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ASSESSMENT OF TRAFFIC SIGN RETROREFLECTIVITY FOR AUTONOMOUS VEHICLES: A COMPARISON BETWEEN HANDHELD RETROREFLECTOMETER AND LIDAR DATA

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Abstract:

This study investigates the critical role of retroreflectivity in traffic signs, particularly in the context of autonomous vehicles (AVs), where accurate detection is paramount for road safety. Retroreflectivity, influencing visibility and legibility, is essential for ensuring safe road conditions. The study aims to assess traffic sign retroreflectivity using handheld retroreflectometers and LiDAR data, offering a comprehensive comparison of results with a specific focus on the RA1 and RA2 traffic sign classes. In a real-world setting, an AV equipped with LiDAR sensors, GPS units, and a stereo camera collects data on traffic signs, including point cloud attributes such as intensity and density. Simultaneously, a handheld retroreflectometer measures retroreflectivity coefficients from identified traffic signs. While retroreflectometers provide precision, they face limitations regarding time-consuming measurements and handling large or elevated signs. In contrast, LiDAR systems efficiently evaluate retroreflective features for numerous signs without such constraints. Despite both methods consistently yielding accurate retroreflectivity, the study reveals a limited correlation between LiDAR point cloud data and handheld retroreflectivity coefficients. The implications of these findings are significant, particularly in the selection and maintenance of retroreflective materials in traffic signs, with direct repercussions on overall road safety. The results offer valuable insights into leveraging LiDAR technology to enhance AVs' detection capabilities. Recommendations for further research include exploring factors influencing LiDAR intensity, establishing a more accurate relationship between intensity and retroreflectivity, correcting the point cloud during intensity calibration, and testing empirical prediction models with a larger sample size. These endeavors aim to generate a robust regression graph and determine correlation coefficients, providing a more nuanced understanding of the intricate relationship between LiDAR data and handheld retroreflectivity coefficients in the context of traffic sign assessment.

Keywords: t*raffic signs, retroreflectivity, autonomous vehicles, LiDAR, traffic safety*

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1. Introduction

Traffic signs are a fundamental element of modern road infrastructure that serves as the primary means of controlling traffic and reducing road accidents. They provide visual information to road users regarding regulations, warnings, guidance, and other essential information. These signs are designed with excellent optical appearances, including shapes, sizes, colors, information content, and retroreflective materials to enhance visibility and detectability (Aldoski & Koren, 2023; Almutairy et al., 2019; Ben-Bassat et al., 2019). Retroreflective condition is a crucial factor that impacts road safety, particularly at night. Therefore, It is imperative that these signs be accurately detectable, legible, and visible during the day and night time, not only for human drivers but also for AVs to achieve their goals (Saleh, 2021), as it allows the operating system to make informed decisions about their surroundings. LiDAR technology provides a powerful tool for assessing traffic sign retroreflectivity, as it can collect detailed data about the environment in real-time. LiDAR technology has emerged as a powerful tool for assessing traffic sign retroreflectivity, as it can collect detailed data about the environment in real-time.

Collaboration between traffic sign agencies and industries is crucial to ensure that traffic signs are visible to human drivers and AVs. The retroreflective properties of existing traffic signs are designed primarily for human drivers, and AVs use them as a primary aid in their driving systems. The AV community has identified traffic sign application, standardization, and design as industry issues, although not as difficult as pavement markings (Federal Highway Administration, 2021). The automotive and vehicle industry emphasizes the necessity for high levels of retroreflection but without quantification. Nevertheless, several participants in the AV industry have observed instances in which excessive retroreflectivity rendered sensors blind. It is unclear whether any studies have addressed sign retroreflectivity to enable AV technology, according to the Federal Highway Administration in 2021.

This study seeks to address the gap in retroreflectivity standards for AVs by comparing traffic sign retroreflective data collected from LiDAR-equipped AVs and handheld devices. The goals include evaluating the relationship between data collected from these two sources, establishing recommendations for retroreflectivity standards tailored for AVs, and developing empirical models for radiometric calibration of mobile LiDAR, which can subsequently be employed for comprehensive traffic sign evaluations.

In the context of advancing AV technologies, ensuring optimal visibility and legibility of traffic signs is paramount for road safety. With a specific focus on the RA1 and RA2 sign classes, this study aims to comprehensively assess traffic sign retroreflectivity. The primary objectives include comparing retroreflectivity measurements obtained through handheld retroreflectometers and LiDAR data, evaluating the effectiveness of LiDAR technology in assessing retroreflectivity, discerning potential correlations and limitations between LiDAR extracted and handheld retroreflectivity coefficient measurements, and offering insights into selecting and maintaining retroreflective materials in traffic signs. These efforts collectively contribute to advancing our understanding of retroreflectivity assessment methods, emphasizing their significance in the ever-evolving landscape of AV technology.

2. Principles of traffic signs retroreflectivity

Retroreflectivity refers to a material's ability to reflect light back toward its source. In the context of traffic signs, retroreflectivity allows the sign's face to reflect light from vehicle headlights back toward the driver, making the sign visible in low-light conditions (Opiela & Andersen, 2007). The Coefficient of Retroreflection (RA) is the standard measure of this particular kind of reflection, calculated as the product of the modulus of illumination intensity (R) to the reflecting area of the sign surface (A), expressed in candelas per lux per square meter ($cd \cdot lx{-}1 \cdot m{-}2$) (Conshohocken, 2008).

The geometry of fixed and vertical traffic signs is meticulously defined by international standards, such as EN 12899-1 (2007) by the European Committee for Standardization (CEN). These standards specify retroreflection coefficients (RA) for different printed colors based on the reflective material employed. The Manual on Uniform Traffic Control Devices (MUTCD) establishes minimum RA values for traffic signs in the United States. Figure 1 illustrates the retroreflectivity phenomenon, depicting the reflection of light from vehicle headlights back toward the driver, while Figure 2 details geometric conditions for traffic sign retroreflection.

Fig. 1. Retroreflectivity phenomenon

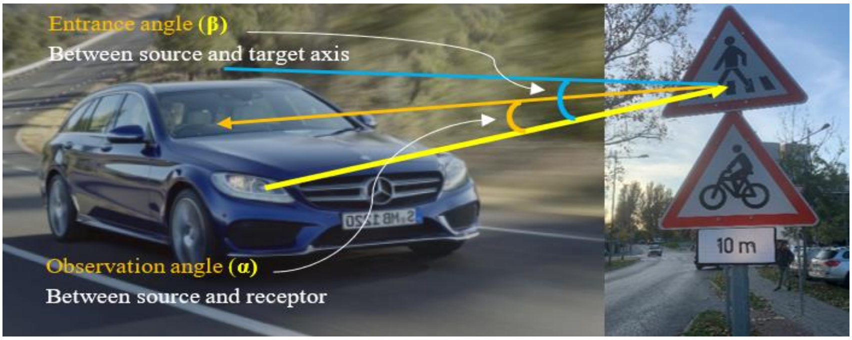


Fig. 2. Geometric conditions for traffic sign retroreflection

Traffic sign retroreflectivity is governed by several principles. The use of retroreflective vinyl or engineering-grade prismatic sheeting is essential to enable the sign to reflect light toward its source, with reflective elements such as prisms or micro prisms creating retroreflection that allows the sign to be viewed from a great distance. Additionally, the angle at which light strikes the sign plays a role in retroreflection, and traffic signs are designed to reflect light regardless of the incident angle. Luminance, which measures the sign's brightness, is critical to ensure visibility in low-light conditions. Regular maintenance, such as cleaning or replacing worn-out signs, is necessary to maintain the retroreflective properties of traffic signs. Furthermore, there are different types of traffic sign retroreflection sheets, each with unique properties that make them suitable for specific applications. The most common retroreflection sheet types, RA1, RA2, and RA3, are defined by European standards (European Committee for Standardization, 2007).

