Characterization of luminescent road markings

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Photoluminescent paints for road marking application 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 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 marking applied on real pavement 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 luminescent road markings could strengthen the visual guidance of drivers on the road with traffic by increasing the visibility distance beyond the headlamp beams during the first few hours of the night, and in unlit areas such as bicycle paths, but the performance depends on the night-time illumination level.

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1. Introduction

The visibility of road markings helps motorists to control their trajectory and to anticipate it. 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.[1] In particular, luminescent road markings are being developed in order to allow the markings to be visible beyond the headlamp beams or in unlit areas, such as bicycle paths. Luminescent properties enable light emission of the markings after absorption of 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 on the spectrum 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.[2] 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 signalling in buildings, based on the luminance in the dark during the first hour of emission.[3] In a road context, we are interested in longer emission times, in various night-time illumination conditions, with road traffic, and in small viewing angles, corresponding to the vision of a motorist (<2.5°) or a cyclist (~ 10°).[4]

Since 2014, corresponding to the first road tests of such "glow-in-the-dark" road marking in The Netherlands,[5] a few publications have explored the possibility of using strontium aluminate crystals for road marking[6-10] or other road applications[11,12]. Giuliani & Auteliano[6] compared different types of luminescent products and showed that the luminescence of strontium aluminate lasts much longer than conventional powders: strontium aluminate pigments produce luminescence during a few hours after excitation (5 to 6 hours above 1 mcd/m²), regardless of the presence of UV in the excitation spectrum (30 lx, ~1000-1500 lx, 20°C). Giuliani and Auteliano[6] also investigated excitation with simulated road traffic, illuminating the samples with a halogen lamp (4-6 lx) during three seconds for each simulated vehicle, from 6 to 20 per minute. No luminescence was obtained from such excitation. Finally, according to five participant's observations, no luminosity was perceived from the powders tested after two hours in the dark (30 min 1050 lx, daylight with UV, 20°C). Botterman and Smet[13] also investigated the relevance of such powders for luminescent road marking 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 decrease through the night. To interpret luminance in terms of visibility, the authors discussed the threshold of 0.3 mcd/m², with reference to the absolute threshold of perception, which is relevant in complete dark, but not on the road. Bullough *et al.*[7] used a threshold of

0.01 cd/m². Their luminescent samples measured in the laboratory provided 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 halide lamp.

In previous work, luminescent marking performances were mostly assessed by comparing the luminance in the dark to a luminance threshold. But since the main function of road markings is visual guidance, the most relevant indicator is the visibility distance of the markings at night.[14] The COST 331 report[15] of the European Commission proposes a method, based on Adrian's work,[16] 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, this 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. Proposed approach

Several modus operandi have been developed in the laboratory to characterise the temporal evolution of the colour and luminance of luminescent road markings samples. In terms of luminance, the easiest characterization is to measure the luminance decay in the dark after constant excitation. But it does not correspond to the real situation on the road. To study the effect of night-time lighting conditions, we also characterized the luminance evolution under constant low illumination, such as moon or light pollution, and under a periodic lighting simulating automotive traffic. Both conditions add some excitation of the product over the night. To investigate more realistic conditions, the luminance during and after a simulated sunset was measured on luminescent road markings applied in an urban innovation demonstrator.

From these laboratory measurements, two use-cases were investigated, a straight road and a bicycle path, through visibility distance computations using the model proposed in the COST 331 report[15] from the European Commission.

3. Material and method

3.1 Laboratory measurements

3.1.1 Luminescent samples

The measurements were carried out on various LuminoKrom® samples (see Figure 1), produced during a research project. Paint was first deposited on aluminium plates and then on asphalt plates made in the partner laboratory, at various stages of the development of the product. Application was manual with a roller or with a road marking machine. Our investigations were not conducted on the same samples received in the course of the research project. Table 1 provides characteristics of the samples used for results illustrations below.

Non-retroreflective samples (R0) are considered in this paper. Chromatic coordinates were measured with a spectro-photometer CM-2500C after 5 minutes of excitation under D65 illuminant enhanced with UV (see normalized spectrum in Figure 2). To characterize daylight reflection with respect to the EN1436[2], the luminance factor β was measured for aluminium samples S1 and S2 in the laboratory, while the luminance coefficient in diffuse illumination Qd was measured for asphalt samples S3 and S4 with a retro-reflectometer LML-XL (see Annex 1 for the definitions of β and Qd). Figure 1 presents a white luminescent paint sample (center), which meets the chromaticity requirements of the EN1436 standard[2], and a green one (right) which does not.

