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Assessing Pavement Marking Durability and Retro-Reflectivity: Enabling and Engineering Factors for Road Safety – A Scoping Review (2015–2025)

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Abstract: The deterioration of pavement markings reduces visibility and compromises road safety by diminishing lane guidance accuracy, particularly under adverse weather and traffic conditions. This scoping review examined the factors influencing pavement marking durability, retro-reflectivity degradation, and maintenance effectiveness across different climatic and operational contexts. Structured searches were conducted in Scopus, Web of Science, ScienceDirect, Transportation Research Record, and Google Scholar for studies published between 2015 and 2025, including relevant grey literature. Fourteen empirical studies met the inclusion criteria and were synthesised through thematic analysis. The findings indicate that material type, bead quality, traffic load, and environmental exposure are dominant determinants of retro-reflectivity loss. Cold plastic markings tend to retain approximately 19% higher retro-reflectivity than thermoplastic, while premium glass beads extend service life by around 50%. High-traffic lanes experienced up to a 91% reduction in retro-reflectivity, whereas rainfall temporarily improved visibility but accelerated long-term wear. Protective coatings and vehicle-mounted retro reflectometers improved monitoring precision and long-term durability. The review concludes that performance-based material selection, adaptive maintenance strategies, and sustainability-oriented procurement can significantly enhance marking longevity and cost efficiency. Future research should focus on predictive maintenance models, integration of computer vision technologies, and long-term field monitoring to support data-driven frameworks that strengthen both safety and environmental performance.

Keywords: Pavement markings, road safety, retro-reflectivity, material durability, maintenance strategies, scoping review

1. INTRODUCTION

To protect the vehicle from hazards on the road, pavement markings are required, providing visual cues for drivers and assisting with lane regulation under varying environmental conditions (Elias et al., 2024; Owusu et al., 2018). Whether pavement markings perform well with respect to retro-reflectivity will vary due to the material composition, application techniques, and exposure to traffic volume and environmental conditions (Babić et al., 2020; Burghardt & Pashkevich, 2023). Thermoplastic and waterborne paints are globally used but degrade at different rates, and in countries experiencing extreme weather events like heavy rain, UV radiation, and snowplow operations, they become prominent (Roy et al., 2022). Research indicates that the quality of glass beads has a great effect on results over time, and that the higher density of glass beads can result in better reflectivity (Owusu et al., 2018; Carlson et al., 2013). The glass beads on the pavement markings perform unpredictably on different types of surfaces, depending on how they are applied, producing unpredictable reflectivity, thus making maintenance difficult (Zhang et al., 2010).

Cost is a factor influencing the choice of appropriate pavement marking materials. Environmental factors, such as solvent-based paints, provide good durability but are responsible for the generation of harmful volatile organic compounds (VOCs) (Burghardt et al., 2021; Barandica et al., 2013). The selection of a pavement marking material that preserves its high performance and environmental impact. For the last decade, advancements in pavement marking technology have led to diverse maintenance strategies and evaluation protocols, which have resulted in inconsistent restriping intervals between jurisdictions (Babić et al., 2018; Park et al., 2019). Different methods of assessing retroreflectivity (RL) also lead to these discrepancies. While many agencies apply handheld static retroreflectometers, others use vehicle-mounted dynamic systems with continuous objective measurements over larger pieces of road (Babić, Fiolić & Žilionienė, 2017). A few recent empirical studies have broadened our knowledge base of the interplay between RL degradation and material properties. Burghardt (2018) showed that the design of structured cold-plastic base layers and premium glass beads together can maintain RL over 200 mcd/m²/lx for more than four years after heavy traffic and winter abrasion and Mosböck and Burghardt (2016), who found an improvement of both retroreflectivity and abrasion resistance of SOLIDPLUS beads in reducing RL loss from 53% to 42% by two million vehicle passes. These results are in accordance with previous studies, which pointed out that bead embedment, coating quality, and refractive index are principal contributors to RL retention and durability. Also, faster laboratory demonstrations by Wang et al. (2023) proved that mechanical abrasion, film smoothness, and bead adhesion have a significant effect on wear quality and pollutant emission profiles during service. Not surprisingly, all degradation models currently exclude environmental variables, including the occurrence of heavy rainfall, ultraviolet light exposure, and freeze–thaw cycles, and operational parameters, including snow ploughing and heavy automotive loaders that enhance bead losses and fatigue rates (Roy et al., 2022; Babić et al., 2020).

Empirical and sustainability studies conducted since 2016 have underlined the value of material innovation and lifecycle efficiency in road marking practice. Cruz, Klein, and Steiner (2016) have performed a lifecycle assessment of solvent-borne, thermoplastic, and cold-plastic-based systems and concluded that cold-plastic and cold-spray systems and their combined solutions reduce greenhouse gases by 50 percent or more of greenhouse gas emissions after ten years, with performance against the standard required for visibility determined by EN 1436. Burghardt (2018) also showed that long-term cost savings of almost 25% can be realized for durable cold-plastic systems equipped with premium beads, for example, extending the life of these systems by between three and five years. These findings support the economic and environmental benefits of performance-based materials in comparison with traditional solvent-based materials, compared to their conventional solvent-borne counterparts. Numerous research gaps persist, including the predictive modelling of combined climatic variability, traffic-induced wear, and material-mediated deterioration to develop detailed deterioration models. Very few studies have built the effects of maintenance timing, partial restriping, or bead replenishment into RL decay predictions. As noted by Babić et al. (2018) and Park et al. (2019), inequalities between flat and structured marking systems and between dry and wet-weather RL performances persist as challenges to standardisation. Accordingly, empirical validation in the mixed traffic and environmental environments presented in current literature is required to guide scalable maintenance policies, to refine sustainability assessments, and to adjust international performance standards for pavement marking durability and retro-reflectivity. The objective of this study is to (i) systematically map and synthesize the empirical literature published between 2015 and 2025 to extend the temporal scope by incorporating foundational and recent findings. This 10-year period illustrates progression from traditional thermoplastic and solvent-borne systems to contemporary sustainable and performance-based technologies, ii) synthesize and describe characteristics affecting the durability and retro-reflectivity of pavement markings related to retro-reflectivity degradation rates in several of the included studies, and iii) outline and report some research gaps or limitations that exist in the current literature on pavement marking performance which will contribute to the subsequent modelling and scalable maintenance policy construction.

2. METHODOLOGY

2.1. Research Design

This scoping review examines what affects pavement markings' longevity and their retro-reflectance, with special emphasis placed on engineering interventions to improve safety for the road. The method for scoping review involved both Civil engineering, Transportation Engineering, and pavement management Research. Lacks in these areas were identified in detail, and corresponding engineering advice could have been given for a solution. The methodology of the scoping review is based on Arksey and O'Malley's (2005) method and advanced by Levac et al. Proposed methodological refinements by Levac et al. (2010) enhance the transparency and comprehensiveness of scoping reviews, in addition to making them more analytically rigorous. In this scoping review, this was followed up with five steps as the methodology: i) research questions; ii) searching for the studies in an organized manner; iii) screening criteria applied to the chosen studies; iv) extracting the studies and charting the data derived from the research; and v) analyzing the data and merging them into a thematic pattern which involves the durability of the pavement marking, its retro-reflectivity and the engineering approach.

2.2. Search Strategy

The research team used the PCC (Population/Problem, Concept and Context) framework by doing an exhaustive search for relevant literature. The population and problem of the study covered pavement markings on road networks, while the Concept focused on durability and retro-reflectivity factors. The context was road safety, pavement performance, and environmental impact. The population–concept–context (PCC) framework offers a methodological framework for delimiting the scopes and objectives of scoping reviews by specifying three critical components; namely, Population (the focus of study), Concept (the relevant aspects of the review) such as durability, retro-reflectivity and influencing factors, as well as Context (the context of environmental or operational aspects, examples being road safety in a specific area); the Climate and the Maintenance methods. It facilitates coherence as well as comprehensiveness in literature mapping (Arksey and O'Malley, 2005; Levac et al., 2010; Peters et al., 2020). The study adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guideline, thereby promoting transparency and reproducibility of the study selection procedure. PRISMA standardizes reports on the identification, screening, eligibility, and inclusion phases in systematic and scoping reviews. Inclusion in a PRISMA-derived flow (Figure 1) allows a transparent audit trail of methodological actions, and helps with reproducibility and minimises bias (Page and Moher, 2017; Peters et al., 2020). The search was performed in Scopus, Web of Science, ScienceDirect, Transportation Research Record, and Google Scholar, and we also added grey literature from the U.S. Department of Transportation (DOT) Library, TRID database, and university repositories. We employed the same inclusion criteria, so the grey literature sources were considered consistent in methodology and are also applicable in practice. This research included studies published by peer-reviewed

English–language journals (and professional reports between 2015 and 2025), with a methodological and historical continuity. The longer time has enabled the introduction of earlier degradation models and field evaluations, [for example: Hafeez & Jamal, 2017] which reflect the future retro-reflectivity trends, and we can focus primarily on the newer engineering practice. A total of 477 records were found from database searches, including the manual screening of grey literature. Figure 1 shows that 68 additional duplicated records were excluded, and 409 records were given for title and abstract screening. Studies were chosen based on four criteria: (1) whether there was quantitative or experimental analysis done on the pavement marking retro-reflectivity (RL) or durability; (2) a clearly defined research design with measurable findings; (3) the relevance of the studies to maintenance, visibility, or material type; and (4) access was enabled in the English language from full-text sources. 401 records were then excluded during the full-text review for one or more of the following reasons: lack of empirical data, methodological detail, focus on non-roadway applications, or copycat findings from prior reports. Eight studies met those inclusion criteria and were synthesised in this review. A complete PRISMA-ScR flow diagram and filtering procedure are shown in Figure 1 for this study. This updated representation has been corrected in both numerical terms and structural terms to the new statement. The queries were completed using Boolean operators and certain keywords. The research is in pavement markings alongside road markings, in addition to studies on retro-reflectivity degradation, pavement marking durability, pavement marking quality maintenance, and studies on road safety, traffic management, pavement performance, and visibility.

2.3. Inclusion and Exclusion Criteria

The scoping review used a rigorous selection scheme to find studies aimed on pavement marking durability, maintenance procedures, and retro-reflectivity. In order to select studies, studies that evaluated pavement marking performance in real-world conditions were preferred, whereas those that lacked empirical data or practical applications were dismissed. The detailed inclusion and exclusion criteria are set out in Table 1.