– Class RA1 retroreflection sheets, which are the lowest grade of retroreflective sheetings, are made of a durable material with bounded glass micro beads or prisms. They are typically used in low-traffic areas such as parking lots, private roads, and residential areas, providing low reflectivity in low-light conditions, and Its reflectivity is visible from about 150 meters. The retroreflection of materials belonging to class RA1 with glass micro beads is about 70 cd·lx−1·m−2, materials belonging to RA1 with bounded micro prisms exhibit significantly higher retroreflection levels of around 200 cd·lx−1·m−2 compared to those with glass micro beads (Ontario Traffic Manual, 2020; ORAFOL Europe GmbH, 2023; Scukanec et al., 2014).
– Class RA2 retroreflection sheets are the most commonly used retroreflective sheetings and are widely used for road signs in urban and suburban areas, providing moderate reflectivity in low-light conditions and visibility up to 230 meters away. RA2 retroreflection sheets are appropriate for use in areas with a speed limit of up to 80 km/h. Materials belonging to this class are retroreflective sheetings that contain encapsulated glass micro beads or prisms and are three times brighter than those belonging to class RA1. The signs made from these materials are clearly visible from a wide viewing angle and in a lighted environment, effectively

warning drivers of approaching danger on the roads. Retroreflection of RA2 sheets with glass micro beads is approximately 250 cd·lx−1·m−2, and for materials with micro prisms, it is around 500 cd·lx−1·m−2 (Ontario Traffic Manual, 2020; ORAFOL Europe GmbH, 2023; Scukanec et al., 2014).

– Class RA3 retroreflection sheets are the top tier of retroreflective sheetings, offering the highest level of reflectivity. They are ideal for use in high-speed areas such as highways and expressways, providing visibility up to 350 meters away, and are suitable for use in areas with a speed limit of up to 130 km/h. Class RA3 retroreflective sheetings are composed of highly efficient micro prisms that enable retroreflection of around 700 cd·lx−1·m−2, providing drivers with excellent visibility in all lighting conditions, including adverse (Ontario Traffic Manual, 2020; ORAFOL Europe GmbH, 2023; Scukanec et al., 2014).

a- Class RA1 b- Class RA2 c- Class RA3

Fig. 3. EN 12899-1:2007 standard traffic sign sheet classes, adapted from (3M Safety Transportation, 2023)

Choice of retroreflection sheet type is contingent upon multiple factors, including the sign's location and the speed limit of the respective area. RA1 retroreflection sheets are deemed suitable for low-traffic zones, providing adequate visibility. RA2 retroreflection sheets are considered appropriate for deployment in a majority of urban and suburban areas, offering a balanced level of reflectivity. In contrast, RA3 retroreflection sheets are reserved for high-speed environments and find particular utility in specialized applications such as work zones and emergency areas, where enhanced visibility is paramount. This strategic selection of retroreflection sheet types ensures optimal performance in diverse traffic scenarios and improves overall road safety.

Retroreflective parameters, notably the Coefficient of Retroreflection (RA), are derived from reflectivity through specific mathematical equations. RA is calculated as the product of reflected light intensity (R) and the reflecting area of the sign surface (A), expressed as $RA = R \times A$, in units of candelas per lux per square meter (cd·lx−1·m−2). Luminance (L), indicating the sign's brightness, is derived from reflectivity (R) and background luminance (B) using the formula $L = R - B$.

2.1. Advantages and disadvantages of retroreflectometers

Most of the advantages and disadvantages of reflectometers are related to the established and standardized use of them in many countries.

Advantages:

– Precision: Retroreflectometers provide precise and standardized measurements of retroreflective parameters.
– Efficiency: They offer a quick and efficient means of assessing the retroreflectivity of traffic signs.
– Field Applicability: Retroreflectometers are designed for field use, allowing for on-site evaluation of retroreflective properties.

Disadvantages:

– Single Point Measurement: Some retroreflectometers offer single-point measurements, limiting their ability to capture variations across the entire sign.
– Dependency on Operator Skill: Results may be influenced by the operator's proficiency in using the device.
– Cost: High-quality retroreflectometers can be relatively expensive.

2.2. Use of LiDAR technology for assessing retroreflectivity

In LiDAR technology, the selection and evaluation of retroreflectivity extend beyond the material composition of traffic signs. It involves the analysis of Point Cloud Intensity, with a specific emphasis on luminance intensity. LiDARs emit laser light, measuring the time it takes for the light to return and creating a three-dimensional representation known as a point cloud. The intensity of each point in the point

cloud reflects the surface's reflectivity, providing critical information about the retroreflective properties of traffic signs.
LiDAR intensity, in this context, refers to the strength of the reflected laser light from the surface of the traffic sign. This intensity is a key factor in determining the retroreflectivity of the sign, as it directly correlates with the sign's ability to reflect light back towards its source. By evaluating LiDAR intensity, one can gain insights into the reflective characteristics of the sign's surface material. This information is pivotal in assessing the retroreflective performance of traffic signs, ensuring that they meet visibility standards and contribute to overall road safety. The foundational principles governing traffic sign retroreflectivity in the context of LiDAR technology and point cloud intensity encompass the following key facets:

1. LiDAR Data Collection: LiDARs emit laser light and measure the time it takes for the light to return to the sensor, enabling the determination of distances to objects in the environment. This information creates a three-dimensional representation of the environment, known as a point cloud.
2. Point Cloud Intensity: The intensity of each point in the point cloud reflects the surface's reflectivity. In the case of traffic signs, the reflectivity of the sign's surface is used to determine its retroreflectivity.
3. Data Processing: LiDAR data requires processing to extract information for Traffic Sign Retroreflectivity Assessment. This may involve data pre-processing, ground filtering, and data registration, among other steps.
4. Algorithms: Several algorithms can be used to analyze LiDAR data and determine the retroreflectivity of traffic signs. Commonly used programming languages for this purpose include Python and MATLAB, which filter out noise and outliers in the data and perform data registration to align multiple scans of the environment.
5. Performance Evaluation: The performance of LiDAR-based Traffic Sign Retroreflectivity Assessment can be evaluated using metrics such as accuracy, recall, and precision. These metrics help determine the effectiveness of the algorithms and techniques used for data processing and analysis.

While LiDAR technology can provide valuable information about the environment, it is important to note that it is not the only technology used in traffic sign retroreflectivity assessment. Other technologies, such as cameras and photometers, can also be used for this purpose. Furthermore, it should be emphasized that while LiDAR technology can aid in improving road safety for AVs and for aiding drivers in making informed decisions about their surroundings, it is not a substitute for responsible driving practices and human awareness.

2.3. Advantages and disadvantages of LiDAR for assessing retroreflectivity

Both the advantages and disadvantages of LiDAR come from the fact, that it is a versatile tool for spatial detection.
Advantages:

- Comprehensive Data Collection: LiDAR provides extensive three-dimensional data, offering a holistic view of the environment.
- Non-Intrusive: LiDAR can collect data from a distance without physical contact with the object, making it suitable for various applications.
- High Resolution: LiDAR can achieve high spatial resolution, capturing intricate details in the environment.

