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Visibility and discomfort glare of LED road studs

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Traffic management and road safety may benefit from self-powered LED road studs but to be effective they need to be visible to road users, without glare, whatever the environmental conditions. Some parameters, such as dry versus wet road surfaces, have not been investigated previously for LED installations. In this context, two experiments have been conducted to study the visibility and discomfort glare produced by a LED road stud. The results suggest tuning the luminous intensity of LED road studs according to the illumination and road surface conditions to ensure visual perception by road users while controlling energy consumption. A quantitative model is provided in order to link the dimming to the environmental parameters.

1. Introduction

The large benefits of light-emitting diodes (LED), for instance in terms of energy consumption, dimming and colour management,[1,2] contribute to the increasing development of LED-based applications, including for lighting and signalling. The development of these applications leads, in turn, to new research questions[3–7] in terms of product design, photometry and colorimetry, as well as technical and human factor evaluations of new applications. In outdoor applications, a number of LED-based products have been proposed, mainly in the field of lighting (road lighting, urban lighting, automotive lighting, etc.).[7–9] In this context, self-powered LED-based products are currently being developed, which could be of benefit to many traffic control devices such as traffic lights, variable message signs and road studs. By using solar cell or piezoelectric technology, such systems save energy and are wiring-free. Dynamic LED control is therefore done remotely via telecommunication systems. Such LED road studs are under investigation for road safety applications (e.g. active lane delineation, pedestrian crossings) and traffic management applications (e.g. tidal flow)[10–13] for which road studs are switched on night and day. Previous work shows that LED road studs may improve vehicle guidance at night, in terms of vehicle lateral control in curves,[11] even compared to conventional retroreflective road studs.[11,12] The dynamic control of LED-based road studs may also be relevant in some daytime applications (or 24/7 applications). For instance, flashing lights on highways may warn the driver about someone driving in the wrong direction; coloured or flashing lights may also guide the driver during foggy weather, or indicate specific areas, such as a railway crossings ahead.[14,15]

Being self-powered, these studs are free of wiring and energy supply problems, not to speak of energy costs. However, this

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technology, either based on solar or piezoelectric energy, is limited in the current state of the art with respect to energy consumption, which is why the very low energy demand of the LED is of interest. Thus, optimal management of the stud energy consumption is required, whatever the application, to deliver the targeted function given the limited available energy. Besides, on the road, any signalling device needs to be visible enough for the incoming drivers without glare.[16,17] These requirements need to hold whatever the external conditions (daytime/night-time, weather conditions).[18,19]

Some previous work has investigated these questions. Wu *et al.*[18] collected subjective evaluations of legibility and glare sensation produced by LED variable-message signs (VMS), under three ambient illumination conditions: bright (30,000 lux), dark (5000 lux) and night (10 lux). Two kinds of VMS were investigated: a LED display panel 'without background', for which the LED pattern forms the outline of the VMS, and a LED display panel 'with background' composed of a rectangular black sign on which a LED pattern is drawn. Evaluations were carried out at short (9.8 m) and long (57 m) distances from the VMS. Twenty-nine participants rated their comfort and glare perception. For the LED display panel with background, the authors found no difference between the 'near' and 'distant' conditions whereas in the case of the display panel without background, viewing comfort is better at long distance than at the short one. In addition, as expected, brighter conditions lower the glare sensation.

The environmental conditions have also been investigated.[19–21] Munehiro *et al.*[19] conducted an experiment about visibility and glare of three LED road delineators under clear and foggy conditions during daytime and night-time. Twenty participants rated the delineators' visibility, their discomfort glare and feeling of safety at 50 m, 100 m, 150 m and 200 m from the delineators on a real road. Ratings were modeled using linear regressions with respect to the luminous intensity, the observation distance and the illumination condition. The authors made recommendations about the required luminous intensity for each tested LED delineator, depending on the illumination conditions (day vs. night, weather conditions). For instance, they proposed 1000 cd during clear daytime and 70 cd during clear night-time (without fog) for amber LED delineators. They found a decrease in visibility, but not in discomfort glare, as the observation distance increased.

Bacelar[20] compared three types of LED road studs with a fixed luminous intensity and one conventional retroreflective stud. Seventeen participants drove at night on a 400 m closed track under various configurations: Street lighting, LED studs, retroreflective studs and a baseline condition (without studs or lighting). They were asked to assess the visibility, the legibility of the trajectory and the glare level on semantic scales in each condition. The 4 cd LED road stud led to good visibility and legibility scores, and low glare levels. Compared to other configurations, 50% of participants preferred the luminous studs and 44% the street lighting.

Alferdinck[21] conducted an experiment with seven participants on a closed track, looking for appropriate LED road stud luminous intensity levels during daytime ($L \approx 5000$ cd/m^2 on the road surface) and night-time ($L \approx 0.02$ cd/m^2), considering various inter-stud distances (from 1 to 7 m). Six levels were proposed, from 'detectable' to 'disturbing', and the participants tuned the stud's luminous intensity in order to reach each of these subjective states. The minimal luminous intensity was found to depend on the inter-stud distance. The author proposed a model of the required luminous intensity in order to reach a given state, in terms of the road luminance and inter-stud distance.

In another study of dynamic marking systems using road studs, Boyd *et al.*[22] recorded qualitative assessments of brightness ('too bright', 'fine' or 'not bright enough') from four experts of three types of road studs in daytime (overcast and sunny), twilight and night-time, first standing 50 m from the stud, and then while driving. Two studs were driven by an illuminance sensor to automatically dim the luminous intensity depending on the ambient light (Stud 1: 14–109 cd, Stud 2: 8.4–139 cd, Stud 3:10 cd). They were judged 'too bright' at night and on overcast days. The fixed 10 cd road stud was judged 'not bright enough' during daytime. The experts were also asked how easy it was to notice whether the studs were on or off. The authors found that during night-time the level of retro-reflection of the road studs due to headlights influenced the answers. It should be noticed that the dimmable stud with the highest retroreflection at night was judged 'not bright enough' under a sunny sky.

