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TECHNICAL PAPER

Evaluating mobile vehicle-mounted retroreflectivity systems against handheld measurements

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Abstract

Traffic signs are essential for road safety, and a key part of ensuring this is that the material has enough retroreflectivity to guarantee visibility at night. Standards such as UNI EN 12899-1:2008 specify minimum retroreflectivity requirements and periodic monitoring. Traditionally, retroreflectivity level is measured using handheld retroreflectometers, but this approach is slow, exposes operators to traffic risks, and only samples a limited number of signs. A mobile vehicle-mounted system has been developed to address these limitations, allowing large-scale data collection at traffic speed. There is a lack of studies comparing vehicle-mounted retroreflectivity measurements with handheld measurements of road signs, despite their importance for roadway maintenance and safety. This study addresses this gap by comparing retroreflectivity coefficients obtained from manual handheld measurements (ZEHNTNER ZRS 6060) and automatic mobile measurements (VISUALISE–Euroconsult system) on the same set of vertical road signs along highway sections in Bologna, Italy. The analysis provides insight into the correlation between the two measurement approaches and their relevance for evaluating the sign condition. Statistical analysis showed a reasonable correlation between the two methods, with a value of $R^2 = 0.504$ for measurements. Results indicate that the mobile system systematically reported higher retroreflectivity values than handheld devices, with a mean bias = +24.79 cd lx^{-1} m^{-2} and identified a larger proportion of accepted signs with 91.1% and 79.8% for mobile vehicle-mounted and manual handheld, respectively. Handheld measurements provide precise point readings, while mobile systems capture a broader, driver-oriented view of sign visibility and enable large-scale network coverage. These operational differences support their complementary roles in retroreflectivity assessment. The findings indicate that mobile measurements can support more efficient network-level screening and contribute to more reliable traffic sign asset management.

Keywords Traffic signs · Retroreflectivity · Handheld measurement · Automatic mobile measurements · Traffic safety

Introduction

Vertical road signage denotes a specific type of roadside indicator intended for road users and ensuring the safety and efficiency of the transportation network [1]. In essence, these signs support drivers in navigating the roadway environment by conveying regulatory, warning, and guidance messages, thereby reducing uncertainty and facilitating appropriate decision-making. A well-informed driver who clearly perceives and interprets road signs is more likely to act safely and confidently, lowering the risk of operational errors that may contribute to crashes [2, 3]. Despite this critical function, the condition and performance of road signs often fall short of required standards. A national survey by ASAPS (2006–2007) demonstrated that 45.8% of examined signs exhibited at least one irregularity, highlighting the need for systematic monitoring and maintenance [4].

Ensuring the adequate visibility and legibility of these signs is paramount during all operational hours [1, 5]. During daylight hours, the correct visibility and perception of vertical signage is achieved through the use of colours, which help drivers in recognizing and distinguishing the various signs. Conversely, at night or in low-light conditions, this task is performed by retroreflective films, which

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are materials that reflect light incident on their surface, coming from the vehicle's headlights, redirecting it almost entirely in the direction of the driver [6, 7].

Vertical signs are continuously exposed to environmental and mechanical stressors that progressively deteriorate both colour and retroreflective performance. Weather conditions such as rain, snow, fog, and frost, along with airborne pollutants and chemical agents, degrade material properties and reduce visibility [8]. Over longer periods, ultraviolet (UV) radiation, temperature cycles, and physical abrasion further break down retroreflective elements and surface coatings [9]. Dirt accumulation also plays a significant role; Khrapova et al. (2019) reported that particulate build-up can reduce retroreflectivity by about 10%, directly affecting nighttime detectability [2]. Laboratory and outdoor studies show that deterioration is nonlinear and colour-dependent. After 16 months of exposure in Prague, blue films exhibited a 17% reduction in reflectance, whereas white films decreased by only 1% [10]. Accelerated weathering tests confirm that blue signs are most vulnerable, while red and yellow signs more quickly reach minimum reflectance limits [11]. To model these degradation mechanisms, researchers typically rely on empirical parameters such as material type, age, and exposure, often excluding harder-to-measure factors like windshield transmission or driver behaviour [12]. Given their exposure to atmospheric agents (rain, snow, frost, fog, etc.), pollution produced by motor vehicles, and occasional chemical attacks (sulfates, marine chlorides, etc.), it is inevitable that the colours and retroreflectivity of vertical signs will deteriorate over time. This deterioration can be significant, resulting in a reduction in the visibility of the sign. Consequently, in order to ensure optimal road safety and to safeguard drivers to the greatest extent possible, Italian and European regulations stipulate that when a specific value denoting the visual characteristics of a sign falls below a predetermined minimum acceptable threshold, the sign must be replaced [6, 8]. The prevailing approach in most traditional inspections involves manual visual observations, which assess sustainability and refraction. However, this method is inherently limited in its methodological rigor. This prompts the question of the reliability of manual surveys, which are associated with subjective perceptions and constrained measurements. These limitations emphasize the necessity to enhance and expedite the processes of signage monitoring and replacement campaigns [13, 14].

The examples cited demonstrate that two main approaches—empirical and experimental—can be used to determine the retroreflectivity coefficient. In both cases, the use of measurement tools is essential for monitoring degradation over time. Current methods are generally divided into two categories: handheld field devices and mobile (vehicle-mounted) retroreflectivity systems. Handheld retroreflectometers are widely used in field applications to measure the retroreflective performance of traffic signs, simulating the geometric relationship between a vehicle's headlights and the driver's eye. Although these devices can be operated during the day, they require physical contact with the sign, making the process slow, labor-intensive, and potentially hazardous [15]. Recent laboratory and field evaluations have also shown that handheld retroreflectometers may exhibit considerable bias and measurement uncertainty. Using a set of 22 stop signs and three different instruments, Remias et al. identified measurable differences in median bias and coefficient of variation (COV) across sign types and materials, confirming that the precision of these devices is limited and that their readings may not fully capture true retroreflective performance [16].

Because of these limitations in precision and operational efficiency, alternative measurement approaches have been explored [17]. Vehicle-mounted systems automatically measure retroreflectivity as the vehicle passes each sign, though they generally require nighttime operation, which increases logistical demands [18]. A 2012 Texas Transportation Institute (TTI) evaluation of the VISUALISE system highlighted the shortcomings of handheld devices in terms of cost, accuracy, and operator safety. It demonstrated that the mobile system could produce reliable and repeatable measurements under real-world conditions [17]. More recently, Aldoski and Koren (2024) compared localized handheld measurements from a portable retroreflectometer with LiDAR-based data obtained from an autonomous vehicle. Although both techniques produced internally accurate results, their correlation was weak, emphasizing the need for further investigation into the comparability of different measurement technologies [15].

