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Materials selection for structured horizontal road markings: financial and environmental case studies



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Abstract

Introduction: On majority of roads, horizontal road markings are essential safety feature that must be periodically renewed to maintain appropriate performance.

Results: The use of a premium road marking system resulted in prolonged the service life as compared to a standard system, which would be financially-neutral in the long term despite much higher unit and initial costs; advantageously, 54% less glass beads and 63% less paint would be required over 10-year life cycle. When these products usage savings are recalculated into raw materials consumption, the premium system would demand about 21% more of titanium dioxide, but that would be offset by approximately 25% reduction in the consumption of acrylic resin and circa 97% reduction in organic solvents usage and emissions.

Conclusions: The results from this analysis can be used by road administrators to select the best systems, by policy makers seeking minimisation of environmental impacts, and by contractors who won performance tenders.

Keywords: Horizontal road markings, Durability, Financial analysis, Sustainability, Road maintenance policy

1 Introduction

Transport belongs to key human activities, necessary for maintaining and development of life quality. Majority of transport is now done in vehicles travelling on paved roads. Traffic density and human inattention can cause majority of accidents, which were reported to be the worldwide leading cause of deaths amongst people 15–29 years old, with economic burden reaching approximately 3% of World's Gross Domestic Product [50]. In 2016 in European Union countries, 25,651 people died and more than 1.4 million were injured in over 1 million of road accidents [28]. Depending on the country, the expenses were estimated at between 0.7 and 3.0 million euro per accident [49]. Therefore, a solution for improved road safety is sought and stressed in various national and international policies [26]. In the recently proposed Third Mobility Package, European Commission recognises the critical importance of pavement markings for both human drivers and for the emerging

technology of automated vehicles [29]: “Member States shall ensure that road markings and road signs are properly designed and maintained in such a way that they can be easily and reliably recognised by both human drivers and vehicles equipped with driver assistance systems or higher levels of automation.”

Horizontal road markings are one of the inexpensive, yet highly effective road safety features, working by establishing travel paths. It was calculated that the financial benefits of their presence approximately sixtyfold exceeded the expenses of their installation and maintenance [38]. However, to maintain their appropriate performance, frequent renewals are required, which are associated with financial and environmental costs. The financial aspect can be critical for road administrators who are spending taxpayers' money and ought to seek maximisation of the benefits. However, environmental perspective has to be included in the decisions, due to the efforts aiming at minimisation of carbon footprint and the necessity for long-term thinking in science and policy [47, 48]. Fortuitously, in the case of the modern solutions for horizontal road markings, it is calculated that the use of most

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environmentally sustainable materials is not associated with additional financial expenditures.

In this article, installation and maintenance of horizontal road markings on motorways shall be assessed from the financial and environmental perspectives. The cases of using standard and premium materials shall be analysed to provide a calculation tool for estimation of long-term financial and environmental burdens. No literature reports that would cover both the initial application of road marking materials and their renewals were found; consequently, this would be the first such assessment.

2 Background

2.1 Horizontal road markings as safety feature

Horizontal road markings are common features seen on almost all modern roads. They serve as guidelines for the drivers, helping them in remaining in their travel paths [17, 22, 44]. In addition, horizontal signalisation in form of solid, dashed, or colourful lines and symbols informs the drivers about oncoming dangers and rules of the road. While they are needed at all times, they are of particular importance at night time [35]. Even though the number of vehicles travelling at night on unlit roads is much lower than during daytime, the number of accidents and their severity are significantly higher as compared to occurring in lit conditions, which is related to lower quantity and quality of available visual cues that can be perceived by drivers in darkness [41]. Research has shown that road markings are then given the most prominent guiding role. Their visibility in vehicles' headlights is achieved by retroreflectivity, expressed as a coefficient of retroreflected luminance (R_L) and measured in $\text{mcd}/\text{m}^2/\text{lx}$ [51]. In a recent field experiment, it was demonstrated that high R_L of road markings under both dry and wet conditions increased driver comfort, particularly for elderly drivers [23]. Even though there might be doubts regarding the correlation of safety benefits and high R_L [31], they were quantified based on statistical analyses of crashes between intersections, on unlit rural roads at night time: an increase of up to 23% in single-vehicle accidents at that conditions could be correlated with a decrease in R_L by $100 \text{ mcd}/\text{m}^2/\text{lx}$ [18]. Hence, it can be imputed that increase in R_L of horizontal road markings can lead to improvement in driving conditions and thus increase in road safety, which would result in increased quality of life and higher mobility. Due to the aforementioned advantages, horizontal road markings, since their first introduction over a century ago, became one of the critical ubiquitous safety features, at present without an alternative.