These studies, summarised in Table 1, highlight the need for tuning the LED road stud's luminous intensity with respect to the illumination conditions. This was made clear when comparing daytime versus night-time conditions, and addressing specific conditions such as fog. Wet road surfaces were also investigated by Gibbons *et al.*[23] for conventional road markings. Thirty-three participants judged, from the passenger seat of two different experimental vehicles at night (with the headlamps on), the visibility distance of six pavement markings in a dry condition or a saturated wet condition (under rainfall), by counting the number of visible skip marks. Luminance and retro-reflectivity were also measured. The same experiment was reproduced during the recovery period (when the pavement marking is drying), with six participants. The visibility distance was found lower in the rainfall condition than in the dry condition. To the

Table 1 Overview of previous studies

Authors	LED device	# subj.	Ambient conditions	Distance	Assessment	Findings and recommendations
Wu *et al.*[18]	VMS	29	30,000 lux, 5000 lux, 10 lux	9.8 m, 57 m	Legibility, glare feeling, comfort	No influence of the distance for VMS without background. Brighter conditions lower the glare sensation.
Munehiro *et al.*[19]	Delineators	20	Clear day, fog day night	50 m, 100 m, 150 m, 200 m	Visibility, discomfort, glare	Decrease of visibility with the distance. No influence of the distance on the discomfort glare. Clear day: 1000 cd; night: 70 cd.
Bacelar[20]	Road studs	17	Night	Driving along 400 m	Visibility, legibility of the trajectory, glare level	Good visibility and legibility and low glare level with 4-cd LED road stud.
Alferdinck[21]	Road studs	7	Day: L_{road} $\approx$5000 cd/m^2 Night: L_{road}=0.02 cd/m^2	98.5 m Inter-distance: 1–7 m	Visibility and glare (from 'detectable' to 'disturbing')	Model of required intensity based on findings that intensity increases with the inter-distance and with the observation angle. $I_{optimal\text{-}Night}$: 0.92 cd
Boyd *et al.*[22]	Road studs of three different manufacturers	4	Day, twilight, night	50 m Driving	Identification of the switched state of the stud. Qualitative brightness assessment from experts	Each road stud is judged 'too bright', 'fine' or 'not bright enough' under various conditions by the experts. The identification at night is influenced by retroreflection of the stud due to headlights.

best of our knowledge, wet conditions have not yet been investigated for LED road studs. In addition, the panel size was between four and 17 participants in the above LED road stud studies. This is low due to the large inter-individual variability: In lighting research, Flynn *et al.*[24] recommend 40 subjects when using an ordinal judgment scale.

The present study aims at studying the visual perception of LED road studs under various external conditions, in order to optimise dimming and, therefore, save energy while ensuring the visual performance of road users. The study focuses on the visibility and the discomfort glare produced by a LED road stud under varying illumination conditions, and compares dry and wet road surfaces. The panel of participants used was above 30, thus larger than in previous studies. Two experiments were conducted. The first one, referenced as the 'Visibility' experiment in the following, addresses two issues. First, we tested whether the road stud visibility would change depending on the road surface condition (dry versus wet). Second, we wanted to model the LED luminous intensity requirement in order to ensure visibility (as rated by the participants) as a function of the illumination (and possibly surface) conditions. The second experiment focuses on the discomfort glare which may be experienced at night, and is referred to as the 'Glare' experiment in the following.

The remainder of the paper is organised as follows. Section 2 is dedicated to the study of LED road stud visibility, in daylight conditions. The 'Visibility' experiment is presented (Sections 2.1 and 2.2) together with the results (Section 2.3) and a visibility model is provided (Section 2.4). Section 3 presents the 'Glare' experiment conducted in artificial night-time conditions. A general discussion on these experiments is proposed in Section 4, while conclusions and future work are presented in Section 5.

2. Visibility of a LED road stud

2.1 Panel

Forty-two participants were involved in this study (24 men, 18 women), who were between 21 and 57 years ($M = 35.8$, $SD = 10.0$). A number of visual tests were conducted with an ErgoVision (Essilor) prior to the experiments: Visual acuity in photopic binocular vision and in mesopic vision, contrast sensitivity (assessed from the number of errors made while reading letters at various contrasts) and time of recovery after glare. Descriptive data about the participants and the results of the vision tests are presented in Table 2.

2.2 Material and method

2.2.1 Road stud

The experiments were carried out with an amber-coloured road stud supplied by DSTA. The luminous intensity distribution of the stud, measured at the IFSTTAR photometry laboratory, is presented in Figure 1(a) for various vertical angles. The stud's luminous intensity could be tuned, with dedicated software also supplied by DSTA.

2.2.2 Experimental settings

The experiment was carried out on a closed track in Guerville, France. The stud was inserted in the road (Figure 1(b)) and was set at a horizontal angle of 0°. Its luminous intensity could be modified from the roadside, via a computer. Preliminary tests suggested that the road stud was visible at 69 m even with the minimum available luminous intensity for a surrounding horizontal illuminance lower than 1000 lux, so no visibility problem was expected during night-time. Therefore, the Visibility experiment was conducted during daytime. The horizontal illuminance (on the road surface) did vary during the experiment, and was recorded with a LMT B520 photometer. Depending on the time of the day, the position of the sun varied.

Table 2. Participants' characteristics and visual capabilities in the Visibility and the Glare experiments

		Panel for the Visibility experiment (%)	Panel for the Glare experiment (%)
Gender	Male	57	53
	Female	43	47
Age	<25	10	8
	25–34	43	42
	35–44	24	28
	45–54	17	14
	>54	7	8
Corrected vision	Yes	48	47
	No	52	53
Visual acuity	12/10	79	78
	10/10	10	8
	8/10	5	6
	6/10	0	0
	4/10	6	6
	2/10	0	0
Contrast sensitivity	Very good (0 err.)	55	53
	Good (≤2 err.)	24	25
	Medium (3–4 err.)	7	6
	Bad (>5 err.)	7	8
	Very bad (>10 err.)	7	8
Mesopic acuity	12/10	0	0
	10/10	5	3
	8/10	47	47
	6/10	31	33
	4/10	12	11
	2/10	5	6
Recovery time after glare	<25 s	36	33
	25–50 s	31	28
	>50 s	33	39

Its position was recorded for each experimental session.

The 42 participants were split into seven groups: six groups (G1 to G6) during a sunny day and one (G7) during a cloudy day. They were seated at 68.75 m from the stud, ensuring an observation angle of 1°. The observation axis was WNW (azimuth of 300° w.r.t. the North).

Each group of six participants first assessed the visibility of the stud on the dry road surface. Each stimulus consisted of switching on the stud for four seconds at a luminous intensity randomly chosen between 0 and 2.2 cd. Once switched off, the participants were asked to rate the stud in terms of visibility, on a 5-point scale, on a paper sheet. They were given 15 seconds to answer the following question: 'In your opinion, the road stud looks':

- 0: switched off;
- 1: switched on, barely visible;
- 2: switched on, not easy to see;
- 3: switched on, visible enough;
- 4: switched on, with glare.

