Discover Sustainability

RESEARCH Open Access

Durability and performance of recycled thermoplastic road markings under natural and accelerated ageing and traffic-induced wear

Hanna Fager[1], Ida Järlskog[1*] and Martin Gunnarsson[2]

*Correspondence:
Ida Järlskog
ida.jarlskog@vti.se
[1]Swedish National Road and Transport Research Institute (VTI), 581 95 Linköping, Sweden
[2]Svevia AB, Herkulesvägen 52, 553 02 Jönköping, Sweden

Abstract

Thermoplastic road markings are vital for traffic safety but have high environmental impacts due to energy-intensive production of binders, pigments, and glass beads. Recycling end-of-life thermoplastic materials can reduce reliance on virgin resources, yet long-term field performance data are scarce. This study evaluates the durability and performance of formulations with 10 and 30% mechanically milled recycled content after 12 months of natural outdoor exposure and under accelerated xenon-arc UV ageing. Field trials under Nordic traffic and climate conditions assessed retroreflectivity (R_L), luminance coefficient (Qd), chromaticity coordinates, and skid resistance in line with European standards. Initially, the 10% recycled formulation met all requirements, while the 30% fell below the Qd threshold. After 12 months, R_L decreased mainly within wheel tracks due to traffic wear, whereas Qd increased for both formulations, especially the 30%. Chromaticity coordinates remained within the white region, indicating stable colour, and skid resistance increased over time. Accelerated xenon-arc ageing caused minor Qd reductions and slight shifts in x, y chromaticity coordinates, reflecting UV-induced binder oxidation without mechanical wear, bead loss, or surface contamination. Comparison of natural weathering in combination with traffic load and artificial ageing highlights the limited ability of UV-only laboratory testing to replicate field-relevant degradation. Overall, the results suggest that thermoplastic road markings containing 10–30% recycled material can maintain performance levels approaching those of conventional materials, although some parameters remained close to or slightly below specified thresholds. While further validation is needed, the findings indicate potential for the use of recycled thermoplastic road markings and highlight the need for comprehensive ageing assessments. By demonstrating the technical viability and performance of recycled thermoplastic road markings, this study supports the potential contribution of such materials to SDGs 9, 11, 12, and 13. These relate to more resilient infrastructure, improved road safety, efficient use of resources, and reduced environmental impacts through the adoption of circular economy approaches, subject to further validation through long-term and life-cycle assessments.

© The Author(s) 2026. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

Keywords Thermoplastic road markings, Recycled materials, Circular economy, Mechanical milling, Accelerated ageing, Sustainable infrastructure

1 Introduction

Road markings are a fundamental element of traffic infrastructure, playing a critical role in road safety, traffic organisation, and efficient mobility [1, 2]. By providing continuous visual guidance, they complement signs and signals to convey regulatory, warning, and navigational information to all road users, including drivers, cyclists, and pedestrians [3, 4]. Clear and durable road markings are essential not only for human drivers but also for automated driving systems, whose lane-keeping and lane-departure algorithms rely on road markings to maintain high detection accuracies [5, 6]. To ensure effectiveness under a range of environmental and traffic conditions, road markings must meet strict performance standards related to coefficient of retroreflected luminance (R_L), luminance coefficient under diffuse illumination (Qd), chromaticity coordinates, skid resistance, and durability [7–10].

A variety of road marking materials are in use worldwide, with regional preferences shaped by climate, traffic density, regulatory frameworks, and historical practices. Globally, water-based paints dominate due to their low cost and ease of application [11]. In contrast, Nordic regions predominantly use thermoplastic road-marking materials, as they offer superior durability under harsh conditions such as studded-tire wear, repeated freeze–thaw cycles, and intensive winter maintenance [3, 12]. From an environmental perspective, thermoplastic road marking materials exhibit a significant carbon footprint, largely driven by energy-intensive production processes for key components such as binders, glass beads, and titanium dioxide (TiO_2) [13–16]. Emerging innovations, including bio-based binders and modified natural resins, offer promising avenues for reducing the environmental impact of thermoplastic formulations [11, 17, 18]. However, these developments alone are not sufficient to achieve substantial emissions reductions. A more immediate and impactful strategy is the recycling of thermoplastic road markings, which conserves raw materials, reduces greenhouse gas emissions, and supports circular economy principles. This approach also aligns with multiple Sustainable Development Goals by enhancing infrastructure sustainability (SDG 9 and SDG 11), reducing reliance on virgin materials and energy use (SDG 12), and improving long-term durability to lower maintenance impacts (SDG 13). This work demonstrates how circular economy approaches in road infrastructure can improve both safety and environmental sustainability.

Road marking materials are exposed to both traffic wear and a variety of severe environmental conditions [19]. These factors accelerate the ageing and degradation of the materials, leading to colour fading, reduced brightness, and the formation of cracks [6, 20–22], indicating that ageing studies are essential for evaluating material durability [23]. Two main approaches are commonly used: natural weathering in field trials, which yields realistic degradation data under actual service conditions but requires long observation periods; and artificial (accelerated) ageing in the laboratory, where materials are exposed to intensified stressors such as UV radiation, elevated temperature, and controlled humidity to simulate long-term service in a shorter time. Xenon-arc UV testing is widely used to replicate solar radiation and its effects on organic binders and pigments

[24]. However, questions remain about the correlation between accelerated UV ageing results and actual in-service performance, particularly for composite materials such as thermoplastic road markings exposed to complex mechanical and environmental stresses.

In a previous work, we demonstrated that recycled thermoplastic road marking material recovered via mechanical milling can be incorporated at 10–20% by weight into new road marking formulations without compromising initial field performance at the NordicCert field trials [25]. However, these results were limited to early-stage measurements, and long-term performance remains unknown. As noted previously by [6] and [22], maintaining long-term durability under real traffic conditions is critical, because mechanical wear and environmental exposure can quickly reduce functional performance.

This study examines the one-year performance of recycled thermoplastic road markings subjected to natural outdoor exposure and accelerated xenon-arc UV ageing. The analysis focuses on visibility and retroreflective properties (R_L and Qd), colour (chromaticity coordinates), and skid resistance, with the objective of identifying consistencies and discrepancies between the two ageing regimes and evaluating the extent to which accelerated UV testing can predict field performance of recycled materials. Building on previous research, the study assesses the in-service durability of recycled thermoplastic road markings after one year of field exposure and complements these findings with laboratory-based accelerated ageing experiments conducted under controlled UV conditions to simulate intensified environmental stress.

This is the first systematic real-world traffic conditions field study of thermoplastic road markings containing recycled content, providing essential insights for the development of sustainable road marking practices and supporting the implementation of circular material strategies in road infrastructure.

2 Method

2.1 Material formulations and applications on the field trials

The recycled thermoplastic materials investigated in the present study are the same formulations as those used in the previous field trial by Fager et al. [25]. The materials consisted of a white thermoplastic extrusion formulation incorporating 10%, 20%, and 30% recycled material obtained by mechanical milling (MM) by weight, alongside a virgin reference formulation. The recycled material formulations were benchmarked against a reference material identical to the white thermoplastic road marking material used as the base formulation.

The recycled MM material originated from a 15 cm-wide longitudinal road marking removed after 12 months of service using a precision cold milling machine. After recovery, particles > 8 mm were cleaned, sieved, and melted into block format for addition into new thermoplastic batches. The virgin base formulation met NordicCert specifications for roll-over class P5 and was manufactured with a binder content of 18–20%, TiO_2 pigment (5–6%), and a premix (glass beads + filler) content of ~ 75%.

