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Effectiveness of smart horizontal markings on drivers' behavior along horizontal curves: A driving simulation study ☆

Francesco Angioi [a,b,*], Juan de Oña [a], Carolina Díaz-Piedra [b], Rocío de Oña [a], Leandro L. Di Stasi [b,c,*]

[a] TRYSE Research Group; ETSI Caminos, Canales y Puertos; Campus Universitario de Fuentenueva s/n, University of Granada, Granada 18071, Spain

[b] Neuroergonomics and Operator Performance Laboratory; Mind, Brain, and Behavior Research Center (CIMCYC); Campus de Cartuja s/n, University of Granada, Granada 18071, Spain

[c] Joint Center University of Granada - Spanish Army Training and Doctrine Command; C/ Gran Via de Colon 48, Granada 18071, Spain

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ABSTRACT

Photoluminescent road markings (PRMs) are a potentially useful visual guidance technology for improving road safety in low-visibility conditions. However, the effectiveness of PRMs requires further research. Moreover, road infrastructure regulations lack guidelines for PRMs design. Here, we aimed at determining the effects of different PRMs colors and widths on transversal and longitudinal driving behavioral indices. We conducted a simulation-based 3x2x2 within-subjects experiment (*PRM*: unlit vs. smart green vs. smart red; *marking width*: conventional vs. wide; *curve direction*: left vs. right). We designed six two-lane rural highway scenarios with nighttime light conditions and no traffic. Each scenario included twenty-four horizontal curves with radii ranging from 120 to 440 m (recommended speed range 60–90 km/h). Thirty participants (age range 20–54 years) drove a semi-dynamic driving simulator for about one hour. Our results showed that the presence of PRMs affected the drivers' transversal behavior. The smart markings induced drivers to keep greater lateral distances from the road edge line than unlit ones along right curves. Smart green markings showed higher variability for vehicle positioning, indicating lower vehicle control. Wider-than-normal markings induced users to drive closer to the edge line at the Tangent-to-Spiral section. Overall, our study showed that smart markings - both green and red - induce the driver to "shy away" from the edge line, thus representing a potential tool for preventing roadway departure events. Further studies are expected to confirm these results by focusing on different PRM layouts, traffic, and weather conditions.

1. Introduction

Roadway departure events on horizontal curves are estimated to be the cause of over 25 % of fatal accidents according to the US Federal Highway Administration (Administration and Highway Safety, 2023). Accidents due to a vehicle leaving the roadway usually involve single vehicles on two-lane rural highways (Donnell et al., 2019). Fatal accidents on such two-lane rural highways are more common during the night (Goswamy et al., 2018), as reduced visibility leads to drivers having an impaired ability to properly perceive colors and shapes (Plainis et al., 2006). Thus, nighttime lighting conditions would increase the difficulties of drivers to properly control their vehicles, both longitudinally and laterally, and to predict the upcoming road geometry (Fiolić et al., 2023). Conventional road markings, which rely on retroreflection, have limited success in terms of the visibility level they provide, as the retroreflection effect does not spread beyond the distance covered by the vehicle's headlamps (Babić et al., 2020), therefore limiting the ability of the driver to predict the upcoming road geometry at nighttime. Moreover, other environmental factors (e.g., rain, snow, fog) may reduce road markings visibility as well (Boyce, 2008). To address these limitations, smart road marking technologies have recently begun to be explored as countermeasures for limited visibility in nighttime lighting conditions (for a recent review see Angioi et al., 2023). One of the alternatives are the photoluminescent road markings

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* Corresponding authors.
E-mail addresses: frangioi@ugr.es (F. Angioi), jdona@ugr.es (J. de Oña), dipie@ugr.es (C. Díaz-Piedra), rociodona@ugr.es (R. de Oña), distasi@ugr.es (L.L. Di Stasi).

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(PRMs; or glow-in-the-dark markings), which make use of photoluminescence technology to produce light without relying on the vehicles' headlamps (Bonneel et al., 2023). PRMs would improve the general visibility of the roadway. Since PRMs would be visible beyond the vehicles' headlamps range (Lin et al., 2023; Xu et al., 2021), they would be useful in low-visibility conditions, such as nighttime and foggy conditions. As noted by Zhu and colleagues (Zhu et al., 2021), this type of horizontal markings lies within the concept of self-explaining roads (Theeuwes, 2021; Theeuwes and Godthelp, 1995), which is designed to intuitively communicate the upcoming road situation to drivers. However, the study of PRMs is currently limited to pilot-level applications (Lin et al., 2023; Studio Roosegaarde, 2013), and no standard regulates their design in terms of colors and width. While both elements would be the most relevant factors when designing road markings (Babić et al., 2022), color would play an essential role in road safety applications as it also conveys a visual message to the drivers (Boyce, 2008), therefore influencing driving behavior (Zhu et al., 2021; Bacelar, 2004; Llewellyn et al., 2021; Portera et al., 2023).