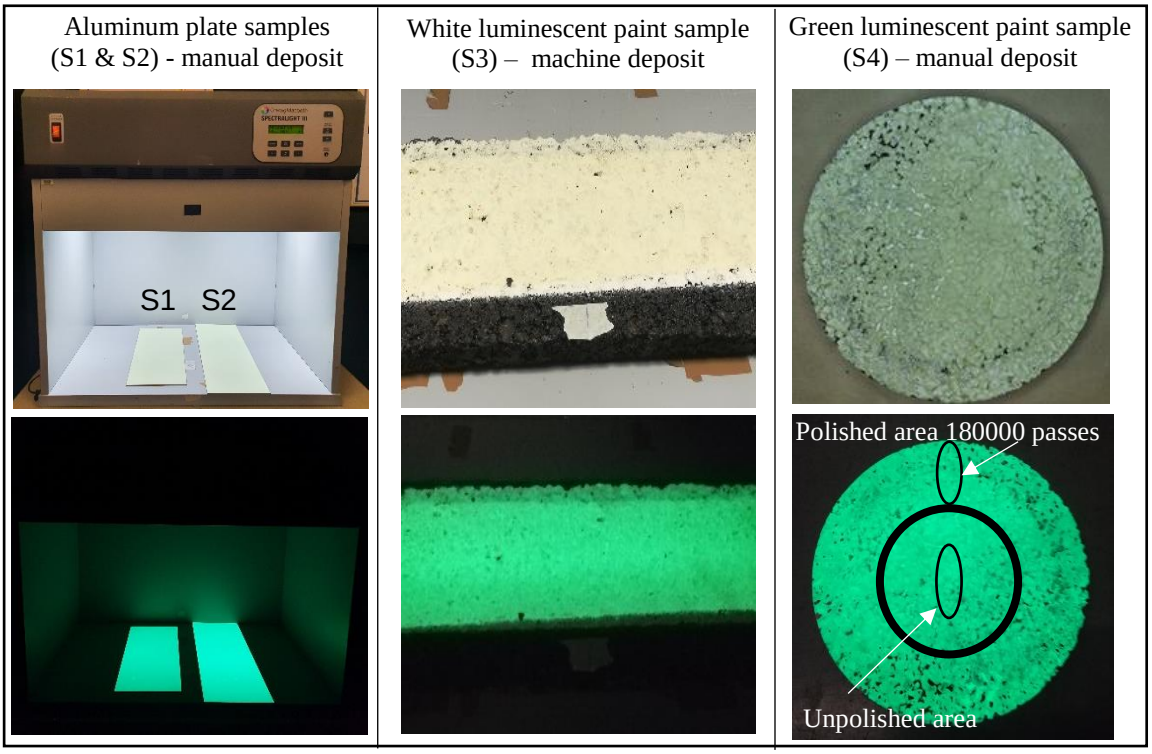

Figure 1 –Left: Aluminium plate samples in the light booth (S1 & S2); Center: White luminescent paint sample S3; Right: Core sample S4 of green luminescent paint artificially ageing with a Wehner & Schulze machine. The ellipses corresponds to the luminance measurement zones.

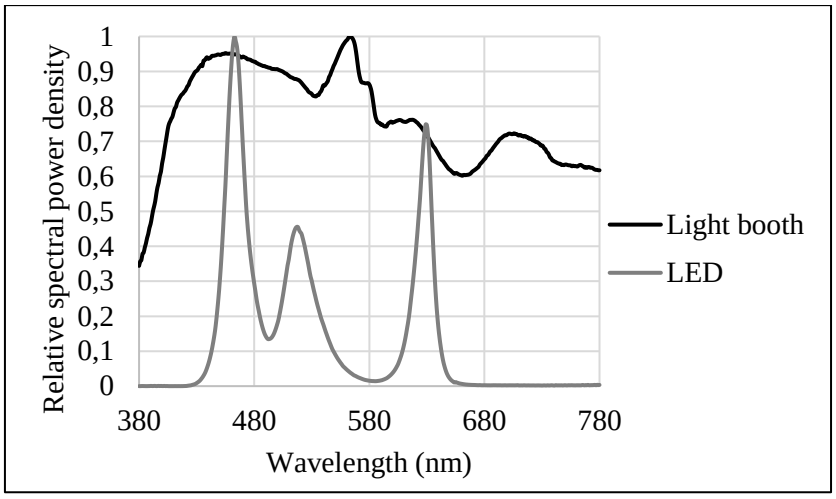

Figure 2 –Normalized spectrum of excitation in the light booth (D65 illuminant enhanced with UV) (in black) and normalized spectrum of LED used to simulate constant illumination and traffic (in grey). Measurements were done with a spectroradiometer CS1000 between 380 and 780 nm.

3.1.2 Colour measurement

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

3.1.3 Luminance measurement in the dark

The simplest characterisation of a luminescent painting 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, see Figure 1, left) at 1.5 klx horizontal illuminance with a D65 illuminant enhanced with ultraviolet (Figure 2). 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.[2] The luminance measured in the dark as a function of time is called the decay curve.

To investigate the product's durability, 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, right).

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.

