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Horizontal road markings for human and machine vision

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Abstract

Horizontal road markings are inalienable feature on almost all roads because their presence results in significant increase in safety for all road users. By providing delineation, they help drivers in keeping the vehicle in the traffic lane. At night time, retroreflectivity (R_L) of road markings, achieved by incorporating glass beads on the marking surface, is perceived by the drivers and its higher level was shown to be associated with lower accident rate. Indeed, usable life of road markings is measured by their R_L. It is demonstrated herein, based on field tests, that for thick-layer structured road marking systems the selection of glass beads has profound effect not only on retroreflectivity, but also on durability. Exemplary financial analysis demonstrates that despite higher one-time expense, savings can be realised in the long-term with the use of premium materials. Moreover, the same high quality and high R_L of horizontal road markings that are needed for human drivers are demanded by machine vision algorithms, which provide guidance in the emerging autonomous vehicles technology. Therefore, maintaining of horizontal road markings at high level is necessary for both the human drivers and to facilitate the development of self-driving vehicles. Furthermore, because of reasonable price and broad availability, durable horizontal road markings have a potential of being one of the solutions to lower accident occurrences in poorly developed countries.

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Keywords: horizontal road markings; retroreflectivity; road safety; road maintenance financing; autonomous vehicles; machine vision

1. Introduction

Transport of people and goods is a key human activity, necessary for economic development and to maintain the quality of life. Unfortunately, due to conflicts in traffic and human inattention, accidents occur quite

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frequently. According to World Health Organisation (2016), over 3,400 people die every day in road accidents. Furthermore, the same report estimates that financial expenses associated with vehicular accidents reach an enormous 3% of World's Gross Domestic Product. Therefore, increase in road safety should be of profound importance for every country and one of the ways to improve the standard of life for all people. The most endangered are unprotected road users in middle- and low-income countries. Toroyan and co-workers (2013) noted that for those countries, comprising 84% of Earth's population, there are 53% of registered vehicles, but that is where 92% of road deaths occur. Road fatality rates per 100,000 citizens are: 24.1 in Africa, 20.1 in middle-income countries, 8.7 in high-income world, and 5.2 in European Union countries. Given the enormous social cost and the financial burden caused by the crashes, an inexpensive and effective solutions for improvement of road safety is necessary.

Horizontal road markings could be such a solution because of the positive effect on road safety that could be achieved at low cost: Miller (1992) has calculated that the financial expense of installation and proper maintenance of road delineation was on average sixty times lower than the costs caused by chaotic traffic and accidents. Such benefit is possible, because driving is a task based on visual input, so there is a necessity of providing information to drivers about position of their vehicles and horizontal delineation serves that purpose. Steyvers and de Waard (2000) demonstrated that the presence of edge lines markings helps drivers maintain the position of vehicle in the centre of the lane. The effect was found by Calvi (2015) to be particularly prominent at curves.

Whereas Autonomous Vehicles (AV) can be considered as an answer to high accidents rates, it must be noted that because AV most of the time rely on Machine Vision (MV) for guiding, they cannot function efficiently on poorly maintained roads. Thus, a solution to a successful MV is improvement of the same horizontal road markings that are needed for human vision and safety on the road. In this article are provided the results from field testing of premium quality road marking materials characterised by high durability, which lowers the long-term financial expenses and environmental burden due to lesser materials consumption, while simultaneously furnishing properties that improve their recognition by MV.

2. Horizontal road markings

2.1. Road markings systems

Horizontal road markings are systems, comprising a base layer and a retroreflective layer (Pocock and Rhoades, 1952). The base layer can be divided into thin-layer markings, usually applied at thickness below 1 mm, and thick-layer markings, with thicknesses that can reach several millimetres. The base layer can be a solventborne or a waterborne paint that dries due to evaporating solvent, a thermoplastic mass that is applied as a hot melt, a cold plastic that polymerizes on the road surface, or plural-component materials with components undergoing chemical reaction on the road surface (Babić et al., 2015). The base layer is a critical component of a road marking system, because it gives the desired colour, forms surface for retroreflection, and holds glass beads. While field studies have shown that the selection of the base system is controlling the durability of thin-layer road marking systems (Burghardt et al., 2016), there are no similar published systematic studies related to thick-layer applications reflectorised with different glass beads. Thick-layer road markings are frequently applied as either regularly or stochastically distributed structures that give a vibroacoustic effect, which warns drivers deviating from the traffic lane. In addition, the presence of the structure facilitates water drainage, which improves R_L under wet conditions and also shelters some of glass beads from the action of passing vehicles and snow ploughs. Thick-layer markings because of their expense are most suitable for roads with high traffic load.

