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CHARACTERISATION OF LUMINESCENT ROAD MARKINGS

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Abstract

Photoluminescent paints for road marking have been evaluated through laboratory measurements and visibility computations. The luminance decay in the dark was measured after constant excitation during at least six hours. To study the effect of night-time lighting conditions, luminance was also measured under a constant low illumination simulating moon and light pollution, and a periodic lighting simulating automotive traffic. Measurements were also carried out on luminescent road markings applied in a full scale mock up. Then, possible uses and limits of photoluminescent road markings were investigated through visibility computations based on the COST 331 model. Findings suggest that luminescent road markings could strengthen the visual guidance of drivers on the road with traffic by increasing the visibility distance beyond the range of the headlamps during the first few hours of the night, but it depends on the night-time illumination level.

Keywords: luminescent road markings, glow-in-the-dark, visibility

1 Introduction

Road markings help motorists to control and anticipate their trajectory. This is especially true at night, when other visual cues are less visible. In unlit areas, retro-reflective markings are visible when illuminated by vehicle headlights. Nowadays, innovative products may increase the visibility distance of visual cues, improving the guidance in unsafe situations (e.g. Shahar et al., 2018). In particular, luminescent road markings are being developed in order to allow the markings to be visible beyond the range of the headlamps. Luminescent markings emit light after absorbing photons from sunlight or headlamps with a delay from a few nanoseconds to several hours. The intensity of this emission depends on the quantity and of the spectral power distribution (SPD) of the light previously absorbed.

To be applied on the road, luminescent markings must ensure performance at least equivalent to traditional markings, especially in terms of colour and brightness during the day, and retro-reflection at night (CEN, 2018). In addition, understanding the temporal evolution of its colour and luminance is required to characterize these products. Standards already exist for safety luminescent products, used for emergency signage in buildings, based on the luminance in the dark during the first hour of emission (ISO 17398, 2004). In the road context, we are interested in longer emission times, in various night-time illumination conditions, with road traffic, and in low viewing angles, corresponding to the vision of a motorist ($<2.5^\circ$) or a cyclist ($\sim 10^\circ$, see Chain & Marchaud, 2008).

Since 2014, corresponding to the first road tests of such “glow-in-the-dark” road markings in the Netherlands (BBC, 2014), a few publications have explored the possibility of using strontium aluminate crystals for road marking (Giuliani & Auteliano, 2014; Bullough et al., 2014; Bacero et al., 2015; Pratico et al., 2016, 2018) or other road applications (e.g. Weise et al., 2019; Saleem & Hosoda, 2021). Giuliani & Auteliano (2014) compared different types of luminescent products and demonstrated that the luminescence of strontium aluminate lasts much longer than with conventional powders. In terms of duration, the afterglow of the best tested product did not last in the dark beyond 2 hours, and simulated traffic of halogen vehicle headlamps did not keep the emission going overnight. The authors based their analyses on a theoretical visibility limit of 0.3 mcd/m^2 . Botterman & Smet (2015) also investigated the relevance of such powder for luminescent road markings depending on the temperature and the illumination. Based on calculations, they estimated that the recharge of the product by the traffic only slows the fall in luminescence which decreases through the night. To interpret luminance in terms of visibility, the authors discussed the threshold of 0.3 mcd/m^2 , with reference to the absolute threshold of perception, which is relevant in the dark, but not on the road. Bullough et al. (2014) used a threshold of 0.01 cd/m^2 . Their luminescent samples measured in the laboratory provide

a luminance in the dark above this threshold from 10 minutes to 4 hours after an excitation under a luminaire providing 50 000 lx with a metal halid lamp.

In previous work, luminescent markings performances was mostly assessed by comparing the luminance in the dark to a luminance threshold. But since the main function of road markings is the visual guidance, the most relevant indicator is the visibility distance of the markings at night (CIE, 1992). The COST 331 report (1999) of the European Commission proposes a method, based on Adrian's Visibility Level model (Adrian, 1989), for calculating the visibility distance from the luminance of a road marking, its width, the geometry of the road and the driver's age.

In this context, the present paper proposes a method to characterize the performance of luminescent road markings based on laboratory measurements and visibility computations with the COST 331 model. The potential use of this type of product is discussed.