3.1.4 Luminance measurement under constant illumination (moon)

Night-time illumination was simulated with a constant horizontal illuminance on the sample of 0.01, 0.05, 0.1 or 0.5 lx with a RGB LED Matrix (behind a diffuser) controlled by Arduino. Although the source spectrum (Figure 2 in grey) was questionable with respect to the night-time illumination spectrum, it allowed providing a controlled low diffuse illuminance on the samples. Using the excitation protocol described in Section 3.1.3, the decay luminance of a luminescent sample was measured every hour during seven hours (average over five measurements) with a luminancemeter PR880 at 2.29° observation angle. The luminance of fully discharged samples was also measured under each illuminance level.

3.1.5 Luminance measurement under cyclic illumination (simulated constant traffic)

The same RGB LED Matrix was used to simulate a periodic illumination due to road traffic. The horizontal illuminance on a central marking line was computed as a function of the distance to the headlamps of a vehicle provided with real LED low-beam headlamps. Then, the horizontal illuminance could be computed as a function of time given the vehicle's speed. Based on this horizontal illuminance profile, it was possible to simulate different vehicle speeds and different traffic densities (in veh/h) by varying the duration and frequency of the intensity profile. Figure 3 presents an example of simulated traffic at 80km/h with a vehicle density of 300 veh/h, *i.e.* 5 vehicles per minute. This periodic lighting was applied during six hours in the dark, the sample being previously excited as in Section 3.1.3. The luminance of luminescence was measured every hour with a luminancemeter PR880 at 2.29° observation angle (average over 5 to 10 measurements) when the LED was switched off.

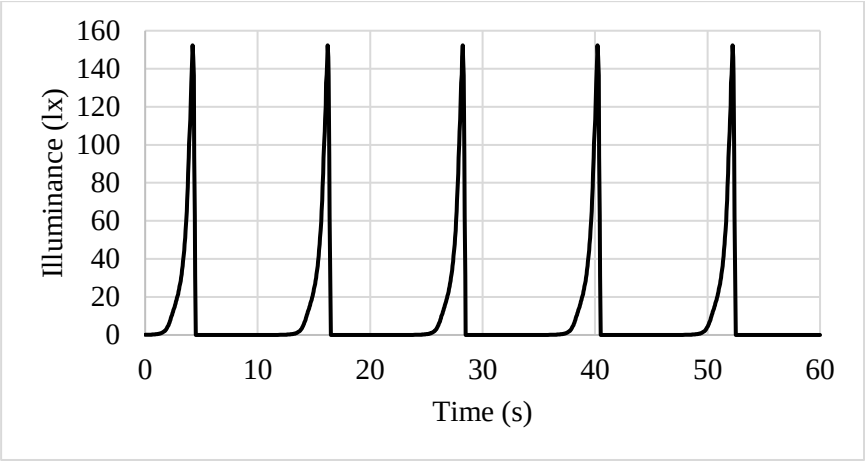

Figure 3. Example of the horizontal illuminance produced on the sample in laboratory with a LED Matrix to simulate a constant traffic at 80 km/h with a vehicle density of 300 veh/h. The figure shows one minute of the signal repeated during six hours in the dark.

3.2 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 in the following. The luminance of the two road markings at 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, during the two hours before civil twilight, was simulated by decreasing every 15 minutes a controlled artificial sun (32 metal halide lamps, 22600 lm, 5600 K). 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.[17] The main characteristics of the mean sunsets are:

- 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 (SD=0.05), and the road surface temperature was around 13°C (13.5°C when the artificial sun was switched on). The mean relative humidity was 77.1% (SD=1.7%).

3.3 Visibility computations

From the laboratory measurements of samples S2 and S3 and the calculation method proposed in the COST 331 report[15] (see Annex 2), 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. These computations were based on the assumption that with equivalent coefficient of retroreflected luminance RL (see Annex 1 for definition), 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.[15]

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 (Qd=60 $mcd.m^{-2}.lx^{-1}$, RL=10 $mcd.m^{-2}.lx^{-1}$) was considered (see Annex 1 for definitions of RL and Qd). A traditional retroreflective marking (Q3 Qd=130 $mcd.m^{-2}.lx^{-1}$, R4 RL=200 $mcd.m^{-2}.lx^{-1}$) lighted 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.

A potentially interesting application being the guidance of cyclists in unlit areas, a bicycle path scenario was also simulated, without headlights or public lighting, in order to calculate the visibility distance of the luminescent marking for cyclists under night-time illumination. In that case, we considered a continuous central line of 3 cm on a 1.5 m width bicycle path with the eye level at 1.5 m. Other characteristics were the same as in the straight road use-case described above.

We used the COST 331 tool (visibili.exe)[15] to compute the visibility distance of the traditional road marking. For the luminescent road marking, the equations detailed in Annex 2 were implemented in *Matlab*.

4. Results

4.1 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 spectrum of the daylight. At night, the luminescence emission spectrum shifts the chromaticity towards green. Figure 4 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.