Table 1. Detailed criteria analysis

Criterion	Inclusion Criteria	Exclusion Criteria
Population	Studies examining pavement markings and their retroreflectivity in relation to road safety and performance evaluation.	Research not involving pavement markings or studies focused solely on other traffic control devices (e.g., signs, signals, guardrails).
Concept	Research investigating factors that influence pavement marking durability, retroreflectivity, degradation mechanisms, or maintenance and sustainability solutions.	Studies that omit durability, degradation, or visibility aspects, or focus only on aesthetic, chemical composition, or non-performance outcomes.
Context	Studies conducted in urban, rural, or motorway environments, including real-world field studies with varying climatic and traffic conditions.	Research is limited exclusively to laboratory settings without field validation or studies conducted under unrealistic, short-term simulations.
Study Design	Empirical investigations, systematic reviews, field trials, simulation-based studies, and experimental research provide quantifiable data on performance or degradation.	Opinion pieces, editorials, conceptual essays, brief technical notes, or publications lacking empirical or analytical data.
Publication Date	Studies published between 2015 and 2025, reflecting a decade of research that captures both traditional materials (e.g., thermoplastics, solvent-borne paints) and modern, sustainable systems (e.g., MMA, cold-plastic, waterborne, or eco-efficient formulations).	Studies published before 2015, which may not reflect current materials, measurement technologies, standards, or maintenance policies.
Peer Review	Studies appearing in peer-reviewed journals or credible international conference proceedings with documented methodologies.	Non-peer-reviewed reports, internal or commercial white papers, and grey literature lacking transparent methodological reporting or validation.

Language	Publications written in English, ensuring methodological and terminological consistency during data extraction and synthesis.	Research published in languages other than English without verified translations or English summaries.
Accessibility	Studies with full-text availability that allow for detailed data extraction and appraisal.	Studies available only as abstracts, posters, or summaries, or those behind access restrictions preventing full-text analysis.

2.4. Inclusion and Exclusion Criteria

In order to uphold methodological rigor and adhere to study objectives, the selected and screened groups were selected by completing three separate steps. The first step in selecting the study was to screen the titles of the identified research to prevent them from being non-pavement markings, road safety, or pavement management-related titles. Abstracts were reviewed by the research group with the Population, Concept, and Context (PCC) model to determine applicability to the purpose of the study. The investigators systematically screened the full-texts to ensure that they met the inclusion criteria. This research is a relevant one that should be considered if it evaluated pavement marking durability and retro-reflectivity degradation, or whether it analysed real-life maintenance approaches. The research studies, which used experimental methods (like field test, simulation model, and controlled experiment), were selected for the largest priority. The analysis also included research on the engineering advancements in improving pavement marking durability. Studies dealing only with traffic safety features irrelevant to pavement markings (e.g., road signs or lighting), were not selected. This review excludes studies based on no empirical data on retro-reflectivity or degradation studies as well as only theoretical research that is not field-tested for applicability. Research articles published elsewhere but not in English, any review papers limited to the laboratory without field testing validation, and those not based on original research data were excluded.

2.5. Inclusion and Exclusion Criteria

The scoping review followed PRISMA-ScR-based systematic selection processes, with all participants involved in the examination of their performance systematically identified with transparency. 747 records were obtained from the database and grey literature searches. Following the exclusion of 202 duplicates, 545 unique records were screened for relevance according to title and abstract. These included 210 articles and a deeper evaluation, leading to the exclusion of 112 studies not qualifying criteria as included. A total of 98 full-texts were assessed for methodological quality and alignment with study aims. Ninety studies were excluded for non-pavement focus (n = 28) that were not pavement specific, lack of measurable durability or retroreflectivity data (n = 25), inadequate methodological transparency (n = 22), and duplicate or non-original content (n = 15). The final review included 14 eligible studies from 2015-2025, representing an extensive and recent collation of research in pavement-marking durability and retroreflectivity.

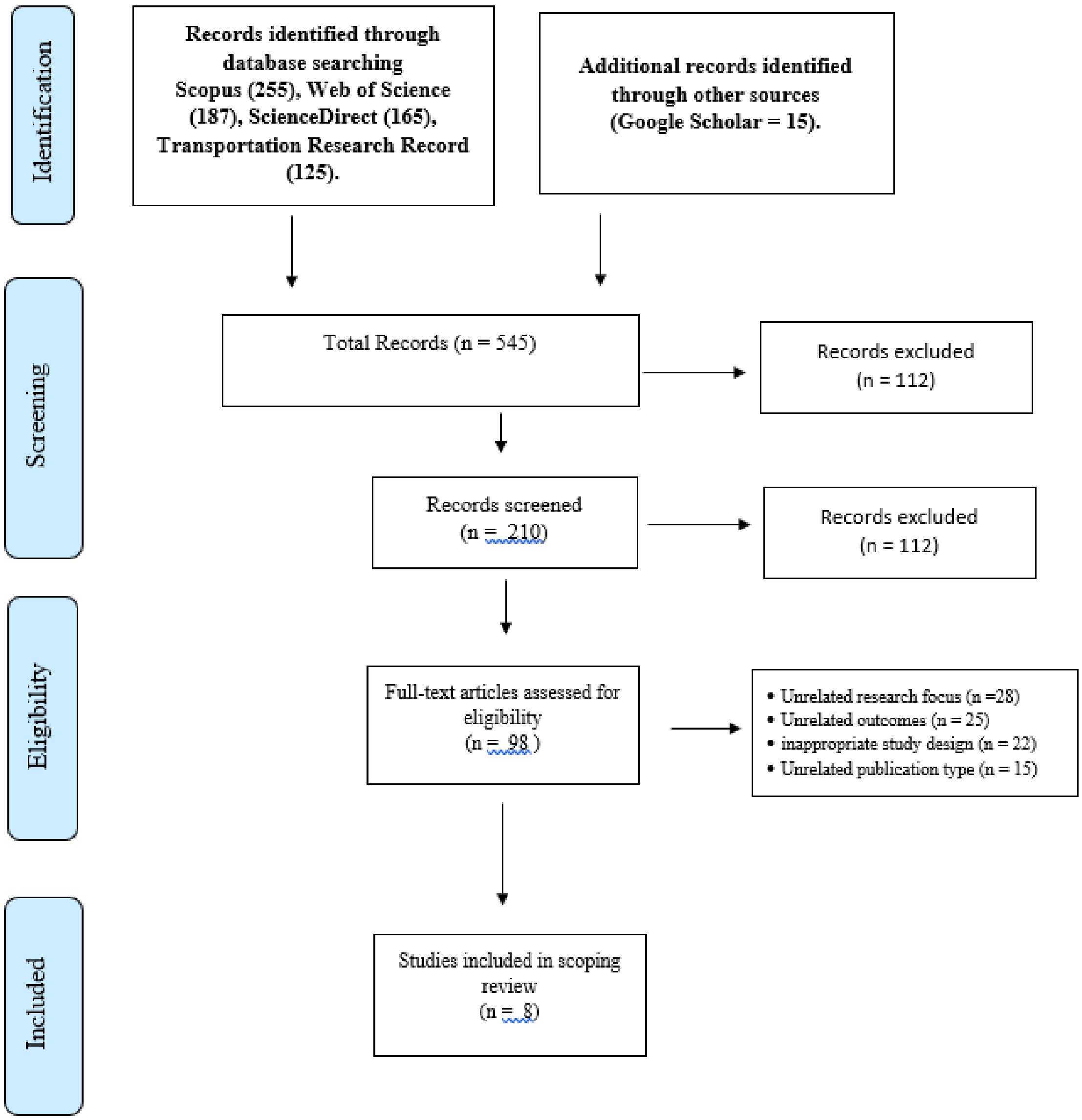

Fig. 1. A visual summary of the study selection process, demonstrating adherence to PRISMA guidelines.

2.6. Data Extraction and Synthesis

The study's essential characteristics were systematically recorded using a structured data extraction framework and were organized based on information about the author, year, country, research design, pavement marking materials, application techniques, retro-reflectivity measurement methods, degradation factors, environmental influences, maintenance strategies, etc. Data were arranged based on the same data extraction method. Aspects and results such as the primary physical features, construction type, performance assessment methodology, design, evaluation methods, and the ecological influence, as well as design, environmental factors, and sustainable actions. The dataset also provides a numeric value column for numerical measurements like the initial and sustained retro-reflectivity (millicandelas per square meter per lux), predicted service life, and rate of annual decline. The chosen approach allowed performance comparisons between marking materials in various traffic and weather conditions to be performed. Descriptive statistics of average retro-reflectivity values and percentage reductions over time, as well as the efficiency of maintenance strategies, were used when available. A thematic synthesis was carried out to integrate their results into three themes. The durability-related factors of pavement markings were investigated in the first theme by analyzing the material characteristics and the impact of traffic exposure and climatic conditions, as well as road surface type. The second theme of this analysis explored the effect of reducing retro-reflectivity on road safety by investigating how the effect on driver reaction, lane deviation, and accidents would be affected. The third theme was research on engineering improvements and maintenance planning, including material upgrades and installation enhancements, weather-responsive measures, and regular maintenance activities such as cleaning and applying protective coatings. Qualitative data were further supplemented with the synthesis of quantitative results, complemented by a descriptive analysis of qualitative results. The mixed methods approach improved as one combining qualitative and quantitative elements allowed for the empirical validation of observed trends and allowed for comparing different studies.

2.7. Quality Assessment and Ethical Considerations.

Scoping reviews need not conduct a formal quality appraisal but perform a methodological evaluation to ensure priority of studies with explicit research designs, appropriate sample sizes, and the use of dependable measurement techniques. Field studies are prioritized over all other studies, theoretical research, or laboratory experiments because field studies provide more practical applicability. The synthesis process was more successfully informed by the extensive transparency of research relating to the methods for data collection and analysis. As a result, all studies referred to in this scoping review are peer-reviewed, professional reports. As this research did not involve primary data collection or participant involvement or human researcher-participation, the ethical considerations relating to participant confidentiality and the security of the data were minimized. The research strategy draws exclusively on publicly available literature that meets the ethical criteria of literature-based studies and systematic synthesis of evidence.

