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Systematic Testing of Road Markings' Retroreflectivity to Increase Their Sustainability through Improvement of Properties: Croatia Case Study

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Abstract: Road markings are important elements of road infrastructure, influencing traffic safety. Since they are deteriorating systems, their upkeep through renewals is important. To assure the quality of the renewal jobs, the systematic testing of retroreflectivity, which is the key performance parameter of road markings, was imposed in Croatia. Results from two decades of annual measurements of renewal jobs are provided. For the first decade, the measurements were taken statically, at spot locations, and later dynamically, across the entire road segments. When the evaluation started, only 1 out of 18 tested job sites was exceeding the minimum requirements; only after 8 years of measurements, 100% of the jobs exceeded the minimum demands. A subsequent switch to dynamic testing revealed that, on average, only 71% of the renewed road markings were in satisfactory condition and approximately 1.22% of the analysed line lengths had grossly substandard retroreflectivity. These results demonstrated that the field verification of jobs quality is necessary and simultaneously showed that static localised testing was not adequate. The outcome underlines the need for the strict supervision of road maintenance contracts to maximise the benefits for the society: through the better visibility of road markings, road safety should also improve, and the entire system will become more sustainable.

Keywords: retroreflection; visibility; road safety; maintenance policy; job supervision

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1. Introduction

Road markings (RMs)—longitudinal or transverse lines or symbols on installed on pavements—are one of the most important safety features on almost all modern roads. They are fundamental elements of road infrastructure that are perceived by drivers; their impact on road safety and drivers' behaviour was recently reviewed [1]. In addition, RMs were reported as necessary for the proper functioning of advanced driver assistance systems [2]. Known and proven material and installation technologies, the existing presence on the majority of roads worldwide, high usefulness for the drivers and also for lane-keeping assistance systems, and effectiveness without any external energy source belong to the advantages of RMs that make them currently irreplaceable. Furthermore, there is no known substitution to the use of RMs because of an excellent cost-to-benefit ratio that they provide [3]. All of this makes RMs a highly sustainable solution for use on almost all paved roads to increase traffic safety.

For appropriate function, RMs must be visible, which is achieved through colour contrasting with the roadway surface; at night, the visibility is enhanced through retroreflectivity [4]. As materials, RMs are speciality heavy-duty industrial maintenance coatings; they are unique because of being dual-layer systems comprising the bottom paint layer and strewn on it a layer of drop-on glass beads (GBs). Of particular importance are the GBs, which simultaneously provide retroreflectivity and protect the paint layer from abrasion [5].

RMs are deteriorating systems, and upon the loss of functional properties, their renewal with another layers of the paint and the GBs is necessary; hence, layer stacking occurs [5]. The environmental sustainability of RMs is directly connected with their functional service life [6], which was reported by us, based on extensive field research supported by laboratory assessment, to be affected by both the initial properties and the choice of materials [7].

Retroreflectivity—the phenomenon of reflecting the light from a vehicle's headlights back towards the driver—is the property of RMs used to determine their performance and to indicate the need for renewal. Retroreflectivity is measured as a coefficient of retroreflected luminance (R_L) and expressed in millicandelas per square metre per lux, mcd/m^2/lx. It is achieved because of the drop-on GBs partially embedded in the paint layer [8,9]. Because the tyres of all vehicles that encroach on the RMs are rolling on the GBs, they can become damaged or extracted from the film, which causes a decrease in R_L [10]. Note: as long as the drop-on GBs are present, tyres have no contact whatsoever with the paint layer—it is physically impossible because the tyre tread is approximately 10× larger than spaces between the GBs. Daytime visibility, assessed as luminance coefficient in diffuse illumination (Qd) and also expressed in mcd/m^2/lx, is an equally important performance parameter as it meaningfully affects the contrast and thus the visibility of RMs. Nonetheless, Qd is seldom considered as critical, because in the vast majority of cases, R_L decreases first.

It has been consistently demonstrated that road users appreciate RMs with high R_L, which make the task of driving in darkness easier [11–13]. Studies have shown that an increase in R_L was associated with a lower crash rate at night on unlit roads in the absence of other interfering factors [14,15], even if some researchers pointed out the weaknesses of such analyses [16]. The minimum R_L that is recommended by the European Union Road Federation to be maintained at all roads at all times is 150 mcd/m^2/lx [17]. This value coincides with the outcome of studies based on a visual assessment of drivers' needs [18,19]. In most European countries, R_L > 200–300 mcd/m^2/lx is demanded from newly applied RMs, but a decrease in R_L to circa 100 mcd/m^2/lx after winter is typically considered as acceptable. The imposition of the minimum initial R_L seems reasonable because of the deteriorating nature of RMs.

Given the above, it is surprising that some road administrators (personal communications) do not routinely verify the R_L of newly applied RMs despite the availability of tools and standardised procedures. To assess the key properties—R_L and Qd—of freshly renewed RMs, before payments to the applicators were made, testing was imposed in Croatia. Herein, the results from systematic evaluation performed at selected roads over two decades are provided. Surprisingly, despite the relative abundance of literature related to RMs, particularly in North America [20], no similar analyses have been reported so far. The different line arrangement and large dataset spanning testing over two decades and multiple renewals makes this a novel contribution. The results presented in this first article on this topic can be used as a reference for road administrators, but they also should be of interest to policymakers, road safety advocates, and—due to the association between poorly maintained RMs and emissions of microplastics—to environmental scientists. The proper utilisation of the provided results would lead to an increased sustainability of RMs: improving their initial quality should translate to prolonged functional service life, which would lead to better visibility for road users. Hence, overall system sustainability—not only from an environmental but also from a social perspective—could be realised.