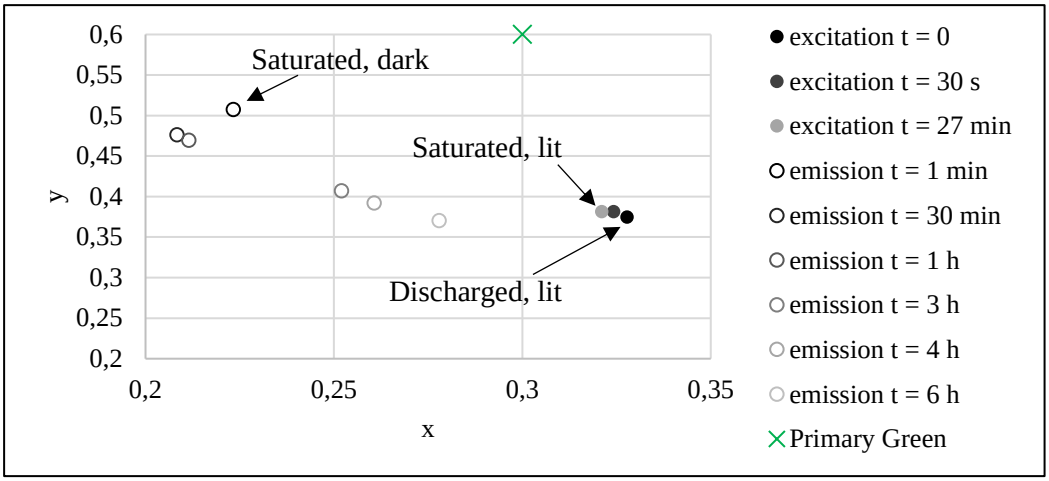

Figure 4 – Evolution of the chromatic coordinates of a luminescent paint sample (S1) during an excitation/emission cycle.

4.2 Luminance measurements

4.2.1 Luminance measurements in the dark

Figure 5 shows the decay curves obtained in the laboratory with two samples (S3 & S4, see Figure 1). The luminance of the white luminescent sample (S3, black curve in Figure 5), which meets the chromaticity requirements of the EN1436 standard[2], 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 this standard from a colour point of view, is two to three times higher (dark green curve in Figure 5).

In terms of durability, the decay curve of an area of the polished core (light green curve in Figure 5) after 180,000 passes is approximately 15% lower than that of the unpolished area (dark green curve in Figure 5).

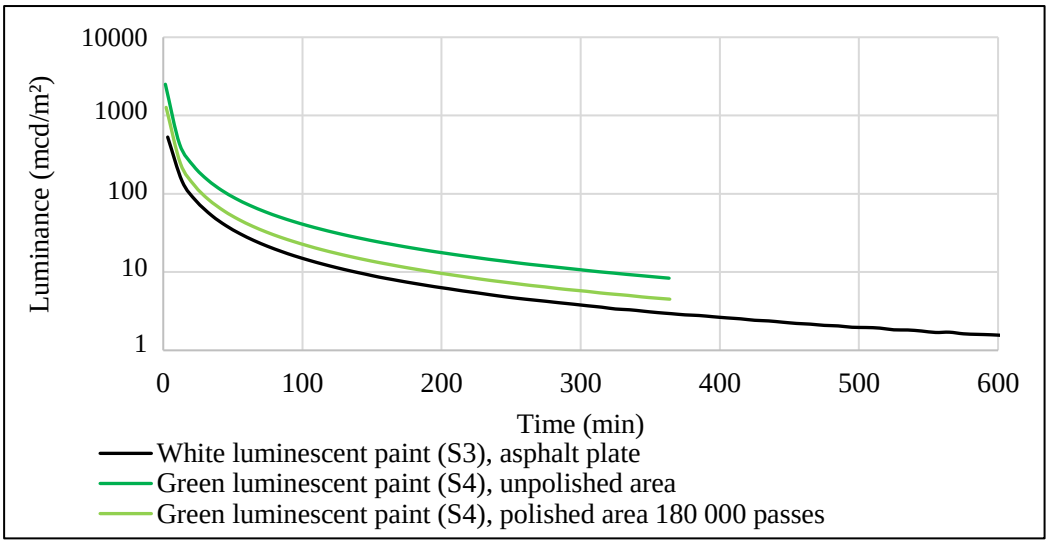

Figure 5 – Decay curves in the dark measured in the laboratory at 2.29° observation angle after 30 min of excitation under 1500 lx in a light booth (D65 illuminant + UV).

4.2.2 Luminance measurement under constant illumination (moon)

Table 2 shows the luminance decay (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 (Table 2), 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 lx under 0.1 lx for sample S1, see Table 2). This result does not depend on the spectrum used to illuminate the sample.

