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A Pavement Marking Inventory and Retroreflectivity Condition Assessment Method Using Mobile LiDAR – Phase 2

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16. Abstract
FHWA has recently released the new MUTCD, which includes requirements for maintaining minimum levels of retroreflectivity for pavement marking. Such regulatory compliance poses a challenge to agencies because conventional visual inspection methods are labor-intensive, and the results can be subjective. MassDOT has recently completed Phase 1 of this study, achieving two goals: 1) it developed automated methodologies for the identification, classification, and retroreflectivity condition assessment of pavement markings employing emerging mobile LiDAR data, and 2) it investigated the feasibility of understanding and predicting deterioration of pavement marking retroreflectivity conditions. Phase 2 of this study leverages the outcomes from Phase 1 of this study and expands the knowledge of pavement marking and mobile LiDAR technology. The outcome of this study will provide critical guidance for MassDOT to implement its minimum retroreflectivity condition assessment and with useful tools and methods for new pavement marking installation QA/QC.

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Massachusetts Department of Transportation (MassDOT)
and
University of Massachusetts Amherst

A Pavement Marking Inventory and Retroreflectivity Condition Assessment Method Using Mobile LiDAR Phase 2

Final Report

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Disclaimer

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Executive Summary

This study of “A Pavement Marking Inventory and Retroreflectivity Condition Assessment Method Using Mobile LiDAR” was undertaken as part of the Massachusetts Department of Transportation (MassDOT) Research Program. This program is funded by the Federal Highway Administration (FHWA) and State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

This study aims to leverage the outcomes from Phase 1 to expand the knowledge of pavement marking and complete the investigation on the feasibility and performance of the LiDAR-based, automated retroreflectivity condition assessment. The detailed objectives of this Phase 2 study are threefold: to materialize the findings from Phase 1 and expand the scope, leading toward an implementable engineering method to meet the Uniform Traffic Control Devices (MUTCD) regulatory requirements, and more importantly, to provide a consistent, accurate and efficient methodology for MassDOT to evaluate the retroreflectivity of its in-service pavement markings:

- **In-service marking:** to continuously monitor pavement marking retroreflectivity conditions and surface material completeness through 13 of the original 14 testing sites with epoxy, thermoplastics, and polyurea materials and 5 additional testing sites with preformed tape materials. Other properties and types will also be investigated, including wet performance marking, recessed marking, skip lines, and raised pavement marker (RPM).
- **Newly installed marking:** to develop new methods to conduct efficient and effective QA/QC on new pavement marking installation, including the retroreflectivity condition change within 0-6 months from installation and other properties (e.g., color, embedment, and uniformity) change within 0-6 months from installation. The results are summarized to develop a draft standard operating procedure (SOP) for the new installation QA/QC.
- **MUTCD compliance:** to develop a draft SOP for routine in-service pavement marking retroreflectivity measurement that meets the compliance requirement by the MUTCD. In addition, a unified database template for state-wide pavement marking management has been developed to accommodate routine in-service pavement marking assessments.

The outcome of this study is summarized as follows:

- ***A Review of Pavement Marking Efforts***. The research team conducted a detailed, updated literature review of available and ongoing research through TRID on pavement marking inventory and condition evaluation methods and mobile LiDAR applications in pavement marking studies.

- ***Mobile LiDAR Data Acquisition***. The research team conducted comprehensive data acquisition and data preprocessing using two mobile LiDAR systems (i.e., Riegl VMZ-2000 and RESEPI XT32) along with the 18 selected testing sections. The LiDAR data collected in 2023 using the Z+F 9020 system by MassDOT was also incorporated into the final dataset. The collected data covers more than 90 miles of different classifications of highways with different pavement marking material types. For each testing section, three data collections were conducted at a 6-month interval to monitor the deterioration of the pavement markings. Additional data collection with mobile LiDAR, handheld retroreflectometer, and mobile retroreflectometer was conducted at the beginning of the study to develop the method and validate the result.
- ***Automated Pavement Marking Retroreflectivity Condition Evaluation***. The research team further developed several algorithms for correcting retroreflectivity measurements on different properties of pavement markings, including recessed/slotted pavement marking, RPM, and wet performance marking. The research team validated the repeatability and accuracy of the developed method for both solid and skip lines. The results demonstrated a close correlation with the mobile retroreflectometer and superior repeatability over the mobile retroreflectometer. The disparity between the developed method from Phase 1 and the mobile retroreflectometer measurements was attributed to the mismatch of locations from both methods. It has clearly demonstrated the feasibility of the LiDAR-based method for fulfilling the MUTCD requirements as a research-based engineering method.
- ***Pavement Marking Retroreflectivity Condition Deterioration***. The research team utilized the developed automated algorithms and methods and investigated the deterioration trends for the three pavement marking materials in the selected testing sections, including polyurea, epoxy, thermoplastic, and preformed tape. With three 6-month observation windows, initial deterioration trends were established, and the difference in materials was investigated. At comparable AADT levels, deterioration rates varied among different tested materials, but polyurea has a minimum annual deterioration at different levels of in-service retroreflectivity and at a lower initial retroreflectivity. The preformed tape also renders relatively stable deterioration, considering its high initial installation retroreflectivity.
- ***New Installation QA/QC SOP***. The research team has developed a complete SOP for providing QA/QC for the newly installed pavement markings within the first 6 months. This SOP provides a systematic, data-driven approach to early QA/QC of pavement marking installations, combining mobile LiDAR technology with spatial analytics and field engineering insight. Early detection of low-performing segments enables timely corrective action, reduces long-term maintenance costs, and supports safer driving conditions.

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List of Acronyms

Acronym	Expansion
AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society of Testing and Materials
CAV	connected and autonomous vehicles
FHWA	Federal Highway Administration
GIS	Geographic Information System
GPS	Global Positioning System
ICP	Iterative Closest Points
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
LiDAR	Light Detection and Ranging
MassDOT	Massachusetts Department of Transportation
MUTCD	Manual on Uniform Traffic Control Devices
NCHRP	National Cooperative Highway Research Program
QA/QC	Quality Assurance and Quality Control
RoME	Road Marking Extractor
RPM	Raised Pavement Marker
SOP	Standard Operating Procedure
SPR	State Planning and Research
TRID	Transport Research International Documentation

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1.0 Introduction

This study of "A Pavement Marking Inventory and Retroreflectivity Condition Assessment Method Using Mobile LiDAR – Phase 2" was undertaken as part of the Massachusetts Department of Transportation (MassDOT) Research Program. This program is funded by the Federal Highway Administration (FHWA) and State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

1.1 Background

Pavement markings are a vital transportation asset and traffic control device that facilitates safe and predictable driver behaviors. Pavement markings' effectiveness depends on their condition, particularly during nighttime and adverse weather, and MassDOT is actively pursuing new and more durable marking materials. To improve marking performance at a national level, the Federal Highway Administration (FHWA) has released Revision 3 of 2009 Manual for Uniform Traffic Control Devices (MUTCD), which includes new provisions for maintaining minimum levels of retroreflectivity for pavement marking. The later release of the 2024 MUTCD adopted the same language for a minimum level of retroreflectivity for pavement marking. Regulatory compliance poses a challenge, as conventional visual inspection methods are labor-intensive, and the results can be subjective. There is a pressing need for MassDOT to develop and implement an effective, efficient inventory and reliable retroreflectivity condition assessment method for pavement marking.

With the fast-paced advancements in mobile data acquisition and machine learning in recent years, automated roadway asset detection and recognition algorithms using mobile light detection and ranging (LiDAR) have become a feasible option for inventorying critical traffic control devices. As many state DOTs, including MassDOT, have been actively collecting mobile LiDAR data, the accumulated point cloud data has become an excellent data repository to support the development of these algorithms. However, the accumulation of these LiDAR data results in creating an intensive data processing and management burden. Therefore, there is an emerging need for MassDOT to leverage the existing and incoming LiDAR point cloud data and develop an effective pavement marking inventory and condition assessment method.

MassDOT has recently completed Phase 1 of this study, achieving two goals: 1) to utilize emerging mobile light detection and ranging (LiDAR) data and develop an automated method for the localization, classification, and retroreflectivity condition assessment for pavement markings, and 2) to investigate the feasibility of identifying deterioration trend of retroreflectivity conditions. The outcomes of Phase 1 of this study have successfully demonstrated that through the investigation of 14 testing sites (with epoxy, thermoplastic, and polyurea materials) during the 24 months, the developed automated, LiDAR-based methods can accurately and efficiently inventory pavement marking and accurately and repeatably assess the corresponding retroreflectivity condition and surface material completeness. Overall, the developed mobile LiDAR and computer vision-based method has shown promise as a viable alternative to address MassDOT's need to develop and implement an effective, efficient inventory and reliable retroreflectivity condition assessment method for pavement marking. From Phase 1 of this study, the following outcomes and developed tools are readily available for Phase 2 of this study.

- **Automated Pavement Marking Extraction.** Phase 1 developed an automated pavement marking extraction algorithm. The developed algorithm is used to identify the delineations of the pavement markings in the 14 testing sections and establish the spatial references in the final inventory database. The new automated pavement marking extraction was customized to fit the workflow of this study, including longitudinal line extraction, break line linkage, and noise reduction.
- **Automated Pavement Marking Retroreflectivity Condition Evaluation.** Phase 1 developed an automated pavement marking retroreflectivity condition evaluation method through the correlation between the retro-intensity from mobile LiDAR and the retroreflectivity measurements from handheld/mobile retroreflectometer. A customized normalization scheme was created to rectify the retro-intensity measurements based on the distance and incidence angle of the scanning beam.
- **Pavement Marking Retroreflectivity Condition Deterioration.** Phase 1 utilized the developed automated algorithms and methods and investigated the deterioration trends for the three pavement marking materials in the selected testing sections, including polyurea, epoxy, and thermoplastic. With three 6-month observation windows, initial deterioration trends were established, and the difference in materials was investigated.
- **Pavement Marking Management using LiDAR.** Phase 1 has developed a complete methodology for automatically inventorying the location of the in-service pavement markings and evaluating their corresponding retroreflectivity condition and binding material loss, leveraging mobile LiDAR and video log imagery data.