2. Methodology

2.1. Data Collection and Measurement Procedures

Data for this study were collected by a laboratory certified according to the standard ISO/IEC 17025 [21]; measurements were taken on request from the road administrator. Standard retroreflectometers, properly calibrated per requirements of the testing laboratory certification, were utilised for measurements. The requirements for the measurement procedures of R_L and Qd are defined in standard EN 1436 [22]. The standard defines a 30 m geometry, which corresponds to a visibility of RMs at a distance of 30 m by a driver with eyes at the height of 1.20 m when the RMs are illuminated with vehicle headlights located 0.65 m above ground. Consequently, the observation angle is 2.29° and the illumination angle is 1.24° to give a 1.05° difference in the angular planes.

The testing laboratory lacked the knowledge about the contractors and the specifics related to the utilised materials, so any conflicts of interest between the testing team and the application crew were avoided. Nonetheless, it was known that in all of the cases, solventborne paints reflectorised with GBs with a refractive index of 1.5 were utilised. Since the measurements were taken relatively shortly after the application of the RMs, it was assumed that the role of paint selection should not affect the outcome [7]. However, the quality of the used drop-on GBs, which was not estimated, might have played a role [23,24]. The results were provided to the road administrator, at whose discretion was acceptance or rejection of the job and/or any financial penalties or rewards to the contractors. Moreover, the laboratory was not informed about the outcome in any of the cases and was not requested to verify the results from the possible re-painting of rejected jobs. The dataset provided herein comprises data collected between 2003 and 2022; R_L and Qd were measured with a static method (spot testing) until 2013, and then R_L was assessed dynamically (entire road segment testing).

Historically, measurements of R_L and Qd were taken statically at predetermined spot locations. Two location selection methods for the static evaluation of R_L and Qd were used: firstly, between 2003 and 2010, the so-called Kentucky method was utilised [25], and then, between 2011 and 2013, locations were selected per ZTV M 02 protocol [26]. According to the Kentucky method, measurements are to be performed in the first third of the length of the road section on which RMs were applied by one application team in one day. In the first third of the section, a single zone of 500 m is to be evaluated with 10 measurements (each in triplicate) 50 m apart. The main disadvantage of this protocol is that the test is performed only on a small section of the application job, leading to potential misrepresentation. This weakness was alleviated through using the procedure described in ZTV M 02: the number of measuring sections depends on the length of longitudinal markings and the area of other markings, as shown in Table 1 and schematically visualised in Figure 1. The measurement segments, all of them 100 m long, are selected randomly throughout the marked section, and data are collected from five locations 25 m apart. For dashed markings, a length of 10 lines is to represent a section, and the measurements are allocated in the middle point of every second line in that section. In relation to the Kentucky method, the randomness of measurement sections helps to create a more representative picture of R_L for the entire length of the marked road [27].

Table 1. Number of measurement sections according to ZTV M 02.

Length of Longitudinal Lines Applied in One Day [km]	Area of the Other Markings Applied in One Day [m^2]	Number of Measurement Sections
<1	<120	1
1–5	120–600	2
>5–10	>600–1200	3
>10	>1200	4

Nowadays, dynamic testing, with a retroreflectometer installed on a moving vehicle, is more frequently used; much more accurate overall assessment can be obtained [27]. During the dynamic testing, R_L is measured almost continuously (raw data point collected every two milliseconds) and then averaged per 50 m sections (other section lengths are also possible) during normal driving with speeds up to 130 km/h. While the main advantages are continuity of data collection and the absence of any obstruction to vehicular traffic, measurements of Qd are not possible because uniform illumination cannot be obtained. A vehicle with the retroreflectometer side-mounted to measure the centre line is shown in Figure 2.

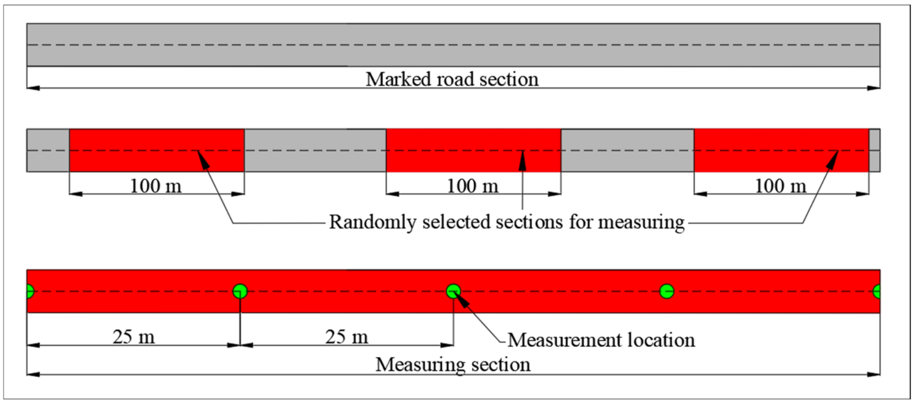

Figure 1. Location of sections for measurements according to ZTV M 02.

Figure 2. Test vehicle with side-mounted retroreflectometer.

2.2. *R_L and Qd Requirements*

The requirements for R_L and Qd in Croatia are listed in Table 2 [28]; there is no differentiation between various locations. The measurements of new or renewed RMs are to be taken between 30 and 60 days after their application, when it is expected that the maximum R_L is achieved [29]. There is no defined time when RMs are to be classified as used; however, mutual understanding is that the term applies after winter exposure. For all of the cases presented herein, Type I materials (paints, applied at layers < 1 mm wet film) were utilised. Note that the Type I and Type II classifications per Croatian requirements [28] do not match the definitions set in standard EN 1436 [22], where the types are differentiated not based on layer thickness or kind of material but on visibility under the conditions of wetness: RMs of Type I are those 'that do not necessarily have special properties intended to enhance the retroreflection in wet or rainy conditions' and Type II are those 'with special properties intended to enhance the retroreflection in wet or rainy conditions'.