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 two-lane road), and can reach 0.1 to 0.3 lx on a full moon night.[18] In addition, ground level illumination due to light pollution in overcast skies can reach levels similar to a full moon.[18] For sample S3 (Figure 1, centre), 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 Qd=200 $mcd.m^{-2}.lx^{-1}$. The Qd of this sample measured outdoor during daytime was 238 $mcd.m^{-2}.lx^{-1}$.

4.2.3 Luminance measurement under cyclic illumination (simulated constant traffic)

Eight decay curves of sample S2 were obtained after constant excitation, one in the dark, and seven under various simulated traffic. Table 3 provides the difference ΔL between the decay curves in the dark with and without traffic of sample S2, each 60 minutes. The expected and observed effect of the constant traffic on luminescence emission is an increase of luminance over time with respect to the decay curve in the dark. As shown in Table 3, the increase was found constant over time. In addition, as plotted in Figure 6, this increase varies linearly with traffic density, and is inversely proportional to the vehicles speed. It could result from the fact that ΔL is proportional to the total amount of illuminance received during the vehicle passing.

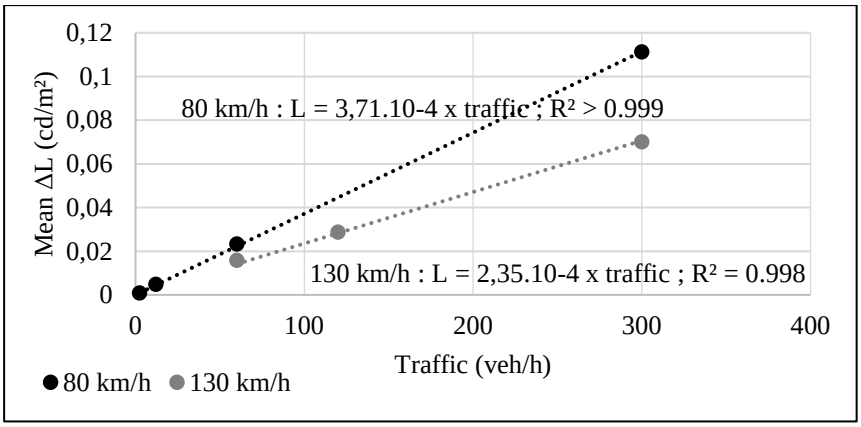

Figure 6: Mean difference ΔL (cd/m²) between the luminance in the dark with traffic and without traffic during the discharge of sample S2 of luminescent paint deposited on an aluminium plate, depending on the simulated traffic (veh/h) at 80 and 130 km/h.

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.

4.3 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 7. As observed in laboratory measurement with other samples, the white luminescent marking (in accordance with the EN1436 requirement[2]) 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).

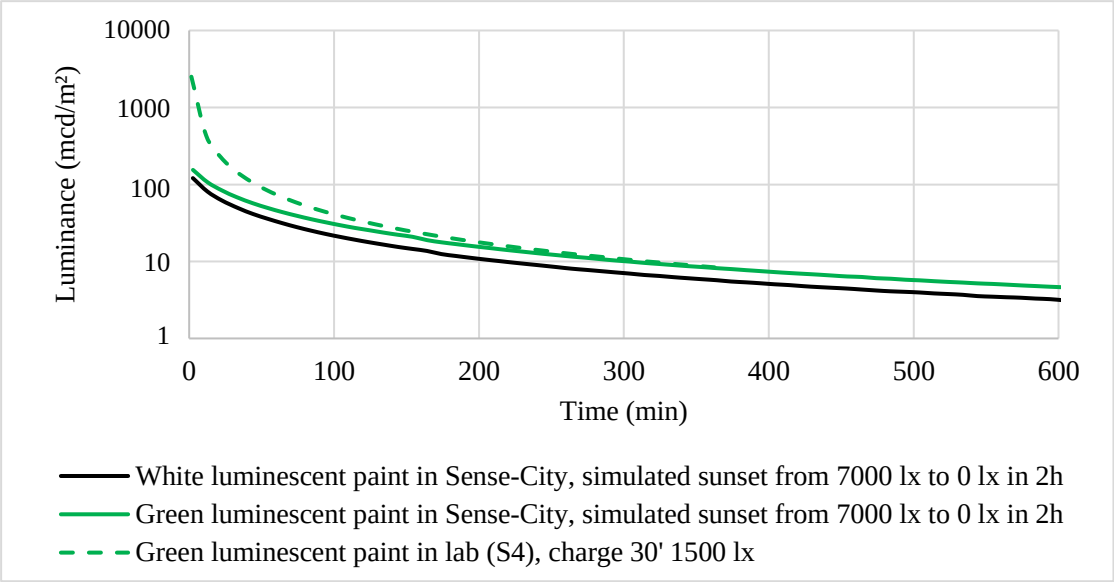

Figure 7: Decay curves in the dark at 2.29° observation angle. Solid lines: in Sense-City after a simulated sunset from 7000 lx to 0 lx in 2 hours; Dotted line: sample S4 of the same green luminescent paint measured in laboratory 30 min of excitation under 1500 lx in a light booth (D65 illuminant + UV)

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 Figure 7 that the luminance of the asphalt sample S4 (dotted curve) is greater than that the one measured in Sense-City (solid green curve). This can be due to the difference in deposit, 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 (Qd = 233 $mcd.m^{-2}.lx^{-1}$) during sunset, between 1 hour and 30 min before full darkness.

