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SUSTAINABLE ROAD MARKINGS FOR SUSTAINABLE URBAN MOBILITY – SELECTION GUIDELINES BASED ON ENVIRONMENTAL AND DURABILITY PARAMETERS

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Abstract:

Proper organisation of road transport path is required for the mobility efficiency, for the comfort of road users, and for safety. Road markings are inexpensive road infrastructure features that make road transport easier and safer; their proper selection is very important. For the use in cities, materials must be durable, provide high-friction surfaces for unprotected road users, and be characterised by minimised emissions of volatile organic compounds, low carbon footprint, and curtailed microplastic and particulate emissions. Enhancement of nighttime visibility is usually less important because of external illumination. Because road markings are deteriorating systems, it is necessary to consider all of these requirements from a long-term perspective that includes multiple renewals. To provide materials selection guidelines, several commonly utilised in Europe types of road markings were compared. Durability was assessed based on field measurements of functional properties and evaluation of erosion (i.e. complete abrasion and removal from the roadway surface that results in the release of microplastics), sometimes extrapolations were necessary. The extent of various types of potential emissions was then assessed and global warming potential was calculated. Several parameters, notably skid resistance, had to be excluded because data was either impossible to quantify or absent; uncertainty in the life cycle assessment calculation that could reach even 30% because of its known fallacies should be noted. The outcome demonstrated that the utilisation of road markings that provided the longest service life was the best choice from the assumed long-term perspective; thus, the claim that 'sustainability is durability' was supported for the nth time. Specifically, road markings made with cold plastic can be indicated as the most suitable and sustainable for the use in urban spaces at heavily trafficked areas because of their low propensity to abrasion (hence, minimised microplastic and particulate emissions), intrinsic high skid resistance, low emissions, and low overall carbon footprint.

Keywords: *cold plastic, road safety, service life, microplastics, skid resistance, global warming potential, infrastructure maintenance*

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1. Introduction

One of the most frequent features seen on almost all paved roads are road markings (RM) – they serve as means to guide traffic and to convey various information to road users. Even though in some strictly residential urban spaces they might be unnecessary (Hamilton-Baillie, 2008), in cases of roads with higher traffic loads RM are needed due to the benefits that they provide (Miller, 1992). RM can be advantageously utilised for highlighting the conflict areas between different road users, particularly pedestrian crossings and bicycle lanes, and also for separation of paths destined and designed for them. The importance of RM was recognised in the European Union, where "*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*." (European Commission, 2019).

Whereas there is plentiful literature related to the effects that the presence of RM has on drivers' behaviour (Babić et al., 2020), herein the RM shall be approached from the perspective of materials and functional properties that they afford. Because of the specificity of urban spaces – higher traffic density with lower speeds, the extensive presence of unprotected road users, and typically also the existence of external illumination – some of the functional parameters for RM selection should be considered slightly differently than in cases of rural roads or motorways. Various models to predict service life of RM were proposed (Babić et al., 2019; Karimzadeh and Shoghli, 2020), as were procedures for monitoring of their quality (Soilán et al., 2022; Boudissa et al., 2024; Babić et al., 2024); nonetheless, none of them appeared to address the functional and practical parameters specific for urban spaces. Quite surprisingly, RM are not considered in various publications related to sustainable urban mobility (Mavlutova et al., 2023; Canitez, 2025) and were omitted in Sustainable Mobility Urban Plans (SUMP) (Gadžo et al., 2024; Hartl et al., 2024). While the topic discussed herein remains mostly separate from the SUMP indicators, some of them (emissions of air pollutants and greenhouse gases and general road safety) fall within the scope of this analysis.

The purpose of this paper is to partially filling this gap in the SUMP for dual audience: (1) the environmental assessment of exemplary commonly used RM would serve the academic researchers, particularly concerned with environmental aspects, and (2) to give guidelines and recommendations for road administrators and policymakers for the selection of the optimum RM for urban spaces. The objective was to provide a comparison based on indicators that could be quantified: durability, carbon footprint, emissions of volatile organic compounds (VOC), emissions of particulates and microplastics, and the frequency of necessary maintenance. Due to inadequate or unquantifiable data for this assessment, out of scope remained visibility during daytime and nighttime, full assessment of skid resistance, dirt pick-up and propensity to discolouration, cost, and ease of application. The issue of the readiness of RM for the implementation of driving automation is mentioned only superficially because of the absence of uniform requirements and often conflicting reported demands (Storsæter et al., 2020; Liandrat et al., 2024). Topics like microplastic and particulate pollution, carbon footprint, and skid resistance of RM are addressed herein, thus enhancing the SUMP indicators.

As an illustration, a comparison of exemplary materials commonly used in Europe is provided based the outcome from various field studies, limited results from laboratory analyses, and professional industrial knowledge. The Global Warming Potential (GWP) for the assessed RM was calculated based on the 'cradle-to-application' data utilised for the preparation of Environmental Product Declarations (EPD) according to the standard EN 15804+A2/C1 (European Committee for Standardization, 2021). Because RM are deteriorating systems, the assessment is given from long-term perspective that includes a series of renewals (Sánchez-Silva and Klutke, 2016). For the functional unit was taken 1.0 m² of RM that were applied and renewed periodically to maintain the desired properties under the total load of 20.0 million weight-adjusted vehicle passes. The weight-adjusted traffic load instead of the more commonly employed time scale was used herein as it permits for comparison of areas exposed to dissimilar type and density of traffic. Out of the scope of this article is prior literature review because of the absence of relevant publications and considerations related to the effect of RM on road user behaviour.

Extensive background information about RM was also excluded because it would be redundant; only the functions of their layers, their life stages, and the most important properties are described along with references to appropriate standards. Due to very limited research on this topic, heavy reliance on experiments and results described in papers originating from Europe was necessary. Based on the analysed aspects of exemplary RM, material recommendations are given for selected areas within urban areas.

2. Materials and methods

2.1. Functions and materials

From the perspective of materials, RM belong to speciality industrial maintenance coatings. They are unique because of being dual layer systems comprising two vastly dissimilar components: an underlaying paint (colour) layer and an overlaying layer of partially embedded glass beads (GB) that provide retroreflectivity (Pocock and Rhodes, 1952) and simultaneously protect the paint layer from abrasions (Burghardt et al., 2022). Only cooperation of these layers can provide the final functional product – visible for road users and simultaneously durable. The GB layer is incorporated in the RM by a drop-on process, i.e. strewing it on the paint immediately after its application while the paint is still in a liquid state. It is a good practice to use GB intermixed with anti-skid particles (ASP) to increase the skid resistance of RM. In cases of RM applied in layers >1 mm thick, the GB and ASP are also incorporated in the paint matrix itself, in the form of 'premix' package, where they function as hard coarse filler, modifier of rheological properties, enhancer in abrasion resistance, and sometimes can also deliver retroreflectivity.

The function of both layers of RM and exemplary materials are listed for reference in Table 1 (Babić et al., 2015). One should observe that multiple types of materials can be used for the paint layer and only their limited choice for the GB layer. RM can be divided into thin layer (applied at wet film builds circa <1.0 mm) and thick layer applications (up to 3 – 6 mm). The thick layer RM can additionally be divided into flat lines and structured (various types of random or regular three-dimensional structures). The structured markings provide enhanced visibility under conditions of wetness (classified per standard EN 1436 as Type II) due to improved moisture drainage, very high friction because of the structures themselves and the presence of coarse fillers, prolonged functional and physical service life because of the effective lesser exposure to the traffic, and vibroacoustic effect warning drivers about departure from their travel path. Some thick-layer materials can be delivered in 'preformed' form, with the properties, including GB, and shapes fixed during manufacturing instead of being formed at the application site. Important from the perspective of this paper are materials that can be applied in thick layers by hand because it is often the preferred and easiest application method within the confines of urban spaces; materials such as rollplastic (a cold plastic designed for providing high friction and application with special roller providing a structure appearance) and bicycle lane plastic (a cold plastic designed for hand application using a squeegee, also furnishing high skid resistance) should be noted. The requirements for materials are specified in the standard EN 1871 (European Committee for Standardization, 2020b).