After a first series of 52 stimuli on a dry road surface, water was sprayed on the stud and on the road surface around it for about four minutes to ensure the pavement was saturated. Then, the same protocol was repeated to collect data on the wet road surface in recovery mode with 52 new stimuli randomly displayed, in the same range of luminous

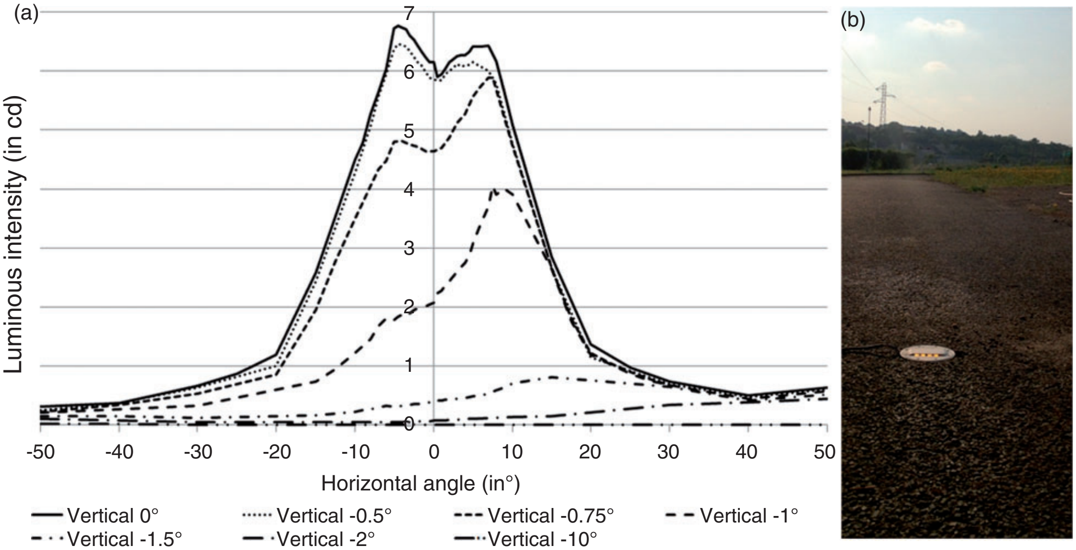


Figure 1 (a) Luminous intensity of the road stud under study for various vertical angles, from -10° to 0°. The stud's luminous intensity was at full power in order to improve the measurement accuracy. (b) The road stud on the closed track in Guerville (France)

intensities. The data collection lasted about 16 minutes, i.e. about 10% of the total time of recovery of the pavement. In the next sections, 'wet road surface' will be used to describe data collected on the road surface in this first stage of the recovery mode. The complete experiment lasted about 45 minutes.

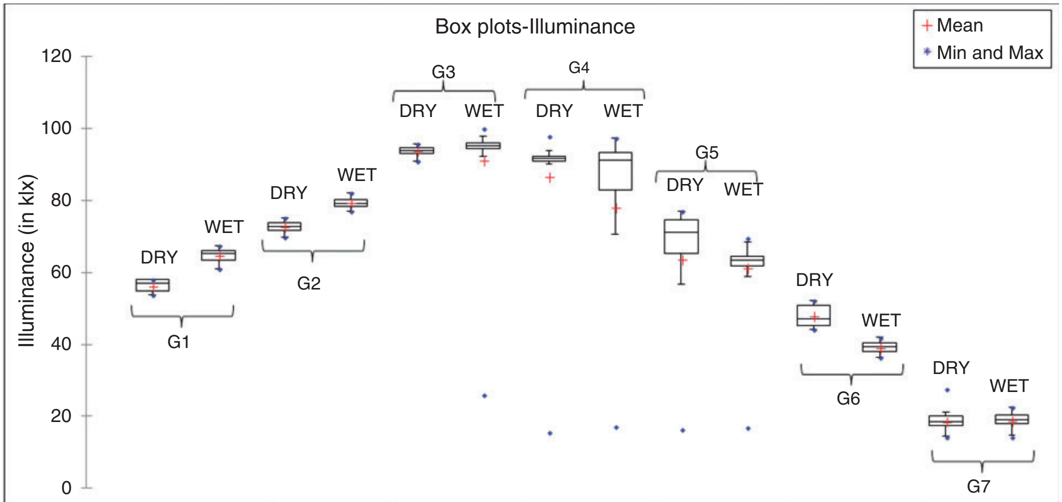
2.2.3 Illumination conditions

Horizontal illuminance was measured close to the stud for each of the 728 stimuli (52 luminous intensities $\times$ 2 surface conditions $\times$ 7 groups). It was decided to record the horizontal illuminance instead of the luminance for practical reasons: For a person from the road authority, illuminance is easier to measure.

During the experiment, horizontal illuminance varied between 14 and 100 klux. Figure 2 shows the range of illuminances for each group of participants and each road surface condition (dry and wet). Elevations and azimuths (defined here as the angle between the 'azimuth w.r.t the North' of the sun and the stud observation axis (300° w.r.t. the North)) during sunny and cloudy days are also reported for each group.

In each group, the delta of sun azimuth (respectively the delta of sun elevation) ranges from 5° to 11° (respectively from 3° to 5°) depending on the group. In addition, it appears from Figure 2 that in most groups, 80% of the illuminance values are within a range of $\pm$5 klux. Thus, discarding the 10% extreme illuminance values in each group, it can be said that each group was exposed to quite stable illumination conditions (both in terms of illuminance and sun position). In order to be consistent with this assumption, the data collected under conditions where illuminance values are not between the lower and the upper bounds of the box plots in Figure 2 have been removed in further statistical analyses (5th percentile and 95th percentile).

A two-way analysis of variance (ANOVA)[25] was conducted on the illuminance, with the 'Group' (seven modalities) and



Group	G1	G2	G3	G4	G5	G6	G7
Hour	10–10.30 am	11–11.30 am	2–2.30 pm	3–3.30 pm	5–5.30 pm	6–6.30 pm	10–10.30 am
Elevation(H)	46°–50°	55°–58°	61°–57°	54°–50°	36°–31°	26°–21°	30°–34°
Azimuth(Az) (user:300°/N)	-189°–-181° Behind	-172°–-160° Behind	-90°–-78° Side	-67°–-59° Sideto Front	-37°–-31° Front	-25°–-20° Front	-170°–-162° Hidden

Figure 2 Box plots of the horizontal illuminance and sun position for each group of participants

the ‘Road Surface Condition’ (two modalities) as factors. A significant main effect was found for the ‘Group’ factor ($F(6,623) = 737.57$, $p < 0.001$). No main effect of the ‘Road surface condition’ was found ($F(1,623) = 1.32$, $p = 0.2503$) but a significant interaction ‘Group × Road surface condition’ was obtained ($F(6,623) = 13.44$, $p < 0.001$). *Post-hoc* Tukey tests comparing wet and dry illuminances in each group found significant differences in groups G1, G2, G4 and G6 but not in groups G3, G5 and G7. Thus, the visibility ratings between wet and dry road surface can only be compared for groups G3, G5 and G7. Besides, mean illuminances were significantly different across all groups, except between G3 and G4 in the dry condition, and between G1 and G5, and G2 and G4 in the wet condition. However, the sun was behind the participants for group G1 (respectively G2) and in front view for group G5 (respectively sideways for group G4). Thus, in the following each group could be said to represent one illumination condition, described by an illuminance and a sun position.

