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Examining the impact of different LED road stud layouts on driving performance and gaze behaviour at night-time

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ABSTRACT

The risks associated with night-time driving on dimly lit roads are substantial and are attributable to the limitations of human visual abilities. As a result, drivers often struggle to distinguish road geometry from ordinary road markings, thus increasing the likelihood of mistakes. These circumstances contribute to a 60 % higher likelihood of road crashes compared to daytime conditions. To mitigate these risks, active LED road studs, which previous studies have shown to have a positive influence on driving performance, can be used. However, there remains a gap in research regarding the optimal arrangement of these studs along road markings for an improvement in driver behaviour and traffic safety. In this study, we assessed the influence of five different LED road stud layouts (unlit, edge, centre, edge-centre, and lane) during night-time driving on two-lane rural highways with curves of different radii (120, 210, 300, 440 m) and directions (left, right). Following a within subject design, thirty-five participants drove in a simulator along a road track with 8 spiralled curves (4 radii × 2 directions) linked to straights. We monitored the longitudinal (i.e., speed), transversal (i.e., lateral position and standard deviation of lateral position) and gaze behaviours.

Our findings indicate that the presence of LED road studs promotes safer driving, by helping drivers to adjust their speed when negotiating curves. Transversal behaviour analysis revealed layout-dependent effects on lateral position. The presence of road studs both at the lane centreline and edge allows drivers to maintain centred trajectories and improve steering control. Gaze behaviour analysis uncovered interesting patterns, demonstrating a strong correlation between road stud layout and the driver's focus on specific road targets. Illuminated markings prompt drivers to concentrate their gaze on distinct points, subsequently altering their transversal behaviour.

1. Introduction

Driving at night on dimly lit roads poses risks to drivers (Johansson et al., 2009) because of their limited ability to detect any movements ahead and discern the shape, colour, and texture of objects along the road. This is due to the limited performance of human vision under low environmental luminance conditions (Liu et al., 2019; Wood, 2020), i.e., scotopic vision (Boyce, 2008). Thus, when driving at night, drivers face greater difficulties in identifying the boundaries of the lane they are moving in, as well as those of adjacent lanes. This, combined with factors such as fatigue, distraction, and driving under the influence, underscores why the probability of a

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road crash is 60 % higher at night than during the day (Chen et al., 2016; Zhang et al., 2016; Plainis, 2006; Owens & Sivak, 1996). Since speeds are higher when traffic density is low, crash severity is also at least two times higher during night hours than during the day (Ackaah et al., 2020; Johansson et al., 2009; Varghese & Shankar, 2007).

To enhance driving performance and safety in dark conditions, solutions like *retro*-reflective road markings and roadside delineators have been installed on roads for years. In this context, road studs have recently gained prominence as they enhance visibility and accurately delineate the lane and the carriageway.

Although traditional (passive) road studs have been widely used, light–emitting diode (LED) road studs have become increasingly popular in recent years thanks to their superior performance (Angioi et al., 2023; Shahar et al., 2018). A key feature of LED road studs is that they are self-illuminating, that is, they emit light on their own, unlike passive road studs, which must first be hit by light from vehicle headlamps before they return the reflected beam into the driver's field of view. Therefore, LED road studs have a superior performance since they are active and visible even in haze and fog. In ordinary visibility conditions, the distance at which they are visible increases from 100 m for passive devices to about 900 m for active LED devices (Reed, 2006). Active road studs provide visual guidance to drivers helping them to achieve greater control of their vehicle trajectories, especially on those curved stretches of road that are recognized as unsafe at night-time (NHTSA, 2008).

The effectiveness of road studs on driving performance has been confirmed with a few research activities in naturalistic and simulated studies. In a driving simulation experiment, Shahar et al. (2018) and Shahar & Brémond, (2014) observed that drivers exhibited centred trajectories within the lane and made fewer steering corrections under studded conditions than they did in unlit conditions without studs. Drivers stated that they perceived roads with studs to be safer and more comfortable than roads without. While the presence of road studs does not result in any significant changes in mean driving speeds (Llewellyn et al., 2021), it increases the confidence levels of drivers at night (Llewellyn et al., 2020).

In a preliminary study (Portera et al., 2023), we investigated the effects of red and white coloured LED road studs placed along the two carriageway edge strips (indicated here as edge layout). Results revealed that white studs performed better in terms of pleasantness and perceived risk. Also, driving performance levels were significantly improved with the white LED studs. However, we observed different behaviours when drivers negotiated left- and right-hand curves. We conjecture that this was a consequence of the specific layout adopted. According to Fig. 1, road studs were installed along the two lateral roadway strips only. As a result, when drivers focus on the inner marking line using the tangent point as an aid to steer the vehicle (Land & Lee, 1994), an asymmetric condition was tested. On left curves (Fig. 1a), the driver's gaze is guided by lane markings of low optical quality. In contrast, on right curves (Fig. 1b), the driver's gaze is aligned with the line of LED road studs, providing an enhanced vision of the curve geometry. Based on this evidence, we inferred that the layout of road studs (i.e., the different combinations of LED road stud positions along the three marking strips) may influence the gaze behaviour and overall performance of drivers.

To the best of our knowledge, no one had ever previously investigated driver gaze behaviour when subjected to different road stud layouts, both passive and active, and the effects of such layouts on night–time driving performance. In this study, we used eye-tracking technology to establish whether a brighter marking delineation could capture the drivers' gaze. We hypothesised that if the driver's gaze was directed toward the markings made brighter by the LED road studs, this would improve his/her ability to control the vehicle longitudinally and laterally along curves.

2. Method

2.1. Experimental design

The experiment followed a repeated measures approach with (i) road stud layout, (ii) curve radii, and (iii) curve direction as experimental factors. Together with the reference "unlit" condition (Fig. 2b), four different LED road stud layouts were investigated: (i) the two carriageway edges ("edge" in Fig. 2c), (ii) the carriageway centreline ("centre" in Fig. 2d), (iii) both carriageway edges and centreline ("edge-centre" in Fig. 2e), and (iv) the lane edges (i.e., the LED are visible only along the travelled lane, "lane" in Fig. 2f). It is worth noting that the edge layout depicted in Fig. 2c had already been considered in our previous study in order to evaluate the effects

Fig. 1. Road stud layout adopted in Portera et al. (2023). Assuming the tangent point mechanism is used (Land & Lee, 1994), in the case of a left turn (a) the gaze is directed toward a road sign without LED studs, which is in contrast with the case for a right turn (b).