R_L plays such a critical role that suitability for use and service life of road markings is evaluated by its level; even if other parameters are also measured, it is R_L that in vast majority of cases fails first. Hence, the service life

(i.e. durability) of road marking can be defined as a period or a traffic load when R_L remains above the required level. Typically, R_L above $200 \text{ mcd}/\text{m}^2/\text{lx}$ is required for new white markings, but road administrators permit its drop after usage in many cases even to $100 \text{ mcd}/\text{m}^2/\text{lx}$. Most recent research indicated that a minimum R_L of $150 \text{ mcd}/\text{m}^2/\text{lx}$ should be maintained at all times for all colours [32], which agrees with the recommendation of European Union Road Federation (ERF) [25]. To maintain appropriate R_L for existing road markings, their renewals are required. It appears valuable to limit the frequency of such renewals from the environmental, traffic disruption, and financial perspective.

2.2 Road marking materials

Horizontal road markings must be treated as systems, comprising the base (colour) layer and the retroreflective (glass beads) layer and only co-operation of these two components provides a fully functional system [42]. While the base layer furnishes adhesion to the roadway, colour, surface for retroreflection, and holds glass beads, the retroreflective layer enables retroreflection to occur and simultaneously protects the colour layer. There are numerous road marking materials that can be used, and their selection depends on the specific needs and availability [5].

The cases discussed herein are thick-layer applications of cold plastic and its renewal with thin-layer applications of paints, which is a typical procedure used on heavily-travelled roads in Europe. The binder for cold plastic materials are acrylate monomers and oligomers, which immediately before application are mixed with a peroxide initiator; polymerisation reaction occurs while the materials are already on the road surface and a hard, durable layer is formed. Glass beads are dropped-on and due to a special sizing co-polymerise with the cold plastic. For the initial application on major roads, the cold plastic markings are applied in form of random or regular structures at thicknesses reaching even 3–5 mm, with glass beads dropped on their surface. The main advantages of structured markings are vibroacoustic effect that warns drivers departing their lane, improved water drainage, which leads to improved R_L under wet conditions, and sheltering of some of glass beads from direct action of tyres and snow ploughs, which additionally increases their service life. These features are considered as significant safety enhancers [33]. When the structure remains intact, but the markings lost their R_L , their performance is renewed with thin-layer applications of paint or with sprayed cold plastic. These modern materials are also based on acrylic binders. They are sprayed at thicknesses approximately 0.3–0.4 mm, with glass beads layer dropped on their surface. Because the renewal materials are less durable than the initially applied cold plastic, more frequent subsequent maintenance is

required. Herein, only the case of paints is discussed, because durability data for sprayed cold plastic from field tests is not available.

Whereas cold plastic is considered a solvent-less material, paints always contain solvents, which are emitted to the atmosphere, where they can contribute to the formation of tropospheric ozone [8, 12]. Whereas the emissions of organic solvents from waterborne paints are very low and usually do not exceed 2%, solventborne paints in Europe are typically permitted to contain up to 25% of volatile organic compounds and as such can be considered less sustainable.