Disadvantages:

- Cost: LiDAR systems can be expensive to acquire and deploy.
- Complex Data Processing: The vast amount of data collected by LiDAR requires sophisticated processing techniques, demanding computational resources.
- Environmental Interference: Adverse weather conditions, such as heavy rain or fog, can hinder LiDAR performance.

Although retroreflectometers excel in providing targeted retroreflectivity measurements, LiDAR offers a broader environmental perspective. The choice between the two technologies hinges on the specific requirements of the assessment, considering factors such as precision, field applicability, data comprehensiveness, and cost constraints.

3. Related work

Traffic equipment performs a crucial role in maintaining the safety of road users by providing vital information and instructions. One of the key factors affecting traffic signs' visibility is their level of retroreflectivity. The traditional method of evaluating the retroreflectivity of traffic signs involves using handheld retroreflectometers, which determine the amount of light reflected toward the observer. However, technological advancements have increased interest in using LiDAR data to assess traffic sign retroreflectivity. This systematic literature review aims to investigate the accuracy and efficiency of these two evaluation methods in order to determine the optimal approach for evaluating traffic sign retroreflectivity.

The importance of traffic signs and road markings in the context of road safety has been comprehensively examined by Babić et al. (2022). Their study has elucidated that, presently, both human operators and vehicular technologies rely on vision as the principal means for information acquisition from the surroundings. Therefore, it is imperative to ensure that all components of road infrastructure, particularly road markings and signs, exhibit optimal visual properties to facilitate effective communication and enhance overall road safety.

Lengyel and Szalay (2018)categorized problems associated with traffic signs into distinct classes, encompassing aspects such as quality, location, quantity, visibility, perception, recognizability, clarity, and interpretability while also considering the impact of permitted speed. Building on this, Lengyel et al. (2021) conducted a field survey to establish the minimal safety level of automatic road sign recognition systems, contributing to the broader research on road sign recognition by humans and AVs.

Despite regulating most traffic signs by the European Committee for Standardization (2007), the prevalence of non-standard traffic signs in many countries introduces unique risks. Calvi et al. (2021) proposed a procedural framework for implementing non-standard signs and markings, incorporating a series of tests to ensure safety and standard adherence.

There have been numerous academic publications on the assessment of retroreflection in traffic signs. The earliest form of retroreflective sheeting was crafted from glass beads. Potters, an American company, pioneered in the 1930s by developing small and precise glass spheres commonly referred to as 'beads.' Originally employed to enhance brightness in cinema screens, these glass beads were later utilized in experiments aimed at retroreflectorizing road markings and traffic signs. This innovative application involved scattering the glass beads onto a layer of wet paint or adhesive, marking the inception of retroreflective sheeting utilizing glass beads. However, the reduced efficiency of glass beads is attributed to only 28% of the surface area being sufficiently reflective at favorable angles, leading to losses when the light encounters the surface of the glass (Lloyd, 2008).

Currently, research efforts are centered around developing more advanced micro prismatic retroreflective sheeting. This type of sheeting is evaluated based on its rotational symmetry, or the impact of rotation on its reflectivity (Hrabánek & Růžička, 2022). Several studies have been conducted to investigate the impact of environmental factors such as dirt, precipitation, temperature, and relative humidity on the retroreflective properties of traffic signs. (Carlson et al., 2017; Khrapova, 2019). While, Saleh, Fleyeh, and Alam (2022) in analyzing the results of their study indicated that the date of installation, direction, location, color, and class of road signs are the variables and crucial factors in determining retroreflectivity of road signs.

The evaluation of retroreflectivity and color of road traffic signs installed on roadways is a multifaceted, time-intensive, perilous, and financially demanding procedure, making it infeasible to determine the point at which a sign surpasses its service life and becomes outdated in several countries, including Sweden (Saleh, 2021) and Hungary. Consequently, researchers have investigated novel approaches to assess the retroreflectivity of road traffic signs, such as the use of deep learning techniques, cameras, photometers, and LiDAR technology. Saleh (2021), employed machine learning algorithms to anticipate the condition of road signs in Sweden. To this end, three classifiers, namely, Artificial Neural Networks (ANN), Support Vector Machines (SVM), and Random Forest (RF), were utilized. It was observed that the scaling of data resulted in an enhancement of the prediction accuracy for all three models.

In a related study, Jamal et al. (2022) conducted a comparative analysis of traditional statistical regression models with three different types of neural networks (Feed-Forward Neural Network (FFNN), Cascade Forward Neuran Network (CFNN), and Elman neural networkNeural Network (ELMNN)) to predict the retroreflectivity of traffic signs in Pakistan. The authors gathered data on 539 in-service signs and evaluated the models' performance using various statistical metrics. The findings revealed that all neural network models outperformed the regression technique, with ELMNN architecture producing the most precise results. Moreover, sign age, sheeting brand, color, and observation angle were the most critical variables in predicting retroreflectivity.

Additionally, Khrapova, Růžička, and Trnka (2020) conducted a study that employed a handheld retroreflectometer to measure RA, followed by a repetition of the measurement using a modern camera system integrated into the vehicle for traffic sign recognition. Statistical analysis was applied to the gathered data. The paper's findings provide an assessment of the efficacy of traffic sign recognition and an overview of other factors that can substantially influence sign detection and recognition distance. Conversely, the number of signs on a post, i.e., one or two, affects the recognition distance, particularly if the signs exhibit identical retroreflection levels, resulting in an anomalous area for determination.

The utilization of LiDAR technology has increased in various fields over the last few years. Despite its broad adoption, its potential in retroreflective analyses of traffic signs remains largely untapped. Ai and Tsai (2016) introduced an automated methodology utilising mobile LiDAR and computer vision to assess traffic sign retroreflectivity. The process involves traffic sign detection, color segmentation, theoretical-empirical LiDAR retro-intensity normalization, and population-based condition assessment. Using a blank white traffic sign with Type 1 engineer grade sheeting, the repeatability test demonstrated consistent results. Additionally, under varying ambient lighting conditions, a 36x36 stop sign displayed uniform LIDAR retro-intensity measurements regardless of the light being on or off. To ensure dependable traffic sign condition assessment, the study underscored the significance of validating retro-intensity repeatability on identical retroreflective objects. The test incorporated a sample placed 0.6 m from the road edge, with a stationary LIDAR device positioned 12.5 m away. Two scenarios were considered: (1) continuous scanning for ten minutes, assessing the consistency of intensity measurement for the same traffic sign captured by continuous scans; (2) discrete triggering of one scan at the beginning of each minute for ten minutes, evaluating the consistency of intensity measurement for different traffic signs captured in discrete scans. On the other hand, Zhang et al. (2019) present a method that employs Mobile Laser Scanning to detect occlusion and estimate the visibility of traffic signs continuously, covering the entire road surface.

Wu et al. (2015) proposed a new method for detecting traffic signs and evaluating their visibility using mobile LiDAR point clouds and corresponding images. The method involves two steps: the detection algorithm which uses the high retroreflectivity of signs in the point clouds, and the visibility estimation method which combines the visual appearance and spatial-related features to evaluate the visibility level of traffic signs. The proposed algorithm is validated using point clouds obtained by a RIEGL VMX-450 LiDAR system and the results demonstrate its efficiency and the potential to improve road safety by providing accurate and objective assessments of traffic sign visibility.