The three formulations containing recycled thermoplastic road marking materials were applied at the NordicCert road trials as 3 mm thick, flat (type I) markings using a manual screed box. The materials were heated to the application temperature (~ 200 °C) and held at this temperature for 1 h to fully homogenise before application. The process

proceeded without any deviations, and the recycled materials performed equivalently to formulations made entirely from virgin raw materials. No differences in viscosity or other properties were observed between formulations with different amounts of recycled content. A more thorough description of the materials and the application on the road trial can be found in [25].

2.2 Natural weathering field trial

Natural weathering was carried out at the NordicCert field trial located in eastern Norway, approximately 180 km northeast of Oslo, Fig. 1. The location is representative of the predominant climate conditions across much of the land area of Norway, Sweden, Iceland, and Finland (Köppen-Geiger classification Dfb) [26]. The field trial was established in 2015 and evaluates and certifies road marking materials prior to approval for the Nordic market.

The road at the field trial is a two-lane rural road with a posted speed limit of 90 km/h. The road surface consists of a stone matrix asphalt (SMA11) that was installed in 2022, and the surface texture is classified as roughness grade RG2, corresponding to a mean texture depth (MTD) in the range of 0.60–0.90 mm. A more detailed description of the test section has been previously published in [25] and [27].

The test section experiences an annual average daily traffic (AADT) in both wheel tracks of approximately 3,200 vehicles, with heavy vehicles accounting for about 10% of the total volume [28]. An estimated 50–55% of vehicles use studded tires during winter, representative of typical driving conditions across Norway, Sweden, Iceland, and Finland. During 2024–2025, the average annual temperature was approximately 6 °C, with recorded extremes ranging from − 24 °C to 32 °C and annual precipitation averages around 570 mm. During the winter months (December to March), snow cover persisted

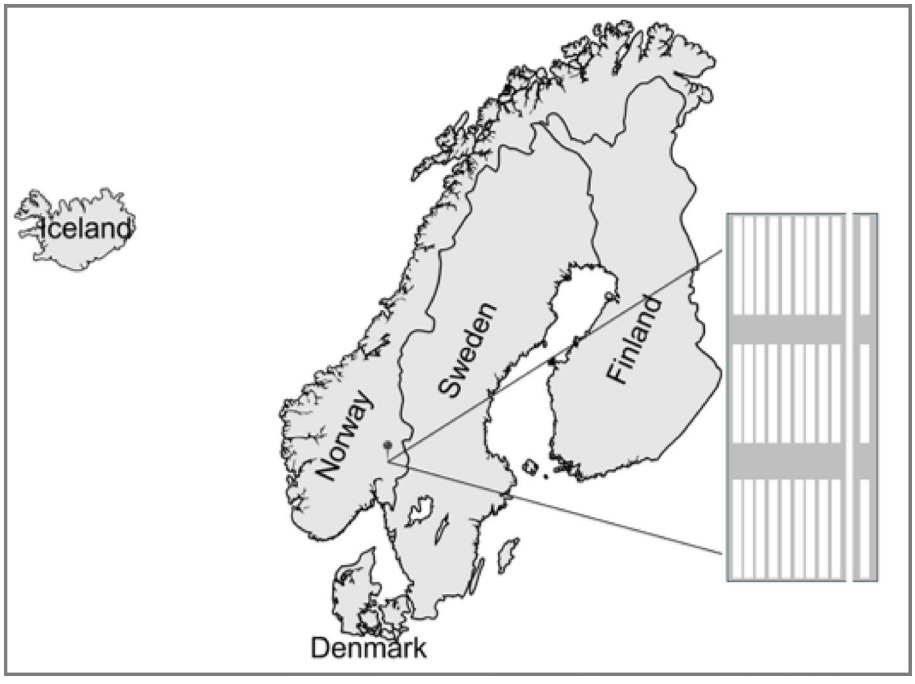

Fig. 1 Location of the test section and a simplified illustration of the application of the road markings

for approximately eight weeks, during which the road was maintained through 116 ploughing operations and 134 salting events [28].

The road markings were applied in September 2024, a detailed description of the application procedure is available in [25], and monitored at baseline two weeks post-application, (herein called *initial measurements*), after approximately 8 months (June 2025), and after 12 months (September 2025). Each material type was applied in nine lines measuring 250 cm × 15 cm in the driving lane, oriented parallel to the direction of traffic. An additional reference line was positioned outside the driving lane, beyond the kerb line, (Fig. 1).

2.3 Performance measurements at the field trial section

Performance measurements were carried out according to EN 1824 [9] and EN 1436 [8] and included coefficient of retroreflected luminance (R_L), luminance coefficient under diffuse illumination (Qd), chromaticity coordinates (x, y), and skid resistance (SRT).

2.4 Measurements of R_L and Qd

R_L and Qd were measured under dry conditions using a portable dynamic retroreflectometer (Delta LTL3500, Denmark) in accordance with EN 1436 [8]. Measurements were taken at three points along the centreline of each road marking, and the reported value for each line corresponds to the average of these measurements. The road markings were not cleaned or washed prior to measurement. However, if a substantial portion of the measurement area was affected by abnormal contamination (e.g., oil stains), the instrument was repositioned along the longitudinal axis to the nearest unaffected area. The performance requirements for white Type I markings are $R_L \geq 150$ mcd/m^2/lx and Qd ≥ 130 mcd/m^2/lx according to NordicCert requirements [28].

2.5 Measurement of chromaticity coordinates

The chromaticity coordinates were measured using a portable spectrophotometer (Konica Minolta CM-25cG, Japan) with measurement geometry 45°/0°, D65 illuminant, and 2° observation angle, and the results were expressed in CIE (x, y) coordinates. Measurements were taken at a single point located at the centreline of each marking. The markings were not cleaned prior to measurements. Chromaticity coordinates are required to fall within the colour boxes specified in EN 1436 [8].

2.6 Measurement of skid resistance

Skid resistance was measured on wet road markings using a Portable Friction Tester (Coralba PFT version 4, Sweden) along the centreline of each marking. The PFT acquires a measurement point approximately every 1.9 cm, resulting in roughly 70 measurements per line, and the skid resistance for each line is calculated as the average of all measurement points. The PFT units were converted to SRT units using an established relationship [29]. The same conversion relationship from PFT to SRT units was applied uniformly to all measurements. The NordicCert skid resistance requirement is ≥ 50 SRT. If notches, joints, or other surface irregularities were present, the measurement area was either reduced or shifted to avoid measurements in the affected regions. Skid resistance measurements were conducted after measurement of R_L, Qd, and chromaticity coordinates.

2.7 Measurement uncertainty and data variability

Measurement uncertainty for R_L, Qd, chromaticity coordinates, and skid resistance arises from both instrument performance and the inherent spatial variability of road marking surfaces. Instrument-related uncertainty is considered low for all methods used in this study, based on manufacturer specifications and information in Wälivaara et al. [29]. In comparison, the dominant source of uncertainty is the spatial heterogeneity of the road marking surfaces, including variations in texture, binder distribution, and glass bead exposure. To mitigate this, multiple measurement points were collected along each marking section, resulting in a combined uncertainty typically in the order of approximately 5% for R_L, Qd, and chromaticity coordinates.

For skid resistance measurements, uncertainty is more difficult to quantify due to the combined influence of surface condition, test speed, water film thickness, and equipment–surface interaction. Although the friction device is regularly calibrated and operated according to standard procedures, the overall uncertainty is primarily governed by surface variability and test-to-test repeatability under field conditions and is estimated to be below 10%.