The external appearance of exemplary thick layer flat line RM is shown in Figure 1; cross-sections through RM are shown in Figure 2.

2.2. Properties of road markings

The most important characteristics of RM, related to functional properties, composition, and practical aspects, are described below. Because of the interconnection between materials and properties, it is often difficult, if not impossible, to separate them. Selected functional parameters of RM and the procedures for their measurements are listed in the standard EN 1436 (European Committee for Standardization, 2018); they are supplemented herein with other characteristics. Importantly, the standard EN 1436 does not provide the demands for particular performance, but only lists its various classes, which aspect is too often confused in literature. Some of the parameters listed below are for reference only as they had to be excluded from the analysis because of being unquantifiable or ambiguous. It must be emphasised that all RM must be homologated before usage; testing is done either in the field, according to the standard EN 1824 (European Committee for Standardization, 2020a) or in laboratory per standard EN 13197 (European Committee for Standardization, 2011a). Whereas Spanish and German homologation is done in laboratory using a turntable (Kepler, 2005), in Poland, Austria, the Netherlands, France, Czechia, and Sweden testing is done in the field according to local specifications.

Daytime visibility

Daytime visibility of RM is measured through luminance coefficient in diffuse illumination (Qd) and expressed in mcd/m²/lx. It is defined in the standard EN 1436 as the quotient of the luminance of a field of the RM in a given direction by the illuminance on the field. Typically, initial Qd 200–250 mcd/m²/lx is achieved in white RM with a decrease to 120–130 mcd/m²/lx considered as acceptable minimum. Alternatively, unitless luminance factor β (defined as the ratio of the luminance of a field of the RM in a given direction to that of a perfect reflecting diffuser identically illuminated) could be used; nonetheless, it is generally considered as less representative for RM. Typically, β >0.8 is demanded.

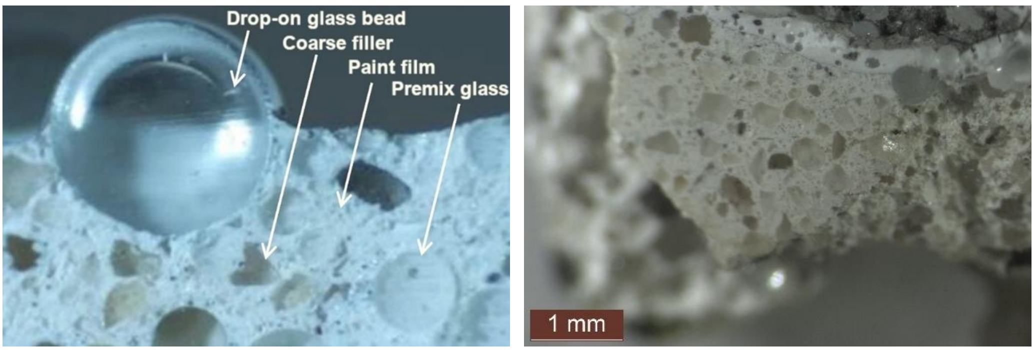
Whereas Qd is an important parameter of the RM themselves, related to their colourimetric performance, it is not tantamount with visibility for the road users, which is determined by contrast ratio and more specifically edge recognition (Spieringhs et al., 2022). Hence, for visibility of RM, the external illumination and the properties of the roadway play more important role than Qd. Evaluation of visibility of various coloured RM that are often used in urban spaces has not been reported so far. Herein, Qd shall be excluded from analysis and only mentioned due to its correlation with the possible dirt pick-up and discolouration of RM.

Table 1. Functions and selected materials used for the layers of road markings.

Layer	Paint layer	Glass beads layer (drop-on layer)
Functions	Adhesion to road surface. Colour contrasting with the roadway. Surface for retroreflection. Adhesion surface for the GB layer.	Retroreflection. Protection of the paint layer from abrasion. Skid resistance.
Selected materials	Solventborne or waterborne paints (dry and/or cure through evaporation of solvents) – only thin layer. Cold plastic (solvent-less; polymerises on the road surface) – thick or thin layer; sometimes also available in preformed version (glued to road surface). Thermoplastic (solid mass, melted at circa 200 °C; solidifies upon cooling on the road surface) – thick or thin layer; also available as preformed shapes. Solvent-less or solventborne plural-component systems including epoxy, urea, urethane, etc. (dry and/or cure through chemical reaction) – thick or thin layer. Tapes (glued to the road surface) – thick layer preformed.	Glass beads (usually diameters 0.2–1.0 mm, known range 0.06–2.00 mm). Glass beads intermixed with anti-skid particles of similar dimensions. Anti-skid particles alone (seldom, for special applications only). Crystalline elements in lieu of GB (used only in some high-end tapes).
Application methods	Thin layer: spray. Thick layer: extrusion, screed box (for flat lane markings), manual spreading with a squeegee (bicycle lane plastic), roller (rollplastic). Preformed thermoplastic: torch. Tapes: glue with pressure-sensitive adhesive or apply to hot bitumen.	Drop-on procedure immediately following application of the paint layer (in tapes and preformed materials – during manufacturing).
Thin layer, applied quantities	Only flat lines. Paints: wet film 0.3–0.6 mm (up to 0.9 mm) / 0.5–1.5 kg/m², resulting in dry film approximately 0.2–0.4 mm (up to 0.6 mm). Solvent-less materials: 0.3–1.0 mm (up to 1.5 mm) / 0.3–2.2 kg/m².	Drop-on application 0.3–0.5 kg/m².
Thick layer: applied quantities	Only solvent-less materials. For flat lines, film 1.5–3.0 mm / 2.5–6.0 kg/m². For structured markings, film <6.0 mm / 3.0–7.0 kg/m².	Drop-on application 0.3–0.5 kg/m².
Abrasion resistance	Thin layer: low. Thick layer thermoplastic: medium (material is designed for abrasion). Thick layer cold plastic and tapes: high.	High or very high.

(a) **(b)**

Fig. 1. External appearance of flat line road markings: (a) Side view of flat line circa 3 mm thick; (b) Top close-up view with visible GB and ASP. Source: Author



(a) **(b)**

Fig. 2. Cross-section through thick layer RM: (a) Thermoplastic RM with labelled GB and ASP; (b) Thick layer cold plastic (layer approximately 2.4 mm) renewed with paint (layer circa 0.4 mm), sample collected in the field. Source: Author

Retroreflection

Retroreflectivity – the phenomenon of reflecting the light from vehicle's headlights back toward the driver – is the key functional parameter for RM. While critical for road safety in unlit areas because it enhances visibility (through augmenting the contrast ratio during nighttime driving), retroreflection has limited importance in the presence of external illumination; nonetheless, because of its correlation with the possibility of abrasion and with the needs of driving automation, it cannot be omitted. In addition, some build-up areas are poorly lit – in such places retroreflectivity plays important role to assure proper visibility of the RM.

Per standard EN 1436, retroreflectivity of RM is measured as coefficient of retroreflected luminance (R_L), expressed in mcd/m²/lx; retroreflection can be measured during the conditions of wetness (RW) and theoretically also under rain (RR). It is defined as the quotient of the luminance of a field of the RM in a direction of observation by the illuminance at the field perpendicular to the direction of the incident light. Retroreflection is achieved solely because of the GB embedded in the paint layer (Vedam and Stoudt, 1978). Based on theoretical calculations, maximum R_L can be achieved with GB having refractive index 1.9 under dry conditions and 2.4 during rain (Shin et al., 2019). With 'standard' GB (characterised by refractive index 1.5), initial R_L 300–350 mcd/m²/lx is achieved in white RM; usually R_L 100 mcd/m²/lx is considered as the minimum acceptable by road administrators despite recommendations of 150 mcd/m²/lx based on the analyses of drivers' visual needs (Lee and Oh, 2005). Higher initial R_L, reaching 1000 mcd/m²/lx, can be achieved with 'premium' GB characterised by refractive index 1.6–1.7 (Burghardt et al., 2022). With the increase of refractive index to >1.9, the GB are losing their glassy character and become crystalline reflective elements; in such cases, at the cost of mediocre R_L, the RW and RR increase significantly (Burns et al., 2007). Normative references and performance requirements related to the GB for the use in RM are described in the standard EN 1423 (European Committee for Standardisation, 2012).