When discussing LiDAR sensors, it is essential to acknowledge that their performance is not uniform and varies depending on the underlying technology. Schulte-Tigges et al. (2022)comprehensively evaluated six different LiDAR sensors across various scenarios. These scenarios encompassed static situations, where both the measured object and the LiDAR sensor remained stationary, and dynamic scenarios, where the sensor was mounted on a moving vehicle approaching the measured object. The outcomes presented in their study underscore substantial differences in the performance of various LiDAR technologies.

In recent studies, He et al. (2023) have introduced a practical technique for evaluating the condition of traffic signs utilizing LiDAR data. The proposed approach involves establishing a correlation between retro-intensity and retroreflectivity readings to determine the minimum retro-intensity thresholds required for assessing the condition of various sheeting types and colors. The study findings indicate that the suggested method can produce reliable outcomes that are comparable to those of manual measurements. The authors propose that this technique has the potential to decrease the effort required for sign retroreflectivity condition assessment and address situations where manual assessment is impractical.

Meanwhile, Kim et al. (2023) have examined the impact of various weather conditions on LiDAR detection performance, using test objects commonly found in Korean road traffic signs. The study findings demonstrate that precipitation and fog led to a

decrease in the number of point clouds (NPC) and intensity, with retroreflective film exhibiting the best preservation of LiDAR performance. Tests conducted on actual roads showed that retroreflective film retained at least 74% of the NPC under clear conditions with intense rain and thick fog, while aluminum and steel were not visible for distances of 20-30 m. The study concludes that empirical tests can be useful in understanding the degradation of LiDAR performance under bad weather conditions.
LiDAR technology has shown potential in assessing traffic sign retroreflectivity, providing reliable outcomes that are comparable to those of manual measurements. Therefore, it can decrease the effort required for sign retroreflectivity condition assessment and address situations where manual assessment is impractical, contributing to improved road safety.
The Vienna Institute for Safety and Systems Engineering (VISSE) has formulated a systematic and methodical approach to define and assess the prerequisites for safe AV technologies. As presented by Tschürtz et al. (2021), this methodology is currently being evaluated through various use cases. Specifically, driving scenarios centred around a road intersection were meticulously defined, and safety-critical situations were identified, analyzed, and assessed at the ZalaZONE proving ground in Hungary. The outcomes of this analysis and testing reveal the potential to proactively enhance a pre-existing sensor concept. This enhancement presents an opportunity to mitigate the complexity of driving scenarios and minimize encounters with unfamiliar situations.

4. Method and data collection

This methodological framework aims to provide the procedures involved in the acquisition and examination of data through handheld retroreflectometer and AV equipped with LiDAR sensors for retroreflectivity evaluation of traffic signs. This framework will offer a comprehensive and methodical approach to ensure accurate and reliable results that can be used for further analysis.

4.1. Study area

The investigation detailed in this study was carried out at the Széchenyi István University campus located in Gyor city, Hungary, as illustrated in Figure 4. The campus encompasses various types of traffic signs, facilitating data collection through both handheld devices and LIDAR technology.

4.2. Test samples

The handheld retroreflectometer device was utilized to measure the retroreflective properties of 112 in-service traffic signs, which were categorized based on their respective technology and type, as shown in Table1. Additionally, the study area was surveyed using an AV-equipped LiDAR technology, covering 60 signs, classified as per Table 2. All data gathered from LiDAR were already measured by the handheld retroreflectometer device.

Fig. 4. Study area, adapted from (Széchenyi István University, 2024)

Table 1. Tested sample was collected by a Handheld retroreflectometer

Number of traffic sign									Retroreflective material class	
	Regulatory				Informative					
Warning	Priority	Prohibitory	Mandatory	Special Regulation	Information	Direction	Additional Panels	Other	RA1	RA2
9	12	41	13	22	14	0	0	0	96	16
9						14		0		
				112					112	

Table 2. Test sample collected by LiDAR.

Number of traffic sign									Retroreflective material class	
	Regulatory				Informative					
Warning	Priority	Prohibitory	Mandatory	Special Regulation	Information	Direction	Additional Panels	Other	RA1	RA2
7	4	26	7	8	8	0	0	0	54	6
7		45				8		0		
				60					60	

4.3. Data collection by handheld retroreflectometer

The RetroSign GRX 554 retroreflectometer was employed to perform all measurements. This device enables the determination of the coefficient of retroreflection (RA) according to the European standard EN 12899-1 (European Committee for Standardization, 2007) for an illumination angle of 5° and observation angles of 0.2°, 0.33°, and 1°. Additionally, each measurement included data pertaining to the color of the sample, ambient temperature, relative humidity, and GPS coordinates.
To ascertain RA values, the initial step involves the calibration of the handheld retroreflectometer by affixing the calibration standard onto the designated 'calibration side.' Subsequently, the front plate is attached to the 'measuring side,' as delineated in Figure 5. Subsequent to calibration, direct measurements are obtained by situating the device perpendicular to the surface of the traffic sign and initiating the measurement process, as depicted in Figure 6-a. The resultant measurement values are visibly displayed by the instrument alongside each observation. Moreover, the handheld retroreflectometer is systematically employed to acquire four readings for each sign color, encompassing the background and the legend. The uniformity of the measuring principle is maintained across all measurements. Figure 6-b provides an illustration of the measurement procedure for the traffic sign face color.
In addition to retroreflectivity measurements, the dimensions of the traffic signs are assessed using tape, and AutoCAD is employed for the determination of both the sign's overall area and the area corresponding to each color. This dimensional data is subsequently integrated into the comprehensive dataset for further analysis.

4.4. LiDAR data acquisition

For data acquisition, a Nissan Leaf vehicle, owned by the Research Centre for Vehicle Industry at Széchenyi István University, was operated, as depicted in Figure 7. The vehicle was equipped with four LiDAR sensors and two GPS receivers mounted on the roof for geo-referencing purposes. The stereo camera on the vehicle provided a detailed video log of the surroundings, complementing the frame information from the scanner. Two Ouster Os1-64 channel sensors were positioned at a 0° orientation angle on the roof of the car, covering a broader angular range. Additionally, two Velodyne VLP16 Puck-16 Channel sensors were mounted on the top right and left edges of the car at 60° and -60° orientation, acting as secondary sensors to increase point cloud density and facilitate object identification.

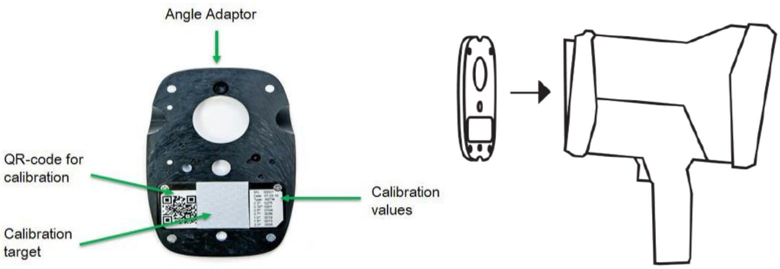
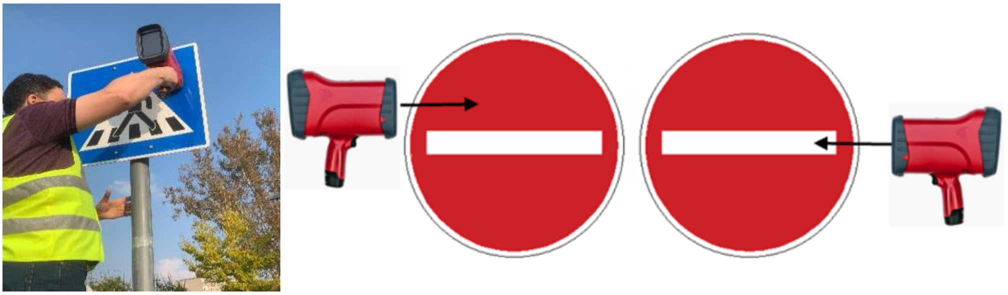