2.3 Results

2.3.1 Preliminary analyses

The experiment was based on the assumption that the visibility of the stud would increase with the stud’s luminous intensity level. This is clear from Figure 3, where the rating frequencies are plotted against the stud’s luminous intensity. In the experiment, a five-point scale was employed in order to distinguish the just noticeable threshold (1), the hardly visible threshold (2), the sufficient luminous intensity level to ensure visibility (3) and the uncomfortable level (4). As each participant was in constant experimental conditions, Spearman and Pearson

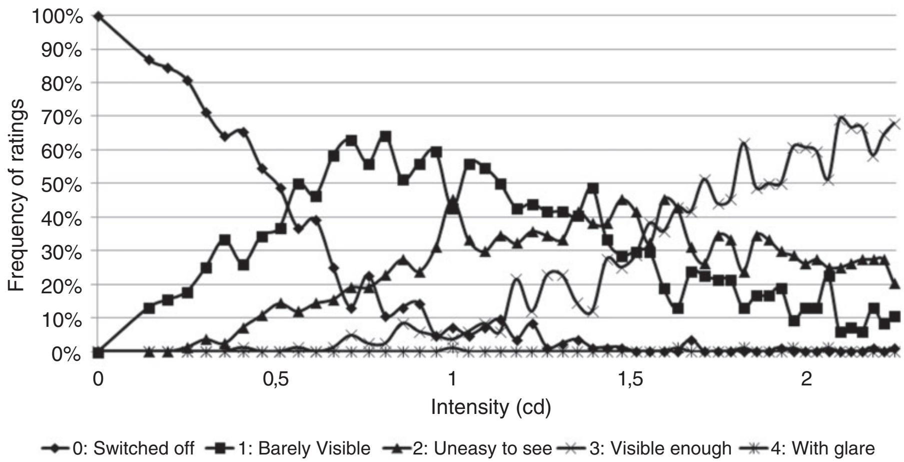


Figure 3 Frequency of ratings for each stud's intensity (100% = all participants)

correlations were found, whoever the participant, between the visibility ratings of each participant and luminous intensity levels ($0.58 < Sp < 0.91$, $M(Sp) = 0.81$, $SD(Sp) = 0.075$ and $0.58 < Pr < 0.92$, $M(Pr) = 0.80$, $SD(Pr) = 0.079$), showing a good understanding and use of the rating scale.

In total, 18.2% of the answers were '0 Switched off', 29.3% were '1 Barely visible', 26.5% were '2 Not easy to see', 26.3% were '3 Visible enough' and 0.08% were '4 With glare' (only obtained for dry road surface and luminous intensities higher than 1 cd). Glare was not expected but '4 With glare' was proposed in the judgment scale in order to confirm this hypothesis. Among the three participants who rated '4 With glare', one shows a high recovery time after glare, the others do not present any specific visual deficiency. It was decided to remove the ratings '4 With glare' from the collected data.

In addition, a hierarchical clustering[26] with percent disagreement distance and average linkage was carried out for each group. Two outliers were identified (in groups 1 and 2) and their data was removed from the statistical analyses; one participant was the only one who did not rate any stimuli above 2 (83% of rating '1 Barely visible') and the other one had low visual capabilities (5/10 visual acuity, 28 errors at the contrast test, 2/10 visual mesopic acuity).

2.3.2 Stud visibility and illumination conditions

According to Section 2.2.3, each group is associated with a given illumination condition: Horizontal illuminance and sun position (azimuth, elevation). The three factors are: The road surface condition, the illuminance, and the sun position. Pairs of conditions for which all these factors were equal except one have been considered in the following analyses. In this section, we focused on the influence of the illuminance level, and of the sun position. The next section investigates the effect of the road surface condition.

For a given road surface condition, ratings of groups with similar qualitative sun positions were compared through the Mann–Whitney test. When the sun is behind the observer (G1 vs. G2), no effect of the horizontal illuminance was found on the visibility (G1DRY(56 klux) vs. G2DRY

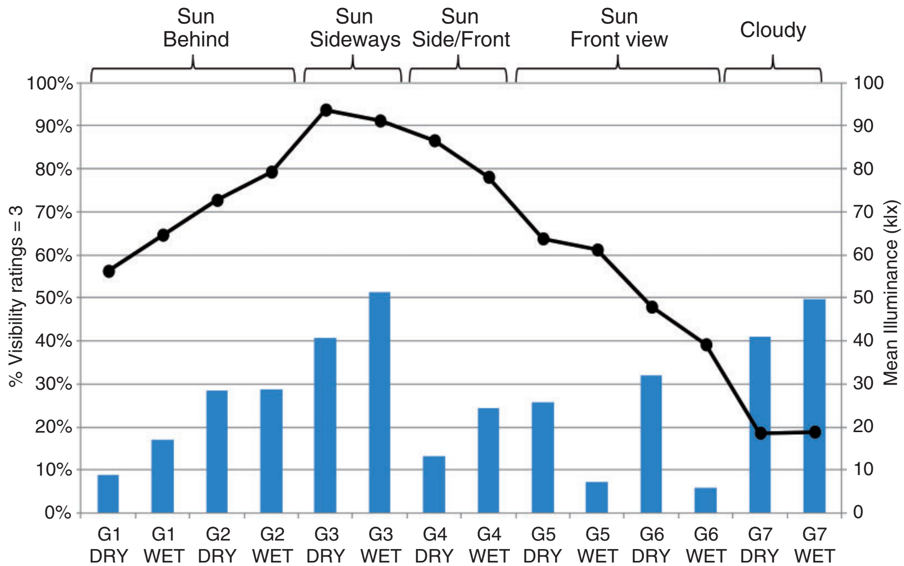


Figure 4 Left scale (bars): Frequency of visibility rating 3 for each group of participants. Right scale (line): Horizontal illuminance (in klux). Top: Qualitative sun position

(73 klux), $p = 0.70$; G1WET(65 klux) vs. G2WET(79 klux), $p = 0.170$). On the contrary, when the sun is in front of the observer (G5 vs. G6), visibility ratings vary depending on the illuminance (G5DRY (64 klux) vs. G6DRY(48 klux), $p < 0.05$; G5WET(61 klux) vs. G6WET(39 klux), $p < 0.05$), the visibility ratings being higher for lower horizontal illuminance (Rank Sum (G6DRY) = 72740.5 > Rank Sum (G5DRY) = 66915.5) in the dry condition but lower in the wet condition (Rank Sum (G6WET) = 74703.0 < Rank Sum (G5WET) = 77925.0).

From Section 2.2.3, the illuminance is not significantly different in G3 and G4 with a dry road surface, and in groups G1 and G5 or G2 and G4 with a wet road surface, but the sun was not in the same position. Mann–Whitney tests were computed on visibility ratings for each pair of groups cited above. Visibility ratings were significantly different (G3DRY vs. G4DRY, $p < 0.001$; G1WET vs. G5 WET, $p < 0.001$; G2WET vs. G4WET, $p < 0.05$), showing an effect of the sun position.