2 Material and method

2.1 Laboratory measurements

2.1.1 Samples

The measurements were carried out on various LuminoKrom® samples, produced during the I-Street research project. Paint was deposited on aluminium plates and asphalt plates made in the laboratory, at various stages of the development of the product. Application was manual with a roller or with a road marking machine. Table 1 provides the characteristics of the samples used in this study (see illustrations Fig. 1). No retro-reflective samples are considered in this paper (all were class R0 according to the EN 1436 standard). Chromatic coordinates were measured with a spectro-photometer CM-2500C after 5 minutes of excitation under D65 illuminant enhanced with UV. Figure 1 presents a white luminescent paint (center) sample, which meets the chromaticity requirements of the EN 1436 standard (CEN, 2018), and a green one (right).

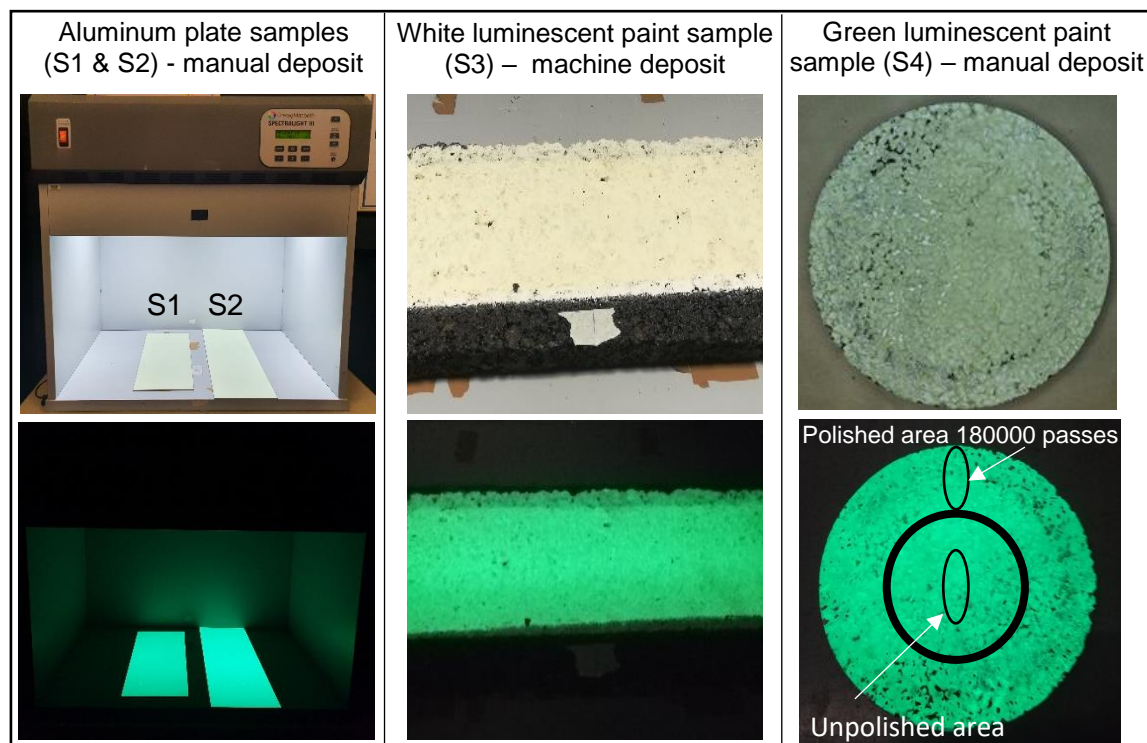


Figure 1 – Examples of samples. Left: Aluminium plate samples in the light booth (S1 & S2); Center: White luminescent paint sample S3; Right: Core sample S4 of green luminescent paint artificially worn with a Wehner & Schulze machine. The ellipses corresponds to the luminance measurement zones.

Table 1 – Laboratory sample characteristics

Name	Support	Application	Chromatic coordinates [x,y]
S1	aluminium	manual (roller)	[0.332,0.374]
S2	aluminium	manual (roller)	[0.330,0.374]
S3	asphalt	machine	[0.337,0.363]
S4	asphalt	manual (roller)	[0.357,0.401]

2.1.2 Colour measurement

The chromatic coordinates of a luminescent paint sample deposited on an aluminium plate (S1) was measured at a 90° observation angle with a spectroradiometer CS1000 during 30 minutes of excitation with a D65 illuminant and then during ten hours of emission in the dark.