The second inalienable component of horizontal road marking systems are glass beads, which provide retroreflection and protect the base layer from abrasion. A very important property of glass beads designed for road markings is their refractive index (RI), which varies from 1.5 for standard materials prepared from recycled glass to 1.9 or more for high-index materials prepared from a virgin glass melt. A unique type of quite recently developed glass beads has RI increased to 1.6-1.7. Those premium glass beads are prepared in a proprietary process from a virgin glass melt, using carefully selected raw materials that furnish improved resistance to scratching. Microphotograph of standard glass beads, with their occasional imperfections, is shown in Figure 1 and exceptional roundness and flawless surface of premium glass beads can be seen in Figure 2.

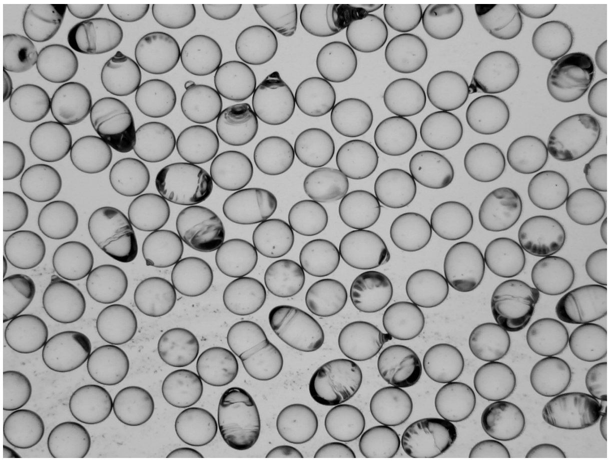

Figure 1. Standard glass beads, fraction 630-700 μm.

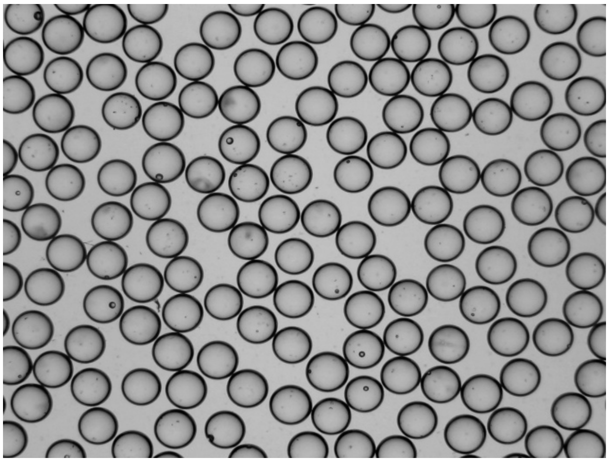

Figure 2. Premium glass beads, fraction 630-700 μm.

2.2. Retroreflectivity as the main feature of horizontal road markings

Horizontal road markings are especially important during night time driving on unlit roads, because that is when the relative number of accidents and their severity are significantly increased despite much lower traffic loads (Plainis et al., 2006). At night, when the number and quality of visual cues are meaningfully limited, the guiding role of horizontal delineation becomes more prominent. However, the markings must be reflectorised to be visible in the vehicles' headlights and that requires the use of glass beads. Retroreflectivity (R_L) occurs when the light is reflected back toward the driver and its level depends on the properties of the road marking system. Zwahlen and Schnell (1999) reported that during night time driving, R_L becomes a natural focus point for all drivers. R_L is measured according to standard norms and reported in millicandela per square metre per lux (mcd/m²/lx) and its level is used to determine the usability of road markings. One cannot discuss horizontal road markings without their R_L, except for very limited special applications. With properly embedded standard glass beads used to reflectorize white paint one can expect the initial R_L around 350 mcd/m²/lx, while premium beads can furnish R_L about 1,000 mcd/m²/lx. Higher R_L, reaching even 2,000 mcd/m²/lx, can be readily initially obtained with high-index glass beads; however, due to their low resistance to scratching and very high price, they are a niche application.

