoxy	White	Big and Small
Line 24	Solid	Paint	White	Small
Line 29	Solid	Thermoplastic	Yellow	Small
Line 39	Skip	Epoxy	Yellow	Big and Small
Line 40	Solid	Epoxy	White	Big and Small

During each test of an individual marking a minimum of two separate trials were conducted. The majority (11) of the markings were evaluated in a single direction, 3 of the markings were evaluated in both direction. All yellow markings were evaluated using only the driver side system. White solid markings were evaluated using only the passenger side system. Two of the white skip markings were evaluated using both the driver and passenger side system.

The testing on the runway was conducted on three separate days with some markings evaluated each day to further test repeatability. Runway testing was conducted during the day for all markings and at night for most of the markings. The runway testing was also used to test the impact of RRPMs. RRPMs were installed on some of the markings and masked over during a portion of the testing, and exposed during other tests. The runway testing was also used to test the impact of drive position on the accuracy of the system. Repeat runs were made on the same markings with the vehicle position in the center of the lane, shifted to the right in the lane, and shifted left in the lane.

One anticipated test area was not able to be used during the testing because the Leetron Vision system was unable to accurately track and evaluate the marking. This test section had very low daytime contrast which made tracking the marking difficult, see image in Appendix B. Without the ability to track the marking the data gathered was effectively useless. This was the only test area where line tracking was a significant problem, but could be a situation seen in the field (this low level of contrast does not occur often) which may be a limitation of the system.

The markings on the runway were evaluated at regular intervals with a handheld retroreflectometer along the entire length of the marking. The measurement interval was approximately 15 feet on solid lines and two measurements per skip on skip lines. The goal was to get a representative value for the retroreflectivity average of the marking and for the retroreflectivity trend along the length of the marking for comparison to the Leetron Vision system mobile data.

Open Road Testing

The open road testing consisted of evaluating 18 different pavement markings under various conditions. The open road test area pavement markings varied in length from approximately 0.1 to 1.0 miles long and consisted of both white and yellow, solid and skip line pavement markings. The road surface types consisted of faded asphalt, dark asphalt, chip seal, and Portland cement concrete (PCC). The markings were tested in three conditions; daytime in fully cloudy conditions, daytime in full sun conditions, and at night. During each test of an individual marking one to three separate trials were conducted for each condition. A description of each marking test area is provided in **Table 9**. Images of each open road test area are provided in Appendix C.

The majority of the sections evaluated were typical road surfaces with typical pavement markings. Several sections offered unique situations to test the capabilities of the mobile retroreflectometer. The two nb 47 and two sb 47 sections were a faded asphalt road surface with a seal coat covering the travel lane between the markings. This setup complicates mobile evaluations because of the numerous contrasting surfaces. The campus skip section was typical PCC but had a unique marking. The marking was standard paint and beads but half the length of each skip had high retroreflectivity, and the other half had low retroreflectivity.

Table 9. Open Road Test Marking Information.

Section Name	Line Type	Road Surface	Marking Material	Color	Bead Type
47 FR edge	solid	Faded Asphalt	Thermoplastic	White	Big and Small
47 FR skip	skip	Faded Asphalt	Thermoplastic	White	Big and Small
47 FR yellow	solid	Faded Asphalt	Thermoplastic	Yellow	Big and Small
campus skip	skip	PCC	Paint	white	Small
jones edge	solid	Chip Seal	Paint	white	Small
jones yellow	solid	Dark Asphalt	Paint	yellow	Small
leo edge	solid	Chip Seal	Thermoplastic	white	Small
leo yellow	skip	Chip Seal	Thermoplastic	yellow	Small
nb 47 skip	skip	Chip Seal/ Faded Asphalt	Thermoplastic	white	Small
nb 47 yellow	solid	Chip Seal/ Faded Asphalt	Thermoplastic	yellow	Small
sb 47 skip	skip	Chip Seal/ Faded Asphalt	Thermoplastic	white	Small
sb 47 yellow	solid	Chip Seal/ Faded Asphalt	Thermoplastic	yellow	Small
snook edge	solid	Chip Seal	Thermoplastic	white	Small
snook skip	skip	Chip Seal	Thermoplastic	white	Small
univ eb skip	skip	Dark Asphalt	Thermoplastic	white	Small
univ eb yellow	solid	Dark Asphalt	Thermoplastic	yellow	Small
univ wb skip	skip	Dark Asphalt	Thermoplastic	white	Small
univ wb yellow	solid	Dark Asphalt	Thermoplastic	yellow	Small

Just prior to the start of the open road testing the Leetron Vision equipment experienced mechanical issues with the passenger side system. The issue was found by the operator while conducting some pretest experiments. The operator had collected some data on some of the markings that were to be included in the testing. This data has been added to the official data set and is included in this report. All data collected during the official testing was collected while using only the driver's side system.

The open road testing was conducted on two separate days. The first day of testing evaluated each of the pavement marking test sections in fully cloudy conditions. The 1 mile test section was also used to evaluate the impact of speed and lane position on the data collection. Two runs each at 40, 50, 60, and 70 mph were recorded on the same test section. Two runs each with the evaluation in the center position, left in lane position, and right in lane position were also recorded on the test section. At the end of the first day of testing 11 of the test sections were evaluated at night. The second day of testing evaluated each marking in full sun conditions with the sun high in the sky. Once the sun was low on the horizon 4 of the sections were evaluated to test the impact of a low sun angle on the measurements. The sun was setting almost directly down the evaluation roadway. Measurements toward and away from the sun were recorded on these marking sections. With the sun at a low angle a noticeable glare was present when heading toward the sun.

Most markings on the open road test area were evaluated at regular intervals with a handheld retroreflectometer along the entire length of the marking. The measurement interval was approximately 40 feet. The goal was to get a representative value for the retroreflectivity average of the marking and for the retroreflectivity trend along the length of the marking for comparison to the Leetron Vision mobile data. All but 2 sections on the open road testing were evaluated for the entire length with a TTI operated and calibrated mobile retroreflectometer. The mobile evaluation allows the researchers to use roads that were not conducive to taking handheld measurements. The mobile retroreflectivity data collection also allowed the researchers to gather additional retroreflectivity data that may better represent the data that should be collected with the Leetron Vision system. While the goal is to compare the mobile system to the handheld retroreflectometer to check accuracy, site conditions such as road undulations or wheel path rutting may unfairly influence the mobile retroreflectivity data. A comparison between both mobile systems and the handheld retroreflectometer will provide better test results.

A small amount of rain (<0.25 inches) fell over the test areas between the night testing and the sunny condition testing. Handheld readings were taken the day before the Leetron Vision mobile test. TTI comparison mobile readings were taken the day before and three days after the Leetron Vision mobile test. The two sets of TTI comparison mobile readings were evaluated for each test section and found less than 10 percent difference for each section (the change in retroreflectivity was not a consistent increase or decrease) other than the University Drive sections (univ eb skip, univ wb skip). The University Drive skip line sections both showed approximately 20 percent reduction in retroreflectivity after the rain event. This change will be discussed during the analysis.

CHAPTER 2: TESTING RESULTS

This chapter describes the results of the data collection effort. All mobile pavement marking retroreflectivity data was submitted to TTI by Leetron Vision. TTI analyzed each data collection file, and each individual test run. Where necessary data were trimmed to best match the specific locations of the comparison retroreflectivity data. Statistical analysis was performed for many factors across the various sets of data. If statistically significant results were found, the practical significance of the difference was also discussed. For the purposes of the discussion in this report a practical difference was a difference of greater than 15 percent. If the mean difference was less than 15 percent then the difference was not considered practically significant. The results of the lab, runway, and open road testing are described in separate sections.

LAB TESTING RESULTS

The objective of the lab testing analysis is to compare the Leetron Vision mobile system (passenger side and driver side) data to handheld retroreflectivity data. Table 3 contains the variables considered in the analysis. In this study, the factor of main interest is Measurement Type. Driver 1 and Passenger 1 are the initial mobile measurements on each side of the vehicle for the mobile system. Driver 2 is the second set of mobile measurements on the driver's side. The Handheld data is the TTI collected measurements using a handheld retroreflectometer. Other factors of interest are Color and Position. Researchers are interested in testing whether the mean retroreflectivity is affected by Measurement Type, Color, or Position.

Table 3. Variables used in the analysis of initial static data

Class	Variable	Values in the data
Response Variable	Retro Value (mcd/m^2/lux)	41.9-1894
Factors	Measurement Type	Driver 1, Driver 2, Passenger 1, Handheld
	Color	White, Yellow
	Position	Center, Left, Right
Block	Marking Sample (Line Number)	1, 2, …, 19

Table 4 shows the sample mean retroreflectivity values by four different measurement types considered in this analysis for each of 19 pavement marking samples. Table 5 presents the sample mean retroreflectivity values by different positions as well as different measurement types for each of 19 samples.

Table 4. Mean retroreflectivity values obtained by different measurement types for each sample (Initial static data)

Marking Sample	Color	Driver 1	Driver 2	Passenger 1	Handheld
1	White	106.4	95.5	106.1	106.8
2	White	215.0	213.7	229.2	236.3
3	White	306.5	279.3	303.5	315.2
4	White	980.9	940.2	812.4	834.5
5	White	128.6		153.9	167.9
6	White	274.8	258.3	270.0	259.5
7	White	351.8		319.1	311.1
8	White	593.5		555.6	572.3
9	White	357.5		301.3	348.5
10	White	783.4	673.1	654.2	643.2
11	White	660.4	630.4	549.1	649.5
12	White	443.0		428.5	430.2
13	White	1165.8	1148.1	896.0	1194.4
14	White	1527.6		1187.3	1657.2
15	Yellow	42.4		64.9	75.3
16	Yellow	302.5		267.1	344.0
17	Yellow	313.0		274.6	325.5
18	Yellow	324.3		329.3	311.3
19	Yellow	574.5		526.4	564.0

Table 5. Mean retroreflectivity values obtained by different measurement types and positions for each sample (Initial static data)

Marking Sample	Color	Driver 1			Driver 2	Passenger 1			Handheld
		Center	Left	Right	Center	Center	Left	Right	
1	White	103.4	105.5	110.4	95.5	96.9	105.7	115.5	106.8
2	White	227.3	199.1	218.5	213.7	217.8	232.4	237.4	236.3
3	White	308.3	283.9	327.1	279.3	291.8	295.6	323.2	315.2
4	White	980.9			940.2	812.4			834.5
5	White	128.6				153.9			167.9
6	White	285.4	253.6	285.4	258.3	261.7	266.8	281.5	259.5
7	White	351.8				319.1			311.1
8	White	593.5				555.6			572.3
9	White	357.5				301.3			348.5
10	White	777.7	789.1		673.1	641.9	670.3	650.4	643.2
11	White	660.4			630.4	549.1			649.5
12	White	443.0				428.5			430.2
13	White	1165.8			1148.1	896.0			1194.4
14	White	1527.6				1187.3			1657.2
15	Yellow	42.4				64.9			75.3

16	Yellow	302.5				267.1			344.0
17	Yellow	313.0				274.6			325.5
18	Yellow	324.3				329.3			311.3
19	Yellow	574.5				526.4			564.0

The 19 pavement marking samples play a role of a blocking variable in the analysis. Note that for Position, left and right are available only for Driver 1 and Passenger 1 while center was available across all 4 levels of Measurement Type. Most (88%) of the retro values for this dataset were obtained at the center position. To isolate the effect of Measurement Type while controlling for the effect of Position, researchers first extracted the retro values measured at the center only. Figure 1 presents box plots with whiskers of the retro values for each measurement type (P = passenger 1, d1 = driver 1, d2 = driver 2, H = handheld) by Marking Sample (Line Number). It can be observed that in general the retro values measured by different methods are close to each other except for a few cases (e.g., Line Numbers 10, 11, 13, 14).

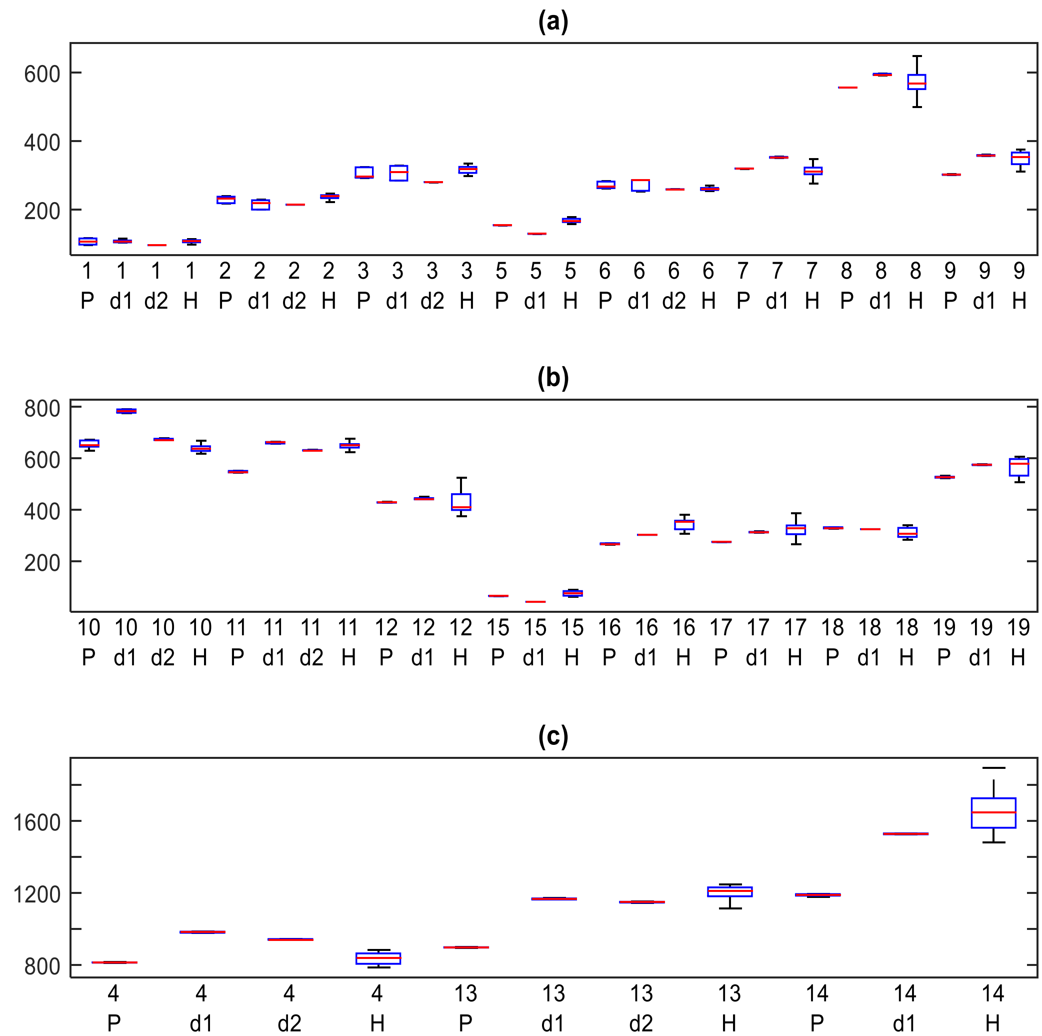


Figure 1. Plot of Mobile Retro Values By Line Number and Measurement Type for (a) Line Numbers 1, 2, 3, 5, 6, 7, 8, 9, (b) Line Numbers 10, 11, 12, 15, 16, 17, 18, 19, and (c) 4, 13, 14

To assess the impacts of Measurement Type and Color on retroreflectivity, researchers applied the ANOVA model having Measurement Type and Color as fixed effects and Marking Sample as a random effect (nested within Color) to the dataset consisting of 686 measurements of retro values measured at the center position. Table 6 contains the analysis output obtained by the restricted maximum likelihood (REML) method implemented in the JMP statistical package (SAS product). It can be observed from Table 6 (see Fixed Effects Tests) that the effect of Measurement Type is statistically significant at $\alpha=0.05$ while the effect of Color in the model is not statistically significant. Table 6 also presents the predicted values (Least Squares Means) for retro values for each level of Measurement Type and Color along with their standard errors. When there are multiple factors in the model, it is not fair to make comparisons between raw cell means in data because raw cell means do not compensate for other factors in the model. The least squares means are the predicted values of the response (retro values) for each level of a factor that have been adjusted for the other factors in the model. Note that the Least Squares Means denotes the least squares means for retro values. To determine which of those factor levels are significantly different, a multiple comparison test procedure (e.g., Tukey's HSD or Fisher's LSD) was also carried out. For Measurement Type, the Tukey's HSD test was employed and the result given under **LSMeans Differences Tukey HSD** of Table 6 shows that the predicted retro values of Driver 1, handheld, and Driver 2 (while they are not statistically different from one another) are statistically significantly different from that of Passenger 1. This result indicates that the driver side system was collecting data that was statistically the same as the handheld retroreflectometer, whereas the passenger side system was not. From a practical difference standpoint the passenger side system resulted in data that was approximately 14 percent different from the handheld retroreflectometer.