Despite increasing interest in mobile retroreflectivity systems, few studies have directly compared their measurements with handheld retroreflectometers on the same signs. In particular, the literature lacks systematic, sign-by-sign comparisons conducted under identical field conditions. Such comparisons are necessary because handheld retroreflectometers, while currently the reference standard for road authorities, have well-documented disadvantages, including labour-intensive operation, safety concerns during field deployment, and measurable bias and uncertainty in real-world performance. This gap is especially relevant for newer systems like VISUALISE mobile system, which collect far more data points and operate under different measurement conditions. Given these limitations, it is important to assess how closely their outputs align with handheld readings. Because handheld devices remain the reference standard for road authorities, understanding how closely mobile outputs align with handheld readings is essential for reliable maintenance and safety decisions. To address this gap, this study compares retroreflectivity values obtained using a handheld device (ZEHNTNER ZRS 6060) with those collected by the VISUALISE mobile system on 248 vertical road signs along a motorway in Italy. Accordingly, the study is confined to analysing the correlation between the methods and assessing what this reveals about their operational suitability for routine sign evaluation.

Materials and methods

This study followed a structured workflow consisting of three main stages: data acquisition, data processing, and analytical evaluation. A summary of the procedure is shown in Fig. 1. Handheld (ZRS 6060) and mobile (VISUALISE) measurements were first collected under comparable field conditions. The datasets were then cleaned, paired by sign ID and location, and harmonized by averaging repeated handheld readings and aggregating mobile measurements to the sign level. After quality control, 248 signs were retained for analysis. The final stage consisted of descriptive statistics, performance classification, and method-comparison analyses, including correlation, bias, and error distribution.

Study area and experimental setup

The study was conducted along two sections of a motorway in the metropolitan area of Bologna, Italy. The selected motorway is a major north–south transportation corridor with high traffic volumes and a variety of vertical road signs. The study area included the northbound and southbound lanes, which represented typical motorway conditions in terms of sign types, installation configurations, and traffic environment [19]. The signs within the surveyed sections covered a representative range of regulatory, warning, directional, and informational signs mounted on both sides of the road. The inventory of signs included various geometric shapes, primarily rectangular and lateral signs, as well as circular regulatory, triangular warning, and arrow-type directional signs. This diversity reflects the typical signs installed on motorways.

The total length of the studied stretch of road was approximately 53 km in each direction. All measurements were conducted under consistent weather and operational conditions in order to prevent environmental factors from significantly influencing the retroreflectivity results.

Measurement equipment and procedures

Two complementary retroreflectivity measurement approaches were adopted in this study: a handheld point-based device and a vehicle-mounted mobile system. Handheld measurements were performed using a Zehntner ZRS 6060 retroreflectometer, a widely used instrument for testing of vertical road signs. This device measures the coefficient of retroreflection at a fixed entrance angle of 5° and an observation angle of 0.33°, as required by UNI EN 12899-1:2008 [8, 20]. The accuracy of the manual reference data was guaranteed by calibrating the Zehntner ZRS 6060 against certified standards before each session, utilizing its shielded optics to maintain comparability with mobile measurements. Measurements are taken directly on the sign surface and can target both the background and the legend. Because of their well-defined geometry and traceable calibration, handheld retroreflectometers operate under defined measurement geometries. They are widely accepted as a standard method for regulatory inspection of vertical traffic signs [21]. However, this method requires operators to stop at each sign, and therefore exposes field crews to traffic hazards. Additionally, the measurement aperture covers only a small portion of the sign surface, which may not reflect the overall visibility performance [15, 22].

To address these limitations, mobile retroreflectivity measurements were carried out using the VISUALISE system (Euroconsult), a vehicle-mounted technology capable of collecting data continuously and at traffic speed, typically at 90 km/h, during nighttime. At this speed, the camera's 17 FPS capture rate ensures a high spatial resolution, recording approximately one frame every 1.5 m. The system integrates calibrated photometric sensors, cameras, and illumination units, and processes captured images to compute retroreflectivity values for multiple colours (white, red, blue, yellow, and green) across the entire visible area of the sign. The system operates at a nominal observation angle of around 0.2°, defined by a fixed 13 cm illuminator-camera offset and around 38 m calibration distance, while entrance angles vary dynamically with sign position and roadway geometry to enable in-situ measurements. Retroreflectivity was measured employing a synchronized low-intensity illuminator with hot-spot reduction to replicate driver-eye geometry under standardized nighttime conditions. The effective spot size is determined by the pixel spatial resolution, which scales linearly with distance. At the standard analysis distance of 38 m, the VGA sensor provides sufficient pixel density to accurately isolate specific colors or legend details without cross-contamination. Data traceability and measurement accuracy were ensured through a rigorous calibration protocol performed before and after each survey campaign using certified reference panels. However, because the vehicle-mounted system operates under a measurement geometry and acquisition protocol that differ from those specified in EN 12899-1, it is not claimed to provide standard-compliant measurements; references to EN 12899-1 and MUTCD requirements are therefore limited