Only recently there were published results from a complex multi-year statistical analysis correlating the number of accidents with the level of R_L. Carlson and co-workers (2013) found that up to 23% reduction of single-vehicle non-weather-related accidents between intersections could be realised with increasing R_L by 100 mcd/m²/lx. Subsequently, the calculation methodology was confirmed (Carlson et al., 2015). Bektas et al. (2015), using slightly different evaluation protocol, also established the relationship, but not at all roads and not as strong. However, there are no reports addressing possible safety benefits of very high levels of R_L, which could be achieved with the novel technology that is discussed below.

3. Autonomous driving and machine vision

Approximately 90% of accidents are currently attributed to a human error (Dingus et al., 2016). Therefore, it is generally accepted that replacement of human drivers with infallible computers equipped with sensors would eliminate those crashes. Whereas there is a technological capability and policy push for AV, it sometimes appears to be forgotten they cannot work properly without appropriately maintained infrastructure, because they rely mostly on MV to determine the location within the travel lane. Various issues associated with planning and policy related to AV were recently reviewed (Faisal et al., 2019).

3.1. Machine vision and horizontal road markings

With the plethora of literature related to AV and MV, notable and quite surprising is lack of visible collaboration between the scientists developing these new advanced technologies and the researchers working on horizontal road markings. Yet, MV is mostly dependent on the quality, clarity, and R_L of horizontal road markings and some of the major obstacles in broad implementation of AV are related to inadequate recognition of travel path.

There are only a few studies directly relating those two factors. About a decade ago, performance of lane departure warning systems was reported to improve with the increase of line R_L (Hadi et al., 2007). It was later recognised that R_L of road markings is needed for all vision-based MV systems for proper night time guidance (Hadi and Sinha, 2011). A patent was issued to inventors who disclosed a pathway determination based on R_L (Stroila et al., 2014). Matowicki and co-workers (2016) reported a malfunction of a MV equipment on a road with markings having R_L of only 50 mcd/m²/lx. Davies (2017) presented the results of laboratory testing of MV with various horizontal markings: detection was reported to depend on line width (broader lines gave better results, even at lower R_L), R_L (higher R_L was easier to detect), and colour (yellow was more difficult to recognise than white); rather poor results were obtained during laboratory-induced rain. Carlson and Poorsartep (2017) after a field experiment reported on the deficiencies, which were noticed when using MV in North American infrastructure. For MV, the main identified issues were lack of line detection in case of poor contrast and incorrect line assignment in case of poorly maintained roads and in strong sunshine (Carlson, 2017). These deficiencies do occur, because MV relies on successful pattern recognition; recent advances in that field were summarised by Narote and colleagues (2018).

There are several critical path recognition issues, which are handled quite well by humans, but must be solved for MV. Various issues addressed below, associated with the quality of markings, are relatively easy to address with the current technology and results furnished herein can be used as the desired solution.

- Absence of horizontal markings in non-residential areas, which is really frequent on rural roads with very low traffic or on narrow ones.
- Obstruction of the markings by snow, ice, dirt, other vehicles, vegetation, etc.
- Lack of standard marking type, which demands complex programming of the MV software for proper classification.
- Poor condition of road surface, where cracks, potholes, and patches may lead to a misperception by the MV.
- Various marking quality, which seldom confuse people, but can confuse MV and cause inappropriate reading.
- Weather-related insufficient visibility of markings, in either inclement weather (snow fall, rain downpour, dense fog) and in excellent sunny weather (due to insufficient or excessive contrast and glare).
- The presence of 'phantom markings', caused either by removal of temporary markings, modification of the driving paths, or by longitudinal cracks or seal lines on the roadway surface.
- Proper handling of temporary markings, with all of their meanings and frequent lack of clarity. While there is a multitude of reports and patents related to AV and MV, there is almost a complete absence of literature related to reading of temporary markings by MV.

3.2. Horizontal road markings for human and machine vision

In Table 1 are listed some of the known issues associated with reading of horizontal road markings by MV with association to known needs for human vision. It is obvious that solving an inefficiency for a human driver simultaneously solves it for MV. The current MV technology, despite access to a broad spectrum of sensors, still does not match human vision, because computers cannot process ambiguous information as correctly as humans.

Table 1. Horizontal road markings and machine vision issues.