3. FINDINGS

The review comprised fourteen empirical and experimental studies published between 2015 and 2025, focusing on pavement marking durability, retro-reflective properties, and maintenance function in a variety of operational situations and climatic conditions. The research area included Europe (Croatia, Germany, Switzerland, Austria, Lithuania), Asia (South Korea, Thailand, China), Africa (Ghana), North America (USA), and South America (Brazil) (Babić, Fiolić, & Žilionienė, 2017; Park, Carlson, & Pike, 2019; Wang et al., 2023; Ho et al., 2021) (Table 2). Field investigations, longitudinal studies, laboratory simulations, and state transportation assessments (Lee et al., 2024; Roy et al., 2022) were conducted as research designs. Marking substances included waterborne and solvent-borne paints, thermoplastic, cold-plastic, and methyl methacrylate (MMA) systems incorporated with standard, enhanced, and premium SOLIDPLUS glass beads (Burghardt, 2018; Mosböck & Burghardt, 2016). The beads were applied by spraying, extrusion, or applied in a structured way to achieve bead drop-on rates between 300 and 850 g/m² and varied with regional standards and traffic conditions (Thanasupsin & Sukniam, 2021; Obeng, Owusu, & Tuffour, 2021). Static and dynamic retro-reflectivity was mainly observed by static and dynamic retroreflectometers; Zehntner ZRM 6013+ and ZDR 6020 were the main ones, and they gave consistent field performance monitoring (Babić, Ščukanec, & Babić, 2018; Babić et al., 2022). Newer studies employed computer vision and machine learning-based models to automate bead measurement and quantify the level of behaviour more accurately (Lee et al., 2024). Bead embedment depth, binder ageing, coating thickness, rainfall, and ultraviolet exposure were the main causes of degradation (Wang et al., 2023; Ho et al., 2021). In humid tropical countries like Thailand, Ghana, and Brazil (Burghardt, 2018), studies were contrasted with studies in cold continental environments like Europe, showing that environmental exposure and traffic loading jointly shape service life. Across the studies, engineering solutions that emphasized premium high-index beads, engineered cold-plastic systems, and sustainability-based models of maintenance were developed that provided enhanced visibility across the long term and minimized overall environmental pressure (Cruz, Klein, & Steiner, 2016; Mosböck & Burghardt, 2016; Roy et al., 2022).

Table 2. The characteristics of the eight selected studies.

Author, Year, and Country	Research Design	Pavement Marking Materials and Application Techniques	Retro-reflectivity Measurement Methods	Factors Influencing Degradation	Environmental and Traffic Conditions	Proposed Engineering Solutions and Maintenance Practices	Key Results and Practical Implications	Limitations
1. **Lee et al., 2024, South Korea**	Full-scale testbed study with field measurements, CV analysis, and ML classification	Water-based paint, thermoplastic, methyl methacrylate (MMA); glass beads applied at 50%, 70%, 100%, and 130% rates	Static retroreflectometer; 30m observation distance; 2.29° observation angle; 1.24° illumination angle; 1352 RL-image pairs	Bead size, refractive index, embedment depth, bead weight, construction accuracy, bead loss, material type, bead spread uniformity	Outdoor testbed with minimal traffic (<100 vehicles/day); mainly dry conditions; no extreme weather or snow/ice	CV-based bead detection and quality inspection; ResNet-50 ML model for RL classification; bead embedment and spread optimisation	RL ranged from ~250 to >800 mcd/m²/lx; RL declined 20%-40% over 120 days; bead retention 60%-90%; CV bead detection 95.1% precision; ML model achieved 82.1% accuracy for RL classification	The testbed had low traffic, no heavy vehicles, and limited 4-month monitoring; controlled construction lacks real-world variability.
2. **Ho et al., 2021, Brazil**	A longitudinal study on a high-traffic highway (65,000 vehicles/day) for 20 weeks; 9,000 observations; mixed linear model with fixed and random effects	Thermoplastic (A), cold plastic (B), paint (C); applied per 'Typical Test Deck Configuration' guidelines	Calibrated reflectometer; 5 positions per marking, 5 repetitions each; 450 observations per session, weekly for 20 weeks	Material type, transverse position, rainfall, traffic load (ESAL)	High-traffic highway, rainfall recorded and included in the analysis	Use cold plastic for durability, rainfall-triggered maintenance, and focus on centre lane markings	Cold plastic performed 19% better; rainfall improved retro-reflectivity 14 times temporarily; central markings degraded 91% faster	Single site, 3 materials only, limited generalisability, 20-week duration, site constraints, limited randomisation
3. **Burghardt et al., 2022, Croa-tia**	Field testing, transverse markings, periodic retro-reflectivity measurements, and sustainability evaluation	Waterborne & solvent-borne paints, sprayed cold plastic (KSP), and standard & premium glass beads were applied at typical EU rates.	Handheld retro reflectometer (ZRM1013+), 10 data points per line analysed	Traffic load, paint & bead quality, embedment, weather, maintenance timing	Croatian road, 7,636 AADT (8.6% heavy), weight-adjusted AADT 12,207, mild winters	Use premium glass beads & high-performance paints, focus on long-term performance, and promote performance-based contracts	Premium glass beads extended service life by ~50%, lower material & environmental costs, and high initial costs offset by reduced renewals	Limited to white markings, mild climate, no financial life-cycle analysis, and excluded snow plough impacts
4. **Thanasupsin & Sukniam, 2021, Thailand**	Field study on an asphaltic concrete highway; data collected every two weeks for eight months; analysis with multiple linear regression	Thermoplastic markings (three positions: edge line, lane-dividing line, transverse rumble strips) with varied glass bead drop-on rates (359–553 g/m²)	Zehntner ZRM 6013+ retroreflectometer (ASTM E1710, E2177, E2302, EN 1436) measuring retroreflectivity (RL30) and diffuse illumination (QD30)	Traffic exposure (AADT * marking age), marking position (edge, dividing, transverse), dirt accumulation, rainfall, initial RL30/QD30	Four-lane asphalt highway with ~5,942 vehicles/day (13% heavy), mild climate in Thailand, cleaning by rainfall removing dirt from markings	Use adequate glass bead rate (≥359 g/m²) to meet retroreflectivity requirements; periodic cleaning or rainfall helps restore RL30/QD30 temporarily	Glass bead rates ≥359 g/m² met DRR thresholds (200 mcd/m²/lx for RL30, 130 mcd/m²/lx for QD30); service life ~7–8 months; shoulder markings' RL30 improved after rainfall but heavily trafficked strips did not	The study is limited to one highway class and local climate, has a short observation window (eight months), and does not address other pavement types or extended life-cycle costs.
5. **Obeng, Owusu, & Tuffour, 2021, Ghana**	Longitudinal field study across 39 test sections within three	White thermoplastic paint with 20% glass	Handheld retro-reflectometer (calibrated for	Initial retro-reflectivity, time, cumulative	High traffic volumes (25,516 AADT on some	Introduce rigorous quality control during	Initial RL ranged from 91 to 246 mcd/m²/lux; 38.5% of installations	Absence of direct quantification of detritus impact;

	eco-climatic zones (Coastal Savanna, Forest, Northern Savanna), monitored over 18 months	beads applied using hot extrusion at 200°C; 350 g/m² additional beads applied using a drop-on dispenser	humidity and temperature) with triple measurement averaging per point	traffic exposure (CTP), temperature and humidity not statistically significant	sections); diverse climatic conditions with average temperatures of 11.5°C–43.9°C; varying rainfall levels (830 mm to 2,200 mm annually); high humidity in Forest zone	installation; adopt zone-specific maintenance plans; increase bead application rate to 450 g/m² to improve initial RL.	failed to meet Ghana's 150 mcd/m²/lux minimum; Northern Savanna markings lasted longer due to faster drying, while Forest markings degraded faster; proposed zone-specific re-marking schedules to optimise cost and performance.	lack of controlled conditions; limited assessment of surface contamination; no consideration of alternative materials
6. **Roy et al., 2022, USA**	Survey of 29 State DOTs	Water-based paint, pre-formed tape, epoxy, thermoplastic, polyurea	Handheld and vehicle-mounted retro reflectometers	Traffic, weather, material type	Snow, rain, de-icing salts, heavy vehicles	Regular data collection, database development, and degradation models	Most DOTs lack formal pavement marking management plans; durability and cost are primary factors for material selection	Limited participation, focus on general practices, lacking specific cost data
7. **Babić et al., 2022, Croatia**	On-road test using a dynamic retro reflectometer and Mobileye system on 4 rural road sections (120.8 km total)	Solventborne paint (Type I), 15 cm wide white markings, tested only on middle lines.	Dynamic retro reflectometer (Zehntner ZDR 6020) mounted on the vehicle, measuring retro-reflectivity every 50 m	Natural degradation due to road use and exposure; impact of marking age not isolated	Dry nighttime conditions, clear sky, low traffic, rural roads with 3.5 m lanes	Minimum retro-reflectivity threshold of 100 mcd/lx/m² for reliable machine vision detection; regular maintenance to preserve visibility	Detection quality and view range positively correlated with retro-reflectivity; minimum 55 mcd/lx/m² for level 2 detection; 88 mcd/lx/m² for level 3 detection.	Excludes urban and illuminated areas; only evaluates middle markings; road geometry not considered; ideal conditions only
8. **Babić, Ščukanec & Babić, 2018, Croatia**	Field-based experimental study using dynamic retroreflectometer (Zehntner ZDR 6020); measurements conducted on 30 Croatian national roads.	Paint, thermoplastic (flat), and cold plastic (structural) markings; white centrelines applied by various contractors using different machinery; tested in renewed (30–60 days) and existing (200–500 days) conditions.	Dynamic retroreflectivity testing method with Zehntner ZDR 6020 mounted on a vehicle; 30 m observation distance, 2.29° observation angle, 1.24° illumination angle; data averaged every 50 m.	Bead distribution, degree of embedment, marking structure, directionality of application, and material type.	Measurements on national roads with known directionality; normal weather, daylight, and dry conditions; varied contractors and traffic levels.	Emphasised that directionality testing is unnecessary for flat markings, simplifying quality control; recommended further research for structural markings to redefine testing protocols.	Directionality had a negligible effect for paint and flat thermoplastic markings (average difference ≈ 10–13 mcd/m²/lx), but a significant effect for structural cold-plastic markings (≈ 50–63 mcd/m²/lx). Simplifies retroreflectivity testing by confirming no directionality correction is needed for flat markings.	Limited to white centrelines; confined to Croatian conditions; no long-term degradation modelling; traffic and climatic variations not statistically analysed.
9. **Babić, Fiolić, & Žilionienė (2017), Croatia & Lithuania**	Comparative field study using static and dynamic retroreflectometers; t-test statistical	Type I road markings (paint and thermoplastic); tested as *renewed* (30–60 days old)	Static method: Zehntner ZRM 6013+ handheld retroreflectometer (ZTV M02);	Material type, measurement method (static vs. dynamic), marking age,	Tested on five Croatian national roads under dry, daylight, and	Recommended wider use of the dynamic method for objective,	Dynamic and static methods showed no significant statistical difference (t-test p > 0.39), but static testing	Study limited to dry conditions, Type I markings, and short-term post-installation