2.8 Artificial xenon-arc ageing

Test panels were fabricated using the same material formulations as those applied in the field trials (MM10% and MM30%). The road marking materials were applied to stainless steel substrates. Artificial ageing was conducted in a xenon-arc weathering chamber (Atlas Suntest XXL+, USA) equipped with daylight filters to simulate the outdoor daylight UV spectrum in accordance with *ISO 4892-2 Method A* [30], using broadband irradiance. *Method A* comprises two consecutive cycles: (i) 102 min of dry exposure at an irradiance of E = 60 ± 2 W/m^2 (irradiance control from 300 nm to 400 nm), a black standard temperature (BST) of 65 °C, a chamber temperature of 38 ± 3 °C, and relative humidity (RH) of 50 ± 10%; followed by (ii) 18 min of water spray at the same irradiance, with all other parameters inactive. The combined cycle duration was 120 min and was repeated to achieve a total exposure time of 168 h.

The selected exposure duration was intended for comparative artificial weathering of the formulations and should not be interpreted as corresponding to a specific period of field exposure.

3 Results and discussion

3.1 Initial measurements (baseline performance)

Initial measurements were conducted in September 2024, two weeks after the application. Both the 10% and 20% MM formulations met the NordicCert requirements for white 3 mm thick, Type I markings ($R_L \geq 150$ mcd/m^2/lx; Qd ≥ 130 mcd/m^2/lx; chromaticity coordinates within the white box; and SRT ≥ 50), with measured values of R_L = 224 and 214 mcd/m^2/lx, Qd = 144 and 135 mcd/m^2/lx, and SRT = 53 for both formulations. The 30% MM formulation met the requirements for R_L (200 mcd/m^2/lx) and chromaticity, and achieved SRT = 53, but failed to meet the Qd requirement, with a measured value of 111 mcd/m^2/lx compared to the threshold of ≥ 130 mcd/m^2/lx.

However, the MM20% sample exhibited a non-homogeneous, sticky surface, which resulted in substantial accumulation of road dust and particles at the field trials (Fig. 2) after 12 months. The same material batch was found to have an abnormally high binder

Fig. 2 MM20% formulation after 12 months at the field trial with significant surface contamination, accompanied by distinct tire marks

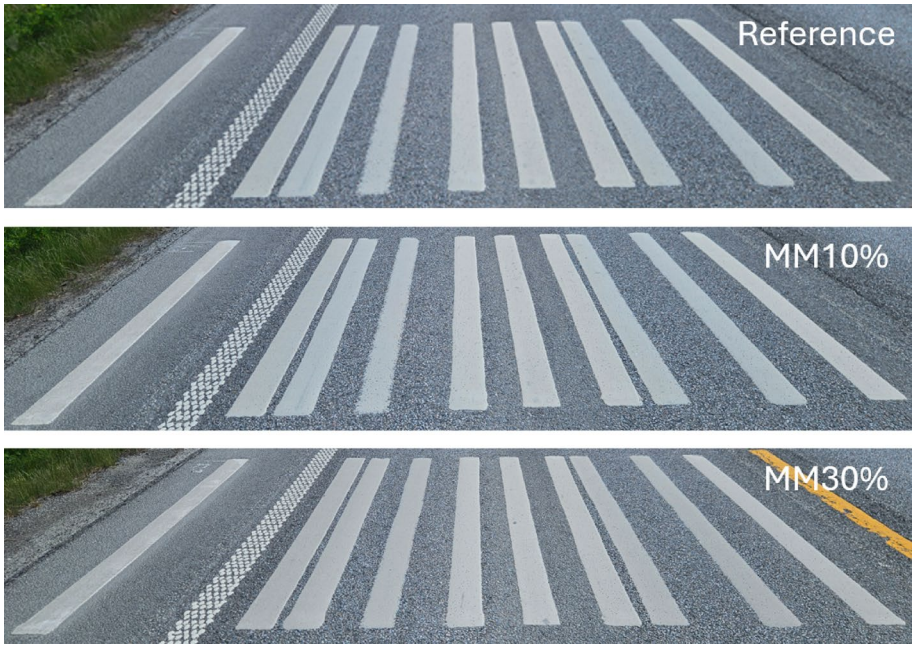

Fig. 3 Photographs taken after 8 months at the field trials. The top image shows the reference material (without recycled content), the middle image shows MM10%, and the bottom image shows MM30%

content and elevated softening point, indicating a likely formulation-related deviation [25]. This was, however, not known at the time of application, and the 20% MM formulation did not behave differently compared to the 10% MM and 30% MM formulation. Together, these observations suggest that the deviation is most likely related to material formulation rather than the application process. As a result, MM20% was considered unrepresentative and was excluded from further analyses to ensure the validity and reliability of the study's findings.

Figure 3 shows photographs of the road markings after 8 months at the field trials. The top image shows the reference material, followed by MM10% and MM30%. The visual

differences between the reference material and MM30% are less pronounced than at the initial measurements, where colour contrasts were more distinct. This is likely due to a combination of factors: the reference material has become less white over time due to abrasion, particulate deposition, and traffic wear, while MM10% and MM30% have become slightly brighter as a result of UV exposure and weathering.

3.2 Natural weathering and traffic-induced wear at NordicCert field trial section (12 months)

Table 1 presents the measured R_L, Qd, and skid resistance values for the virgin reference and recycled-content materials at the initial measurements and after one year of natural exposure. All materials exhibited reductions in R_L compared to baseline. The reduction was largest for the reference material (190 units), followed by MM10% (78 units) and MM30% (46 units). Daylight visibility, as measured by Qd, improved with increases compared to baseline for MM10% and MM30%, and a minor reduction for the reference material. The higher skid resistance recorded after 12 months, compared with initial measurements, can be attributed to the progressive changes in surface texture caused by traffic loading and environmental exposure. Immediately after application, thermoplastic road markings often exhibit a relatively smooth surface, as anti-skid aggregates are partially embedded within the binder and may be covered by a thin binder-rich film. With continued traffic loading, abrasion of the thermoplastic matrix occurs, leading to the exposure of embedded aggregates and the removal of the initial smooth surface layer, thereby increasing surface micro-texture, which is a key contributor to skid resistance. In addition, weakly bonded particles are selectively removed during early service life, resulting in a surface increasingly dominated by durable, skid-resistant aggregates [31–33]. Over time, these processes produce a more stable and roughened surface condition, explaining the higher skid resistance values typically observed after one year of field exposure.

Figure 4 presents the variation of R_L values between lines that are exposed to different numbers of wheel passages. Line 1 (located outside the driving lane, see Fig. 1) is not exposed to traffic and is therefore excluded from the evaluation according to NordicCert procedure. The error bars indicate the maximum and minimum values, while the coloured lines represent the average value. Under NordicCert evaluation, compliance is assessed per roll-over class using measurements from a single representative line within each class (not averaged across lines). A representative line for each roll-over class is selected based on wheel passage measurements. For the purpose of this study, mean values are reported for each line to enable evaluation of R_L and Qd variability in relation to differences in wheel passage exposure across the driving lane. The wheel tracks (lines 3,

Table 1 Initial performance parameters R_L (mcd/m^2/lx), Qd (mcd/m^2/lx), chromaticity coordinates (x, y), and skid resistance (SRT units) and corresponding values after 12 months of natural weathering and traffic-derived wear at NordicCert field trials

Material	R_L initial	R_L 12 mo	Qd initial	Qd 12 mo	SRT initial	SRT 12 mo	ΔR_L	ΔQd	ΔSRT
Reference	372	182	227	218	51	69	−190	−9	+13
MM10%	224	146*	144	150	53	64	−78	+6	+11
MM20%	214	114*	135	143	52	67	−100	+8	+14
MM30%	200	154	111*	132	53	63	−46	+21	+10

The values are presented as mean values from the nine road marking lines for each material. Values marked with * do not fulfil the NordicCert requirements for white 3 mm thick, Type I markings ($R_L \geq 150$ mcd/m^2/lx; Qd ≥ 130 mcd/m^2/lx; chromaticity coordinates within the white box; and SRT ≥ 50)