Table 6. JMP output for the analysis of mobile retro values to assess the impact of measurement type and color based only on the center data

Response Mobile Retro Value
Summary of Fit

RSquare	0.978801
RSquare Adj	0.978676
Root Mean Square Error	54.4527
Mean of Response	486.486
Observations (or Sum Wgts)	686

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Measurement Type	3	3	664	36.2606	<.0001*
Color	1	1	17	1.3634	0.2591

Effect Details
Measurement Type
Least Squares Means Table

Level	Least Sq Mean	Std Error
Driver 1	444.86553	96.780503

Level	Least Sq Mean	Std Error
Driver 2	433.95416	97.049685
Handheld	438.47266	96.652763
Passenger 1	376.84223	96.780503

LSMeans Differences Tukey HSD

α=0.050

Level			Least Sq Mean
Driver 1	A		444.86553
Handheld	A		438.47266
Driver 2	A		433.95416
Passenger 1		B	376.84223

Levels not connected by same letter are significantly different.

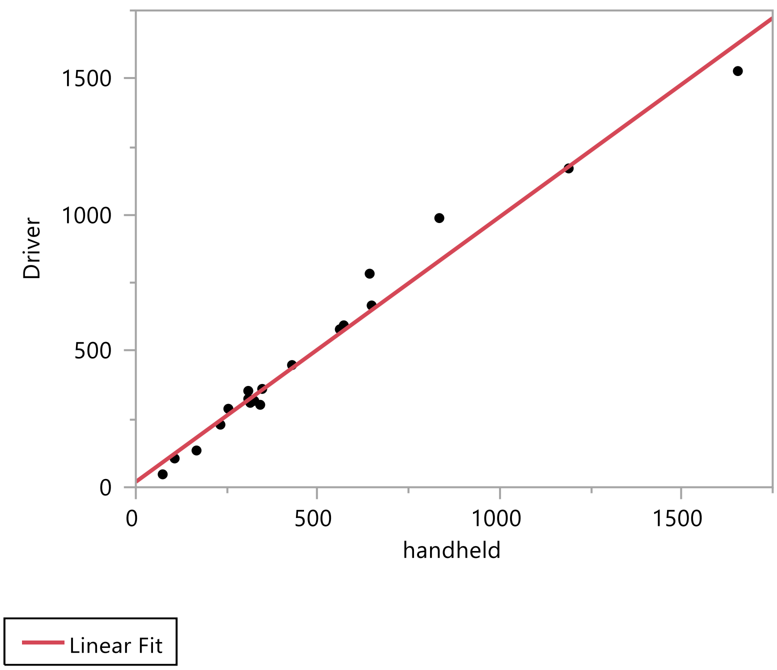
Color

Least Squares Means Table

Level	Least Sq Mean	Std Error
White	536.37839	99.17329
Yellow	310.68890	165.93674

Researchers also compared the mean retro values computed for each Marking Sample and Measurement Type. In this way, the mobile data and handheld data can be paired for each Marking Sample. Tables 7 and 8 contain the scatter plots of the mean retro values for each pair of (handheld, Driver 1C) and (handheld, Passenger 1C) where ‘C’ stands for ‘measurements at center’, respectively, along with the summary of the fit results. Table 7 shows that the points fall close to the least squares line with the slope (0.97) that is close to 1, and the intercept is also not statistically different from 0, which suggests that mean retro values from Driver 1C and handheld match fairly well. On the other hand, the slope (0.72) of the least squares line of Table 8 is significantly less than 1, which indicates that the mean retro values from Passenger 1C tend to be systematically smaller than the values from handheld.

Table 7. Bivariate Fit of Driver 1C By handheld



Linear Fit

Driver 1 = 19.781306 + 0.9727836*handheld

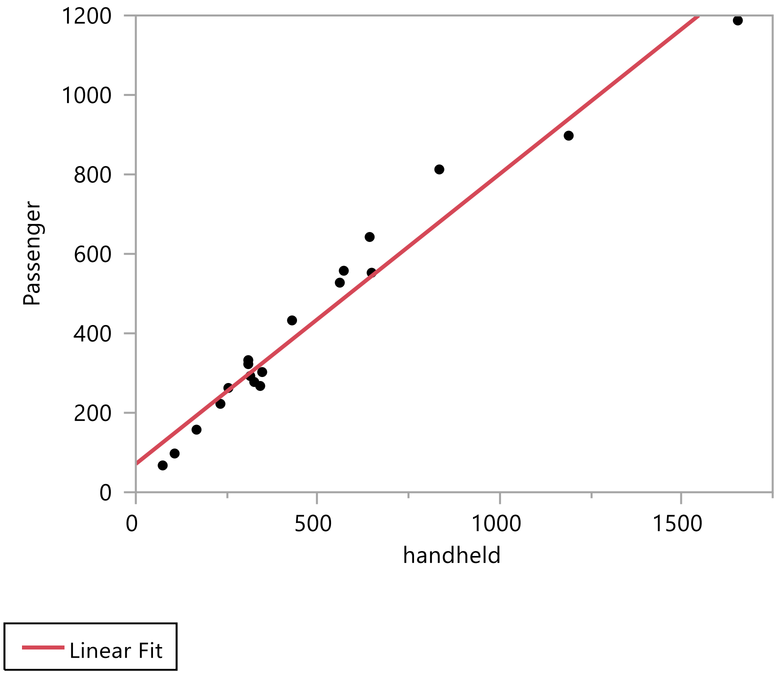
Summary of Fit

RSquare	0.976539
RSquare Adj	0.975159
Root Mean Square Error	60.58536
Mean of Response	498.3183
Observations (or Sum Wgts)	19

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	19.781306	22.73334	0.87	0.3963
Handheld	0.9727836	0.036569	26.60	<.0001*

Table 8. Bivariate Fit of Passenger 1C By handheld



Linear Fit

Passenger 1 = 71.298411 + 0.7297785*handheld

Summary of Fit

RSquare	0.959368
RSquare Adj	0.956978
Root Mean Square Error	60.3477
Mean of Response	430.295
Observations (or Sum Wgts)	19

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	71.298411	22.64416	3.15	0.0059*
Handheld	0.7297785	0.036426	20.03	<.0001*

Next, researchers assessed the impacts of Measurement Type and Position on retroreflectivity. The analysis was based on the subset of the data consisting of 235 measurements for white markings measured by Driver 1 and Passenger 1. Because there was no variation in Position for the handheld data and Driver 2 data, those data were excluded from the analysis. The focus of the analysis was to determine if the mobile system itself had variation at different measurement positions. Yellow marking data were also excluded because those were measured only at the center position. Researchers applied the ANOVA model having Measurement Type (with two levels Driver 1 and Passenger 1) and Position (with three levels: left, right, and center) main effects and the Measurement Type*Position interaction as fixed effects and Marking Sample as a random effect to the dataset consisting of 235 measurements of retro values. Table 9 contains the analysis output obtained by the restricted maximum likelihood (REML) method implemented in JMP. It can be observed from Table 9 (see Fixed Effects Tests) that the interaction effect of Measurement Type*Position is statistically significant at α=0.05, which suggests that the effect of Position varies with the level of Measurement Type. The interaction plot (LS Means Plot) in Table 9 along with the predicted values (Least Squares Means) for retro values for each level of Measurement Type and Position indicates that the predicted retro value for the center position and Passenger 1 is statistically significantly lower than the others. Whether this difference is practically significant or not can be determined based on engineering judgement.

Table 9. JMP output for the analysis of mobile retro values to assess the impact of Position on retroreflectivity for white markings based on the Driver 1 and Passenger 1 data

Response Mobile Retro Value
Summary of Fit

RSquare	0.981341
RSquare Adj	0.980934
Root Mean Square Error	45.7163
Mean of Response	433.5372
Observations (or Sum Wgts)	235

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Measurement Type	1	1	216	27.6391	<.0001*
Position	2	2	216.1	0.2462	0.7820
Position*Measurement Type	2	2	216	18.5984	<.0001*

Effect Details
Measurement Type
Least Squares Means Table

Level	Least Sq Mean	Std Error
Driver 1	541.48101	97.905085
Passenger 1	505.60163	97.890853

Position

Least Squares Means Table

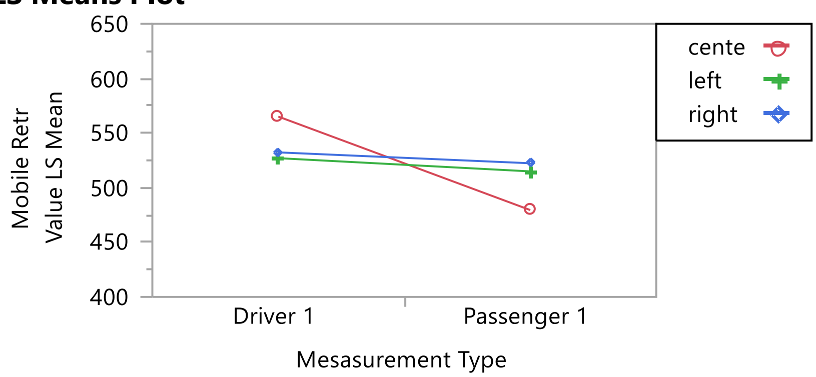
Level	Least Sq Mean	Std Error
center	522.31041	97.794286
left	520.97249	98.068529
right	527.34106	98.100489

Position*Measurement Type

Least Squares Means Table

Level	Least Sq Mean	Std Error
center,Driver 1	565.09838	97.870582
center,Passenger 1	479.52244	97.870582
left,Driver 1	527.02336	98.281413
left,Passenger 1	514.92161	98.281413
right,Driver 1	532.32129	98.408912
right,Passenger 1	522.36082	98.281413

LS Means Plot



LSMeans Differences Tukey HSD

α=0.050

Level				Least Sq Mean
center,Driver 1	A			565.09838
right,Driver 1	A	B		532.32129
left,Driver 1		B		527.02336
right,Passenger 1		B		522.36082
left,Passenger 1		B		514.92161
center,Passenger 1			C	479.52244

Levels not connected by same letter are significantly different.

Note from Figure 1 that for Marking Samples 13 and 14, only the measurements from Passenger 1 are noticeably lower than those from the other measurement types. To see whether those outlying observations significantly affected the analyses in Tables 6, 8, and 9, researchers performed the additional analyses after removing those outlying observations from Passenger 1 for Marking Samples 13 and 14.

Table 10 replicates the analysis in Table 6 after removing the measurements from Passenger 1 for Marking Samples 13 and 14. Although the Tukey's HSD test for Measurement Type given under **LSMeans Differences Tukey HSD** still indicates that the predicted retro values of Passenger 1 are statistically different from those of Driver 1, handheld, and Driver 2, it can be seen that the difference between Passenger 1 and the others is not practically significant this time.

Table 10. JMP output for the analysis of mobile retro values to assess the impact of measurement type and color based only on the center data without Passenger 1 data for Marking Samples 13 and 14

Response Mobile Retro Value Position=center

Summary of Fit

RSquare	0.988591
RSquare Adj	0.988523
Root Mean Square Error	39.52025
Mean of Response	478.2735
Observations (or Sum Wgts)	676

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Measurement Type	3	3	654	11.8927	<.0001*
Color	1	1	17	1.3523	0.2609

Effect Details

Measurement Type

Least Squares Means Table

Level	Least Sq Mean	Std Error
Driver 1	443.17045	100.18610
Driver 2	432.73750	100.32351
Handheld	436.77759	100.12113
Passenger 1	411.00735	100.19624

LSMeans Differences Tukey HSD

α=0.050

Level		Least Sq Mean
Driver 1	A	443.17045
Handheld	A	436.77759
Driver 2	A	432.73750

Level		Least Sq Mean
Passenger 1	B	411.00735

Levels not connected by same letter are significantly different.

Color

Least Squares Means Table

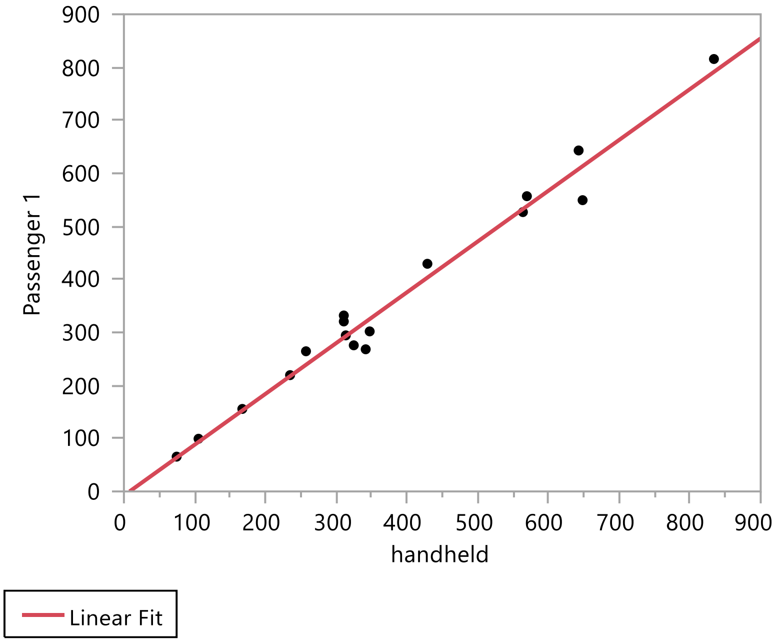
Level	Least Sq Mean	Std Error
White	547.34646	102.72796
Yellow	314.49999	171.88914

Table 11 replicates the analysis in Table 8 without the measurements from Passenger 1C for Marking Samples 13 and 14. It can be observed from the table that now the points fall close to the least squares line with the slope (0.96) that is much closer to 1 than before, and the intercept is also not statistically different from 0, which suggests that mean retro values from Passenger 1C and handheld match fairly well.

Table 12 replicates the analysis in Table 9 without the measurements from Passenger 1C for Marking Samples 13 and 14. Although the Tukey's HSD test result for the interaction effect given under **LSMeans Differences Tukey HSD** indicates that the predicted retro values of Passenger 1C are still statistically lower than those of Driver 1 and (right, Passenger 1), the difference seems to be much smaller than that of Table 9 and does not seems to be practically significant.