2.1.3 Luminance measurement in the dark

The simplest characterisation of a luminescent paint is to measure the luminance decay in the dark after constant excitation. The paint was excited for 30 minutes in a light booth (Spectralight III X-Rite) at 1.5 klx horizontal illuminance with a D65 illuminant enhanced with ultraviolet (see Figure 1, left). Then, the sample was placed in a dark room and the luminance was measured every 10 minutes with a spectroradiometer PR770 during six to ten hours. The measurement was carried out with an observation angle of 2.29° corresponding to a driver according to the EN1436 standard (CEN, 2018). The luminance measured in the dark as a function of time is called the decay curve.

To investigate the durability of the product's afterglow, the measurements were also conducted after artificial ageing. To that purpose, a core sample of a Very Thin Layer Asphalt Concrete plate (S4) was polished with 180000 roller passes with a Wehner & Schulze machine. Then, the decay curves of the polished area and of the central unpolished area were measured (see Figure 1).

The emission in complete darkness is a theoretical reference situation, which does not correspond to the real situation on the road. To study the effect of night-time lighting conditions, two scenarios have been studied in the laboratory: constant low illumination, such as moon or light pollution, and periodic lighting, simulating automotive traffic.

2.1.4 Luminance measurement under constant illumination

Night-time illumination was simulated with a constant horizontal illuminance on the sample of 0.01, 0.05, 0.1 or 0.5 lx, using a RGB LED Matrix (behind a diffuser) controlled by Arduino. Although the SPD was questionable, it allowed providing a controlled low diffuse illuminance on the samples. Using the same excitation protocol described in Section 2.1.3, the decay luminance of a luminescent sample was measured every hour during seven hours (averaged over five measurements) with a luminancemeter PR880 at a 2.29° observation angle. The luminance of fully discharged samples was also measured under each illuminance level.

2.1.5 Luminance measurement under cyclic illumination

The same RGB LED Matrix was used to simulate a periodic illumination due to road traffic. The horizontal illuminance variation on road markings due to real LED low-beam headlamps was simulated. Based on the horizontal illuminance profile, it was possible to simulate different vehicle speeds and different traffic densities (in veh/h). This periodic lighting was applied during six hours in the dark, the sample being previously excited as in Section 2.1.3. The luminance of luminescence was measured every hour with a luminancemeter PR880 at a 2.29° observation angle (averaged over 5 to 10 measurements) when the LED was switched off.

2.2 Measurements on real road markings

To investigate more realistic conditions, a white and a green luminescent road markings were applied in an urban innovation demonstrator located in a climatic chamber, called Sense-City

(<https://sense-city.ifsttar.fr>). The luminance of the two road markings at a 2.29° observation angle was measured with a spectroradiometer PR740 every five minutes during three simulated sunsets representative of those occurring during a year in Lyon, France, and then every ten minutes during six hours in the dark. The sunset was simulated by decreasing every 15 minutes a controlled artificial sun (32 metal halid lamps, 22600lm, 5600K) during the two hours before civil twilight. The three sunsets were determined conducting a hierarchical ascendant clustering analysis (euclidean distance) of the horizontal illuminance measured during the two hours before the civil twilight in 2018, extracted from the IDMP Database of ENTPE (<http://idmp.entpe.fr/mesfr.htm>). The main characteristics of the mean sunsets are as follows:

- C1: from 2500 lx at -120 min to 11 lx at -15 min, 32.6% of the year,
- C2: from 7000 lx at -120min to 17 lx at -15 min, 42.2% of the year,
- C3: from 11000 lx at -120 min to 30 lx at -15 min, 23.8% of the year.

The ambient temperature was kept constant at 12°C ($\text{SD}=0.05$), and the road surface temperature was around 13°C (13.5°C when the sun was switched on). The mean relative humidity was 77.1% ($\text{SD}=1.7\%$).