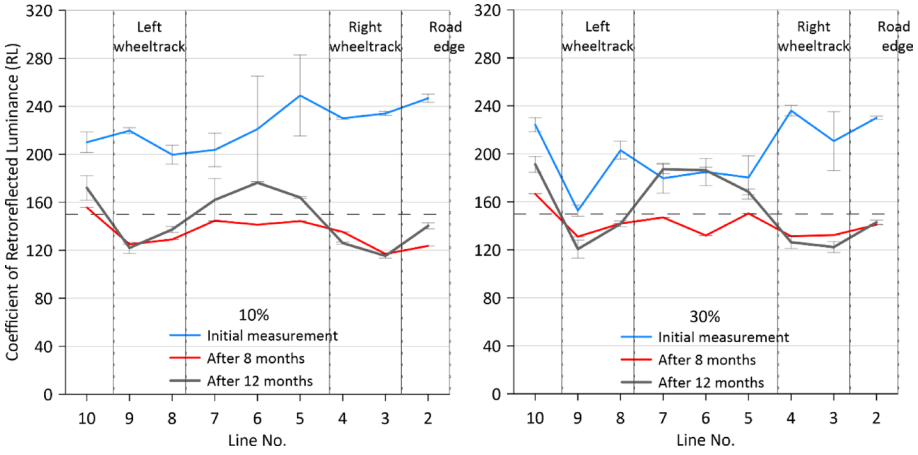

Fig. 4 R_L values for MM10% (left) and MM30% (right) where the initial measurement is marked with a blue line, measurements after 8 months with a red line, and measurements after 12 months with a black line. The performance requirement, $R_L \geq 150$ mcd/m^2/lx, is marked with a dashed line

4, 8, 9) are clearly distinguishable, as R_L values decrease more within than outside the wheel tracks (lines 2, 5, 6, 7, 10), where the road markings are subjected to less traffic. This behavior is consistent with previous field observations showing that the retroreflectivity commonly deteriorates during winter due to intensified mechanical wear from studded tires, which impose highly concentrated contact stresses on the marking surface [34]. Aggressive abrasion accelerates surface wear, including fracture, dislodgement, or embedment of glass beads that are critical for retroreflection [35, 36]. In addition, the road marking surface may become polished or covered by wear debris, such as rubber and asphalt particles, further reducing optical performance [34, 37]. Mean R_L values for lines in between wheel tracks (lines 6,7, and 8) improved for both MM10% and MM30% after 12 months compared with 8 months. This can be explained by a change in the wear regime; when traffic transitions to non-studded summer tires, lower abrasion intensity combined with shear-dominated friction promotes removal of surface contaminants and gradual cleaning of the marking [34]. This is most pronounced for lines that are exposed to a medium amount of traffic. Furthermore, thermoplastic extrusion road marking systems contain glass beads distributed throughout the material, allowing previously embedded beads to become exposed as the surface layer is worn [35]. Elevated temperatures and precipitation during spring and summer further facilitate glass bead exposure and surface cleaning, leading to a partial restoration of retroreflective performance [37].

For MM30%, R_L values in-between the wheel tracks returned to levels comparable to the initial measurements. Lines located directly within the wheel tracks still exhibited values below the threshold (dashed line) for both MM10% and MM30%. A clear correlation between the reduction in R_L and the cumulative number of wheel passages was observed for each marking line, as presented in Table 2, and is visually evident in Fig. 4. This relationship becomes particularly pronounced after 12 months of service, indicating that traffic-induced mechanical wear is a dominant factor governing the long-term retroreflective performance of markings positioned within the wheel tracks.

Linear regression analysis was performed using one-year R_L values for each line (2–10) in relation to the number of wheel passages. The analysis revealed a strong and statistically significant negative relationship between traffic loading and RL ($R^2 \approx 0.70$, $p < 0.01$ for both materials), indicating that RL decreases as the number of wheel passages

Table 2 Mean values and standard deviations for R_L and Qd values for MM10% and MM30% at initial measurement, after 8 months, and after 12 months [28]

Line no.		10	9	8	7	6	5	4	3	2
Initial measurements	R_L (mcd/m²/lx) MM10%	210 ± 10	220 ± 3	200 ± 10	204 ± 17	221 ± 54	249 ± 41	230 ± 1	234 ± 2	247 ± 4
	Qd (mcd/m²/lx) MM10%	152 ± 4	144 ± 4	145 ± 6	158 ± 15	148 ± 17	153 ± 25	136 ± 8	137 ± 11	123 ± 3
	R_L (mcd/m²/lx) MM30%	224 ± 7	153 ± 6	203 ± 9	180 ± 15	185 ± 14	180 ± 22	236 ± 5	211 ± 30	230 ± 2
	Qd (mcd/m²/lx) MM30%	122 ± 4	106 ± 17	105 ± 11	120 ± 4	119 ± 11	113 ± 14	105 ± 3	101 ± 7	106 ± 8
After 8 months	R_L (mcd/m²/lx) MM10%	156 ± 7	125 ± 3	129 ± 5	145 ± 4	141 ± 11	144 ± 2	135 ± 15	117 ± 1	124 ± 2
	Qd (mcd/m²/lx) MM10%	172 ± 3	166 ± 5	165 ± 3	178 ± 3	166 ± 9	179 ± 5	178 ± 4	166 ± 10	161 ± 3
	R_L (mcd/m²/lx) MM30%	167 ± 3	131 ± 3	142 ± 2	147 ± 5	132 ± 6	150 ± 5	131 ± 6	132 ± 5	141 ± 2
	Qd (mcd/m²/lx) MM30%	155 ± 9	153 ± 6	147 ± 12	141 ± 6	150 ± 9	160 ± 9	149 ± 6	142 ± 3	131 ± 7
After 12 months	R_L (mcd/m²/lx) MM10%	172 ± 13	122 ± 6	137 ± 3	162 ± 22	176 ± 1	164 ± 1	126 ± 1	115 ± 2	140 ± 3
	Qd (mcd/m²/lx) MM10%	160 ± 10	155 ± 9	150 ± 12	150 ± 15	148 ± 8	172 ± 10	149 ± 12	139 ± 10	149 ± 12
	R_L (mcd/m²/lx) MM30%	191 ± 8	121 ± 9	142 ± 3	187 ± 5	186 ± 3	168 ± 3	126 ± 6	122 ± 6	143 ± 2
	Qd (mcd/m²/lx) MM30%	132 ± 12	132 ± 3	127 ± 4	135 ± 11	127 ± 1	147 ± 2	133 ± 7	127 ± 4	131 ± 7

increases. The regression model suggests that each additional 100,000-wheel passages reduces R_L by approximately 10–13 units. A repeated-measures analysis of R_L at the initial, 8-month, and one-year time points showed a statistically significant effect of time for both materials ($p < 0.05$). R_L decreased markedly during the first 8 months, followed by a partial recovery or stabilisation between 8 months and one year. This pattern was consistent across both MM10% and MM30%. Overall, the results indicate that R_L degradation is both strongly time-dependent and significantly influenced by traffic loading. Additionally, the difference in performance between the two materials appears to decrease over time.

For Qd, the values increased over time, an effect that was particularly pronounced for MM30%, Fig. 5. MM30% exhibited values below the requirement at the initial measurement, but clearly exceeded the requirement after 8 months, and remained above or close to the limit after 12 months. MM10% consistently showed values well above the requirement at all measurement occasions. The statistical analysis demonstrated that both materials (MM10% and MM30%) experienced significant changes in Qd over time. This indicates a clear temporal effect on Qd development for both materials. However, linear regression analysis of the one-year Qd values showed no statistically significant correlation with wheel passages for either material. This suggests that traffic load alone cannot explain the observed variation in Qd, and that other factors, such as environmental conditions, surface characteristics, or material-specific ageing mechanisms are likely contributing to the changes over time.