Table 11. Bivariate Fit of Passenger 1C By handheld without measurements for Marking Samples 13 and 14

Bivariate Fit of Passenger 1C By handheld



Linear Fit

Passenger 1C = -7.697007 + 0.9581452*handheld

Summary of Fit

RSquare	0.978415
RSquare Adj	0.976976
Root Mean Square Error	30.4849
Mean of Response	358.3708
Observations (or Sum Wgts)	17

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-7.697007	15.86688	-0.49	0.6346
handheld	0.9581452	0.036745	26.08	<.0001*

Table 12. JMP output for the analysis of mobile retro values to assess the impact of Position on retroreflectivity for white markings based on the Driver 1 and Passenger 1 data without measurements from Passenger 1 for Marking Samples 13 and 14

Response Mobile Retro Value
Summary of Fit

RSquare	0.991848
RSquare Adj	0.991662
Root Mean Square Error	28.21678
Mean of Response	406.51
Observations (or Sum Wgts)	225

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Measurement Type	1	1	206	31.0312	<.0001*
Position	2	2	206	0.6655	0.5151
Position*Measurement Type	2	2	206	11.9267	<.0001*

Effect Details
Measurement Type
Least Squares Means Table

Level	Least Sq Mean	Std Error
Driver 1	553.78418	108.05473
Passenger 1	530.04240	108.05566

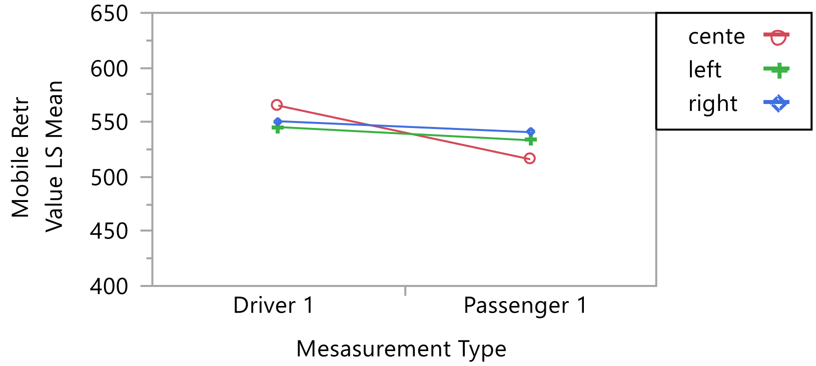
Position
Least Squares Means Table

Level	Least Sq Mean	Std Error
center	540.53750	108.01892
left	539.40655	108.11363
right	545.79581	108.12468

Position*Measurement Type
Least Squares Means Table

Level	Least Sq Mean	Std Error
center,Driver 1	565.09838	108.04086
center,Passenger 1	515.97662	108.05840
left,Driver 1	545.45743	108.18725
left,Passenger 1	533.35568	108.18725
right,Driver 1	550.79673	108.23139
right,Passenger 1	540.79489	108.18725

LS Means Plot



LSMeans Differences Tukey HSD

α=0.050

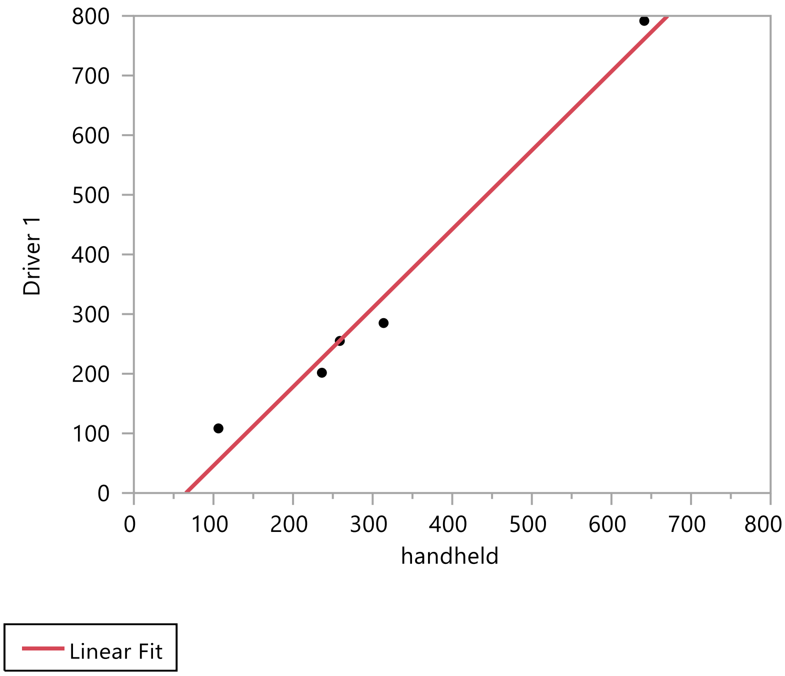
Level				**Least Sq Mean**
center,Driver 1	A			565.09838
right,Driver 1	A	B		550.79673
left,Driver 1	A	B		545.45743
right,Passenger 1		B		540.79489
left,Passenger 1		B	C	533.35568
center,Passenger 1			C	515.97662

Levels not connected by same letter are significantly different.

Researchers also compared the mean retro values obtained for each Marking Sample and Measurement Type for other positions of Driver 1 (Driver 1L, Driver 1R), Passenger 1 (Passenger 1L, Passenger 1R) as well as Driver 2 (center) with the mean retro values from handheld. Tables 13-17 contain the scatter plots of the mean retro values for each pair of (handheld, Driver 1L), (handheld, Driver 1R), (handheld, Driver 2C), (handheld, Passenger 1L), and (handheld, Passenger 1R), respectively, along with the summary of the fit results. Note that the number of observations is small in these cases, and the fit of the line can be easily affected even by the existence of a single unusually low or high value. The results thus need to be interpreted with caution. In Table 13, the slope (1.32) of the least squares line is significantly larger than 1, which seems to have been caused by a much higher mean value for Driver 1L compared to handheld for Marking Sample 10. In Tables 14-17, it can be observed that the points fall pretty close to the least squares line with the slope (1.05 for Driver 1R, 1.02 for Driver 2C, 1.06 for Passenger 1L, or 0.996 for Passenger 1R) that is close to 1, and the intercept is also not statistically different from 0. Based on this limited data, the mean retro values from each of Driver 1R, Driver 2C, Passenger 1L, or Passenger 1R and handheld seem to match fairly well.

Table 13. Bivariate Fit of Driver 1L By handheld

Bivariate Fit of Driver 1L By handheld



Linear Fit

Driver 1L = -86.42401 + 1.3218933*handheld

Summary of Fit

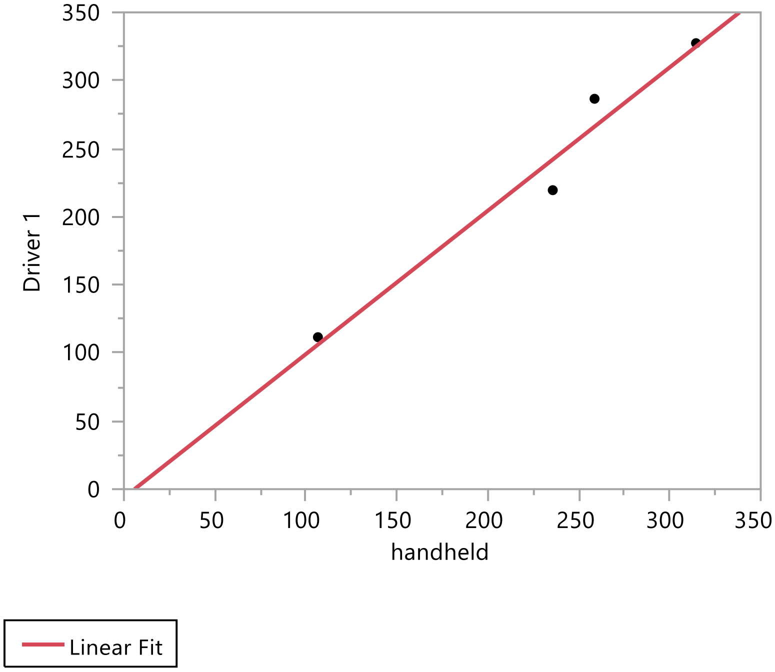
RSquare	0.978684
RSquare Adj	0.971579
Root Mean Square Error	45.0947
Mean of Response	326.2601
Observations (or Sum Wgts)	5

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-86.42401	40.53598	-2.13	0.1228
Handheld	1.3218933	0.112634	11.74	0.0013*

Table 14. Bivariate Fit of Driver 1R By handheld

Bivariate Fit of Driver 1R By handheld



Linear Fit

Driver 1R = -6.140152 + 1.0525696*handheld

Summary of Fit

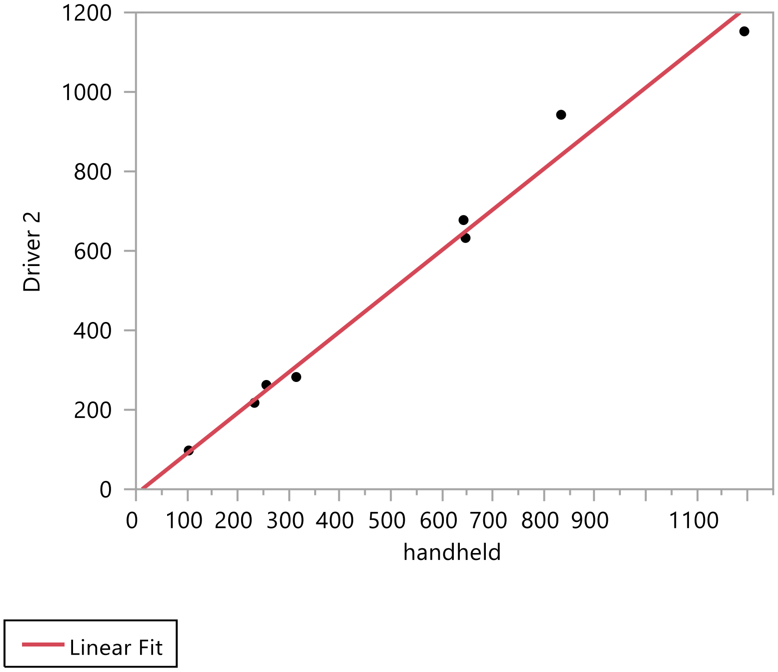
RSquare	0.965211
RSquare Adj	0.947816
Root Mean Square Error	21.59742
Mean of Response	235.3697
Observations (or Sum Wgts)	4

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-6.140152	34.17238	-0.18	0.8740
Handheld	1.0525696	0.141301	7.45	0.0175*

Table 15. Bivariate Fit of Driver 2C By handheld

Bivariate Fit of Driver 2C By handheld



Linear Fit

Driver 2C = -12.36668 + 1.0231593*handheld

Summary of Fit

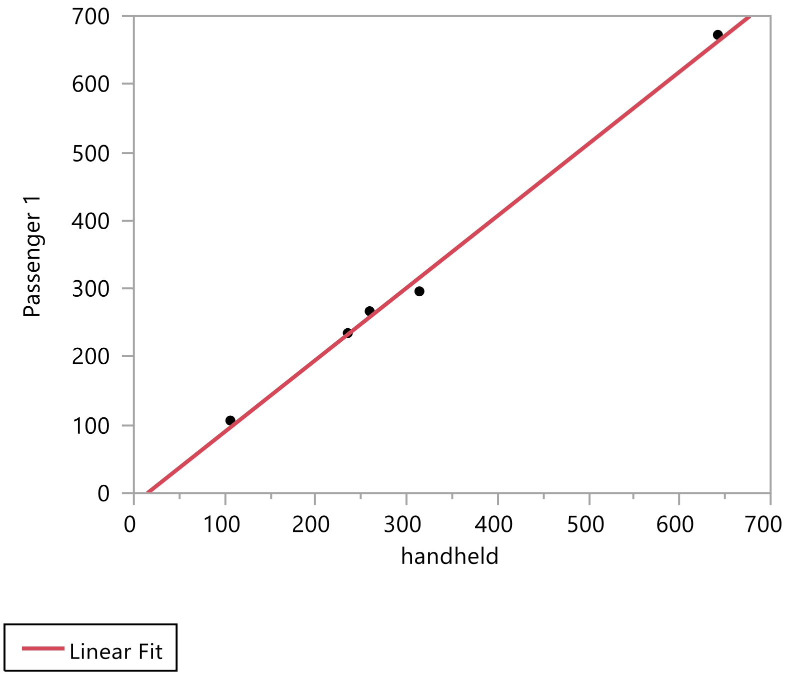
RSquare	0.98411
RSquare Adj	0.981462
Root Mean Square Error	51.62264
Mean of Response	529.8278
Observations (or Sum Wgts)	8

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-12.36668	33.52946	-0.37	0.7249
Handheld	1.0231593	0.053077	19.28	<.0001*

Table 16. Bivariate Fit of Passenger 1L By handheld

Bivariate Fit of Passenger 1L By handheld



Linear Fit

Passenger 1L = -15.69255 + 1.0565652*handheld

Summary of Fit

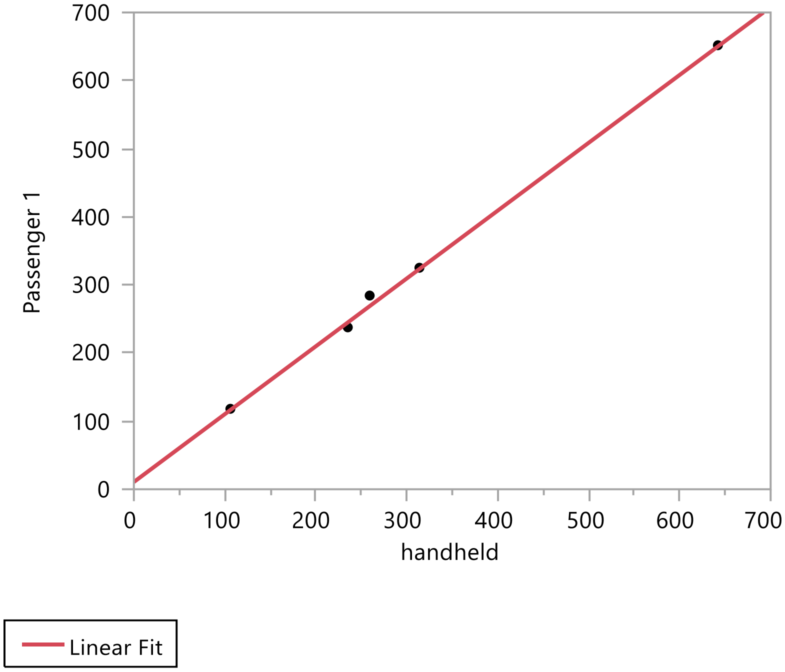
RSquare	0.996333
RSquare Adj	0.995111
Root Mean Square Error	14.81596
Mean of Response	314.1583
Observations (or Sum Wgts)	5

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-15.69255	13.31818	-1.18	0.3236
Handheld	1.0565652	0.037006	28.55	<.0001*

Table 17. Bivariate Fit of Passenger 1R By handheld

Bivariate Fit of Passenger 1R By handheld



Linear Fit

Passenger 1R = 10.642687 + 0.9960382*handheld

Summary of Fit

RSquare	0.998544
RSquare Adj	0.998059
Root Mean Square Error	8.791707
Mean of Response	321.5975
Observations (or Sum Wgts)	5

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	10.642687	7.902935	1.35	0.2708
Handheld	0.9960382	0.021959	45.36	<.0001*

RUNWAY TESTING RESULTS

The objectives of the runway testing analysis are to 1. Evaluate precision of mobile (passenger and driver) data in terms of repeatability; 2. Assess the impacts of Condition, Marking Color, RRPM, and Position on mean retroreflectivity of mobile data; 3. Compare mobile (passenger and driver) data to handheld data.

Table 18 contains the variables considered in the analysis. In this study, the factors of interest are Measurement Type, Color, Position, Condition, and RRPM.