This study aims to leverage the outcomes from Phase 1 of this study, expand the knowledge for pavement marking, and complete the investigation on the feasibility and performance of the LiDAR-based, automated retroreflectivity condition assessment.

1.2 Objectives and Detailed Work Tasks

The detailed objectives of this Phase 2 study are threefold: to materialize the findings from Phase 1 and expand the scope, leading toward an implementable engineering method to meet the MUTCD regulatory requirements, and more importantly, to provide a consistently accurate and efficient methodology for MassDOT to evaluate the retroreflectivity of its in-service pavement markings:

- **In-service marking**: to continuously monitor pavement marking retroreflectivity conditions and surface material completeness through 13 out of the original 14 testing sites with epoxy, thermoplastics, and polyurea materials and additional testing sites with waterborne and preformed tape materials. Other properties and types will also be investigated, including wet performance marking, recessed marking, skip lines, and raised pavement marker (RPM).
- **Newly installed marking**: to develop new methods to conduct efficient and effective QA/QC on new pavement marking installation, including the retroreflectivity condition change within 0-6 months from installation and other properties (e.g., color, embedment, and uniformity) change within 0-6 months from installation. The results will be summarized to develop a draft standard operating procedure (SOP) for new installation QA/QC.
- **MUTCD compliance**: to develop a draft SOP for routine in-service pavement marking retroreflectivity measurement that meets the compliance requirement of the MUTCD. In addition, a unified database for state-wide pavement marking Management will be developed to accommodate the routine in-service pavement marking assessment and the new installation QA/QC.

The detailed tasks completed in this study are listed as follows:

- ***Task 1 - Review of Pavement Marking Inventory and Condition Evaluation Efforts***: The research team conducted a detailed literature review of available and ongoing research and implementation efforts for pavement marking inventory and retroreflectivity condition evaluation that have been made by MassDOT, other transportation agencies, and the research community since Phase 1 of this study, with a particular focus on the new requirement in the MUTCD.
- ***Task 2 - Mobile LiDAR Data Acquisition***: Besides the original 14 testing sites covering epoxy, thermoplastic, and polyurea materials from Phase 1 of this study, the research team identified additional testing sections to cover additional materials of preformed tape and properties of wet performance marking, recessed marking, skip lines, and RPM. The data collection interval of 6 months, the same as Phase 1, is also followed in this phase. In addition, the research team worked with MassDOT to identify new pavement marking installation projects and collect the corresponding mobile LiDAR, imagery, and other

necessary survey data and measurements for the installation QA/QC monitoring. The data collection was conducted during the installation, 1 month after the installation, 3 months after the installation, and 6 months after the installation.

- ***Task 3 - Pavement Marking Retroreflectivity Condition Deterioration Evaluation***: The research team followed the same process as Phase 1 of this study to conduct retroreflectivity condition deterioration evaluation for all the testing sites, covering epoxy, thermoplastic, polyurea, and preformed tape. Additional properties of wet performance material, recessed marking, RPMs, etc., were included within the testing sites, where separate algorithms and results were developed.
- ***Task 4 - New Pavement Marking Installation QA/QC***: The research team developed new methods to conduct QA/QC during and after the new pavement marking installation, including the retroreflectivity condition within 0-6 months from installation. The research team summarized the results from the selected new installation project and developed an SOP for new installation QA/QC.
- ***Task 5 - Pavement Marking Management SOP and Database Development***: Based on the outcome of Tasks 1-4, the research team developed an SOP for routine in-service pavement marking retroreflectivity measurement that meets the compliance requirement of the MUTCD. In addition, the research team developed a prototype database for state-wide pavement marking management that can accommodate the routine in-service pavement marking assessment and the new installation QA/QC. The database should be seamlessly integrated with the existing road inventory file and can be continuously updated by the new field LiDAR survey and new pavement marking installation.
- ***Task 6 - Reporting of Results:*** The research team prepared the final report and the corresponding PowerPoint-based project presentation with all the technical details.

1.3 Organization of this Report

This report is organized as follows. Section 1 introduces the background, research needs, objectives, and the detailed work tasks of this research project. Section 2 presents the proposed method, including the literature review, the developed algorithms for processing mobile LiDAR data for inventory and retroreflectivity condition information extraction, the investigation of the deterioration trends of different pavement marking materials, and the developed SOPs for QA/QC for new installation and in-service pavement markings. Section 3 presents the results of the proposed method. Section 4 summarizes the findings and results of this project and recommendations for future studies.

2.0 Research Methodology

The research methodology for this study consisted of three main parts: a review of existing data and technologies, collection of the mobile LiDAR data, and the processing of the mobile LiDAR data for pavement marking inventory and condition assessment. Section 2.1 presents a review of the literature related to the existing effort for pavement marking inventory and retroreflectivity condition assessment methods, updated from Phase 1 of this study. Section 2.2 presents an overview of the research methodology, followed by Sections 2.3 through 2.8, which describe the methods for mobile LiDAR data acquisition and processing for pavement marking extraction, retroreflectivity condition evaluation, and surface condition evaluation.

2.1 Literature Review

2.1.1. Pavement Markings

The roadway network throughout the night appears significantly different from the network during the day. Road markings provide drivers with a level of expectancy, where the organization of the roadway, including road markings, provides drivers with an expectation of their driving behaviors (1). During the daytime, drivers may not have issues understanding roadway conditions; however, daylight is no longer available for drivers to perceive and understand roads at night fully. The difference between lighting conditions is also reflected in the differences between fatalities between the day and night. In 2021, about 60% of fatalities in urban areas occurred at night, and about 44% of fatalities in rural areas occurred at night (2). Visibility concerns are related to motor vehicles and more vulnerable groups, such as pedestrians. Pedestrian fatalities in 2021 saw around 77% of fatalities occurring at night (3). Pedestrian conspicuity may be a concern, where pedestrians at night may face issues with drivers noticing them (4), which could be resolved through the retroreflectivity highlighting pedestrian crossings. As such, it is important to monitor, improve, and maintain the roadway infrastructure that aids nighttime traffic safety. Research shows that the retroreflectivity of pavement markings and signs increases the distance of visibility and clarity of perception for drivers at night (5,6). Road users may benefit by using standardized practices revolving around visible infrastructure like pavement markings (7).

The MUTCD notes that the visibility of pavement markings can be adversely impacted by snow, debris, and water on or near the markings (8). Oregon DOT has identified several factors that influence the visibility of pavement markings, which include: infrastructure condition, pavement marking locations, placement quality, usage, material, color, contrast, design, condition, configuration, width, pattern, raised pavement markers, retroreflectivity, and local snow removal practices (9). Other studies have further explored these factors. For color, immediately noticeable colors, such as white, may stand out better than other colors, such as black (10). A combination of different factors may also impact visibility, such as contrast and distance, where more contrast is required for objects further away to be noticed (11). The increased width of pavement markings and continuous markings have been linked with increased driver sight distances (6).

Visibility has been heavily considered to be related primarily to human perception; however, as vehicle automation improves in the coming years, infrastructure accommodating sensors could also be considered. Past research has shown that automated vehicles may also rely on the ability to detect road markings to behave expectedly. Road marking complexity, for instance, although understandable through human perception, may have issues with machine vision for camera detection (12). Like human perception, machine vision using cameras or LiDAR can have issues due to other factors like the type of markings present and weather conditions. Flat pavement markings may not be as detectable due to rain-decreasing contrast and lack of drainage. In contrast, structured pavement markings, which may allow for drainage, may have less water present, reducing water's impact on perceiving road markings (13).

These limitations to the perception of pavement markings describe many variables that could contribute to a traffic crash, including the retroreflectivity of the markings. This literature review discusses pavement markings, retroreflectivity, and mobile LiDAR to illuminate the asset management potential for mobile LiDAR to assess pavement marking conditions across a transportation network.

The pavement marking materials used vary based on the anticipated conditions on the roadways and the budget of the managing agency. Factors such as durability, cost, and environmental impact may play a role in deciding what material to use (14). Paints, thermoplastics, and tapes are common and can be supplemented with raised pavement markers and colored markings. The guidance provided by the MUTCD for material selection states that the materials should maintain their specified color throughout their life cycle and that markings should not contribute to a loss of vehicle traction in the roadway (8).

MUTCD has undergone several revisions since the 2009 version was initially released. Revision 3, released in late 2022, establishes legal minimum standards on retroreflectivity for pavement markings. Before this revision, legal standards behind the minimum retroreflectivity had not been established. However, this revision was incorporated into the MUTCD to ensure pavement marking visibility (8). The costs of implementing such a standard have been analyzed, and it has been determined that because the rule's lifesaving capacity outweighs costs, the rule has been implemented. Standards declare that retroreflectivity must be maintained above 50 mcd/m^2/lx underneath dry conditions for roadways with speeds of 35 mph or greater. Guidance declares that retroreflectivity should be maintained above 100 $mcd/m^2/lx$ underneath dry conditions for roadways with 70 mph or greater speeds. Some exclusions include roadway markings with sufficient ambient lighting or having traffic volumes of less than 6,000 vehicles per day. The MUTCD states, “Markings that must be visible at night shall be retroreflective unless ambient illumination assures that the markings are adequately visible. All markings on Interstate highways shall be retroreflective” (8). Guidance is also provided for retroreflective raised pavement markings concerning spacing and design. The newly released 2024 MUTCD adopted the same language as the Revision 3 of the 2009 MUTCD for maintaining minimum levels of retroreflectivity for pavement markings.