A strong correlation between R_L and visibility of RM at night has been established (Guan et al., 2024). This improved visibility is most likely the reason for reported meaningful decrease in collisions as R_L increases (Avelar and Carlson, 2014). The increased RW may be one of the keys to the reported lower accidents rate in the presence of RM designed for nighttime wet visibility (Park et al., 2019). Important additional aspect related to R_L is associated with the role of GB in protecting the coating layer from abrasion. It was reported that such abrasion – associated with the emissions of microplastics – can occur only after the decrease in R_L to <100 mcd/m²/lx (Burghardt and Pashkevich, 2023).

Furthermore, increased R_L results in increased lidar response (Ai and Tsai, 2016; Che et al., 2019; Soilán et al., 2022) and in higher contrast ratio for machine vision (Burghardt et al., 2023c; Biermeier et al., 2025a). Because one could envisage the use of driving automation that relies on machine vision (Storsæter et al., 2020), the importance of R_L is likely to increase. At present, no minimum lidar response intensity or contrast ratio from RM for reliable guidance has been unequivocally established and inconsistencies in the existing reports must be pointed out (Biermeier et al., 2025b; Liandrat et al., 2024), so this interesting practical aspect related to an emerging technology has to be omitted.

Skid resistance

Despite profound importance, skid resistance of RM is addressed in literature quite seldom (Burghardt et al., 2023a), even though assuring high friction is especially important for unprotected road users (Harlow, 2005; Dorocki and Wantuch-Matla, 2021; Chen et al., 2023), especially during wet weather (Hippi and Kangas, 2022). It is achieved because of the layer of GB and / or the ASP, but it also can be obtained through macroscopic structure of the RM and the presence of coarse fillers incorporated in the paint layer. Only limited research on this topic can be found (Anderson et al., 1982, Harlow, 2005; Coves-Campos et al., 2018; Su et al., 2022; Bao et al., 2024; Bao et al., 2025); comprehensive systematic reports are still missing, so there is a meaningful knowledge gap related to the choice of materials for ASP and the changes of skid resistance under traffic. The macroscopic structure of the roadway surface was reported as also playing an important role, albeit the correlation was not straightforward (Pasetto and Barbati, 2013). In addition, there is a complex interplay of various effects, not fully elucidated, simultaneously affecting R_L and Qd.

While skid resistance performance classes are listed in the standard EN 1436, details related to the test procedure and equipment were relegated to the standard EN 13036-4 (European Committee for Standardisation, 2011b). Friction of RM is measured using a pendulum British Skid Resistance Tester (SRT) and expressed as unitless Pendulum Test Value (PTV). It is defined as the loss of energy as the standard rubber-coated slider assembly slides across the test surface; hence, it is not an empirical index but an engineering quantity (Chu et al., 2020). The test protocol and equipment are designed to imitate a patterned car tyre slipping with blocked wheels on a wet surface at the speed of 50 km/h (Fwa, 2021). It was reported that equipment calibration per standard ASTM E 303 (ASTM, 1993), considered generally as equivalent to the standard EN 13036-4, could be as associated with errors up to 60% (Guo et al., 2020). Skid resistance of RM is very sensitive to positioning of the SRT, so for practical purposes in the field work with RM the accuracy of ±2 PTV should be expected; in literature the accuracy of 5% is reported (Hiti and Ducman, 2014). A weakness of the test procedure is inability to reliably measure structured RM; while it might be possible to use a different instrument, its performance on RM has not been validated despite some attempts (Wälivaara, 2007; Schacht and Oeser, 2014).

Carbon footprint

Carbon footprint, quantified as GWP, became important as a measure to estimate the environmental impact of a product or a process. Life Cycle Assessment (LCA) performed on various exemplary RM indicated that the highest carbon footprint was associated with systems furnishing the shortest service life (Cruz et al., 2016). It is important to note that LCA of RM must be performed only from a long-term perspective (initial application followed by a series of renewals to maintain the RM within the desired parameters) because considering a one-time application event gives skewed results with deteriorating systems (Sánchez-Silva and Klutke, 2016; Jia et al., 2017). There are numerous inherent weaknesses of LCAs, leading often to dissimilar outcome depending on the data source, assumptions related to the boundaries, etc. (Achenbach et al., 2016; Konradsen et al., 2024). In case of RM, the exclusion of road traffic disruption during application, positive effects on road safety during the usage of RM, and potential pollution with microplastics and other particulates during their abrasion must be noted. Minimising the GWP ought to be sought to assure sustainability.

Harmful ingredients

Ingredients that can pose a risk to people or environment once RM are formed should be absent. Importantly, this does not apply to chemicals that are being modified to become benign during the process of forming RM; hence, warning and hazard labels on the materials do not always imply that they would bear any hazard during the use phase. The presence of harmful ingredients that may leach to the environment should cause an a priori rejection of a particular RM. In this context, emissions of VOC and microplastics are not considered as harmful ingredients; they are addressed herein separately. Reports of associating the materials for RM with various hazardous ingredients and emissions often describe obsolete or local issues, so they should be treated with caution.

There are numerous articles claiming the presence and leaching of toxic substances from RM, especially $PbCrO_4$ pigment (Fukuzaki et al., 1986; O'Shea et al., 2021; Turner and Filella, 2022). However, such contamination is only a residual issue of local importance. Pigments containing lead or chromium are not being used in countries like Poland or Czech Republic since 1990s, in Austria, Germany, and Scandinavia since 2000s, and in the United States since 2010s or earlier – their elimination occurred not necessarily because of legislative bans, but also due to requirements in tenders. Currently, innocuous organic pigments are utilised instead (Hunger, 2005; Stratmann et al., 2020). The key pigment for all white RM, TiO_2, over which recently there was a notable fuss due to alleged carcinogenicity, was shown as being harmless based on multiple cohort studies (Le et al., 2018; Hansa et al., 2023); the European Court of Justice sided with the industry and vacated politically motivated legislation requiring special precautions and hazard labelling that failed to account for the final usage of the pigment (Riebeling et al., 2020). Nanoparticles of any kind are typically not used in commercially used RM, so specific hazards associated with their dimensions do not apply.

In all RM there are some additives, typically comprising 1–5% of the entire formulations; their selection is always done to eliminate or minimise the contents of any hazardous substances, as is mandated by local regulations and demands in tenders. Occasional reports may be irrelevant; for example, the potential leaching of alkylphenol ethoxylates (Markiewicz et al., 2017) disregarded the ban on such additives in Europe (nonetheless, based on professional knowledge, in North America this additive is commonly utilised). Amongst the additives one should list polymeric materials that are necessary for maintaining high properties of thermoplastics – upon abrasion they are considered as secondary microplastics.

Field studies of GB used in Europe confirmed them to be free from toxic elements (Migaszewski et al., 2022); upon release from the RM, they are just benign fully amorphous glass particles that undergo slow disintegration in the environment. The prior reports warning of contaminated GB (Sandhu et al., 2013; dos Santos et al., 2013) were describing a local American issues that were a result of inadequate quality controls. Associating the presence of GB as a proxy for environmental contamination with toxic materials, as is sometimes done (Turner and Keene, 2023; West-Clarke and Turner, 2024), without distinguishing and emphasising the distinction between the current and erstwhile issue, failure to account for the service life of RM, or potential alternate sources of GB, is a poor practice as it may direct resources on studying and remediating insignificant or obsolete issue.