Table 18. Variables used in the analysis of Leetron Riverside data

Class	Variable	Values in the data
Response Variable	Retro Value (mcd/m^2/lux)	25-528
Factors	Measurement Type	Driver Mobile, Passenger Mobile, Handheld
	Color	White, Yellow
	Position	Center, Left, Right
	Condition	Day, Dusk, Night
	RRPM	Yes, No
Block	Line Number	17 levels (1 NB, 2, NB,…, 40 SB)

1. Analysis on repeatability of mobile (passenger and driver) data

A relative standard deviation (RSD) or the Coefficient of Variation (% CV) given by

$$s_r\left(\%\right) = 100\, s/\bar{x} \quad \left(\bar{x} > 0\right)$$

is often used as a measure of repeatability. Because repeatability is the precision obtained in the best possible circumstances (same operator, same marking, same light condition, same position), only the test runs repeated under the same conditions (marking, light condition, RRPM, and position) were used to obtain the estimate of the CV. Table 19 contains the summary statistics of retro values for the same marking (39SB for Driver Mobile and 40 SB for Passenger Mobile), same light condition (night), same RRPM (no RRPM), and same position (center) for each of Driver Mobile and Passenger Mobile. It can be observed from the table that the means from different test runs are close for each of Driver Mobile and Passenger Mobile (within 2 percent of the mean for all three tests on each marking. The % CV are mainly between 14-21% although the precision for Driver Mobile seems to be slightly higher than that for Passenger Mobile. The %CV are within 11 percent of the mean for all three tests on each marking.

Table 19. Summary Statistics of retro values measured under the same conditions for each of Driver Mobile and Passenger Mobile data

Measurement Type (Line Number)	Test	N Rows	Mean	Std Dev	% CV
Driver Mobile (39SB)	1	19	226.1	36.9	16.3%
	2	19	230.3	39.6	17.2%
	7	19	224.0	31.8	14.2%
Passenger Mobile (40SB)	1	19	295.9	59.9	20.2%
	2	19	296.6	63.4	21.4%
	7	19	299.9	52.7	17.6%

Tables 20 and 21 contain the results of various F-tests for testing whether the variances (standard deviations) of retro values are equal across different test runs (1, 2, 7) as well as the ANOVA test results for testing whether the means are significantly different across different test runs for each of Driver Mobile Retro data (summarized in Table 19) and Passenger Mobile data, respectively. It can be observed from Tables 20 and 21 that neither the variances nor the means are significantly different across different test runs (p-values are all greater than α=0.05) for each of Mobile Retro data and Passenger Mobile data.

Table 20. JMP Output for Analysis of Driver Mobile Retro Values

Measurement Type=Driver Mobile

Equal Variance Tests for testing equality of variances

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	0.1087	2	54	0.8972
Brown-Forsythe	0.2017	2	54	0.8180
Levene	0.2954	2	54	0.7455
Bartlett	0.4292	2	.	0.6510

Analysis of Variance (ANOVA) for testing equality of means

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Test	2	392.686	196.34	0.1494	0.8616
Error	54	70987.566	1314.58		
C. Total	56	71380.252			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
1	19	226.140	8.3180	209.46	242.82
2	19	230.332	8.3180	213.66	247.01
7	19	224.014	8.3180	207.34	240.69

Std Error uses a pooled estimate of error variance

Table 21. JMP Output for Analysis of Passenger Mobile Retro Values

Measurement Type=Passenger Mobile

Equal Variance Tests for testing equality of variances

Test	F Ratio	DFNum	DFDen	Prob > F
O'Brien[.5]	0.1960	2	53	0.8226
Brown-Forsythe	0.5062	2	53	0.6056
Levene	0.9015	2	53	0.4121
Bartlett	0.2910	2	.	0.7475

Analysis of Variance (ANOVA) for testing equality of means

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Test	2	170.89	85.45	0.0246	0.9757
Error	53	184030.51	3472.27		
C. Total	55	184201.40			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
1	19	295.905	13.519	268.79	323.02
2	19	296.597	13.519	269.48	323.71
7	18	299.942	13.889	272.08	327.80

Std Error uses a pooled estimate of error variance

2. ***Analysis to assess the impacts of Condition, Color, RRPM, and Position on mean retroreflectivity of mobile data***

This section will analyze the impacts of ambient light condition, marking color, RRPM presence, and measurement position on the mobile retroreflectivity data. The data analysis is performed separately for Driver Mobile and Passenger Mobile data.

2.1 Impacts of Condition and/or Color

2.1.1 Driver Mobile

To isolate the impacts of Condition and/or Color, the subset of the data consisting of the retro measurements for Driver mobile measured at the center position was extracted. Note that most (90%) of the 1,139 measurements for Driver Mobile were obtained at the center position. For the other positions (left, right), the effects of Condition and RRPM turned out to be confounded and so the other positions were not included in this analysis.

Researchers first performed the line-by-line analysis to assess the impact of Condition. During the course of the analysis for each line, it was observed that when RRPM=No, Condition was either Day or Night and when RRPM=Yes, Condition was either Dusk or Night. The impact of Condition was, thus, assessed separately for each of RRPM=No and RRPM=Yes.

Table 22 summarizes the results of the one-way ANOVA tests assessing the impact of Condition (Day vs Night) when there is no RRPM. It can be observed that for Line Numbers 14 SB and 17 SB, the effect of Condition is statistically significant. The difference between the predicted values for Day and Night does not seem to be practically significant, however.

Table 22. The results of one-way ANOVA for each marking to assess the impact of Condition (day vs night) for Driver Mobile data when there is no RRPM

Line Number	Color	P-value for the ANOVA test	Predicted values	
			Day	Night
10 NB	Yellow	0.2509	187.192	193.441
10 SB	Yellow	0.3275	190.860	184.524
14 SB	Yellow	**0.0004**	130.806	116.809
17 SB	Yellow	**0.0001**	160.377	142.579
18 NB	White	0.1509	282.043	305.547
18 SB	White	0.6705	305.948	300.895
29 SB	Yellow	0.3676	145.079	140.571
39 SB	Yellow	0.4858	221.586	226.829

Note: Statistically significant results are given in bold.

Table 23 summarizes the results of the one-way ANOVA tests assessing the impact of Condition (Dusk vs Night) when there is RRPM. It can be observed that the effect of Condition is statistically significant for all three pavement markings. The difference between the predicted values for Day and Night also seems to be practically significant. During the testing the operator modified the software setting to better account for the presence of the RRPMs. This change was made between the dusk and night measurements. The change was made because the operator found that some RRPMs were not being filtered and were included in the data creating a higher average value.

Table 23. The results of one-way ANOVA for each marking to assess the impact of Condition (Dusk vs Night) for Driver Mobile data when there is RRPM

Line Number	Color	P-value for the ANOVA test	Predicted values	
			Dusk	Night
2 NB	Yellow	**< .0001**	228.549	185.456
2 SB	Yellow	**< .0001**	205.322	164.081

39 SB	Yellow	**0.0008**	217.739	177.416

Note: Statistically significant results are given in bold.

Researchers also performed the analyses considering multiple pavement markings together. The ANOVA model having Condition and Color as fixed effects and Line Number as a random effect was applied to the dataset consisting of 566 retro measurements with RRPM=No for the eight pavement markings of Table 22. Table 24 contains the analysis result. It can be observed from Table 24 that the effect of Condition is not statistically significant at α=0.05 while the effect of Color is significant. This analysis is not evaluating the accuracy of the mobile system for the different color markings, it is noting that the two different color markings have statistically significant differences which is expected because white markings typically have higher retroreflectivity levels. It can also be seen from the **Least Squares Means Table** that there is not a significant difference between the predicted retro values for day and night.

Table 24. JMP Output for the analysis of driver mobile retro values to assess the impact of condition when RRPM=No

Response RetroValue RRPM=no
Summary of Fit

RSquare	0.780635
RSquare Adj	0.779856
Root Mean Square Error	31.2242
Mean of Response	198.0951
Observations (or Sum Wgts)	566

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Condition	1	1	557.8	0.7436	0.3889
Color	1	1	6.043	20.5040	0.0039*

Effect Details
Condition
Least Squares Means Table

Level	Least Sq Mean	Std Error
Day	234.59541	14.016373
Night	232.19563	14.092034

Color
Least Squares Means Table

Level	Least Sq Mean	Std Error
White	296.70099	24.230054

Level	Least Sq Mean	Std Error
Yellow	170.09006	13.963636

The ANOVA model having Condition as a fixed effect and Line Number as a random effect was applied to the dataset consisting of 323 measurements with RRPM=Yes for the three pavement markings of Table 23. The variable Color was not included because all of the markings in the data are Yellow markings. Table 25 contains the analysis result. It can be observed from the table that the effect of Condition is statistically significant at α=0.05. The difference in the predicted retro values between dusk and night (given in the Least Squares Means table) also seems to be practically significant. These differences as previously noted are likely due to the change in the software setting to better account for the presence of RRPMs.

Table 25. JMP Output for the analysis of driver mobile retro values to assess the impact of condition when RRPM=Yes

Response RetroValue RRPM=yes
Summary of Fit

RSquare	0.178525
RSquare Adj	0.175966
Root Mean Square Error	45.93196
Mean of Response	204.8782
Observations (or Sum Wgts)	323

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Condition	1	1	320.4	54.3202	<.0001*

Effect Details
Condition
Least Squares Means Table

Level	Least Sq Mean	Std Error
Dusk	217.20320	6.8051197
Night	175.43567	7.7407209

2.1.2 Passenger Mobile

To isolate the impact of Condition, the subset of the data consisting of the retro measurements for Passenger mobile measured at the center position was extracted. Note that most (88%) of the 931 measurements for Passenger Mobile were obtained at the center position. All of the markings for Passenger Mobile were White markings. It was observed that when RRPM=No, Condition was either Dusk or Night (for Line Numbers 18 NB and 18 SB), or Day, Dusk, or Night (for Line Number 40 SB), and when RRPM=Yes, Condition was either Dusk or Night (for Line Numbers 1 NB and 3 SB). The impact of Condition was, thus, assessed separately for each of RRPM=No and RRPM=Yes.

Researchers first performed the line-by-line analysis for the Passenger Mobile data. Table 26 summarizes the results of the one-way ANOVA tests assessing the impact of Condition (Dusk, Night or Dusk, Night, Day) when there is no RRPM. It can be observed that for Line Numbers 18 NB and 18 SB, the effect of Condition is statistically significant. The difference between the predicted values for Dusk and Night seems to be practically significant for 18 SB. For Line Number 40 SB, the effect of Condition is not statistically significant. The differences among the predicted values for Dusk, Night, and Day also seem to be practically insignificant.

Table 26. The results of one-way ANOVA for each marking for assessing the impact of Condition (day vs night) for Passenger Mobile data when there is no RRPM

Line Number	N	P-value for the ANOVA test	Predicted values		
			Dusk	Night	Day
18 NB	57	**0.0032**	271.339	313.484	.
18 SB	57	**0.0339**	239.440	327.705	.
40 SB	170	0.9415	291.496	289.410	286.701

Note: Statistically significant results are given in bold.

Table 27 summarizes the results of the one-way ANOVA tests assessing the impact of Condition (Dusk vs Night) when there is RRPM. It can be observed that the effect of Condition is statistically significant for both pavement markings, 1 NB and 3 SB. The difference between the predicted values for Dusk and Night does not seem to be practically significant, however.

Table 27. The results of one-way ANOVA for each marking to assess the impact of Condition (Dusk vs Night) for Passenger Mobile data when there is RRPM

Line Number	N	P-value for the ANOVA test	Predicted values	
			Dusk	Night
1 NB	114	**0.0114**	247.746	223.284
3 SB	114	**0.0050**	323.463	290.566

Note: Statistically significant results are given in bold.

Researchers also performed the analyses considering multiple pavement markings together. The ANOVA model having Condition as a fixed effect and Line Number as a random effect was applied to the dataset consisting of 284 retro measurements with RRPM=No for the three pavement markings of Table 26. Table 28 contains the analysis result. It can be observed from Table 28 that the effect of Condition is not statistically significant at α=0.05 when all three markings are considered together. Note that when all three markings are analyzed simultaneously, the effect of 18 SB measurements gets attenuated because of the effects of measurements from other pavement markings.

Table 28. JMP Output for the analysis of driver Passenger retro values to assess the impact of condition when RRPM=No

Response RetroValue
Summary of Fit

RSquare	0.027402
RSquare Adj	0.020479
Root Mean Square Error	57.81407
Mean of Response	291.6738
Observations (or Sum Wgts)	284

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Condition	2	2	206.7	1.9815	0.1405

Effect Details
Condition
Least Squares Means Table

Level	Least Sq Mean	Std Error
Day	291.91409	12.526782
Dusk	285.55797	7.560954
Night	301.34898	8.151210

The ANOVA model having Condition as a fixed effect and Line Number as a random effect was applied to the dataset consisting of 228 measurements with RRPM=Yes for the two pavement markings of Table 27. Table 29 contains the analysis result. It can be observed from the table that the effect of Condition is statistically significant at α=0.05. The difference between the predicted values for Dusk and Night does not seem to be practically significant, however.

Table 29. JMP Output for the analysis of driver mobile retro values to assess the impact of condition when RRPM=Yes

Response RetroValue
Summary of Fit

RSquare	0.352744
RSquare Adj	0.34988
Root Mean Square Error	53.01226
Mean of Response	276.0445
Observations (or Sum Wgts)	228

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Condition	1	1	225	14.8289	0.0002*

Effect Details
Condition
Least Squares Means Table

Level	Least Sq Mean	Std Error
Dusk	285.60426	36.537298
night	256.92487	36.789441

2.2 Impact of RRPM

2.2.1 Driver Mobile

The assessment of the impact of RRPM for Driver Mobile was made based on the 39 SB night center data for which only RRPM varies while the other variables (Condition=night, Position=center, and Color=Yellow) are all fixed. Table 30 contains the result of the one-way ANOVA analysis of the Driver mobile data to assess the impact of RRPM. It can be observed from the table that the effect of RRPM is statistically significant at α=0.05. Table 30 also presents the predicted values for retro values for each level of RRPM along with their standard errors. It can be observed that the predicted value for RRPM = no is statistically significantly higher than that for RRPM=yes. These differences as previously noted are likely due to the change in the software setting to better account for the presence of RRPMs. This change was made after the RRPM = no measurements were recorded.

Table 30. JMP Output for the ANOVA analysis of driver mobile retro values to assess the impact of RRPM based on the 39 SB night center data

Response RetroValue

Summary of Fit

RSquare	0.282279
RSquare Adj	0.27258
Root Mean Square Error	34.57546
Mean of Response	214.4758
Observations (or Sum Wgts)	76

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	34792.96	34793.0	29.1042
Error	74	88464.20	1195.5	**Prob > F**
C. Total	75	123257.16		<.0001*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
RRPM	1	1	34792.959	29.1042	<.0001*

Effect Details

RRPM

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
No	226.82894	4.5796310	226.829
Yes	177.41628	7.9321535	177.416

2.2.2 Passenger Mobile

The assessment of the impact of RRPM for Passenger Mobile could not be made because there were no measurements for which only RRPM changes while the other variables are fixed. Unfortunately, the value of Condition changes whenever RRPM changes for all of the line numbers in the Passenger Mobile data.

2.3 Impact of Position

2.3.1 Driver Mobile

The assessment of the impact of Position for Driver Mobile was made based on the 39 SB data for which only the level of Position varies while controlling for the effects of other variables (Condition=dusk or night, RRPM=yes or no, and Color=Yellow). The analysis was done separately for dusk and night. (The day data were excluded because the position was fixed at the center for the day data at 39 SB.) Note that all of the measurements under the dusk condition have RRPM and those under the night condition have no RRPM. (There were originally 19 measurements made under the night condition with RRPM for 39SB, but they were removed from the analysis to avoid confounding). Table 31 contains the result of the one-way ANOVA analysis of the Driver mobile data to assess the impact of Position. It can be observed from the table that the effect of Position when Condition=dusk is statistically significant at α=0.05 while the effect of Position when Condition=night is not statistically significant. Table 31 also presents the predicted values for retro values for each level of Position along with their standard errors. The Tukey's multiple comparison test suggests that the predicted retro value at the center is statistically higher than those for the other positions although the difference does not seem to be practically significant.