Figure 4 shows the frequency of visibility ratings equal to 3 (i.e. ensuring a good visibility of the stud) among all the tested luminous intensities, for each group and each road surface condition; average illuminance and sun position are also reported. For each road surface condition, a Kruskal-Wallis test was conducted to compare data from each group, each one representing a given illumination condition. As highlighted in Figure 4, for both the dry road surface ($H(6,N = 1820) = 155.33$, $p < 0.001$) and the wet road surface ($H(6,N = 1820) = 355.96$, $p < 0.001$), a main effect of the group was found on visibility ratings. Thus, the visibility ratings depend on the interaction between illuminance and sun position.

2.3.3 Road surface condition

According to Section 2.2.3, the visibility ratings between wet and dry road surface can only be compared for Groups 3, 5 and 7. Wilcoxon signed-rank tests show that for a given illumination condition, visibility differs between dry and wet road surface (G3DRY vs. G3WET, $p<0.001$, $r=0.24$; G5DRY vs. G5WET, $p<0.001$, $r=0.45$; G7DRY vs. G7WET, $p<0.001$, $r=0.31$). According to Figure 4, the visibility is better for Groups 3 and 7 with wet road surface whereas it is better with dry road surface for Group 5, i.e. when the sun is in front view.

2.3.4 Conclusions

Non-parametric statistical analyses lead to the following findings:

1) Within the stud's luminous intensity range, there is no glare during daytime whatever the external conditions;
2) As expected, for all participants, visibility ratings increase with the stud's luminous intensity;
3) The sun position, the horizontal illuminance and their interaction impact the visibility rating;
4) In most conditions, the road stud's required luminous intensity is higher on a dry road surface compared to a wet one. Recommendations can thus be provided for a dry road surface and applied to all conditions. As no glare was reported for the wet road surface, it could be relevant to keep the same luminous intensity in case of rain. However, if the sun is in front of the road users, the luminous intensity of the road stud must increase to ensure enough visibility on a wet road surface.

From these findings, the required luminous intensity can be predicted to ensure enough visibility for any external conditions. A quantitative model is therefore proposed.

2.4 Visibility model

A visibility model can be proposed from the experimental data. For that purpose, a specific model was computed for each road surface condition (dry model and wet model). Model estimations and validations are first presented. Luminous intensity recommendations taking into account both road surface conditions are then proposed.

2.4.1 Model estimation and validation

The visibility ratings were collected as ordinal data. Thus, for each step of the rating scale (0 vs. 123, 01 vs. 23, or 012 vs. 3), a binary visibility function can be considered (respectively threshold visibility function, difficult visibility function, or enough visibility function), and a logistic model may be applied to the data. In this paper, we focus on fair visibility, so that the data was split into two classes: Insufficient visibility (ratings 0, 1 and 2) and enough visibility (rating 3). For each road surface condition, a logistic regression was applied, predicting the percentage (P) of road users with enough visibility of the stud from its luminous intensity (I), the horizontal illuminance (E) and the sun position. In Section 2.3, a qualitative sun position was considered. For modeling, the sun position can be quantified by the azimuth (the angle between the azimuth w.r.t the North and the direction of observation) (Az) and the sun elevation (H).

The logistic model is given in Equation 1. Parameter values, computed from the XLSTAT software, are reported in Table 3.

$$P=\frac{1}{1+\exp(-(a_0+a_1{*}I+a_2{*}E+a_3{*}Az+a_4{*}H+a_5{*}E{*}H))} \quad (1)$$

The residual deviance (Dry model: -2log-likelihood -2LLM = 2446.1 > -2LL0 = 1446.2, Wet model: -2log-likelihood -2LLM = 2405.0 > -2LL0 = 1156.9) and the pseudo-R^2 of McFadden (Dry model: RMF = 0.409, Wet model: RMF = 0.519) were computed in order to quantify the relevance of the models through the significant link between the set of independent variables and the

Table 3 Logistic regression: Parameter estimation and Wald test

	Factors	Unit	Parameters	Chi^2 of Wald	*p*-Value
Dry	Constant	–	a_0=0.953	1.37	0.242
	Intensity (*I*)	cd	a_1=3.672 cd^{-1}	407.51	<0.001
	Illuminance (*E*)	klux	a_2=-0.162 klux^{-1}	126.85	<0.001
	Azimuth/observer (*Az*)	deg	a_3=0.011 deg^{-1}	31.75	<0.001
	Elevation (*H*)	deg	a_4=-0.097 deg^{-1}	12.78	<0.001
	$E \times H$	klux.deg	a_5=0.003 klux^{-1}.deg^{-1}	65.97	<0.001
Wet	Constant	–	a_0=0.083	0.011	0.918
	Intensity (*I*)	cd	a_1=4.024 cd^{-1}	371.48	<0.001
	Illuminance (*E*)	klux	a_2=−0.323 klux^{-1}	232.65	<0.001
	Azimuth/observer (*Az*)	deg	a_3=0.005 deg^{-1}	10.87	0.001
	Elevation (*H*)	deg	a_4=-0.049 deg^{-1}	5.58	<0.05
	$E \times H$	klux.deg	a_5=0.005 klux^{-1}.deg^{-1}	163.81	<0.001

dependent variable.[27] In addition, Wald tests[27] were computed, showing the contribution of the factors to the models (see Table 3). In accordance with the findings in Section 2.3, all factors have a significant contribution. Especially, for both road surface conditions, the logistic models highlight that the luminous intensity, as expected, is the variable which most affects the visibility, followed by the illuminance and its interaction with the sun elevation.

The area under the curve (AUC) of the receiver-operating characteristic curve provides a quantitative indication of the relevance of the prediction. It expresses the probability of the model to place a positive answer before a negative one. The dry model (respectively the wet model) has an AUC = 0.901 (respectively AUC = 0.937), which suggests an excellent discrimination, according to Hosmer and Lemeshow.[28] Finally, in order to quantify the quality of predicted proportions, the Hosmer–Lemeshow test[28] was employed (Dry model: $C(8) = 11.827$, $p = 0.159$, Wet model: $C(8) = 4.689$, $p = 0.790$). The non-significance of the results ($p > 0.05$) validates the models.[27,28]

2.4.2. Luminous intensity recommendations

The benefit of such a model is that it can predict the proportion (and confidence interval) of positive answers about road stud visibility, given the model's parameters. Conversely, from external parameters, using Equation 2, it is also possible to choose the road stud's luminous intensity leading to a given rate of positive answers (say, $P = 95\%$ of rating '3 Visible enough'). As an example, Figure 5(a) shows the luminous intensity required to ensure 95% of visibility as a function of the horizontal illuminance and the sun elevation with 45° azimuth (the sun is in front of the road users) for a dry (in black) and a wet (in grey) road surface. It can be noticed that a higher luminous intensity is required for a dry road surface in case of high sun elevation and low illuminance, whereas at low sun elevation, a higher luminous intensity is required for a wet road surface, especially when the illuminance increases. These predictions are consistent with previous findings (see Section 2.3).