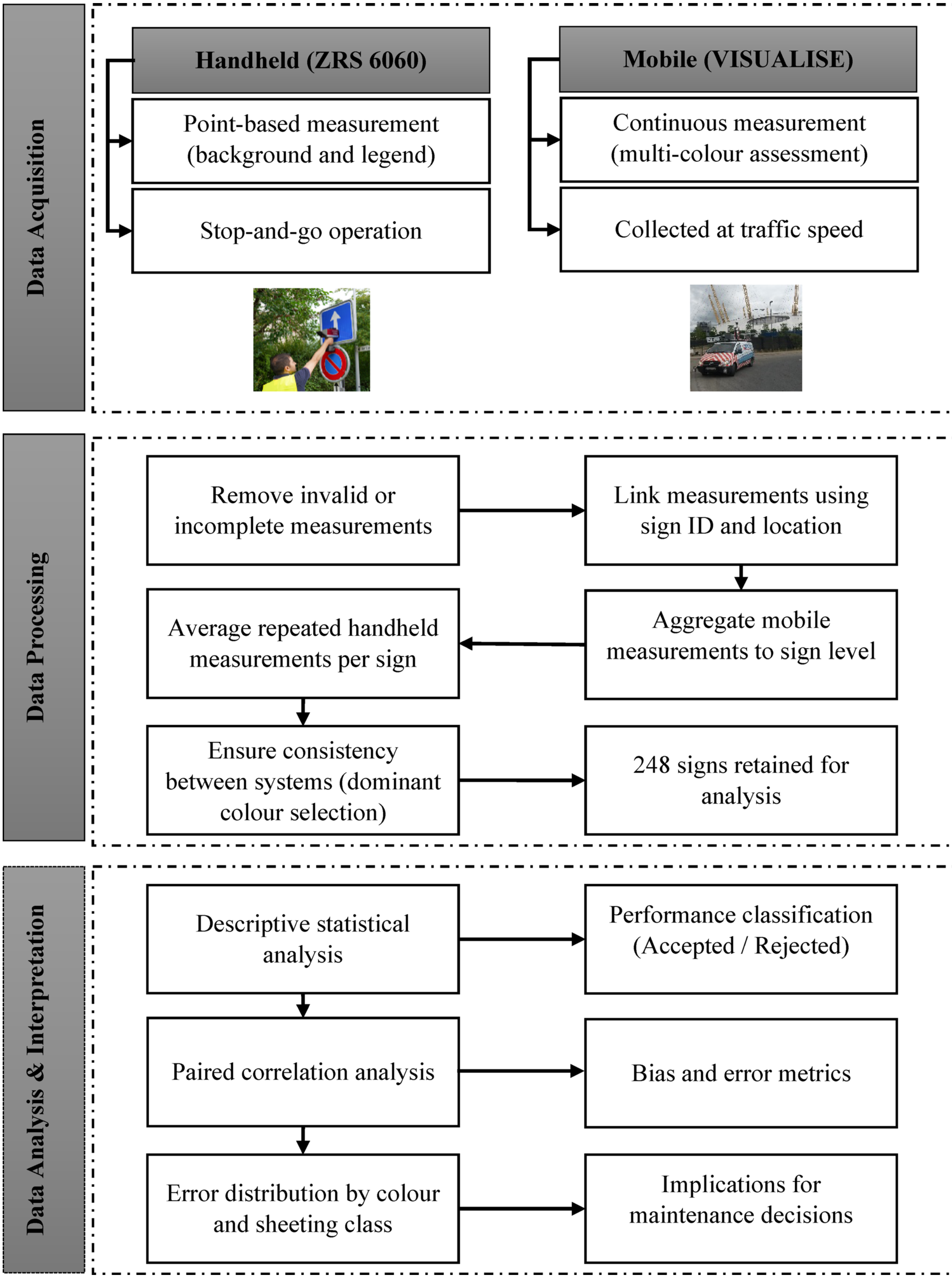

Fig. 1 Experimental workflow

Table 1 Comparison of handheld and mobile retroreflectivity measurement systems

Parameter	Handheld (ZRS 6060)	Mobile (VISUALISE)
Geometry	0.33°/5°	~0.2° observation angle
Measurement type	Point-based	Continuous
Operator safety	Requires stopping	Collected at traffic speed
Data volume	80–160 signs/day	400–500 km/day
Colours measured	Background + legend	Full spectrum (white, red, blue, yellow, green)
Advantages	High accuracy, standardized	High coverage, driver perspective
Disadvantages	Labor-intensive, limited sampling	Requires calibration,possible bias

to comparative screening and maintenance decision contexts. This approach allows the inspection of hundreds of kilometers per day, significantly improving data-collection efficiency and operator safety [17]. In addition, sign performance is measured from the roadway during normal driving conditions, so that the data can represent visibility as perceived from a driver's viewpoint rather than from an individual close-range measurement. As a result, the visibility of signs under in-service conditions is captured more realistically, reflecting the way retroreflective materials perform when viewed from an approaching vehicle [23]. However, the present study does not include human factors experiments, visibility-distance validation, or photometric equivalence analyses relative to driver headlamp–eye geometry; therefore, references to a driver-oriented perspective should be interpreted in an operational rather than perceptual sense. All measurement campaigns were conducted under dry conditions with no active precipitation. A summary of the main characteristics, strengths, and limitations of the two measurement approaches is presented in Table 1.

The field measurement campaign was carried out in two successive stages to allow a direct comparison between the two assessment approaches under similar operational conditions. During the first stage, stop-and-go surveys were performed along the selected motorway sections. At each sign location, the handheld device was carefully positioned against the sign surface, and retroreflectivity readings were recorded on site. Measurements were taken systematically across all identified signs. In the second stage, the same road sections were surveyed using a vehicle equipped with the mobile retroreflectivity system. Data acquisition was performed continuously at normal traffic speed without interrupting the flow of vehicles. As the vehicle passed each sign, the system automatically detected the sign, captured the necessary measurements, and stored the data together with its corresponding geographic coordinates. Figure 2 presents the two instruments used in this study: the handheld retroreflectometer used during stationary field surveys and the vehicle-mounted system applied for continuous, network-level data collection.

Both measurement systems used in this study rely on specific components to allow accurate retroreflectivity assessment. The handheld retroreflectometer (Zehntner ZRS 6060) uses an internal light source and a photodetector arranged at fixed angles to measure the light reflected from the sign surface. This setup allows operators to take precise point measurements of both the background and legend directly on the sign, following standardized testing geometry.

The VISUALISE mobile system, on the other hand, is equipped with two high-resolution cameras, a synchronized illumination unit, a GPS receiver, and a precision odometer. These components work together to continuously capture retroreflectivity data from the entire visible surface of signs while the vehicle is moving. Because the measurements are collected from the road at driving speed, they provide a

Fig. 2 Visual representation of the two retroreflectivity measurement systems **a** handheld and **b** vehicle-mounted VISUALISE system

Table 2 Characteristics of the signs

Parameter	Matched subset
Total signs measured	248
Southbound	118
Northbound	130
Blue sheeting	20
Green sheeting	110
Red sheeting	111
White sheeting	7

Table 3 Quantities and units used

Quantity	Symbol	Description	Unit
Coefficient of retroreflection	RA	Retroreflectivity of traffic sign surface	cd lx^{-1} m^{-2}
Measurement difference	ΔRA	Difference between mobile and handheld measurements	cd lx^{-1} m^{-2}
Mean bias	μΔRA	Mean difference between methods	cd lx^{-1} m^{-2}
Standard deviation	SD	Dispersion of retroreflectivity measurements	cd lx^{-1} m^{-2}
Mean absolute error	MAE	Mean absolute deviation between methods	cd lx^{-1} m^{-2}
Root mean square error	RMSE	Quadratic mean deviation between methods	cd lx^{-1} m^{-2}
Pearson correlation coefficient	r	Linear correlation between methods	–
Coefficient of determination	R2	Proportion of variance explained	–
Sample Size	N	Number of signs	–
Entrance angle	β	Angle between illumination axis and sign normal	degrees (°)
Observation Angle	α	Angle between incident and reflected rays	degrees (°)

realistic representation of how drivers see signs under real conditions.

Data processing and selection of comparable signs

The dataset is based on 248 traffic signs for which the measurements were made using the handheld retroreflectometer as well as the vehicle-mounted mobile system. While the mobile system surveyed 1107 signs along the corridor, the measurements were intentionally made on a subset of the signs by the handheld retroreflectometer. No measurements were discarded based on the quality of the measurements. For each sign, the dominant colour was selected to ensure consistency with the handheld device, which records a single colour per sign, while the mobile system captures data of the whole sign. Among the included signs, 118 were located on the southbound carriageway and 130 on the northbound carriageway. The matched signs encompassed a representative range of retroreflective materials and colours, including 20 blue, 110 green, 111 red, and 7 white signs. The characteristics of the signs are summarized in Table 2. This composition ensured that the comparison between measurement methods captured the diversity of materials commonly used across the motorway network. For clarity and auditability, Table 3 summarizes the quantities, symbols, and units used throughout the study.

Table 4 Distribution of signs by retroreflective colour

Colour	Number of signs	Percentage (%)	Typical function
Red	111	44.8	Regulatory and warning signs
Green	110	44.3	Guide signs
Blue	20	8.1	Obligation signs
White	7	2.8	Supplementary or service signs
Total	248	100.0	–

Experimental results and discussion

Descriptive statistical analysis

A descriptive statistical analysis is employed to characterize the dataset utilized for the evaluation of the performance of handheld and vehicle-mounted retroreflectivity measurement systems. The purpose of this analysis is to establish the analytical context for subsequent evaluations by means of quantifying the composition, distribution, and variability of the measured traffic signs. Some characterization is fundamental to understand that the comparative assessment presented in subsequent sections is based on a comprehensive interpretation of the data.