In contrast to R_L, the influence of line position (wheel track, between wheel tracks, or road edge) was less distinct for Qd. This is consistent with the fact that the Qd value

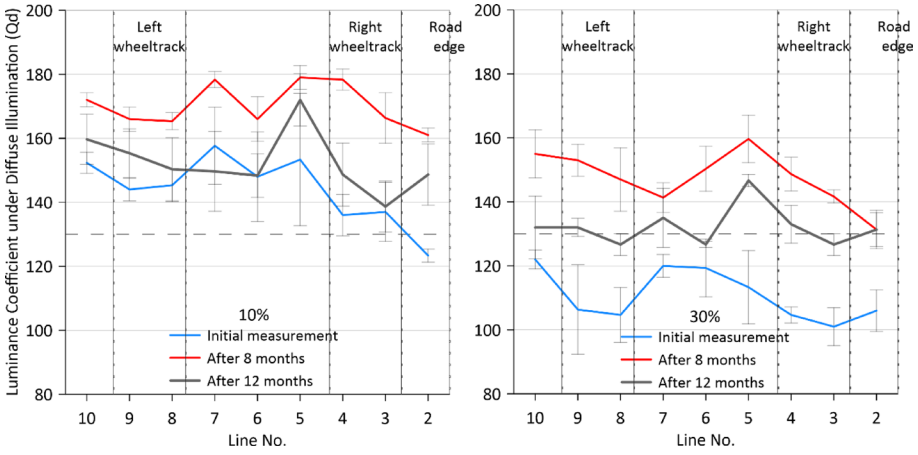

Fig. 5 Qd values for MM10% (left) and MM30% (right) where the initial measurement is marked with a blue line, measurements after 8 months with a red line, and measurements after 12 months with a black line, the error bars show min/max values. The performance requirement, Qd ≥ 130 mcd/m^2/lx is marked with a dashed line

is governed by how efficiently incident daylight is reflected back toward the observer, which depends strongly on the microscale surface geometry of the road marking rather than on directional traffic loading effects [8, 38]. Surface roughness affects Qd primarily through its influence on diffuse reflection and light scattering behavior. The observed improvement in Qd value with time is likely associated with photo-oxidative ageing of the binder, which alters the surface characteristics of the marking material. Ultraviolet radiation promotes oxidation reactions within the polymers in the binder, leading to hardening and embrittlement of the surface layer [39, 40]. As the binder becomes stiffer and more brittle, its ability to flow, smear, or re-level the surface under thermal or mechanical loading is reduced. In addition, UV-induced degradation may result in micro-cracking and subtle surface roughening, thereby modifying the surface texture at the microscale.

These ageing-related changes can be explained by photo-oxidative reactions within the polymeric binder, where ultraviolet radiation promotes chain scission and oxidative degradation of the polymer network. Such processes increase the stiffness and brittleness of the surface layer and cause gradual development of micro cracks and surface heterogeneities. The resulting surface evolution alters the light scattering behaviour of the road marking surface, increasing diffuse reflection, and thereby contributing to higher Qd values over time.

Studies on polymer surface ageing have shown that UV irradiation can significantly alter surface characteristics, producing e.g., microscale grooves, cracks, and surface particulates that increase the surface roughness [40]. Such roughening promotes more diffuse reflection by redistributing incident light over a wider range of angles, thereby increasing the proportion of reflected light directed toward the observer. In contrast, a smooth, binder-rich surface tends to produce predominantly specular reflection, directing light away from the observer and resulting in lower Qd values [41, 42]. Consequently, UV-driven surface ageing processes can lead to improved daytime luminance performance.

The chromaticity coordinates are presented in Fig. 6. The figure to the left shows natural weathering, while the figure to the right shows artificial ageing. For natural weathering, both the reference material, MM10%, and MM30% remain well within the

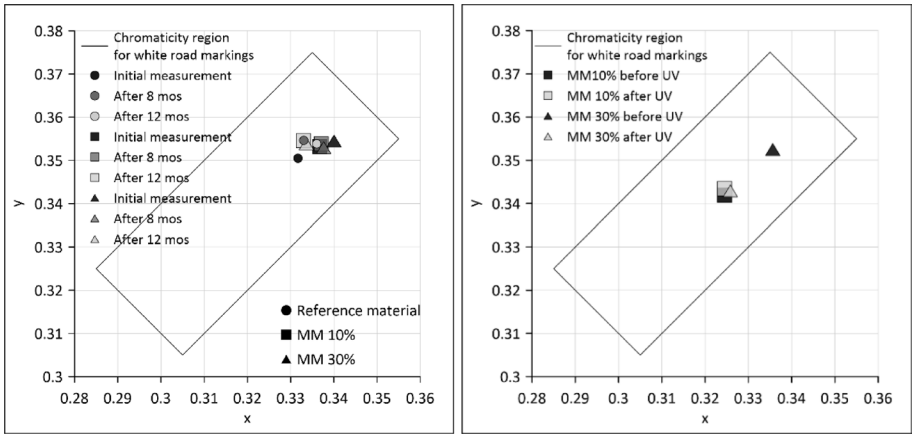

Fig. 6 To the left: chromaticity coordinates for the reference material (circles), MM10% (squares) and MM30% (triangles) after the initial measurement, after 8 months, and after 12 months of natural weathering at the field trials. To the right: chromaticity coordinates for MM10% (squares) and MM30% (triangles) before and after 168 h artificial ageing

specified chromaticity region for white road markings at all measurement occasions. The observed differences are minimal, both between the three materials and across the different measurement periods. This indicates stable colour characteristics over time and suggests that increasing the proportion of recycled material does not adversely affect the chromaticity coordinates of the road markings. For artificial weathering, the chromaticity coordinates for all samples remained well within the defined chromaticity region for white road markings. Prior to UV exposure, MM30% displayed a slightly more yellowish tone (higher x and y value) compared with MM10% (both before and after UV exposure). After UV ageing, however, MM30% exhibited chromaticity values similar to those of MM10%, indicating that UV exposure reduces both yellow and red tones and shifts the colour toward a whiter appearance. This change may be attributed to surface oxidation and slight erosion of the binder, which exposes more TiO_2 particles at the surface. The increased exposure of TiO_2 enhances light scattering, leading to higher perceived whiteness, despite ongoing binder degradation. The magnitude of this effect depends on the crystal form of TiO_2, rutile is UV-stable and minimizes polymer breakdown, whereas anatase can accelerate degradation through its higher photocatalytic activity [43–45].

3.3 Artificial xenon-arc ageing

Figure 7 summarises the results of xenon-arc artificial ageing conducted under controlled laboratory conditions. Changes in Qd were compared before and after ageing. In these laboratory samples, no drop-on material was present on the surface and the glass beads embedded within the thermoplastic material remained largely unexposed due to the absence of traffic-induced wear or abrasion. Consequently, R_L measurements were not considered representative under these conditions as R_L is strongly dependent on bead exposure and retroreflection geometry that develops under mechanical wear in service. Therefore, R_L was excluded from the artificial ageing analysis, and Qd was used as the primary indicator of surface optical changes.