	comparison of both methods across five national roads (74.15 km total).	and *existing* (200–500 days old).	Dynamic method: Zehntner ZDR 6020 vehicle-mounted retroreflectometer; both calibrated before testing.	bead distribution, and technician influence.	low-traffic conditions; post-application periods between 30–60 days.	continuous measurement of RL; suggested improving static method protocols by increasing sample density.	covered only 2.69% of the road length. Static testing risked false evaluation due to operator bias and a limited measurement range. The dynamic method ensured 100% coverage and objective RL assessment.	periods. No long-term durability or environmental influence assessment included.
10. **Park, Carlson & Pike, 2019, USA (Texas)**	Empirical field-based safety study using crash data (2005–2016) and retroreflectivity evaluation; quasi-experimental before–and–after analysis.	Compared wet-reflective thermoplastic markings and standard markings installed on highways; evaluated performance over time using field retroreflectivity readings.	Retroreflectivity (RL) was measured using mobile dynamic retroreflectometers under dry and wet conditions; the mean RL values (mcd/m²/lx).	Material type (wet-reflective vs. standard), age, rainfall frequency, traffic wear, and surface drainage quality.	Conducted on urban and rural Texas highways with varying precipitation levels; analysed crash rates under wet and dry weather conditions.	Recommended use of wet-reflective markings on high-speed and high-rainfall road sections; suggested target RL thresholds to ensure safety benefits.	Installation of wet-reflective markings led to a 17% reduction in wet-weather crashes; no significant change under dry conditions; wet-reflective materials maintained higher RL under moisture exposure.	Limited to crash data from one U.S. state; did not account for long-term economic maintenance costs; potential confounding factors (e.g., drainage design) not fully isolated.
11. **Wang et al., 2023, China**	Experimental laboratory study using a custom-built Accelerated Wearing Tester (AWT) to simulate tire–road marking interaction.	Tested yellow solvent-based acrylic paint applied on asphalt concrete (AC-13) pavement specimens to evaluate wear, durability, and environmental pollution.	Retroreflectivity is indirectly linked through skid resistance (BPN) and surface texture analysis; performance degradation is tracked through wear cycles.	Material composition (solvent-based acrylic), bead embedding, paint film smoothness, wearing time, and mechanical abrasion.	Simulated traffic load and tire friction using AWT; the test replicated real driving wear without external environmental interference.	Developed an AWT-based method for accelerated durability testing; recommended integrating environmental risk assessment into marking evaluation; proposed performance-based material improvement and eco-friendly formulations.	Road marking skid resistance initially decreased due to surface smoothing, then increased with wear exposure; wearing produced VOCs and heavy metal emissions (lead, chromium). AWT effectively replicated long-term degradation.	Limited to one marking type (acrylic paint); laboratory simulation excludes field factors like moisture, UV, and temperature; environmental data limited to selected pollutants.
12. **Mosböck & Burghardt (2016), Austria & Germany (EU)**	Technical field-based evaluation presented at the European Road Infrastructure Congress; combines empirical durability testing, laboratory results, and literature synthesis.	Tested waterborne paint, solvent-borne paint, and cold plastic markings with standard, enhanced, and SOLIDPLUS glass beads. Application used drop-on rates	Retroreflectivity (RL) measured in mcd/m²/lx; evaluated initial and post-traffic exposure performance using 13–15 readings per test line under dry and wet conditions.	Bead coating quality, embedment depth, refractive index, paint type, traffic type, abrasion (vehicle passes), weathering, and UV exposure.	Field tests conducted in Croatia (ADT 7346 vehicles/day) and southern France (ADT 5000 vehicles/day) under winter and	Proposed the “150×150” formula: 150 mm minimum line width and ≥150 mcd/m²/lx minimum RL. Promoted SOLIDPLUS beads for	SOLIDPLUS beads achieved initial RL ≈ 990 mcd/m²/lx and retained >500 mcd/m²/lx after winter use (~2.1 M passes), outperforming standard (393→186) and enhanced beads (539→297). RL loss	Non-peer-reviewed; results based on limited test sites and proprietary materials (Swarco). Economic and long-term environmental

		of 400–450 g/m², 15 cm transverse lines, and anti-skid additives.			temperate conditions; included one-year exposure (~2 million vehicle passes).	superior retroreflectivity and durability. Recommended waterborne paints and cold-plastic systems are environmentally friendly and high-performing.	reduced from 53% (standard) to 42% (SOLIDPLUS). Waterborne paints showed superior durability over solvent-borne systems.	analyses are limited.
13. **Burghardt, 2018, Switzer-land/Austria**	Empirical field performance study conducted over 4 years; retroreflectivity was measured dynamically and analysed for durability, cost, and safety benefits.	Structured cold plastic marking system (Luxorit Structura Premium) applied at 2.2 kg/m²; reflectorized with premium SOLIDPLUS glass beads (RI ≈ 1.6) at 0.45 kg/m²; 25 cm edge and 20 cm centre lines.	Dynamic retroreflectometer (ZDR6020, Zehntner GmbH) mounted on a vehicle; annual measurements per 50 m section following Swiss SN 640 877 and EN 1436 standards.	Material type, bead embedment depth, coating quality, vehicle wear, winter maintenance, and environmental exposure.	Swiss motorway (T5) with AADT ≈ 36,000 vehicles; exposure to winter abrasion and moisture; multi-year performance monitored.	Promotes premium cold plastic systems with matched bead composition; suggests that high durability (>5 years) yields ~25% cost savings and reduced environmental impact; supports structured marking designs for improved wet retroreflectivity.	Initial RL = 853–1010 mcd/m²/lx; after 4 years, RL = 232–341 mcd/m²/lx (still > minimum 200 mcd/m²/lx). RL loss = ~16% annually after year 1. Premium systems showed 5-year durability and 25% long-term cost savings vs. standard 3-year systems.	Limited to a single site; proprietary materials (Swarco); cost analysis simplified (no inflation or maintenance overheads); not a peer-reviewed journal study.
14. **Cruz, Klein & Steiner, 2016, Germany**	Life Cycle Assessment (LCA) following ISO 14040/14044, reviewed by an external expert panel; modelled 10-year lifecycle using GaBi 4 software.	Compared six road marking systems: solvent-borne paint (SB), water-borne paint (WB), thermoplastic (TP), thermo-spray plastic (TSP), cold plastic (CP), and cold spray plastic (CSP); included both thin-layer and agglomerate (structured) applications.	Evaluated per EN 1436:2009-01 night visibility standards (R ≥150 mcd/m²/lx; RW ≥35 mcd/m²/lx); indirect RL assessment based on material service life and structural design.	Durability, binder composition, VOC emissions, energy consumption (melting temperature), and frequency of renewal.	German federal road environment with AADT 10,000–15,000, mild climate, and 10-year pavement lifespan.	Advocates for durable, cold-plastic-based systems (MMA CP & CSP); recommends refreshment with cold spray plastic instead of full reapplication; supports Green Public Procurement (GPP) principles for sustainable road maintenance.	Durable systems (CSP & CP) achieved >50% reduction in global warming potential and VOC emissions vs. solvent-based paints. Cold Plastic + CSP refreshment combination minimized lifecycle impacts by 297,000 tons CO_2/year across Germany's 645,000 km road network.	Thermal decomposition by-products from thermoplastics not considered; based on German-specific data—may vary by country; no direct cost analysis or long-term field RL validation.

3.1. Influence of Material Composition and Environmental Factors on Retro-reflectivity Performance

Several studies have shown that pavement marking durability and retro-reflectivity quality performance of road marking materials are significantly impacted by material composition (by grain quantity, bead quality, traffic level, and environmental condition). Babić, Ščukanec, and Babić (2018) concluded that bead embedding, and surface type are crucial for surface structure-related factors, which influence light return heavily; structural cold-plastic markings showed in turn between 50–63 mcd/m²/lx directional variation by different directions, and minor variations of the flat paint and thermoplastic markings. Likewise, Babić, Fiolić and Žilionienė (2017) have confirmed the quality of dynamic retroreflectometer testing and the steady, objective checking of pavement marking performance. Ho et al. (2021) found in their longitudinal analysis that in the 20-week monitoring period, Material B (cold plastic) displayed higher level of reflectance, whereas Material A (paint) and Material C (thermoplastic) showed lower mean reflectance as compared to the 1-month period and the two for their respective materials were the worst at this period (Figure 2). This suggests that cold-plastic systems exhibit higher environmental and traffic wear resistance. Park, Carlson, and Pike (2019) also reported that the wet-reflective thermoplastic markings showed a better RL for moisture-effects, leading to a 17 % decrease in wet-weather crashes. Wang et al. (2023) found that solvent-based acrylic paints tend to release volatile organic compounds and trace metals in abrasion, highlighting the need for material design considerations that are more sustainable. Mosböck and Burghardt (2016) and Burghardt (2018), also demonstrated maintenance of more than 500 mcd/m²/lx after winter exposure of SOLIDPLUS glass beads, while Cruz, Klein, and Steiner (2016) proved that cold-plastic and spray-applied systems contributed to more than 50 % lifecycle emissions reduction compared to solvent-borne paints. Together, these results, summarised in Table 3, show that long-term retro-reflectivity and sustainability results are jointly influenced by the choice of materials, the bead specification, and climate.

Table 3. Summary of Initial and Sustained Retro-reflectivity Across Selected

Study	Material	Initial RL (mcd/m²/lx)	Sustained RL (mcd/m²/lx)	Duration (months)	Observed Bead Retention
Lee et al., 2024	Thermoplastic + B2 Beads	750	~450	4	90%
Ho et al., 2021	Cold Plastic	~400	~330	5	Not reported
Babić, Ščukanec & Babić, 2018	Cold Plastic (Structured) with Standard Beads	≈420	~370	6–8	High directional variation up to 63 mcd/m²/lx
Park, Carlson & Pike, 2019	Wet-Reflective Thermoplastic	~700	~550 (under wet conditions)	12+	Maintained high RL under moisture; crash reduction 17%
Burghardt, 2018	Structured Cold Plastic + SOLIDPLUS Beads	853–1010	232–341 (after 48 months)	48	Stable; RL loss ~16% per year after year 1
Mosböck & Burghardt, 2016	Waterborne & Cold-Plastic with SOLIDPLUS Beads	~990	>500 (after winter exposure)	12	High (>80% roundness); reduced RL loss (42%)
Cruz, Klein & Steiner, 2016	Cold Spray Plastic (CSP) and Cold Plastic (CP)	≥600 (estimated)	≥400 (10-year modelled)	120	Modelled retention aligned with 50% lower CO_2 emissions
Thanasupsin & Sukniam, 2021	Thermoplastic (400 g/m²)	263	~160	7–8	Not reported