Issue	Description	References
Retroreflectivity	Current advanced MV require R_L>50 mcd/m²/lx	Carlson, 2017
	Minimum R_L for human drivers should be above 68 mcd/m²/lx	Parker and Meja, 2003; Burns et al., 2006
	Minimum R_L for older drivers should be above 150 mcd/m²/lx	Parker and Meja, 2003
	R_L>150 mcd/m²/lx recommended for all colours at all times for comfortable driving	Gibbons et al., 2012
	European Road Federation (ERF) proposed that a minimum of 150 mcd/m²/lx should be maintained at all lines at all times	
	Drivers notice and appreciate R_L>500 mcd/m²/lx	Burghardt et al., 2017; Pashkevich et al., 2017
	Field experiment demonstrated increased comfort of drivers at roads with high R_L, with particular benefit for elderly drivers	Diamandouros and Gatscha, 2016
	Laboratory experiment shown increased comfort of drivers with enhanced R_L	Horberry et al., 2006
Line width	Wider markings facilitate their detection by MV and limit the number of false detections	Davies, 2017; Carlson, 2017
	Statistical analysis shown that up to 38% accident reduction could occur with lines 15 cm wide (as compared to lines 10 cm)	Park et al., 2012
	Lines 15 cm wide are recommended by ERF	
	Lines 15 cm wide are now required in California for all of the lines on state roads	State of California, 2017
Contrast ratio	Contrast ratio between the marking and the pavement should be above 2:1, with better results achieved with MV at 3:1 contrast ratio	Carlson, 2017
	Glare is severely impairing driving ability	Theeuves et al., 2002
	Glare contributes to increase of crashes at intersections	Hagita et al., 2011; Mitra, 2014
	Glare might cause effects similar to driving in fog, when, due to a perceptual quirk, drivers think they are driving far more slowly than they actually are, and therefore increase their speed	Snowden et al., 1998
Clarity	Sharp edges of markings would be advantageous for detection and would eliminate ambiguities caused by seal marks	Carlson, 2017
	Clarity of horizontal road markings was reported to be preferred by human drivers and through association with aesthetics having influence on perception of road safety and thus the safety itself	Żakowska, 1997
Unification	Unification of markings across various countries is necessary for reliable MV and universality of AV	Carlson, 2017
	Difficulty of comprehension of vertical road signs by foreign drivers is well-established and the same occasionally may apply to horizontal signage, particularly for temporary marking	Shinar et al., 2003
	Unification of road signage across countries was proposed as a method of lowering the number of accidents and fatalities by up to 5,000 annually on Trans-European Road Network	Räsänen and Horberry, 2006
	Raised pavement markings (‘Bott’s Dots’) cannot be reliably classified by MV under all conditions	Carlson, 2017
	‘Bott’s Dots’ are being discontinued on state roads in California	State of California, 2017

4. Field evaluation of road markings

4.1. Durability of horizontal road markings

Horizontal road marking systems for human and machine vision must meet the requirements of clarity and retroreflectivity, must be durable to lower environmental burden and simultaneously, to be a solution for less-developed countries and be socially and politically accepted in the developed states, they must be reasonably inexpensive. Herein are presented the results from field testing of thick-layers structured cold plastic road marking systems done in three countries. Reflectorisation with three types of glass beads: standard, 30% premium (mixed with 70% standard), and 100% premium permitted for the assessment of the influence of glass beads. Nonetheless, it must be emphasised that at the three test fields were used base layer materials from different manufacturers, application was done by different crews, and weather conditions were different, which all could have profound influenced the outcome.

It must be understood that evaluation of road marking systems is difficult due to high level of uncertainty caused by numerous factors affecting their performance. While it is shown herein that the selection of glass beads can be the controlling parameter in durability (i.e. service life), it must be acknowledged that the climatic conditions, application quality, and road geometry can be equally important. Several researchers were struggling with finding correlation parameters for road markings durability and the appropriate model comprising majority of factors is still not developed in spite of some progress (Migletz et al., 2001; Zhang and Wu, 2006; Sitzabee et al., 2009; Hummer at al., 2011; Wang et al., 2016). As an example of critical influence of climatic conditions, we can provide the instance of thin-layer application of the same waterborne road marking systems in Croatia and in Poland: whereas in Croatia a three-year durability was achieved, in Poland the marking was destroyed during winter by snow ploughs (Burghardt et al., 2019).