Fig. 5. RetroSign GRX 554 handheld retroreflectometer calibration, (DELTA – a part of FORCE Technology, 2020)



a- Field data collection b- Background c- Legend

Fig. 6. Measure the traffic sign background and legend

Throughout the one-minute and 33.7-second route, the vehicle encountered and recorded 60 traffic signs, saved as (.bag) files. However, the LiDAR sensors did not support raw data export into a standard (.las) format output file. Consequently, a custom Python script was developed to convert the raw data into point cloud data (.pcd) format. This script generated 1874 (.pcd) files per LiDAR, with each file representing 0.05 seconds of data acquisition. Using the Foxglove Studio package, which provides information about the time and location of the vehicle, the location and time of each traffic sign were identified. The collected data underwent further analysis using Cloudcompare, an open-source 3D point cloud and mesh processing software. This analysis facilitated the visualization of specific frames and the extraction of LiDAR intensity for each sign.

4.5. Data analysis

After the extraction and preparation of data collection from the handheld device and LiDAR, the data were analyzed using Microsoft Office Excel for the exportation of measured data and the creation of measurement reports. Additionally, a stepwise statistical process employing the Statistical Package for Social Sciences (SPSS) was applied to develop relationships and comparisons between the collected data. These analytical techniques were employed to provide a thorough understanding of the underlying patterns and correlations within the data, thus contributing to a more comprehensive interpretation of the results. This rigorous approach enhances the reliability and validity of the findings, thereby enabling the establishment of sound conclusions and recommendations based on the analyzed data.

5. Results and discussions

This section presents and discusses the results obtained from our comprehensive assessment of traffic sign retroreflectivity using a handheld retroreflectometer and LiDAR data. The culmination of our study focused on the RA1 and RA2 traffic sign classes. It brought insights into the accuracy and correlation of retroreflectivity coefficients obtained through these two distinct methodologies. Examining real-world data collected utilising an AV equipped with advanced sensor technologies contributes to understanding retroreflective material selection and maintenance implications for overall road safety. Through meticulous analysis, we uncover the nuances of the relationship between LiDAR point cloud data and handheld retroreflectivity coefficients, shedding light on these measurement approaches' potential applications and limitations. The ensuing discussions delve into the significance of our findings, offering a platform for informed recommendations and future research directions within traffic sign retroreflectivity assessment.

5.1. Retroreflectometer data

The present study involved measuring and analyzing retroreflective coefficients for a total of 112 traffic signs, comprising 96 signs classified as RA1 and 16 signs classified as RA2. Among the sample, 93 signs (83% of the total) were equipped with stickers indicating the reflectivity material used, and for the remaining signs, the sheet class was determined by contacting manufacturers. This determination involved comparing the type of adhesive sheet used to ensure a comprehensive representation of retroreflective materials used in traffic signs. The signs were further categorized into groups based on similar colors in the unified sign, as detailed in Table 3, providing a comprehensive breakdown of this classification. All data acquired from the sample underwent classification and analysis to identify the factors influencing retroreflective performance in traffic signs, as follows (Table 3).

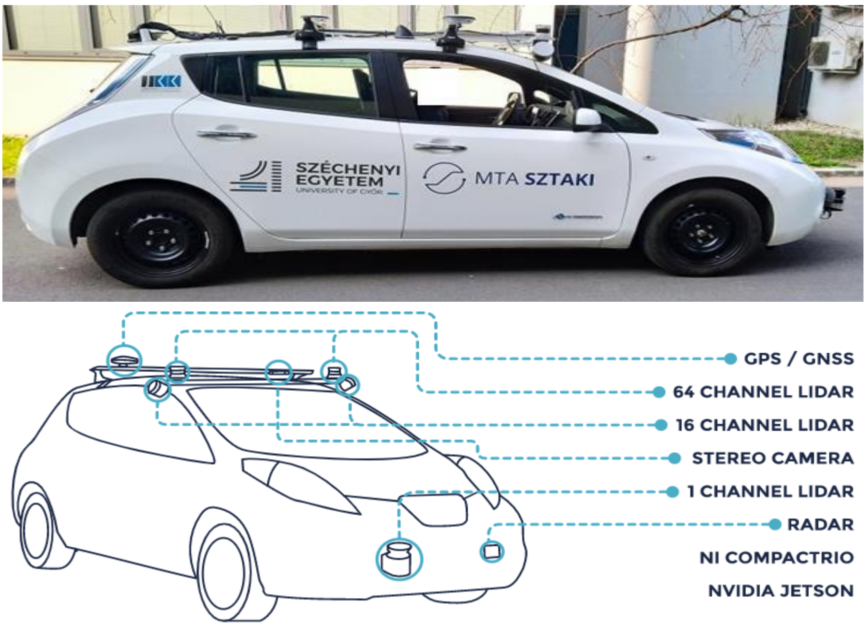


Fig. 7. Nissan leaf mounted with LiDARs

Table 3. Classification of retroreflective materials in traffic signs

Traffic sign colors	Traffic sign sheet class				Total	
	RA1		RA2			
	No.	%	No.	%	No.	%
White and gray (WG)	5	5.2	0	0.0	5	4.5
White and blue (WB)	36	37.5	13	81.3	49	43.8
White and red (WR)	35	36.5	2	12.5	37	33.0
Red and blue (RB)	20	20.8	1	6.2	21	18.7
Total	96	100	16	100	112	100

5.1.1. Traffic signs conforms to the standards

The RetroSign handheld instrument is used in the measuring process and is placed directly on the sign surface to minimize the impact of daylight. The measurement procedure is based on substitution calibration, necessitating regular calibration of the instruments. These instruments are equipped with an internal light source that corresponds to the standard source outlined in the European standard EN 12899-1 (European Committee for Standardization, 2007), as well as a photoreceptor with spectral sensitivity that is consistent with a standard photo-optical observer. The geometry of the instrument should be selected to comply with European specifications, which includes an observation angle of 0.33° and an entrance angle of 5° (see Figure 8).

The retroreflective coefficients of all traffic signs were meticulously measured and compared with the specified retroreflection coefficients for Class RA1 and RA2, as delineated in the European standard EN 12899-1. According to the standard, the retroreflective coefficient value should not fall below 70% (excluding white color) of the values provided in Tables 4 (European Committee for Standardization, 2007). The findings revealed that 49 signs (43.8%) did not meet the stipulated standard requirements, comprising 45 RA1 and 4 RA2 signs. Conversely, 56.2% of the signs adhered to the standards, encompassing 51 Class RA1 traffic signs and 12 RA2 signs. A detailed breakdown of the comparison between measured retroreflectivity coefficients and standards is encapsulated in Table 5. These results underscore the critical importance of avoiding substandard materials and ensuring adequate maintenance of traffic signs to mitigate potential risks to road safety.