Characteristics of the matched traffic sign dataset

The matched dataset comprised 248 vertical traffic signs for which retroreflectivity values were obtained using both handheld and vehicle-mounted systems. Among these, 118 signs (47.6%) were located on the southbound carriageway and 130 signs (52.4%) on the northbound carriageway. This balanced distribution captured variations in exposure, orientation, and traffic conditions across both travel directions. The dataset included a representative range of retroreflective materials and colour classes characteristic of European motorway networks. As summarized in Table 4, red and green signs dominated the dataset, representing 44.8% and 44.3%, respectively. Blue signs, typically used for obligation or mandatory indications, accounted for 8.1%, while white signs commonly associated with warning or supplementary information comprised 2.8% of the total.

Statistical summary of measurements

Descriptive statistics of retroreflectivity values obtained from both measurement systems were computed. These statistics provide a quantitative assessment of the performance distribution and qualify an initial assessment of the measurement behavior associated with each method. Table 4 summarizes the main parameters, including the mean, median, standard deviation (SD), minimum, and maximum values calculated for the matched subset of 248 signs.

Table 5 and Fig. 3 summarize the descriptive statistics of retroreflectivity measurements obtained using both the vehicle-mounted automatic system and the handheld manual device. On average, the mobile system recorded a higher coefficient of retroreflection (mean = 75 cd lx^{-1} m^{-2}) compared to the handheld measurements (mean = 50 cd lx^{-1} m^{-2}). The higher mobile readings could be attributed to the fact that the mobile system is visibility-oriented; it captures retroreflective response under dynamic viewing conditions similar to those experienced by drivers, whereas handheld systems are primarily compliance-oriented and performed at fixed, standardized geometries. The dispersion of measurements was also greater for the mobile system (SD = 68.49) relative to the handheld method (SD = 58.12), showing higher variability. The minimum and maximum values reflect this difference: mobile measurement ranged from 1 to 515 cd lx^{-1} m^{-2}, whereas handheld measurement ranged from 3 to 464 cd lx^{-1} m^{-2}. Median values followed the same trend (67 vs. 37 cd lx^{-1} m^{-2}). These results show that the vehicle-mounted system tends to yield higher retroreflectivity readings, potentially due to differences in geometry, sensor calibration, or measurement conditions.

Table 5 Descriptive statistics of retroreflectivity measurements obtained by handheld and mobile systems

Measurement Systems	Mean (cd lx^{-1} m^{-2})	Median	SD	Min	Max
Handheld (ZRS 6060)	50	37	58.12	3	464
Mobile (VISUALISE)	75	67	68.49	1	515

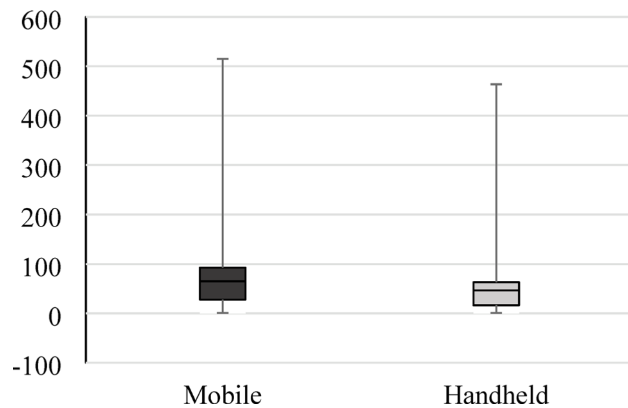

Fig. 3 Boxplot of retroreflectivity measurements obtained by handheld and mobile systems

Performance assessment of retroreflectivity measurements

Performance evaluation criteria

All retroreflectivity measurements collected using the handheld and vehicle-mounted systems were evaluated against the minimum performance thresholds established by the EN 12899-1:2008 standard for vertical road signs. In this framework, the measured coefficient of retroreflection was compared with the corresponding threshold values defined for RA1 and RA2 retroreflective sheeting classes using a measurement geometry of 20′ observation angle and + 5° entrance angle, as shown in Table 6. Signs with measured RA values equal to or greater than the specified minimum were classified as Accepted, which shows that the sign provides adequate retroreflective performance for safe driver recognition under nighttime conditions. On the other hand, signs with RA values below the required value were classified as Rejected, which shows insufficient retroreflective performance and a potential need for maintenance or replacement.

EN 12899-1 threshold values are applied to vehicle-mounted measurements for comparative screening purposes only, as the mobile system is not claimed to fully replicate the standard's prescribed measurement geometry and spectral conditions. Similar to what previous third-party evaluations of the VISUALISE system have relied on comparisons with handheld measurements performed under ASTM E1709 protocols [17].

This classification approach provides a clear way to evaluate the condition of traffic signs in real operating environments. Using the same assessment criteria for both handheld and vehicle-mounted measurements ensures that the results are directly comparable. It also makes it possible to evaluate how well each method identifies signs that meet the required performance standards established by regulations.

Table 6 Minimum coefficient of retroreflection for Class RA1 and RA2 sheeting according to EN 12899-1:2008 (cd lx^{-1} m^{-2}) [8]

Class	Geometry of measurement	White	Yellow	Red	Green	Dark Green	Blue	Brown	Orange	Grey
RA1	20′ + 5°	50	35	10	7	#	2	0.6	20	30
RA2	20′ + 5°	180	120	25	21	14	14	8	65	90

Table 7 Performance results by colour for handheld and vehicle-mounted retroreflectivity measurements

Colour	System	Accepted (No.)	Accepted (%)	Rejected (No.)	Rejected (%)
Red	Handheld	88	79.3	23	20.7
	Vehicle-mounted	106	95.5	5	4.5
Green	Handheld	91	82.7	19	17.3
	Vehicle-mounted	95	86.4	15	13.6
Blue	Handheld	14	70.0	6	30.0
	Vehicle-mounted	20	100	0	0
White	Handheld	5	71.4	2	28.6
	Vehicle-mounted	5	71.4	2	28.6
Total	Handheld	198	79.8	50	20.2
	Vehicle-mounted	226	91.1	22	8.9

Performance evaluation results

The performance evaluation of retroreflectivity measurements was carried out on the matched dataset of 248 traffic signs, measured by handheld and vehicle-mounted systems. Each measurement was assessed against the minimum performance thresholds defined by the EN 12899-1:2008 standard, and signs were classified as accepted or rejected based on whether their measured coefficient of retroreflection met or exceeded the specified values. This approach facilitates a direct comparison between handheld and mobile measurements and establishes a solid basis for the evaluation of road signs under actual operating conditions.

The performance evaluation showed differences in classification between handheld and vehicle-mounted retroreflectivity measurement systems. Of the 248 signs analyzed, the handheld retroreflectometer classified 79.8% as compliant with the minimum retroreflectivity thresholds defined by UNI EN 12899-1:2008 (95% CI 74.8–84.9%), whereas the vehicle-mounted system identified 91.1% as meeting the required performance levels (95% CI 87.6–94.7%), indicating higher compliance detection by the mobile system. This discrepancy of 11.3 percentage points indicates that the mobile system consistently reported higher compliance levels than the handheld method.