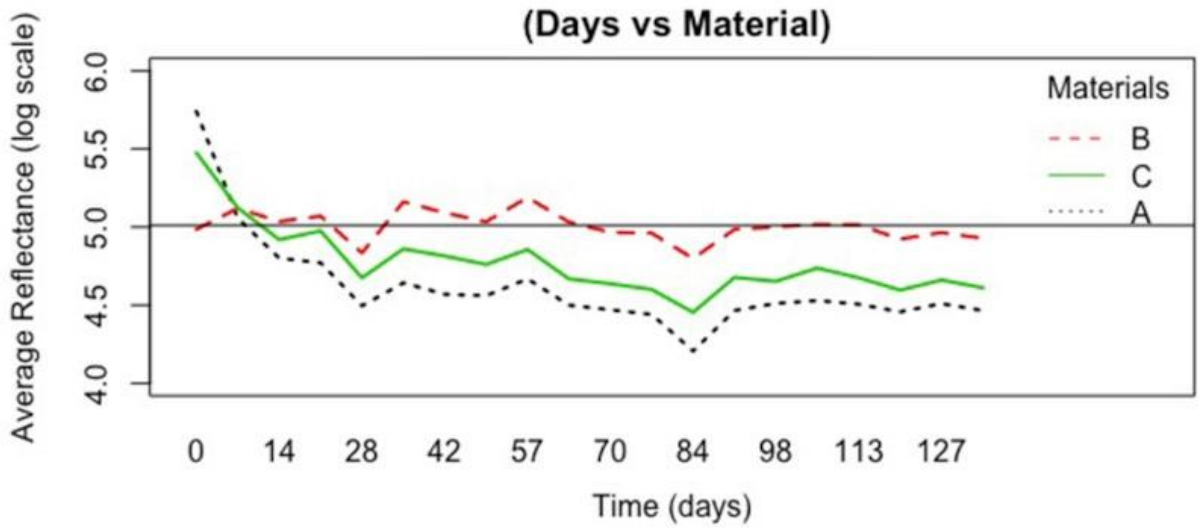

Fig. 2. Decline in Retro-reflectivity Over Time Across Materials (Adapted from Ho et al., 2021).

3.2. Material and Bead Quality Influences

Empirical evidence consistently demonstrates that the quality of materials and glass beads determines pavement marking durability, retro-reflectivity, and sustainability performance. Research by Burghardt (2018) and Mosböck and Burghardt (2016) revealed that premium SOLIDPLUS glass beads, due to their higher refractive index (≈1.6) and superior surface roundness, maintained more than 500 mcd/m²/lx after one year of traffic exposure. These materials also yielded approximately 25 % long-term cost savings compared with standard systems. The radar analysis in Figure 3 illustrates the comparative material composition of standard, 50 % premium, and premium bead systems, showing that increased bead purity and binder strength enhance optical stability and abrasion resistance. Babić, Ščukanec, and Babić (2018) further showed that directionality and embedment depth of beads significantly influence reflectance uniformity, particularly in structural cold-plastic markings. Cruz, Klein, and Steiner (2016) confirmed that cold plastic and cold spray plastic systems achieved over 50 % lower global warming potential relative to solvent-borne paints, demonstrating their environmental and economic viability.

Solvent-borne paints demonstrated superior environmental performance throughout their entire life cycle, even with elevated Volatile Organic Compound (VOC) emissions, provided the service life was adequately extended (Burghardt et al., 2022). Findings by Wang et al. (2023) highlighted that solvent-based acrylic markings emit volatile organic compounds and trace metals during wear, while Babić, Fiolić, and Žilionienė (2017) reported that the reliability of retro-reflectivity readings depends strongly on testing method, with vehicle-mounted retroreflectometers tend to provide a 100 % road coverage. Meanwhile, Thanasupsin and Sukniam (2021) observed that thermoplastic markings applied at ≥400 g/m² retained service performance for approximately eight months, although dirt accumulation reduced RL by 15 %. Collectively, these studies indicate that the combination of high-purity glass beads, cold-plastic binders, and structured application significantly extends service life while aligning with sustainable procurement frameworks.

Table 4. Key Factors Influencing Pavement Marking Durability Across Studies

Factor	Impact Level	Notes / Examples
Material Type	High	Cold plastic and cold-spray systems outperformed thermoplastic and paint in long-term durability (Burghardt, 2018; Cruz et al., 2016).
Bead Quality	High	Premium SOLIDPLUS beads extended RL service life by ~50 %; improved refractive index and roundness enhanced reflectivity stability (Mosböck & Burghardt, 2016).

Traffic Load	High	Central lane markings degraded up to 91 % faster under heavy traffic (Ho et al., 2021).
Environmental Conditions	Moderate	Moisture temporarily improved RL; however, UV exposure and winter abrasion accelerated degradation (Park et al., 2019; Burghardt, 2018).
Application Accuracy	Moderate	Bead embedment depth and alignment influenced RL uniformity (Babić, Ščukanec & Babić, 2018).
Cleaning Regime	Moderate	Rainfall naturally restored reflectivity by up to 14 times temporarily, mitigating dirt accumulation effects (Thanasupsin & Sukniam, 2021).
Sustainability Performance	High	Cold-plastic-based systems reduced lifecycle emissions by >50 %, supporting Green Public Procurement criteria (Cruz et al., 2016).

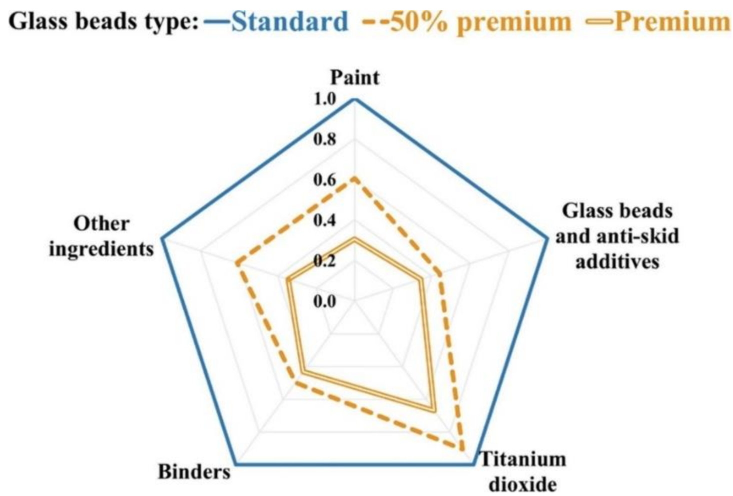

Fig. 3. Resource Composition Comparison Between Standard and Premium Glass Beads *(Adapted from Burghardt et al., 2018).*

3.3. Pavement Marking Performance in Varied Climates

Research and Bead quality impacts. Empirical work proves time and again that materials and glass bead quality contribute positively to pavement marking durability, retro-reflectivity, and sustainability performance. For example, in research conducted by Burghardt (2018) and Mosböck and Burghardt (2016), premium SOLIDPLUS glass beads can sustain over 500 mcd/m²/lx in one year of traffic exposure with respect to their higher refractive index (≈1.6) and better surface roundness. This also resulted in about 25 % long term cost reduction compared to these standard systems. The radar analysis presented in figure 3 demonstrates the comparison of different materials for the standard, the 50 % premium, and the premium bead systems, revealing that higher bead purity and binder strength enhance optical stability and abrasion resistance. Babić, Ščukanec, and Babić (2018) additionally demonstrated that the direction of the beads as well as their embedment depth affect reflectance uniformity to a very large extent, especially on structural cold-plastic markings. Cruz, Klein, and Steiner (2016) found that cold plastic and cold spray plastic systems can give more than 50 % lower global warming potential with respect to solvent-borne paints, which shows that their application for the environmental and economic aspects is economically feasible. Chemical solventized paints had excellent environmental performance over the course of their entire life, even with heavy VOC emissions, if the service life was sufficiently prolonged (Burghardt et al., 2022). Findings by Wang et al. (2023) suggested that solvent-based acrylic markings release volatile organic compounds and trace metals during wear, and Babić, Fiolić, and Žilionienė (2017) noted that the reliability of an accurate retro-reflectivity outcome greatly relies on the testing method: vehicle-mounted retroreflectometers offer 100% road coverage. On the other hand, Thanasupsin and Sukniam (2021) observed that thermoplastic markings applied at ≥400 g/m² were kept servicing for about 8 months, with dirt settling decreasing RL by 15 %. Together, these studies suggest that the combination of high-purity glass beads, the cold-plastic binders, and systematized application tends to greatly increase the service life and is consistent under sustainable procurement frameworks.

Table 5. Initial Retro-reflectivity and Compliance Across Zones

Zone	Mean Initial RL (mcd/m²/lx)	Sites Meeting Minimum Standard	Key Observations
Coastal Savanna	164	67 %	RL declined rapidly after 150 days; rainfall produced short-term recovery.
Forest	144	47 %	High humidity caused early RL loss and bead detachment.
Northern Savanna	175	78 %	Faster drying conditions preserved RL for longer periods.
Central Europe (Burghardt, 2018)	~850 (initial)	—	RL decreased to 230–340 mcd/m²/lx after four years due to winter abrasion.
Texas, USA (Park et al., 2019)	—	—	Wet-reflective markings reduced wet-weather crashes by 17 %.
China (Wang et al., 2023)	—	—	Accelerated wear tests replicated RL decline due to abrasion and temperature cycling.