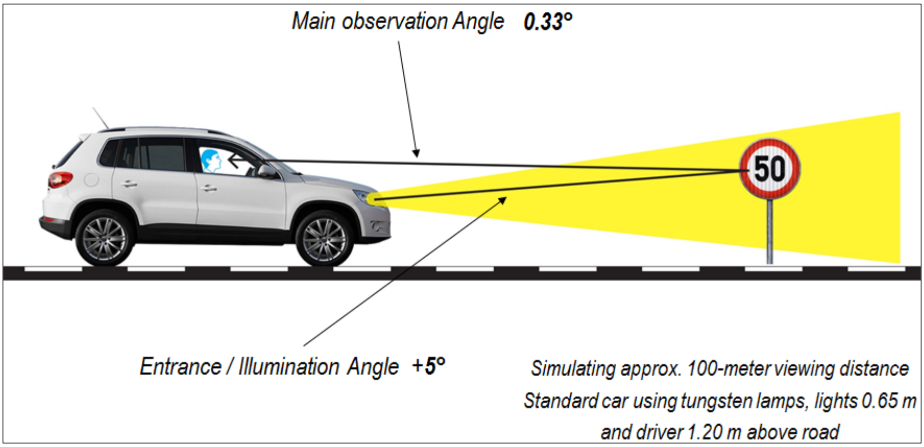


Fig. 8. Entrance and observation angle for a traffic sign geometry by EN-12899, (DELTA – a part of FORCE Technology, 2020)

Table 4. Coefficient of retroreflection R_A ($cd.lx^{-1}.m^{-2}$)

Sheet Class	Geometry of measurement		Color								
	α	β1 (β2=0)	White	Yellow	Red	Green	Dark Green	Blue	Brown	Orange	Gray
RA1	20'	**+5°**	**50.0**	**35.0**	**10.0**	**7.0**	-	**2.0**	**0.6**	**20.0**	**30.0**
		+30°	24.0	16.0	4.0	3.0	-	1.0	0.2	8.0	14.4
		+40°	9.0	6.0	1.8	1.2	-	#	#	2.2	5.4
RA2	20'	**+5°**	**180.0**	**120.0**	**25.0**	**21.0**	**14.0**	**14.0**	**8.0**	**65.0**	**90.0**
		+30°	100.0	70.0	14.0	12.0	11.0	8.0	5.0	40.0	50.0
		+40°	95.0	60.0	13.0	11.0	5.0	7.0	3.0	20.0	47.0

# indicates "Value greater than zero but not significant or applicable"
α= observation angle and β = entrance angle

Table 5. Comparison of measured retroreflective coefficients with standard requirements.

Traffic sign colors	Traffic signs conform to standards				Total	
	RA1		RA2			
	No.	%	No.	%	No.	%
WG	2	3.9	0	0.0	2	3.2
WB	16	31.4	9	75.0	25	39.7
WR	18	35.3	2	16.7	20	31.7
RB	15	29.4	1	8.3	16	25.4
Total	51	100	12	100	63	100
Traffic sign colors	**Traffic signs out of standard ranges**				**Total**	
	RA1		**RA2**			
	No.	%	No.	%	No.	%
WG	3	6.7	0	0.0	3	6.1
WB	20	44.4	4	100	24	49.0
WR	17	37.8	0	0.0	17	34.7
RB	5	11.1	0	0.0	5	10.2
Total	45	100	4	100	49	100

5.1.2.Traffic signs degradation

The gradual loss of color brightness or fading due to exposure to environmental factors, such as sunlight, weather conditions, and pollution, is known as color degradation. In the context of traffic signs, the color degradation phenomenon can significantly affect their visibility and legibility, potentially leading to safety hazards on the road. To ensure the effectiveness of traffic signs over time, it is crucial to select durable materials and colors that are less susceptible to color degradation. An analysis of the percentage of color degradation for various sign colors, as presented in Table 6, reveals that gray signs exhibit the highest degradation at 75%, followed by white signs at 50.6%. In contrast, red and blue signs showcase the lowest color degradation, with measured values of 42.0% and 41.9%, respectively. These findings emphasize the importance of selecting resilient sign colors that maintain visibility and legibility over extended periods.

The configuration of traffic signs was found to impact their deterioration as well. In particular, the background was more vulnerable to color degradation than the legend, while the square shape was more prone to deterioration than rectangular, circular, and triangular shapes. However, it should be noted that the study area only had two signs with an octagonal shape, which displayed the highest percentage of degradation among all the shapes examined, as presented in Table 7. Furthermore, the study evaluated the impact of material category on retroreflective performance, and it was found that the RA2 material category had a more significant effect on retroreflective performance than the RA1 category. These results underscore the importance of selecting higher-quality materials to enhance the durability and effectiveness of traffic signs.

Table 6. Color degradation of traffic signs

Total area of measured traffic signs (cm^2)					
	White	Red	Bule	Gray	Total
legend	62529	54023	5625	7650	129827
background	54750	21953	121070	0	197773
Total area	117279	75976	126695	7650	327600
Color rate out of the standards range according to legend and background (cm2)					
legend	30878	15296	1800	5738	53712
Ratio	49.4%	28.3%	32.0%	75.0%	41.4%
Background	28484	16600	51315	0	96399
Ratio	52.0%	75.6%	42.4%	0.0%	48.7%
Total color area out of the standards range (cm2)					
Total area	59362	31896	53115	5738	150111
Ratio	50.6%	42.0%	41.9%	75.0%	45.8%

Table 7. Degradation of traffic signs by shape composition

Sign shape	Total number of signs	Number of sign out of range	Ratio
Square	41	20	48.8%
Circular	43	18	41.9%
Triangular	17	5	29.4%
Rectangular	9	4	44.4%
Octangular	2	2	100.0%
Total	112	49	43.8%

5.2. LiDAR data

LiDAR technology applies laser pulses to determine the distance between an object and the transmitter. The resulting output of this process is known as point cloud data which provides the characterization of the measured entity. The point cloud data is composed of basic information such as point intensity, the density of the point cloud, range, reflectivity, color, and other data qualities. In the assessment of traffic sign quality compared to retroreflectivity, this research used LiDAR scores due to their ability to provide large-scale coverage in a short period of time. However, the accuracy of the results in extracting and evaluating traffic signs depends on the verification of the information provided by LiDAR on point intensity of the point cloud.

5.2.1. Intensity of LiDAR data

The point cloud data contains intensity or return signal strength, which is a valuable attribute for analysis. This attribute can potentially be utilized to estimate the retroreflectivity of traffic signs. To extract the LiDAR point cloud intensity, various software packages were employed. First, the collected data file was converted into an 1874 .pcd file frame for each LiDAR using Python, and the vehicle's time and position were identified using the Foxglove software. This process helped to determine the frame in which the sign appears at the specified distance (10m) in the camera, as illustrated in Figure 9. Subsequently, the identified frame was opened using the ClouldCompre software, which is a 3D point cloud and open-source mesh processing software. The cloud points were then enlarged by a factor of 5 to enhance the visibility of the traffic sign. The traffic sign was manually and accurately selected, and all other points were removed from the frame. The higher and lower cloud intensities were obtained, as depicted in Figure 10. The intensities obtained from the point cloud data are presented in Figure 11. The highest intensity of cloud points was observed from the left OSL LiDAR 5060, while the lowest intensity value was recorded as 9. Similarly, the highest intensity value for the right OSL LiDAR was 4548, and the lowest was 6.

Moreover, the relationship between the maximum recorded intensity value and the white color and the minimum intensity value and the blue color emphasizes the potential for intensity measurements to indicate retroreflective properties of traffic signs. Based on the standard parameters (European Committee for Standardization, 2007) of the tested traffic signs, the white color was associated with the highest intensity value, while the blue color was associated with the lowest intensity value.