As summarized in Table 7 and Fig. 4, compliance rates varied by sign colour. Green signs showed high acceptance for both systems, with compliance rates of 82.7% for handheld and 86.4% for mobile measurements, while red signs exhibited a larger discrepancy between systems (79.3% handheld versus 95.5% mobile). Blue and white signs presented lower acceptance levels, particularly in handheld measurements, with compliance rates of 70.0% and 71.4%, respectively. These results should not be interpreted as indicating that blue or white signs perform worse. For white signs, the low acceptance percentage is explained by the small sample size (n = 7), which limits the representativeness of the finding. However, the case of blue signs is different. Their reduced acceptance is partly linked to environmental exposure and material properties. Blue signs are used for service and informational purposes, often installed at lower mounting heights or near motorway exits, where they are subject to road spray, dust, and particulate accumulation. These conditions accelerate material deterioration. Furthermore, blue pigments in retroreflective sheeting are known to be more vulnerable to UV degradation, which diminishes their long-term optical efficiency. Together, these factors explain the relatively lower compliance rate of blue signs compared with green or red signs [13]. The combined influence of UV exposure and pollution on material degradation can vary substantially between urban and rural environments, as location-specific UV levels and pollutant concentrations may alter degradation rates and mechanisms, making broad generalization difficult without accounting for these contextual differences [24]. Average retroreflectivity values, seen in Fig. 4, further support this

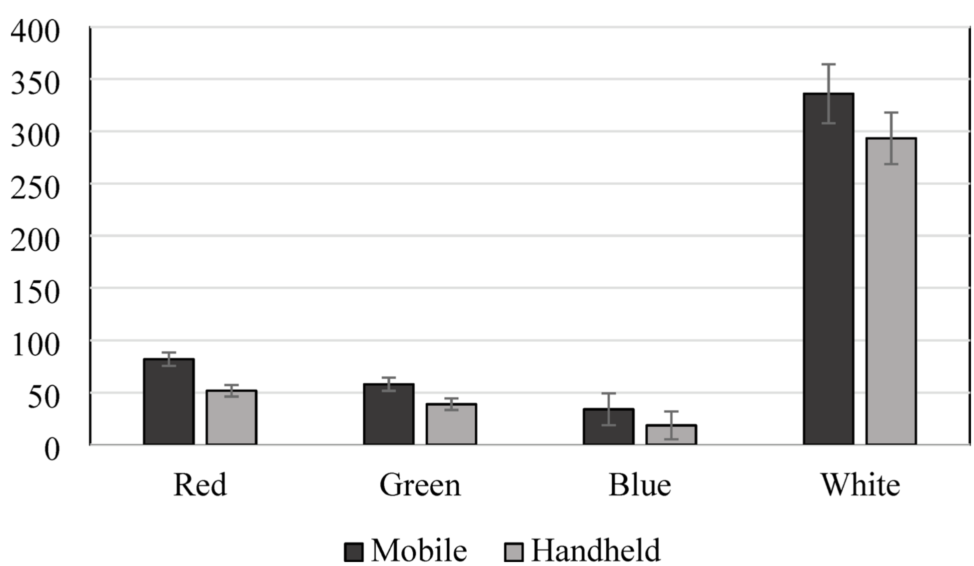

Fig. 4 Summary of average RA by colour for handheld and mobile systems

interpretation. White signs exhibited the highest mean RA for both systems (293.3 cd lx^{-1} m^{-2} for handheld; 336 cd lx^{-1} m^{-2} for mobile), followed by red signs (51.7 vs. 82.0 cd lx^{-1} m^{-2}) and green signs (38.9 vs. 58.0 cd lx^{-1} m^{-2}). Blue signs showed the lowest average retroreflectivity (18.6 cd lx^{-1} m^{-2} handheld; 34.0 cd lx^{-1} m^{-2} mobile). In all cases, the mobile system recorded higher mean values than the handheld device. Given that only seven white signs were included, these values are not statistically representative and should be interpreted with caution.

Further stratification by retroreflective sheeting class (Table 8) indicated that RA2 materials consistently achieved higher compliance rates than RA1 across all colours. For example, RA2 red signs achieved compliance rates of 82.1% (handheld) and 95.8% (mobile), compared with 62.5% and 66.7% for RA1 red signs, confirming the superior optical performance of higher-grade retroreflective sheeting under field conditions. These results are consistent with the expected optical behavior of higher-performance sheeting, which provides greater retroreflective efficiency and superior long-term performance under field conditions [25].

In summary, the vehicle-mounted system classified a higher proportion of signs as accepted than the handheld device (91.1% vs. 79.8%). This difference is consistent with the systematically higher retroreflectivity values measured by the mobile system and indicates a systematic measurement offset between the two approaches.

Relationship between handheld and vehicle-mounted measurements

A comparative analysis of retroreflectivity measurements from handheld and vehicle-mounted systems is presented, focusing on correlation, systematic bias, and classification consistency with regulatory thresholds. Because the two systems differ in measurement geometry, spatial sampling, and data aggregation, the results should be interpreted as a method-comparison exercise rather than an evaluation of absolute measurement accuracy. The analysis is based on a single measurement per sign using the vehicle-mounted system and an average of three handheld readings; therefore, short-term repeatability and temporal reliability were not evaluated. The reported correlation and bias values thus reflect differences between the two measurement methods rather than within-system variability over time.

Given the potential for measurement error with both the handheld and mobile instruments and the lack of replicate data and inter-operator observations or hierarchical metadata within the dataset, the assessment is conducted as a method comparison and network level screening assessment rather than an evaluation for interchangeability or substitution. Descriptive evaluation is conducted for the metrics calculated; inference is not made regarding the equivalence of the two instruments.

Statistical correlation and measurement comparison

A paired statistical analysis was conducted on the 248 vertical traffic signs that were measured by both the handheld and vehicle-mounted systems. The comparison shows a reasonable linear relationship between the two measurement approaches, with a Pearson correlation coefficient of $r=0.710$ (95%CI 0.642, 0.766), a coefficient of determination $R^2=0.504$ (95%CI 0.412, 0.587), and a p-value less than 0.001 (statistically significant). This indicates that a higher coefficient of retroreflection recorded by one method tends to higher values measured by the other. The results also show a clear systematic bias between the two methods. The vehicle-mounted system recorded retroreflectivity values that were 24.79 cd lx^{-1} m^{-2} higher than those obtained from handheld measurements. This offset can largely be attributed to fundamental differences in measurement geometry

Table 8 Performance results by colour and sheeting class (RA1 vs. RA2)

Colour	Class	System	Accepted (No.)	Accepted (%)	Rejected (No.)	Rejected (%)
Red	RA1	Handheld	10	62.5	6	37.5
		Vehicle-mounted	10	66.7	5	33.3
	RA2	Handheld	78	82.1	17	17.9
		Vehicle-mounted	96	95.8	4	4.2
Green	RA1	Handheld	27	65.9	14	34.1
		Vehicle-mounted	34	82.9	7	17.1
	RA2	Handheld	64	92.8	5	7.2
		Vehicle-mounted	61	88.4	8	11.6
Blue	RA1	Handheld	4	80.0	1	20.0
		Vehicle-mounted	5	100	0	0
	RA2	Handheld	10	66.7	5	33.3
		Vehicle-mounted	15	100	0	0
White	RA2	Handheld	5	71.4	2	28.6
		Vehicle-mounted	5	71.4	2	28.6