2.3 Glass beads for road marking

Retroreflection in road markings is achieved because of glass beads, which should be embedded in the colour layer to approximately 60% of their diameter [46]. Typical glass beads used for this purpose are prepared from recycled window glass and thus have refractive index (RI) 1.5. Such glass beads ought to meet the requirements set by norm EN 1423:2012 [30] in terms of roundness, clarity, air inclusions, contents of heavy metals and metalloids, and other properties. This type of glass beads can provide R_L in white paint, under field conditions, of approximately 400 mcd/m²/lx.

Because higher R_L was reported as advantageous [18, 23, 35], a premium type of glass beads was developed and commercialised [7, 13]. The premium beads are reported as being prepared from virgin raw materials in a proprietary process and are characterised by RI increased to 1.6–1.7, very high roundness and exceptional surface quality, minimised air inclusions, and improved resistance to scratching. Combination of these properties permitted for achieving retroreflectivity that can reach even 1000 mcd/m²/lx in the field conditions in white paint. Due to the selected materials and the production cost, the premium glass beads are significantly more expensive than standard. Because increase in RI and improved resistance to scratching was achieved partially by incorporation of titanium dioxide (TiO₂) [43], the premium beads might appear somewhat less environmentally friendly than standard beads that are devoid of TiO₂. However, as shall be demonstrated, their properties can overcome such objection.

2.4 Sustainability of road marking systems

The environmental aspect of every product is especially important, because minimisation of the carbon footprint belongs to the key European Union action items [27]. Appropriate design of products and processes is vital in achieving environmental sustainability, while legislation should support it [37]. The most common and reliable method for estimating environmental sustainability is cradle-to-grave Life Cycle Assessment (LCA) [34].

According to two separate LCA performed according to ISO 14040 protocols [36] on thin layer road marking systems, the main impactor was not the selection of materials, but the overall durability of the systems [8, 20]. While different types of road marking materials were reported as being better or worse in the separate LCA categories, the differences appeared insignificant as long as the same service life was achieved. Based on reported results from field tests, high-performance waterborne road marking paint could be considered as the most sustainable solution because it could furnish a two-year durability whereas an aromatic solvent-containing solventborne paint failed within 6 months [8]. Simultaneously thin-layer cold plastic application was reported as better than a low-end waterborne or a solventborne paint because such paints provided lower service life [20]. These evaluations assumed that standard glass beads would be utilised in both cases.

Sustainability assessment of glass beads has been done on request of the industry [19]. The energy consumption to produce the glass beads was listed as the main impactor, covering approximately 50% of all of the environmental costs. Cullet and other raw materials acquisition was calculated to be the second most important and transport of the glass beads third. Preparation of glass beads from raw materials can be considered as having equal impact because the required energy demand is similar.

3 Methodology

Two cases of the usage of road marking materials are analysed herein. Premium materials are compared with standard materials in terms of service life, costs, and environmental impact. For the assessment, analysed was not a one-time event of road marking application, but their series until the expected roadway surface renovation, which was assumed to be 10 years, as in the LCA [8, 20].

Whereas in some cases it is possible to perform analyses based on theoretical or extrapolated properties, service life of horizontal road markings is preferably tested under the actual usage conditions, in the field, even though there is a plethora of factors affecting their performance. Therefore, the provided results, which are the base of the environmental and financial case studies presented herein, are constructed based on data collected from field tests done in Poland and in Switzerland, at motorways with similar traffic load. Service life was evaluated based on the measured R_L until it dropped below 150 mcd/m²/lx, which is the ERF-recommended minimum value.

To calculate the financial impact of using premium road marking materials, collected were current net sale prices in Poland for standard materials. They were appropriately increased to accommodate higher expenses of premium materials, for which retail prices are not available. The cost of labour and other expenses of the applicator companies were estimated based on the

results from recent road maintenance tenders in Poland. Environmental assessment required evaluation of several publicly-available Safety Data Sheets (SDS) and Technical Data Sheets (TDS) to obtain information about paint and cold plastic composition.