Table 31. JMP Output for the ANOVA analysis of driver mobile retro values to assess the impact of Position based on the 39 SB data

Response RetroValue Condition=dusk
Summary of Fit

RSquare	0.102517
RSquare Adj	0.086346
Root Mean Square Error	44.09476
Mean of Response	207.4002
Observations (or Sum Wgts)	114

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	24652.73	12326.4	6.3396
Error	111	215822.63	1944.3	**Prob > F**
C. Total	113	240475.35		0.0025*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Position	2	2	24652.727	6.3396	0.0025*

Effect Details
Position
Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
center	217.73917	5.058016	217.739

Level	Least Sq Mean	Std Error	Mean
Left	189.44003	10.116032	189.440
Right	184.00433	10.116032	184.004

LSMeans Differences Tukey HSD

α=0.050

Level			Least Sq Mean
center	A		217.73917
Left		B	189.44003
Right		B	184.00433

Levels not connected by same letter are significantly different.

Response RetroValue Condition=night
Summary of Fit

RSquare	0.004283
RSquare Adj	-0.01104
Root Mean Square Error	36.09077
Mean of Response	225.5582
Observations (or Sum Wgts)	133

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	728.37	364.19	0.2796
Error	130	169330.70	1302.54	**Prob > F**
C. Total	132	170059.07		0.7565

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Position	2	2	728.37417	0.2796	0.7565

Effect Details
Position
Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
center	226.82894	4.7803396	226.829
Left	221.87306	5.8546964	221.873
Right	227.33733	5.8546964	227.337

2.3.2 Passenger Mobile

The assessment of the impact of Position for Passenger Mobile was made based on the 40 SB data for which only the level of Position varies while controlling for the effects of other variables (Condition=dusk or night, RRPM=no, and Color=White). The analysis was done separately for dusk and night. (The day data were excluded because the position was fixed at the center for the day condition at 40 SB.) Also, 38 measurements with RRPM=yes were excluded, so the RRPM was controlled at no for the remaining data. Table 32 contains the result of the one-way ANOVA analysis of the Passenger mobile data to assess the impact of Position. It can be observed from the table that the effect of Position is not statistically significant for both Condition=dusk and Condition=night.

Table 32. JMP Output for the ANOVA analysis of passenger mobile retro values to assess the impact of Position based on the 40 SB data

Response RetroValue Condition=dusk

Summary of Fit

RSquare	0.010874
RSquare Adj	-0.01623
Root Mean Square Error	78.3052
Mean of Response	296.2295
Observations (or Sum Wgts)	76

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	4920.75	2460.37	0.4013
Error	73	447614.46	6131.70	**Prob > F**
C. Total	75	452535.20		0.6709

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Position	2	2	4920.7476	0.4013	0.6709

Effect Details

Position

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
center	291.49582	12.702781	291.496
Left	310.16521	17.964446	310.165
Right	291.76101	17.964446	291.761

Response RetroValue Condition=night

Summary of Fit

RSquare	0.015064
RSquare Adj	0.003269
Root Mean Square Error	56.97939
Mean of Response	293.4759
Observations (or Sum Wgts)	170

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	8292.63	4146.31	1.2771
Error	167	542190.74	3246.65	**Prob > F**
C. Total	169	550483.36		0.2816

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Position	2	2	8292.6273	1.2771	0.2816

Effect Details

Position

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
center	289.40954	5.8769756	289.410
Left	306.46568	9.2432779	306.466
Right	290.54509	9.2432779	290.545

2.4 Comparison of Driver Mobile and Passenger Mobile data based on the nighttime 18 SB and 18 NB data

Researchers also compared Driver Mobile and Passenger Mobile data based on the 18 SB and 18 NB data measured during night. Other conditions could not be included because day data were obtained only for Driver Mobile and dusk data were obtained only for Passenger Mobile on those markings. As can be observed from Table 33, there was no significant difference in mean retroreflectivity values between nighttime Driver Mobile and Passenger Mobile data for 18 SB and 18 NB markings.

Table 33. Comparisons of Driver Mobile and Passenger Mobile data based on the nighttime 18 SB and 18 NB data

Response RetroValue

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	5969.15	2984.58	0.7926
Error	71	267348.35	3765.47	**Prob > F**
C. Total	73	273317.51		0.4566

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	1	1643.74	1643.74	0.4330
Pure Error	70	265704.61	3795.78	**Prob > F**
Total Error	71	267348.35		0.5127

Source	DF	Sum of Squares	Mean Square	F Ratio Max RSq

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Measurement Type	1	1	5403.9803	1.4351	0.2349
Line Number	1	1	471.8547	0.1253	0.7244

Effect Details

Measurement Type

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
Driver Mobile	303.49069	10.234924	303.350
Passenger Mobile	320.59468	9.954462	320.595

Line Number

Least Squares Means Table

Level	Least Sq Mean	Std Error	Mean
18 NB	309.51563	9.954462	309.516
18 SB	314.56974	10.234924	315.045

3. Comparison of mobile (passenger and driver) data and handheld data

Researchers compared the mean retro values computed for each Line Number and Measurement Type. In this way, the mobile data and handheld data can be paired for each Line Number. Table 34 contains the sample mean retroreflectivity values by three different measurement types considered for each of 17 lines in the Riverside dataset.

Table 34. Mean retroreflectivity values obtained by three measurement types for each section (Leetron Riverside data)

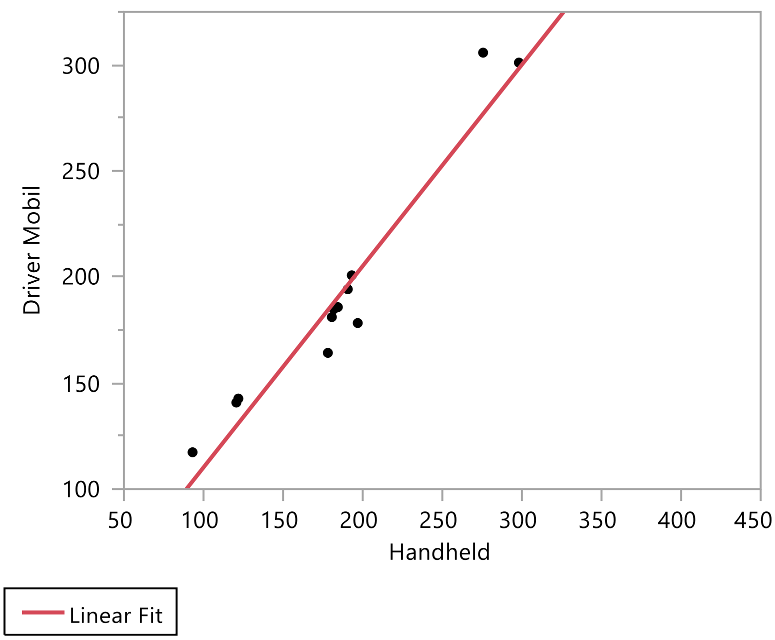
Line Number	Color	Driver Mobile	Passenger Mobile	Handheld
1 NB	White		223.3	230.5
10 NB	Yellow	193.4		191.2
10 SB	Yellow	184.5		182.2
14 SB	Yellow	116.8		93.3
15 SB	Yellow	200.4		193.8
16 SB	White		331.2	414.8
17 SB	Yellow	142.6		122.8
18 NB	White	305.5	313.5	276.3
18 SB	White	300.9	327.7	299.3
2 NB	Yellow	185.5		184.5
2 SB	Yellow	164.1		178.7
24 SB	White		307.7	351.3

29 SB	Yellow	140.6		120.7
3 SB	White		290.6	313.5
39 SB	Yellow	177.4		197.8
40 SB	White		290.5	264.6
8 SB	White	181.0	167.2	181.2

Tables 35 and 36 contain the scatter plots of the mean retro values for each pair of (handheld, Driver 1) and (handheld, Passenger 1) in Table 34, respectively, along with the summary of the fit results. Table 35 shows that the points fall close to the least squares line with the slope (0.95) that is close to 1, and the intercept is also not statistically different from 0, which suggests that mean retro values from Driver Mobile and handheld match fairly well. On the other hand, the slope (0.65) of the least squares line of Table 36 is significantly less than 1, which indicates that the mean retro values from Passenger Mobile tend to be systematically smaller than the values from handheld.

Table 35. Bivariate Fit of Driver Mobile By handheld

Bivariate Fit of Driver Mobile By Handheld



Linear Fit

Driver Mobile = 15.252308 + 0.9495905*Handheld

Summary of Fit

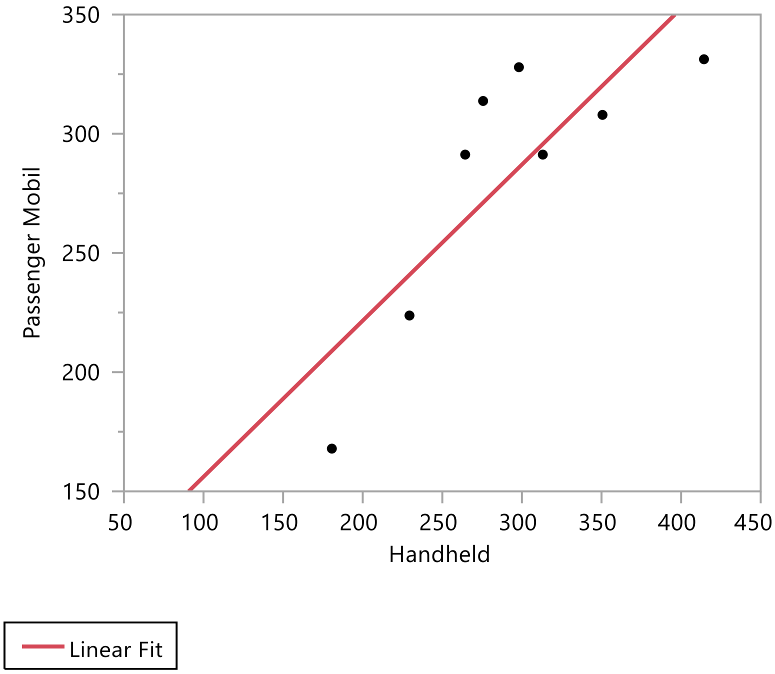
RSquare	0.935657
RSquare Adj	0.929223
Root Mean Square Error	15.38068
Mean of Response	191.0578
Observations (or Sum Wgts)	12

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	15.252308	15.23998	1.00	0.3405
Handheld	0.9495905	0.078746	12.06	<.0001*

Table 36. Bivariate Fit of Passenger Mobile By handheld

Bivariate Fit of Passenger Mobile By Handheld



Linear Fit

Passenger Mobile = 90.614852 + 0.6548337*Handheld

Summary of Fit

RSquare	0.676163
RSquare Adj	0.62219
Root Mean Square Error	35.18359
Mean of Response	281.4552
Observations (or Sum Wgts)	8

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	90.614852	55.33416	1.64	0.1526
Handheld	0.6548337	0.185009	3.54	0.0122*

OPEN ROAD TESTING RESULTS

The objectives of the open road test analysis are to 1. Compare mobile (passenger and driver) data to TTI handheld and/or TTI comparison data; and 2. Evaluate the impacts of Condition, Speed and Position on mean retroreflectivity of mobile data; 3. Assess the impacts of Marking Color and Marking Type on accuracy of driver mobile data compared to the TTI handheld data.

Table 37 contains the variables considered in the analysis. In this study, the factors of interest are Measurement Type, Color, Type, Condition, Position, and Speed.

Table 37. Variables used in the analysis of Leetron open road data

Class	Variable	Values in the data
Response Variable	Retro Value (mcd/m^2/lux)	0-779
Factors	Measurement Type	Driver Mobile, Passenger Mobile, TTI Comparison, TTI Handheld
	Color	White, Yellow
	Type	Skip. Solid
	Condition	Cloudy, Night, Sunny, Unknown
	Position (snook skip only)	Center, Left, Right
	Speed (snook skip only)	40, 50, 60, 70
Block	Section Name	18 levels (47 FR edge, 47 FR skip, …, univ wb yellow)

1. ***Comparison of mobile (passenger and driver) data and TTI handheld and/or TTI comparison data***

Tables 38 shows the sample mean retroreflectivity values by four different measurement types considered for each of 18 sections in the open road testing. Not all measurement types were used in each section.

Figure 2 presents box plots with whiskers of the retro values for each measurement type (D = driver mobile, P = passenger mobile, C = TTI comparison, H = TTI handheld) by Marking

Section Number. It can be observed that in general the mean retro values measured by different methods are close to one other except for a few cases (e.g., Section 3 (47 FR yellow), Section 9 (nb 47 skip), Section 10 (nb 47 yellow), Section 11 (sb 47 skip).

Table 38. Mean retroreflectivity values obtained by four measurement types (Field data)

Section Number	Section Name	Color	Type	Driver Mobile	Passenger Mobile	TTI Comparison	TTI Handheld
1	47 FR edge	white	solid	667.9		640.7	599.5
2	47 FR skip	white	skip	542.9		573.9	547.2
3	47 FR yellow	yellow	solid	366.8		309.6	308.4
4	campus skip	white	skip	330.5		321.9	
5	jones edge	white	solid		191.4		202.5
6	jones yellow	yellow	solid	97.6		98.5	87.6
7	leo edge	white	solid		378.5		373.5
8	leo yellow	yellow	skip	134.8		140.6	154.6
9	nb 47 skip	white	skip	355.2		361.4	400.0
10	nb 47 yellow	yellow	solid	289.6		250.6	
11	sb 47 skip	white	skip	229.6		268.5	
12	sb 47 yellow	yellow	solid	211.7		194.4	215.0
13	snook edge	white	solid	154.4		142.6	
14	snook skip	white	skip	169.2		162.7	
15	univ eb skip	white	skip	206.7	238.6	222.4	
16	univ eb yellow	yellow	solid	146.6		140.3	
17	univ wb skip	white	skip	237.7	266.4	254.9	
18	univ wb yellow	yellow	solid	131.9		130.8	