Volatile organic compounds (VOC)

The presence of VOC in RM is the result of using organic solvents in paints; in waterborne paints VOC contents are minimised, but current technology does not permit for their complete removal. In addition, there are minor emissions of VOC from cold plastics (a result of evaporation of the monomers before polymerisation occurs). One should note here that due to differences in definitions, VOC contents and VOC emissions may be different and contents may vary significantly depending on the choice legislation (Burghardt and Pashkevich, 2018). To account for semi-volatile ingredients and dissimilar photochemical reactivity of various solvents, tropospheric ozone formation potential (OFP) based on maximum incremental reactivity of total organic gases should be used for quantification instead of VOC (Luecken and Mebust, 2008; Burghardt and Pashkevich, 2018). Toluene, a commonly used solvent that is often undesired and has high OFP, creates a difficult case because its solubility parameters permit for improved adhesion of RM to the roadway (thus, longer service life can be achieved) and simultaneously it has lower carbon footprint than aliphatic solvents. For urban spaces, like for all other applications, the OFP generally ought to be minimised. Solvents considered as harmful, such as xylenes or chlorinated paraffins, should not be used.

Service life (including particulate and microplastics emissions)

Important is understanding the life stages of RM – from *functional* service life (when the required parameters are met or exceeded), through *physical* (when the requirements are not necessarily fulfilled but the materials remain on the road and can undergo abrasion), to *erosion* (the relatively rare event of complete physical removal from the road due to the action of vehicular traffic or snow ploughing). It must be noted that tyres of the passing vehicles normally have no contact whatsoever with the paint layer, but roll on the GB; hence abrasion can occur only after the GB and ASP are extracted from the paint. Consequently, during the functional service life, emissions of particulates (and microplastics) can be considered as negligible. Good maintenance practices demand that RM are renewed before they encroach on the physical service life period; the sustainability calculations assume renewals at the end of functional service life. Maximisation of the service life (both functional and physical) is necessary and ought to be considered as one of the most important parameters of all RM.

Unfortunately, RM are often permitted to fall into disrepair; hence, consideration must be given to the physical service life as well. Usually, the length of *physical* service life is not measured; only recently the differences between thin layer and thick layer RM were assessed in the field (Burghardt and Pashkevich, 2025). It was found that the choice of the coating layer materials was controlling the rate of erosion. The issue of abrasion and erosion of RM gained recently a lot of interest because it was associated with microplastic pollution. The plethora of articles claiming that RM were a significant contributor to microplastic pollution was recently critically reviewed and inappropriate claims were rebutted based on the evidence collected in the field (Burghardt and Pashkevich, 2023). Estimate of annual erosion of <5% was reported based on two decades of research done in Germany (DSGS, 2022); it would concur with research originating in China, where RM were claimed to be responsible for circa 0.7% of all microplastics with the caution of deviations reaching 300% (Wang et al., 2019).

Abrasion resistance is achieved primarily due to the layer of GB; after their extraction from the film the 'premix' coarse materials within the paint layer matrix play critical role. Therefore, only cold plastic and tapes can be considered as highly durable. Thermoplastics are the only type of RM designed for abrasion – as they wear-off, fresh 'premix' GB are exposed and R_L is continuously delivered (Burghardt et al., 2023b). This special feature augments the visibility of thermoplastic RM for increased road safety, but at the cost of particulate emissions. Another unique characteristic of thermoplastic RM is the possibility of using non-polymeric binders, material derived from esterified rosin oil that provides the same quality thermoplastic RM as polymeric binder (Mirabedini et al., 2020; Yılmaz et al., 2024).

Dirt pick-up resistance

One of the important yet commonly omitted issues is discolouration of RM due to dirt pick-up or dirt accumulation (one should observe that these are not always tantamount), leading to the decrease in R_L and Qd and the departure from colour requirements. Quite surprisingly, no literature reports related to this topic could be found. Within the current known technologies, there is no feasible solution to this issue; it can only be alleviated to some extent. Based on professional knowledge, dirt pick-up is associated with the paint itself and the dirt accumulation also with the quantity of the drop-on GB. In waterborne paints, initially high dirt pick-up may occur

because of the migration of the coalescent to the film surface and its very slow evaporation (van der Kooij and Sprakel, 2015; Võ and Morris, 2014).
To minimise dirt accumulation, circa 0.4 ±0.1 kg/m² of GB is typically recommended – it furnishes the desired protection of the paint from abrasion, assures retroreflectivity, and permits for sufficient spacing between the GB to allow for washing of the paint surface during heavy rain or street cleaning. In cases of thermoplastic RM, it is critical to select material appropriate for a particular climate and location to minimise the dirt pick-up along with the assurance of other desired properties. Nonetheless, in hot climates discolouration is unavoidable due to the oils from asphalt surface being picked-up by tyres and then deposited on the RM. Mechanical cleaning of RM is often a viable solution to increase R_L and Qd that occurred due to dirt accumulation and pick-up. Since it could not be quantified for the purpose of this article, dirt pick-up and discolouration of RM were not assessed.

Drying time

As a parameter influencing the traffic obstruction during application of RM, drying time should be considered important for roads carrying meaningful traffic loads; indeed, some marking activities are done at night to minimise this negative effect. Only one paper describing the effect of material selection on drying time and the associated traffic flow could be found (Fiolić et al., 2017), but the issue was included in an LCA of road reconstruction (Itoya et al., 2013). Classes of drying times are specified in German technical guidelines ZTV-M (ZTV-M, 2013); usually materials with classes T1–T3 (drying <20 minutes) should be utilised for urban spaces. As a caution, one must note that the measured and reported drying time class is not always directly correlated with the period when the road can be opened to traffic; for example, paints and cold plastics may require additional time after full drying or curing to maximise the adhesion of GB and thus longevity of the RM. This interesting practical aspect has not been thoroughly studied so far.

Cost

Even though financial expenses associated with the application of RM do not belong to their properties, they are very important from utilitarian perspective and cannot be disregarded. All of the studies done so far indicate that materials that provide the longest service life are – from the long-term perspective – the least costly (Pike and Bommanayakanahalli, 2018; Burghardt and Pashkevich, 2020). Contrary and inconsistent results were also published, albeit the analysis was done solely on thin-layer materials and some assumptions seemed to be pertaining to low-end materials with very short service life and improper maintenance procedures (Asdrubali et al., 2013). The great uncertainty associated with the expenses due to the need of controlling the traffic during application has to be noted. As a recommendation for good practice, long-term performance contracts under strict supervision of quality are the best option; they are a win-win situation. It is therefore unfortunate that the road administrators very often ask in tenders for a one-event price instead of calculating for an extended period of service life. An assessment from the simultaneous perspective of LCA and Life Cycle Costing Analysis, which is often done on other road infrastructure projects (Suwarto et al., 2024), is due also for RM.

Ease of application

For large jobs, RM are applied by professional crews with specialised machines that are designed for specific materials. However, for small jobs and within the confines of urban spaces, some RM are applied by hand spreading; for such jobs, the materials must be designed properly. This practical aspect is difficult to quantify, so it should be considered only on case-by-case basis. No relevant literature reports could be found.

3. Data and calculations

Whereas all of the parameters listed above are important, they cannot be weighed equally or even be considered as partial contributors; their ranking also does not seem appropriate. For example, while the presence of hazardous ingredients should be a reason for an a priori rejection of a particular RM, the issue of application difficulty could be alleviated by using alternate equipment. In some of the cases, the listed parameters of the analysed exemplary materials are too similar, can be controlled through the selection of additional materials (especially friction), or are overly difficult to quantify, so they were ignored; hence, in the presented assessment only those properties that allow for differentiation were considered. Consequently, R_L, Qd, drying time, the presence of harmful ingredients, the financial expenses, skid resistance, and the ease of application remain disregarded.