2.1.2. Retroreflectivity

Due to the conservation of energy, all emitted light is either reflected, absorbed, or transmitted. The percentages of reflection, absorption, and transmission are a function of the material the light reaches. The reflected light from roadway objects is the focus of this research, and it begins with the concept of bi-hemispherical reflectance, which states that reflected light is distributed over all viewing angles. This perspective is important when studying how much reflected light reaches a driver’s eye. The bi-directional reflectance distribution function quantifies this by accounting for the diffusion of reflectivity with two (5) variables that define the direction of the sensor or observer and two (5) variables defining the direction of the light source relative to the normal plane (17).

Reflective cases include retroreflective, perfect diffuse reflection, and perfect specular reflection. Retroreflection reflects light to the source along the same approach angle and occurs with glass beads and reflectors designed for this purpose. Diffuse reflection scatters the approaching light equally in all directions and occurs with rough or matte surfaces. Specular reflection reflects light away from the source at an equal angle to that of its approach and occurs with mirrors and reflective metals (18,19). Luminance is a measure of the amount of light in a given area visible to an observer from a given viewing angle. It is given in milli candelas per square meter (mcd/m^2). At the same time, illuminance measures how much light illuminates the surface. The ratio of luminance to illuminance in units of candelas per square meter per lux ($mcd/m^2/lux$) is a measurement of retroreflected luminance (20).

Retroreflectivity is greatly affected by environmental factors. The presence of water during or after rainfall can significantly reduce the retroreflectivity of the objects along the road (21-24). This is primarily due to increased specular reflection caused by water films on retroreflective surfaces (21,25). Additionally, the presence of water causes refraction along with the retroreflective objects, which can change the angle of reflection and reduce the amount of light reflected at the driver (19,23,25). Water droplets themselves can reflect, absorb, or transmit light internally, altering the angles and quality of the light exiting the water droplet. Research efforts have suggested that it may be possible to predict the performance of a retroreflective object in wet conditions based on its performance in dry conditions. Still, more testing is needed to develop it further (22).

Although a derivation of wet condition retroreflectivity may not yet be completed, methods of minimizing the impact of watery conditions have been explored. One instance could be by changing the structure of the pavement markings. Traditional pavement markings may be flat, meaning they may be submerged in water, causing issues with perception. Some of these issues are alleviated by changing this structure to incorporate drainage. One method is by adding verticality to markings (13), while another may be to change the method of paint application, where instead of fully painting lines, dots could be applied, allowing for the raised section to protect glass beads on the sides of the dot increasing durability, while also allowing for drainage (26). These different methods carry various outcomes for retroreflectivity, which may prove useful for studying more in-depth under varying conditions.

Traffic, maintenance activities, weather, orientation, and precipitation all contribute to the gradual degradation of the retroreflectivity of pavement markings (20,27). The first year of service life for pavement markers sees a loss of 33-40% of initial retroreflectivity, where the loss of wet retroreflectivity occurs at a higher rate than that of dry retroreflectivity (6). As such, inspecting facilities is necessary to determine the remaining effectiveness of the retroreflective objects, and it can serve as a cost-saving measure to prevent premature replacement of those objects. Manual visual nighttime inspections and retroreflectometers are two common types of asset inspection.

- ***FHWA-SA-22-028***: This report provided guidance for maintaining minimum in-service retroreflectivity for longitudinal markings, which increase with higher roadway design speeds (15).
- ***FHWA-SA-22-029***: Methods are identified for assessing the economic impacts of minimum retroreflectivity standards by comparing the life-cycle costs of different materials (16).

Standards ASTM D7585-10 and ASTM E1710-18 provide guidance for evaluating the retroreflectivity of pavement markings with hand-operated instruments and a portable retroreflectometer, respectively (30, 31). These instruments are not oriented for mobile use and primarily serve to check individual locations rather than monitor the infrastructure as a continuous network. However, ASTM E3320-21 provides guidance on using a mobile retroreflectometer intended to be operated at traffic speeds in dry conditions (32). Although ASTM E3320-21 may have the potential to be adapted to collected data for wet conditions, a standard defining mobile data collection of wet road conditions has yet to be defined. A standard defining the specifics behind using mobile LiDAR for pavement marking information collection also remains undefined.

2.1.3. Mobile LiDAR

LiDAR technology measures distance by emitting laser light and monitoring the reflection of that laser light with a sensor. As these LiDAR devices can be precisely located in space, the three-dimensional imagery created with the sensor is geolocated. It has applications in surveying, asset management, and research fields. The scale of the data collected can vary depending on the sensors used and the method of collection employed in the field, ranging from flyovers of entire neighborhoods to crack detection in pavements. This vast expanse of data can be gathered in a fraction of the time it would take to manually survey similar areas of interest. For highly accurate and detailed data, LiDAR collection can be done with multiple passes of the area of study, which improves the geolocation quality and allows for the averaging of multiple data sets (33).

As previously discussed, traditional retroreflectivity testing requires manual inspection or individually operated portable tools, which expose field crews to the dangers of moving traffic. Mobile LiDAR and remote sensing may be viable alternatives, allowing inspectors to analyze a site while driving through it or standing offsite and observing, respectively. This improved safety metric makes mobile LiDAR inspections very appealing for state DOTs.

In addition to mapping geometric data, LiDAR tracks the intensity of the laser light returned to the sensor, providing valuable information regarding the reflectivity of objects in the study area. These intensity values require calibration and processing before they can be used to assess the reflectivity of objects, as they are affected by environmental and procedural variables like laser range, power, angles, receiver aperture, system and atmospheric transmittance, and beam divergence (34–38). This calibration was categorized into levels ranging from zero to three by Kashani et al., which include raw intensity (no correction), intensity correction, intensity normalization, and rigorous radiometric calibration. Another classification method separates the methods into theoretical or model-driven and empirical approaches (39).

A consideration for data collection would be a potential standardization or guidance for the physical deployment of LiDAR units, where intensity data calibrations, which may be dependent on angle, distance, and various other factors, may have more variation depending on the configuration used by individual practitioners. Depending on the means of data extraction, the actual deployment may lead to a loss in data quality if optimal setups are not explored and used (40). Comparing intensity data from LiDAR to infrared retroreflectivity collected by a retroreflectometer, intensity data under some conditions may be positively related to the retroreflectivity seen from pavement markings, opening the potential for intensity data to be from LiDAR data collections in place of mobile reflectometers (41).

The theoretical approaches involve manipulating the laser range equation to account for the environmental and procedural variables. Research efforts have led to the development of various laser range equations (34–36,42–44). Because the source and sensor for the lasers are very close together in LiDAR equipment, the intensity output is a measurement of the retroreflectivity of the objects detected. As such, mobile LiDAR equipment functionally serves as a microcosm for retroreflectivity in the driver’s eye. Automated methods for identifying the location of pavement markings within these large data sets begin by first extracting the roadway extends from extraneous data beyond the edge of the pavement. Guan et al. reviewed the different extraction methods. They identified that most methods rely on aspects of roadway geometry, but others have overlaid other data sources like video, maps, and airborne data to verify pavement extents (45). A combination of factors such as color, intensity, and distances between relevant points have been used to extract pavement markings by type. However, due to the variation of intensity data or disregard for retroreflectivity, retroreflectivity was not derived for these markings (46,47).

The results of this data collection are often projected onto a two-dimensional plane for analysis, where detection thresholds are applied to identify pavement markings (48–53). Because of this two-dimensional projection, the results can be skewed by the distance from the sensor to the pavement marking in question. On such occasions, researchers have normalized the intensity values by the distances and angles of these more distant data points (54–58). Rather than adjusting the recorded intensities, some researchers have made the thresholds for detection dynamic concerning distances and angles (40,59,60). Once these thresholds have been identified and applied, morphological operators are used to cluster the pixels of the resultant image. Additional parsing has been done to classify the pavement markings by their geometry and orientation (48–50,54,57,59–61). Of these methods reviewed, some successfully classified specific pavement markings. The research of Zhang et al. 2016 successfully classified sixteen (29) varieties of pavement markings with a combination of a linearly modeled intensity correction method and region-grow image processing (54).

Researchers have been able to analyze the LiDAR point cloud data directly without image processing. While the precision of the results is better maintained, the processing time and costs were prohibitive in those cases (56,61–63). However, the technology is improving in assessing point cloud data efficiently. More recently, Jung et al. used point cloud data to develop an algorithm of marking parameters to identify roadway markings, even when the markings were incomplete or degraded (64). Algorithms have also been developed that extract pavement lane markings from point clouds with an 88% success rate (65). Other algorithms have also succeeded in dealing with worn or incomplete markings, successfully extracting 12 types of road markings in an urban environment (66). Three-dimensional laser profiling data has been used with 90.8% accuracy to detect and identify different roadway markings, but no condition assessment was completed with this method (67). Other methods have extracted condition assessments of roadway markings. However, these may not directly determine retroreflectivity but use empirical data to determine different levels of deterioration, where highly deteriorated markings would correspond to markings under 100 $mcd/m^2/lx$ based on empirical data (68). Mobile LiDAR has been successfully employed to assess the retroreflectivity of roadway signs with a combination of theoretical and empirical techniques (69,70). Mobile LiDAR has also successfully been used to determine the retroreflectivity of roadway markings. However, in the methodology used, limitations on the range of retroreflectivity were found due to the data collected, where the model could only predict a limited range in retroreflectivity due to saturation in the data used. Although successful with white paint markings, in the case of yellow paint markings, the upper range of measurable retroreflectivity was 80 $mcd/m^2/lx$, which would be lower than the guidance provided by the MUTCD for retroreflectivity, meaning that the proposed method may be unable of identifying all pavement markings needing maintenance (71).

2.1.4. Summary

Retroreflectivity testing with mobile LiDAR has been undertaken primarily in controlled environments and has produced variable results. Though many factors can impact the quality of the data collected, there is a need for standardization with the approaches for acquiring and processing these data to produce reliable results on a network scale. The benefits of this technology for asset management applications have not been fully realized. Repeated scans allow the functional life cycle of pavement markings to be better understood and managed without premature sweeping replacements.