4 Field testing

4.1 Locations and materials

Evaluation of service lives of the two compared road marking systems was done based on measurements of R_L collected by the road authorities or on their request, using a dynamic method that permits for averaging the results over the entire evaluated stretch instead of obtaining spot data. Details about the test fields and used road marking materials are provided in Table 1. Due to various policy limitations, it was not possible to perform a side-by-side evaluation; nonetheless, because of similar traffic loads, road characteristics, and winter climatic conditions, the results are comparable. The materials were applied by local companies that won appropriate tenders, using their established methods, and the only modification was the use of premium glass beads in Switzerland. The brand names of the products used by them were not disclosed; only the basic information related to the type of material was given.

Testing of the renewal systems at these test stretches could not be accomplished so far, but preliminary evaluation at another road is being done and there is sufficient field data from other test fields to justly assume their service life, depending on the utilised materials.

4.2 Results of field evaluations

Results from these field tests, provided in Table 2, were already presented and discussed elsewhere [7, 14]. Herein, they are given for the purpose of deeper environmental and financial analyses. Since the minimum requirements in Switzerland and in Poland are different and there is a dissociation between Polish practice and legislature, the recent ERF recommendation of $150 \text{ mcd/m}^2/\text{lx}$ was assumed as the minimum acceptable R_L for both test fields. Even though in previous work the service life was provided calculated number of per weight-adjusted vehicle passes to justly compare outcomes from roads

carrying different traffic load, durability for calculations presented herein is more conveniently expressed in years because of similar traffic loads and climatic conditions.

With the premium system, not only the initial R_L was higher than in the case of standard system, but also service life was disproportionately longer. Whereas standard system failed in 2 years (even if road administrator in Poland permitted for further drop in R_L and usage for 3 years), the premium system after the same period and comparable number of weight-adjusted vehicle passes exhibited R_L higher than measured in newly applied standard system. The failure points given in Table 2 were estimated based on exponential line fit through the collected data points, until R_L drop to $150 \text{ mcd/m}^2/\text{lx}$ was to occur. Because of climatic conditions not allowing for road marking work during winter, durability is given herein in full years.

While longer service life of the premium cold plastic system was confirmed, the possibility of achieving a two-year durability for renewal is not firmly established. Nonetheless, preliminary results from a secondary road, with much lesser vehicular traffic, support the hypothesis that in such a case also a selection of premium materials (high-performance waterborne paint reflectorised with premium glass beads instead of a typical solvent-borne paint and standard glass beads) can furnish a two-year durability [16]. These preliminary results agree with prior field research, in which both longitudinal and transverse line arrangement was used to demonstrate that even with high vehicular traffic encroaching on the markings, the use of premium materials permitted for obtaining multi-year durability [10, 11]. It must be simultaneously noted as a caution that the same premium thin-layer road marking system that easily survived 2 years in Croatia, even in a transverse line arrangement, when tried in Poland has failed after winter, which was due to excessive snow removal operations [15].

5 Financial and environmental analyses

The use of premium system resulted in markings that were capable of withstanding the highest traffic load (Cf. Table 2). However, critical issue for the road

Table 1 Characteristics of the test stretches and applied materials

Test field	Road, speed limit	Stretch length [km]	AADT ^a			Base layer, applied mass	Glass beads, drop-on mass	Minimum R_L [mcd/m ² /lx]	
			All	Heavy	Weight-adjusted			Initial	Used
Switzerland	T5, 120 km/h	0.4	34,965	1573	45,976	Premium cold plastic, 2.2 kg/m ²	Premium, 0.45 kg/m ²	350	250
Poland	A4, 140 km/h	12.9	18,041	3703	43,962	Cold plastic, 2.5 kg/m ²	Standard, 0.35 kg/m ²	250 ^b (200 ^c)	100 ^b (200 ^c)

^aAnnually Adjusted Daily Traffic (AADT). Weight-adjusted AADT is calculated per Austrian standard ONR 22440-1 [3]

^bMinimum R_L required by the road administrator in tenders

^cMinimum R_L according to Polish law [24]