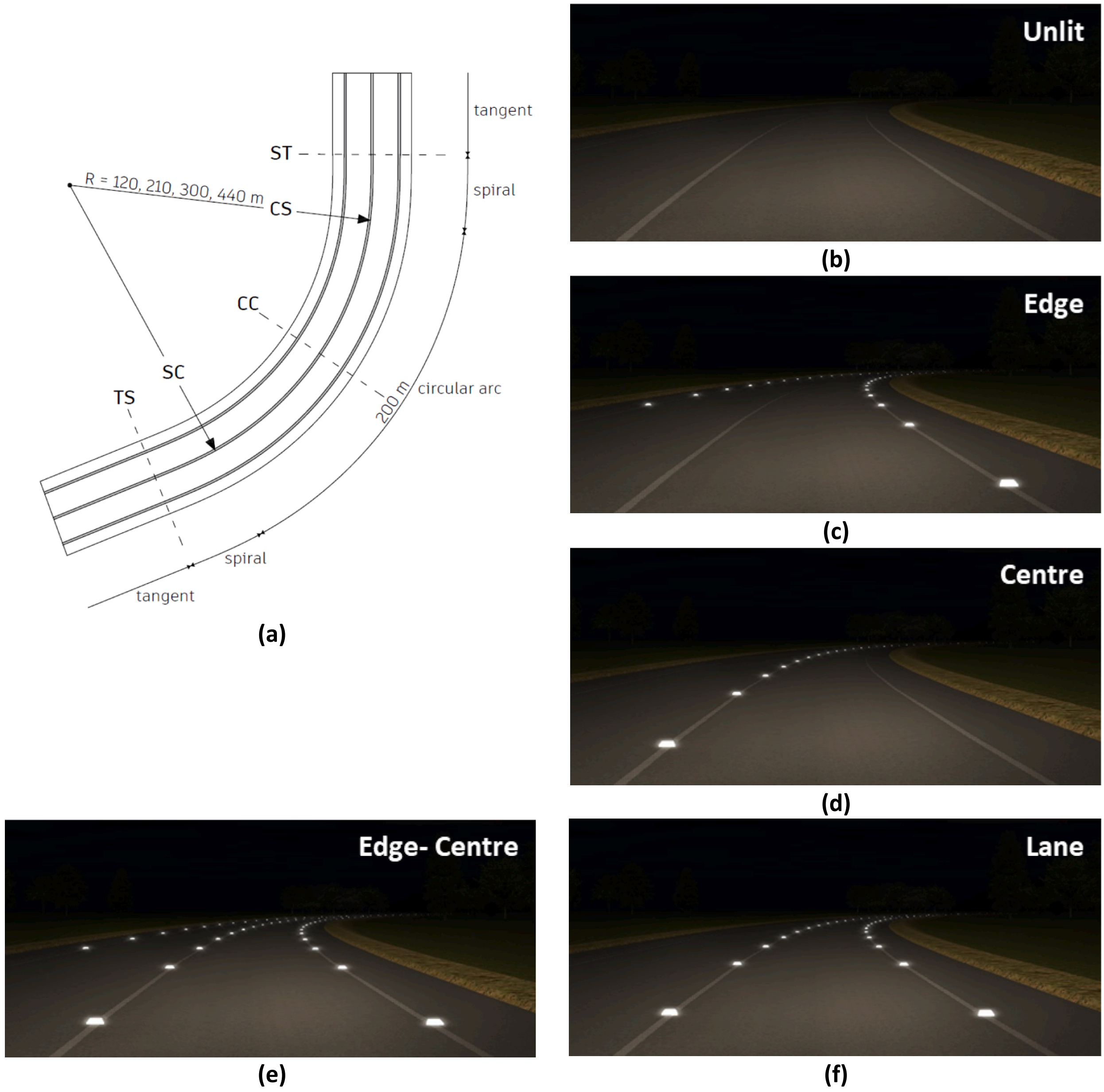


Fig. 2. Plan scheme (a) of the geometric factors of curves and curve termini. Frames taken from the driver point of view for (b) unlit condition, (c) edge, (d) centre, (e) edge-centre, and (f) lane road studs. Road studs were always placed 8 m apart.

of colour on driving performance (Portera et al., 2023).

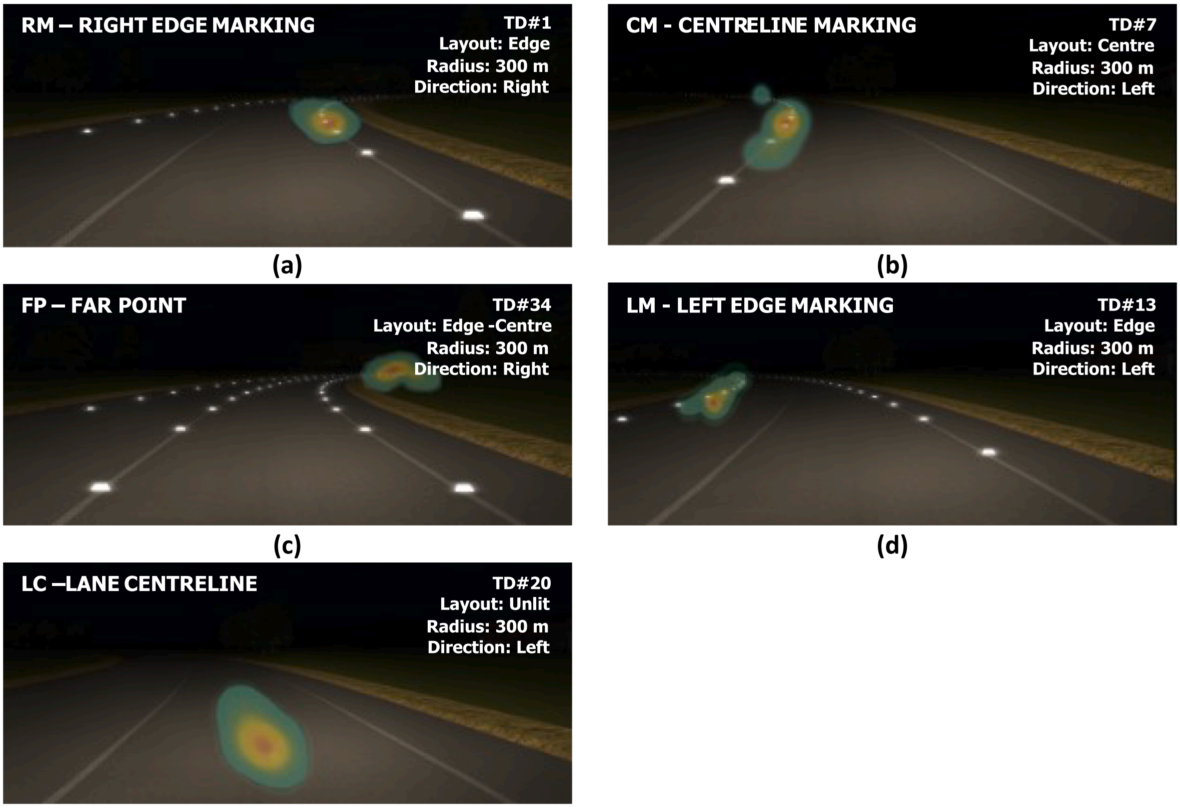
Consistent with Portera et al. (2023), we set the white LED as the only road stud colour. Four different spiralled curves with radii equal to 120, 210, 300, and 440 m, and the two directions, right and left, were considered for the design of the road track. A total of five different scenarios were reproduced with the same road geometry, each including only one road stud layout. In each scenario, all possible combinations of radii (4) and curve directions (2) were reproduced, for a total of (4 × 2 =) 8 curves. Three behavioural outcomes were considered in the data analysis: (i) the speeds at tangent–to–spiral (TS) and at the curve centre (CC) termini (Fig. 2a); (ii) the lateral distances between the vehicle centre of gravity (CoG) of the vehicle and the lane centreline at TS and CC termini; and (iii) the standard deviation of lateral position (SDLP) along the entire curve, i.e., between TS and spiral-to-tangent (ST) termini. An eye tracker was employed to record the gaze behaviour of participants while negotiating the curves. The eye fixation value (period of stable gaze) was recorded for each curve from the TS to curve-to-spiral (CS) termini, i.e., along the segment in which the driver gaze was directed on the curve, with heatmaps as the outcome (see Section 2.3 for more details).