Table 2. Requirements for R_L and Qd [mcd/m^2/lx] of RMs in Croatia.

Marking Type	Type I (Paints—Thin Layer Applications)				Type II (Thermoplastic, Cold Plastic, Tape—Thick Layer Applications)			
Line Condition	**New or Renewed**		**Used**		**New or Renewed**		**Used**	
Parameter	R_L	Qd	R_L	Qd	R_L	Qd	R_L	Qd
Minimum required value	200	130	100	100	300	160	150	130
Verification range [(a)]	180–220	110–150	90–110	90–110	270–330	140–180	130–170	110–150

[(a)] If the average R_L or Qd was within the verification range, confirmation measurements were to be performed. If values were below the verification range, the marking job was to be rejected. The verification range was abandoned in 2019.

2.3. Measurement Locations

The data presented herein are limited to six bidirectional single carriageway roads in Croatia; the traffic load (per official counts) at the assessed segments and the lengths of analysed longitudinal markings are listed in Table 3. Measurements were taken at road sections that were renewed regardless of their location in towns, villages, or in rural areas. Data for only longitudinal markings (edge and centre lines) are provided because of the different materials and renewal schedules for some of the transverse markings and pedestrian crossing 'zebra' stripes. For subsequent data presentation, it is assumed that the right edge line was on the right in the direction of the increasing kilometre marks. Static measurements were taken in 4 sections, between 30 and 60 days after application, in the same locations for both the Kentucky and the ZTV M 02 methods. Since 2014, R_L was assessed using the dynamic procedure (Qd was not measured) and comprised the entire line markings' lengths. For clarity of presentation, results from all lines measured dynamically were combined because the analysis of raw data indicated no meaningful differences. Importantly, the dynamic testing was conducted between 30 and 150 days after the renewal of the RMs per modified request from the road administrator that departed from the standard requirements. Such an occasionally prolonged period between the renewal job and measurements could have in some cases affected the outcome. In total, the static measurements were taken at 840 points (10–20 locations per line per road per annum). The total examined line length using a dynamic retroreflectometer was 2867 km (circa 930 km of roads—3 lines per road, with some sections marked with a centre double line).

Table 3. Selected information about the roads with the analysed RMs.

Road	Analysed Line Lengths [km] [(a)]	Annually Average Daily Traffic (AADT)		
		Light Vehicles	**Heavy Vehicles**	**Weight-Adjusted AADT [(b)]**
D36	33–49	3963	422	6917
D55	40–48	5228	486	8630
D30	59–72	5550	581	9617
D37	26–36	4743	546	8565
D7	80–91	5831	614	10,129
D2	84–87	3983	550	7833

[(a)] Length variations of the analysed RMs were due to the different lengths of renewals in particular years, exclusion of sections undergoing construction, regions obscured from dynamic testing by stopped or overtaken vehicles, etc. [(b)] Weight adjustment per standard ONR 22440-1 [30].

3. Results

3.1. Static Measurements of R_L and Qd

The average R_L values for RMs applied at different roads, from the year-by-year testing at the same spots between 2003 and 2013, are shown in Table 4, Qd values are in Table 5, and their averages are visualised in Figure 3. For data presentation clarity, standard deviations are omitted. Consistently, in all of the cases, increases were measured not only in the number of accepted jobs but also in the measured values, from an average

R_L of 200 to 293 mcd/m^2/lx (an increase of 46%) and from an average Qd of 145 to 177 mcd/m^2/lx (an increase of 22%). The levelling off of the values can be explained by approaching the maximum achievable with the utilised materials. Higher R_L values can be obtained only with GBs having an increased refractive index; the use of such GBs and the advantages that they bring, particularly in combination with the highest quality paints, were discussed by us elsewhere [7]. In the case of the centre line, which exhibited the highest average increase in R_L, one might also consider the effects of directionality [31]; however, for the cases studied herein, the R_L of the centre line was always measured in the direction of application of the markings.

Table 4. Retroreflectivity (R_L) [mcd/m^2/lx]; results from static testing 2003–2013.

Road	Line	Year											R_L Change 2003–2013
		2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	
D36	Centre	142	223	242	252	261	271	272	285	290	305	308	117%
	Right edge	189	204	237	247	253	260	264	268	286	288	290	54%
	Left edge	164	235	241	248	251	260	262	267	281	288	289	76%
D30	Centre	198	252	262	266	278	286	285	296	311	325	326	64%
	Right edge	256	258	262	266	269	262	284	297	298	301	302	18%
	Left edge	208	216	225	238	256	267	266	276	321	312	322	55%
D37	Centre	188	198	248	294	210	288	270	251	312	308	315	68%
	Right edge	216	230	235	241	250	219	268	271	256	267	272	26%
	Left edge	240	256	252	256	264	266	282	294	292	288	292	22%
D7	Centre	189	219	228	289	290	295	300	307	313	310	318	69%
	Right edge	220	262	280	263	267	250	271	279	285	288	290	32%
	Left edge	239	255	264	306	272	232	278	285	293	290	294	23%
D2	Centre	190	221	247	293	279	270	281	287	269	293	298	57%
	Right edge	211	257	271	272	278	245	262	267	266	280	283	34%
	Left edge	190	226	290	273	273	261	269	271	273	276	277	46%
D55	Centre	201	244	250	255	261	261	285	282	271	291	289	43%
	Right edge	187	207	236	235	248	224	254	262	267	265	267	43%
	Left edge	176	195	231	233	241	244	239	244	246	248	239	36%
Percentage passing (R_L > 220 mcd/m^2/lx)		22%	67%	100%	100%	94%	94%	100%	100%	100%	100%	100%	–
Percentage for verification (180 ≤ R_L ≤ 220 mcd/m^2/lx)		61%	33%	0%	0%	6%	6%	0%	0%	0%	0%	0%	–
Percentage failing (R_L < 180 mcd/m^2/lx)		17%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	–
Average R_L		200	231	250	263	261	259	272	277	285	290	293	46%

Table 5. Daytime visibility (Qd) [mcd/m^2/lx]; results from static testing 2003–2013.