4.2. Test fields and materials

Cold plastic structured thick-layer systems were applied on major dual carriageway roads in Switzerland, in Croatia, and in Poland. Application was done by local companies, using their standard procedures and equipment. The base layer materials, delivered by the applicators, were reflectorised with standard, premium, and premium mixed glass beads. The tested premium glass beads were SOLIDPLUS brand (M. Swarovski GmbH; Amstetten, Austria), characterised by exceptional roundness, improved resistance to scratching, and RI slightly increased to augment R_L, but still belonging to Class A according to the norm EN 1423:2012. Standard glass beads were furnished by the applicators. All of the tested glass beads were meeting Class 1 requirements of EN1423:2012 norm in terms of heavy metals and metalloids contents. Periodic measurements of R_L were done by independent parties using a dynamic method, with a retroreflectometer installed on a vehicle, which collects data during normal driving every few milliseconds and then provides average results for 50-100 m stretches.

In Table 2 is provided the basic information about the test stretches and the materials. There were two test fields in Croatia on the same road, with the same materials, but with application three years apart and at different lines. Weight-adjusted Annually Averaged Daily Traffic (AADT) was calculated according to the standard ONR 22440-1 (Austrian Standards Institute, 2010), where one heavy vehicle (comprising all buses and all vehicles over 3,500 kg gross vehicle weight rating) counts as eight light vehicles. Using weight-adjusted AADT permits for good comparisons of road stretches with different traffic loads. A significant limitation for the subsequent analysis was the unavailability of data regarding winter maintenance.

Table 2. Characteristics of the test stretches and applied materials.

Test field	Country, road, speed limit	Stretch length [km]	AADT			Base layer, applied mass	Glass beads, drop-on mass
			All	Heavy	Weight-adjusted		
1: all lines	Switzerland, T5, 120 km/h	0.4	34,965	1,573	45,976	Premium cold plastic, 2.2 kg/m²	100% premium, 0.45 kg/m²
2a: middle lines, 2b: edge lines	Croatia, D10, 100 km/h	23.2	12,204	986	19,106	Cold plastic, 2.2 kg/m²	30% premium, 0.35 kg/m²
3: middle lines	Poland, A4, 140 km/h	12.9	18,041	3,703	43,962	Cold plastic, 2.5 kg/m²	Standard, 0.35 kg/m²

4.3. Results of field evaluations

Results for the test stretch in Switzerland were also presented elsewhere (Burghardt, 2018). Herein, additional analysis and comparison with other systems is furnished. Retroreflectivity measured on all of the test fields are provided in Table 3. The results demonstrate clearly that with the use of 100% premium glass beads, notably higher initial R_L was achieved (average 949 mcd/m²/lx) than with 30% premium glass beads (average 482 mcd/m²/lx), which was only slightly higher than obtained for standard system (average 438 mcd/m²/lx, which was outstanding result, indeed). The differences after three years were proportionate to the initially recorded, based on both the time scale and the vehicular traffic scale, which accounted for much lower AADT in Croatia. Whereas we repeat here the caution that different traffic loads, climatic conditions, and used cold plastic could have played significant role, the results are consistent across countries and the trend is maintained.

Table 3. Retroreflectivity.

Test field	Line	Retroreflectivity (R_L) [mcd/m²/lx][(a)]							R_L loss [mcd/m²/lx]	
		Initial	1 year	2 years	3 years	4 years	5 years	6 years	First year	Next years
1	Edge right	1010 (153)	567 (127)	547 (163)	446 (93)	341 (52)	–	–	443	11
1	Middle	853 (96)	374 (67)	374 (92)	335 (46)	232 (20)	–	–	479	7
1	Edge left	984 (151)	688 (62)	675 (120)	518 (94)	372 (36)	–	–	296	16
2a	Middle eastbound	600 (66)	n/a[(b)]	n/a[(b)]	289 (42)	273 (51)	208 (44)	215 (33)	104[(c)]	25
2a	Middle westbound	545 (61)	n/a[(b)]	n/a[(b)]	180 (51)	174 (47)	177 (59)	152 (25)	122[(c)]	9
2b	Edge right eastbound	524 (168)	410 (91)	357 (97)	388 (101)	–[(d)]	–	–	114	11
2b	Edge left eastbound	402 (55)	385 (57)	317 (54)	325 (56)	–[(d)]	–	–	17	30
2b	Edge right westbound	418 (137)	350 (93)	257 (70)	292 (68)	–[(d)]	–	–	68	29
2b	Edge left westbound	404 (95)	366 (85)	257 (63)	295 (69)	–[(d)]	–	–	38	36
3	Middle eastbound	484 (98)	n/a[(b)]	158 (53)	–	–	–	–	163[(e)]	–
3	Middle westbound	391 (70)	n/a[(b)]	149 (44)	–	–	–	–	121[(e)]	–