2.2. Equipment and road scenarios

The experiment was carried out with the fixed-base driving simulator (AV Simulation, France) in the Road Safety and Driving Simulation Laboratory (RSDS Lab) at the Politecnico di Torino. The simulator was equipped with three 32-inch monitors (resolution 1920 × 1080 pixels, frequency 60 Hz, 130°×20° field of view), a fully equipped driving position including seat, instrument panel, steering wheel with force feedback, pedals, manual transmission, and vibration pads for returning road roughness, wheel roll and impact. In the course of the experiments, the image of the cockpit on the screens allowed drivers to visualise the width of the vehicle and lend verisimilitude to the simulation. A Dolby Surround 5.1 sound system provided a realistic reproduction of the car engine, nearby traffic and the surrounding environment. SCANeR Studio® simulation software was used to build the driving scenarios, run the simulation, and acquire the driving data. The simulator had previously been validated for longitudinal (Bassani et al., 2018) and transversal behaviour (Catani & Bassani, 2019). Pupil Labs Core eye tracker (https://pupil–labs.com/products/core/) was used to collect the driver gaze data.

All five scenarios were based on the same road alignment of a two-lane rural highway. The road alignment was designed in accordance with the Italian standards for road geometric design (Ministero delle Infrastrutture e dei Trasporti, 2001) and the Italian Highway Code (Legislative Decree 30 April 1992, No. 285) and featured 3.75 m wide lanes and 1.5 m wide shoulders (Road type C as per the Italian standard). The total length of the road was 6.9 km including 8 spiralled curves obtained by combining four radii (120 m, 210 m, 300 m, 440 m) and the two directions (left and right). We selected four radius values to collect behavioural data at different speeds. In accordance with Italian standards (Ministero delle Infrastrutture e dei Trasporti, 2001), the four radii correspond to design speeds of 60, 75, 85, and 100 km/h respectively. Each circular arc of curves was 200 m long (from SC to CS in Fig. 2a), but the spiral length (L) was calculated from the radius (R) in accordance with Italian geometric design rules (L = R/9) (Ministero delle Infrastrutture e dei Trasporti, 2001). To ensure that the experience of preceding curves did not influence the speed adopted on successive ones, straight segments of sufficient length were introduced between two consecutive horizontal curves. The lengths of the straight segments varied between 110 m, used to connect curves with larger radius, and 330 m, used to connect curves with a sharper radius. Finally, the alignment was designed so that the curve radius gradually changed within the range 120–440 m curve by curve.

All scenarios shared the same landscape, environment, and road geometry. As already mentioned, they differed only in the layout of the white LED road studs. The few vehicles travelling in the opposite direction were only encountered along tangents to mimic realistic conditions, and to preclude any influence on driver behaviour along curves. In accordance with Portera et al. (2023), all LED road studs



(a) (b) (c) (d) (e)

Fig. 3. Pictures provide examples of gaze heatmaps retrieved from different test drivers (TD), which indicate the different road elements gazed at along the tests: (a) right edge marking (RM), (b) centreline marking (CM), (c) far point (FP), (d) left edge marking (LM), and (e) lane centreline (LC).

were spaced 8 m apart along curves.

2.3. Eye tracking

The eye-tracker revealed the driver's gaze behaviour following extraction of the gaze heatmaps. From an examination of these outcomes and in line with previous works (Fiolić et al., 2023; Land & Lee, 1994; Lappi, 2014; Lappi et al., 2013), we observed that drivers tended to focus their gaze on a specific element of the road while driving along the curve. Therefore, we established the five gaze targets showed in Fig. 3 that indicate where each driver generally oriented his/her gaze: (i) the right edge marking (RM), (ii) the centreline marking (CM), (iii) the far point (FP), (iv) the left edge marking (LM), and (v) the lane centreline (LC). We calibrated a multinomial logit model to predict the probabilities of the various possible outcomes of a categorically distributed dependent variable, given a set of independent (real-, binary-, or categorical-valued) variables (see section 3.3).

2.4. Participants

Participants were recruited by email from a list of more than four hundred volunteers who had already been involved in previous studies. Of those who accepted the invitation, thirty-five were randomly selected and took part in this repeated–measure, within-subject fully randomized experiment, including males (20) and females (15) with ages ranging from 21 to 59 (M = 30.8; SD = 9.3). All drivers were required to have held a driving license for more than one year. Driving experience was adjudged by the kilometres travelled per year (M = 12,209; SD = 11,767) and the number of years in possession of a driver's license (M = 13; SD = 7.8). The participants signed an informed consent in accordance with the European General Data Protection Regulation form prior to the experimental session, and they did not receive any benefits or payments. The experiment was conducted in compliance with the Code of Ethics of the World Medical Association (WMA, 2013). The sample size was determined by G-power (Kang, 2021) setting the effect size at.25, the significance level (α) at.05, and the power at 95 %.