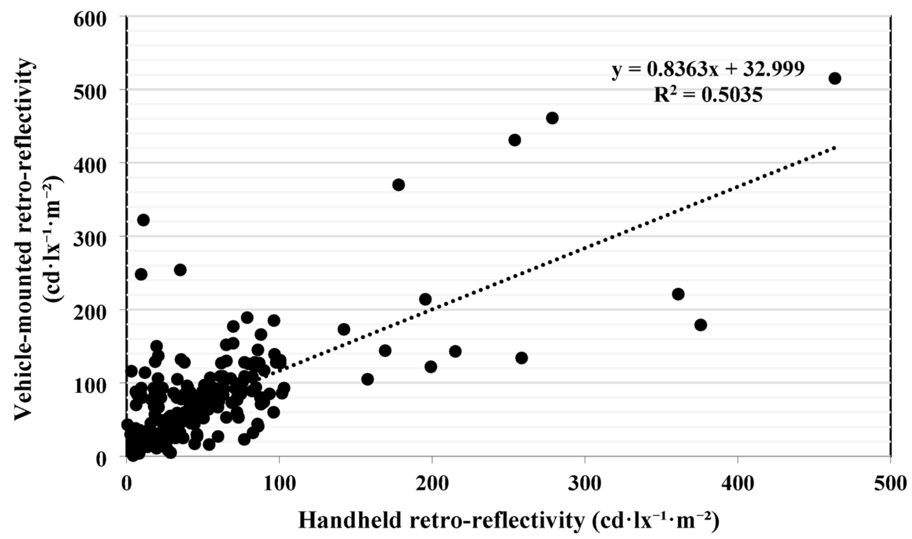

Fig. 5 Scatter plot showing the relationship between handheld and vehicle-mounted retroreflectivity measurements

Table 9 Comparative summary of paired retroreflectivity measurements

Parameters	Value	95% Confidence Interval
Pearson correlation coefficient (r)	0.710	[0.642, 0.766]
Coefficient of determination (R^2)	0.504	[0.412, 0.587]
Mean bias (ΔRA) (cd lx^{-1} m^{-2})	+24.79	[18.60, 30.90]
P-value	<0.001	

and sampling technique: the handheld retroreflectometer evaluates a small, localized point on the sign surface, which may include areas affected by ageing or surface degradation, whereas the vehicle-mounted system integrates light return from the entire visible surface [18]. To illustrate the relationship between the two methods, a scatter plot of the two measurements is presented in Fig. 5.

The spread of the points illustrates the measurement variability introduced by differences in calibration, sign condition, and field geometry.

A summary of the key comparative metrics is presented in Table 9, which presents the positive bias between the two measurement techniques. Paired-samples analysis showed that retroreflectivity values measured by the vehicle-mounted system were significantly higher than those obtained using the handheld device (mean difference = 24.79 cd lx^{-1} m^{-2}; 95% CI 18.60–30.90; $p < 0.001$). These results show that although the two measurement methods are moderately related, they cannot be used as direct substitutes for one another.

Error distribution and measurement differences

A measurement difference was carried out to explore the distribution and variability between handheld and vehicle-mounted retroreflectivity measurements. This analysis aims to assess how much the two approaches diverge from one another on a sign-by-sign basis. The distribution of the measurement differences ΔRA is presented in Fig. 6.

The histogram shows that most values cluster in the positive range, particularly between 0 and + 50 cd lx^{-1} m^{-2}. The findings confirm that the vehicle-mounted system tends to report a higher coefficient of retroreflection compared to the handheld device. However, the distribution exhibits a spread, indicating considerable variability in the degree of difference between the two methods. Most signs display only slight differences, with only a small proportion exceeding ± 100 cd lx^{-1} m^{-2}. These larger discrepancies are particularly evident in signs with advanced aging or heterogeneous surface conditions, which affect the spatial uniformity of reflected light

A quantitative summary of the measurement differences is provided by error-based performance metrics presented in Table 10. The mean absolute error (MAE) was calculated as 35.43 cd lx^{-1} m^{-2}, representing the average magnitude of deviation between the two systems. The root-mean-square error (RMSE) was 54.99 cd lx^{-1} m^{-2}. The two measurement systems show consistency; however, moderate differences can still be observed due to variations in their sensor field of view, sampling geometry, and integration methods.

Error distribution by colour and sheeting class

Categorizing the analysis by sign colour showed different variations in correlation and error characteristics, as seen in Table 11. The highest correlation was observed for green signs with $r = 0.724$ and $R^2 = 0.524$, which also exhibited the lowest errors (MAE = 25.85 cd lx^{-1} m^{-2}, RMSE = 35.79 cd lx^{-1} m^{-2}). The two measurement systems demonstrate a

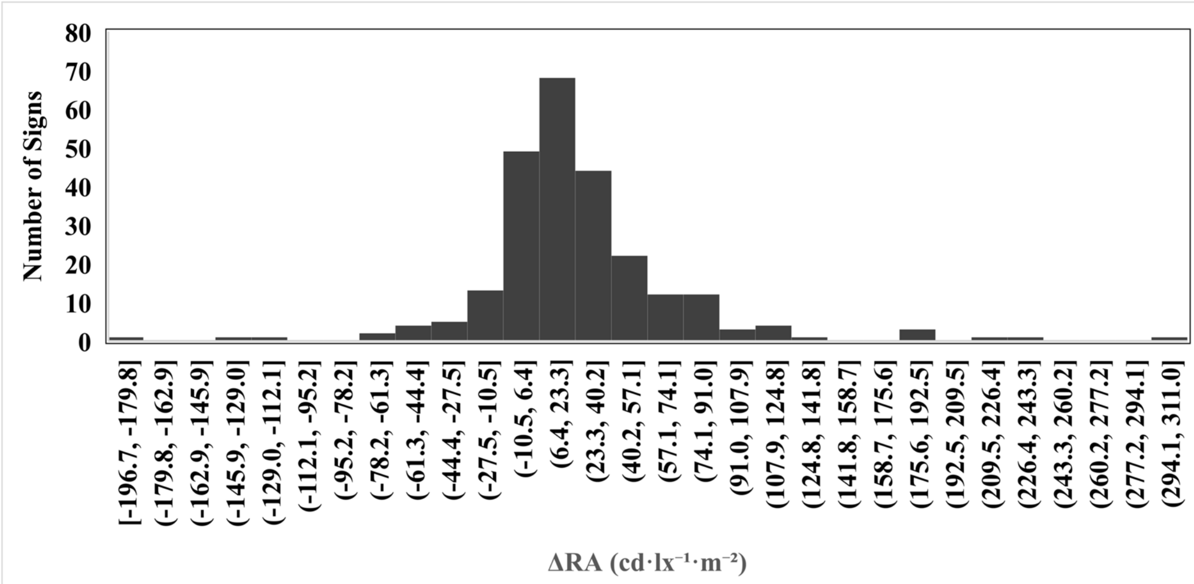

Fig. 6 Distribution of measurement differences

Table 10 Error Metrics for Mobile vs. Handheld Measurements

Metric	Value (cd lx^{-1} m^{-2})
Mean Absolute Error (MAE)	35.43
Root Mean Square Error (RMSE)	54.99

relatively high degree of consistency in their evaluation of green retroreflective materials. Red signs displayed weaker.