Road	Line	Year											Qd Change 2003–2013
		2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	
D36	Centre	155	157	159	163	167	171	171	176	169	169	167	8%
	Right edge	149	154	149	158	161	166	167	169	180	178	181	21%
	Left edge	154	163	144	150	155	161	169	173	169	176	178	16%
D30	Centre	149	154	153	160	167	169	170	162	160	176	176	18%
	Right edge	138	153	154	157	153	145	156	168	172	170	175	27%
	Left edge	139	162	164	167	170	150	158	159	168	166	168	21%
D37	Centre	156	148	140	167	169	172	141	168	167	169	170	9%
	Right edge	137	145	116	144	146	120	150	153	175	171	174	27%
	Left edge	110	119	129	143	149	152	155	152	170	178	180	63%
D7	Centre	138	139	139	158	162	178	169	170	172	171	174	27%
	Right edge	144	195	155	146	153	166	164	166	167	169	181	26%
	Left edge	168	157	146	161	168	181	174	178	179	177	180	8%
D2	Centre	140	141	134	154	169	165	168	165	162	168	169	21%
	Right edge	135	185	141	141	156	167	165	169	178	175	173	27%
	Left edge	134	161	148	147	160	169	170	164	173	171	174	30%
D55	Centre	157	162	162	165	171	181	187	194	203	190	196	25%
	Right edge	137	147	152	159	164	165	180	185	188	178	182	33%
	Left edge	164	180	162	144	158	169	180	177	187	173	179	9%
Percentage passing (Qd > 130 mcd/m^2/lx)		33%	67%	44%	67%	89%	83%	94%	100%	100%	100%	100%	–
Percentage for verification (110 ≤ Qd ≤ 130 mcd/m^2/lx) [(a)]		67%	33%	56%	33%	11%	17%	6%	0%	0%	0%	0%	–
Average Qd		145	157	147	155	161	164	166	170	174	174	177	22%

[(a)] Failures (i.e., Qd < 110 mcd/m^2/lx) were not recorded.

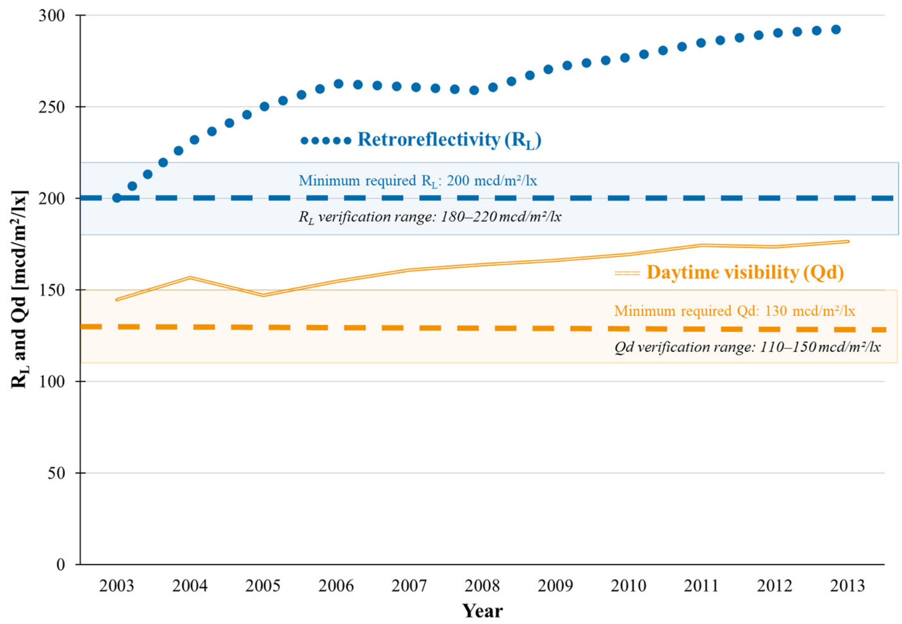

Figure 3. Average year-to-year R_L and Qd of RMs tested at spot locations.

To check whether the measured differences were statistically significant, analyses of variance (ANOVA) using Bonferroni correction with the confidence level set at 0.05 were performed for both R_L and Qd, despite the drawback of relatively small sample size. For both variables, ANOVA's sphericity assumption was violated (Mauchly's $p < 0.005$), so Greenhouse–Geisser correction was used. Overall, a within-subject test demonstrated statistically significant differences over the years in both R_L [F (3.401, 57.817) = 51.011, $p < 0.005$, $\eta^2 = 0.750$)] and Qd [F (3.187, 54.177) = 21.985, $p < 0.005$, $\eta^2 = 0.564$)].

3.2. Dynamic Testing of R_L

With the development of dependable equipment for the dynamic testing of R_L, static measurements were abandoned as less reliable, more labour-intensive, and associated with hazard to the measurement team. The results from the dynamic testing conducted at the same roads between 2015 and 2022 are shown in Table 6. Even though the verification range was abandoned in 2019, the collected data were split into bins that included it. Measurements were not necessarily taken 30–60 days after renewal but rather in autumn; hence, the RMs were renewed, but the period they were in service could reach even 5 months. Since dynamic testing permits for continuous measurements, data are shown for the number of kilometres of each R_L range. The average full acceptance rate (i.e., $R_L > 220$ mcd/m^2/lx) and the acceptance ranges for individual roads are charted in Figure 4, which should be compared with the 100% acceptance that was measured statically at spot locations (Cf. Figure 3). Amongst interesting observations, one should note a meaningful decline in R_L that occurred in 2017–2018 and again in 2022 with only 62–66% average distances for all roads exceeding the acceptance level. The average R_L decreased from >290 mcd/m^2/lx measured in 2012, 2013, and 2016 to only 240 mcd/m^2/lx in 2022. The measured R_L values were not changing systematically and varied between the roads—we cannot provide a tenable explanation at present. These results may indicate, amongst other possibilities, (1) the lack of systematic correlation between R_L measured at spot locations and at the entire marked lines, (2) poor workmanship, (3) lower quality of materials, (4) adverse effects during the measurements, and/or (5) different periods between the application and evaluation—exact reasons for R_L values lower than were measured previously remain unknown.