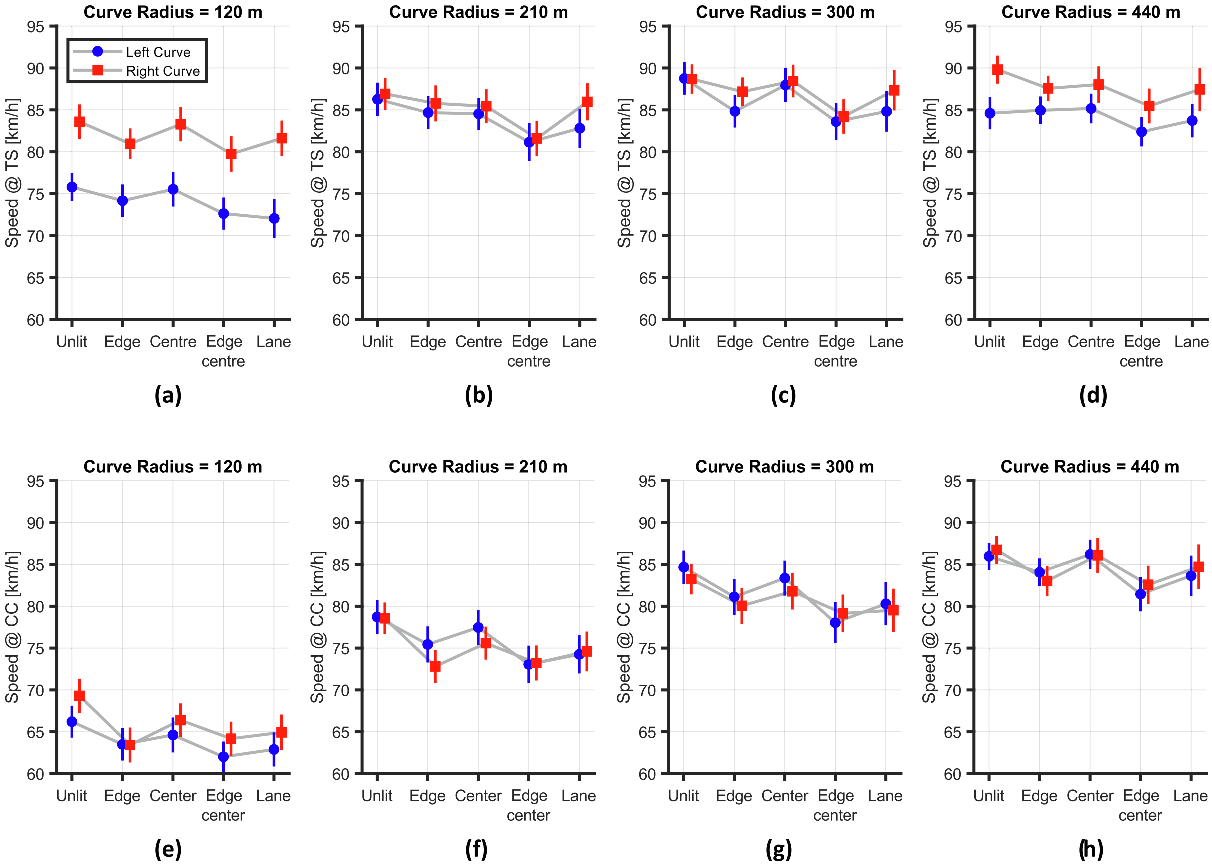


Fig. 4. Speeds approaching the curve @TS termini (a,b,c,d), and at the centre of the curve @CC termini (e,f,g,h) across the four road stud layouts and the reference (unlit) condition. (a,e) Curves with a 120 m radius; (b,f) curves with a 210 m radius; (c,g) curves with a 300 m radius; and (d,h) curves with a 440 m radius. In all the graphs, the symbol indicates the average value, while the error bars indicate the standard error of mean.

2.5. Procedure

Participants were tested individually with a four-step protocol, consisting of (i) a pre-drive questionnaire, (ii) the driving simulator training, (iii) the eye tracker calibration, and (iv) the five simulations. Participants filled out a pre-questionnaire to collect personal information (age, driving story, general health state). Thereafter, they were introduced to the training session where they were shown the functions of the simulated vehicle; then they took part in a practice trial on a test circuit for at least 3 min to familiarize themselves with the simulator. After that, the eye tracker was fitted and calibrated. Finally, the simulation started, with the five scenarios employed following a complete balance design to minimize the potential confounding effects of treatment order, making the results more robust and generalizable, and ensuring a fair distribution of experimental conditions among participants. Between every two drives, a rest time of 1 min was administered. Before driving any new scenario, the eye tracker was recalibrated to maintain accuracy during the acquisition. To ensure an authentic reproduction of night driving conditions, the study was conducted in a completely dark room.

2.6. Statistical analysis

Numerical data were analysed as per the repeated measures analysis of variance (RM-ANOVA). The significance level (α) was always set to.05. The Bonferroni correction for multiple comparisons was also applied. For the gaze data (categorical variable), the multinomial logistic regression model was used (Kwak & Clayton-Matthews, 2002) to understand what factors influenced gaze behaviour. It extends the binary logistic regression model to handle categorical outcomes with more than two unordered categories. It estimates the probability of an observation belonging to each category as a function of independent variables.