There is not enough research regarding the calibration of mobile LiDAR for retroreflectivity testing. While radiometric calibration has been discussed in the literature, it has focused either on specific pieces of equipment or on obtaining other types of information. Though helpful, these studies do not directly relate to the task at hand, and research that directly addresses retroreflectivity with a broader range of equipment would assist DOTs with beginning to incorporate mobile LiDAR to this end. There is a need to leverage the capability of mobile LiDAR to study how it can help automatically inspect the retroreflectivity of pavement markings and to monitor its deterioration.

2.2 Overview of the Proposed Methodology

In this study, the research team adopted the same processing methodology for pavement marking condition evaluation. Figure 2.1 shows an overview of the proposed method, the same as Phase 1. For data acquisition, the research team collected comprehensive video log image data, mobile LiDAR point cloud data, and the metadata for the 19 testing sites selected by the MassDOT engineer. For the processing methods, the research team developed three automated algorithms to extract pavement marking from point cloud data, evaluate the corresponding retroreflectivity condition, and extract the surface condition of the corresponding pavement marking from the video log images. By leveraging Phase 1's outcome, the research team further developed additional algorithms for extracting and assessing retroreflectivity conditions of different pavement marking properties, such as wet performance, solid and skip lines, recessed markings, RPM, etc.

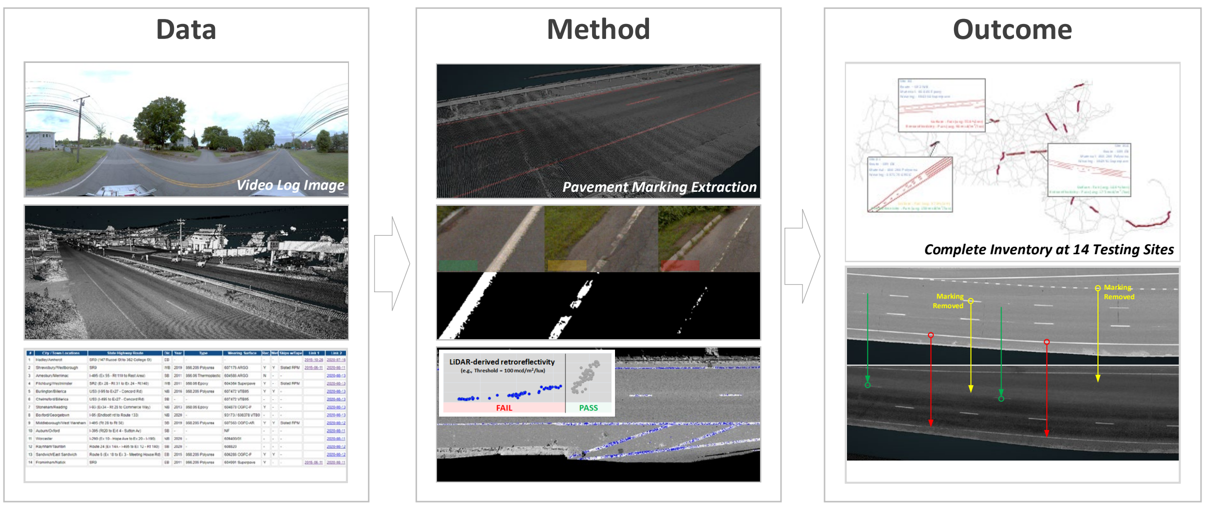


Figure 2.1: Overview of the proposed methodology

2.3 Data Acquisition

In this study, 13 out of 14 testing sites from Phase 1 and 5 additional testing sites for this phase were selected by MassDOT to include distinctive characteristics of the pavement markings so that the overall feasibility of the LiDAR-based method can be comprehensively conducted. The original Site #1 was dropped for logistical reasons. Figure 2.2 shows the details of the selected testing sites and their corresponding locations.

The 18 representative testing sections cover different roadway classifications (including seven state highways, three US highways, and eight interstates), different pavement marking materials (including thermoplastic, polyurea, epoxy, and preformed tape), and different special properties (seventeen sections with recessed markings, thirteen sections with wet performance markings, and fourteen sections with RPMs).

	#	City / Town Locations	State Highway Route	Dir.	Year	Material		Rec.	Wet	RPM
						Edge	Skip			
	2	Shrewsbury/Westborough	SR9 (S Quinsigamond Ave to I-495)	WB	2019	Polyurea	Polyurea	Y	Y	Y
	3	Amesbury/Merrimac	I-495 (Ex 55 to Rt 110 to Rest Area)	SB	2011	Thermo	Thermo	N	N	P
	4	Fitchburg/Westminster	SR2 (Ex 28- Rt 31 to Ex 24- Rt140)	WB	2011	Epoxy	Epoxy	Y	N	Y
	5	Burlington/Billerica	US3 (I-95 to Ex27- Concord Rd)	NB	2016	Polyurea	Polyurea	Y	Y	N
	6	Chelmsford/Billerica	US3 (I-495 to Ex27- Concord Rd)	SB	2015	Thermo	Thermo	Y	Y	N
	7	Stoneham/Reading	I-93 (Ex34- Rt 28 to Commerce Way)	NB	2013	Epoxy	Epoxy	Y	N	N
Phase 1	8	Boxford/Georgetown	I-95 (EndloottRd to Route 133)	NB	2020	Thermo	Tape	Y	Y	Y
	9	Middleborough/West Wareham	I-495 (Rt 28 to Rt 58)	SB	2019	Polyurea	Polyurea	Y	Y	Y
	10	Auburn/Oxford	I-395 (Rt20 to Ext 4- Sutton Ave)	SB	2012	Polyurea	Tape	Y	N	Y
	11	Worcester	I-290 (Ex 10- Hope Ave to Ex 20- I-190)	NB	2020	Polyurea	Tape	Y	Y	N
	12	Raynham/Taunton	SR24 (Ex 14A - I-495 to Ex 12- Rt 140)	SB	2020	Polyurea	Tape	Y	Y	Y
	13	Sandwich/East Sandwich	US6 (Ex 18 to Ex 3- Meeting House Rd)	EB	2015	Polyurea	Polyurea	Y	Y	Y
	14	Framingham/Natick	SR9 (I-90 to Grove Rd)	EB	2011	Polyurea	Polyurea	Y	N	P
	15	Milford	I-495 (Ex67- Rt 62 to Ex50- Rt 85)	SB	2022	Tape	Polyurea	Y	Y	Y
	16	Worcester	I-290 (Ex19- Shrewsbury to Ex24- Plantation St)	EB	2022	Tape	Polyurea	Y	Y	P
Phase 2	17	Middleborough	I-495 (Ex19A- Rt 24 to Ex 15- Rt 44)	SB	2021	Tape	Polyurea	Y	Y	Y
	18	Gardner	SR2 (Ex83- Rt 101 to Ex90 Rt 140)	WB	2022	Tape	Polyurea	Y	Y	P
	19	Peabody	SR128 (Ex29- I-95 to Ex41- Endcott St)	NB	2022	Thermo	Thermo	Y	Y	Y

Figure 2.2: Details and locations of the selected testing sites

The data acquisition system used in this study is an integrated mobile LiDAR system, RIEGL VMZ-2000, which consists of three primary components, including the LiDAR sensor, the precise positioning system, and the camera system. Figure 2.3 shows the overview of the data acquisition system used in this study (left: overview; middle: camera and mobile LiDAR; right: control panel). The same sensor was used in Phase 1 of this study.

Figure 2.3: Integrated data collection vehicle with RIEGL system

Additional data collection was also carried out using two other sensors, including RESEPI XT32 (representing the low-coast solution) and Z+F 9020 (representing the current MassDOT's LiDAR instrumentation. Figure 2.4 shows the configuration of these two sensors.

Figure 2.4: Integrated data collection vehicle with RESEPI (L) and Z+F (R) systems

2.4 Pavement Marking Extraction and Retroreflectivity Condition Evaluation

In this phase, the same pavement marking extraction and retroreflectivity condition evaluation methods were adopted as reported in Phase 1 of this study, whereas the pavement marking extraction method was customized based on the RoME method developed by Oregon State University (46) and the retroreflectivity evaluation method was calibrated based on the patented method developed by Georgia Institute of Technology (49, 50). The same theoretical-empirical model was adopted to build the look-up table for the translation between LiDAR retro-intensity and retroreflectivity.

However, one of the key developments in this phase is to adjust the scanning pattern of the LiDAR sensors, especially for RESEPI, whose scanning patterns are different from those of the RIEGL and the Z+F LiDAR sensors. Figure 2.5 shows the scanning angle adjustments using the look-up table from previous studies. The figure illustrates different combinations of incidence angles and scanning ranges for the same section of roadway and how they affect the normalization results. As the XT32 sensor in the RESEPI system uses a 360-scanning fan (+15 degree to -55 degree), each beam of the scan requires a more detailed normalization adjustment within the same scanning frame.