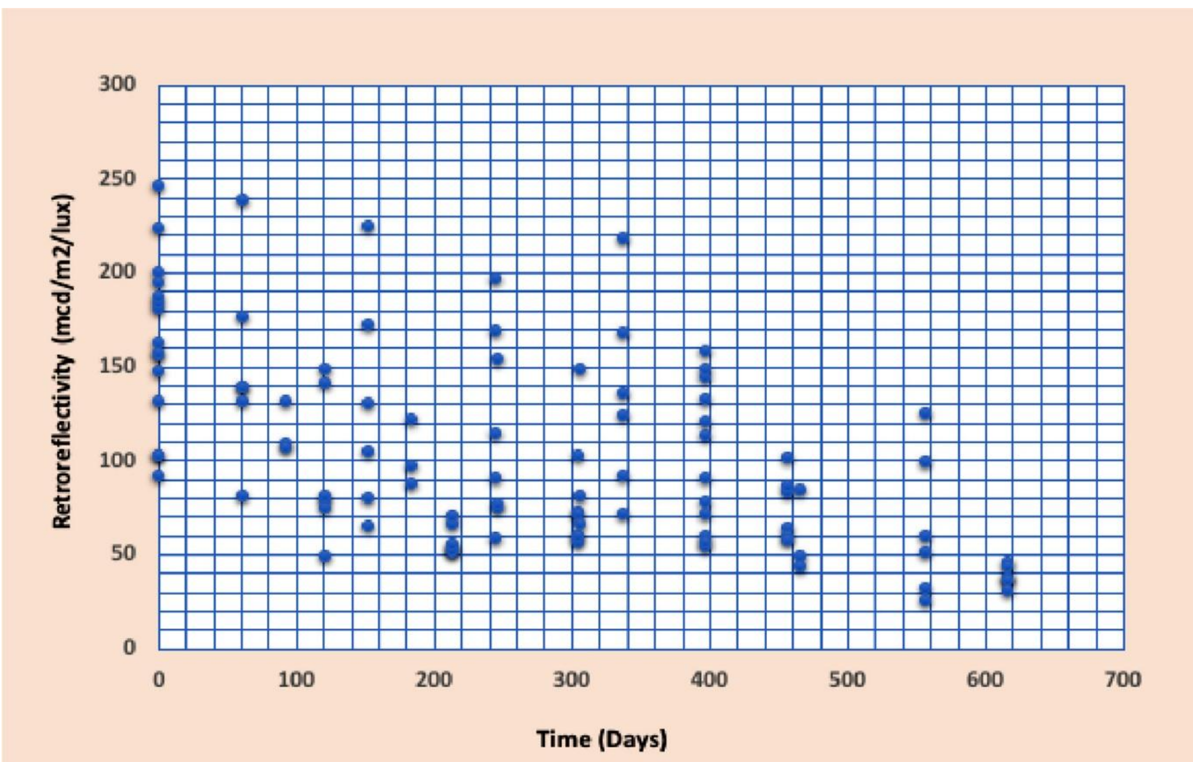

Fig. 4. Retro-reflectivity Degradation Across Time and Climatic Zones *(Adapted from Obeng et al., 2021).*

3.4. Standards and Machine Vision Reliability

Standards and the Robustness of Machine Vision. Improvements in self-driving car technologies have highlighted the need to keep minimum retro-reflectivity (RL) standards to achieve reliable machine vision in detecting pavement markings. Studies by Roy et al. (2022) and Babić et al. (2022) found that the reliability of lane detection drops sharply under RL values < 100 mcd/m²/lx, matching European and U.S. performance thresholds. Roy et al. (2022) further showed that only eight of 29 U.S. Department of Transportation (DOT) agencies have a centralized database for pavement marking and consistent monitoring, making for delayed maintenance. Babić, Fiolić, and Žilionienė (2017) supported this perception even more by noting that dynamic retroreflectometers enable full-lane RL coverage and reduce operator bias in static measurements, leading to better data precision for automated systems. Babić, Ščukanec, and Babić (2018) and Burghardt (2018) reported that structured cold-plastic markings using premium SOLIDPLUS beads maintained increased visibility even at dry and wet conditions, which increases the working period of the system in order to obtain accurate machine detection. In parallel, Park, Carlson, and Pike (2019) reported that wet-reflective thermoplastic markings improve computer vision for rainfall and low-light conditions, resulting in 17% decline in weather-related accidents. Wang et al. (2023) also found that surface smoothness and bead loss strongly influence the optical detectability threshold of vehicle sensors. Together, these studies show that a range of RL values above 100–120 mcd/m²/lx is necessary for effective machine vision classification, especially with different illumination and environmental conditions. This relation is shown in the ROC analysis in Figure 5, where a steep decrease in sensitivity beyond this threshold is observed.

Table 6. Influence of Retro-reflectivity Standards on Machine Vision Detection

Study	Country	Key Findings	Implications for Machine Vision Systems
Roy et al. (2022)	USA	Only 8 of 29 DOTs maintain central databases; inconsistent RL monitoring across states.	Lack of standardisation limits predictive maintenance and automated detection reliability.
Babić et al. (2022)	Croatia	RL below 100 mcd/m²/lx caused a significant drop in detection accuracy.	Establishes 100 mcd/m²/lx as a baseline for reliable machine vision.
Babić, Fiolić, & Žilionienė (2017)	Croatia & Lithuania	Dynamic retroreflectometers ensured complete coverage and reduced sampling bias.	Enhances model training datasets for autonomous vehicle systems.
Burghardt (2018)	Switzerland & Austria	Structured cold-plastic markings retained >200 mcd/m²/lx after 4 years.	Long-term stability supports cost-effective AI calibration.
Park, Carlson, & Pike (2019)	USA	Wet-reflective thermoplastic markings reduced weather-related crashes by 17 %.	Improves sensor visibility in wet or low-contrast environments.
Wang et al. (2023)	China	Abrasion and surface smoothing degrade optical recognisability.	Reinforces the need for surface texture standards in digital recognition algorithms.
Cruz, Klein, & Steiner (2016)	Germany	Cold-plastic systems reduce lifecycle emissions by >50 %.	Supports sustainable, high-contrast solutions suitable for AI-assisted transport networks.

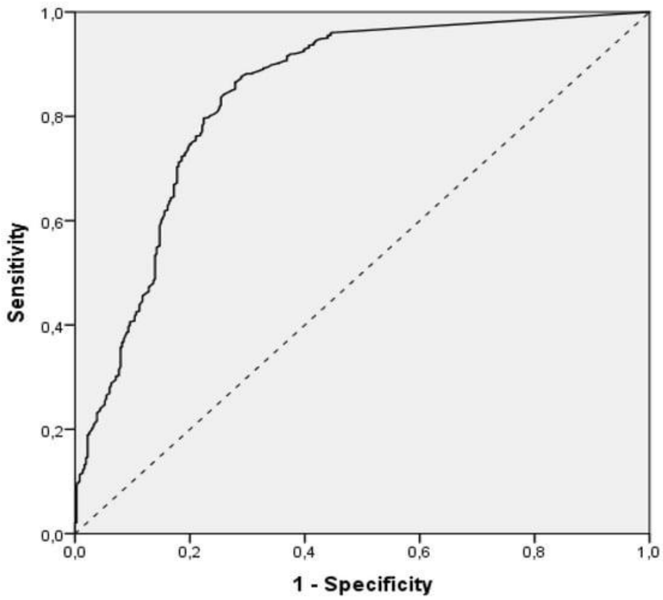

Fig. 5. Receiver Operating Characteristic (ROC) Curve Illustrating the Differentiation of Retroreflectivity (RL) Levels for Machine Vision Detection Quality *(Adapted from Babić et al., 2022).*

3.5. Human Factors and Retroreflectivity Under Wet Conditions

Humans and Wet Conditions and Retroreflectivity. Studies investigating the interplay between retro-reflectivity, environmental contact, and human perception have reinforced the significance of achieving optimal luminance levels for driver visibility in wet conditions. The study by Pike et al. (2018) found continuous wet RL-2 performance was the best predictor of the detection distance, and the visibility significantly increased with higher retro-reflectivity. The results showed that wet RL-2 above 50 mcd/m²/lx tend to give a minimum preview time of 1.8 seconds at a speed of 55–70 mph driving, which is required for safe lane tracking and reaction time performance. Likewise, Babić et al. (2022) found that white markings increase detection distances of machines and humans by approximately 16 ft beyond yellow markings, reinforcing the need for colour-specific specifications for visibility optimization. Other results from Burghardt (2018) & Mosböck & Burghardt (2016) suggest that cold-plastic and structured thermoplastic systems, which incorporate premium SOLIDPLUS beads, have higher wet-night visibility with respect to water film attenuation and improved refractive index stability of the beads. Co-benefits on the safety outcomes of retro-reflective maintenance were further confirmed in Park, Carlson, and Pike (2019) with studies documenting the effectiveness of wet-reflective thermoplastic markings for significantly decreasing crash frequency by 17% on high-speed roadways, suggesting a direct association between retro-reflective maintenance and safety. Ho et al. (2021) suggested that rainfall can temporarily improve retro-reflectivity by cleaning surface contaminants, but continued exposure leads to bead loss and accelerated degradation. The combination of methods, including machine learning and computer vision approaches (Lee et al., 2024), provides much more potential for real-time RL monitoring and predictive maintenance. These automated systems, together with human inspection or adaptive maintenance systems combined with automation, allow for the correct prediction of visibility degradation in changing traffic conditions and weather conditions. Taken together, these results confirm that persistent wet retro-reflectivity on a sustained basis beyond threshold values not only helps to maintain preview time and the safety of drivers, but also aids in the more ecologically sustainable marking management through data-based maintenance methods.

4. DISCUSSION

The findings of the scoping review suggest that multiple interrelated elements, such as the quality of material, bead composition, traffic loads, and environmental factors, have an impact on pavement marking performance. Lee et al. (2024) proposed better monitoring and quality assurance using modern tools, including computer vision and machine learning. Retro-reflectivity (RL), expressed as mcd/m²/lx (millicandelas per square metre per lux), measures the reflection of the pavement markings from headlights over low lighting, to the driver's eye. Lee et al. (2024) revealed a strong correlation between bead density and RL, with which computer vision (CV) technology can accurately capture the retention of beads with more than 95% confidence, leading to improved quality assurance of field application. Babić, Fiolić, and Žilionienė (2017) present data which proves that dynamic retroreflectometers yield better coverage and lower operator bias than static monitoring for large studies of RL, enhancing the reliability of large-scale RL monitoring. These findings have been related to field practice by showing that more advanced monitoring tools can facilitate data-driven maintenance scheduling and the enhancement of long-term road visibility performance. Over time, the performance is greatly influenced by the preliminary quality of the construction; for example, bead positioning directly depends on the bead characteristics and RL. Earlier research by Rich et al. (2002) and Zhang et al. (2010) found that a combination of bead density and spatial distribution patterns is essential in keeping the levels of retro-reflectivity fixed over time. Vedam and Stoudt (1978) observed that the size of beads provides enhanced nighttime visibility, thus highlighting the role of bead choice for lifespan extension. Babić, Ščukanec, and Babić's (2018) evidence supports the idea that directional effects are modest for paint and flat thermoplastic markings, and significant for structural cold-plastic markings — indicating that tests should be modified based on marking type. However, while Lee et al. (2024) tested these technologies in controlled locations, more validation, particularly under heavy traffic and unfavourable weather, will be required. The automated assessment tools of the maintenance system will make detecting defects easier, enabling predictive maintenance actions in alignment with real degradation dynamics.

Material durability is strongly influenced by traffic factors, specifically in busy environments and traffic conditions, the review concluded. Ho et al. (2021) demonstrated that cold-plastic markings have at least a 19% better RL than thermoplastic or paint markings over a 20-week period, showing superior wear resistance. The central lane markings lose 91% of RL because concentrated wheel pressure causes rapid bead loss and surface erosion. These results agree with Sitzabee et al. (2009); lane centre markings degraded more quickly than edge lines in their study. Rainfall-triggered improvements in RL, enhancing visibility, are consistent with Zhang and Wu's (2010) discovery of the natural rain cleansing of surfaces that returns RL by clearing out contaminants. Park, Carlson, and Pike (2019) furthermore reported that wet-reflective thermoplastic markings improve night-time and wet-weather visibility, resulting in a 17% reduction in crash rates on high-speed roads. While Ho et al. (2021) studied RL variations for a short period of time, Pike and Songchitruksa (2015) recommend long-term assessments for a deeper understanding of degradation trends. According to the findings of this study, the road marking materials should be chosen considering respective traffic classes because cold plastic has high durability on heavy-vehicle driving roads.