Retroreflectivity, which usually determines the functional service life, shall not be considered herein because of its limited importance in lit urban spaces. Instead, physical service life shall be regarded as more important. Herein, for the first time is published information about physical service life obtained for various thin layer RM from a field testing of materials applied as transverse lines (Burghardt et al., 2022); discrepancies from the referenced report are a result of using the average for the entire transverse line and R_L 100 mcd/m²/lx as the threshold for the end of functional service life. Because of the absence of similar data for thick layer RM, circuitous calculations were required; they are acknowledged as a weakness of this text, even though the results concur with industrial practical experiences. Based on a field study, paint was shown as undergoing erosion at the rate approximately twelve times faster than cold plastic (Burghardt and Pashkevich, 2025), which served herein as an indicator for the physical service life of cold plastic. The service life and composition were assumed to be the same for all cold plastic varieties (flat, structured, rollplastic, and bicycle lane plastic); no reliable data related to the differences was publicly available. For thermoplastic, results from a proprietary laboratory turntable study (Nicholls et al., 2019; Mohamed et al., 2020) were used; note that mechanical abrasion testing with equipment like Taber abraser is not a viable protocol for such evaluation because of different mode of action. Because of the possibility of using for thermoplastic RM polymeric or non-polymeric binders or their mixture (Burghardt et al., 2023b), two scenarios are provided. While the properties are generally expected to be equivalent (Mirabedini et al., 2020), there might be some advantages in using non-polymeric binder in providing better adhesion of GB (due to 'stickiness' of the binder) and also improved dirt pick-up resistance (based on professional recommendations in the United States). The choice of binder affected the carbon footprint (Cashman et al., 2016). The data sources are summarised in Table 2; the assumed accuracy is based on the results from repeated field experiments and does not depart from typical industrial knowledge.

GWP, based on the available EPD and databases Ecochain Helix 4.3.1, Ecoinvent 3.8 (Steubing et al. 2016), was calculated for the evaluated RM for the cradle-to-application boundaries. As functional unit was assumed 1.0 m² of marked surface, periodically renewed at ½ of the physical service life period (number of renewals rounded to one decimal point). This unusual assumed extension of the service life, even though not recommended, is often found in practice; also, it permitted for more fair inclusion of thermoplastics with their design for abrasion. One must note that due to the absence of fully reliable data for materials specific for RM, the accuracy of the LCA calculations can be subjectively estimated at ±30%. Such high uncertainty is a consequence of the following: (1) transportation of the manufactured materials to the application site, which was not included – a standard European lorry with a 50% load factor would add 131 kg CO_2 eq./1000 kg/1000 km; (2) application process – small jobs like marking of 'zebra' pedestrian crossings are known in the industry to be less efficient than marking of longitudinal lines; (3) sources of raw materials for the manufacture – impact of long-distance imports could be significant, as 9.4 kg CO_2 eq./1000 kg/1000 km is typically assumed for a standard boat shipping container; (4) specific raw materials – majority of the data used for the calculations was for 'generic market' or for a similar product within its class; (5) the choice of database – sometimes the differences are meaningful (Konradsen et al., 2024). Whereas it was reported that stacking of such uncertainties might result in unrealistic results (Marsch et al., 2025), it was not the case herein; a sensitivity analysis would be superfluous for this report – a dedicated research is expected to be published soon.

Pertinent information about the evaluated materials, collected based on publicly available literature like safety data sheets, performance certificates, and results from laboratory testing (Burghardt et al., 2022), is provided in Table 3. The assumed spreading rates do not depart from industrial practice. It was taken that the GB layer would comprise a mixture containing by weight 50% 'premium' GB, 20% 'standard' GB, and 30% ASP, as for the field experiment with the transverse lines (Burghardt et al., 2022). Such high contents of ASP are typically recommended for flat lines RM applied in areas where high friction is demanded. For simplicity and because of low environmental impact of the ASP, the special formulations and structures that do not demand the use of ASP for achieving high friction were not considered separately.

Table 2. Data sources and accuracy assumptions related to service life

–	Thin layer materials	Cold plastic	Thermoplastic
Functional service life	Field study, transverse lines (Burghardt et al., 2022). Accuracy ±10% can be assumed.	Field study, structured longitudinal lines (Burghardt et al., 2020), 6× times slower R_L decay than with transverse lines when using similar drop-on GB; for analysis taken as matching sprayed cold plastic in transverse lines. Accuracy ±20% can be assumed.	Laboratory turntable study (proprietary). Accuracy ±20% can be assumed.
Physical service life	Field study, transverse lines same as for functional service life (this paper). Accuracy ±20% can be assumed.	Field study, pedestrian crossings, erosion comparison with paint (Burghardt and Pashkevich, 2025); assumed 12× more durable than paint. Accuracy ±10% can be assumed.	Laboratory turntable study (proprietary). Accuracy ±20% can be assumed.

Table 3. Properties of the assessed materials

	Solventborne paint (aromatic-free)	**Solventborne paint (containing 24% toluene)**	**Waterborne paint (typical, quick-set)**	**High-performance waterborne paint**	**Sprayed cold plastic**	**Cold plastic (all varieties)**	**Thermoplastic, polymeric binder**	**Thermoplastic, non-polymeric binder**
Material code	*SAF*	*SAR*	*WBQ*	*WHP*	*KSP*	*KP*	*TPH*	*TPR*
Applied material (wet mass) [kg/m²]	0.6	0.6	0.6	0.6	0.5	6.0	6.0	6.0
Applied glass beads [kg/m²]	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
VOC emissions [(a)]	24.5%	24.5% [(b)]	4.3%	2.5%	1.0% [(c)]	1.0% [(c)]	0.0% [(d)]	0.0% [(d)]
OFP [g O_3/kg paint]	228	975	35	21	135 [(c)]	135 [(c)]	0 [(d)]	0 [(d)]
Drying time estimate [minutes]	19	16	12 (33) [(e)]	15 (56) [(e)]	11	15	5	5
Binder and non-volatile organics (potential microplastics)	14%	18%	21%	19%	43%	24%	15%	5%
Functional service life [million vehicle passes] (transverse lines)	0.8	3.1	3.5	3.2	5.6	5.6 [(f)]	14.6 [(f)(g)]	14.6 [(f)(g)]
Physical service life [million vehicle passes] (estimate from transverse lines) [(h)]	2.3	4.4	5.3	7.6	7.1	52.8 [(f)]	17.5 [(f)(g)]	17.5 [(f)(g)]

[(a)] Emissions of VOC, comprising total organic gases – all volatile and semi-volatile organic ingredients regardless of their boiling point; it may be different from VOC contents as defined in the European Union (European Parliament, 2004). [(b)] Contains 24.0% toluene. [(c)] Assumed as comprising 80% methyl methacrylate and 20% *n*-butyl acrylate. [(d)] VOC emissions <0.1% are expected from thermoplastic materials themselves; the emissions and energy consumption due to the application process are included only in GWP calculations. [(e)] In parentheses, washout resistance time (Cf. Babić et al., 2015). [(f)] Estimated / extrapolated for transverse lines (Cf. Table 2). [(g)] For thermoplastic RM, functional service life meaningfully increased due to abrasion (i.e. particulate emissions), at the cost of shorter physical service life. [(h)] Based on measured R_L <50 mcd/m²/lx.

4. Results

4.1. Considered parameters

The results are summarised in Table 4 and the relative impacts of various materials in selected parameters (against average value in each category, which was considered as 1.0) are charted in Figure 3; long-term perspective was assumed. Particulate and microplastics emissions from the thermoplastics were adjusted to account for the abrasion during usage (it was assumed, based on the proprietary turntable study, that abrasion would commence after 3.2 million vehicle passes whereas the functional service life would be maintained because of the 'premix' GB; no field data is available). Higher carbon footprint of the application process of thermoplastic that demands heating of the materials to circa 200 °C was included in the GPW calculations. Description of the results related to the various properties, along with the most notable impacts of the analysed RM, is provided below. A tabulated summary for the considered parameters (based on the provided results) and excluded parameters (based on the professional industrial knowledge) is provided in Table 5.