Table 2 Results from field tests

Test field	Switzerland		Poland	
	Premium		Standard	
Period	Vehicle passes ^a	R_L [mcd/m ² /lx] ^b	Vehicle passes ^a	R_L [mcd/m ² /lx] ^b
Initial	2.6	952 (148)	1.0	421 (74)
1 year	11.6	543 (158)	7.9	n/a
2 years	18.5	532 (176)	16.3	153 (49)
3 years	27.6	433 (109)	25.2	117 (45)
4 years	36.3	315 (71)	–	–
Failure estimate ($R_L < 150$ mcd/m ² /lx)	5 years (68 million weight-adjusted vehicle passes per carriageway)		2 years (16 million weight-adjusted vehicle passes per carriageway)	

^aNumber of weight-adjusted vehicular passes per carriageway, in millions

^bAverage for the test area for all lines (edges and lane-division), standard deviations provided in parentheses

administrators, and indirectly for the society, is financing of such materials and applications. Hence, the costs of materials and application are examined. The analysis is then extended to the marking materials and raw materials consumption, which should directly translate to environmental benefits and is equally important. In both cases, a 10-year life cycle of road surface would be utilised, which can be expected at a motorway and is a standard in LCA. A unit of 1 m² of painted surface, regardless of its location within the roadway, was assumed for uniformity.

5.1 Financial assessment

Exact costing of road marking application and maintenance remain unknown because it depends on complex relations between manufacturers and applicators. The materials are seldom purchased on a commodity market, but directly from manufacturers and at prices depending on quantities and business associations. In addition, price volatility of both the materials and labour add to the uncertainty, notwithstanding the regional differences due to policy, taxation, transport, and other factors. It is not really possible to obtain exact values from the road administrators, either, because in tenders there are frequently bundled additional services not necessarily related to the road markings and because applicator companies may have dissimilar costing structures. Therefore, values provided below have to be considered only as a general guideline and as such burdened with error that is difficult to estimate.

The cost data was obtained through queries to 25 companies and re-sellers involved in the business of road marking in Poland, out of whom 15 responded. The enquiry was for 1 t of each material and its application. The prices for premium materials were roughly estimated, based on previous indications. Conversion from Polish zloty (PLN) to euro (EUR) was done per average exchange rate from 2018, as published by Polish National Bank [39]. Results of the query are shown in Table 3. It must be

underlined that in other countries these prices may vary greatly. In addition, it is very likely that these prices would drop very significantly for the deliveries of larger quantities; nonetheless, they can be used as an indication, not affecting the overall picture and expense ratios.

The results of financial analysis is presented in Table 4, with the assumptions of durabilities of cold plastic systems reported in Table 2 and prices given in Table 3. The scenarios include additionally the road marking renewal with standard system (solventborne paint reflectorised with standard glass beads, furnishing one-year service life) and with premium system (high-performance waterborne paint reflectorised with premium glass beads, furnishing two-year service life). Usage of materials was appropriately adjusted to reflect the actual application data provided in Table 1.

The analysis shown in Table 4 clearly demonstrates that extended durability of premium road marking systems does not can translate to higher long-term costs despite much higher initial expense and assumed increased labour costs. The least expensive solution for the initial application is the use of premium cold plastic system furnishing extended durability – savings of about 35% can be realised. The same does not hold true for renewal systems if one assumes the very high cost of

Table 3 Estimated costs (prices in EUR/kg) of selected road marking materials and labour in Poland

Material	Standard materials			Premium materials ^a
	Low	Average	High	
Cold plastic ^b	1.85	2.25	3.03	3.03
Paint ^c	1.50	1.72	2.07	2.59
Glass beads	0.43	0.58	0.80	6.63
Labour – cold plastic ^d	0.58	0.85	1.15	1.15
Labour – paint ^d	0.46	0.49	0.57	0.57

^aPrice estimate

^bIncludes appropriate quantity of peroxide initiator

^cToluene-containing paint as standard material and waterborne high-performance paint as premium material