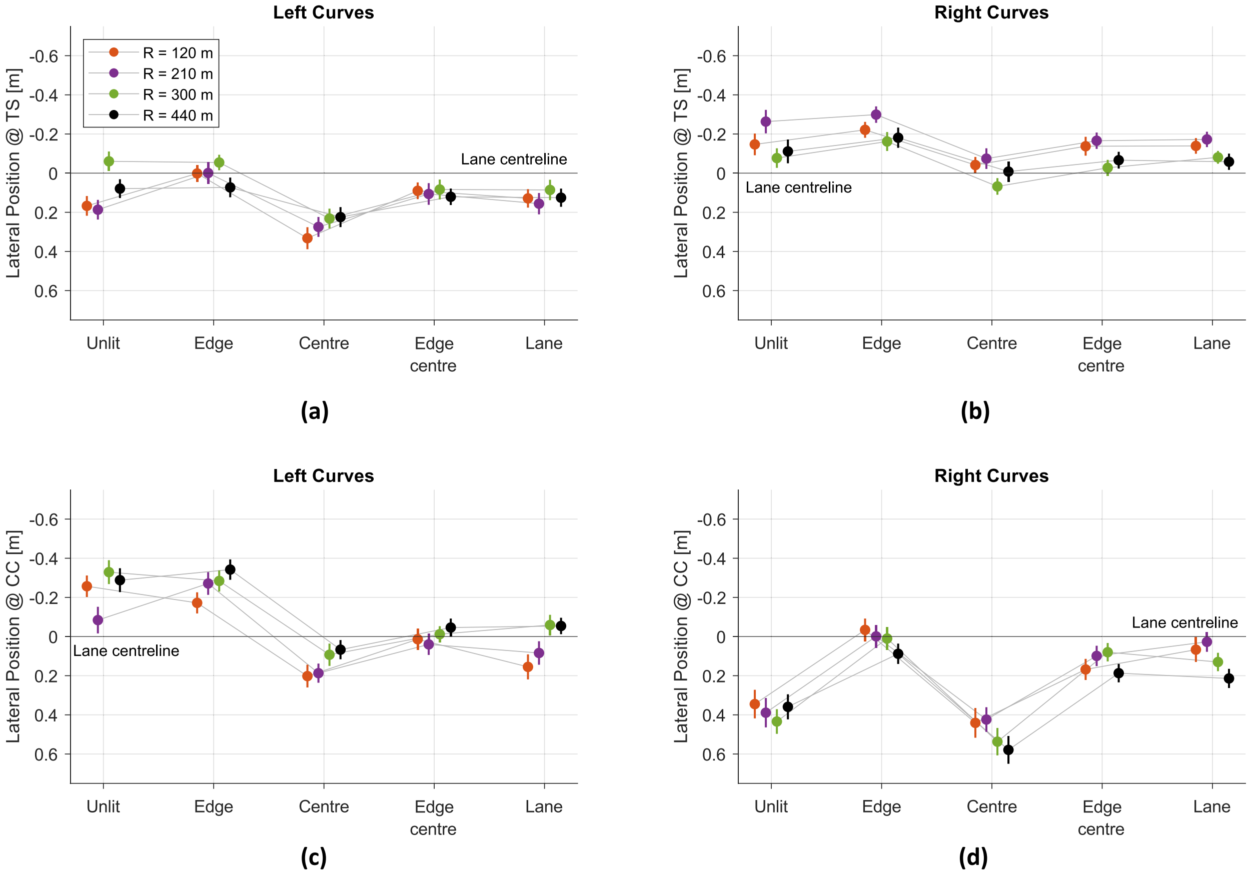


Fig. 5. (a,b) Lateral position approaching the curve @TS termini, and (c,d) at the centre curve @CC termini for (a,c) left and (b,d) right curves. Negative values indicate that the vehicle CoG was on the left side of the lane centreline, while positive values indicate that the CoG was on the right side of the lane centreline. In all the graphs, the symbol indicates the average value, while the error bars indicate the standard error of mean.

3. Results

3.1. Speed behaviour

The speeds observed when approaching (TS termini) and in the middle of curves (CC termini) are shown in Fig. 4. The figure evidences that right curves were always travelled at higher speeds than the corresponding left ones, and that drivers adopted higher speed values in the absence of road studs. The sharper the radius, the higher the speed reduction between the approaching zone (TS) and the curve centre (CC). Most importantly, it is evident that the presence of LED road studs resulted in lower speeds (when compared to unlit conditions) in all the layouts considered.

RM-ANOVA revealed that at a TS section the layout of road studs significantly influenced the speed ($F_{4,136} = 7.24, p < .001$), as well as the curve radius ($F_{3,102} = 49.52, p < .001$) and curve direction ($F_{1,34} = 97.17, p < .001$). Furthermore, the first-order interaction *Radius* × *Direction* revealed a significant effect ($F_{3,102} = 24.70, p < .001$). The post-hoc comparisons on road stud layouts revealed significant speed differences between unlit vs. edge (corrected–$p = .049$), and unlit vs. edge-centre (corrected–$p = .006$). Regarding curve radius, significant differences (corrected-$p < .05$) emerged between the sharpest radius (120 m) and the other radii (210, 300, and 440 m), with the lowest speed recorded along the sharpest one.

At CC termini, road stud layout and curve radius influenced driver speed ($F_{4,136} = 9.88, p < .001$; and $F_{3,102} = 188.28, p < .001$, respectively). Two out of three two-way first-order interactions, i.e., the *Layout* × *Direction*, and *Radius* × *Direction*, were statistically significant ($F_{4,136} = 3.09, p = .018$; and $F_{3,102} = 5.84, p < .001$, respectively). Post hoc comparisons for road stud layouts revealed significant differences between unlit vs. edge (corrected-$p < .001$), unlit vs. edge-centre (corrected-$p < .001$), and unlit vs. lane (corrected-$p = .042$). As for curve radius, we observed significant differences across all the possible combinations (corrected-$p < .05$).

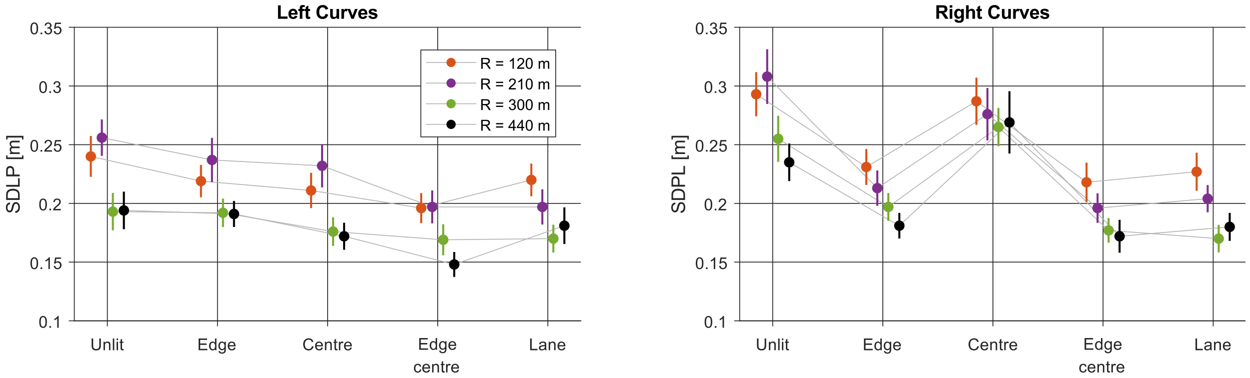
3.2. Lateral behaviour

Driver lateral behaviour along curves was measured through the lateral position and TS and CC termini in Fig. 5, while the SDLP between the TS and ST termini is represented in Fig. 6. We fixed the reference point in the middle of the lane, so positive lateral position values are on the right side of the lane centreline. The figure evidences that when entering the curve, the presence of LED road studs (used in the centre, edge–centre, and to delimit the lane) prompts drivers to move toward the right side of the lane. A similar trend was observed for left curves at the CC termini, while a different trend was observed for right curves.

Approaching the curve (TS termini), LED road stud layouts significantly influenced the lateral position of drivers ($F_{4,136} = 25.79, p < .001$); additionally, curve direction was also found to have an influence ($F_{1,34} = 29.34, p < .001$). However, curve radius did not statistically influence the lateral position ($p > .05$). The *layout* × *radius* and *radius* × *direction* first order interaction revealed significant effects ($F_{12,408} = 1.80, p = .046$; and $F_{3,102} = 14.10, p < .001$, respectively). Finally, the second order interaction between the three experimental factors *layout* × *radius* × *direction* had an influence on lateral position ($F_{12,408} = 2.17, p = .012$). The post-hoc comparisons for road stud layouts revealed significant lateral position differences between unlit vs. edge (corrected-$p = .024$), and unlit vs. centre (corrected-$p < .001$).

At the CC site, road stud layout, and curve direction statistically influenced the driver's lateral position ($F_{4,136} = 63.77, p < .001$; and $F_{1,34} = 25.99, p < .001$, respectively). All the first and second order interactions, i.e., *layout* × *radius,* the *radius* × *direction,* and *layout* × *radius* × *direction*, revealed significant effects ($F_{4,136} = 28.10, p < .001$; $F_{3,102} = 10.78, p < .001$; and $F_{12,408} = 2.92, p < .001$, respectively). The post-hoc analyses for road stud layouts showed significant lateral position differences between the following pairs: unlit vs. edge (corrected-$p < .001$), and unlit vs. centre (corrected-$p < .001$).