[(a)]Average of dynamic readings per entire stretch, standard deviations provided in parentheses. [(b)]Measurements were not done. [(c)]Calculated from R_L loss in the first three years. [(d)]Testing continues. [(e)]Calculated from R_L loss in the two years.

The loss of R_L was higher for middle lines (lane division within a carriageway) than for edge lines, which is reasonable and expected because of the higher number of vehicles encroaching on the markings (Craig et al., 2007). Performance at the edge lines was following the same durability patterns. Unfortunately, relevant data from Poland for the standard system at edge lines cannot be obtained. The poor results obtained with the standard glass beads in Poland could also be the result of somewhat worse quality of cold plastic, inappropriate coating of glass beads, inadequate quality of application (particularly bead embedment – but, inappropriate glass bead embedment would lead to low initial performance, which was not the case), and numerous environmental factors (especially winter maintenance). At Croatian test field, there was a notable difference of 55 mcd/m²/lx (9%) between middle lines at the two carriageways; the difference continued for the subsequent years and during the sixth year increased to 63 mcd/m²/lx (29%). Similar difference was measured for the edge lines in the eastbound direction. We are unable to pinpoint the reasons for such a difference, but along with occasional lack of R_L loss or even its increases after usage (Cf. Table 3 for second and third year at test field 2b) these inconsistencies can serve as an example of the difficulties and uncertainties in assessment of horizontal road markings.

Predictions of durability (i.e. length of service, before (1) R_L<150 mcd/m²/lx recommended by the ERF, (2) R_L<200 mcd/m²/lx demanded for motorway by Swiss authorities, and (3) R_L<300 mcd/m²/lx required in Switzerland for new motorway markings), based on passes per carriageway of the weight-adjusted AADT, are given in **Error! Not a valid bookmark self-reference.**. To estimate the durability, exponential line fit for the entire test period was used (Abboud and Bowman, 2002); correlation with R^2>0.8 based on least squares analysis, except for one case, was calculated. Because measurements were done only once per year, multiple piecewise prediction model could not be applied to distinguish between summer (road traffic only) and winter (road traffic and snow ploughs) effects (Hummer et al., 2011). Much larger R_L loss during the first year of usage indicated that the analysis should be separated into at least two fragments, but also might indicate the 'diminishing returns' observed by Abu-Lebdeh et al. (2012).

Table 4. Predicted durability of the tested road marking systems.

Test field	Glass beads	Weight-adjusted AADT	Line location	Initial R_L [mcd/m²/lx]	Estimated durability [millions of weight-adjusted vehicle passes per carriageway], based on exponential line fit			
					R_L<300 mcd/m²/lx	R_L<200 mcd/m²/lx	R_L<150 mcd/m²/lx	Exponential line fit (R^2)
1	100% premium	45,976	Edge right	1010	33	44	51	0.90
			Middle	853	25	35	42	0.81
			Edge left	984	35	46	55	0.94
2a	30% premium	19,106	Middle eastbound	600	14	21	27	0.98
			Middle westbound	545	10	17	22	0.89
2b	30% premium	19,106	Edge right eastbound	524	18	30	39	0.61
			Edge right westbound	418	11	26	37	0.89
			Edge left eastbound	402	18	30	39	0.98
			Edge left westbound	404	7	17	23	1.00
3	Standard	43,962	Middle eastbound	484	7	13	17	–
			Middle westbound	391	4	11	16	–

5. Financial scenarios

One of the key parameters in selection of road marking systems by road administrators and by contractors is financial assessment. In doing such a valuation for this paper, it was necessary to make numerous assumptions and educated guesses, because the actual costing always remains a business secret of the manufacturers and applicators; therefore, the expense scenarios provided herein are to serve only as a guideline. In Table 5, financial scenarios for two- and three-year durability of the standard system is compared with multi-year durability of a system reflectorised with 100% premium glass beads. While the scenarios in Table 5 contain a time scale, it can be converted to the AADT scale to better convey the message; however, in such a case the effects of winter maintenance should be taken into account; such analysis is beyond the scope of this work.