Table 6. Results from dynamic testing of R_L between 2015 and 2022.

Road	Year	2015	2016	2017	2018	2019	2020	2021	2022	Multi-Year Average
D36	Distance R_L < 180 mcd/m^2/lx	5.70 km (17.4%)	2.30 km (5.0%)	22.05 km (47.7%)	29.65 km (62.0%)	4.15 km (8.7%)	6.55 km (13.6%)	1.45 km (2.9%)	15.45 km (31.8%)	10.91 km (24%)
	Distance 180 ≤ R_L ≤ 220 mcd/m^2/lx	6.30 km (19.2%)	2.75 km (6.0%)	12.45 km (26.9%)	7.60 km (15.9%)	4.85 km (10.1%)	5.65 km (11.8%)	2.50 km (5.2%)	6.75 km (13.9%)	6.1 km (14%)
	Distance R_L > 220 mcd/m^2/lx	20.80 km (63.4%)	41.10 km (89.0%)	11.75 km (25.4%)	10.55 km (22.1%)	38.95 km (81.2%)	35.70 km (74.6%)	44.50 km (91.9%)	26.35 km (54.3%)	28.71 km (63%)
	Average R_L [mcd/m^2/lx]	242	264	184	163	269	274	319	215	241
D30	Distance R_L < 180 mcd/m^2/lx	3.80 km (6.4%)	3.40 km (5.7%)	14.00 km (23.5%)	11.60 km (19.5%)	3.15 km (5.4%)	12.85 km (21.2%)	2.30 km (3.8%)	19.00 km (31.6%)	8.76 km (15%)
	Distance 180 ≤ R_L ≤ 220 mcd/m^2/lx	9.35 km (15.7%)	11.45 km (19.2%)	20.55 km (34.5%)	17.40 km (29.2%)	9.35 km (16.1%)	8.55 km (14.1%)	2.00 km (3.3%)	3.25 km (5.4%)	10.23 km (17%)
	Distance R_L > 220 mcd/m^2/lx	46.30 km (77.9%)	44.65 km (75.1%)	25.05 km (42.0%)	30.65 km (51.3%)	45.50 km (78.5%)	39.00 km (64.7%)	56.40 km (92.9%)	37.85 km (63.0%)	40.67 km (68%)
	Average R_L [mcd/m^2/lx]	262	254	212	225	282	249	315	250	256
D2	Distance R_L < 180 mcd/m^2/lx	5.50 km (6.4%)	7.30 km (8.6%)	2.25 km (2.7%)	0.75 km (0.9%)	0.45 km (0.5%)	12.15 km (14.4%)	4.05 km (4.7%)	4.90 km (5.7%)	4.66 km (6%)
	Distance 180 ≤ R_L ≤220 mcd/m^2/lx	7.25 km (8.5%)	11.40 km (13.4%)	4.15 km (4.9%)	1.95 km (2.3%)	1.30 km (1.5%)	12.85 km (15.2%)	5.45 km (6.4%)	8.80 km (10.4%)	6.64 km (8%)
	Distance R_L > 220 mcd/m^2/lx	72.70 km (85.1%)	66.15 km (78.0%)	78.65 km (92.4%)	81.55 km (96.8%)	83.15 km (98.0%)	59.05 km (70.4%)	76.15 km (88.9%)	71.35 km (83.9%)	73.59 km (87%)
	Average R_L [mcd/m^2/lx]	258	260	330	310	307	240	298	292	287
D7	Distance R_L < 180 mcd/m^2/lx	3.50 km (3.9%)	0.25 km (0.3%)	0.15 km (0.2%)	5.65 km (6.4%)	3.00 km (3.4%)	2.35 km (2.5%)	37.80 km (42.1%)	21.75 km (24.1%)	9.3 km (10%)
	Distance 180 ≤ R_L ≤220 mcd/m^2/lx	5.70 km (6.3%)	0.45 km (0.5%)	1.10 km (1.2%)	19.90 km (22.4%)	27.65 km (31.0%)	11.55 km (12.7%)	22.70 km (25.3%)	35.90 km (39.7%)	15.61 km (17%)
	Distance R_L > 220 mcd/m^2/lx	81.0 km (89.8%)	89.60 km (99.2%)	88.35 km (98.6%)	63.15 km (71.2%)	58.30 km (65.6%)	76.75 km (84.8%)	29.35 km (32.6%)	32.70 km (36.2%)	64.9 km (72%)
	Average R_L [mcd/m^2/lx]	281	408	333	240	234	264	193	205	270
D37	Distance R_L < 180 mcd/m^2/lx	8.95 km (26.8%)	7.00 km (21.0%)	12.60 km (37.5%)	7.50 km (30.2%)	6.60 km (19.1%)	7.60 km (23.1%)	3.00 km (9.1%)	5.55 km (16.5%)	7.35 km (23%)
	Distance 180 ≤ R_L ≤ 220 mcd/m^2/lx	9.30 km (27.8%)	14.45 km (43.3%)	11.20 km (33.3%)	9.35 km (37.7%)	3.20 km (9.2%)	6.10 km (18.5%)	2.45 km (7.5%)	7.50 km (22.3%)	7.94 km (25%)
	Distance R_L > 220 mcd/m^2/lx	15.15 km (45.4%)	11.95 km (35.7%)	9.80 km (29.2%)	7.95 km (32.1%)	24.85 km (71.7%)	19.10 km (58.4%)	27.40 km (83.4%)	20.60 km (61.2%)	17.1 km (52%)
	Average R_L [mcd/m^2/lx]	208	219	172	199	268	235	293	227	228
D55	Distance R_L < 180 mcd/m^2/lx	0.95 km (2.0%)	1.25 km (2.7%)	3.05 km (6.5%)	0.85 km (1.8%)	1.10 km (2.3%)	0.35 km (0.9%)	2.55 km (5.4%)	3.35 km (7.2%)	1.68 km (4%)
	Distance 180 ≤ R_L ≤220 mcd/m^2/lx	3.45 km (7.4%)	3.20 km (6.9%)	3.90 km (8.4%)	6.50 km (13.9%)	4.00 km (8.6%)	3.80 km (9.5%)	4.05 km (8.6%)	7.15 km (15.3%)	4.5 km (10%)
	Distance R_L > 220 mcd/m^2/lx	42.45 km (90.6%)	42.25 km (90.4%)	39.70 km (85.1%)	39.25 km (84.3%)	41.35 km (89.1%)	35.55 km (89.6%)	40.60 km (86.0%)	36.20 km (77.5%)	39.66 km (87%)
	Average R_L [mcd/m^2/lx]	282	347	329	311	260	261	268	249	288
Averages for all roads	Distance R_L < 180 mcd/m^2/lx	28.4 km (8%)	21.5 km (6%)	54.1 km (15%)	56 km (16%)	18.4 km (5%)	41.8 km (12%)	51.1 km (14%)	70 km (19%)	42.68 km (12%)
	Distance 180 ≤ R_L ≤220 mcd/m^2/lx	41.3 km (12%)	43.7 km (12%)	53.3 km (15%)	62.7 km (18%)	50.3 km (14%)	48.5 km (14%)	39.1 km (11%)	69.3 km (19%)	51.05 km (14%)
	Distance R_L > 220 mcd/m^2/lx	278.4 km (80%)	295.7 km (82%)	253.3 km (70%)	233.1 km (66%)	292.1 km (81%)	265.1 km (75%)	274.4 km (75%)	225 km (62%)	264.65 km (74%)
	Average R_L [mcd/m^2/lx]	256	292	260	241	270	254	281	240	262