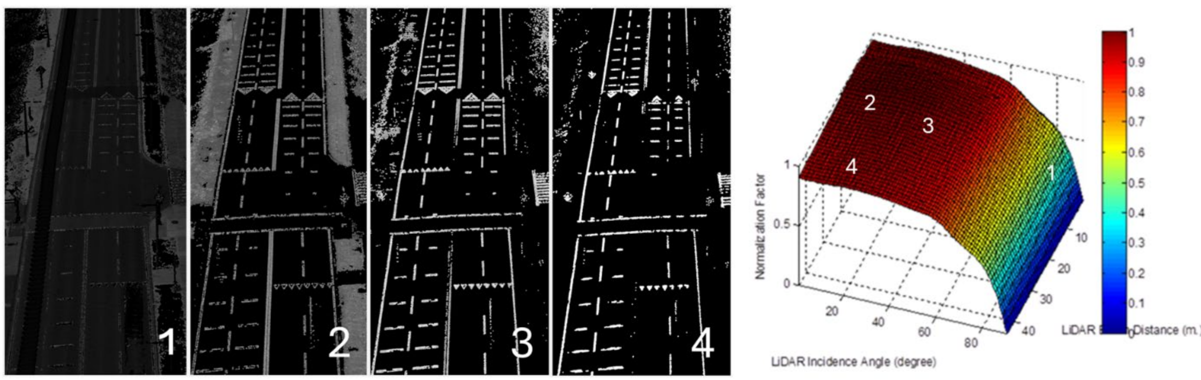


Figure 2.5: Examples of how incidence angle impacts retroreflectivity measurements

2.6 Special Processes for Pavement Marking Attributes

The objective of special processes for pavement marking is to describe in detail how the customization of the algorithms or the adjustments in models are introduced for processing different pavement marking attributes of interest, including recessed/slotted marking, RPM, wet performance marking, etc.

2.6.1 Recessed/Slotted/RPM Marking

The processing of recessed or slotted pavement markings and RPMs requires distinct methodologies due to their unique physical configurations and their impact on sensor-based retroreflectivity measurements. Recessed markings are often implemented to extend the lifespan of pavement markings, particularly in regions exposed to heavy snowplow activity. These markings are embedded below the road surface, which changes the interaction angle between incident light and the marking surface. However, this impact varies depending on the marking type. For recessed edge lines, geometry does not significantly distort the incident angle, and as such, no special correction is necessary. Conversely, recessed skip lines, which are intermittent and aligned with the lane center, may exhibit altered reflectivity due to different incident angles. In these cases, a minor correction based solely on incidence angle is applied to ensure accurate reflectivity readings under both dry and wet conditions. Figure 2.6 shows recessed skip markings and how they are captured by mobile LiDAR.

Figure 2.6: Examples of slotted skip pavement markings

The detection and processing of RPM present a more complex challenge due to their protruding geometry and highly reflective surfaces. The proposed methodology adopts a resolution-dependent approach. When high-resolution data is available (e.g., RIEGL or Z+F sensor in this study), such as that from dense mobile LiDAR or close-range imaging, a 3D model matching algorithm is employed. This method uses the Iterative Closest Point (ICP) algorithm to align known geometric models of RPMs with observed point cloud data, enabling precise localization and classification of RPMs based on their shape and dimensions. However, in scenarios where only low or mid-resolution data is accessible (e.g., RESEPI in this study), direct 3D modeling is not feasible. Instead, a longitudinal profile analysis is performed by scanning the retroreflectivity signal along the vehicle path to identify isolated intensity spikes, which typically correspond to RPMs. These peaks in signal are indicative of the high reflectance and distinct geometry of RPMs. To further enhance accuracy, a correction for incidence angle is applied, as the angle at which the sensor beam strikes the RPM can cause substantial variation in observed intensity. Figure 2.7 shows an example of the peaks observed from the longitudinal scan with RPMs.

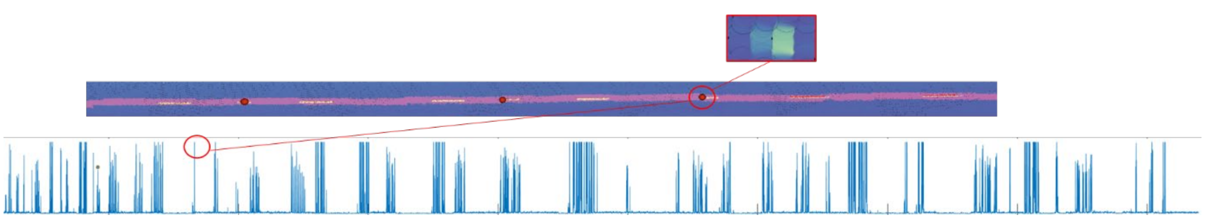


Figure 2.7: Observed RPM peaks in the point cloud data with high retroreflectivity

By integrating both geometric and signal-based approaches, this methodology ensures robust and scalable identification and correction of markings and RPMs across different data quality levels. This dual-resolution framework enhances the reliability of automated pavement marking assessments and supports the broader deployment of sensor-based roadway condition monitoring systems.

2.6.2 Wet Performance Marking

The evaluation of wet reflective pavement markings requires careful consideration of the altered optical properties caused by moisture. A key challenge is the difference in refractive index between dry and wet conditions, which affects how incident light interacts with the marking surface. To address this, a wet correction factor is introduced to systematically overestimate the measured retroreflectivity under wet conditions and subsequently apply a correction to obtain more accurate values. This factor accounts for the change in light behavior of reflection, refraction, and scattering due to water coverage and is empirically derived based on the refractive index values provided by the marking manufacturers. The correction model applies the factor to the reflected light intensity using the formula:

$$I_{\text{reflect}} = I_{\text{incident}}[(1 - k_s)\cos(\vartheta) + k_s]$$

where k_s is a scalar correction coefficient associated with the refractive index, and ϑ represents the angle of incidence. Experimental results (Figure 2.8) show a strong linear relationship between uncorrected and corrected retroreflectivity measurements but skewed from the perfect diagonal direction, validating the necessity of the approach. The application of this correction factor requires prior knowledge of the material composition of the markings, which is obtained from field data collection at each site with wet pavement markings for calibrating the k_s values for each type of material.

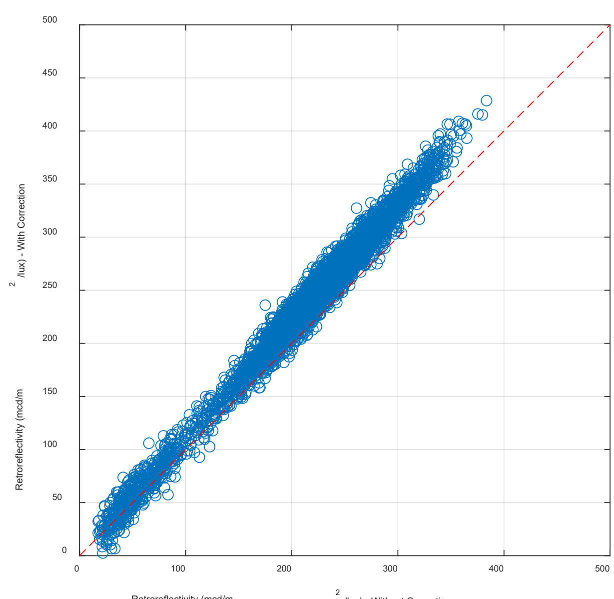


Figure 2.8: Correlation between calculated retroreflectivity with and without wet refraction index correction

2.7 New Installation QA/QC SOP

The development and implementation of an SOP for QA/QC of newly installed pavement markings is critical to ensuring long-term visibility and safety on roadways. This effort targets the early-stage monitoring of pavement marking retroreflectivity to detect premature degradation and support timely corrective actions. In this study, three distinct installation sections were monitored across different highway classifications and materials, including thermoplastic materials on SR116 (C# 125513) and I-90 (C# 114901) and polyurea material on I-91 (C# 112337). These installations serve as the testing sites for the new SOP.

The initial retroreflectivity readings for all three installations were above 600 mcd/m²/lux, which exceeds the minimum retroreflectivity significantly. However, even within a short three-month observation period, the markings exhibited a rapid reduction in retroreflectivity ranging from 25% to 30% per month. This degradation rate, if sustained, could bring the markings below acceptable thresholds within months, potentially requiring early maintenance or reapplication. Even though such a rapid decline is expected in practice as the reflecting material and the binding between the reflecting material and the binder are settling in within the first few months of installation, it highlights the importance of early-stage QA/QC protocols that can identify problematic sections immediately after installation. Traditional visual inspections or point-based retroreflectometers are insufficient in spatial granularity and scalability. Thus, the new SOP leverages mobile LiDAR systems for comprehensive, high-resolution, and spatially continuous evaluation.

The proposed SOP consists of the following structured steps, designed to be repeated monthly during the early post-installation period (e.g., the first 3 to 6 months):

- ***Mobile LiDAR Data Collection***: Each month, mobile LiDAR systems are deployed along the project corridors. The systems are calibrated to capture not only geometric data but also laser intensity values, which are processed to estimate retroreflectivity. The survey should cover the full extent of the newly applied markings, capturing both skip and edge lines at highway speeds.
- ***Data Preprocessing and Retroreflectivity Mapping***: The raw LiDAR data are processed using a combination of intensity correction algorithms (to adjust for range, angle of incidence, and surface type) and spatial referencing tools to align the reflectivity profile to roadway coordinates. This yields continuous retroreflectivity maps for each corridor segment.
- ***Threshold-Based Deviation Analysis***: For each project, average reflectivity values are computed over consistent intervals (e.g., every 10 ft). The algorithm then identifies subsections of at least 100 ft in length where the reflectivity is consistently and significantly lower than the corridor average, defined in this SOP as more than 100

mcd/m²/lux below the mean. These "underperforming" segments are automatically flagged.

- ***Correlation with Engineering and Installation Data***: Flagged segments are cross-referenced with known field installation logs and material application records. Information such as application temperature, ambient humidity, surface preparation, or material batch number is reviewed to identify any correlations between poor performance and field variables.
- ***Targeted Field Investigation***: Once low-performing sections are verified, field engineering teams conduct on-site inspections. This may include handheld retroreflectometer validation, physical inspection of adhesion and bead coverage, or even sample extraction for lab testing. The goal is to confirm whether deterioration is due to workmanship, material quality, or site conditions.
- ***Reporting and Contractor Feedback***: A QA/QC report is generated that documents findings, identifies systemic issues, and provides actionable feedback to the installation contractor. This feedback loop supports accountability and continuous improvement.