Measurements of Qd show that both MM10% and MM30% exhibit values well above the specified requirement both prior to, and following, artificial ageing. The boxplots are based on ten measurements, where the box boundaries represent the 25th and 75th

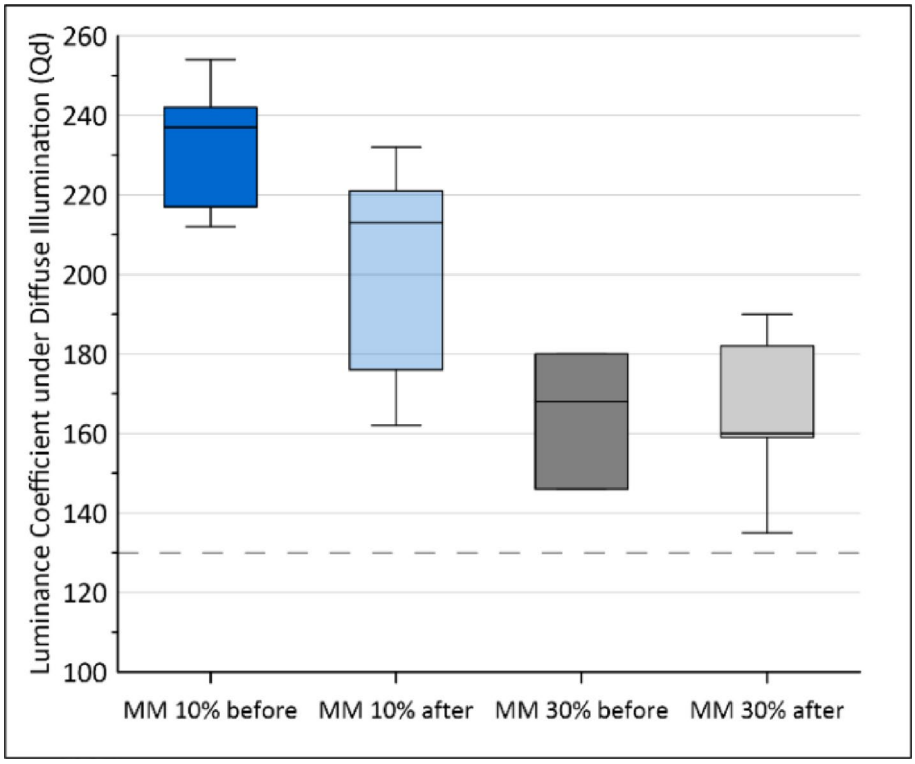

Fig. 7 Qd-values for MM10% (blue boxes) and MM30% (grey boxes) before and after xenon-arc artificial ageing. The requirement, Qd ≥ 130 mcd/m^2/lx is marked with a dashed line

percentiles, the whiskers indicate the 10th and 90th percentiles, and the line within each box denotes the median value. Both MM10% and MM30% show a slight decrease in Qd after ageing, inconsistent with the results from the natural weathering.

3.4 Comparison between natural weathering and xenon-arc artificial ageing

Despite identical TiO_2 content in MM10% and MM30% formulations, natural weathering for 12 months caused an increase in Qd for both materials, with a slightly larger increase for MM30%. This could potentially be explained by differences in polymer matrix properties or pigment dispersion [46] but is not examined further, as it falls outside the scope of this study. In contrast, artificial xenon-arc ageing resulted in slight decreases in Qd, reflecting polymer oxidation and yellowing, without significant exposure of TiO_2 [43]. These results highlight the different mechanisms of long-term outdoor weathering with traffic exposure versus short-term, high-intensity laboratory UV exposure (without mechanical wear) and the role of the polymer binder in controlling diffuse reflectance.

Natural weathering combines UV radiation, moisture cycles, temperature fluctuations, and abrasive wear from traffic and winter maintenance. This complex stress environment leads to accelerated glass bead loss, surface roughening, and contamination by rubber particles and dust [35, 36]. Xenon-arc artificial ageing primarily targets photodegradation and thermal oxidation of the binder and pigments, but lacks mechanical abrasion, so bead embedment remains intact and surface contamination is absent. These differences are important because retroreflectivity loss in the field can be dominated by bead loss and surface contamination rather than pure UV-induced optical degradation [47].

The data also indicate that natural weathering has minimal effect on the (x, y) chromaticity coordinates, indicating stable colour over time for both MM10% and MM30%. In contrast, artificial xenon-arc ageing caused a slight shift toward lower x and y values, particularly for MM30%, reflecting a minor reduction in yellow and red tones and a slightly whiter appearance. This difference is likely due to rapid UV-induced binder oxidation and limited TiO_2 exposure under laboratory conditions, whereas gradual binder erosion during outdoor exposure preserves colour stability.

The differences observed between natural and accelerated ageing highlight the limitations of laboratory xenon-arc UV exposure as a stand-alone predictor of in-service performance of thermoplastic road markings. While artificial ageing can effectively reveal the susceptibility of thermoplastic binders to photodegradation and minor changes in colour and Qd, it does not account for key field-relevant factors such as mechanical bead loss, surface contamination from traffic wear, or the full effects of moisture and temperature variations. Consequently, predictions of long-term performance based solely on short-term laboratory UV exposure may underestimate or misrepresent actual field performance, particularly for recycled thermoplastic formulations where matrix properties and binder-pigment interactions can differ from virgin materials. Previous research has highlighted that artificial weathering methods, such as xenon-arc exposure, often simulate a high-noon UV scenario but do not adequately reproduce field conditions involving moisture, temperature cycles, and mechanical abrasion, leading to potential misrepresentation of service-life performance when used in isolation [48–50]. Moreover, comprehensive multi-factor ageing studies have shown that combined environmental stresses affect durability and optical performance in ways that xenon-arc ageing alone cannot capture [51, 52]. The first version of EN 1871 [53] included a method where Tröger wear abrasion was evaluated after UV exposure, reflecting an awareness that both photochemical degradation and mechanical wear contribute to field ageing of road marking materials. However, no standardised multi-factor accelerated ageing protocol is currently available that fully reproduces the combined environmental and traffic-related stresses experienced under real service conditions. Our findings highlight the need for an artificial ageing protocol that combines UV exposure with mechanical abrasion, subzero temperature cycling, and relative humidity variations from approximately 50–00% with frequent periods near saturation, relevant for Nordic conditions. Such an approach would provide a more robust basis for assessing the durability and visibility of recycled road markings and help establish more reliable correlations between laboratory ageing results and real-world performance, ultimately guiding formulation and specification decisions for sustainable marking materials. By demonstrating the technical feasibility and performance of recycled thermoplastic road markings, this study highlights their potential role in supporting more sustainable material strategies within road infrastructure systems. These findings suggest possible alignment with several United Nations Sustainable Development Goals, including SDG 9 (Industry, Innovation, and Infrastructure) through more resilient transport systems, and SDG 11 (Sustainable Cities and Communities) via improved road safety and mobility.

In addition, the reduced reliance on virgin materials indicates potential contributions to SDG 12 (Responsible Consumption and Production) by enabling more efficient resource use within a circular economy framework. The long-term durability and performance of recycled materials also suggest relevance to SDG 13 (Climate Action), as

improved material longevity may reduce maintenance frequency and associated environmental burdens. However, these contributions should be interpreted cautiously, as a comprehensive life-cycle assessment and full-scale implementation studies are required to quantitatively confirm the environmental and sustainability benefits of the proposed approach.

4 Conclusions

Based on the results of this study, the incorporation of recycled thermoplastic road marking material represents a promising approach for reducing the use of virgin raw materials without compromising traffic safety or functional performance. Thermoplastic road markings containing 10% and 30% mechanically milled recycled material generally demonstrated performance close to the specified requirements after one year of exposure under real-world Nordic traffic and climate conditions, although some parameters showed values at or below threshold levels. By demonstrating the technical feasibility of reducing reliance on virgin materials and enabling the circular use of resources, these findings support the potential for more sustainable material strategies in road marking systems. Such approaches are aligned with the objectives of the SDGs related to resilient infrastructure, sustainable cities, responsible consumption, and climate action, pending confirmation through future life cycle and large-scale implementation studies.