Table 4. Long-term GWP and emissions potential of the analysed RM

Material code	*SAF*	*SAR*	*WBQ*	*WHP*	*KSP*	*KP*	*TPH*	*TPR*
Number of renewals [(a)]	13.0	5.3	4.5	3.7	3.1	0.7	1.9	1.9
GWP [kg CO_2 eq.]	44	16	13	11	10	10	19	18
Microplastic emissions [kg]	1.1	0.6	0.6	0.4	0.7	0.8	1.7 [(b)]	0.6 [(b)]
Particulate emissions [kg]	5.9	2.4	2.0	1.7	1.6	3.3	11.6 [(b)]	11.6 [(b)]
OFP [kg O_3]	1.8	3.1	0.1	0.0	0.2	0.4	0 [(c)]	0 [(c)]

[(a)] Assumed periodic renewals of 1.0 m² marked surface with the same materials at ½ of the physical service life for 20.0 million vehicle passes. [(b)] Adjusted for abrasion during functional service life. [(c)] Emissions due to application process not accounted but included in GWP calculations.

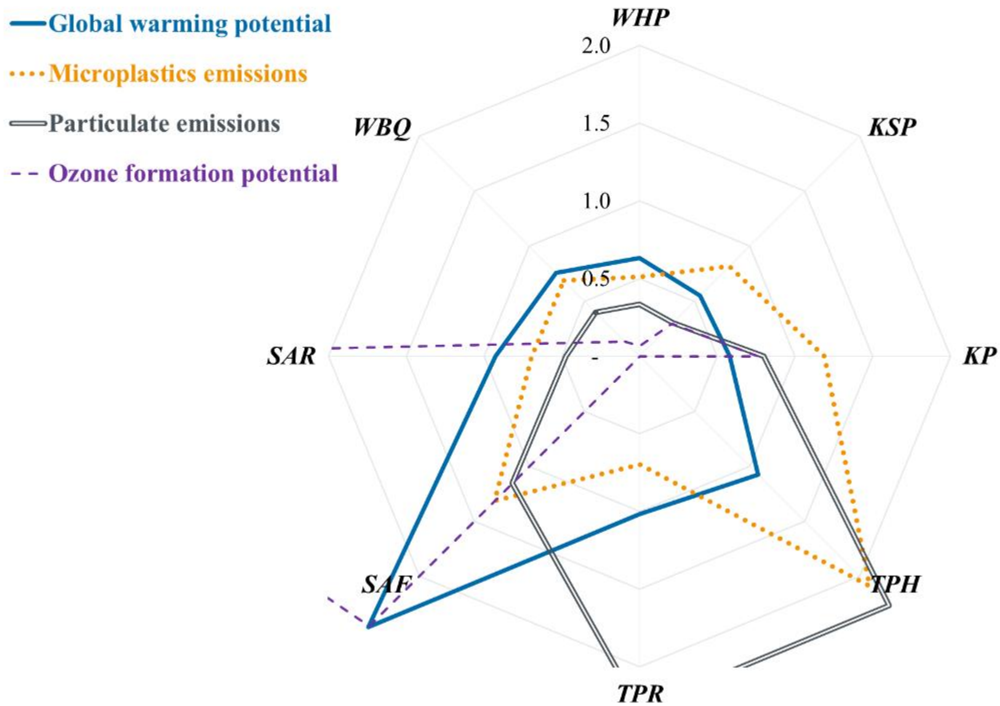


Fig. 3. Comparison of the key properties relative to the average values of each property assumed as 1.0 (assumed periodic renewals of 1.0 m² marked surface with the same materials at ½ of physical service life for 20.0 million vehicle passes).

Table 5. Summary of results. [(a)]

Material code	SAF	SAR	WBQ	WHP	KSP	KP	TPH	TPR
Carbon footprint	– –	+	+	++	++	++	+	+
Microplastic emissions	–	0	0	+	0	0	– –	0
Particulate emissions	–	0	+	++	++	0	– –	– –
OFP	–	– –	+	+	+	0	++	++
Skid resistance	0	0	0	0	0	++	++	++
Ease of application	0	0	0	0	0	0	–	–
Drying	0	0	–	–	0	0	++	++
Dirt pick-up and discolouration	0	+	– –	– –	+	0	0	0
Cost	– –	– –	0	0	0	++	++	++
Hazardous ingredient	0	– –	+	++	+	+	+	++

[(a)] ++ - best, + - good, 0 - neutral, – - poor, – – - worst

Ozone Formation Potential (OFP)

The advantage of thermoplastics (material codes *TPH* and *TPR*) is evident; they are truly solvent-less RM. Nonetheless, for waterborne paints and cold plastic systems the OFP was also low, <0.5 kg O_3/m² for the analysis period. Total long-term OFP >1.8 kg O_3/m² was expectedly calculated for the solventborne paints (materials *SAF* and *SAR*); this property alone disqualifies them from being recommended for the use in urban spaces.

Carbon footprint

All of the materials had similar long-term GWP, 10 – 19 kg CO_2 eq./m²; because of the aforementioned uncertainties, this range can be considered as essentially equal. The exception was solventborne paint (material code *SAF*), with GWP 44 kg CO_2 eq./m²; despite being the poorest choice in repeated field experiments, this paint was reported as meeting the Green Public Procurement core criteria and is qualified, based on a turntable testing, for the use on public roads. Its very high calculated GWP can serve as a confirmation that excessive reliance on composition with the effective disregard of service life is the most significant weaknesses of the recently published Green Public Procurement criteria for RM (Burghardt and Pashkevich, 2021). The same weakness is known in North American specifications, where not only the composition is set but also a specific binder from a specified manufacturer can be demanded (TXDOT, 2017). Interestingly, cold plastic (material code *KP*) was shown to be as the most environmentally-friendly despite the assumed spreading rate 10× larger than for paints; it was possible because of its durability. It should be noted here that cold plastic, particularly applied as structured longitudinal markings, is usually renewed not with itself, but with thin layer materials; this additional aspect was omitted herein.

Service life

With the disregard for functional service life (i.e. maintaining R_L > 100 mcd/m²/lx) and concentration on the physical period (i.e. the period when R_L <100 mcd/m²/lx is recorded and abrasion can occur), the advantage of using cold plastic (material code *KP*), became obvious. Cold plastic is designed for exceptional durability because of the intermixed of hard coarse fillers and *in situ* polymerisation to form tough film. Indeed, its excellent durability was reported by German road markings research institute, based on >20 years of field testing (DSGS, 2022).

Whereas the *physical* service life was connected with abrasion and thus emissions of particulates that included microplastics, it has to be emphasised again that within the *functional* service life period such emissions must be assumed as negligible, except for thermoplastics. Emissions of particulates 1.6–3.3 kg/m² per 20 million vehicle passes were possible from thin layer materials (except the paint *SAF* that had much higher calculated emissions potential) and from cold plastic. Both thermoplastics, due to their design for abrasion, had the potential of releasing >11.5 kg/m² of particulates during the analysed period. These emissions would comprise, besides the few secondary microplastic particles, benign inorganic materials such as $CaCO_3$ and TiO_2; in thick layer applications, the 'premix' materials – coarse inorganic particles that can be commonly found in the environment and GB would dominate. The release of GB and ASP from the drop-on materials was disregarded because they are innocuous inorganic materials (Migaszewski et al., 2022).