Fig. 6 shows the results of SDLP along left and right curves. On left curves, the presence of LED road studs improves driver lateral



(a) (b)

Fig. 6. Standard deviation of lateral position (SDLP) recorded between the tangent-to-spiral (TS) and spiral-to-tangent (ST) termini for the different road stud layouts, curve radii and (a) left and (b) right curve directions. In all the graphs, the symbol indicates the average value, while the error bars indicate the standard error of the mean.

control, especially along the smaller radius curves (120 and 210 m). A similar trend was observed along right curves, with the sole exception of the case related to road studs placed along the carriageway centreline, where SDLP values are within the domain of the unlit condition case for all the four investigated radii.

RM-ANOVA reveals that SDLP was influenced by road stud layout ($F_{4,136} = 27.99, p < .001$), the curve radius ($F_{3,102} = 33.25, p < .001$) and curve direction ($F_{1,34} = 20.14, p < .001$). The first order *layout* × *direction* interaction was also found to be significant ($F_{4,136} = 14.73, p < .001$). Post hoc comparisons for road stud layouts indicate significant differences (corrected-$p < .05$) between unlit and edge, unlit and edge-centre, and unlit and lane. Concerning the effects of curve radii, we observed significant differences (corrected–$p < .05$) for all the possible combinations, except for the comparisons between 120 and 210 m, and between 300 and 440 m.

3.3. Gaze behaviour

The gaze data were analysed by conducting a multinomial logistic regression analysis to determine the predominant zone or element fixated upon by drivers when negotiating curves with different road stud layout, radius, and direction. The results of the omnibus likelihood ratio test performed to calibrate the model revealed that the p–value associated with the curve radius was.208, i.e., the curve radius did not impact on the gaze strategy adopted by drivers. We then calibrated a new model considering layout and curve direction as factors influencing drivers' gaze behaviour. A good model-data agreement (Deviance = 2699), and a favourable balance between goodness of fit and model complexity (AIC = 2747, BIC = 2866) were achieved. The global significance test using the chi-square statistic was highly significant ($\chi 2 = 241$, df = 20, $p < .001$), underscoring the statistical superiority of the model over a null model.

These results collectively support the suitability of the multinomial logit model for elucidating the relationships between predictor variables and response variable categories. However, it is noteworthy that the value of $R^2 = .0820$ accounts for a limited proportion of the explained variance, implying the potential influence of unaccounted factors (e.g., gender, age, driving experience, speed, visibility). The predicted probability of fixing a specific area or element estimated by the model is provided in Fig. 7.

4. Discussion

4.1. Longitudinal behaviour

Regarding the effects of layout on speeds, we observed that the presence of LED road studs led to a reduction in speed compared to the unlit condition (Fig. 4). It is worth noting that a reduction in speed resulting from the implementation of a road treatment is considered beneficial in safety terms, since it suggests greater prudence when negotiating curves, reduces the risk of a collision, and

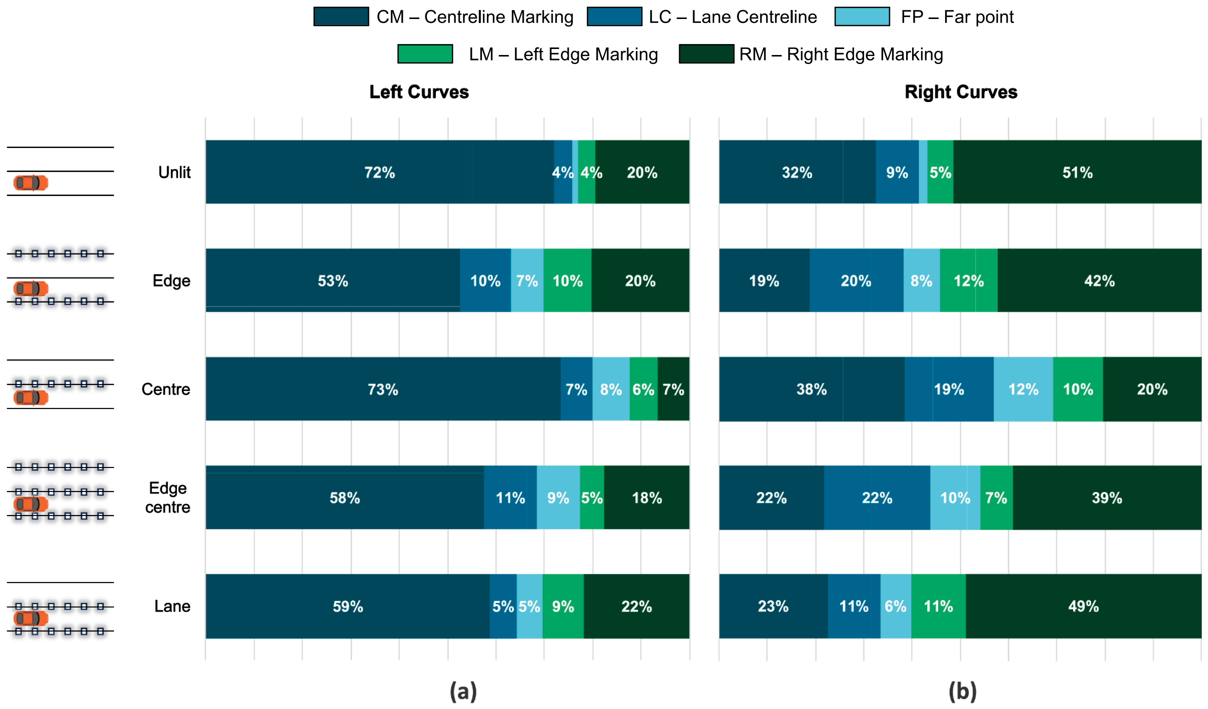


Fig. 7. Predicted probability of looking at an area or element across the five different road stud layouts for (a) left curves and (b) right curves. The areas and elements considered for predicting the probability are those indicated in Fig. 3.

may lower the severity in the event of a crash. In our experiment, we observed significantly lower speeds with respect to the unlit (reference) conditions when we adopted a layout in which the driver sees the LED studs along both the edge and centre of the carriageway. In fact, in both TS and CC termini, the edge–centre layout provided the highest and most statistically significant speed reduction (mean difference of 4.2 and 5.0 km/h, respectively). We argue that this arrangement improves drivers' awareness of the position of their vehicle, while also prompting a reduction in speed to provide more lateral control as the vehicle approaches the curve. The driver therefore needs to adopt and maintain a lower speed to better negotiate the curve while steering the vehicle into the lane, as evidenced well in Fig. 4 (lower speed values in the CC section are evidenced in comparison to the TS section).