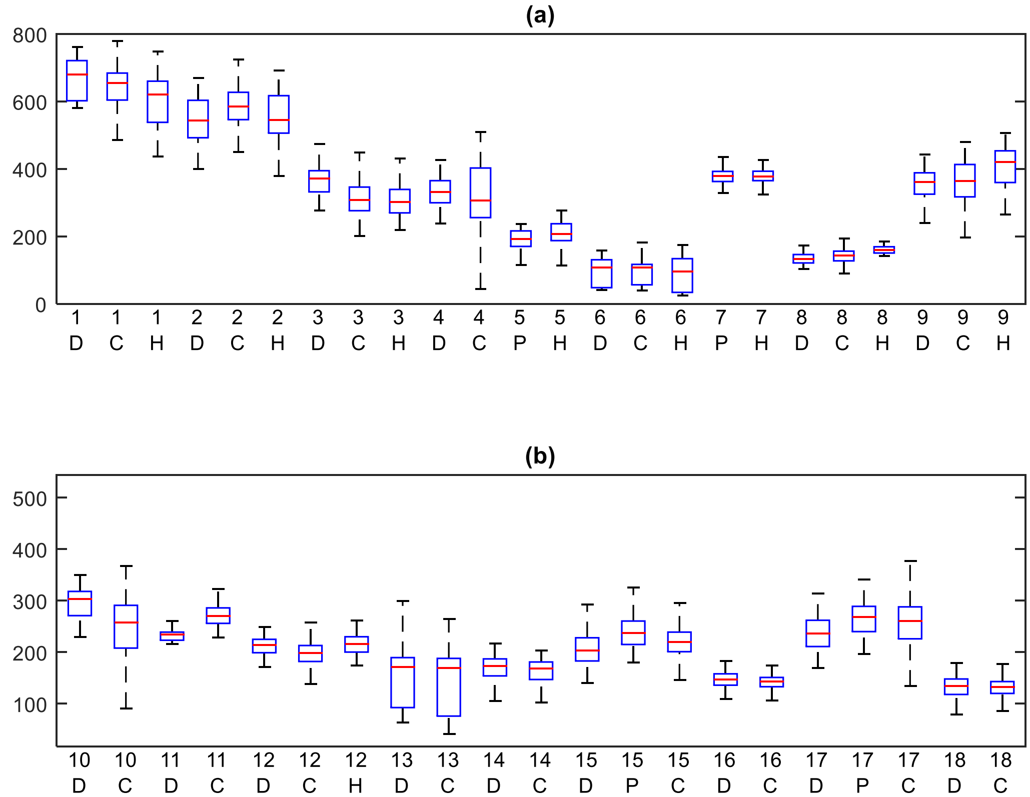
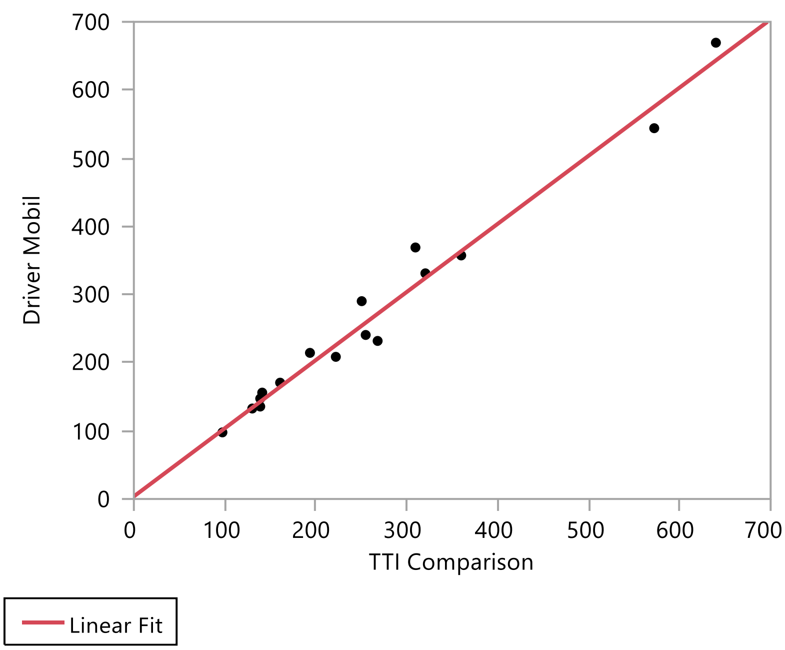


Figure 2. Plot of Retro Values By Section Number and Measurement Type for (a) Section Numbers 1-9 and (b) Section Numbers 10-18

Researchers also compared the mean retro values computed for each Section Name and Measurement Type by least squares fitting. Tables 39 and 40 contain the scatter plots of the mean retro values for each pair of measurements (TTI comparison, Driver Mobile) and (TTI handheld, Driver Mobile) in Table 2, respectively, along with the summary of the fit results. Passenger Mobile could not be compared against other measurement types because of the limited data. (Note from Table 2 that only two pairs of means were available for comparison of Passenger Mobile and either of TTI Comparison or TTI Handheld.) Table 39 shows that the points fall very close to the least squares line with the slope (0.9997) that is almost 1, and the intercept is also not statistically different from 0, which suggests that mean retro values from Driver Mobile and TTI Comparison match very well. The slope (1.06) of the least squares line of Table 40 is also fairly close to 1, and the intercept is also not statistically different from 0, which again suggests that mean retro values from Driver Mobile and TTI Handheld match in general.

Table 39. Bivariate Fit of Driver Mobile By TTI Comparison



Linear Fit

Driver Mobile = 3.7722716 + 0.9997204*TTI Comparison

Summary of Fit

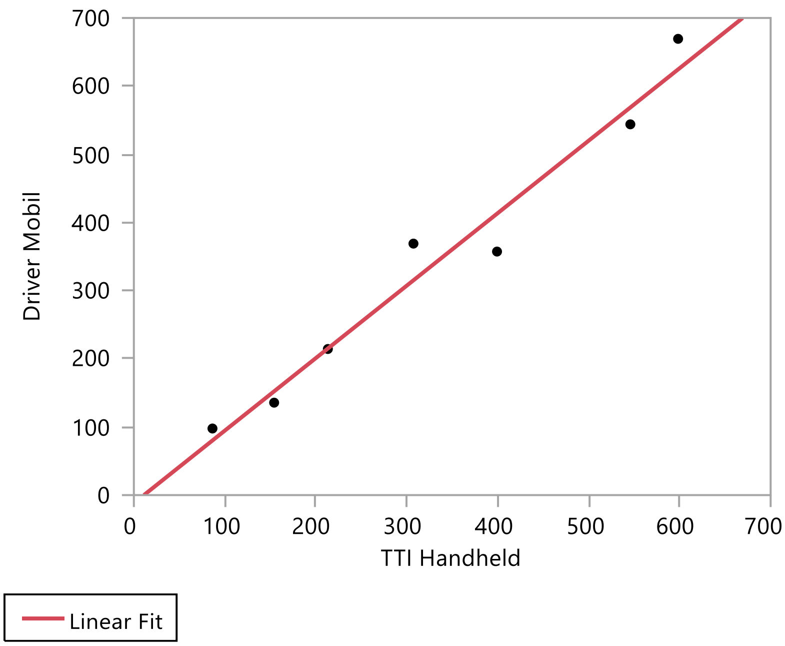
RSquare	0.975592

RSquare Adj	0.973848
Root Mean Square Error	25.36928
Mean of Response	267.0686
Observations (or Sum Wgts)	16

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	3.7722716	12.81066	0.29	0.7727
TTI Comparison	0.9997204	0.042262	23.66	<.0001*

Table 40. Bivariate Fit of Driver Mobile By TTI Handheld



Linear Fit

Driver Mobile = -11.73105 + 1.0634581*TTI Handheld

Summary of Fit

RSquare	0.965863
RSquare Adj	0.959036
Root Mean Square Error	42.68645
Mean of Response	339.5482
Observations (or Sum Wgts)	7

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-11.73105	33.65343	-0.35	0.7416
TTI Handheld	1.0634581	0.08941	11.89	<.0001*

Figures 3 through 6 were developed to further show the comparison between the various Leetron Vision Runs and the TTI handheld and comparison data for several of the test areas. The impact of the lighting condition (cloudy, night, sunny, sunny-glare) will be discussed in the next section. When looking at the various runs it is important to not focus too much on differences between individual data points but more so on the overall trend and values displayed. Due to collecting data from a mobile platform the start and stop point and the exact point of aggregating the data into the points used to create the figures will create some differences in the appearance of the lines.

Figure 3 is from the Snook white skip line area. This area was also the location of the speed and position testing. The data shows that the various data collection time frames follow a similar trend and are close to each other in magnitude.

Figure 3. Plot of Snook White Skip Data

Figure 4 is from the univ eb white skip line area. This area was influenced by the rain between the Leetron Vision cloudy/night data collection and the sunny condition testing. The

TTI Comparison 1 and 2 data show a clear difference in the data between the two data collection periods. The trend for all of the data was consistent and for the most part the overall magnitudes were similar.

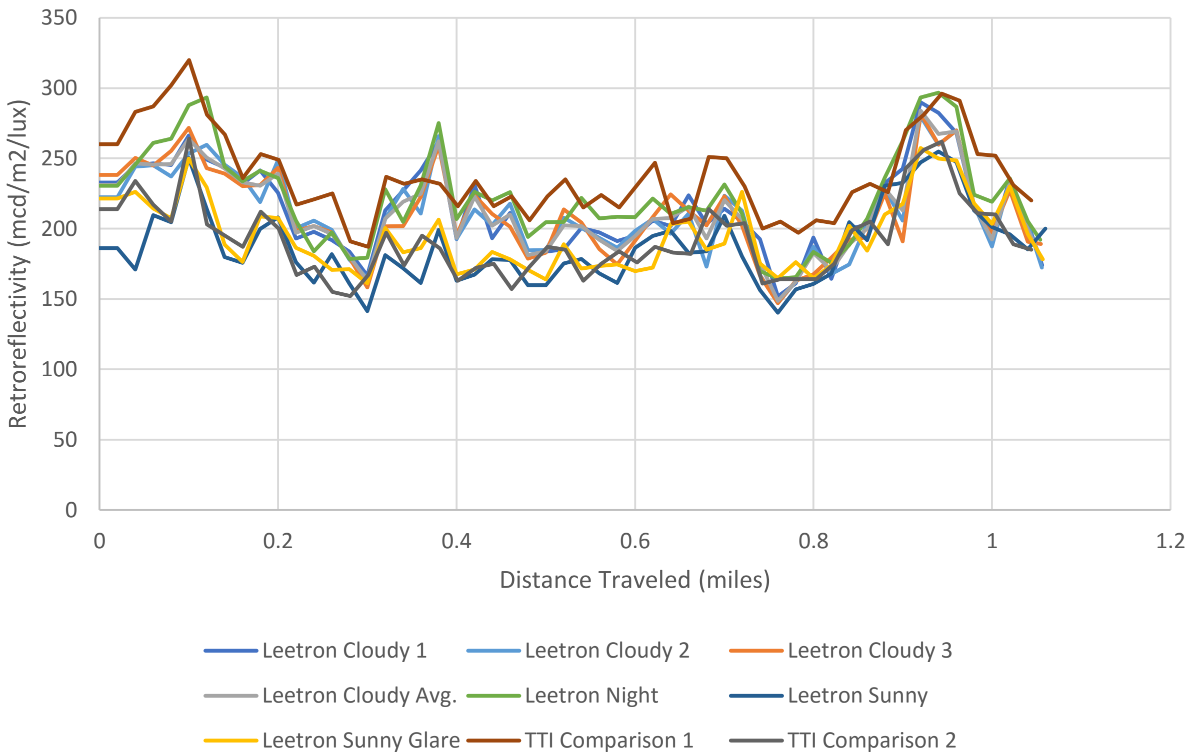


Figure 4. Plot of Univ EB White Skip Data

Figure 5 is from the univ wb yellow solid data collection. Figure 6 is from the leo yellow skip data collection. Both sections showed similar trends in the data collected in the various conditions with the various instruments. In Figure 6 the TTI handheld data does appear to be higher in magnitude than the other measurements systems along the second half of the section. This could be due to the smaller sample size from the handheld data collection, systematic differences between mobile and handheld in this area, or a general error between mobile and handhelds.

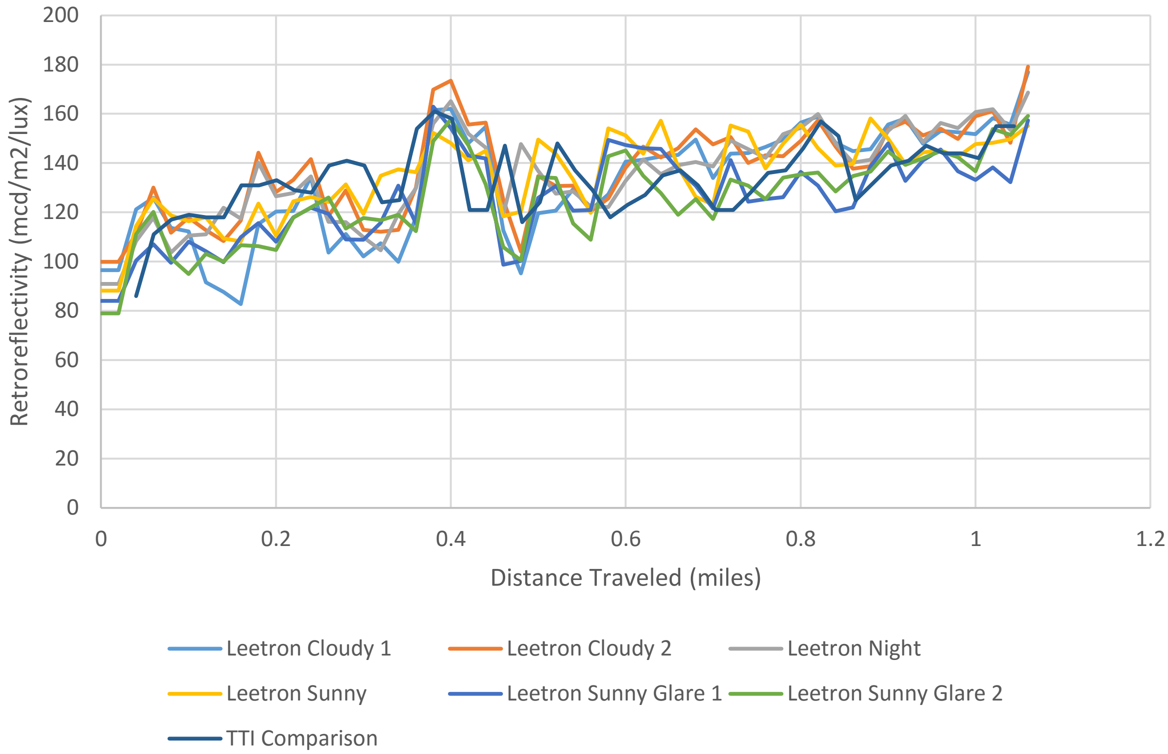


Figure 5. Plot of Univ WB Yellow Solid Data

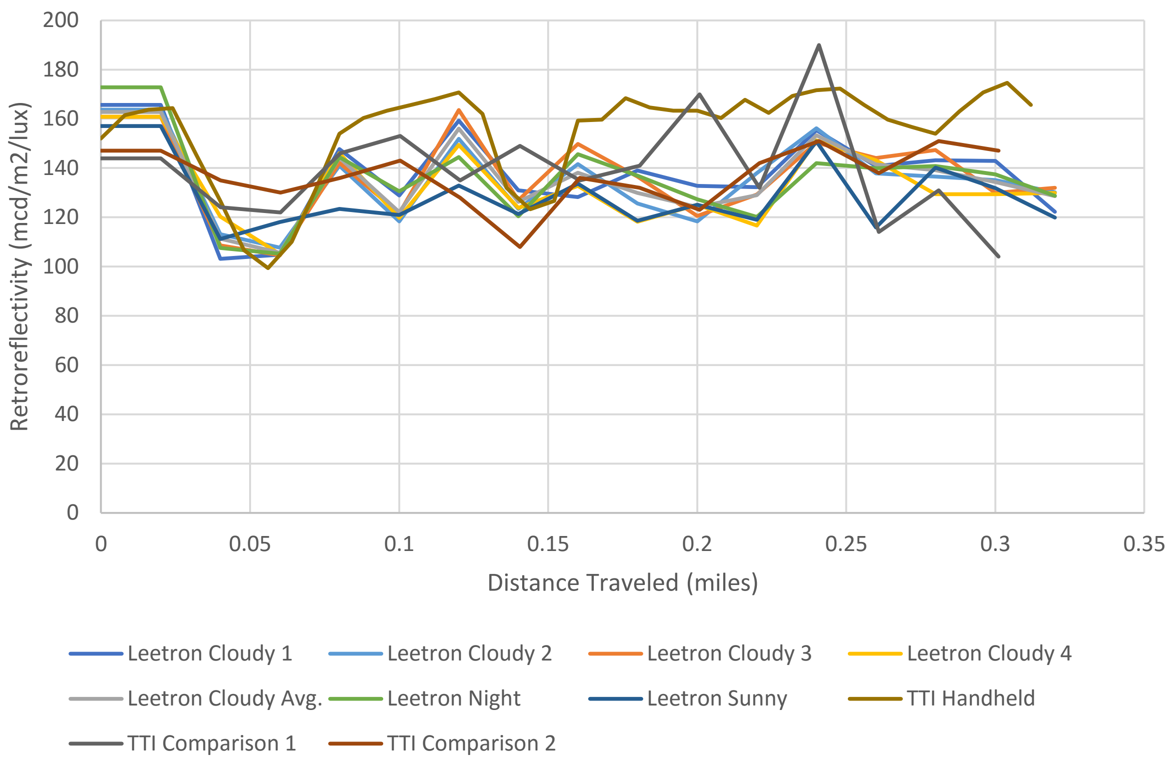


Figure 6. Plot of Leo Yellow Skip Data

2. ***Analysis to assess the impacts of Condition, Speed, and Position on mean retroreflectivity of driver mobile data***

2.1 Impact of Position Based on the Snook Skip Data obtained at 60 mph under the cloudy condition

The evaluation of the impact of Position is made based on the Snook white skip Driver Mobile data only. To avoid confounding with other factors, the subset of the Snook skip data corresponding to Speed Limit=60 (the data for other speed limits were obtained only at the center position) and Condition=cloudy (the data for other conditions were obtained only at the center position). The number of retained observations was N=429. The ANOVA model having Position as a fixed effect and Test as a random effect was applied to the dataset consisting of 429 retro measurements. Table 41 contains the analysis result. It can be observed from Table 41 that the effect of Position is not statistically significant at α=0.05. There does not seem to be a statistically significant difference in mean retroreflectivity across different positions.