4.4 Visibility computations

Based on the laboratory luminance measurements, two use-cases are investigated through visibility distance computations: a straight road and a bicycle path.

4.4.1 Straight road use-case

From the laboratory measurements described above and the calculation method proposed in the COST 331 report[15], the visibility distance of the luminescent marking beyond the headlight beam was calculated, and compared to the visibility distance of a traditional retroreflective marking in a low beams headlight as defined in the COST 331 tool (Intensity

factor 1, 10000 cd below the cut-off, 1000 cd between cut-off and the horizontal, 200 cd above the horizontal, 0 cd outside ±10° to the sides and ±5° up/down). Our computations assume that the luminescent marking is equivalent to the traditional road marking in terms of retro-reflection (same RL).

The luminance of the luminescent road markings was estimated from the decay curves computed from the measurements in the dark (L_{dark}) and from the offsets due to constant illumination (ΔL_{night}) and simulated traffic ($\Delta L_{traffic}$) determined in previous sections.

$$L(t) = L_{dark}(t) + \Delta L_{night} + \Delta L_{traffic} \quad (1)$$

The conclusions of our visibility computations depend on the luminescent sample, on the night-time ambient lighting, on the traffic and on the assumptions used for comparisons (RL & Qd 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 EN1436 standard[2], 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 reach the standard in terms of colour, 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.

The traffic increases the visibility of luminescent markings, but the benefit strongly depends on the night-time ambient illumination. Figure 8 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 (Q3 Qd=130 $mcd.m^{-2}.lx^{-1}$, R4 RL=200 $mcd.m^{-2}.lx^{-1}$). This “useful time” is given as a function of the traffic (in veh/h) at 80 km/h, for various illumination conditions and two ages (20 and 60 years old).

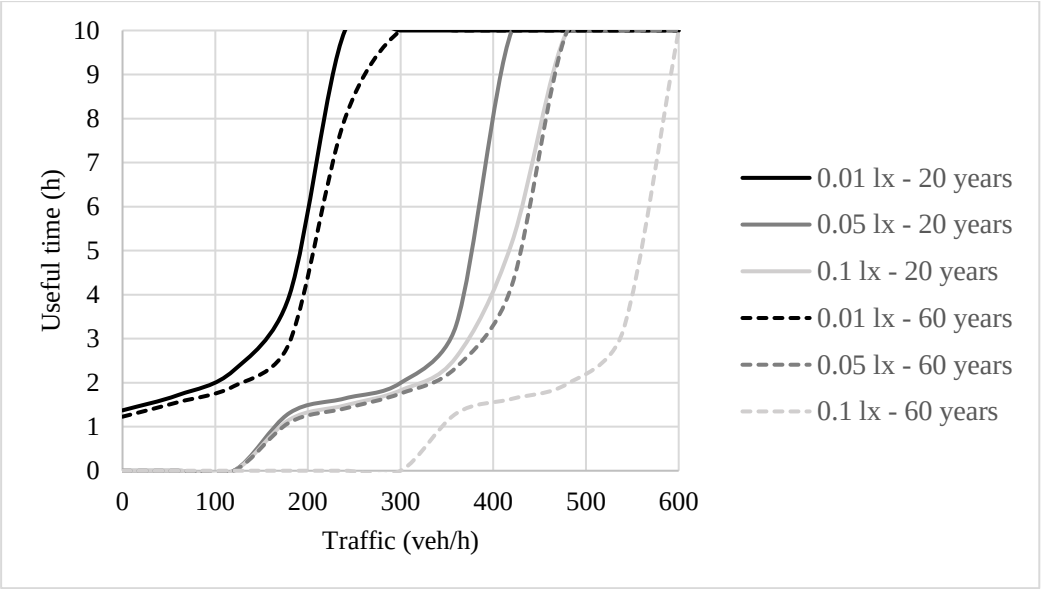

Figure 8 – Useful time (h) as a function of the traffic density (veh/h) at 80 km/h under 0.01 lx (black), 0.05 lx (dark grey), or 0.1 lx (light grey). The useful time is the time during which the visibility distance of a white luminescent road marking (S3) (beyond the low beam headlight) is higher than the one of a traditional road marking (Q3 Qd=130 $mcd.m^{-2}.lx^{-1}$, R4 RL=200 $mcd.m^{-2}.lx^{-1}$) in low beam headlights, assuming that both markings have the same RL. Solid line: 20 years old driver. Dashed line: 60 years old driver.