The calculated potential emissions of microplastics per assumed 20 million vehicle passes were quite low, only 0.4–0.8 kg/m²; the exceptions were the systems *THP* and *SAF*, which could emit >1.1 kg/m². The high content of a polymeric binder in sprayed cold plastic (material code *KSP*) was annulled because of the long service life that it could provide. The thermoplastic with polymeric binder (material code *THP*) was calculated to be a major contributor; hence, the thermoplastic with non-polymeric binder (material code *TPR*) is a better option. To put these potential emissions of microplastics in appropriate perspective, one must compare them with the contribution from other road-related sources; only <3% of such microplastics were assigned to RM based on a field research even in the harsh Nordic climate where thermoplastic RM and studded tyres are used (Vijayan et al., 2022; Blomqvist et al., 2023; Rathnaweera et al., 2023).

4.2. Excluded parameters

Skid resistance

This very important parameter had to be excluded from this assessment because of dissimilar interconnecting factors and the absence of reliable data. In case of typical flat-line RM (i.e. those not specifically designed for high friction), skid resistance can be controlled through the selection of ASP. Additionally, the macro roughness of roadway was reported as playing important role with thin-layer RM (Pasetto and Manganaro, 2008). In all of the cases of thin layer materials assessed herein, with the utilised mixture of drop-on materials, skid resistance 40–50 PTV was measured at the test field (unpublished data); hence, given the uncertainty associated with the roadway surface and the practical accuracy of field measurements, no valid differentiation was possible for the purpose of this paper. Nonetheless, to obtain the minimum required PTV >45, the utilisation of 20–30% of ASP is necessary. Caution should be paid to the selection of the ASP because they were reported as not equally effective in both short- and long-term (Coves-Campos et al., 2018; Burghardt et al., 2023a). One must note that it is not possible to simultaneously obtain high skid resistance and high R_L and Qd, unless 'premium' GB are used in combination with transparent ASP.

A separate case are materials designed for providing high friction, with composition enhanced through incorporation of additional or specifically selected coarse fillers intermixed with the paint layer. With structured RM, rollplastic, and bicycle lane plastic, PTV >55 can be easily achieved (even though measurement of structured markings and rollplastic cannot be considered as reliable). The incorporation of ASP amongst the drop-on GB in such cases is not always necessary. No reliable literature on this topic was published so far.

Ease of application

While no special difficulties would be anticipated with any of the assessed materials, one must note that the use of cold plastic (material code *KP*) is advantageous for smaller jobs because it can be conveniently applied by hand using either a screed box (flat lines), a squeegee (bicycle lane plastic; flat lines), or a roller (rollplastic; a structured application). Accurate dosing of the peroxide initiator and its uniform dispersion in the paint are absolutely necessary to assure high durability. Thermoplastics (material codes *TPH* and *TPR*) can be applied by hand using a screed box to obtain flat lines; the difficulty is the need to heat the materials, so appropriate cooker is necessary. If the thermoplastics are delivered in form of 'preformed' sheets (arrows, stripes, letters, and other symbols), not assessed herein, they can be very conveniently applied with a gas torch. The dispersion of GB on such hand-applied materials can be done by hand strewing. In case of bicycle lane plastic usually only ASP are used in lieu of the GB. The application of random or regular structures used at longitudinal lines is less preferred for pedestrian crossings due to the difficulty in manoeuvring the machines in small areas.

One must herein also consider the hazards and risks associated with the application process, especially handling the materials. While the exposure to VOC was reported as insignificant (Szpakowska-Kozikowska and Mniszek, 2014), improper handling of hot thermoplastic could cause burns (Riley et al., 1991). No similar reports related to cold plastic could be found, but allergic dermatitis must be noted as a potential hazard (Lugović-Mihić et al., 2024).

Drying

Drying times were sufficiently similar for all of the analysed RM to be excluded from this assessment, even though the use of thermoplastic could allow for expedited re-opening of the road to traffic. The use of paints is somewhat disadvantageous in this aspect; in case of waterborne paints, one should also note the risk of washout if rain occurs before the paint becomes fully resistant to moisture. Given their lower durability, paints should not be used to mark roads in urban setting except if marginal traffic exposure is expected.

Dirt pick-up resistance

This parameter had to be excluded because no reliable data is available; thorough study is hereby noted as a research need. At the test field for the assessed materials no excessive dirt accumulation or pick-up were observed. Quantification of the discolouration through Qd revealed that at the end of functional service life Qd >130 mcd/m²/lx was measured for all of the tested materials except waterborne paints where Qd 100–120 mcd/m²/lx was recorded.

Cost

Expenses were not calculated because of different focus of this article and very limited data related to the expenses of actual application process. Prior assessment, in which the indicative materials costs based on industrial information, survey from contractors, and analysis of winning tenders were considered, demonstrated the advantage of using durable materials (Burghardt and Pashkevich, 2020). Similar results could be concluded from North American perspective (Abboud and Bowman, 2002; Songchitruksa et el., 2010; Pike and Bommanayakanahalli, 2018), even though the differences between market prices, practices, and materials can be really meaningful. The expenses of application process (including the overhead, amortisation, etc.) were estimated at about 50% of the total costs; hence, the superior long-term performance that the high-end materials provide permit for limiting the overall expenses in spite of their much higher unit prices.

One must keep in mind that the expenses due to RM installation and maintenance were reported as being 60× lower than the costs of chaotic traffic and accidents in their absence (Miller, 1992). Given enormous financial burden of vehicular accidents (Wijnen et al., 2019) and the consistently reported effectiveness of RM in preventing them, any costs are insignificant as compared to the benefits.

Hazardous ingredients

None of the assessed RM contained substances that would cause concern. The emissions of microplastics and the VOC were excluded from this parameter. All of the evaluated materials were selected to assure full compliance with European safety regulations, so no hazard warnings would be present after the RM were formed and became ready for opening of the road to traffic. It is important to note that, based on professional knowledge, the requirements set in tenders or regulations pertaining to RM are often more strict than the general legislative norms; for example, this was the reason for elimination of $PbCrO_4$ from RM before official ban on such pigment went into effect.

5. Discussion

Whereas broadly falling into the scope of sustainable urban mobility, the RM topic remains distinct from majority of the SUMP indicators (Gadžo et al., 2024). In the context of this article, these indicators are not associated with the active transport, but with the passive infrastructure. Nonetheless, the outcome of the comparative analysis concurs with the needs to minimise the emissions of VOC and particulates including microplastics. Carbon footprint, which was assessed herein, quite surprisingly was not reported amongst SUMP indicators; as with other parameters, the use of the recommended highly durable materials would lead to its minimisation. Through correlating the quality of RM and traffic safety (Zahidy et al., 2024; Babić et al., 2020), another SUMP indicator was served. Specific role serve pedestrian crossings – as the areas of conflict between protected and unprotected road users they must be visible and have appropriate friction so slips and falls would not occur – this aspect was addressed herein, albeit full quantification could not be provided because of dissimilar effects of the diverse analysed RM and the absence of reliable data.

This assessment comprised products commonly utilised in central Europe, so some of the presented results are specific to moderate climates. Disregarded were special locations such as the Nordic countries where studded tyres are utilised (Laurinavičius et al., 2009; Lundberg et al., 2021) or hot dry climates where excessive discolouration frequently occurs (Chen et al., 2023); separate assessments are required. At present, conceptual laboratory work with including anatase TiO_2 nanoparticles to enhance RM with self-cleaning ability (Taheri et al., 2017; Lima Jr. et al., 2024) does not seem a practical option because of the inherent risks associated with the use of nanoparticles and low applicability to field condition. Amongst research needs is also evaluation of other materials and colours. Because reliable data is not available, evaluation of various colours could not be done. Yellow was only recently mentioned (Skierczyński et al., 2024), albeit thick layer structured markings were not evaluated. Red RM, which are commonly utilised for marking of bicycle paths and creating additional warning zones around pedestrian crossings were, quite surprisingly, not deeply studied despite their common use and importance (Auteliano and Giuliani, 2021). Orange RM, which are used in Austria in lieu of yellow as temporary markings and are recently being introduced for the same purpose in the United States (Lammers et al., 2021) were not assessed, either; the same applied to blue and green RM. It was observed that in Poland blue RM used to indicate parking spaces reserved for handicapped people are sometimes applied without either GB or ASP – such practice should be strongly discouraged because of excessive risk of slippage; this topic demands local investigation. Excluded from this assessment were plural component systems (which, maybe except epoxy paint for very limited applications, are not used in Europe), tapes (they are used rarely due to being prohibitively expensive, but are known to furnish long service life), and preformed markings (no field data available); their testing is due.