Natural weathering led to a reduction in the coefficient of retroreflected luminance (R_L) for all materials, primarily governed by traffic-induced mechanical wear, glass bead loss, and surface contamination. At the same time, the luminance coefficient under diffuse illumination (Qd) increased for the recycled formulations, particularly for MM30%, which is attributed to gradual surface ageing, micro-scale roughening, and enhanced diffuse light scattering under combined UV exposure, moisture, temperature variations, and abrasion. Chromaticity coordinates remained stable during natural exposure, confirming that increased recycled content did not adversely affect colour performance. All field-applied formulations also met the performance requirements for skid resistance after one year.

In contrast, accelerated xenon-arc UV ageing produced different degradation patterns. While both recycled formulations remained within the specified limits for Qd and chromaticity, slight decreases in Qd and minor shifts toward lower x and y values (for MM30%) were observed. These changes reflect UV-driven photodegradation of the binder under laboratory conditions, but the absence of mechanical abrasion, bead loss, and surface contamination limits the ability of xenon-arc ageing to reproduce field-relevant degradation mechanisms. Consequently, accelerated laboratory testing alone would have underestimated certain degradation modes observed during natural ageing.

Overall, the results confirm that recycled thermoplastic road markings with 10% and 30% recycled content can maintain acceptable performance over at least one year of service, supporting their suitability for practical implementation. This study provides the first systematic evidence from real-world traffic conditions demonstrating the technical feasibility of circular use of thermoplastic road marking materials within the transportation sector.

Beyond material performance, successful large-scale implementation will require further development in logistics, recycling infrastructure, and coordination between road authorities, contractors, and material producers. Future work should include full-scale

validation of milling and recycling processes, optimization of sorting and quality control methods, and evaluation of formulations with recycled contents exceeding 50%. Long-term performance should be assessed using combined laboratory and field ageing protocols, and a comprehensive life cycle assessment (LCA) is needed to quantify the environmental and economic benefits of recycled thermoplastic road markings relative to virgin materials.

Acknowledgements
The authors would like to thank Julia Danell from Svevia for her valuable contributions to material handling and formulation, application of material at the test site, and insightful discussions. The authors would also like to thank Morten Hafting from Ramboll for permission to use the photographs in Figs. 2 and 3. All material applications at the NordicCert field trial were carried out by Svevia after permission from NordicCert, who holds all necessary permissions from the Norwegian Public Roads Administration. Measurements of the road markings were conducted during scheduled road closures in accordance with NordicCert procedures and were collected in close coordination with the personnel responsible for the trial. Some of the figures were created with BioRender.com.

Author contributions
H.F., I.J., and M.G. contributed to the conceptualization, investigation, and methodology of the study. H.F. was responsible for project administration and validation. H.F. and I.J. wrote the original draft of the manuscript. I.J. prepared the visualizations. H.F., I.J., and M.G. reviewed and edited the manuscript. All authors read and approved the final manuscript.

Funding
Open access funding provided by Swedish National Road and Transport Research Institute (VTI). This work was carried out within InfraSweden, a strategic innovation program jointly funded by Sweden's Innovation Agency (Vinnova), the Swedish Research Council for Sustainable Development (Formas), and the Swedish Energy Agency. The project was funded by Vinnova under grant no. 2024-00144.

Data availability
The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Declaration of generative AI and AI-assisted technologies in the writing process
During the preparation of this work the author(s) used ChatGPT (OpenAI) to support language editing, text refinement, and grammatical review of selected sections. All content generated or revised with the assistance of this tool was subsequently reviewed and edited by the author(s), who take full responsibility for the accuracy, integrity, and scientific content of the publication.

Ethical approval and consent to participate
Not applicable.

Received: 17 February 2026 / Accepted: 8 July 2026
Published online: 16 July 2026

References

1. Damjanović M, Stević Ž, Stanimirović D, Tanackov I, Marinković D. Impact of the number of vehicles on traffic safety: Multi-phase modeling. Mech Eng. 2022;20(1):177–97. https://doi.org/10.22190/FUME220215012D.
2. Formosa N, Quddus M, Man CK, Singh M, Morton C, Masera CB. Evaluating the impact of lane marking quality on the operation of autonomous vehicles. J Transp Eng Part A: Syst. 2023;150(1). https://doi.org/10.1061/JTEPBS.TEENG-7688.
3. Järlskog I, Fager H, Gustafsson M, Ridderstedt I. Measures to reduce the wear of road markings and thereby decrease the spread of microplastics, VTI Report 1207A. Linköping, Sweden: Swedish National Road and Transport Research Institute; 2024.
4. Soilán M, Riveiro B, Martínez-Sánchez J, Arias P. Segmentation and classification of road markings using MLS data. ISPRS J Photogrammetry Remote Sens. 2017;123:94–103. https://doi.org/10.1016/j.isprsjprs.2016.11.011.
5. Biermeier S, Kemper D, García-Hernandez A. Road marking visibility for automated vehicles: Machine detectability and maintenance standards. Case Stud Constr Mater. 2025;22:e04430. https://doi.org/10.1016/j.cscm.2025.e04430.
6. Lu X, Wu H, Li L, He R, Guo H. Confined photocatalysis and interfacial reconstruction for durability wettability in road markings. Colloids Surf A. 2026;729:138902. https://doi.org/10.1016/j.colsurfa.2025.138902.
7. CEN. 2013. EN 1790:2013 Road marking materials - Preformed road markings. 2013, European Committee for Standardization, Brussels.
8. CEN. 2018. EN 1436:2018 Road marking materials - Road marking performance for road users. 2018, European Committee for Standardization, Brussels.