2.3 Visibility computations

From the laboratory measurements of samples S2 and S3 and the calculation method proposed in the COST 331 report (1999), the visibility distance of the luminescent marking beyond the headlamp beam was estimated, and compared to the visibility distance of a traditional retroreflective marking in low beam headlights. Computations were based on the assumption that with equivalent R_L , the luminescent markings only provide significant added value if it is visible beyond the beam of the headlights. The visibility distance corresponds to a Visibility Level threshold of 10 (COST 331, 1999).

A continuous central line of 7.5 cm width on a straight and flat road with lane width of 3.5 m and dark asphalt ($Q_d=60 \text{ mcd/m}^2/\text{lx}$, $R_L=10 \text{ mcd/m}^2/\text{lx}$) was considered. A traditional retroreflective marking ($Q_3 Q_d=130 \text{ mcd/m}^2/\text{lx}$, $R_4 R_L=200 \text{ mcd/m}^2/\text{lx}$) illuminated by the theoretical low beam headlights of the COST 331 tool (intensity factor 1, i.e. 10000 cd) was taken as a reference for comparison.

3 Results

3.1 Colour variations

The colour of luminescent markings changes over time. During the day, it depends on the reflection and fluorescence properties of the product, and on the SPD of daylight. At night, the luminescence emission spectrum shifts the chromaticity towards green. Figure 2 shows the “colorimetric trajectory” during the excitation and the emission in the dark of a sample of luminescent paint (S1). The significant change in colour between day and night raises questions about the appropriate measurement method to characterize this class of products.

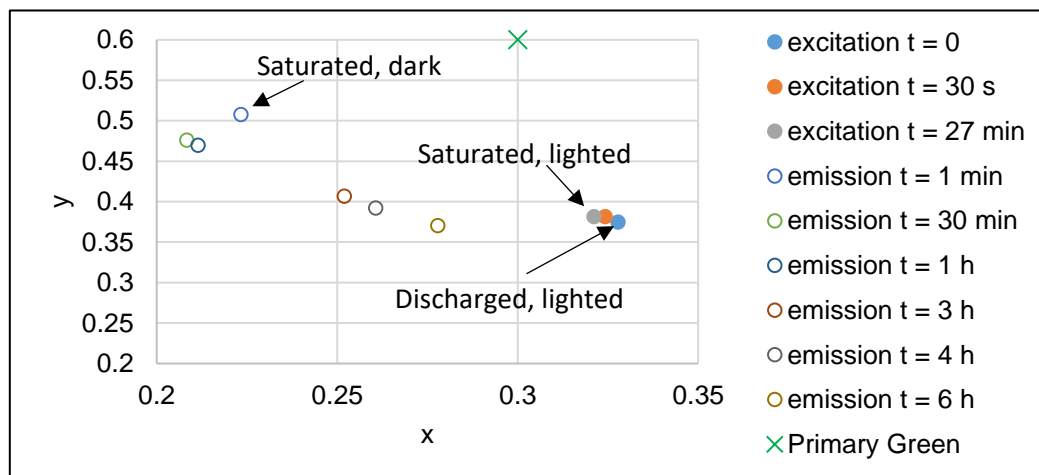


Figure 2 – Evolution of chromatic coordinates of a luminescent paint sample (S1) during an excitation/emission cycle.

3.2 Luminance measurements

3.2.1 Luminance measurement in the dark

Figure 3 shows the decay curves obtained in the laboratory with two samples (S3 & S4, see Fig. 1). The luminance of the white luminescent sample S3 (black curve in Figure 3), which meets the chromaticity requirements of the EN 1436 standard (CEN, 2018), decreases from 28.6 mcd/m² after one hour of emission in the dark to 7.2 mcd/m² after 3 hours, down to 1.6 mcd/m² after 10 hours. The luminance of the green sample (S4), which does not meet the chromaticity requirements of this standard, is two to three times higher (dark green curve in Figure 3).

In terms of durability, the decay curve of an area of the polished core (light green curve in Figure 3) after 180,000 passes is approximately 15% lower than that of the unpolished area (dark green curve in Figure 3).