This SOP provides a systematic, data-driven approach to early QA/QC of pavement marking installations, combining mobile LiDAR technology with spatial analytics and field engineering insight. Early detection of low-performing segments enables timely corrective action, reduces long-term maintenance costs, and supports safer driving conditions. It should be noted that the research team noticed one challenge in reflectivity analysis, which is the presence of rumble strips. It introduces highly variable geometry and causes reflectivity readings to fluctuate by ±50 mcd/m²/lux if left uncorrected for low-resolution point cloud data (e.g., RESEPI sensor in this study). These features can lead to false identification of low-reflectivity zones unless specifically accounted for in preprocessing. The SOP includes a spatial filter that masks known rumble strip locations or applies geometric compensation based on surface normal estimation.

2.8 Routine In-Service Pavement Marking MUTCD Compliance

The objective of this task was to evaluate the feasibility of conducting routine annual pavement marking surveys using the existing mobile LiDAR sensor owned and operated by MassDOT, the Z+F mobile 9020 LiDAR system, from the pavement survey group. The motivation for this initiative is to support compliance with the MUTCD standards, which require pavement markings to maintain adequate levels of retroreflectivity. The Z+F system was assessed for its capability to support a standardized data acquisition and processing workflow, with an emphasis on scalability, repeatability, and compliance output. The following components were developed to support this assessment:

- ***Template Geodatabase***: A standardized geospatial data structure was designed to catalog pavement markings along state-owned corridors. This included attributes such as marking type (e.g., skip and edge lines), color, width, material, and associated retroreflectivity measurements. The structure enables both spatial and attribute-based queries to evaluate compliance with MUTCD thresholds. Figure 2.9 shows an example of the geodatabase with populated results.

Width	Type	Color	Function	Material	Retro
6	Solid	Yellow	Centerline	Thermoplastic	138.3
6	Solid	Yellow	Centerline	Thermoplastic	184.2
6	Solid	Yellow	Centerline	Thermoplastic	126.3
6	Solid	Yellow	Centerline	Thermoplastic	123.3
6	Solid	Yellow	Centerline	Thermoplastic	143.6
6	Solid	Yellow	Centerline	Thermoplastic	184.2
6	Solid	Yellow	Centerline	Thermoplastic	117.2
6	Solid	Yellow	Centerline	Thermoplastic	117.9
6	Solid	Yellow	Centerline	Thermoplastic	157.2
6	Solid	Yellow	Centerline	Thermoplastic	131.4
6	Solid	Yellow	Centerline	Thermoplastic	135.7
6	Solid	Yellow	Centerline	Thermoplastic	183.3

Figure 2.9: Examples of the pavement marking geodatabase with key attributes

- ***Annual Survey Planning Protocol***: The protocol is designed to integrate with MassDOT's existing pavement survey data scheduling.
- ***Road Context***: The pilot tested the data collected from different road contexts, where data were collected from different lateral positions and speeds to evaluate data quality and operational feasibility. Data from US 6 (rural arterial) and SR 126 (urban minor arterial) were evaluated, and successful marking detection and retroreflectivity measurements were demonstrated. Figure 2.10 shows examples of extracted GIS data, including the marking information following the geodatabase template.

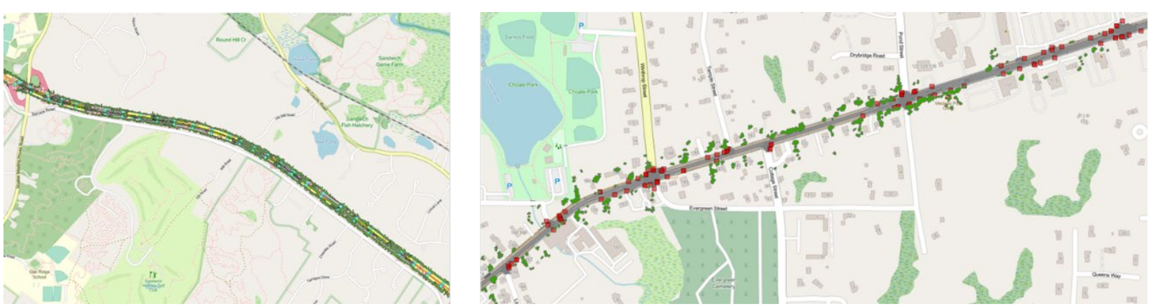


Figure 2.10: Examples of extracted GIS data layers for pavement marking

3.0 Results

The results of this study are presented to answer two additional questions that were unanswered in Phase 1, including 1) whether the mobile LiDAR-based method is repeatable and accurate for skip and edge lines, and for different LiDAR systems; 2) additional observations for the deterioration agree with those of Phase 1 and what are new for preformed tape. Subsections 3.1 and 3.2 present the corresponding findings for these three fundamental questions. To avoid duplicating the existing effort, the results similar to the findings from Phase 1 are not presented in this section.

3.1 Pavement Marking Inventory

In this study, mobile LiDAR and video log imagery data were collected along the selected 18 representative testing sections covering different roadway classifications and pavement marking materials, covering three timestamps six months apart. Using the developed pavement marking extraction algorithm, the retroreflectivity condition evaluation method (with normalization), and the surface percentage loss estimation method, a complete inventory geodatabase containing all the pavement property and condition information was derived.

In this study, the retroreflectivity condition and the loss of material can be estimated at different intervals thanks to the continuous measurements from mobile LiDAR and video log images. To make a consistent reporting interval (e.g., mobile retroreflectometer), the continuous measurements were aggregated based on a 100 ft. interval and then reported to the geodatabase for pavement marking inventory. A separate database storing all the raw, continuous measurements for retroreflectivity and loss of material was also created and referenced to each of the 100 ft. sections.

3.2 Retroreflectivity Condition Evaluation

3.2.1 Retroreflectivity Repeatability and Accuracy

- ***Repeatability***: To assess the robustness and reliability of LiDAR-based retroreflectivity estimation, a series of controlled repeatability experiments were conducted using two different LiDAR sensor platforms. The objective was to determine whether the measurement output remains consistent across repeated runs and whether this consistency is maintained across various pavement marking materials, retroreflectivity ranges, and environmental lighting conditions. In addition to Phase 1, both RIEGL and RESPEI systems were used to conduct two consecutive surveys that run over the same roadway segment under nominally identical conditions. Pavement markings included a variety of materials (thermoplastic, polyurea, and tapes) and both longitudinal and transverse configurations. Data were collected over approximately 4,000 feet of roadway, and retroreflectivity estimates were derived using the LiDAR-based method from Phase 1. The results demonstrate a high degree of repeatability in LiDAR-derived retroreflectivity measurements regardless of the system. As shown in Figure 3.1, the retroreflectivity profiles for Run 1 and Run 2 are nearly indistinguishable (RIEGL results as shown in the left graph), with minimal deviation observed across the full distance range. The signal consistency is maintained despite fluctuations in marking geometry and ambient lighting. As shown in the right graph, both the RIEGL and RESEPI systems (regardless of data density) confirm the strong correlation between runs. Both sensors exhibit coefficients of determination (R^2) approaching 0.99, indicating excellent repeatability and minimal sensor-induced variance.

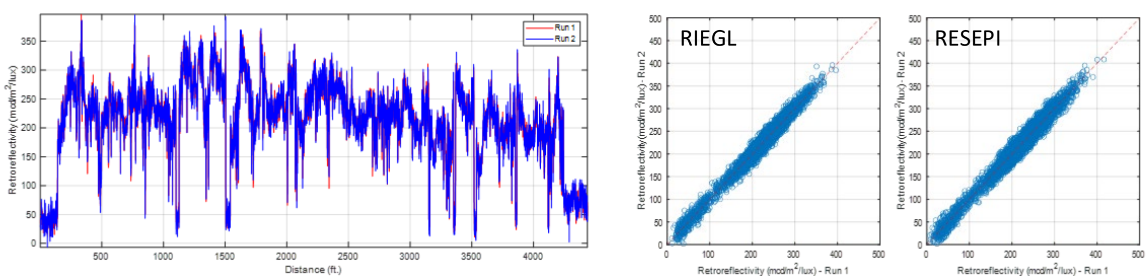
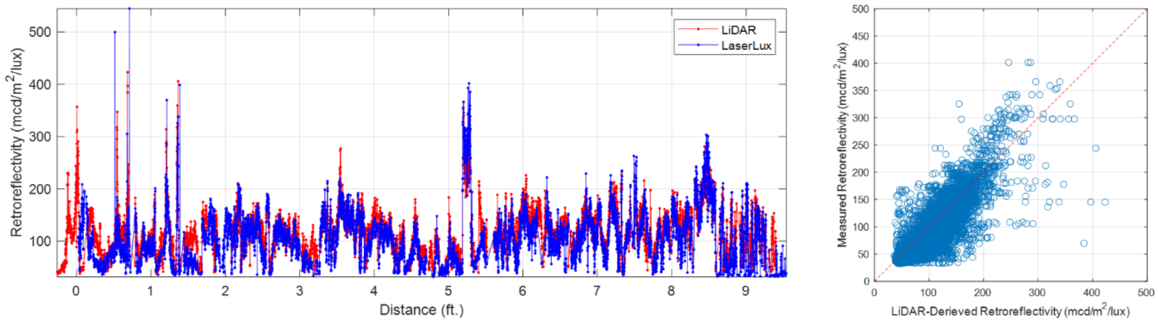


Figure 3.1: Repeatability of retroreflectivity measurements using different LiDAR systems