Similarly, Figure 5(b) reports the luminous intensity against the horizontal illuminance and the azimuth when the sun elevation is 40°, to ensure enough visibility to 95% of road users. In this case, at low illuminances, the luminous intensity required for a dry road surface is higher than for a wet road surface. The opposite trend is observed for higher horizontal illuminance values.

Therefore, it would be relevant to base the luminous intensity recommendations on the dry model, but taking the wet model into account when it requires a higher luminous

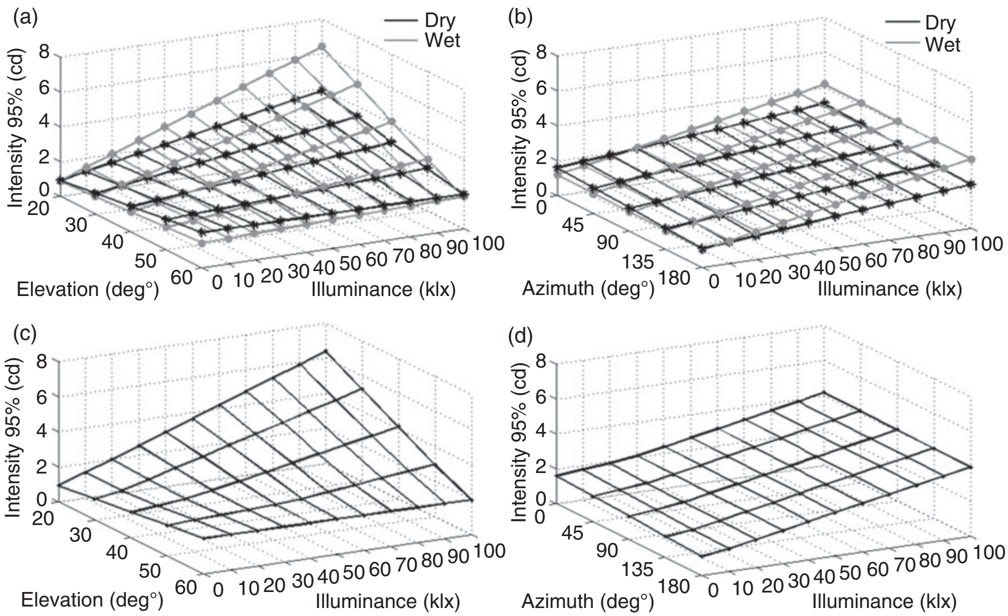


Figure 5 Top: Required luminous intensity (I_{dry} and I_{wet}) to ensure 95% of positive answers (i.e. 95% of the ratings = 3) against the horizontal illuminance and (a) the elevation (azimuth = 45°) (b) the azimuth (elevation = 40°). Bottom: Maximum luminous intensity (I_{dry}, I_{wet}) against the horizontal illuminance and (c) the elevation (azimuth = 45°) (d) the azimuth (elevation = 40°)

intensity than for a dry road surface. Equation 2 integrates the proposed recommendations. Figures 5(c) and 5(d) show the luminous intensity predictions based on this argument. As illustrated in Figure 5, luminous intensity recommendations exceed 2.2 cd, the maximum luminous intensity of the tested road stud. However, the model is not limited to this road stud and recommendations can be applied to road studs with a higher maximum luminous intensity. In practical situations, for which the stud cannot reach the recommended luminous intensity, the best one can do is to tune it to the maximum available luminous intensity.

3. Discomfort glare of LED road stud

According to the previous experiment, discomfort glare is not experienced during daytime in the tested range of luminous intensities (up to 2.2 cd), so the situation where this issue may emerge is at night. Therefore, an experiment was conducted in order to study discomfort glare produced by road studs in dark conditions.

3.1. Panel

Thirty-six participants were involved in this study (19 men, 17 women), with ages between 21 and 57 years ($M = 36.0$, $SD = 10.3$). The same visual tests as in the Visibility

$$\begin{cases} I_P = max[I_{DRY}(P, E, Az, H), I_{WET}(P, E, Az, H)] \\ I(P, E, Az, H) = \frac{1}{a_1}\left[\ln\left(\frac{P}{1-P}\right) - a_2E - a_3Az - a_4H - a_5E \times H\right] \end{cases} \tag{2}$$

experiment were conducted prior to the experiments: Visual acuity in binocular vision and in mesopic vision, contrast sensitivity and time of recovery after glare. Descriptive data about the participants and the results of their vision tests are presented in Table 2.

3.2. Material and method

The same amber-coloured stud as in the Visibility experiment was employed (Section 2.2.1). The experiment was carried out during the day, but indoors in a dark room, in order to reproduce night-time photometric conditions. The participants were seated 30 m from the stud, at 1° angle of observation of the stud. The average horizontal illuminance on the road surface was controlled at 1 lux[29] which corresponds to typical condition under moonlight. The goal of most applications with LED road studs is to provide visual information to the driver at a distance where the headlights do not reach the studs, otherwise retroreflective road studs can be employed. Therefore, headlights were not taken into account in the experimental setup.

According to preliminary tests, the road surface reflection properties do not seem to influence glare perception, at least in the conditions of the experiment, that is, without an oncoming vehicle. Thus, a wet road surface was not investigated during this experiment.

Thirteen luminous intensities from 0.1 to 0.6 cd (with luminance values between 422 and 2600 cd/m^2) were randomly presented to each subject. The stud was switched on for two seconds, and then two minutes was left until the next stimulus in order to allow participants to recover visual adaptation. After each stimulus, the participants were asked to answer the following question: 'Do you experience some level of glare from the road stud?':

- 1: No, not at all;
- 2: No, it is just acceptable;
- 3: Yes, it is disturbing;
- 4: Yes, it is unbearable.

The answer was verbal, in order to avoid any lighting during the dark adaptation phase. The scale was based on the 9-point De Boer scale,[30] but it was reduced to a 4-point scale in order to allow the participants to easily remember the scale before the beginning of the experiment.

3.3. Results

First, a hierarchical clustering[26] was conducted using the percent disagreement distance with average linkage (Statistica). From this cluster analysis, one outlier was found. Without any visual deficiency, this outlier answered 'Unbearable' at low intensities (0.14 cd, 0.23 cd, 0.27 cd, 0.43 cd). His data were removed from further analyses.

Frequencies of ratings were computed for each tested luminous intensity (Figure 6). To ensure 100% of 'no glare' answers, the stud luminous intensity has to be set at the minimum available value, i.e. 0.1 cd. This corresponds to 422 cd/m^2 at the observation point of view of 1°. With other settings, more than 5% of observers were disturbed by the stud.