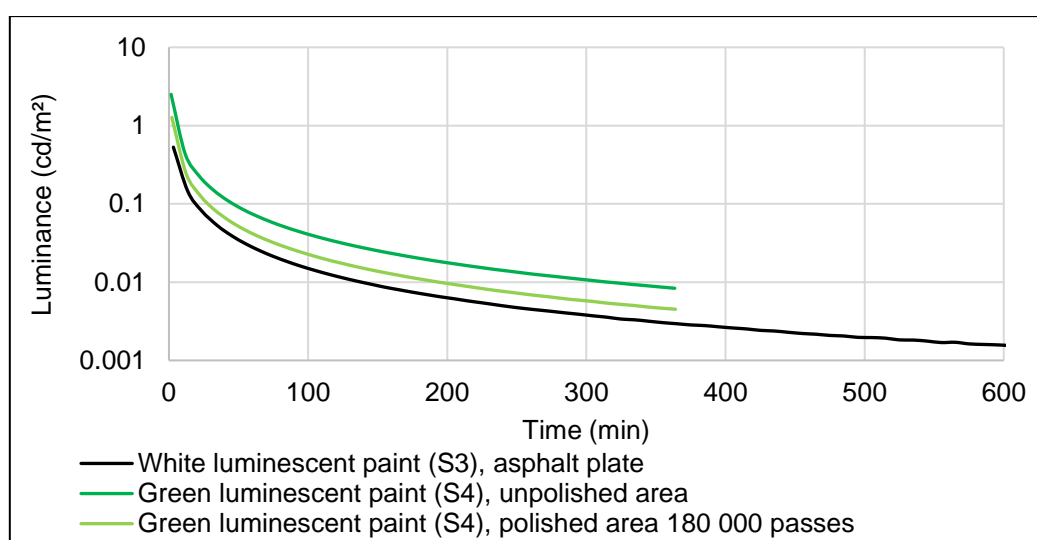


Figure 3 – Decay curves in the dark measured in the laboratory at 2.29° observation angle after 30' min of excitation under 1500 lx in a light booth (D65 illuminant + UV).

3.2.2 Luminance measurement under constant illumination (moon)

Table 2 shows the decay curve (under 0.1 lx and in the dark) of sample S1 deposited on an aluminium plate. As expected, the luminance during the emission under constant low illumination is higher than in the dark. The significant point is that the difference between the two is stable over time, and proportional to the illuminance (for $E \leq 0.5$ lx). This difference, which corresponds to the luminance "bonus" specifically related to ambient lighting, can also be estimated by measuring, under this very low lighting, the luminance of the discharged sample (22.5 mcd/m² under 0.1 lx for sample S1, see Table 2).

Table 2 – Difference ΔL between the luminance (mcd/m²) under 0.1 lx and in the dark during emission of sample S1 of luminescent paint deposited on an aluminium plate

Time (min)	Luminance decay under 0.1 lx (mcd/m ²)	Luminance decay in the dark (mcd/m ²)	Difference ΔL (mcd/m ²)
60	74,3	50,3	24,0
180	36,8	13,9	23,0
240	32,2	9,9	22,3
300	30,0	7,6	22,4

360	28,6	6,2	22,4
420	27,8	5,1	22,6

On a moonless night, the horizontal illumination on the roadway is around 0.01 lx (between 0.008 and 0.016 lx measured by the authors on a dual two-lane road in the open country). It increases during moonrise up to 0.03 lx or even 0.08 lx depending on the period (measurements carried out by the authors on the same dual two-lane road), and can reach 0.1 to 0.3 lx on a full moon night (Kyba, 2017). In addition, ground level illumination due to light pollution in overcast skies can reach levels similar to a full moon (Kyba, 2017). For sample S3 (Figure 1, center), an increase of 2.1 mcd/m² was measured under 0.01 lx, of 9.9 mcd/m² under 0.05 lx, of 19.5 mcd/m² under 0.1 lx and of 98.6 mcd/m² under 0.5 lx with respect to the decay curve in the dark. The offset (in mcd/m²) is comparable to the luminance values of a Q5 traditional road marking with $Q_d=200$ mcd/m²/lx. The Q_d of this sample measured outdoor during daytime was 238 mcd/m²/lx.

3.2.3 Luminance measurement under cyclic illumination (traffic)

The expected and observed effect of the periodic traffic on luminescence emission is an increase of luminance over time with respect to the decay curve in the dark. The increase is constant over time. In addition, this increase varies linearly with traffic density (Figure 4), and is inversely proportional to the simulated vehicles speed.