9. CEN. 2020. EN 1824:2020 Road marking materials - Road trials. 2020, European Committee for Standardization, Brussels.
10. CEN. 2020. EN 1871:2020 Road marking materials - Paint, thermoplastic, and cold plastic materials - Physical properties. 2020, European Committee for Standardization, Brussels.
11. Mirabedini SM, Zareanshahraki F, Mannari V. Enhancing thermoplastic road-marking paints performance using sustainable rosin ester. Prog Org Coat. 2020;139:105454. https://doi.org/10.1016/j.porgcoat.2019.105454.
12. Gunnarsson M, Mári Á. Road marking and microplastics in Scandinavia: An overview of the available knowledge of microplastics in the Scandinavian road marking industry. SVMF Report; 2022.
13. Dai Y, Dong H, Sun L, Li J, Zhang T, Geng Y, Liu Z. Life cycle environmental impact assessment of titanium dioxide production in China. Environ Impact Assess Rev. 2024;105:107412. https://doi.org/10.1016/j.eiar.2023.107412.
14. Gázquez MJ, Bolívar JP, Garcia-Tenorio R, and F., V. A Review of the Production Cycle of Titanium Dioxide Pigment. Mater Sci Appl. 2024;5(7). https://doi.org/10.4236/msa.2014.57048.
15. Maldybayev G, Korabayev A, Sharipov R, Al Azzam KM, Negim ES, Baigenzhenov O, Alimzhanova A, Panigrahi M, Shayakhmetova R. Processing of titanium-containing ores for the production of titanium products: A comprehensive review. Heliyon. 2024;10(3):e24966. https://doi.org/10.1016/j.heliyon.2024.e24966.
16. Middlemas S, Fang ZZ, Fan P. A new method for production of titanium dioxide pigment. Hydrometallurgy. 2013;131–2. https://doi.org/10.1016/j.hydromet.2012.11.002.
17. Yilmaz B, Deniz İ, Fazli H, Bekircan O, Gültekin E, Pranovich A. Development of biobased, sustainable and environmentally friendly glycerol ester rosins for the production of thermoplastic road marking paint. J Appl Polym Sci. 2024;141(38). https://doi.org/10.1002/app.55961.
18. Yilmaz B, Deniz İ, Fazli H, Bekircan O, Pranovich A, Karaoğul E. Rosins BioResources. 2024;19(2):2160–78. https://doi.org/10.15376/biores.19.2.2160-2178. Sustainable Thermoplastic Road Marking Paint Production from Natural Modified.
19. Liu T, Yu A, Hu J, Cao Q, Zhang M. Effects of Ultraviolet Irradiance and Temperature on the Yellowing Behavior of White Pavement Markings. Appl Sci. 2026;16:1744. https://doi.org/10.3390/app16041744.
20. Aktan F, Schnell T. Performance evaluation of pavement markings under dry, wet, and rainy conditions in the field. Transp Res Rec. 2004;1877(1):38–49. https://doi.org/10.3141/1877-05.
21. Hou Q, Ai C, Boudreau N. An Automated Pavement Marking Retroreflectivity Condition Assessment Method Using Mobile LiDAR and Video Log Images. J Infrastruct Syst. 2024;30(2). https://doi.org/10.1061/JITSE4.ISENG-239.
22. Qiao F, Kazimi AA, Ekezie E, Du J. 2023. Synthesizing Best Practices for Long-Life Pavement Markings. in International Conference on Transportation and Development 2023.
23. Wang N, Li Q, Zhang L, Wang J. Anti-aging and durability performance of pavement markings under multifactor coupling effects. Constr Build Mater. 2025;484:141840. https://doi.org/10.1016/j.conbuildmat.2025.141840.
24. Kuvshinnikova O, Boven G, Pickett JE. Weathering of aromatic engineering thermoplastics: comparison of outdoor and xenon arc exposures. Polym Degrad Stab. 2019;160:177–94. https://doi.org/10.1016/j.polymdegradstab.2018.12.011.
25. Fager H, Järlskog I, Gunnarsson M, Danell J, Aneklev N. Recovery methods, material characterization, and performance assessment of recycled thermoplastic road markings. Case Stud Constr Mater. 2025. https://doi.org/10.1016/j.cscm.2025.e05072. 23.
26. Kottek M, Grieser J, Beck C, Rudolf B, Rubel F. World map of the Köppen–Geiger climate classification updated. Meteorol Z. 2006;15(3):259–63.
27. Fors C, Johansen TC, Fager H, Linköping. Sweden: Swedish National Road and Transport Research Institute.
28. Hafting M, Fors C, Linköping. Sweden: Swedish National Road and Transport Research Institute.
29. Wälivaara B. Validation of VTI-PFT version 4, Measurements on plane and profiled road markings, Report No. Linköping, Sweden: Swedish National Road and Transport Research Institute; 2007.
30. ISO. 2013. Plastics — Methods of exposure to laboratory light sources —Part 2: Xenon-arc lamps. ISO 4892-2:2013. 2013.
31. Henry JJ, Anderson DA, Hayhoe GF. 1981. Skid resistance of pavement marking materials: Volume I, Report No. FHWA/RD-80/199. Washington DC.
32. Burghardt TE, Pashkevich A, Piegza A, Antoni K. Thermoplastic road markings – Description and microplastic pollution estimate in Sweden. J Environ Manage. 2023;348:119183. https://doi.org/10.1016/j.jenvman.2023.119183.
33. Kováč M, Brna M, Pisca P, Jandačka D, Decký M. The Influence of Road Pavement Materials on Surface Texture and Friction. Sustainability. 2023;15:12195. https://doi.org/10.3390/su151612195.
34. Smadi O, Hawkins N, Nlenanya I, Bektas BA. Pavement markings and safety. Report No., Iowa State University, Center for Transportation Research and Education; 2010.
35. Mazzoni LN, Vasconcelos K, Albarracín O, Bernucci L, Linhares G. Appl Sci. 2024;14:4205. https://doi.org/10.3390/app14104205. Field Data Analysis of Pavement Marking Retroreflectivity and Its Relationship with Paint and Glass Bead Characteristics.
36. Wenzel KM, Burghardt TE, Pashkevich A, Buckermann WA. Glass beads for road markings: surface damage and retroreflection decay study. Appl Sci. 2022;12(4):2258. https://doi.org/10.3390/app12042258.
37. Zhao L, Ding H, Sun J, Wu G, Xing H, Wang W, Song J. Prediction of service life of thermoplastic road markings on expressways. Sustainability. 2023;15:15237. https://doi.org/10.3390/su152115237.
38. CIE. 2001. Road surface and road marking reflection characteristics. CIE 144:2001. 2001: Commission Internationale de l'Éclairage.
39. Yousif E, Haddad R. Photodegradation and photostabilization of polymers, especially polystyrene. SpringerPlus. 2013. https://doi.org/10.1186/2193-1801-2-398. 2(398.
40. Kotnarowska D. Influence of Ageing with UV Radiation on Physicochemical Properties of Acrylic-Polyurethane Coatings. J Surf Eng Mater Adv Technol. 2018;8(4). https://doi.org/10.4236/jsemat.2018.84009.
41. Gillespie TD. 1992. Fundamentals of vehicle dynamics. 1992: Warrendale, Pa. Society of Automotive Engineers.
42. van Ginneken B, Stavridi M, Koenderink JJ. Diffuse and specular reflectance from rough surfaces. Appl Opt. 1998;37(1):130–9. https://doi.org/10.1364/AO.37.000130.
43. Hashimoto K, Irie H, Fujishima A. TiO2 photocatalysis: a historical overview and future prospects. Jpn J Appl Phys. 2005. https://doi.org/10.1143/JJAP.44.8269. 44.
44. Diebold U. The surface science of titanium dioxide. Surf Sci Rep. 2003;48(5):53–229. https://doi.org/10.1016/S0167-5729(02)00100-0.

45. Fujishima A, Zhang X, Tryk DA. TiO2 photocatalysis and related surface phenomena. Surf Sci Rep. 2008;63(12):515–82. https://doi.org/10.1016/j.surfrep.2008.10.001.
46. Wang DL, Watson SS, Sung LP, Tseng IH, Bouis CJ, Fernando R. Effect of TiO2 pigment type on the UV degradation of filled coatings. J Coat Technol Res. 2011;8(1):19–33. https://doi.org/10.1007/s11998-009-9216-y.
47. Burghardt TE, Pashkevich P, Babić D, Mosböck H, Babić D, Žakowska L. Microplastics and road markings: the role of glass beads and loss estimation. Transp Res Part D: Transp Environ. 2022;102. https://doi.org/10.1016/j.trd.2021.103123.
48. Lv Y, Huang Y, Yang J, Kong M, Yang H, Zhao J, Li G. Outdoor and accelerated laboratory weathering of polypropylene: a comparison and correlation study. Polym Degrad Stab. 2015;112:145–59. https://doi.org/10.1016/j.polymdegradstab.2014.12.023.
49. Oehler H, Wanner M, Aktas L, Neumann M, Lellinger D, Alig I. Site specific weathering of coatings: II Comparison of natural weathering and accelerated protocols for Central Europe and Florida. J Coat Technol Res. 2025;22:739–61. https://doi.org/10.1007/s11998-024-01005-3.
50. Atlas Weathering Guidebook. 2019. Technical guide on weathering testing and standards for polymers and coatings. 2019: Atlas Material Testing Solutions.
51. Owusu V, Tuffour YA, Obeng DA, Salifu M. Degradation of Retro-Reflectivity of Thermoplastic Pavement Markings: A Review. Open J Civil Eng. 2018;8(3). https://doi.org/10.4236/ojce.2018.83023.
52. Mohamed M, Abdel-Rahim A, Kassem E, Chang KH, McDonald AG. Laboratory-Based Evaluation of Pavement Marking Characteristics. J Transp Eng Part B: Pavements. 2020;146(2). https://doi.org/10.1061/JPEODX.0000168.
53. CEN. 2000. EN1871:2000 Road marking materials - Physical properties. 2000, European Committee for Standardization, Brussels.

Publisher's note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.