The effect of visual characteristics was investigated with non-parametric tests (Mann–Whitney in the case of two independent groups, Kruskal–Wallis for more than two independent groups). Glare ratings with similar characteristics were merged. A non-parametric Kruskal–Wallis test and a non-parametric *post-hoc* test were conducted on the three samples corresponding to different times to recovery ($H(2,468) = 9.4619$, $p < 0.05$, Mean ranks: 249.84 (<25 s), 247.35 (25 s$<x<$50 s), 212.17(>50 s)): Participants with the highest time to recover after glare felt less glare than the others (>50 s vs. 25 s$<x<$50 s: $p = 0.0705$, > 50 s vs. < 25 s: $p = 0.0320$, < 25 s vs. 25 s $<x<$ 50 s: $p = 1.000$). This result could be explained by the fact that the participants with the highest time to recovery were less adapted to the dark

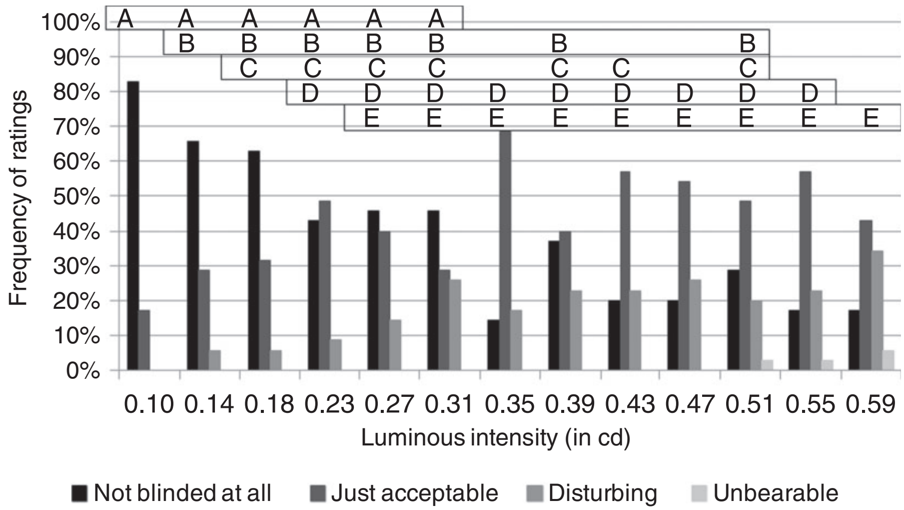


Figure 6 Frequency of glare ratings according to the tested luminous intensity, and classes (A–E) of non-significantly different luminous intensities for glare feeling

than the others and therefore were less sensitive to discomfort glare. However, this question deserves more investigation in future work. In addition, similarly to Sivak *et al.*,[31] no statistically significant difference between subjective glare judgment of participants with and without visual correction was found (Mann–Whitney test: Correction vs. No correction, $p = 0.412$), even if the corrected participants provide higher ratings on average than the non-corrected ones ($M_{corrected} = 2.01 > M_{no\text{-}corrected} = 1.66$). In previous work, no consensus has been reached about the effect of the age on discomfort glare.[32] Likewise in our experiment, correlation with age was found for the following visual characteristics, mesopic acuity ($Pr = -0.658$, $p < 0.001$) and contrast sensitivity ($Pr = 0.547$, $p = 0.001$) and there was no significant difference in the rating distribution by these characteristics (Mesopic acuity: $\geq 8/10$ vs. $< 8/10$, $p = 0.412$; Contrast sensitivity: $H(2{,}468) = 1.930$, $p = 0.380$).

Finally, a non-parametric Friedman test and a non-parametric *post-hoc* test were performed on glare ratings to study the effect of the luminous intensity. The Friedman test ($Q(12) = 104.07$, $p < 0.001$) shows significant differences in producing glare. Luminous intensities for which the glare feeling is not significantly different (according to comparisons of mean ranks with non-parametric *post-hoc* test) are highlighted in Figure 6. Five classes emerge, the first one being related to the most comfortable range [0.10: 0.31 cd]. All these levels are lower than the recommended luminous intensity during night provided in previous work[20,21] (see Table 1).

According to previous work,[17,33] the level of discomfort glare depends on the viewing angle. In the experiment, observers stared directly at the stud, which corresponds to a 'worst case' methodology. Therefore, in most cases, setting the stud luminous intensity to 0.1 cd will not produce any glare at all, even if the stud captures drivers' gaze.

4. Discussion

4.1 Summary of the main results

The visibility and discomfort glare of a LED road stud were investigated. The results confirm that visibility mostly depends on the road stud's luminous intensity. Consistent with previous work,[18,19,21] our findings suggest that the luminous intensity of the road studs should be tuned according to the illumination conditions, in order to be visible whatever the illumination (horizontal illuminance on the road, sun position), and without causing glare at night. The stud visibility depends on the background illumination conditions, which is qualitatively consistent with Weber's law.[34] It was also found that the road surface condition (dry/wet) may impact visibility but not glare.

A quantitative model is proposed for luminous intensity dimming under daylight in order to ensure visibility level (based on the percentage of participants assessing enough visibility). According to the proposed model, the required stud's luminous intensity increases with horizontal illuminance, and as the sun elevation decreases. The road surface condition should be also considered for a quantitative visibility model: The highest luminous intensity is required when the sun is low (4.01 cd for [DRY, $E = 100$ klux, $Az = 0°$, $H = 20°$]) especially for a wet road surface (6.46 cd for [WET, $E = 100$ klux, $Az = 0°$, $H = 20°$]). Such a fine tuning may allow some energy savings, but it requires the corresponding parameters to be available from some sensors, to be broadcasted to the road stud controller.

For 1° observation on the stud axis, a mean luminous intensity of 1.54 cd is recommended whatever the road surface condition from the proposed model for cloudy days (illuminance < 30 klux). During sunny days, recommended luminous intensities range from 1.57 cd to 4.01 cd for a dry road surface, and from 1.41 cd to 6.46 cd for a wet road surface. Dimming, especially under cloudy days, makes it possible to save energy. In addition, under 1° in dark conditions, the stud's luminous intensity should be as low as 0.31 cd in order to limit discomfort glare, and a luminous intensity of 0.1 cd (corresponding to $L = 422\,cd/m^2$ in our settings) would make it possible that less than 5% of the road users are disturbed by the stud when looking at it.

The model's recommendations can be considered as target values. In practice, the luminous intensity control will be affected over time by parameters such as lumen depreciation, junction temperature, which is a major issue for amber LEDs,[35–37] and the uncertainty of stud position and thus on its angular output throughout the service life (due to wrong implementation, buckling pavement for instance). If the stud manufacturer has some knowledge on the photometric behaviour of the LED stud, it may be included, to some extent in the control device.