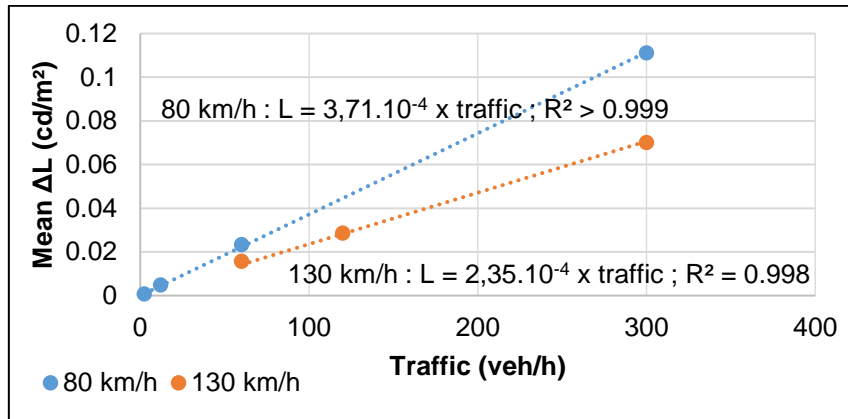


Figure 4: Mean difference ΔL (cd/m²) between the luminance in the dark with traffic and without traffic during the discharge of sample S2 of luminescent paint deposited on an aluminium plate depending on the simulated traffic (veh/h) at 80 and 130 km/h.

For the white luminescent sample S3 (Figure 1, center), an average increase of 10.9 mcd/m² was measured under a traffic of 120 veh/h at 80 km/h. In this case, the contribution of the simulated automotive lighting corresponds to an increase of 150% after 3 hours, compared to the emission in the dark.

3.3 Measurement in controlled environment on real road markings

Examples of decay curves obtained after two hours of simulated sunsets are shown in solid lines in Figure 5. As observed in laboratory measurement with other samples, the white luminescent marking (in accordance with the EN1436 requirement) emitted less luminescence than the green one. The measurements show small differences from one sunset to another, especially after several hours of emission in the dark (< 10% for white luminescent marking, < 5% for the green one). During the first two/three hours of emission in the dark, the luminance was lower after the darker sunset (up to 20% for the white luminescent road marking).

Note that the solid green curve was obtained with the same green paint pot (S4) as the core manually painted shown in Figure 1 (right). We see in Figure 5 that the luminance of the asphalt sample (dotted curve) is greater than that of the one measured in Sense-City (solid green curve). This can be due to the difference in application, in particular the lower and more realistic paint density in Sense-City, and to the lower horizontal illuminance, below 200 lx, received during the last half hour of excitation in Sense-City.

Finally, the measurements in Sense-City showed that the luminescent markings tested are brighter than a traditional Q5 class white marking ($Q_d = 233 \text{ mcd/m}^2/\text{lx}$) during sunset, between 1h and 30 min before full darkness.