Other positive results for speeds come from the edge-centre and the lane layouts at the CC sections (mean difference of 3.7 and 3.6 km/h, respectively). With these two layouts, the driver is forced to adopt the appropriate speed required to maintain the vehicle within the boundaries of the marked lane. Conversely, the centre layout exhibited no statistically significant differences with respect to the unlit condition. Taken together, the results suggest that when the lane or the carriageway are fully delimited, the spatial perception of the curve entry section improves, and also that drivers react with a greater degree of caution when approaching the curve. We also believe that this result is related to the specific distribution of the LED road studs along the track, since they were installed on the curved sections only. We would anticipate that a uniform distribution on both straight and curved sections of a track could produce different effects on speed, but this implies higher installation and maintenance costs.

Differences and similarities between this and other studies related to identical or similar safety countermeasures, e.g., retroreflective markings, should also be viewed in light of the differences in the environmental visibility conditions at night-time (i.e., normal vs. reduced visibility), and the distribution of the treatments along the road (i.e., uniform vs. along curves only). Our findings on speed are aligned with our previous research (Portera et al., 2023) where the use of white and red LED road studs with the edge layout did not lead to an increase in vehicle speed compared to the unlit condition. The results also resonate with the outcomes reported by Llewellyn et al. (2021) on real roads, and Shahar et al. (2018) on simulated roads, who recorded no relevant before/after variations in speed between unlit and uniformly LED studded road segments including both straights and curves, as well as approach stretches to intersections. Conversely, Fiolić et al. (2023) observed that an improvement in the quality of horizontal road strips vis-à-vis the use of high-performance retroreflective marking results in an increase in driving speed. However, it should be noted that this increase was a modest one at 2 % only albeit it occurred along both curves and straights. In conclusion, we believe that when LED road studs are installed along curves, drivers negotiate the same curves more cautiously, as their perception of the geometry of the road ahead is improved by the delimitation of the space within which to drive the vehicle.

4.2. Lateral behaviour

It is widely accepted that the implementation of a road treatment improves the lateral behaviour of vehicles when drivers (i) stay closer to the lane centreline, as this minimizes the risk of collision with both oncoming vehicles and potential fixed roadside installations (Bassani et al., 2019), and (ii) decrease the number of steering wheel corrections performed in order to maintain their intended trajectory (Verster & Roth, 2011). In this study, the analysis of lateral behaviour, i.e., lateral position and SDLP, revealed statistically significant differences between the two curve directions and the four road stud layouts. Considering the influence of gaze on the transversal behaviour of drivers, the analysis and interpretation of lateral behaviour was conducted in light of the results obtained through the observation of gaze behaviour (see previous Section 3.3). Additionally, it is worth noting that the vehicle cockpit was displayed on the vision system during the simulations (Fisher et al., 2011). The presence of the cockpit influences the visibility of road markings and studs in the immediate surroundings of the vehicle.

Fig. 7a shows that on left curves in unlit conditions the majority of drivers (i.e., three out of four) direct their gaze at the central marking, relying on this line for visual guidance. It is worth noting that drivers seem to react to the sight of the studded lateral marking by shying away from the studs (Fig. 5c). We believe that this behaviour is the same as that observed by Gates et al. (2012) in the case of rumble strips. Indeed, rumble strips are perceived as an obstacle to be avoided and this behaviour was replicated in our experiment when drivers cautiously kept a certain distance from the LED road studs to avoid contact with the wheels. With the presence of the visual guidance offered by the stud delineation on the right marking (i.e., edge, edge–centre, and lane), the average lateral position fell close to the lane centreline (i.e., around the 0 value). In this scenario, a visual "gate" effect was observed (Ariën et al., 2013). The road studs placed along the two horizontal markings delimiting the lane helps the driver to maintain a centred trajectory within said lane.

Along right curves in unlit conditions, two out of four drivers look at the right edge marking (Fig. 7b). Again, in studded conditions, more drivers stayed further to the left in the lane as a reaction to the augmented perception of the marking. Fig. 5b and Fig. 5d illustrate this behaviour, with data referred to edge, edge–centre and lane layouts, with lateral position values smaller (around the null value) than those for the unlit condition and a centre layout resulting from a combination of the "gate" and "shy away" effects.

These results also concur with our earlier observations (Portera et al., 2023) in which different lateral behaviours with the edge layout for left and right curves were evaluated. As in previous experiments, we found that the edge layout was only effective on right curves. Moreover, this finding agrees with that of Shahar et al. (2018) and Shahar & Brémond (2014), who found that the edge-centre layout improved the lateral position on both left and right curves.

Viewed as a whole, the results for lateral position indicate better lateral behaviour and safer outcomes in favour of layouts where the lane is fully delineated by LED road studs, i.e., the edge–centre and lane layouts. Accordingly, the SDLP outcomes indicate that these two layouts are associated with the smallest values for this behavioural parameter. In other words, when the lane is delineated with LED road studs on both sides, drivers significantly improve their lateral control with respect to the unlit condition. In contrast, when LED studs are installed along the central marking only, there is a deterioration in driver lateral control with SDLP values similar to those recorded in unlit conditions, in particular along right curves.

4.3. Gaze behaviour

The gaze behaviour depicted in Fig. 7a indicates that along left curves drivers generally oriented their gaze towards the centreline marking (CM). Our analyses on heatmaps suggest that drivers normally negotiated left curves by adopting the tangent point mechanism (Land & Lee, 1994), with other road elements being less frequently utilized. As drivers switched driving scenario from unlit to edge layout, some individuals shifted their gaze from CM to alternative approaches aligned with the placement of studs. Similarly, the centre layout appeared to have a significant impact on drivers' gaze behaviour, prompting a majority to focus on the centreline marking (CM), particularly those who initially had the same gaze target in the unlit condition. These findings suggest that the different LED road stud layouts influenced the gaze behaviour of some drivers only, while others maintained the gaze already exhibited in unlit conditions. Conversely, in the cases of edge–centre and lane layouts, the fixated elements exhibited substantial divergence. This discrepancy is likely attributable to the abundance of delineations which means drivers can choose from a number of road elements for visual guidance.

For right curves in unlit conditions (Fig. 7b), the predominant gaze target was the RM (51 % of the cases). In this case, RM activates the tangent point mechanism. However, the CM target was also gazed at by a relevant percentage of drivers (32 %). Upon transitioning from unlit to edge layout, drivers who initially used the CM as their gaze target shifted to look at the RM and LM, corresponding to the areas where studs were installed. In the case of the centre layout, the percentage of drivers who looked at CM increased significantly (to almost two out of five). Finally, as for left curves, the edge–centre and lane layouts offered a diversified range of gaze behaviours, with an increment in those adopting the tangent point mechanism to orient their gaze towards the right marking (RM).