Table 41. JMP output for analysis of driver mobile retro values to assess the impact of Position

Response RetroValue
Summary of Fit

RSquare	0.068504
RSquare Adj	0.064131
Root Mean Square Error	22.74265
Mean of Response	168.0163
Observations (or Sum Wgts)	429

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Position	2	2	5.018	0.9019	0.4628

Effect Details
Position
Least Squares Means Table

Level	Least Sq Mean	Std Error
Center	169.43636	3.9057158
Left	171.51818	4.7835054
right	163.81581	3.9353135

2.2 Impact of Speed Based on the Snook Skip Data obtained at the center position under the cloudy condition

The evaluation of the impact of Speed is also made based on the Snook white skip Driver Mobile data only. To avoid confounding with other factors, the subset of the Snook skip data corresponding to Position=center (the data for other positions were obtained only under Speed Limit=60) and Condition=cloudy (the data for other conditions were obtained only under Speed Limit=60). The number of retained observations was N=494. The ANOVA model having Speed as a fixed effect and Test as a random effect was applied to the dataset consisting of 494 retro measurements. Table 42 contains the analysis result. It can be observed from Table 42 that the effect of Speed is not statistically significant at α=0.05. There does not seem to be a statistically significant difference in mean retroreflectivity across different speed levels.

Table 42. JMP output for analysis of driver mobile retro values to assess the impact of Speed

Response RetroValue
Summary of Fit

RSquare	0.042214
RSquare Adj	0.03635
Root Mean Square Error	22.61466
Mean of Response	172.2227
Observations (or Sum Wgts)	494

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Speed	3	3	5.006	0.4995	0.6987

Effect Details
Speed
Least Squares Means Table

Level	Least Sq Mean	Std Error
40	175.11818	4.0463049
50	174.23114	4.0516183
60	169.43636	3.3037941
70	171.52727	4.0463049

2.3 Impact of Light Condition

Figure 7 presents the plot of mean retro values for each condition (shown in different colors) and Test by Section Name. It can be observed that in general the mean retro values measured under different conditions are pretty close to one other.

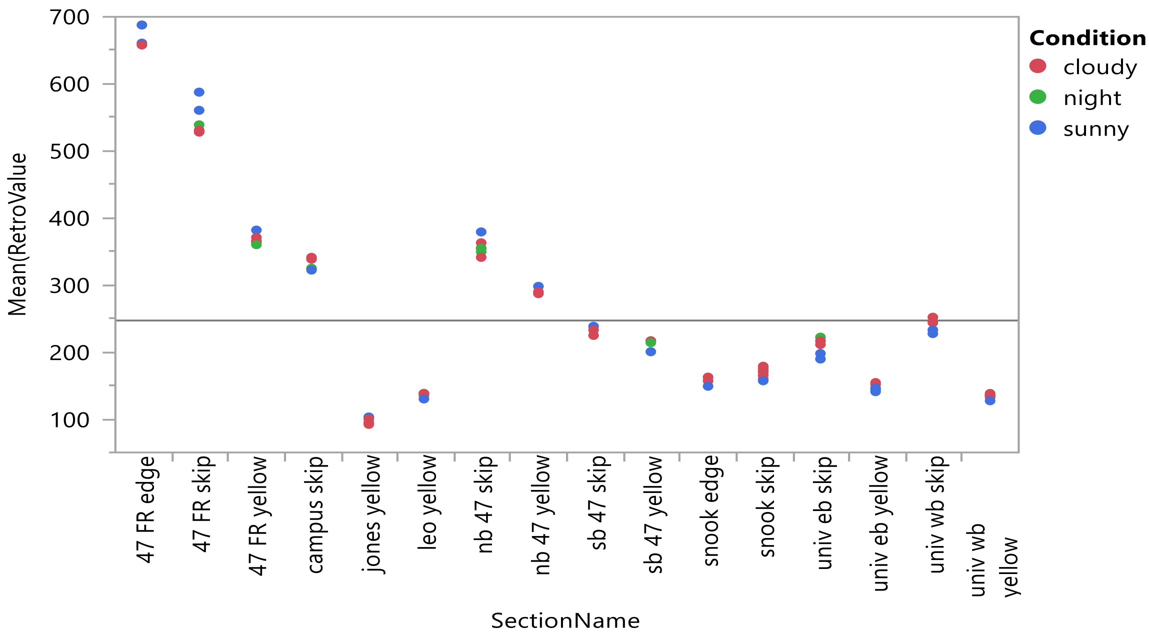


Figure 7. Plot of Mean Retro Values for Different Condition and Test By Section Name

Because it was suspected that the sunny condition will have a varying impact on each individual section depending on the direction of data collection, researchers performed the section-by-section analysis to assess the impact of Condition. Table 43 summarizes the results of the one-way ANOVA tests assessing the impact of Condition (cloudy, night, sunny). It can be observed that for Sections 47 FR skip, sb 47 yellow, snook skip, univ eb skip, univ eb yellow, univ wb skip, and univ wb yellow, the effect of Condition is statistically significant. The difference between the predicted values for cloudy and sunny or cloudy, sunny, and night does not seem to be practically significant, however. As previously mentioned there was a little rain between the cloudy/night measurements and the sunny measurements. The conditions were dry during all measurements, but the rain may have impacted retroreflectivity measurements. TTI conducted comparison tests before and after the rain event and found the impact of the rain was less than ±10 percent for most sections. The univ eb skip, and univ wb skip, both indicated changes of approximately -20 percent. The changes in retroreflectivity, especially for the two noted univ sections, could be part of the explanation for the varying retroreflectivity levels collected by the Leetron system between the cloudy/night and sunny conditions.

Table 43. The results of one-way ANOVA for each segment to assess the impact of Condition (cloudy, night, sunny) for Driver Mobile data

Section Name	P-value for the ANOVA test	Predicted values		
		cloudy	sunny	night
47 FR edge	0.6539	656.200	674.333	
47 FR skip	**0.0379**	526.786	573.120	537.000
47 FR yellow	0.5347	365.257	380.167	358.083
Campus skip	0.0901	339.067	321.467	322.067
Jones yellow	0.7678	95.226	100.250	102.444
Leo yellow	0.3267	135.853	129.235	136.294
nb 47 skip	0.0721	352.294	378.438	349.758
nb 47 yellow	0.4363	286.212	296.294	
sb 47 skip	0.1713	226.813	235.533	
sb 47 yellow	**0.0062**	215.229	199.563	212.406
snook edge	0.2309	157.873	147.426	
snook skip	**< .0001**	170.449	156.315	166.664
univ eb skip	**< .0001**	211.840	191.398	221.963
univ eb yellow	**< .0001**	152.231	142.801	
univ wb skip	**< .0001**	247.269	228.194	
univ wb yellow	**0.0119**	135.111	128.364	134.383

Note: Statistically significant results are shown in bold.

For the university sections (univ eb skip, univ eb yellow, univ wb skip, and univ wb yellow), sunny data were actually collected in two different conditions (sunny and sunny-glare). Researchers conducted the additional analysis comparing sunny, sunny-glare, and cloudy for those sections. Table 44 summarizes the results of the one-way ANOVA tests assessing the impact of Condition (cloudy, sunny, sunny-glare). It can be observed that for Sections univ eb skip, univ eb yellow, and univ wb skip, the predicted value for sunny is not statistically different from that for sunny-glare while both values are statistically different from the predicted value for cloudy. For univ wb yellow, the predicted value for cloudy is not statistically different from the predicted value for sunny although both values are statistically different from the predicted value for sunny-glare. In spite of statistical differences, the differences among the predicted values for cloudy, sunny, sunny-glare, do not seem to be practically significant.

Table 44. The results of one-way ANOVA for the university sections to compare different light conditions (cloudy, sunny, sunny-glare) for Driver Mobile data

Section Name	P-value for the ANOVA test	Predicted values		
		cloudy	sunny	sunny-glare
univ eb skip	**< .0001**	211.840	187.630	195.167
univ eb yellow	**< .0001**	152.231	145.963	141.206
univ wb skip	**< .0001**	247.269	230.870	225.519
univ wb yellow	**0.0005**	134.383	134.648	125.222

Note: 1. Statistically significant results are shown in bold; 2. Shaded values within each section are not statistically different.

3. Analysis to assess the effects of Marking Color and Marking Type on accuracy of driver mobile data compared to the TTI handheld data

Evaluation of the impacts of Color and Type on accuracy of driver mobile data as compared to the TTI handheld data was based on the data from 7 Sections (consisting of 800 measurements) for which both driver mobile data and handheld data were available. Figure 8 presents the plot of those retro values for each of Driver Mobile and TTI Handheld measurement type (shown in different color) by Section Name.

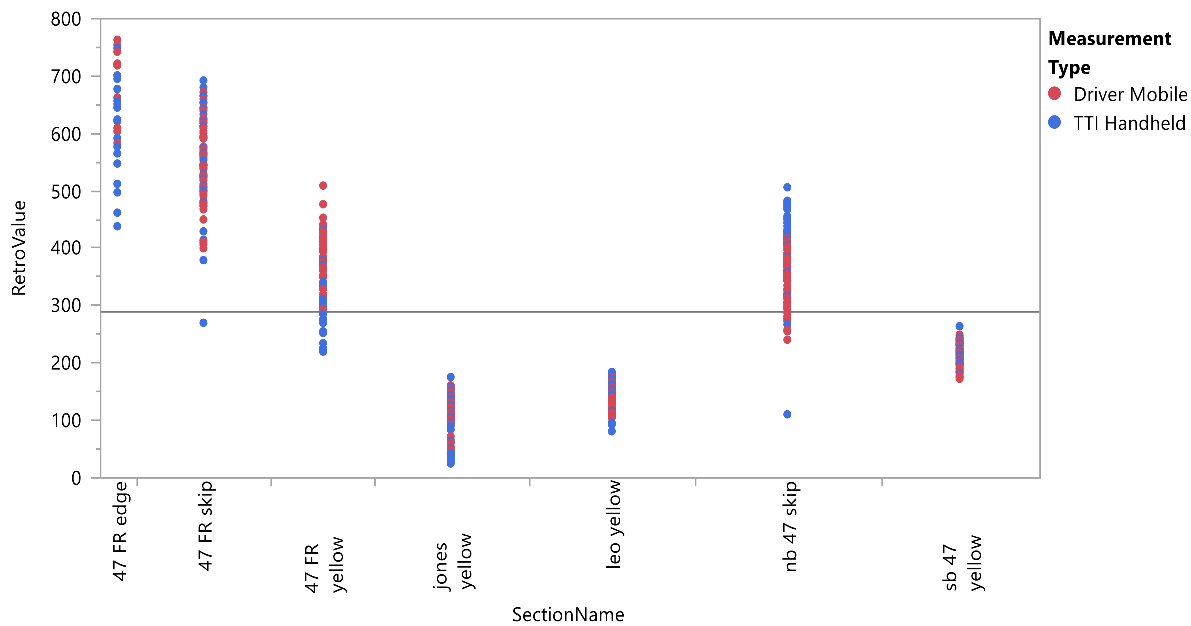


Figure 8. Plot of Retro Values for Different Measurement Type By Section Name

Figure 9 presents the plot of mean retro values for each of Driver Mobile and TTI Handheld measurement type (shown in different color) by Section Name. Except for 47 FR edge, 47 FR yellow, and nb 47 skip, the mean retro values obtained from driver mobile data seem to be close to those obtained from the handheld data.

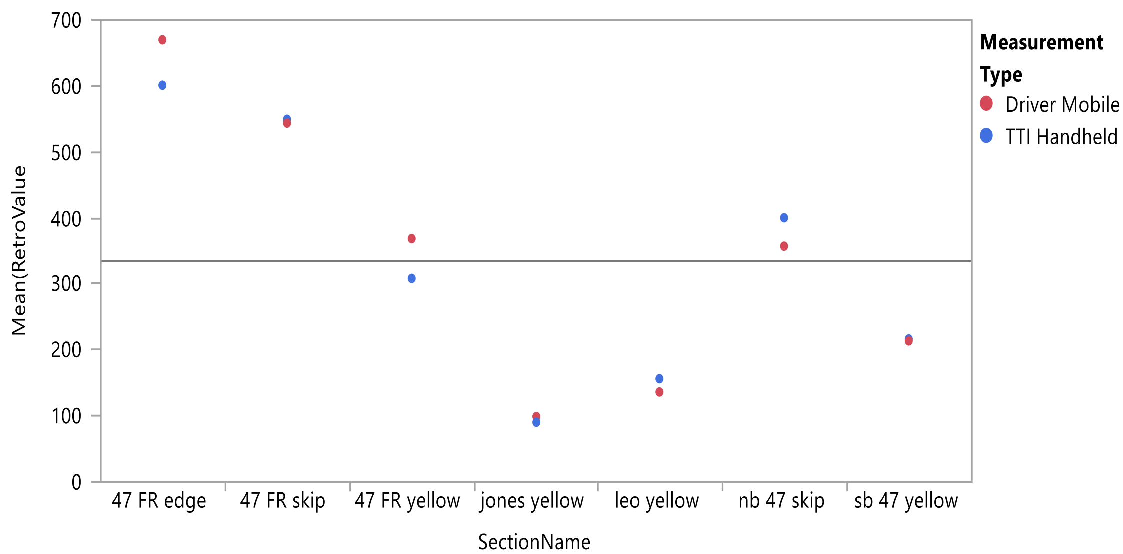


Figure 9. Plot of Mean Retro Values for Different Measurement Type By Section Name

Table 45 summarizes the results of two sample t-tests for equality of mean retroreflectivity for Driver Mobile and TTI handheld as well as the percent error and the absolute percent error computed based on the sample mean retro values of Driver Mobile as compared to those of TTI Handheld. It can be observed that for 47 FR edge, nb 47 skip, leo yellow, and 47 FR yellow, the differences are statistically significant. However, the differences seem to be practically insignificant for all but one section (47 FR yellow).