One of the implications of this study is the connection between the R_L values of the RMs and the potential emissions of microplastics from them. RMs were initially reported as a meaningful source of microplastic pollution; nonetheless, while theoretical ponderings indicated high levels of emissions, field research indicated that erosion (i.e., the complete abrasion) of RMs occurred quite seldom and was associated with extraordinary usage conditions or with grossly negligent maintenance, and the protective role of drop-on GBs, which simultaneously deliver R_L, was emphasised [5]; hence, it was reasoned that unless the R_L values decreased below a threshold level, no meaningful abrasion and thus emission of microplastics would be taking place. So far, no reliable report related to abrasion of RMs at longitudinal lines was published.

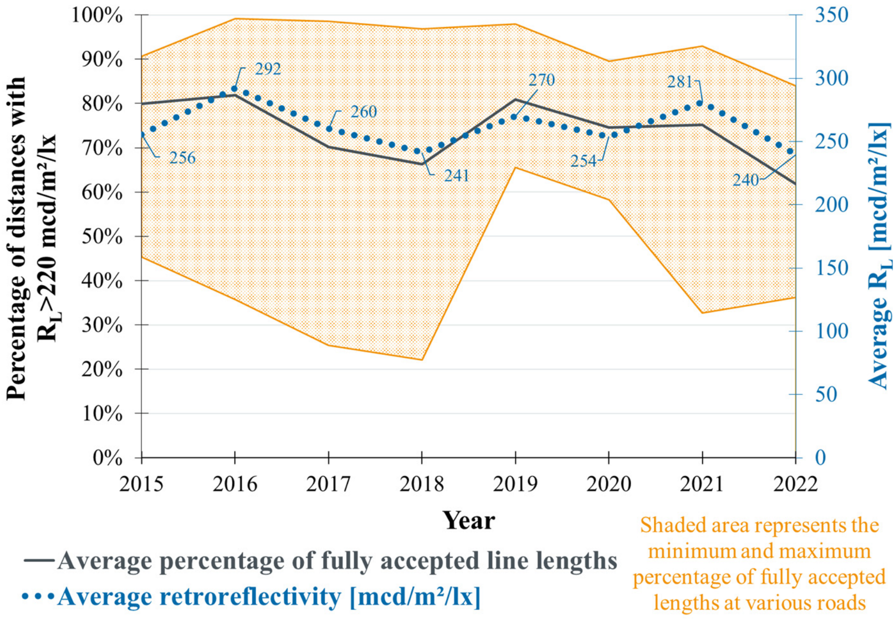

Figure 4. Line lengths of RMs with $R_L > 220$ mcd/m^2/lx (full acceptance range) and average R_L.