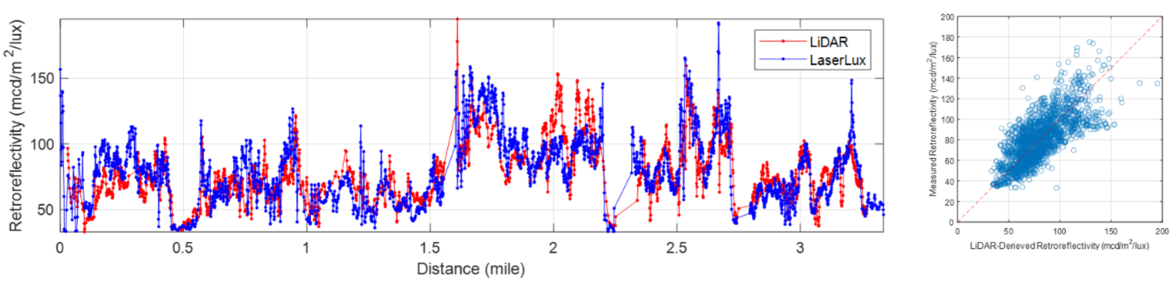
- ***Accuracy***: The accuracy of the method represents how close the measurement from mobile LiDAR is to the ground truth. For LiDAR-based pavement marking retroreflectivity measurement, due to the dynamic nature of the data collection, it is challenging to make a fair comparison with any "ground truth." In this study, the research team continued using the RoadVista LaserLux mobile retroreflectometer as the baseline for comparison, as it is an approved method and system by ASTM for pavement marking retroreflectivity measurement. The data collected from these two systems was conducted along the same section of the road with the same starting and ending points. Similar results were observed in this study compared with those of Phase 1. Figure 3.2 shows the previously reported comparison between the mobile retroreflectometer measurements and the aggregated LiDAR-derived retroreflectivity along Site #9. As discussed in Phase 1, although most of the scattered points were evenly and tightly distributed along the diagonal direction, which indicates a good correlation, it can be observed that some of the measurements farther depart from the diagonal line. These outliers may be attributed to the mismatch of the locations where measurements were conducted by the two methods.



(a) (b)

Figure 3.2: Correlation between retroreflectometer measurements and LiDAR-derived retroreflectivity for solid lines (originally reported in Phase 1)

Accuracy for Skip Line: This study further investigated the accuracy of skip lines. Similar results were observed as solid lines. Figure 3.3 shows the skip line results for Site #9. These findings validate the use of mobile LiDAR systems for condition evaluation of pavement markings, offering a scalable alternative to traditional point-based retroreflectivity assessments for both skip and solid lines. Notably, no substantial bias was observed between solid and skip lines, supporting the generalizability of the approach. Similar to solid lines, the outliers may be attributed to the mismatch of the locations where measurements were conducted by the two methods, as the LaserLux system aggregates the results for 0.01 miles, while the LiDAR-based method provides point-based measurement.



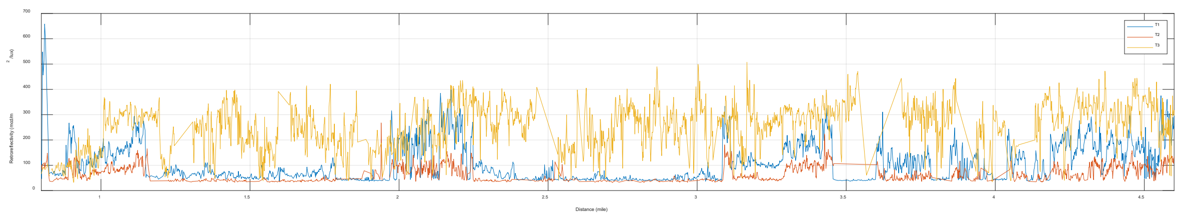
(a) (b)

Figure 3.3: Correlation between retroreflectometer measurements and LiDAR-derived retroreflectivity for skip lines

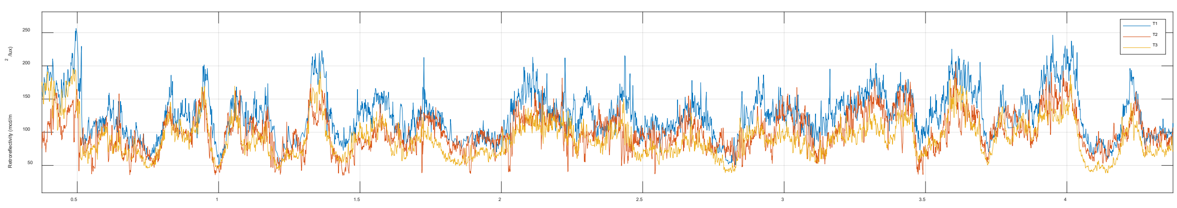
3.2.2 Retroreflectivity Deterioration

One of the main objectives of this study is to continue investigating the feasibility of the LiDAR-based retroreflectivity condition evaluation method for identifying temporal retroreflectivity condition deterioration. In this study, four types of materials were studied along the 18 selected testing sites, including polyurea, epoxy, thermoplastics, and preformed tape.

- ***Polyurea***: When the initial retroreflectivity was less than 100 mcd/m²/lux, the average change during Phase 2 remained modest, around 10 mcd/m²/lux, suggesting a slower degradation rate once reflectivity is already low, as shown in Figure 3.4(a) between T2 and T1. For markings with initial values between 100–200 mcd/m²/lux, the average rate of deterioration increased to approximately 30 mcd/m²/lux, indicating a more active wearing process during this mid-range performance stage, as shown in Figure 3.4(b) between T2 and T1, or T3 and T2. Markings that initially exceeded 200 mcd/m²/lux showed the most significant deterioration, with average reductions exceeding 50 mcd/m²/lux, as shown in Figure 3.4(a) between T3 and T2. In particular, markings with values above 300 mcd/m²/lux during the first six months demonstrated a steep drop, likely reflecting a combination of mechanical wear and environmental degradation acting on high-performance materials. The data from Phase 1 indicate an average change that is less than 10 mcd/m^2/lux, which is consistent with this study.



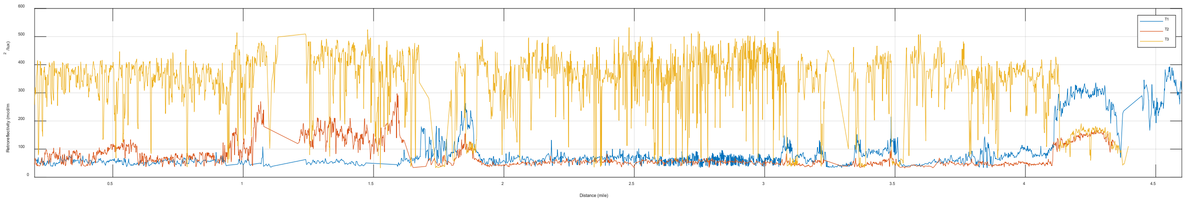
(a)



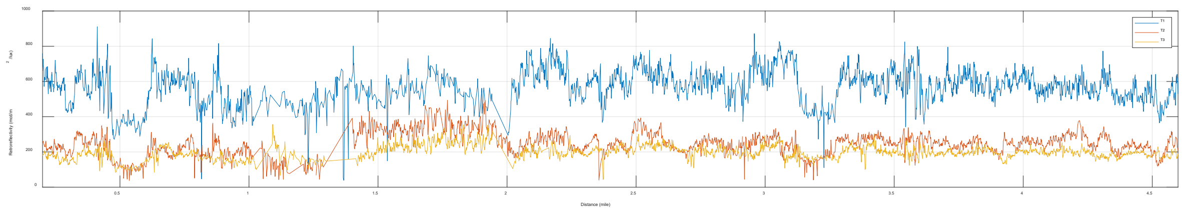
(b)

Figure 3.4: Retroreflectivity deterioration results for a sample polyurea site

- ***Epoxy***: When the initial retroreflectivity was less than 100 mcd/m²/lux, the average change during Phase 2 remained modest, around 10 mcd/m²/lux, suggesting a slower degradation rate once reflectivity is already low, as shown in Figure 3.5(a) between T2 and T1. For markings with initial values between 100–200 mcd/m²/lux, the average rate of deterioration increased to approximately 30 mcd/m²/lux, indicating a more active wearing process during this mid-range performance stage, as shown in Figure 3.5(b) between T3 and T2. Markings that initially exceeded 200 mcd/m²/lux showed the most significant deterioration, with average reductions exceeding 100 mcd/m²/lux, as shown in Figure 3.5(a) between T3 and T2 and in Figure 3.5(b) between T2 and T1. In particular, markings with values above 400 mcd/m²/lux during the first six months demonstrated a steep drop, likely reflecting a combination of mechanical wear and environmental degradation acting on high-performance materials. The data from Phase 1 indicate an average change of approximately 10 mcd/m^2/lux, which is consistent with this study.



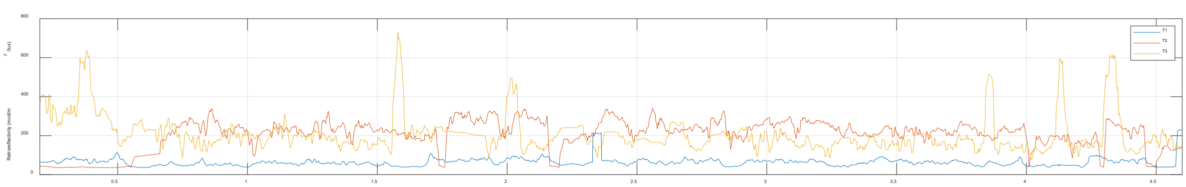
(a)



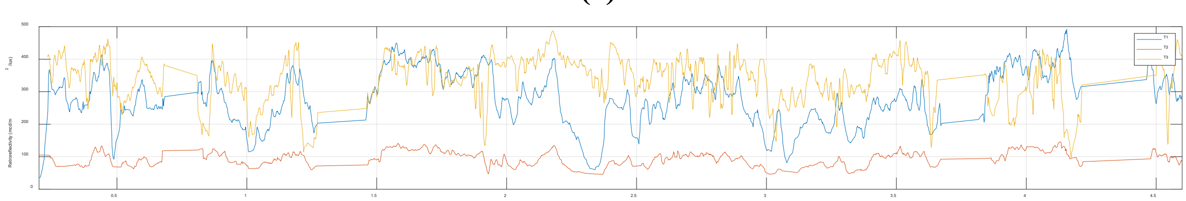
(b)

Figure 3.5: Retroreflectivity deterioration results for a sample epoxy site

- ***Thermoplastic***: When the initial retroreflectivity was less than 100 mcd/m²/lux, the average change during Phase 2 remained modest, around 30 mcd/m²/lux, suggesting a slower but higher than other materials, degradation rate once reflectivity is already low, as shown in Figure 3.6(a) between T2 and T1. For markings with initial values between 100–200 mcd/m²/lux, no observations were made. Markings that initially exceeded 200 mcd/m²/lux showed the most significant deterioration, with average reductions exceeding 100 mcd/m²/lux, as shown in Figure 3.6(b) between T3 and T2. In particular, markings with values above 300 mcd/m²/lux during the first six months demonstrated a steep drop, likely reflecting a combination of mechanical wear and environmental degradation acting on high-performance materials. The data from Phase 1 indicates an average change that is approximately 20-30 mcd/m^2/lux, which is consistent with this study.