correlation r = 0.329, R^2 = 0.108, and higher errors MAE = 41.11 cd lx^{-1} m^{-2} and RMSE = 61.91 cd lx^{-1} m^{-2}, indicating larger variability in the measurements. Blue signs exhibited minimal correlation with a value of 0.072, though their MAE and RMSE values were lower than those of red and white signs. White signs had the highest error levels with MAE = 138.63 cd lx^{-1} m^{-2} and RMSE = 152.76 cd lx^{-1} m^{-2}, due to their high luminance and reflective variability. However, the small sample size (n = 7) presents limitations on the reliability of the conclusions. The results show substantial variation in the correlation across colours: green, with the largest sample size, shows the highest correlation and lowest errors, indicating reliable consistency between measurement systems, whereas white, with the smallest sample size, exhibits the weakest correlation and highest errors, due to the greater measurement uncertainty.

The Bland–Altman analysis shown in Fig. 7 illustrates the agreement between mobile and handheld retroreflectivity measurements by examining the distribution of their differences as a function of the mean value. The analysis reveals a positive mean bias of 24.79 cd lx^{-1} m^{-2}, indicating that the vehicle-mounted system systematically reports higher retroreflectivity values than the handheld device. The 95% limits of agreement range from −71.63 to 121.20 cd lx^{-1} m^{-2}, with non-negligible uncertainty as reflected by their 95% confidence intervals (lower LoA: −89.43 to −53.32 cd lx^{-1} m^{-2}; upper LoA: 98.58 to 143.74 cd lx^{-1} m^{-2}). While most observations fall within these limits, the increasing spread at higher mean retroreflectivity values suggests heterogeneity in measurement differences, likely related to differences in measurement geometry and spatial integration between the two systems. These results indicate the presence of systematic bias and moderate agreement, confirming that the two methods should not be considered interchangeable.

A heteroscedasticity check based on the Bland–Altman residuals showed a positive correlation between the absolute measurement difference and the mean retroreflectivity (Pearson r = 0.61, $p < 0.001$), indicating increasing variability at higher retroreflectivity levels.

The results, categorized by sheeting class as shown in Table 12, revealed substantial differences in measurement between RA1 and RA2 materials. RA2 signs showed high correlation coefficients between the two systems, with r = 0.700 and a moderate coefficient of determination of

Table 11 Error metrics categorized by sign colour

Colour	n	r	R^2	MAE (cd lx^{-1} m^{-2})	RMSE (cd lx^{-1} m^{-2})	Mean Bias (ΔRA)
Blue	20	0.072	0.005	20.41	31.82	15.47
Green	110	0.724	0.524	25.85	35.79	19.60
Red	111	0.329	0.108	41.11	61.91	30.49
White	7	0.254	0.065	138.63	152.76	42.43

Fig. 7 Bland–Altman plot showing the distribution of differences between Vehicle-mounted and handheld retroreflectivity measurements

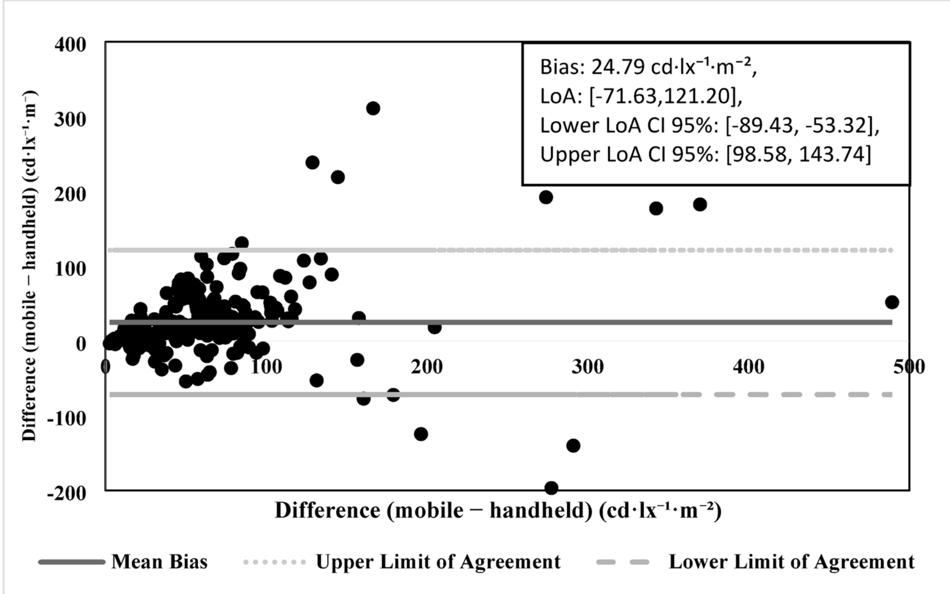

Table 12 Error metrics categorized by sheeting class

Sheeting class	n	r	R^2	MAE (cd lx^{-1} m^{-2})	RMSE (cd lx^{-1} m^{-2})	Mean bias (ΔRA)
RA1	62	0.052	0.003	23.59	44.98	22.71
RA2	186	0.700	0.490	39.37	57.95	25.48

R^2 = 0.490. However, they also exhibited slightly higher errors, MAE = 39.37 cd lx^{-1} m^{-2} and RMSE = 57.95 cd lx^{-1} m^{-2}, and a mean bias of 25.48 cd lx^{-1} m^{-2}. On the other hand, RA1 signs showed almost no correlation (r = 0.052, R^2 = 0.003) but slightly lower errors with a value of MAE = 23.59 cd lx^{-1} m^{-2} and RMSE = 44.98 cd lx^{-1} m^{-2} and a mean bias of 22.71 cd lx^{-1} m^{-2}. The correlation between the measurement methods appears to depend strongly on the properties of the retroreflective materials, which affect characteristics such as angular response and light distribution [26]. The results indicate that RA2 achieves a higher correlation. This closer alignment is likely due to the advanced design of microprismatic sheeting, which enhances light return efficiency but also introduces more complex optical behavior. Measurements of RA2 materials tend to show slightly larger errors. This reflects their greater sensitivity to measurement geometry and viewing conditions. RA1 signs exhibit a weaker correlation between handheld and mobile measurements. This reduced correlation is linked to the simpler optical design of RA1 sheeting, which leads to more variable interactions with measurement geometry. These trends are illustrated in Fig. 8.

These colour-related interpretations should be regarded as speculative, as the study did not include per-sign information on sheeting manufacturer, installation age, orientation, or surface cleanliness, and therefore cannot link the observed differences to specific degradation mechanisms.