For this study, we assumed, based on professional experiences and limited field studies [5], that drop-on GBs must be present and protect the underlaying paint layer if R_L values of >100 mcd/m^2/lx were recorded. Nonetheless, cautions related to the possibility of damage to the GBs instead of their extraction from the film must be heeded [10]. Such low R_L values, below the minimum requirement for used markings (Cf. Table 2), were found to be present also in this study of renewed RMs; data for the distances of such sections are provided in Table 7 (note that these distances were included in Table 6 as belonging to $R_L < 180$ mcd/m^2/lx). The distances were very short indeed: out of the total tested 2867 km of lines, $R_L < 100$ mcd/m^2/lx was measured at only 35.0 km (i.e., 1.22%). However, one should note that the majority of the grossly substandard R_L was measured at D36, which is a curvy road through a hilly region (the low R_L was measured mostly at the inner line markings at curves) and at route D30, which is undergoing a road construction (hence, excessive damage due to heavy vehicles and dirt accumulation was occurring in some sections). If the curvy route D36 and route D30 were to be excluded, a substandard R_L would apply to only 9.8 km out of the measured 2024 km (i.e., 0.48% of the total distance). However, that is a notable length of RMs not meeting even the minimum R_L requirements especially because the period before renewal and measurements was not grossly excessive. It is very likely that the RMs at the curves were exposed to so many vehicle passes that not only the point of the highest R_L was missed but also major deterioration took place. This important issue may be associated with the modelling of the deterioration of RMs; various models were presented [20,32,33], including one based on the Croatian dataset [34].

Nonetheless, regarding microplastic pollution, one cannot consider that RMs with R_L values of <100 mcd/m^2/lx *would* contribute, but only *could*—this threshold value should be treated as an indicator of the oncoming abrasion. Importantly, visual assessment of the associated representative images (taken by the dynamic retroreflectometer equipment) indicated no meaningful regions with erosion (i.e., complete abrasion). Analysis of the other available dynamic R_L testing data and associated images, particularly from measurements taken before renewals, is required to clarify the issue of RMs erosion and abrasion at longitudinal lines.

Table 7. Distances of RMs with grossly substandard retroreflectivity (R_L < 100 mcd/m^2/lx).

Year	2015	2016	2017	2018	2019	2020	2021	2022	Range
D36	2.25 km (6.86%)	0.05 km (0.11%)	0.85 km (1.84%)	7.80 km (16.32%)	0.05 km (0.10%)	0.05 km (0.10%)	<0.05 km	2.60 km (5.36%)	0.00–7.80 km (0.00–16.32%)
D30	0.40 km (0.67%)	0.05 km (0.08%)	0.15 km (0.25%)	0.30 km (0.50%)	0.15 km (0.26%)	3.50 km (5.79%)	0.70 km (1.15%)	6.30 km (10.48%)	0.05–6.30 km (0.08–10.48%)
D2	0.25 km (0.29%)	<0.05 km	0.05 km (0.06%)	<0.05 km	<0.05 km	1.30 km (1.55%)	0.45 km (0.53%)	1.30 km (1.53%)	0.00–1.30 km (0.00–1.55%)
D7	0.30 km (0.33%)	0.05 km (0.06%)	<0.05 km	0.10 km (0.11%)	<0.05 km	<0.05 km	0.35 km (0.39%)	<0.05 km	0.00–0.35 km (0.00–0.39%)
D37	1.00 km (2.99%)	0.10 km (0.30%)	1.00 km (2.98%)	0.50 km (2.02%)	0.75 km (2.16%)	0.55 km (1.68%)	0.55 km (1.67%)	1.10 km (3.27%)	0.10–1.10 km (0.30–3.27%)
D55	0.05 km (0.11%)	<0.05 km	<0.05 km	<0.05 km	<0.05 km	0.05 km (0.13%)	<0.05 km	<0.05 km	0.00–0.05 km (0.00–0.13%)

4. Discussion

The initially measured poor performance of the tested RMs was subjectively, but based on the practices observed in the field and unrelated non-systematic testing, attributed to the lack of supervision: the road administrator probably accepted in good faith that all of the work was completed lege artis. Only occasional visual checks were made (personal communication), but without instrumental measurements taken by an independent party, it was not really possible to assure constant quality. Once the policy of checks was implemented, the work quality had to increase because inadequate performance parameters, objectively measured according to established procedures, could become the basis for rejection of the job, thus forcing the contractors to repeat the work at their own expense. In addition, the road administrator could exclude a contractor delivering inadequately completed jobs from future tenders. Whereas there could be other reason for the increase in the jobs' quality than the claimed supervision, it is the simplest and most tenable explanation for the increase in the initially measured properties.

Whereas there was a steady increase in R_L and Qd at the measurement locations after job supervision was enacted, subsequent testing of the entire road stretches using a dynamic retroreflectometer revealed that adequate R_L values could be present at only 22% of the tested line length of some roads. We cannot pinpoint the main reason for such results after the switch to dynamic R_L measurements—while substandard workmanship could be the easiest explanation, there are other equally plausible explanations. The use of the static measurements could be burdened with a systemic error associated with the selection of locations (for example, disregarding curves) and significantly smaller number of data points; this could be a valid explanation even if it seems to contradict previously reported good data correlation [35]. It is also possible that the period between the renewal of the RMs and the testing could be excessive in some cases, so the RMs became worn [10]. An equally tenable explanation was suggested by a representative of a local applicator company (personal communication): the decrease in the quality of paint. Particularly, limiting the content of titanium dioxide pigment, which has a high refractive index that is necessary for obtaining retroreflection [36], could cause a significant decrease in R_L. This could be a valid issue since it was shown that compositional changes to make a paint more environmentally friendly could cause higher long-term emissions due to lower durability. Since all of the tested RMs were renewed, potential effects of lower or higher governmental expenditures could be excluded in these cases.

While the absence of control sections, where R_L would be tested but not reported to the road administrator, may be considered as a weakness of this study, one must note that it would be a futile effort and contrary to good practices. Failure to report such stretches to the road administrator could also be a violation of the laws. Therefore, the authors assume that job quality increase or decrease was uniform regardless of the testing. Amongst research needs, to confirm the results presented herein from the dynamic testing, simultaneous spot testing at the same roads in the same or different locations should be performed.