^dIncludes labour, amortisation, profit, and other applicator costs

Table 4 Cost analysis for premium and standard systems, including renewals

Initial application system		Standard	Premium		
Cold plastic	Applied quantity [kg/m ²]	2.5	2.2		
	Price [EUR/kg]	2.25	3.03		
	Price [EUR/m ²]	5.63	6.66		
Glass beads	Applied quantity [kg/m ²]	0.35	0.45		
	Price [EUR/kg]	0.58	6.63		
	Price [EUR/m ²]	0.20	2.98		
Materials cost [EUR/m ²]		5.83	9.64		
Labour [EUR/m ²] ^a		0.85	1.15		
Application cost [EUR/m ²]		6.68	10.79		
Durability [years]		2	5		
Application cost per year [EUR/m ²]		3.34	2.16		
Renewal systems		Standard	Premium	Standard	Premium
Paint	Applied quantity [kg/m ²]	0.5	0.5	0.5	0.5
	Price [EUR/kg]	1.72	2.59	1.72	2.59
	Price [EUR/m ²]	0.86	1.29	0.86	1.29
Glass beads	Applied quantity [kg/m ²]	0.4	0.4	0.4	0.4
	Price [EUR/kg]	0.58	6.63	0.58	6.63
	Price [EUR/m ²]	0.23	2.65	0.23	2.65
Materials cost per renewal [EUR/m ²]		1.09	3.95	1.09	3.95
Labour per renewal [EUR/m ²] ^a		0.50	0.57	0.50	0.57
Renewal cost [EUR/m ² /event]		1.59	4.52	1.59	4.52
Durability of renewal system [years]		1	2	1	2
Number of renewals per 10 years		8	4	5	3
Total renewals costs [EUR/m ²]		12.74	18.06	7.96	13.55
Total cost [EUR/10 years/m ²]		16.08	21.40	10.12	15.71

^aIncludes labour, amortisation, profit, and other applicator costs

premium glass beads and other price increases. However, combination of the initial application with premium system and subsequent renewals also with premium materials would be cost-neutral (saving per decade of approximately 0.37 EUR/m²). Whereas the calculations show that the financial savings could be maximised with the use of initial premium system and then subsequent standard systems renewals, one must consider that it is due only to the price of premium glass beads and premium waterborne road marking paint. Should their price drop, which is very likely in case of increased demand, their utilisation would become most advantageous in direct costs as well. Price volatility is not included in the calculations, even though it could play a profound role. Similarly, additional costs associated with storage and transportation of solventborne paints, which due to flammability require special procedures, are not included in the calculations.

5.2 Environmental assessment

Whereas the exact composition of road marking materials remains proprietary, contents of certain key ingredients

were estimated based on disclosures done in SDS, TDS, and publicly-available certificates. Amongst the components, the most important role from the perspective of LCA play TiO₂, the solvents, the resin (which was herein assumed to be solely acrylic), and the glass beads. Fillers, like calcium carbonate, do not contribute much, because they do not require meaningful processing and are broadly available. Additives, even if they were to be relatively environmentally harmful, are incorporated in small quantities and as such can be ignored for the purpose of this analysis.

In Table 5 is provided an estimate of the materials usage for horizontal road markings per 10-year road surface life cycle, assuming the usage per application and durabilities and provided in Table 4 for the cases of standard and premium systems. The calculations demonstrate that with the premium systems there can be 63% lesser consumption of paint and 54% lower usage of glass beads. However, more correct is accounting for increased contents of resin and TiO₂ in the premium systems than is present in the standard. Increased contents