Overall, these results reveal that any change in driver gaze behaviour is only partly conditioned by the roadway delineation systems. Some drivers keep their gaze directed toward elements of the road space that are not illuminated, while others modify their behaviour seemingly without explanation. While these results may highlight our failure to consider other factors that might influence the decision on what to look at along a curve, it does highlight the complex and subjective nature of the human decision-making process in terms of what we choose to look at when behind the steering wheel (Lappi et al., 2013). Along the roadway, a series of intrinsic and extrinsic factors may play a role in influencing driver gaze behaviour. Finding measures that harmonize the gaze patterns of all drivers in a uniform manner is challenging and the complexity of gaze behaviour was evident even in the dark driving scenario we dispensed to participants in which few road elements were clearly visible. In conclusion, our results illustrate the complex nature of the gaze behaviour adopted by drivers during curve negotiation, but do not identify the particular gaze patterns predominantly used in each layout. Nevertheless, the behavioural results do indicate that the presence of LED road studs improves curve negotiation behaviour, particularly in terms of vehicle transverse position and trajectory control. The variability in visual behaviour is, therefore, attributable to the driving habits of individual drivers. While the presence of LEDs benefited drivers (by providing them with the necessary optical guidance to accurately negotiate the curves), this effect was not uniform across all drivers.

4.4. Layout – Curve direction interaction

The three RM-ANOVAs carried out on the dependent variables of this study, i.e., speed, lateral position and SDLP, evidenced that the two–way first–order interaction between the road stud layout and the curve direction was always significant (see Section 3 for more details). The three variables shown in Fig. 8 confirm that the edge–centre and lane layouts performed better overall since they help drivers to negotiate the curves at a lower speed (Fig. 8a), to maintain a central trajectory in the lane (Fig. 8b), and enable better lateral control of the vehicle within the lane (Fig. 8c). It is worth noting that the differences between the performances of the two above-mentioned layouts with the unlit condition are always statistically significant (corrected-$p < .05$). These results are consistent

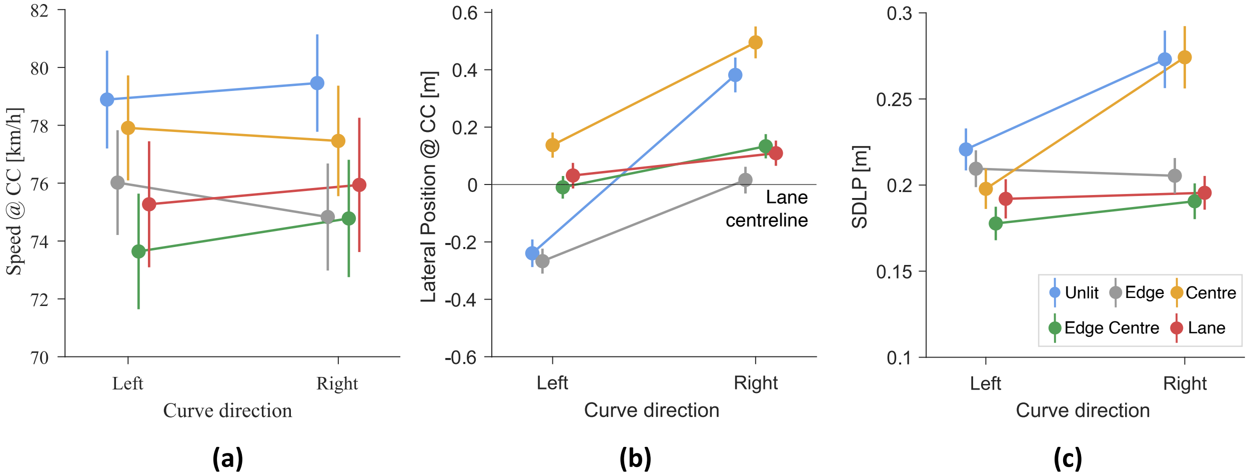


Fig. 8. Two-way first–order interaction between the road stud layout and the curve direction for (a) speed, (b) lateral position, and (c) standard deviation of lateral position (SDLP). Points indicate average values, while bars indicate the standard error of the mean.

with (Charlton, 2007), who demonstrated how marking treatments that delineate the curve and increase the momentary perception of speed induce drivers to enter the curve at a lower speed. In this work, we confirm and extend the outcomes from Charlton (2007) also for night-time driving conditions.

5. Conclusions

In this study, we assessed the effects of four different white LED road stud layouts along horizontal curves on driving performance and gaze behaviour. From data analyses, we concluded that the presence of LED road studs enabled drivers to maintain a more safety-oriented behaviour with respect to the unlit condition. In particular, the use of LED road studs encourages drivers to adopt appropriate speeds when approaching and negotiating curves. An analysis of transversal behaviour revealed that at the centre of the curve, the road stud layout had a significant impact on lateral position, and this effect varied between left and right curves. Notably, certain layouts promoted better lateral control on left curves, while others were more effective on right curves.

Furthermore, our investigation into gaze behaviour revealed interesting patterns. Although the results did not reveal a common tendency in gaze behaviour, we observed that the vision system of drivers was positively influenced by LED stud illuminated curves, enabling drivers to improve their transversal behaviour.

Taken together, our findings highlight the link between the significant and positive improvement in driver behaviour during night–time conditions and the adoption of LED road studs. Furthermore, when choosing a particular road stud layout, it is imperative to consider the curve direction. For both left and right curves, the “edge–centre” and “lane” layouts emerge as the optimal choice for improving driving performance. They allow drivers to maintain control of a central trajectory within the lane, reducing the likelihood of a collision with oncoming vehicles or fixed installations along the roadside. These two layouts involve different installation and maintenance costs. It is worth noting that the “lane” layout requires the same number of road studs as the “edge-centre” one, considering that the same curve requires road studs in both directions. However, road studs on the centreline that direct the light beam in the two opposite directions are only necessary in the “lane” layout, while along the two marking strips delimiting the carriageway road studs equipped with a unidirectional beam would suffice.

The simplicity of our road scenarios, characterized by free-flow conditions involving only horizontal curves, together with weather conditions that favour visibility (dry road surface, no fog), may somewhat limit the external applicability of our findings. For this reason, it is recommended that future research efforts examine the solutions proposed here while also considering the influence of other environmental factors. It is important to note that our study lacked the presence of oncoming vehicles or other road lighting devices, resulting in changes in ambient luminance determined primarily by LED lights. Therefore, the results should be interpreted with caution, and future studies should mitigate the influence of other potentially confounding variables. It should be noted that the effect of simulated LED road studs may differ from that observed on real roads due to potential differences in brightness perceived by drivers. Therefore, future research should include a validation study to determine whether any difference in visual perception between real and simulated LED road studs may result in differences in behaviour on the road and in the driving simulator. Another aspect to consider in future studies is the relationship between gaze strategies and driving performance for different types of road markings (unlit vs. studded) and ambient lighting conditions (daytime vs. night-time). A greater understanding of this relationship would help us understand whether prompting drivers to adopt specific gaze patterns is beneficial for road safety. Finally, field tests are recommended to validate the results obtained here and ensure the real–world applicability of our research outcomes.

CRediT authorship contribution statement

Alberto Portera: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marco Bassani:** Writing – review & editing, Writing – original draft, Supervision, Resources, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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