The topic of retroreflectivity was mostly ignored in the context of this paper that concentrated on the needs of human road users and drivers in lit areas. However, given the emergence of automated driving features in modern vehicles, retroreflectivity during dry and wet conditions demands attention. The main sensors that perceive RM are cameras and lidars (Marti et al., 2019); while camera is sensitive to illumination and fails in the presence of glare, lidar is sensitive to moisture and the level of retroreflectivity – hence, a combination of these two sensors seems advantageous (Formosa et al., 2024). To accommodate the needs of these sensors, structured RM reflectorised with 'premium' GB are the best option because they provide much better nighttime optical visibility under wet conditions and allow for high lidar response (Burghardt et al., 2023c). The minimum values of contrast ratio and retroreflectivity for reliable functioning of machine vision were not established so far despite proliferation of driving automation, so it is difficult to direct materials research into augmenting RM to fulfil the requirements. The minimum contrast ratio recommendations given by North American researchers (Carlson and Poorsartep, 2017) appear to depart from the reality due to the disregard for line continuity and edge detection.

Unsavvy researchers may indicate new emerging materials as providing better results. However, the recent publishing hype about luminescent materials for RM (Lin et al., 2023) can be dismissed from three practical perspectives: such solutions are very costly (the current commercial price can be estimated at >10× higher than the cost for the highest quality durable RM), the added benefit of their use is effectively nought (they are effective only in the dark, while urban spaces are lit and vehicles are equipped with headlights), and their environmental impact is relatively high because of the necessity to include rare earth elements (Schreiber et al. 2021). The conceived use of RM for scavenging air pollution through incorporation of anatase TiO_2, can be discounted as well: a thorough study demonstrated that their long-term effectiveness was almost nil (George et el., 2016). Efforts on other ideas have not been broadly published. Hence, no emerging RM concepts appear to be meeting the sought optimum.

6. Recommendations

The reason for the recommendations given below is illustrated in Figure 4: a visual comparison between improperly (paint, Figure 4a) and properly (cold plastic, Figure 4b) selected materials after exposure to vehicular traffic (Burghardt and Pashkevich, 2025). This must be heeded by road administrators and policymakers who ought to prioritise quality and long-term performance over low price per one application event. Not only materials selection is needed but also high quality of the application jobs; poorly trained work crews may make mistakes in application that result in accelerated erosion of RM. Long-term performance contracts seem to be the win-win option for the road administrators (i.e. the taxpayers), the contractors, and the environment because the applicating contractors for their own financial interest would select the best and most durable materials. Hence, free market economy instead of regulations could be used for the benefit of all (de Medeiros et al., 2014). However, for success of such contracts, appropriate supervision of quality and verification of long-term performance by the road administrators are necessary. Follow-up on all infrastructure and infrastructure maintenance contracts is needed to properly assess the selection of technologies and make adjustments as needed (Kornalewski et al., 2020).

Results of this comparison indicate that for urban spaces RM that are the most resistant to abrasion during the physical service life period should be used – specifically, cold plastic (including rollplastic and bicycle lane plastic) can be indicated. However, despite this straightforward recommendation, the choice must depend on the specific needs, the traffic load, vehicle types, and location within the roadway. Good guidelines for such selection are provided in Austrian standard ONR 22441 (Austrian Standards Institute, 2015); the point system described therein can be used to identify the areas with high or low traffic load and assist in proper selection of RM types. Guidelines, based on the results from this analysis, industrial recommendations for the best practices, and customs in several countries, are furnished in Table 6; these suggestions can also be used for other road types.

To assure high friction (and also to prolong the service life), the use of 20–30% ASP intermixed within the drop-on GB layer is necessary for all applications; the rare exceptions, where ASP should be used without the GB are coloured flat lines where retroreflectivity is not needed.

(a) **(b)**

Fig. 4. 'Zebra' pedestrian crossings after exposure to circa 5 million vehicle passes. (a) Paint; (b) Cold plastic. Source: Author

Table 6. Recommendations for RM selection in urban spaces

Location	Low traffic load	High traffic load	Skid resistance
Longitudinal lines, main roads (white and yellow RM)	Cold plastic flat or structured, thermoplastic flat or structured	Structured cold plastic	>45 PTV
Longitudinal lines, minor roads with low traffic	Sprayed cold plastic, waterborne paint	-	>45 PTV
Pedestrian crossings, stop lines	Structured cold plastic, rollplastic	Structured cold plastic, rollplastic	>60 PTV
Bicycle lanes crossing roadway	Bicycle lane plastic, thermoplastic	Bicycle lane plastic	>55 PTV
Special markings (reserved parking spaces, coloured markings, arrows, etc.)	Structured cold plastic, bicycle lane plastic, rollplastic, 'preformed' thermoplastic	Structured cold plastic, bicycle lane plastic, rollplastic, 'preformed' thermoplastic	>55 PTV
Pedestrian or bicycle pavement areas (no motorised vehicles)	Waterborne paint, sprayed cold plastic	Waterborne paint, sprayed cold plastic, thermoplastic, bicycle lane plastic	>55 PTV
Roadway areas excluded from any traffic	Waterborne paint, sprayed cold plastic	Waterborne paint, sprayed cold plastic	>45 PTV
Paving stones	No road markings (use contrasting stone colours)	No road markings (use contrasting stone colours)	>50 PTV
'Red carpet' high friction areas	Special flat cold plastic	Special flat cold plastic	>65 PTV

It is strongly suggested to maintain skid resistance for longitudinal lines >45 PTV and for areas exposed to unprotected road users >55 PTV. In critical areas, 'red carpet' high-friction surfaces with >65 PTV can be installed; they were reported to be quite effective (Karim et al., 2012). The external appearance of the recommended RM for pedestrian crossings – rollplastic (i.e. cold plastic applied by hand with a special roller) – is shown in Figure 5; one can observe the uneven surface that provides the exceptional friction and minimises the abrasion through sheltering some of the material from direct contact with tyres of passing vehicles.

7. Conclusions

Based on the presented evaluation, structured cold plastic (including rollplastic and bicycle lane plastic) appears to be the best choice for RM in urban spaces because it is solvent-less, capable of providing high skid resistance, can be conveniently applied by hand, and foremost is highly resistant to abrasion. Thermoplastic materials, despite many advantages, may contribute to particulate pollution because of their design for abrasion to maintain functional properties; nonetheless, they are also a good choice. Materials applied in thin layers, such as sprayed cold plastic and waterborne paints, are appropriate only for marking of areas not exposed to significant vehicular traffic; they are relatively easily abraded and have no intrinsic anti-skid properties. Solventborne paints should be avoided due to the emissions of VOC and the associated OFP. Unless particular type of RM is specifically designed for providing friction, the utilisation of the drop-on GB intermixed with ASP is necessary to assure the protection of the paint layer from abrasion and to provide appropriate skid resistance for the safety of unprotected road users. Materials should be selected suitably for a specific location; long-term perspective should always have priority over one-time event. Foremost, for the safety of all road users, all RM must be maintained appropriately; renewals before erosion commences, preferably before the functional service life is exhausted, is strongly recommended. Since road safety is positively influenced by RM, they should never be allowed to fall into disrepair.

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(a) **(b)**

Fig. 5. Pedestrian crossing marked with rollplastic: (a) Overview; (b) Close-up showing the irregular surface with dropped-on GB and ASP. Source: Author

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