Table 5 Materials usage and emissions, estimates

First application system	Standard (2 years)		Premium (5 years)	
	Standard	Premium	Standard	Premium
Renewal system				
Required renewals per 10 years	8	4	5	3
Materials usage [kg/m ² /10 years]				
Cold plastic	2.5	2.5	2.2	2.2
Paint	4.0	2.0	2.5	1.5
Glass beads	3.6	2.0	2.5	1.7
Titanium dioxide content				
Cold plastic	10.0%	10.0%	12.5%	12.5%
Paint	7.0%	10.0%	7.0%	10.0%
Glass beads	0.0%	13.0%	0.0%	13.0%
Acrylic resin content				
Cold plastic	25.0%	25.0%	30.0%	30.0%
Paint	15.0%	17.5%	15.0%	17.5%
Solvent (VOC) contents of paint	23.0%	2.0%	23.0%	2.0%
Solvents OFP [kg O ₃ /kg paint] ^a	0.24–0.76	0.02	0.24–0.76	0.02
Ingredients usage [kg/m ² /10 years]				
Titanium dioxide	0.53	0.70	0.45	0.64
Acrylates	1.23	0.98	1.04	0.92
Solvents (VOC)	0.92	0.04	0.58	0.03
OFP [kg O ₃ /m ² /10 years] ^a	0.96–3.04	0.04	0.60–1.90	0.03

^aOFP of solventborne paint assumes a range between an aromatic-free paint (like used typically in Austria) and a toluene-containing paint (like used typically in Poland) [12];

of these ingredients are deemed necessary for improved performance measured in the field. In such case, the use of premium system would demand about 21% more TiO₂ than is estimated for the standard system, but acrylic binder need is lowered by approximately 25%; furthermore, organic solvents usage drops by 97% (due to the use of waterborne paint) and to the similar extent is limited Ozone Formation Potential (OFP). Whereas increased TiO₂ consumption is disadvantageous, reduction in consumption of other ingredients brings a definite advantage.

6 Discussion

It is unfortunate that in majority of tenders, service life of road marking systems is overlooked and the one-time application is considered instead of the long-term requirement. The presented financial calculation, based on typical retail prices in Poland and assumed higher prices for premium materials, is demonstrating that even very high initial costs are annulled if prolonged service life is achieved. The calculated savings of 0.37 €/m² per decade may appear insignificant, but given that approximately 3,436,371 m² of road surface was marked in Poland in 2014 at national roads [9], total savings could possibly reach about 125,642.18 € per year. It should be kept in mind that in Poland the national roads comprise only

circa 7% of all public roads. Such savings could be transferred for improvement of infrastructure, which was demonstrated to have positive effect on road safety [1].

The price gap for premium systems as compared to the standard materials is assumed to be caused not only by the raw materials selection and production technology, but also by lower demand. It is, therefore, very likely that with additional market penetration, the premium road marking solutions would become less costly than they are now. A significant drawback of this analysis is the need for assumptions and using retail prices instead of the actual sale prices. While this deficiency is not possible to overcome, it can be supposed that the actual prices would remain reasonably proportional to the retail prices, at least within one market and purchase quantity.

Environmental assessment based on materials usage calculation confirms the advantages of premium road marking systems in terms of materials consumption and emissions. Amongst the natural resources necessary for preparation of premium systems, one must list increased consumption of TiO₂, which is added to enhance the performance of premium glass beads and thus achieve the service life benefit and lower usage of other materials. However, from the perspective of LCA, it should be neutralised by the lesser overall energy and transport demand because of the increased service life. Meaningful

reductions in other key raw materials are definitely realised with the use of premium systems because of the achieved longer service life.

An important environmental and health perspective comprise emissions of solvents, which not only generally harmful per se, but are also contributing to the formation of tropospheric ozone; however, their assessment from that perspective is beyond the scope of this article. Seldom addressed is an important issue of possible dust formation from wear and tear of road markings. In this issue, critical role play glass beads, which are protecting the base layer from abrasion, thus meaningfully limiting dust formation. Therefore, appropriate upkeep of the horizontal road markings can be considered not only a road safety matter, but also an environmental issue. Modern road marking materials for the use in majority of Europe should be free from heavy metals (like lead) and toxic volatiles (like chlorinated solvents), but the use of toluene is permitted in some countries. The use of toluene as a solvent for road marking paints may be advantageous despite general push toward its elimination, because toluene-based paints may, in some cases, provide better paint adhesion to roadway surface and thus prolong the service life [9]. In addition, in LCA analysis, toluene was judged as better than aliphatic solvents due to required lesser processing [8]. Waterborne paints used in European Union should be free from alkylphenol ethoxylates, but in other areas of the globe there may be no such restrictions.