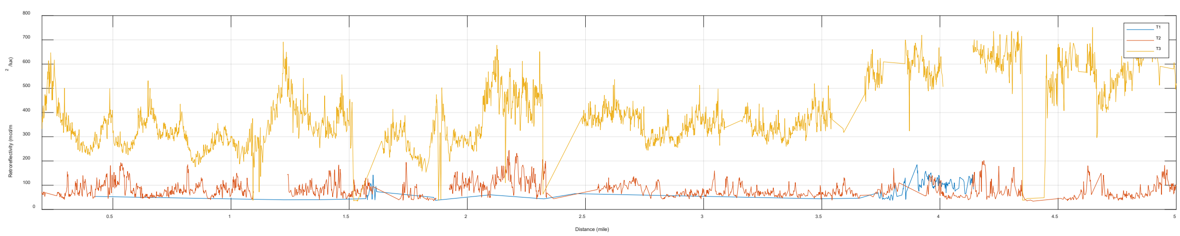
(a)



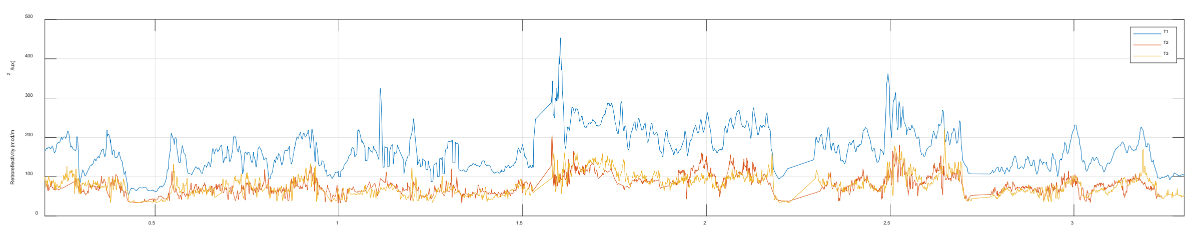
(b)

Figure 3.6: Retroreflectivity deterioration results for a sample thermoplastic site

- ***Preformed Tape***: When the initial retroreflectivity was less than 100 mcd/m²/lux, the average change during Phase 2 remained modest, around 10 mcd/m²/lux, suggesting a slower degradation rate once reflectivity is already low, as shown in Figure 3.7(a) between T2 and T1, and in Figure 3.7(b) between T3 and T2. For markings with initial values between 100–200 mcd/m²/lux, the average rate of deterioration increased to approximately 10-20 mcd/m²/lux, indicating a more active wearing process during this mid-range performance stage, as shown in Figure 3.7(b) between T2 and T1. Markings that initially exceeded 200 mcd/m²/lux showed the most significant deterioration, with average reductions exceeding 100 mcd/m²/lux, as shown in Figure 3.7(a) between T3 and T2 and in Figure 3.7(b) between T2 and T1. In particular, markings with values above 400 mcd/m²/lux during the first six months demonstrated a steep drop, likely reflecting a combination of mechanical wear and environmental degradation acting on high-performance materials. No observations were made in Phase 1 of this study.



(a)



(b)

Figure 3.7: Retroreflectivity deterioration results for a sample tape site

In summary, A comprehensive analysis was conducted to compare retroreflectivity deterioration trends across multiple pavement marking materials under typical roadway operating conditions, even though three timestamps for the analysis at each testing site remain limited. The purpose of this summary is to consolidate findings from material-specific evaluations and to establish a generalized understanding of deterioration behavior and influencing factors. The initial retroreflectivity performance varied significantly by material type at the time of installation. Typical measured initial values included:

- Polyurea: 300–400 mcd/m²/lux
- Epoxy: 400–600 mcd/m²/lux
- Thermoplastic: 300–400 mcd/m²/lux
- Preformed Tape: 500–600 mcd/m²/lux

A consistent trend observed across all materials is that higher initial retroreflectivity corresponds to a faster rate of deterioration. That is, markings that begin with high reflectivity (e.g., >400 mcd/m²/lux) tend to decline more rapidly in the early months following installation compared to markings that begin at lower performance levels. This inverse relationship highlights a diminishing return effect, where the benefit of high initial reflectivity is partially offset by accelerated wear. Longitudinal monitoring indicates that, regardless of material type, retroreflectivity typically stabilizes around 50 mcd/m²/lux after sustained exposure, which appears to represent the terminal baseline performance in the absence of reapplication or maintenance intervention. Significantly, polyurea exhibits minimal fluctuations in deterioration over the course of longitudinal analysis despite not possessing the highest initial retroreflectivity. The preformed tape also renders relatively stable deterioration, considering its high initial installation retroreflectivity.

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4.0 Conclusion

This study aims to leverage the outcomes from Phase 1 of this study to expand the knowledge for pavement marking and complete the investigation on the feasibility and performance of the LiDAR-based, automated retroreflectivity condition assessment. The detailed objectives of this Phase 2 study are threefold: to materialize the findings from Phase 1 and expand the scope, leading toward an implementable engineering method to meet the MUTCD regulatory requirements, and more importantly, to provide a consistently accurate and efficient methodology for MassDOT to evaluate the retroreflectivity of its in-service pavement markings:

- **In-service marking**: to continuously monitor pavement marking retroreflectivity conditions and surface material completeness through 13 of the original 14 testing sites with epoxy, thermoplastics, and polyurea materials and 5 additional testing sites with preformed tape materials. Other properties and types will also be investigated, including wet performance marking, recessed marking, skip lines, and raised pavement marker (RPM).
- **Newly installed marking**: to develop new methods to conduct efficient and effective QA/QC on new pavement marking installation, including the retroreflectivity condition change within 0-6 months from installation and other properties (e.g., color, embedment, and uniformity) change within 0-6 months from installation. The results are summarized to develop a draft standard operating procedure (SOP) for the new installation QA/QC.
- **MUTCD compliance**: to develop a draft SOP for routine in-service pavement marking retroreflectivity measurement that meets the compliance requirement by Revision 3 of the MUTCD. In addition, a unified database template for state-wide pavement marking management has been developed to accommodate routine in-service pavement marking assessments.

The outcome of this study is summarized as follows:

- ***A Review of Pavement Marking Efforts***. The research team conducted a detailed, updated literature review of available and ongoing research through TRID on pavement marking inventory and condition evaluation methods and mobile LiDAR applications in pavement marking studies.

- ***Mobile LiDAR Data Acquisition***. The research team conducted comprehensive data acquisition and data preprocessing using two mobile LiDAR systems (i.e., Riegl VMZ-2000 and RESEPI XT32) along with the 18 selected testing sections. The LiDAR data collected in 2023 using the Z+F 9020 system by MassDOT was also incorporated into the final dataset. The collected data covers more than 90 miles of different classifications of highways with different pavement marking material types. For each testing section, three data collections were conducted at a 6-month interval to monitor the deterioration of the pavement markings. Additional data collection with mobile LiDAR, handheld retroreflectometer, and mobile retroreflectometer was conducted at the beginning of the study to develop the method and validate the result.

- ***Automated Pavement Marking Retroreflectivity Condition Evaluation***. The research team further developed several algorithms for correcting retroreflectivity measurements on different properties of pavement markings, including recessed/slotted pavement marking, RPM, and wet performance marking. The research team validated the repeatability and accuracy of the developed method for both solid and skip lines. The results demonstrated a close correlation with the mobile retroreflectometer and superior repeatability over the mobile retroreflectometer. The disparity between the developed method from Phase 1 and the mobile retroreflectometer measurements was attributed to the mismatch of locations from both methods. It has clearly demonstrated the feasibility of the LiDAR-based method for fulfilling the MUTCD requirements as a research-based engineering method.
- ***Pavement Marking Retroreflectivity Condition Deterioration***. The research team utilized the developed automated algorithms and methods and investigated the deterioration trends for the three pavement marking materials in the selected testing sections, including polyurea, epoxy, thermoplastic, and preformed tape. With three 6-month observation windows, initial deterioration trends were established, and the difference in materials was investigated. At comparable AADT levels, deterioration rates varied among different tested materials, but polyurea has a minimum annual deterioration at different levels of in-service retroreflectivity and at a lower initial retroreflectivity. The preformed tape also renders relatively stable deterioration, considering its high initial installation retroreflectivity.
- ***New Installation QA/QC SOP***. The research team has developed a complete SOP for providing QA/QC for the newly installed pavement markings within the first 6 months. This SOP provides a systematic, data-driven approach to early QA/QC of pavement marking installations, combining mobile LiDAR technology with spatial analytics and field engineering insight. Early detection of low-performing segments enables timely corrective action, reduces long-term maintenance costs, and supports safer driving conditions.

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