Table 5. Financial scenarios based on durability of the analysed road marking systems.

Expense allocation	Standard system		Premium system				
Labour, fixed costs, profit	15%		20%				
Cold plastic (at 2.20 kg/m²)	80%		85%				
Glass beads (at 0.45 kg/m²)	5%		20%				
Initial expense	100%		125%				
Expected durability [years]	2	3	2	3	4	5	6
Relative total cost per 10 years, assuming 2-year standard durability	100%	–	125%	83%	63%	50%	42%
Relative total cost per 10 years, assuming 3-year standard durability	–	100%	188%	125%	94%	75%	63%

The results presented in Table 5 clearly demonstrate that the higher initial expense associated with the purchase of premium road marking materials may lead to substantial long-term financial savings. It is obvious that the worst choice are road marking systems with low durability. The advantage for contractors who won performance-based tenders should be obvious, but it can be extended also to road administrators and the entire society. Thus, highly durable road markings can be seen as the relatively inexpensive solution sought to improve road safety in less developed countries.

Inflation and price volatility were not included in the comparison, even though all those skilled in business analyses would admit that they could play a significant role. The financial scenarios also exclude any indirect effects like those associated with road safety, even though increased R_L was correlated with lower number of crashes (Carlson et al., 2013). Furthermore, social benefits of improved mobility of senior citizens and thus increased equal access to infrastructure, caused by increased R_L and thus comfort of driving, are not being calculated. Benefits for improved MV capability are disregarded, too.

6. Discussion and Conclusions

The differences between performance of road marking systems reflectorised with premium, 30% premium, and standard glass beads were clear in terms of R_L and systems durability. It has to be noted that R_L achieved with 100% premium glass beads was significantly exceeding the existing norms, which never call for more than 300 mcd/m²/lx initially. The presented results indicate that the norms might need to be adjusted to match the newly available technologies, in agreement with Jaffe and co-workers (2002) who envisaged constant modification of the standards with technological change to maximise the benefits and to promote further development.

Cradle-to-grave Life Cycle Assessments (LCA) done on thin-layer road markings demonstrated that the main parameter for environmental friendliness was not the choice of paints, but the durability of the entire road marking systems (Burghardt et al., 2016a; Cruz et al., 2016). We are not aware of any published LCA related to thick-layer road marking systems but believe that, like in case of paints, durability would also be the controlling environmental parameter. Given enormous expense associated with accidents, the main financial impactor in analysis of horizontal road markings effectiveness was calculated to be the number and severity of accidents, but the second impactor was reported to be system durability (Pike and Bommanayakanahalli, 2018).

Since market penetration of road markings with high R_L is rather low, lacking are analyses related to its influence on road safety, on fatigue and comfort of drivers, and other associated effects. Based on survey results showing that drivers notice high R_L (Burghardt et al., 2017; Pashkevich et al., 2017) and the reported lesser drivers' stress on well-marked roads (Horberry et al., 2006; Diamandouros and Gatscha, 2016) meaningful positive effects can be anticipated.

It was shown that majority, if not all, of the current issues with the use of MV to recognise and properly classify horizontal road markings are the same deficiencies that impair their human perception. Presented herein road marking systems are meeting and exceeding the expectations of the human drivers and MV. Therefore, their maintenance at highest standards would serve not only human drivers, but also AV, which was recently recognised by European Commission (2018) in the proposed Third Mobility Package: "*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*."

In the foreseeable future, horizontal road markings are going to guide not only humans driving their vehicles, but also computer-controlled automobiles. Human drivers must be able to take over steering of self-driving vehicles until full automation becomes standard on all vehicles and all roads; therefore, maintenance of horizontal signalisation infrastructure at appropriately high level is an absolute necessity. The recently developed technology for premium glass beads that can furnish R_L meaningfully beyond the current norms is meeting the requirement for high clarity and visibility of pavement markings. Since road safety is significantly influenced by horizontal road markings and high-end premium solutions provide excellent results in terms of R_L, durability, overall price, and environmental friendliness, their use as the first choice for horizontal road markings on primary roads would be reasonable. Because horizontal road markings are inexpensive and effective safety features; they are one of the easy to implement solution sought for countries with disproportionally high accident rates.

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