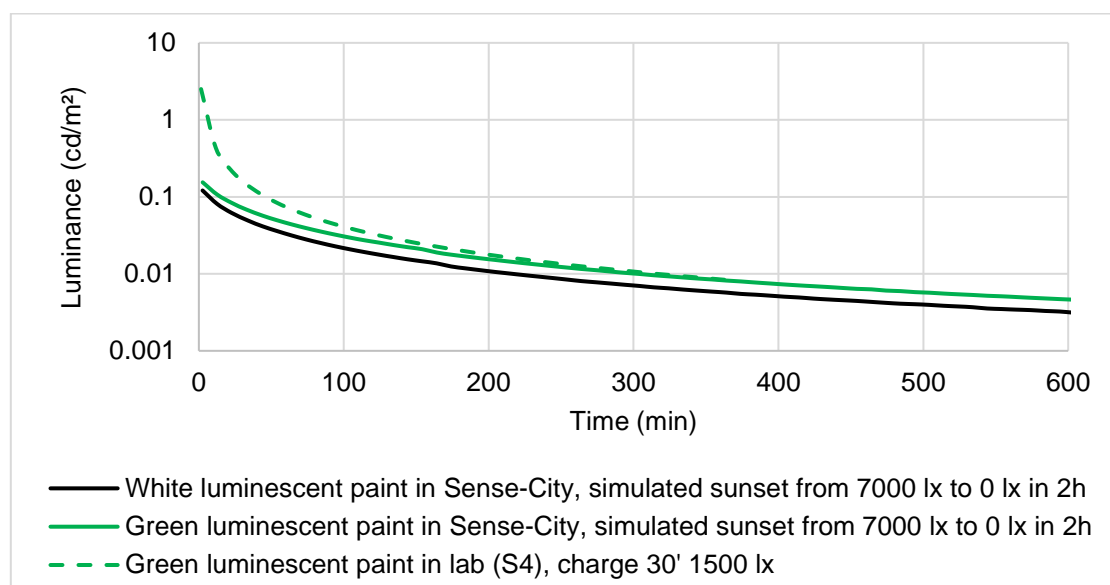


Figure 5: Decay curves in the dark at 2.29° observation angle. Solid lines: in Sense-City after a simulated sunset from 7000 lx to 0 lx in 2h; Dotted line: sample S4 of the same green luminescent paint measured in laboratory 30' min of excitation under 1500 lx in a light booth (D65 illuminant + UV)

3.4 Visibility computations

From the laboratory measurements described above and the calculation method proposed in the COST 331 report (1999), the visibility distance of the luminescent marking beyond the range of the headlights was calculated, and compared to the visibility distance of a traditional retroreflective marking illuminated by conventional low beam headlamps. Our findings assume that the luminescent marking is equivalent to the traditional road marking in terms of retro-reflection (same R_L).

The luminance of the luminescent road markings was estimated from the decay curves computed from the measurements in the dark and from the offsets due to constant illumination and simulated traffic. The conclusions of our visibility computations depend on the considered luminescent samples, on the night-time ambient lighting, on the traffic and the assumptions used for comparisons (R_L & Q_d of traditional markings, type of headlights).

Under an ambient illumination of 0.01 lx and without traffic, a white luminescent marking (sample S3), which meets the chromaticity requirements of the EN 1436 standard (CEN, 2018), could be visible between one and two hours after the start of the night in a straight line at a distance greater than the traditional marking (illuminated with low beam headlights). With sample S2, which does not meet the required chromaticity, this advantage could last between two and three hours under 0.01 lx and one hour under 0.1 lx. The visibility distance of a traditional road marking with high beam headlights is always higher than the one of a luminescent marking without headlights.

Traffic increases the visibility of the luminescent markings, but the benefit is very dependent on the night-time ambient illumination. Figure 6 shows the time during which a white luminescent road marking (sample S3, Figure 1, center) could be visible beyond the low beam headlights at a greater distance than a traditional retroreflective road marking (Q_3 $Q_d=130 \text{ mcd/m}^2/\text{lx}$, R_4 $R_L=200 \text{ mcd/m}^2/\text{lx}$). This “useful time” is given as a function of the traffic (in veh/h) at 80 km/h, for various illumination conditions and young and older drivers (20 and 60 years old).