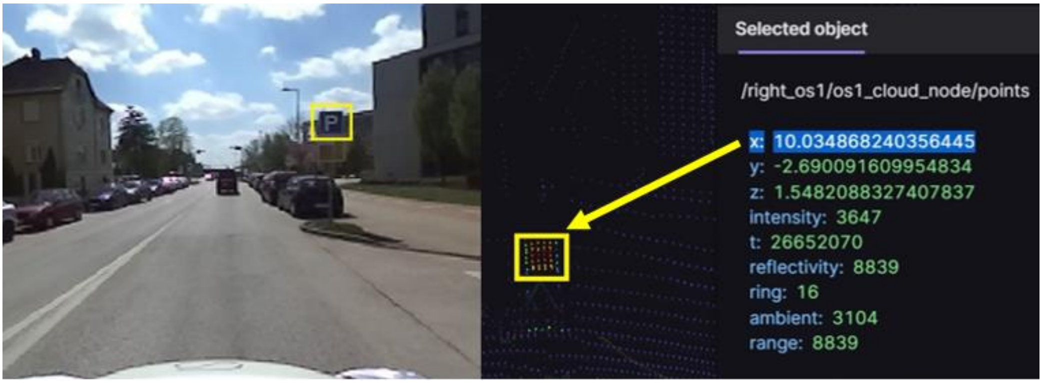


Fig. 9. Distance between traffic sign and LiDAR by Foxglove

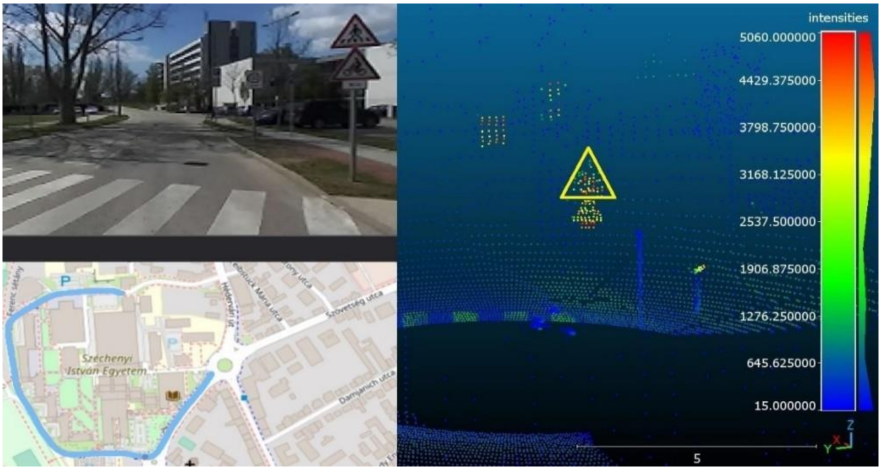


Fig. 10. LiDAR max intensity

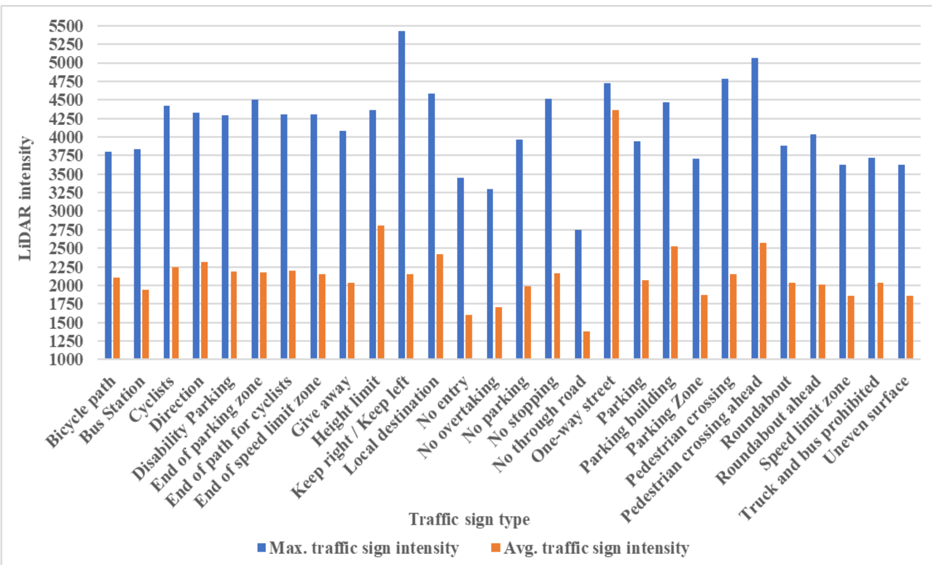


Figure 11. Average and maximum intensity according to traffic sign type

5.2.2. Relation between LiDAR and handheld data

The investigation into the relationship between LiDAR intensity and handheld retroreflectometer measurements was undertaken to achieve the objectives of this study. A comprehensive correlation analysis was executed to scrutinize the association between raw intensity data derived from the Ouster Os1-64 LiDAR and retroreflectivity coefficients acquired through handheld measurements. The selection of this specific LiDAR was predicated on its superior performance, as demonstrated in a preceding analysis of point cloud data, where it outperformed the Velodyne LiDAR. The analysis concentrated on the RA1 and RA2 traffic sign classes, with the outcomes being elucidated in Table 8.

Table 8. Retroreflectivity coefficient and LiDAR intensity in traffic sign analysis

Traffic sign colors	Average handheld retroreflectivity coefficient (Ra) (cd.lx-1.m-2)	Standard deviation of Ra	Average LiDAR intensity	Standard deviation of LiDAR intensity
WB	62.01	69.77	2260	579.61
WR	82.10	93.35	2129	557.90
RB	23.15	13.9	2154	461.59
All Signs except RB	70.98	77.28	2205	542

Upon closer examination of the results in Table 9, a consistent trend emerges within the "All Signs except RB" category, wherein higher values for both retroreflectivity and LiDAR intensity are consistently observed compared to individual color categories. Furthermore, varying standard deviations within each color category suggest differing degrees of uniformity in the distribution of retroreflectivity and LiDAR intensity values.

The findings of this study reveal a limited correlation between LiDAR intensity and handheld retroreflectivity coefficients, as depicted in Figure 12. Using the Modified Z-Score method, the illustration represents the correlation graph post-removal of outliers. The observed constraint in correlation can be attributed to the inherent disparities in the methodologies employed during measurement.

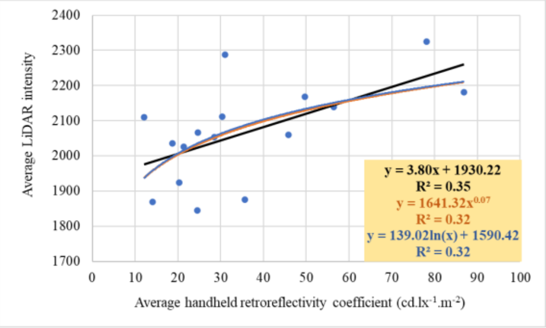
Handheld retroreflectometers adopt a localized assessment approach, targeting specific points on traffic signs for retroreflectivity evaluation. While this method ensures meticulous measurements, it may not comprehensively capture the overall reflective characteristics of the entire sign surface, especially in the presence of surface heterogeneity and environmental contaminants. In contrast, LiDAR technology generates an exhaustive point cloud through the emission of laser beams across a broader spatial area. Challenges arise from discrepancies in measurement scale, orientation, and surface coverage, hindering the establishment of a robust correlation.