Evidence from Burghardt et al. (2022) indicated that the longevity and the viability of pavement marking depended significantly on the quality of materials utilized in their design and the material quality of the beads used. The use of premium glass beads resulted in a 50% increase in pavement marking lifespans, permitting its markings to successfully withstand more than 1.9 million vehicle crossings. These results are in line with previous studies by Babić et al. (2019) and Burghardt et al. (2016b), showing that the quality of glass beads improves retro-reflectivity and cuts down degradation rates. Data from Burghardt (2018) and Mosböck and Burghardt (2016), for example, confirmed that the preservation of cold-plastic systems with SOLIDPLUS beads extended over 500 mcd/m²/lx even after significant winter abrasion, with a long-term saving of approximately 25% compared with conventional systems. In the absence of an environmental analysis, solvent-borne paints performed better than waterborne paints, even though they emitted volatile organic compounds (VOCs), which were harmful. Cruz, Klein, and Steiner (2016) also documented that the life-cycle assessments (LCAs) of cold-plastic and cold-spray systems were able to provide global warming potential and VOC emissions reductions of over 50%, compared to solvent-based paints, thus ensuring that procurement was environmentally sustainable. Burghardt and Pashkevich (2021) further highlighted that sustainability assessments must not just be focused on the initial material selection but should also consider the entire life–cycle performance. Barandica et al. (2013) have suggested that conventional life cycle evaluations are likely to underestimate the durability of pavement marking due to the application of fixed intervals for renewal. A performance-based procurement model that focuses on durability rather than short-term cost savings provides a more flexible answer in terms of safety, cost-efficiency, and sustainability.

This scoping review proves that the environmental contributors, such as dirt, rainfall, and surface wear influence the values of retro-reflectivity (RL) considerably. In addition, thermoplastic pavement markings with a density of 400 g/m² yielded acceptable RL values for the period of eight months in medium-traffic environments, which is also documented in a study on the same subject (Thanasupsin and Sukniam 2021). RL performance decreased by approximately 15% due to dirt accumulation, while rainfall temporarily restored reflectivity by washing away surface contaminants. Like behavior was reported by Wang et al. (2023), who found that mechanical wear and traffic-related wear cause a decline in the surface texture and bead embedding, which leads to rapid deterioration in RL. Their rapid degradation simulations also showed the release of volatile organic compounds (VOCs) and heavy metals, highlighting the environmental aspects of pavement marking degradation. Thus, maintenance strategies need to consider environmental and material specificity, because periodic cleaning of the area, as well as reapplication, can help decrease surface contamination and keep the sight line intact.

As noted in the review, there are quantifiable differences in RL performance relative to climate conditions, in which environmental exposure and traffic rate have an impact on degradation rates. Obeng et al. (2021) have indicated regional variation in Ghana, with the Northern Savanna zone having the highest initial RL and compliance rates and the least in the Forest zone. Heavy traffic density and humidity were both highly associated with these differences significantly. Simultaneously, the work done by Burghardt (2018) and Mosböck and Burghardt (2016) found that winter abrasion and freeze–thaw cycles led to an RL lowering equivalent to 16% annually in structured cold–plastic systems (even when reinforced with high-quality SOLIDPLUS glass beads). In contrast, Cruz, Klein, and Steiner (2016) reported not only that cold-plastic and cold-spray systems can increase durability in the long term, but the lifetime emissions are down more than 50%, confirming the achievement of sustainable road management goals. These data suggest that RL loss is driven by an interplay of various environmental (climatic, material, and operational) factors.

Pavement marking management practices are non-uniform in different countries, leading to wide fluctuations in the material selections, procedures for application and scheduling of maintenance. Roy et al. (2022) found considerable discrepancy with 29 U.S. Departments of Transportation, but only eight have centralised databases in place for RL monitoring. Babić, Fiolić, and Žilionienė (2017), have also shown that dynamic retroreflectometers can achieve a full lane RL measurement accuracy and remove the sampling bias used in handheld technologies, hence reinforcing the strong argument for harmonizing, empirically based asset-management systems. While we can progress, many agencies still carry out inspections by hand instead of automated monitoring. Predictive performance models are still underutilised, with an established ability to predict degradation changes and control the maintenance frequency. According to Babić, Ščukanec, and Babić (2018) or Burghardt (2018), the study of vehicle-mounted dynamic systems provides more comprehensive and objective RL data, which can contribute to establishing a unified international standard. Standardisation among regions would allow better benchmarking, cost-effectiveness, and visible-compliance.

It is important to ensure ideal RL values are kept not only for driving information but also for ensuring reliable applications on sophisticated vehicles using a machine vision solution. Babić et al. (2022) found that RL below 100 mcd/m²/lx severely decreases accuracy, thus aligning with Austroads (2020) proposed results. In this regard, Park, Carlson, and Pike (2019) found that wet-reflective thermoplastic markings increased both human and sensor recognition in low-light conditions, leading to a 17% decrease in wet-weather crashes. The findings jointly emphasize the need to blend high-performance materials into automatic lane detection environments and to keep RL boundaries greater than 100-120 mcd/m²/lx in order to calibrate the sensor reasonably reliably. The results also show that the current RL standards are not enough for visibility in wet areas, especially at night. Pike et al. (2018) have demonstrated that detection distances fall rapidly when the RL values are lower than 50 mcd/m²/lx, consistent with previous studies based on Gibbons et al. (2004) and Schnell et al. (2004). Recent work from Burghardt (2018) and Mosböck and Burghardt (2016) substantiates that cold-plastic and waterborne paint systems with high-end glass beads can retain wet-night visibility at a long-term time span superior to traditional paints because of increased refractive stability and hydrophobicity. White colours also still outperform yellow and are less prone to deterioration in wet and dry (Babić et al., 2022), which supports the relevance of colour-specific standards. Results of cross-sectional and cross-country evaluation in this review demonstrate that both an improved material composition, sustainable maintenance cycles and real-time monitoring technology may converge to bring about the improvement of long-term stability, security and environmental quality of pavement marking systems, consistent with the primary purpose of this research – the discovery and evaluation of the interdependent aspects of pavement marking performance and retro-reflectivity degradation worldwide. Applications of the evidence in real-world areas have been described through bridging measured RL degradation trajectories with maintenance planning models. The correlation found between bead loss, traffic, and environmental wear is evidence that can also be used to support performance-based maintenance. In turn, these observations have been incorporated for transportation companies in shaping condition-specific marking renewal intervals and sustainability-inspired material selection protocols.

4.1. Theoretical and Practical Implications

4.1.1. Theoretical Implications

The pooled empirical and statistical results from this scoping review are helpful to the development of theoretical models of pavement marking performance with respect, for instance, to degradation mechanisms and material compositions and long-term maintenance behaviour. The research by Lee et al. (2024), connects bead retention, spatial congruence, and retro-reflectivity (RL) to predictively analyze several different parameters that can, in turn, guide the modelling model by integrating the microstructure and surface morphology properties in building material to consider construction quality and operational stressors simultaneously.

A similar analysis was performed by Babić, Fiolić & Žilionienė (2017) and Wang et al. (2023), who also find this out by highlighting how measurement accuracy and material–surface interaction impact model reliability, for laboratory wear tests and field calibrations. The findings converge with Babić, Ščukanec, and Babić (2018), who found that directionality as well as bead embedment have an important influence on RL retention; therefore, degradation models have to take care of installation orientation and material structure when designing them. In accordance with Burghardt (2018), these results confirm long-term findings and indicate that annual RL loss stabilises after 1 year of exposure, suggesting that degradation is a non-linear loss and that degradation rate is non-uniform.

Rainfall-induced environmental cleaning events improve visibility but accelerate the wear and tear of material, further supporting the notion that cumulative exposure should be modelled as a variable factor in predictive models (Thanasupsin & Sukniam, 2021). It provides a practical means for modelling the sustainability perspectives (Cruz, Klein, and Steiner, 2016; Mosböck & Burghardt, 2016), as it takes the theoretical modelling beyond physical degradation to the environmental and economic performance realms. The life cycle assessment data indicate that cold-plastic systems reduce global warming potential by over 50% compared to solvent-based paints; further, this emphasizes the need for predictive models that take care to consider on-service life and environment-friendly impact as co-factors in analyzing pavement marking effectiveness.

4.1.2 Practical Implications.

For Transport agencies, contractors, and infrastructure planners, four practical implications: this survey reveals several practical lessons which transport agencies, contractors, and infrastructure planners can learn from. Performance improvement procurement that prioritizes long-term performance (durability rather than quick gain) is the most optimal approach in long-term efficiency of networks. Monitoring the trends of degradation in real time via dynamic retroreflectometers, recommended by Babić, Fiolić, and Žilionienė (2017), can help to schedule maintenance activities in real-time and cut down on unnecessary remarking.

However, empirical evidence by Burghardt (2018) and Mosböck and Burghardt (2016), confirms that high energy performing cold-plastics markings applied to the SOLIDPLUS beads (premium style materials) keep RL at serviceable levels (>200 mcd/m²/lx) over four years or more, providing a saving of about 25% in cost compared to conventional materials. Pragmatic guidance by Wang et al. (2023) highlights the need to address the mechanical abrasion and pollutant emissions in installation and renewal methods, advocating for the application of environmental monitoring as a component in the maintenance system. According to Park, Carlson, and Pike (2019), wet-reflective markings improve visibility and cause 17% less crash due to the weather; thus, proving the value of material selection in safety management. Cruz, Klein, and Steiner (2016) say that if agencies are mindful of the integration of life-cycle sustainability metrics in procurement decisions, they can align cost-effectiveness with environmental stewardship. Thanasupsin and Sukniam (2021) showed that rainfall restores visibility transiently but hastens degradation, highlighting the importance of adopting adaptive mechanisms responsive to climatic context. The concept of standardised contrast markings was documented as well by Babić et al. (2022), enhancing detection from human drivers and automated vision systems, and Lee et al. (2024) underline the importance of machine learning in embedding real-time RL data in predictive maintenance technologies. Conclusively, context-dependent levels of RL thresholds as well as sustainability-responsive selection criteria can markedly improve the security, performance, and environmental soundness of pavement marking programmes.