It has been repeatedly shown by us, based on results from field tests, that the use of high-end materials for RMs would lead to lower long-term costs and simultaneously lower environmental impact because such materials are capable of significantly prolonging the functional service life of RMs [7]. Hence, it was consistently shown that sustainability was tantamount with the durability. Consequently, long-term performance-based contracts for the maintenance of RMs were envisaged as the best solution that would benefit the following simultaneously:

- The road administrators and taxpayers—through lowering the overall expenses;
- The road users—through increased quality and thus better visibility of RMs;
- The applicator companies—through stability of work and guaranteed revenues; and
- The environmental sustainability—through the selection of the most durable materials that were shown to be the least costly in such cases.

From the perspective of environmental protection, the imposition of such contracts could be an example of employing a free market economy in selecting the most efficient and sustainable solutions instead of regulatory actions [37,38]. As a method to further increase the sustainability of RMs, one should additionally propose the use of Type II structured RMs that provide simultaneously much better visibility for drivers, are better recognised by driver assistance systems, and are generally known to be more durable than Type I flat line markings. The utilisation of properly selected GBs could enhance the properties and the sustainability further, particularly through prolonging functional service life [7]. While discussing such possibilities is beyond the scope of this report, one must note that control of the quality of RMs would be necessary. Indeed, the absence of supervision was very likely the chief contributing factor to the reported overall failure of a maintenance contract in North America [39].

Even though there was a reported correlation between R_L and road safety [14,15], it is not possible to positively make such a correlation based on the data provided herein due to a plethora of other factors that could have played a role. Nonetheless, as shown in Table 8 [40], there was a decrease in the number of road accidents, fatalities, and injuries in Croatia between 2003 and 2013 but with their severity increasing. Since 2013, the number of accidents slightly increased, but there was a continuous decrease in the number of fatalities and injuries and their severity. The three-year average fatality rate per distances driven in Croatia remained very high, at 20.0 and 10.4 per 10^9 kilometres travelled, correspondingly for the periods 2010–2012 and 2020–2022, which positions Croatia in the top four out of 25 European Union countries reporting such data, with rates more than twice the average [41]. There is enormous expense associated with vehicular crashes [42]; in Croatia, it was estimated at 0.9–1.5 $\times$ 10^9 euros—approximately 2.3% of the country's gross domestic product [40]. Hence, the use of such a relatively simple and inexpensive safety solution as the maintenance of RMs in good condition appears a good and sustainable investment [43], particularly since it was reported that a better quality of RMs was associated with a higher obedience of traffic rules [44].

Table 8. Road accidents in Croatia.

Year	All Accidents			Fatalities				Injuries			
	Number	Rate per 100,000 Residents	Rate per 100,000 Vehicles	Number	Rate per 100,000 Residents	Rate per 100,000 Vehicles	Severity (a)	Number	Rate per 100,000 Residents	Rate per 100,000 Vehicles	Severity (a)
2003	92,102	2074	5582	701	15.8	42.5	0.76%	26,153	589	1585	28%
2013	34,021	799	1849	368	8.6	20.0	1.08%	15,274	359	830	45%
2023	34,604	898	1822	274	7.1	14.4	0.79%	14,204	368	748	41%
Change 2003–2013	−63%	−61%	−67%	−48%	−46%	−53%	42%	−42%	−39%	−48%	58%
Change 2013–2023	2%	12%	−1%	−26%	−17%	−28%	−27%	−7%	3%	−10%	−9%
Change 2003–2023	−62%	−57%	−67%	−61%	−55%	−66%	4%	−46%	−38%	−53%	45%

(a) For the purpose of this report, severity is defined as the proportion of accidents ending with a fatality or an injury to all accidents. Calculations are not adjusted for accidents with multiple victims.

The outcome of this research resulted in the uncovering knowledge voids that should be filled with new research. Amongst the topics other than mentioned above, we can list the following: (1) the validity of spot measurement methods in predicting the R_L values of the entire marked areas, (2) the exact reasons for substandard R_L at some locations, (3) accurate determination of the maximum achieved R_L under specific traffic loads and with different materials, (4) the possibility of evaluation of R_L under wet conditions as a requirement for the acceptance of jobs where RMs of Type II are demanded, (5) modelling and field research related to the emissions of microplastics from RMs as a function of the R_L decrease, (6) the evaluation of renewal jobs completed by different application crews as a method of pinpointing some of the measured discrepancies, and (7) testing of the used materials in cases of less-than-perfect field performance under laboratory and/or controlled field conditions.

5. Conclusions

In conclusion, to maintain the high initial quality of RMs, supervision is necessary, as was shown based on the presented outcome. Within 10 years of systematic testing at spot locations, significant increases in R_L were measured from 200 mcd/m^2/lx to >290 mcd/m^2/lx; Qd also increased—the renewal jobs reached full acceptance level. Nonetheless, after the switch to dynamic testing of the entire line lengths, meaningfully lower R_L values were measured, with an average that decreased to only 240 mcd/m^2/lx; in some cases, only 22% of the line lengths exceeded the minimum requirement. This decrease, not systematic but rather randomly occurring at different roads and different times, remains troublesome as it may indicate either the inadequacy of prior testing procedures or emerging issues like a decrease in the materials quality. Amongst other results, one must note that circa 1.22% of the tested total line lengths had $R_L < 100$ mcd/m^2/lx.

Since RMs belong to the basic road safety elements, they should remain well maintained to be visible for drivers under all conditions—road administrators are obliged to do so per statutory requirements. Furthermore, the recent requirement in the European Union for the installation of the Lane Keeping Assistant function in all new vehicles underlines the importance of such maintenance, because properly defined RMs are necessary for the correct functioning of this feature. RMs are a sustainable solution with a very low environmental impact and carbon footprint in comparison with the benefits that they provide, so their appropriate maintenance is in the interest of the entire society.

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