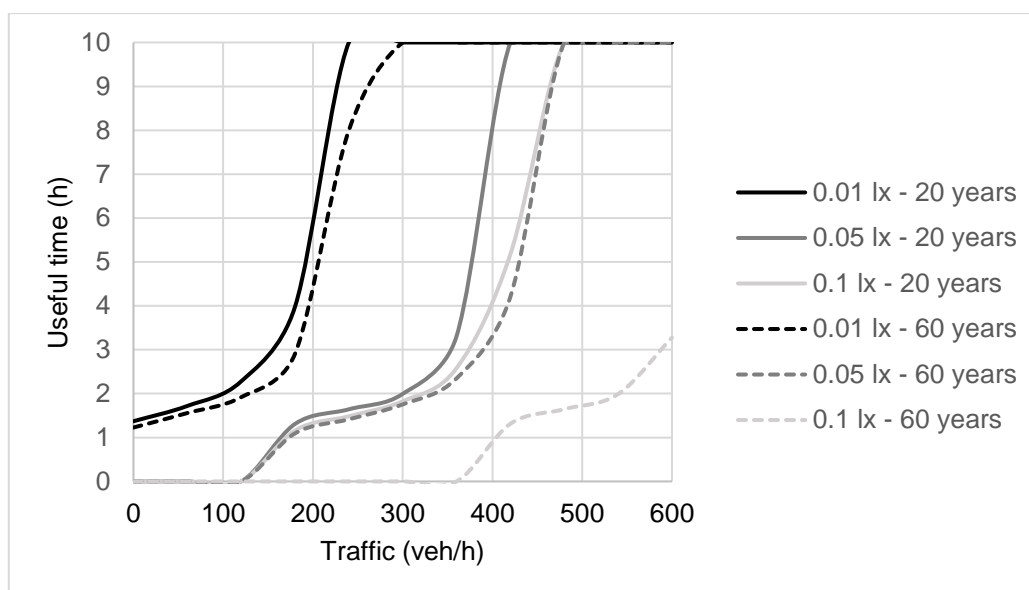


Figure 6 – Useful time (h) as a function of the traffic density (veh/h) at 80 km/h under 0.01 lx (black), 0.05 lx (dark gray), or 0.1 lx (light grey). The useful time is the time during which the visibility distance of a white luminescent road marking (S3) (beyond the low beam headlight) is higher than the one of a traditional road marking (Q3 $Q_d=130 \text{ mcd/m}^2.\text{lx}$, R4 $R_L=200 \text{ mcd/m}^2.\text{lx}$) in low beam headlights, assuming that both markings having the same R_L . Solid line: 20 year-old driver. Dashed line: 60 year-old driver.

According to Figure 6, the excitation from a traffic of 300 vehicles/hour, traveling at 80km/h with low beam headlights, allows a white luminescent marking to be visible during the first two hours of the night, or even all night under 0.01 lx, at a greater distance than the traditional marking taken as reference (see Section 2.3). The gain in visibility provided by luminescent marking is lower for the older drivers, but when the traffic is high enough, an increase of visibility distance beyond the headlights can improve their safety.

4 Conclusions

In this paper, a repeatable and simple laboratory measurement procedure on luminescent samples associated with visibility computations was proposed to characterise the performance of luminescent road markings. Our findings show that for equivalent performance in terms of R_L and Q_d , luminescent markings may strengthen the visual guidance of drivers on the road by increasing the visibility distance beyond the headlamps range under favourable night-time lighting conditions and with traffic. Depending on the conditions, the benefit may last a few minutes or the whole night through. Beyond the range of the headlamps, luminescent markings are of interest when the luminescence significantly increases the luminance of the marking compared to the reflection alone, which is possible in low light conditions on unlit roads. These conclusions are mainly based on measurements conducted on samples in the laboratory (dry sample, controlled temperature, artificial polishing), or in a controlled environment (artificial sunset), and on the visibility calculations carried out with the COST 331 method.

Some assumptions in our computations are questionable. The visual adaptation level does not take into account the headlamps in the computation of the visibility distance beyond the headlight beams. In addition, we assumed that the luminescent marking are retroreflective, while our computations were based on luminance measurement of a non-retroreflective sample (R0 class). Findings need to be confirmed with homologated retro-reflective luminescent road markings.

Measurements in laboratory conditions differ from real situations. On the one hand, the simulated scenarios are simplified, and in particular, the excitation phase of the products is somehow conventional, not directly related to what happens during the day and twilight. As highlighted with our measurements in the Sense-City full scale mock-up, the lower illuminance

at the end of the sunset leads to a lower luminescence in the first hours of darkness. In addition, light sources used in the laboratory excitation can be discussed. Especially, our simulation of night-time illumination could be improved using another, more realistic, spectral power distribution. Similarly, the traffic simulation may have overestimated the effect of traffic, as actual headlamps may use either LEDs or halogen sources; the latter contains less exciting short wavelengths. On the other hand, it is questionable whether the performance measured on (roller paint) samples produced in laboratory represents the performance of paints applied with a controlled density on the pavement with dedicated machines.

Our findings need to be confirmed by more systematic on-site measurements, under different conditions (e.g. temperature, humidity). Therefore, the experimental deployment of these products on experimental sites, and *in situ* monitoring methods will provide an improved feedback on performance whatever the external conditions and wear. Others scenarios could also be investigated, such as cycle paths and urban and road lighting.

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