Implications of measurement bias for maintenance decision-making

The positive bias observed between mobile and handheld measurements has important implications for maintenance decision-making. While the mobile system provides efficient, network-level coverage and a driver-oriented assessment of sign visibility, the approximately + 24.79 cd lx^{-1} m^{-2} offset may lead to an overestimation of compliance when regulatory thresholds defined by standards are applied directly. For example, signs with retroreflectivity values close to the minimum acceptable limits when measured by the mobile system are at risk of being falsely classified as compliant, potentially delaying necessary replacement. Rather than treating mobile and handheld measurements as interchangeable, mobile systems should be integrated into maintenance workflows as screening tools, with handheld measurements reserved for signs whose mobile-measured retroreflectivity falls within a defined margin around the regulatory threshold. Such use of mobile measuring systems would allow road authorities to exploit the efficiency and advantages of mobile systems while maintaining consistency with established compliance standards.

From an operational perspective, the bias identified in this study suggests that calibration or conversion strategies may be required when mobile measurements are used to support compliance-based maintenance decisions. One approach is the application of bias-correction models derived from

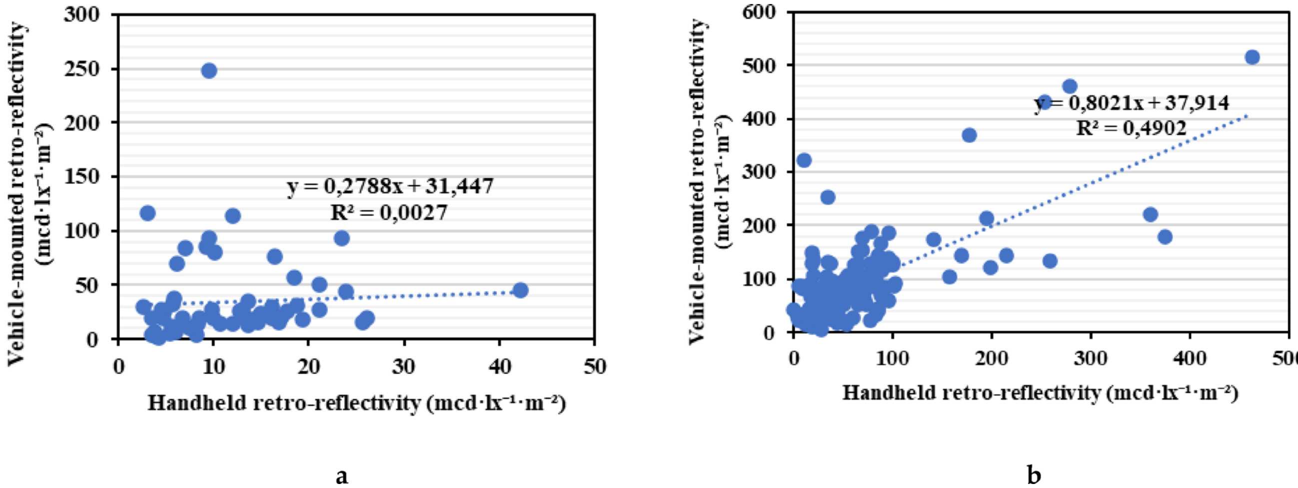

Fig. 8 Scatter plots comparing handheld and vehicle-mounted retroreflectivity measurements for **a** RA1 and **b** RA2 sheeting materials

paired handheld and mobile measurements. Alternatively, and more conservatively, mobile systems could be calibrated using a decision-oriented "factor of safety", whereby signs are flagged for further inspection or replacement when mobile-measured retroreflectivity values fall within a predefined buffer above the regulatory threshold. This approach reduces the risk of false acceptance while preserving the advantages of mobile inspections.

From a network-planning perspective, the placement and use of infrastructure sensors in transportation systems has been extensively studied under the traffic sensor location problem (TSLP), where the objective is to determine the quantity and position of sensors that maximize network coverage, flow observability, and information gain under resource constraints. For example, Owais (2022) reviews three decades of sensor placement research, highlighting how optimal location strategies can balance coverage and cost in large networks [27]. Extensions of this problem include formulations that ensure the uniqueness of path flow identification using active vehicle identification sensors [28] and adaptive optimization frameworks that address sensor placement under uncertainty using flow-constrained inference [29]. Although our study does not explicitly solve a sensor location optimization problem, these concepts can inform future planning of mobile measurement routes and inspection frequencies to improve representative network coverage while accounting for uncertainty and budget limitations.

Conclusions and recommendations

The main objective of this study was to evaluate and compare the performance of handheld and vehicle-mounted retroreflectivity measurement systems for vertical traffic signs under real motorway operating conditions. Two methods were employed: the Zehntner ZRS 6060 manual handheld retroreflectometer, representing the standard point-based measurement approach, and the automatic VISUALISE vehicle-mounted system, which allows continuous data acquisition at traffic speed. Retroreflectivity measurements were collected on the same set of 248 signs using both systems, enabling a direct, sign-level comparison of measurement behaviour, statistical correlation, and compliance classification with the UNI EN 12899-1:2008 performance thresholds.

Based on the comparative analysis, the main findings of this study can be outlined as follows:

- Handheld and vehicle-mounted retroreflectivity measurements show consistent trends but only moderate correlation (r = 0.710, R^2 = 0.504), indicating that the two methods are not interchangeable.
- Vehicle-mounted measurements exhibit a positive bias of 24.79 cd lx^{-1} m^{-2} relative to handheld readings, which can lead to overestimation of compliance when regulatory thresholds are applied directly.
- Measurement correlation varies with sign colour and retroreflective sheeting class, with higher consistency observed for green signs and RA2 materials.
- Greater variability for red, blue, and RA1 signs reflects material-specific optical behaviour and sensitivity to environmental and geometric factors.
- Vehicle-mounted systems offer substantial advantages in efficiency and network-level coverage, but also may be affected by dynamic field conditions such as variable viewing distance and vehicle motion, which introduce additional uncertainty

This study was conducted on a single motorway corridor and included a limited number of white signs, which constrains the generalization of some colour-specific findings. Repeatability, inter-operator variability, and temporal reliability were not assessed due to the absence of replicate measurements and structured variance components. As a result, errors-in-variables regression, mixed-effects modeling, and formal repeatability/reproducibility (R&R) analyses could not be performed. These limitations imply that the two measurement systems should not be considered interchangeable, and the results should be interpreted within the context of comparative screening rather than instrument equivalence. Future work should also focus on bias-aware calibration or decision-buffer frameworks to support robust compliance assessment and maintenance decision-making. When richer datasets become available, the inclusion of replicate measurements, quality stratification, or alternative preprocessing assumptions would also enable the application of global sensitivity analysis techniques to assess the robustness of correlation, bias, and classification outcomes as demonstrated in previous transportation engineering studies [30, 31]. In addition, future studies may explore advanced analytical or machine-learning approaches when larger and more diverse datasets become available. These findings support the complementary use of handheld and vehicle-mounted systems to improve the efficiency and reliability of traffic sign maintenance strategies.

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Author contributions Conceptualization: V.V., C.L., D.C.; methodology: C.B., S.M., M.P.; validation: V.V., C.L.; formal analysis: C.B., S.M., M.P.; investigation: C.B., S.M., M.P.; data Curation: C.B., S.M., M.P.; writing—Original Draft: C.B., S.M., M.P.; Writing—Review & Editing: V.V., C.L.; Visualization: V.V., C.L.; Supervision: V.V. All authors have read and agreed to the published version of the manuscript.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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