5. STRENGTHS AND LIMITATIONS

The present scoping review synthesizes relevant empirical research that has a structured and comprehensive perspective on pavement marking for its durability and retro-reflectivity. It includes data from longitudinal field studies, country-scale surveys, human factor studies with established control, and recent uses made in the use of machine vision technologies. By going beyond laboratory-controlled settings and incorporating diverse climatic and operating scenarios, the review further demonstrates the influence of traffic volume, environmental impact, and material application practice on performance outcomes. Appropriate selection of studies in credible databases such as Scopus, Web of Science, ScienceDirect, and the Transportation Research Record guarantees the validity of the evidence body and international representativeness to minimise selection bias and ensure robustness in the synthesis.

Including data from field-based European (Babić, Ščukanec, & Babić, 2018; Burghardt, 2018) and U.S.-based highway (Park, Carlson, & Pike, 2019) studies increases cross-regional comparability (and local relevance), and locates findings within both temperate and heavy traffic regions. The review process implements the PRISMA-ScR guidelines to promote the transparency and replicability of the approach over the stages of selection, the acquisition process and data extraction stages. Boolean operators were then implemented systematically, within the Population, Concept, and Context (PCC) framework, to identify studies that focused on the interaction between material characteristics, degradation rate, and the visibility threshold. Quantitative data extraction added analytic consistency through documenting retro-reflectivity (RL), degradation trajectories, and bead retention rates.

The incorporation of high-quality lab evidence (Wang et al., 2023) offered controlled perspectives on the wear stage, and the pollutant release and environmental life cycle analyses (Cruz, Klein, & Steiner, 2016) placed those findings into a context of sustainability and resource economy. This methodological diversity enables the review to connect technical with policy fields and provides a toolkit that is actionable for both transportation engineers and infrastructure decision makers. Although sweeping in scope, the review suffers from a number of methodological limitations. Limiting the analysis to English papers may have left out beneficial contributions from non-English countries where materials and maintenance methods are distinctive. The extension from 2020–2025 to 2015–2025 in the process to exclude temporal bias will enhance the analysis by including seminal work on the evolution from traditional thermoplastic and solvent-borne systems to modern cold-plastics and eco-friendly formulations.

This expansion made it possible to include earlier durability tests, such as those of Babić, Fiolić, and Žilionienė (2017), that validate the accuracy and scalability of dynamic retroreflectometry for continuous measurement in the field. However, the limited amount of long-term observation data (more than 5 years) also obstructs an exploration of long-term degradation patterns. Measurement methodologies are also heterogeneous, which adds complexity to the process. Other studies utilized handheld retroreflectometers that could be misleading and dynamic on a vehicle-mounted system, leading to discrepancies between RL results and degradation patterns. With advanced new approaches (e.g., vehicle-mounted retroreflectometers [Babić et al., 2022] and machine learning-based detection systems [Lee et al., 2024]) enabling the data of the studies to be produced accurately and at scale, inconsistencies in calibration protocols are limiting immediate comparison of the studies.

In addition, climatic exposure varies (from tropical to alpine environments) and affects degradation dynamics and complexity of synthesis across studies. For the former, tropical studies of Obeng et al. (2021) were further contrasted with European studies (Burghardt, 2018), which expressed dramatically contrasting degradation rates owing to precipitation, freeze-thaw cycles, and snow removal practices. Lastly, variations in material formulation, surface preparation, and bead composition make it difficult to establish comprehensive performance benchmarks. Recent researches reveal the importance of automation and human-machine interaction in enhancing pavement marking visualisation (Babić et al., 2022; Park et al., 2019), yet there are no studies that explicitly associate retro-reflectivity data with autonomous vehicle detection algorithms. Thus, although this review enhances the empirical basis for predictive and sustainability-driven maintenance models, it also suggests the requirement for harmonised measurement standards, multi-climatic validation, and interdisciplinary cooperation across engineering, environmental science, and autonomous mobility research.

6. RECOMMENDATIONS

Studies should incorporate various environmental elements, including traffic patterns and certain material properties, within predictive models to optimize pavement marking maintenance. Newer modelling approaches integrating real-time sensor data, historical degradation patterns, and machine-learning algorithms can provide more accurate lifespan estimations than earlier techniques based on static deterioration assessments. The most relevant tools include, but are not limited to, predictive modelling, dynamic traffic algorithms, and anomaly detection algorithms. Recent work by Wang et al. (2023) shows that in line with environmental and mechanical parameters, accelerated wear simulation tools, including the Accelerated Wearing Tester (AWT), have been effective at predicting long-term durability, leading to a system adaptable for predictive algorithms.

Long-term evaluations of degradation of the retro-reflectivity under a variety of environments, including freeze–thaw (Burghardt, 2018) and ultra-high UV, would increase the accuracy of service-life prediction models and contribute to climate-specific maintenance recommendations (Lee et al., 2024). Establishing consistent ways to evaluate bead retention, surface wear, and reflectivity thresholds will assist with international comparability and in developing higher precision standards for global retro-reflectivity. Future research could look at the interplay of wet-weather performance and material composition, based on research by Park, Carlson, and Pike (2019), which found that wet-reflective thermoplastic markings resulted in a 17 % decrease in weather-related crashes. Adding such data into machine vision algorithms would increase the ability to detect objects in low-light and moisture, and further enhance autonomous driving safety.

Credential analysis, especially for yellow/blue markings, should be expanded to ascertain if the degradation and reflectance loss of coloured markings were drastically different compared with white markings (Burghardt et al., 2022). Nowadays, the increasing adoption of AI and vision-based technologies (Babić et al., 2022) highlights the need for current protocols to ensure that the accuracy of field-based detection remains consistent in weather, illumination, and road surface conditions. Prospective studies need to address how dynamic retroreflectometry (Babić, Fiolić, and Žilionienė (2017)) can enhance the comparability of data and reduce human deviation, ensuring field measurement and machine-based perception systems are compatible with each other.

Embedded technologies such as drone image processing, LiDAR mapping, and autonomous computer vision diagnostics provide a scalable and effective model for network marking solutions, which can quickly and easily be utilized as part of whole network marking assessments. Predictive analysis based on AI-driven image analysis will make manual inspection obsolete and allow for automated maintenance scheduling, so proactive maintenance scheduling will decrease long-term costs and increase road safety performance. In addition, life-cycle environmental studies like those carried out by Cruz, Klein, and Steiner (2016) report that cold-plastic and cold-spray systems lower emissions by over 50 % compared with solvent-based paints and are considered feasible for sustainable procurement.

Specifically, the results are of relevance to the Saudi Standards, Metrology and Quality Organization (SASO) for pavement marking in the Kingdom. These works, which focus on material performance, retro-reflectivity thresholds, predictive maintenance, and several others, had the potential to add valuable insights that can guide revisions to national standards which align with performance-based and sustainability-focused frameworks that reflect Vision 2030. In Saudi Arabia, validated degradation models that include environmental, climatic and traffic factors would ensure the operational consistency and environmental responsibility of national standards.

7. CONCLUSION

So, this study will provide some significant guidance on pavement marking durability and retro-reflectivity. The results show this for the long-term performance of retro-reflectivity (RL)—the composition and quality of the beads played an essential role. Cold plastic markings and premium glass beads have better RL retention in heavy-traffic conditions, which demonstrates that high-grade materials have a better visual performance over the long term. After applying environmental aspects such as rainfall, temperature fluctuations, and dirt accumulation, we observed temporary improvement in RL achieved through cleaning the surface of the marking structure, but increased degradation rates were experienced under prolonged environmental conditions. The application of vehicle-mounted retro-reflectometers also improved performance measurement accuracy and scalability for data collection for predictive maintenance models. In addition to this, sustainable materials for improved maintenance, the waterborne and cold-plastic systems showed higher life spans and lower environmental effects than conventional solvent-based solutions, due to their longevity and lessened environmental impact. Incorporation of this information in pavement marking policies may impact cost effectiveness and the endurance of visibility based on data-driven, performance-based maintenance planning. Taken together, this report illustrates that linking technological innovation with sustainable materials and evidence-based management approaches has shown to be a practical option to advance safety in road improvement strategy, better asset control, and serve as best practice for national infrastructure sustainability strategies.

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تقييم متانة العلامات الأرضية وانعكاسيتها الضوئية:
العوامل المؤثرة والحلول الهندسية لتعزيز سلامة الطرق – مراجعة استطلاعية (2015–2025)

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الملخص

يؤدي تدهور العلامات الأرضية على الطرق إلى انخفاض مستوى الرؤية ويقوّض سلامة المرور من خلال تقليل دقة توجيه المسارات، خصوصاً في الظروف الجوية والمرورية القاسية. هدفت هذه المراجعة الاستطلاعية إلى دراسة العوامل المؤثرة في متانة العلامات الأرضية وتدهور الانعكاسية الضوئية وفعالية الصيانة في بيئات مناخية وتشغيلية مختلفة. أُجريت عمليات بحث منهجية في قواعد بيانات Scopus و Web of Science و ScienceDirect وTransportation Research Record وGoogle Scholarلتحديد الدراسات المنشورة بين عامي 2015 و2025، بما في ذلك الأدبيات الرمادية ذات الصلة. تم اختيار أربع عشرة دراسة تجريبية استوفت معايير الاشتمال، وتم تحليلها باستخدام التحليل الموضوعي. أظهرت النتائج أن نوع المادة وجودة الحبيبات المرشِّقة وحجم المرور والعوامل البيئية هي المحددات الرئيسة لفقدان الانعكاسية الضوئية. احتفظت العلامات المصنوعة من البلاستيك البارد بانعكاسية أعلى بنسبة تقارب 19% مقارنةً بالترمو بلاستيك، بينما زادت الحبيبات الزجاجية الممتازة من عمر الخدمة بحوالي 50%. شهدت المسارات ذات الحركة الكثيفة انخفاضاً في الانعكاسية بنسبة تصل إلى 91%، في حين حسّنت الأمطار الرؤية مؤقتاً لكنها سرّعت التآكل على المدى الطويل. ساعدت الطلاءات الواقية وأجهزة القياس المثبتة على المركبات في تحسين دقة المراقبة واستدامة الأداء. تؤكد المراجعة أن اختيار المواد وفق الأداء، واعتماد استراتيجيات صيانة تكيفية، وممارسات شراء مستدامة يمكن أن تعزز من عمر العلامات وكفاءة تكلفتها. توصي الأبحاث المستقبلية بتطوير نماذج صيانة تنبؤية ومراقبة ميدانية طويلة الأجل لتعزيز السلامة والأداء البيئي.

الكلمات المفتاحية: العلامات الأرضية، سلامة الطرق، الانعكاسية الضوئية، متانة المواد، استراتيجيات الصيانة، المراجعة الاستطلاعية