Comparing our results to those in the literature, such as the work of Ai and Tsai (2016), who employed laboratory tests with continuous scanning for ten minutes rather than field tests and assessed intensity measurement consistency for the same traffic sign captured by continuous scans, we note distinct methodological differences. Additionally, Ai and Tsai utilized theoretical-empirical LiDAR retro-intensity normalization, while our study involved real-time scanning for each traffic sign, with an extraction time of 0.05 seconds for LiDAR raw intensity.

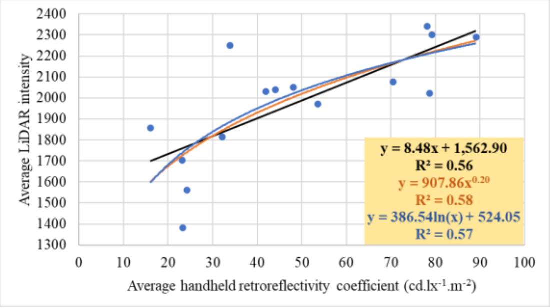
Subsequent investigations should consider strategies for effectively integrating point-specific handheld measurements into LiDAR analysis. Exploring the influence of factors such as surface orientation and material heterogeneity on the correlation between LiDAR intensity and handheld retroreflectivity coefficients is imperative for advancing our understanding of the complexities involved in these measurements.

Concerning the regression lines, linear, power, and logarithmic functions were tested. The R2 coefficients, although modest and quite similar for the three types of functions, indicate that power and logarithmic functions better fit the point cloud in the lower region of retroreflectivity. Notably, White-Red signs exhibit the highest correlation at 0.58, followed by White-Blue with a value of 0.45. However, Red-Blue combinations yield contradictory results, showing almost no correlation or even a reverse function between retroreflectivity and LiDAR intensity. This phenomenon requires further investigation, leading to the exclusion of RB combinations from the summary 12/d figure. The summary case demonstrates an R2 of 0.45, positioning it between the W-R and W-B figures.

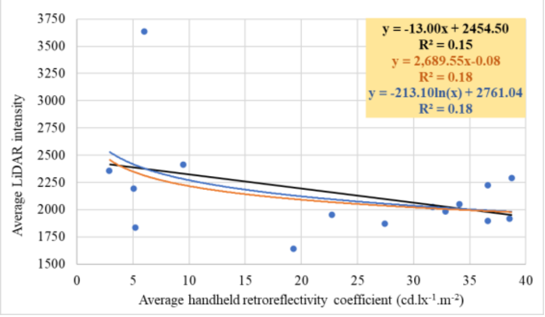
A comprehensive investigation and interpretation are imperative to fully elucidate these variations' significance. This inquiry should specifically explore the potential implications of the findings for visibility, safety, and other crucial factors influencing the performance of traffic signs. The nuanced understanding derived from this research will contribute to an enhanced comprehension of optimal traffic sign characteristics and their broader implications for road safety within both academic and practical domains.



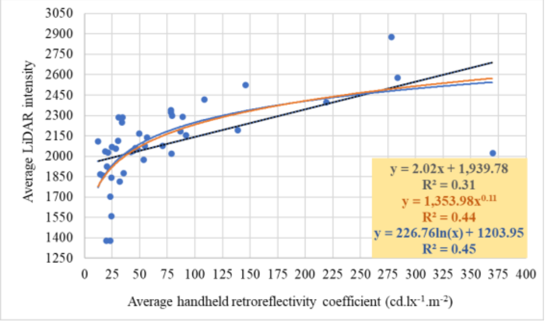
a- WB Signs



b- WR signs



c- RB signs



d- All investigated traffic signs except RB signs.

Fig. 12. Relations between the LiDAR intensity and handheld retroreflectivity coefficient

5.2.3. LiDAR intensity color degradation analysis

The method employed to address color degradation in LiDAR intensity involves categorising extracted intensity into range groups, as outlined in Table 9. Examining LiDAR intensity ranges reveals distinct patterns in color degradation, elucidated by the discretized intensity values.

Significantly, the intensity range of 3000-3999 exhibits the highest frequency within RA1, constituting 56% of its total occurrences, while the intensity ranges of 4000-4999 and 2000-2999 contribute 32% and 12%, respectively. This distribution underscores the prevalence of mid-range intensities in RA1. In contrast, RA2 displays a markedly different profile, with the absence of values in the 2000-2999 range and a predominant concentration in the 3000-3999 range, constituting 50% of its total occurrences.

The white and blue color degradation scheme reveals a pronounced preference for high-intensity values (3000-3999), comprising 60% of its total occurrences. Conversely, white and gray demonstrate a relatively even distribution across the 2000-2999 and 4000-4999 ranges. The color degradation schemes involving white and red and blue and red exhibit a preponderance of mid-range intensities (3000-3999), constituting 75% and 50% of their total occurrences.

These nuanced findings provide valuable insights into the differential impacts of color degradation across distinct intensity ranges, underscoring the importance of tailored processing approaches based on the specific color degradation scheme employed. Such observations contribute to a refined understanding of LiDAR data quality and inform future strategies for color degradation mitigation in LiDAR applications.

Table 9. LiDAR intensity color degradation range groups and occurrences

LiDAR intensity range	RA1	RA2	WG	WB	WR	RB	Total
2000-2999	3	0	2	1	0	0	3
3000-3999	14	1	1	9	3	2	15
4000-4999	8	1	1	5	1	2	9
Total	25	2	4	15	4	4	27

6. Conclusions

In conclusion, this study aimed to comprehensively assess the retroreflectivity of traffic signs through the application of handheld retroreflectometers and LiDAR technology. The meticulous measurement and analysis of retroreflective coefficients for 112 traffic signs, classified as RA1 and RA2, revealed that 43.8% of the signs did not meet the specified standards outlined in the European standard EN 12899-1. The significance of adhering to these standards was underscored, emphasizing the critical importance of avoiding substandard materials and ensuring proper maintenance to mitigate potential risks to road safety.

The investigation also explored the relationship between LiDAR intensity and handheld retroreflectometer measurements, revealing a constrained correlation. The limitations in correlation were attributed to distinct methodologies in measurement processes, with handheld retroreflectometers focusing on localized assessments. At the same time, LiDAR technology generated exhaustive point clouds across a broader spatial area. The regression analysis indicated that power and logarithmic functions better fit the point cloud in the lower region of retroreflectivity.

Additionally, the study identified factors influencing the deterioration of traffic signs, such as shape and material category, highlighting the vulnerability of certain configurations to color degradation. The findings suggested that the RA2 material category had a more significant effect on retroreflective performance than the RA1 category, emphasizing the importance of selecting higher-quality materials to enhance the durability and effectiveness of traffic signs.

Furthermore, the research delved into LiDAR intensity color degradation analysis, revealing distinct patterns in color degradation across intensity ranges. These observations provided valuable insights into the impacts of color degradation, informing future strategies for color degradation mitigation in LiDAR applications.

In summary, this study contributes to the literature on traffic sign retroreflectivity for AVs, emphasizing the need for accurate measurements to enhance road safety. The research findings have implications for the maintenance and material selection of traffic signs, offering valuable insights for improving durability, visibility, and overall road safety. Future research is recommended to explore factors influencing LiDAR intensity in more detail and establish accurate relationships through empirical prediction models and a larger, diversified sample. The nuanced understanding derived from this research contributes to an enhanced comprehension of optimal traffic sign characteristics and their broader implications for road safety in both academic and practical domains.

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