According to Figure 8, the excitation from a traffic of 300 vehicles/hour traveling at 80 km/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 3.3). The gain in visibility provided by luminescent marking is less important for the elderly than for the young people, but when the traffic is high enough, an increase of visibility distance beyond the headlights can improve their safety.

4.4.2 Bicycle path use-case

For the bicycle path use-case, 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 of samples S2 and S3.

On an unlit bicycle path, luminescent markings may improve the visibility compared to a traditional marking visible at up to 10 m (Q3) or 20 m (Q5) when the night is dark without lighting other than the sky ($E \leq 0.5$ lx). In addition, the darker the night, the greater the visibility distance with luminescent markings in the first hours of the night. Even if it does not replace public lighting regarding the visibility of objects, a green luminescent marking can provide visual guidance, when public lighting is not possible, on rural sections or during periods of

extinction, up to at least the 50 meters required for a safe trip[19], during the first hour of the night. It can also improve the identification of bicycle lanes at night compared to other infrastructure, if it is strictly dedicated to these lanes.

5. Discussion

5.1 Main findings and comparisons with previous work

Measurements of luminescent road markings, carried out in the laboratory and in a controlled environment, have made it possible to isolate several factors influencing the performance of luminescent paints. Visibility computations based on these measurements provide first ideas of what can be expected with such innovative products. Especially, for equivalent performance (in terms of RL and Qd), luminescent markings may increase the visibility distance beyond the headlamp beams during the first few hours of the night. Improved performance may last longer under certain favourable night-time lighting conditions and with traffic. Without automotive lighting, especially on unlit cycle paths, it seems that a gain can be obtained compared to traditional markings, mainly at nightfall, during the end of sunset and during the first few hours of the night.

Comparisons with previous work is not easy because the performance depends on various factors, including the painting formula, the excitation illuminance and spectrum, and the temperature. Yet, our findings on luminance decay in the dark seems consistent with previous work. In Bullough *et al.*[7], the luminance of the tested products does not last more than four hours in the dark above 10 mcd/m². No luminosity of the powders tested by Giuliani and Auteliano[6] was perceived after two hours in the dark. Regarding the traffic contribution, our findings are similar to Botterman and Smet[13], who found that the simulation of 30 cars at 20 m/s every 5 min slows down the luminance decay, which decreases however along the night. According to Giuliani and Auteliano[6], halogen headlamp cannot help to maintain excitation during the night.

5.2 Limits and future work

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 assume that the luminescent markings have the same RL as traditional markings, but our computations were based on luminance measurement of non-retroreflective samples (R0 class). Our 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 the 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, spectrum: future work is needed for a better understanding on the importance of low wavelength content in the illuminant spectrum. Similarly, the traffic simulation may have overestimated the traffic effect, as actual headlamps may use LEDs, xenon or halogen sources; the latter contains less exciting short wavelengths. In addition, we assume a constant traffic whereas real road traffic decreases in the middle of the night. Our simulated scenarios lead to overestimate the performance of the product. 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 on night-time illumination and simulated traffic were obtained on aluminium plates and extended to asphalt samples. They could be verified on other asphalt samples.

Our findings also 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 performances whatever the external conditions and wear. Others scenarios could also be investigated, such as after urban and road lighting extinction.

6. Conclusion

A repeatable and simple laboratory measurement procedure on luminescent samples was proposed and associated to visibility computations, to characterise the performance of luminescent road markings. Our findings show that for equivalent performance in terms of RL and Qd, luminescent markings could strengthen the visual guidance of drivers on the road beyond the headlamp under favourable night-time lighting conditions and with traffic. Depending on the conditions, the benefit may last between a few minutes and all night. Outside the beam of the headlights, or on bicycle paths, 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 (end of twilight, night) on unlit roads or paths. Our 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. These findings need to be confirmed by more systematic on-site measurements, under different conditions (*e.g.* temperature, humidity).

Conflict of interest

The authors declare no potential conflicts of interest with respect to the research, authorship and/or publication of this paper.

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Annex 1: Definition from the EN1436 standard

With respect to the EN1436 standard[2], the retro-reflection of a road marking under vehicle headlamp illumination is assessed with the coefficient of retroreflected luminance RL (in $mcd.m^{-2}.lx^{-1}$). It is defined as the ratio of the luminance of the road marking observed at 2.29° to the illuminance on the surface perpendicular to the incident light direction (illuminant A, 1.24° lighting angle).

The reflection under daylight or road lighting is assessed with the luminance coefficient in diffuse illumination Qd (in $mcd.m^{-2}.lx^{-1}$), defined as the ratio of the luminance of the road marking observed at 2.29° to the illuminance due to diffuse lighting (illuminant D65). It can also be assessed with the luminance factor β, defined as the ratio of the luminance of the road marking to the luminance of a lambertian diffuser, both illuminated at 45° with a D65 illuminant and observed at 0°.