Table 45. The results of two sample t-tests for equality of mean retroreflectivity for Driver Mobile and TTI Handheld and the percent error and absolute percent error for each marking

Section Name	Color	Type	Driver Mobile	TTI Handheld	P-value for the t-test	Percent Error	Absolute Percent Error
47 FR edge	white	solid	667.9 (n=14)	599.5 (n=17)	**0.0215**	11.4%	11.4%
47 FR skip	white	skip	542.9 (n=81)	547.2 (n=34)	0.8035	-0.8%	0.8%
nb 47 skip	white	skip	355.2 (n=117)	400.0 (n=41)	**0.0006**	-11.2%	11.2%
leo yellow	yellow	skip	134.8 (n=102)	154.6 (n=40)	**<.0001**	-12.8%	12.8%
47 FR yellow	yellow	solid	366.8 (n=59)	308.4 (n=28)	**<.0001**	18.9%	18.9%
jones yellow	yellow	solid	97.6 (n=87)	87.6 (n=45)	0.2339	11.5%	11.5%
sb 47 yellow	yellow	solid	211.7 (n=96)	215.0 (n=39)	0.3590	-1.6%	1.6%

Notes: 1. 'n' denotes the number of measurements; 2. Statistically significant results are given in bold; 3. Percent Error=(Driver Mobile-TTI Handheld)/TTI Handheld; 4. Absolute Percent Error=|Percent Error|.

Table 46 presents the Mean Absolute Percent Error (MAPE) computed as the average of the absolute percent errors for each category of Marking Color or Marking Type. Although the MAPE on yellow (11.2 percent) is greater than MAPE on white (7.8 percent), the difference (which is less than 3 percent) does not seem to be practically significant. The difference between skip and solid is also less than 3 percent and is not practically significant. In summary, the impact of Marking Color or Marking Type on the accuracy of the mobile system does not seem to be practically significant.

Table 46. Mean Absolute Percent Error (MAPE) by Color or Type

	Category	# of Sections	MAPE
Color	white	3	7.8%
	yellow	4	11.2%
Type	skip	3	8.3%
	solid	4	10.9%

Researchers also performed the analyses considering multiple sections together for each category. The ANOVA model having Measurement Type as a fixed effect and Section Name as a random effect was applied to the dataset consisting of 304 retro measurements for white markings. Table 47 shows the analysis result, which indicates that the effect of Measurement Type is not statistically significant at $\alpha=0.05$. Table 47 also contains the predicted mean retro values for each of Driver Mobile and TTI Handheld. Again, it can be seen that the difference between the predicted mean retroreflectivity for Driver Mobile and TTI Handheld is only about 3 percent, which is also considered to be practically insignificant.

Table 47. JMP output for testing the equality of mean retroreflectivity for Driver Mobile and TTI Handheld when the marking color is white

Response RetroValue Color=white

Summary of Fit

RSquare	0.687689
RSquare Adj	0.686655
Root Mean Square Error	68.50906
Mean of Response	460.7566
Observations (or Sum Wgts)	304

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Measurement Type	1	1	300.1	3.1008	0.0793

Effect Details

Measurement Type

Least Squares Means Table

Level	Least Sq Mean	Std Error
Driver Mobile	507.85515	76.509793
TTI Handheld	523.17949	76.640100

Table 48 contains the result of applying the ANOVA model having Measurement Type as a fixed effect and Section Name as a random effect to the dataset consisting of 496 retro measurements for yellow markings. It can be observed from the table that the effect of Measurement Type is statistically significant at α=0.05. The difference between the predicted mean values for Driver Mobile and TTI Handheld does not seem to be practically significant, however.

Table 48. JMP output for testing the equality of mean retroreflectivity for Driver Mobile and TTI Handheld when the marking color is yellow

Response RetroValue Color=yellow

Summary of Fit

RSquare	0.856516
RSquare Adj	0.856225
Root Mean Square Error	35.96472
Mean of Response	184.1835
Observations (or Sum Wgts)	496

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Measurement Type	1	1	491	4.1205	0.0429*

Effect Details

Measurement Type

Least Squares Means Table

Level	Least Sq Mean	Std Error
Driver Mobile	200.99419	55.385543
TTI Handheld	193.87346	55.428111

Next, the researchers tested the equality of mean retroreflectivity between Driver Mobile and TTI Handheld for each of skip markings and solid markings. First, the ANOVA model having Measurement Type as a fixed effect and Section Name as a random effect was applied to the dataset consisting of 415 retro measurements for skip markings. Table 49 presents the analysis result, which indicates that the effect of Measurement Type is statistically significant at α=0.05. The difference between the predicted mean values for Driver Mobile and TTI Handheld (about 7%) does not seem to be practically significant, however.

Table 49. JMP output for testing the equality of mean retroreflectivity for Driver Mobile and TTI Handheld when the marking type is skip

Response RetroValue Type=skip

Summary of Fit

RSquare	0.897312
RSquare Adj	0.897063
Root Mean Square Error	54.35988
Mean of Response	338.4675
Observations (or Sum Wgts)	415

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Measurement Type	1	1	411	16.8516	<.0001*

Effect Details

Measurement Type

Least Squares Means Table

Level	Least Sq Mean	Std Error
Driver Mobile	343.60098	116.76609
TTI Handheld	368.08898	116.83344

Table 50 contains the result of applying the ANOVA model having Measurement Type as a fixed effect and Section Name as a random effect to the dataset consisting of 385 retro measurements for solid markings. It can be observed from the table that the effect of Measurement Type is statistically significant at α=0.05. The difference between the predicted mean values for Driver Mobile and TTI Handheld (about 7%) does not seem to be practically significant, however.

The accuracy of the driver mobile system as compared to the handheld system does not seem to be significantly affected by marking color or marking type.

Table 50. JMP output for testing the equality of mean retroreflectivity for Driver Mobile and TTI Handheld when the marking type is solid

Response RetroValue Type=solid
Summary of Fit

RSquare	0.919679
RSquare Adj	0.919469
Root Mean Square Error	44.66637
Mean of Response	236.2623
Observations (or Sum Wgts)	385

Fixed Effect Tests

Source	Nparm	DF	DFDen	F Ratio	Prob > F
Measurement Type	1	1	380	20.1535	<.0001*

Effect Details
Measurement Type
Least Squares Means Table

Level	Least Sq Mean	Std Error
Driver Mobile	329.43628	116.40467
TTI Handheld	307.56539	116.43015

CHAPTER 3: FINDINGS

A summary and discussion of the findings from the data collection and analysis are provided in this chapter. This testing was designed to evaluate the Leetron Vision mobile pavement marking retroreflectometer across a range of factors. These factors are typically encountered during data collection and their impact needs to be minimized in order to have a system that can continually collect accurate retroreflectivity data across a range of pavement markings in a variety of conditions.

LAB TESTING

The lab testing looked at several variables in a controlled environment using pavement marking samples. Comparing the accuracy of the mobile system to the handheld system had good results. The driver side system did not have statistically significant different mean values than the handheld retroreflectometer. The passenger side system had statistically significant different (lower) results than the handheld retroreflectometer, but this was influenced by the results of two highly retroreflective markings. When those two markings were removed from the analysis the results were better. The difference was still statistically significant but not of practical significance. Position testing did not yield any significant differences for the driver or passenger system. The color of the markings did not have an impact on the test results.

RUNWAY TESTING

The runway testing allowed for testing at speed in a controlled environment. The repeatability of the measurements were good with less than a 2 percent difference between mean values of repeat runs. The means and variances were not statistically significantly different across the subset of repeat runs analyzed. When the driver’s side system and passenger’s side system were used to evaluate the same markings the differences in the data were not statistically significantly different.

Looking at ambient light conditions provided varied results. Day vs night data collection without RRPMs resulted in data that were mostly not statistically significantly different. Some tests were statistically significant but were not practically significant. Dusk vs night data collection with RRPMs resulted in data that were statistically significantly different and practically different. The operator revised the system settings between the two sets of data being collected to better account for the RRPMs. This is the likely cause of the difference between the data sets. The second data set more closely matched the handheld data on the markings.

Position testing for the driver's side yielded a significant impact of position, but was not considered practically significant (it was close to being a practical difference). Position testing for the passenger's side did not yield significant differences.

Data collection on white pavement markings did not yield significant differences between the mobile system (driver or passenger) and the handheld retroreflectometer. Yellow pavement marking data collection (only collected with driver's side) yielded a significant difference to the handheld, but the difference was not considered practically significant. Overall the driver's side data was not significantly different than the handheld retroreflectometer. Overall the passenger's side data was lower than the handheld retroreflectometer.

OPEN ROAD TESTING

The open road testing represents the testing that most closely represents how the system will be used in the field. Typical road surfaces and pavement markings were evaluated in typical data collection conditions. Due to the passenger side unit not functioning during the testing the majority of the analysis was only conducted for the driver's side system.

Overall the driver's side system did not have statistically significant different mean values compared to the TTI handheld or TTI comparison retroreflectivity values. The retroreflectivity trend along the test sections was consistent between the Leetron Visions system and the TTI evaluations. The impact of measurement position on the driver's side data was not significant. The impact of speed on the driver's side data was not significant.

Neither line type (solid or skip), or the road surface appear to be influencing factors. The presence of RRPM's did not impact the open road testing. All of the open road testing was conducted after the operator modified the software to better account for RRPMs.

Data collected during the day with a high sun, during the day with a low sun angle behind or toward the measurement system, during the day in cloudy conditions, and data collected at night showed little difference in average retroreflectivity. The differences for some individual section showed a significant impact of the ambient light conditions but the differences were not practically significant.

The acquire frequency was not tested, because the Leetron Vision system records the raw data and allows that data to be post process at any acquire interval that is desired. This would yield the same data along a test section, regardless of the acquire frequency chosen. Specific software settings were not evaluated, though the operator did modify some setting over the course of the testing as conditions changed. The operator choose the settings they thought were best for the testing being conducted. Due to the weather conditions and the limited time for data collection the impact of temperature was not able to be evaluated.

SUMMARY

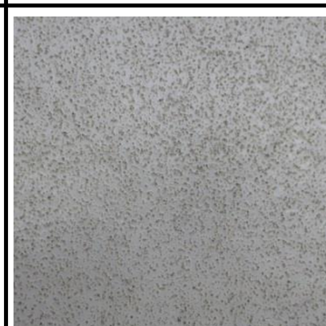
The testing and results described in this report provide quantitative information as to the accuracy and repeatability of data collected with the Leetron Vision mobile pavement marking retroreflectometer across a range of factors. Table 51 provides a summary of the results.

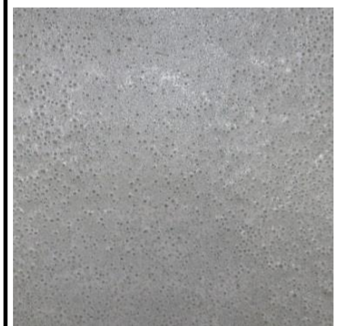
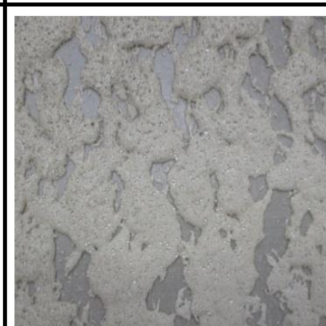
Table 51. Summary of Test Results

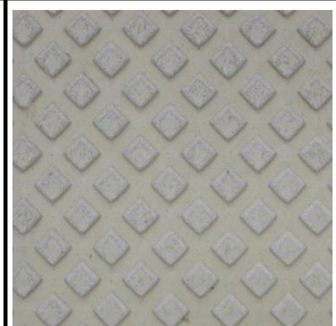
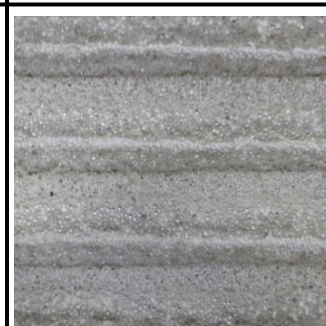
Factor Tested	Impact [1,2]	Notes [1]
Retroreflectivity Level	Not practically significant	In most cases the differences were not statistically significant.
Marking Color	Not practically significant	In most cases the differences were not statistically significant.
Line Type	Not practically significant	In most cases the differences were not statistically significant.
Road Surface Type	No indication that road surface type had an impact	
Data Collection Speed	Not statistically significant	
Drive position Sensitivity	Not statistically significant	

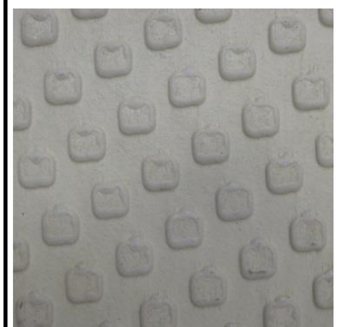
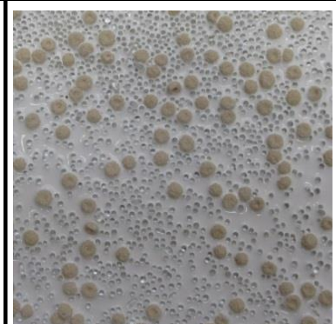
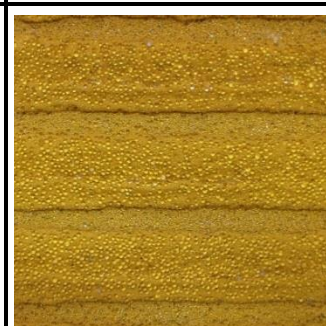
RRPM Presence	Not statistically significant*	*After final RRPM adjustments were made to the system.
Ambient Light	Not practically significant	In most cases the differences were not statistically significant. Some results were impacted by rain on the day between test runs.
Repeatability of Measurements	Not statistically significant	Less than 2% difference in mean values between repeat runs

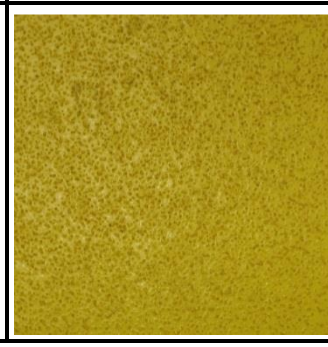
1. Statistical significance determined at a 95% confidence level (or equivalently at a 5% significance level).
2. Practical significance if difference exceeded 15% of the mean retroreflectivity.

Panel	Color	Binder	Beads	Notes	Image
1	W	Epoxy	Type 3	photo luminescent beads	
2	W	Paint	Type 2		
3	W	Paint	Type 3		
4	W	Tape			

Panel	Color	Binder	Beads	Notes	Image
5	W	Epoxy	Type 2 and 3		
6	W	Thermoplastic	Type 2		
7	W	Thermoplastic	Type 3	6 inches wide	
8	W	MMA	Mix with Small High Index	structured marking 6 inches wide	

Panel	Color	Binder	Beads	Notes	Image
9	W	Paint	Type 3		
10	W	Tape		diamond patterned structured tape	
11	W	Thermoplastic	Mix with Small High Index	diamond patterned structure	
12	W	Thermoplastic	Type 1 and 4	inverted profile structure	

Panel	Color	Binder	Beads	Notes	Image
13	W	Tape		square patterned structured tape	
14	W	Epoxy	Type 4 and Cluster		
15	Y	Epoxy	Type 2 and 3	6 inches wide	
16	Y	Thermoplastic	Type 1 and 4	inverted profile structure	

Panel	Color	Binder	Beads	Notes	Image
17	Y	Epoxy	Type 2 and 3		
18	Y	Tape		diamond patterned structure	
19	Y	Tape			

APPENDIX B:
RUNWAY TEST AREAS

Lines 1 (solid white on far left), 2 (yellow skip between solid whites), and 3 (solid white on right)

Line 8 (white skip)

Line 10 (yellow solid)

Lines 14 (skip left/solid right), 15 (yellow skip), 16 (white skip), and 17 (double solid)

Lines 17 (double solid) and 18 (white skip)

Line 24 (white solid)

Line 29 (yellow solid)

Lines 39 (yellow skip) and 40 (white solid on right)

Low Contrast Area, Yellow Skip and White Solid Markings

APPENDIX C:
OPEN ROAD TEST AREAS

47 Frontage Road

Campus Skip

Jones Road


Leonard (Leo) Road

47 North Bound

47 South Bound

Snook

University East Bound

University Westbound

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