The key ingredient for the increased service life appear to be the premium glass beads, which due to their characteristics allow for obtaining maximum performance from the base layer materials. Whereas some function improvement could be obtained in solventborne paint used with premium glass bead as well, results from field testing demonstrated that the sufficient increase in service life of the paint-based renewal system can be achieved only with high-performance waterborne paint [16]. It is very likely that the exceptional performance would also be obtained with the sprayed cold plastic, but the results from field testing are not available at present.

In this report excluded are additional possible advantages of using premium materials, particularly premium glass beads, even though they may play very important role for the whole society. High R_L that is achieved and maintained with premium system can lead to lowering accident rate [4, 18]. As such, given enormous financial expenses associated with road accidents, any additional costs could be easily offset, particularly given that preventing a fatal road accident was estimated to be only 0.04–0.20% of the costs caused by it [49]. It must be additionally mentioned that high R_L has a potential of improving the quality of life and mobility of elderly population, who were reported to strongly depend on

horizontal road markings while driving [45]. Furthermore, recent calculation showed the advantage of lesser frequency of road marking activities [40].

7 Conclusions

The analysis presented in this article demonstrates some of the benefits of using premium road marking systems as compared to the standard systems, based on case studies from field tests done in Switzerland and in Poland. Even though the studies were from motorways, it can be reasonably expected that similar advantages can be achieved at other roads. Indeed, in the case of pedestrian crossings where the premium and standard glass beads were compared side-by-side, the same conclusions were drawn [13].

The case studies presented herein were done on cold plastic, solventborne paint, and waterborne high-performance paint, reflectorised with either standard or premium type of glass beads. However, these were given only as examples and it is likely that similar, or even better outcome can be obtained with different road marking materials. The influence of climatic conditions and various local considerations was also not taken into account. Similar assessment of thermoplastic (hot melt) road markings should be carried out because of their broad use worldwide. The aforementioned sprayed cold plastic is planned to be assessed, once field data is collected. Separate case studies that would comprise parameters like driver comfort and road safety are also envisaged. Quite surprisingly, current safety assessment of major roads did not include retroreflectivity of road markings [2]; it may be valuable to incorporate such data in future safety audits.

These case studies indicate that the price of the most environmentally sustainable materials is not higher than for the currently used low-end products as long as a multi-year effects are considered. Consequently, the best option to promote such solutions appear to be long-term performance contracts under strict supervision of the road administrators demanding the quality requirements. Private companies that win such tenders always seek maximisation of their profits and thus would use the materials of highest durability. Hence, poor solutions, demanding high resources, would be marginalised and quickly abandoned. It would be an example of employing the free market economy to push the most environmentally sustainable products, which appears to be more advantageous approach than using legislative bans on certain materials [6, 21]. For a real success in providing excellent quality road markings (and thus increasing road safety and mobility), which are environmentally friendly and bring financial benefits to the taxpayers, the applicators, and the materials manufacturers, a close co-operation and understanding of interests and needs of all the involved parties is necessary.

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Authors' contributions

The authors confirm contribution to the paper as follows: study conception and design: TEB; data collection: AP and independent parties; analysis and interpretation of results: TEB, AP; manuscript preparation: TEB. Both authors reviewed the results and approved the final version of the manuscript.

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Availability of data and materials

The datasets analysed during the current study are available on request.

Competing interests

Tomasz E. Burghardt is employed by a manufacturer of road marking materials. Commercial support from his employer was limited to providing a sample of premium glass beads at no cost for the field trial. The findings, interpretations, and conclusions are his own and not necessarily that of his employer and are not to serve as an endorsement of any road marking system from any manufacturer. Anton Pashkevich does not declare any conflicts of interest.

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