Annex 2: COST 331 method

The visibility level VL is the ratio between the luminance contrast and the contrast threshold. It is computed in COST 331[15] as follows:

$$VL = \Delta L / \Delta L_{th} = (L_t - L_b)\alpha^2 / (A + B\alpha)^2 \quad (1)$$

with α the apparent size of the road markings (in minutes of arc), L_t the luminance of the road markings (in cd/m^2) and L_b the luminance of the road surface (in cd/m^2). A and B are computed from the road surface luminance L_b:

- If $L_b \geq 0.6$ cd/m^2: $\begin{cases} A = \log\left(10.086\, L_b^{0,2509}\right) + 0.27154\, L_b^{0.5867} \\ B = 0.09588\, L_b^{0.466} \end{cases}$
- If $L_b < 0.00418$ cd/m^2: $\begin{cases} \log A = 0.2355 + 0.173 \log L_b \\ \log B = -0.6835 + 0.5275 \log L_b + 0.0227\, (\log L_b)^2 \end{cases}$ (2)
- If $0.00418 \leq L_b < 0.06$ cd/m^2: $\begin{cases} \log A = 0.1355 + 0.3372 \log L_b + 0.0866\, (\log L_b)^2 \\ \log B = -1.0485 + 0.3190 \log L_b \end{cases}$

The road surface luminance L_b is deduced from the product of the horizontal night-time illuminance E (lx) and the Qd ($mcd/m^2.lx$) of the road surface.

The visibility distance (VD) of the road marking is obtained for VL=10, *i.e.* when the contrast is 10 times higher than the contrast threshold. Therefore, the visibility distance is the distance at which the apparent size α of the road marking allow to obtain VL=10, *i.e.*:

$$(L_t - L_b)\alpha^2 / (A + B\alpha)^2 = 10 \quad (3)$$

To that purpose, we need to solve the following equation to find $\alpha_{VL=10}$:

$$(B^2 - ((L_t-L_b)/10))\ \alpha^2 + 2AB\ \alpha + A^2 = 0 \quad (4)$$

In addition, according to COST 331, the target size (in minutes of arc) of a road marking can be estimated from the apparent solid angle ω (in sr) with the following equation:

$$\alpha = 3879\ \omega \quad (5)$$

Based on integral computations, COST 331 report provides a simplified computation of the solid angle ω of a continuous line of width *l* starting at distance *d* from the vehicle, considering the height *h* of the observer' eyes as:

$$\omega = 0.5\ h\ l\ /\ d^2 \quad (6)$$

Then, the visibility distance (VD) of a luminescent road marking was deduced from $\alpha_{VL=10}$ as follows:

$$VD = \frac{\sqrt{0.5\ h\ l}}{\alpha_{VL=10}/3879} \quad (7)$$

With this model, the visibility distance is obtained for a road user of 20 years'old. For a 60 years' old road user, L_b and (L_t-L_b) need to be replaced in the above equations by $L_{b60} = L_b/1.692$ and $(L_t-L_b) = (L_t-L_b)/1.692$.

Table 1 – Laboratory sample characteristics

Name	Support	Application	Chromaticity coordinates [x,y]	Luminance factor β or luminance coefficient in diffuse illumination Qd (Class in EN1436[2])
S1	aluminium	manual (roller)	0.332,0.374	β = 0.739 (B5)
S2	aluminium	manual (roller)	0.330,0.374	β = 0.916 (B5)
S3	asphalt	machine	0.337,0.363	Qd = 238 $mcd.m^{-2}.lx^{-1}$ (Q5)
S4	asphalt	manual (roller)	0.357,0.401	Qd =187 $mcd.m^{-2}.lx^{-1}$ (Q5)

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

Time (min)	Luminance decay under 0.1 lx (mcd/m²)	Luminance decay in the dark (mcd/m²)	Difference ΔL (mcd/m²)
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

Table 3 Difference ΔL (in mcd/m²) between the luminance decay curve obtained with simulated traffic and without simulated traffic during luminescence emission in the dark of sample S2.

Speed (km/h)	Traffic (veh/h)	ΔL (mcd/m²)						Mean ΔL [SD] (mcd/m²)
		1h	2h	3h	4h	5h	6h	
80	300	107,0	108,9	110,2	114,6	110,9	111,3	110,5 [2,6]
	60	21,0	23,0	23,0	23,3	23,6	23,5	22,9 [1,0]
	12	4,9	5,4	5,0	4,6	4,8	4,5	4,9 [0,3]
	2.4	2,7	0,8	0,9	1,0	0,7	0,7	1,1 [0,8]
130	300	66,8	68,8	69,7	70,7	72,8	72,0	70,1 [2,2]
	120	27,6	28,2	28,8	29,1	29,0	29,4	28,7 [0,7]
	60	14,7	14,8	18,4	16,0	15,6	15,1	15,8 [1,4]