4.2 Limits and future work

Several limitations apply to this study. First, the model was built with few data, and with no data in some parts of the parameters' ranges. Visibility data were not collected in overcast conditions and would deserve further investigation to achieve more energy saving. Besides, recommended luminous intensity levels (Section 4.1) are higher than the tested stud capacity (2.2 cd). It would be useful to collect new data with a more powerful road stud in the model's domain where high luminous intensity values are required, in order to adjust the proposed model. In addition, even if the glare level remains low for luminous intensities up to 6.5 cd in previous work,[20,21] it has to be confirmed in future work.

The wetness conditions were not measured in this experiment. Indeed, LED tuning depending on the exact water conditions on the road around the studs was considered non-realistic, either technically (water height over the road surface depends on a number of physical and geometrical factors, and varies along the road) or economically (the deployment of water height sensors was not considered an option). Thus, it appeared more realistic to classify the road state in terms of dry/wet. The configuration which was considered in this experiment corresponded to a wet road after rain (i.e. in recovery mode), where the photometric properties of the road were modified (w.r.t. a dry road), with more specularity, in order to see if it impacts the stud visibility. Therefore, as a pilot study, dry and wet road surfaces were compared. Findings open up new perspectives to fully investigate the wet condition by testing various wetting rates.

The proposed discomfort glare level corresponds to someone looking in the dark at a stud which is suddenly switched on: This is a 'worst case' situation leading to conservative recommendations. People would not always stare at the studs, but in some applications this may be relevant. For instance, when using LEDs on curves,[11] one may expect the driver to look at the tangent point, where studs will be present. Therefore, in most cases, setting the stud luminous intensity to 0.1 cd will not produce glare. It can also be noticed that our findings are lower than those recommended in previous work where the discomfort glare judgments were collected through dynamic observations (4 cd recommended),[20] or where several studs were presented together (0.92 cd recommended).[21]

Findings about visibility and discomfort glare are related to a particular situation. A number of factors were not considered here, such as vehicle speed (the participants were seated on a chair), distance to the stud, and so on. Another approach would be to collect the visibility judgment from dynamic observation of the road stud.[20,22] Our experiment conditions were limited to one vertical angle (1°). In future work, it would be relevant to study the distance effect, especially for a wet road surface which has specific reflection properties.

Finally, measurement with one stud is not enough for direct application on the road. Previous work investigated the visibility of a set of studs[21] but no findings are currently available to compare the visibility of one stud versus a set of studs. New parameters need to be controlled, such as the number of studs, the distance between studs, possibly the shape of their alignment (in curves, straight lane, lateral positions, same versus different colours, same versus different luminous intensities, etc.). Besides, vision science models may contribute to predicting the visibility and glare from one stud to several, and this will be the first step in our future effort towards investigating the visual effect of series of studs.

4.3 Dimming and energy savings

Our experiments show that the luminous intensity of the stud can be tuned to the illumination conditions while ensuring visibility and avoiding discomfort glare. It even points out the need, if one wants to use such systems both night and day, to adapt the stud's luminous intensity at least to the day/night condition: A constant luminous intensity would either produce important glare at night, or fall below the visibility threshold during the day. In addition, dimming the stud's luminous intensity according to the external conditions would allow energy savings, compared to providing the maximum required luminous intensity level at all times. In order to quantify the benefit of stud dimming in terms of power consumption, energy saving (ES) can be calculated according to Equation (3), which gathers the findings from the Visibility and Glare experiments.

$$ES(\%) = 1 - \left[\omega_{night} * W_{night} + \omega_{day} * (\omega_{wet} * W_{wet} + \omega_{dry} * W_{dry})\right] \quad (2)$$

where ω_i is the weight of the illumination condition i, and W_k is the average power needed in order to provide the required luminous intensity in condition k.

As an example, we used the sun azimuth, sun elevation and horizontal illuminance measured in Vaulx-en-Velin (France) every minute during the year 2013. Four driving directions were considered (South-, North-, West- and East-bound). For each direction, the stud's luminous intensity required to ensure enough visibility for 95% of users was computed for each minute of the year during daytime from the dry and wet model predictions, and set to 0.1 cd at night (see Section 3.3). Light intensity was considered proportional to power demand:[2,8,38] light output is proportional to forward current[38] under a constant LED junction temperature and there is a linear relation between current and provided luminous flux.[2] This assumption is limited in practice for amber LEDs because when reaching high powers, the junction temperature increases resulting in a decrease of light output.[35,36] Therefore, the estimated energy savings are underestimated with our linear consumption model compared to a more realistic one, taking into account the temperature sensitivity.

Percentages of power demand were calculated as a ratio between the required luminous intensity and the maximum luminous intensity. The average power demand was then computed over the year, for the dry condition, for the wet condition and at night. Finally, the energy saving was computed from Equation (3) taking into account the weather characteristics of the city (43% of rainy days per year).

Table 4 reports the energy savings computed for various driving directions in the example of Vaulx-en-Velin (France). Taking into account the external conditions leads to 79% to 83% energy savings depending on the driving direction, compared to providing the maximum required luminous intensity at all times. The saving is mainly due to dimming during night-time (49% of the savings), which is also required for stud performance. During daytime, about 31% of energy savings is found in most driving directions (N/S, S/N, E/W). Taking into account the dry/wet road surface condition only leads to 4–7% difference in energy savings (ES_{dry}-ES_{wet} = 7.5% (N/S), 5.6% (S/N), 6.6% (E/W), 4.5% (W/E)).

These findings suggest that the luminous intensity of the road stud has to be tuned to the illumination conditions to ensure both visual performance and energy savings. This is especially interesting for self-powered LED installations on highways. Our study focused on one road stud, but this result is promising for all traffic control devices using LEDs, such as traffic lights, variable-message signs or road signs.

5. Conclusion

Two experiments were conducted in order to study the visibility and discomfort glare produced by an amber-coloured LED road stud. During daytime, the visibility of the stud varies according to the illumination conditions: Horizontal illuminance on the road surface and sun position, and differs between wet in recovery mode and dry surfaces. A

Table 4 Energy-saving estimation for various road orientations in Vaulx-en-Velin (France)

Observation orientation	Global	Daytime – Global	Daytime – Dry	Daytime – Wet
South-bound	83.0%	34.0%	22.2%	14.7%
North-bound	80.3%	31.3%	19.3%	13.7%
West-bound	81.7%	32.7%	20.8%	14.2%
East-bound	78.6%	29.6%	17.7%	13.2%

quantitative model was proposed to compute the percentage of good visibility ratings depending on the stud's luminous intensity and the illumination conditions. In addition, discomfort glare can be found under dark conditions and the minimum available road stud's luminous intensity seemed to be the most suitable to avoid glare. Thus, the stud can be dimmed while ensuring good visual conditions to road users. To quantify the benefit of dimming, an energy saving calculation was proposed. It was demonstrated with an example that more than 80% energy savings can be achieved by dimming the stud according to the time of the day, the illumination conditions and the surface condition.

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