Among the various colors used for roadway delineators, green (Angioi et al., 2023) and red (Portera et al., 2023) have been examined for their potential effectiveness in traditional and smart marking applications under nighttime conditions. Green is the most employed color in photoluminescent paint applications for horizontal markings (for a recent review see Lin et al., 2023). PRMs have been tested for both edge line delineation (Bonneel et al., 2023) and crosswalks (Mateo Sanguino et al., 2024), demonstrating the ability to improve nighttime visibility while replacing the standard retroreflective technology. Green is considered the most comfortable color for prolonged exposure to a low-light environment (Chrzanowski, 2013) and conveys a message of safety (Sheikholeslami et al., 2020), which aligns with its common use as a "go" instruction in standard traffic devices (Huang et al., 2014). On the other hand, red has been frequently used in nighttime smart delineation technology (e.g., smart LED; Portera et al., 2023), and has been tested as a perceptual cue to reduce vehicle speeds along horizontal curves (Montella et al., 2015). In the traffic context, red is commonly associated with warning or danger (Díaz-Román et al., 2015; Pravossoudovitch et al., 2014) and is typically used to ensure optimal visibility of critical information (Rash and Manning, 2003), even from a greater distance (i.e., the longest wavelength of light within the visible spectrum).

Regarding the width, previous naturalistic studies pointed out that wider-than-normal (traditional) road markings may have a beneficial effect in terms of accident prevention (Park et al., 2012) and speed reduction (Calvo-Poyo et al., 2020). In addition, a study using a video-perception task found that different widths would affect speed perception, with drivers perceiving a higher speed with wider-than-normal (traditional) road markings (Garach et al., 2022), potentially positively affecting road safety. Other studies pointed out that the presence of wider-than-normal road markings would induce drivers to approach more closely to the edge of the road, which implies a reduction in the risk of head-on crashes, although it might increase the risk of run-off-road accidents (for a systematic review see Babić et al., 2020). However, the impact of smart road marking design (colors, visibility, width, etc.) on driving behavior still requires further research (Portera et al., 2023; Portera and Bassani, 2024).

Here, we used a simulator-based approach to increase our knowledge of the effects associated with incorporating different PRMs on the road, to clarify whether PRMs could be a useful tool to prevent roadway departures. We focused on examining the effects of two different colored PRMs (smart green vs. smart red, and a control condition: unlit [white retroreflective]), as well as their widths, on driver behavior along horizontal curves. We hypothesized that the presence of the PRMs, in comparison to unlit markings, would improve the visibility of the roadway edge and therefore generate a shift towards the carriageway center of the vehicle's trajectories.

2. Methodology

2.1. Participants

Thirty-seven young adult drivers took part in the study (mean [M] age = 26 ± standard deviation [SD] = 6.50 years, range = 20 – 54 years). All the participants held a European car driving license and they had normal or corrected-to-normal vision. Two participants were excluded from the initial sample since they exhibited an inadequate level of alertness before the driving session, as indicated by a score above 3 on the Stanford Sleepiness Scale (SSS) (Hoddes et al., 1973), thus confirming a high level of sleepiness (Díaz-Piedra et al., 2019; Morales et al., 2017). Moreover, five individuals were excluded due to abnormal trichromatic color vision ($n = 1$), noncompliance due to motion sickness ($n = 2$), and technical problems ($n = 2$). This resulted in a sample of 30 participants (age M ± SD = 25.90 ± 6.73 years, range = 20 – 54 years; 16 women). We considered the number of participants appropriate based on a previous cohort, where authors found statistically significant differences in behavioral metrics (Zhu et al., 2021; Portera et al., 2023). Participants were unaware of the hypotheses under investigation and received an economic compensation of 20 € for their participation.

2.2. Experimental design

We carried out a simulation-based 3 x 2 x 2 within-subjects experiment (*PRM*: unlit [white retroreflective markings] vs. smart green vs. smart red; *marking width*: conventional [centerline = 10 cm; edge line = 15 cm] vs. wide [centerline = 30 cm; edge line = 30 cm]; *curve direction*: left vs. right). During the driving task, we recorded (i) the lateral position, (ii) the longitudinal instantaneous speed, and (iii) acceleration at the Tangent-to-Spiral (TS) and Curve Center (CC) sections (see Fig. 1). The lateral position values refer to the distance between the vehicles' center of gravity and the lane axis. Positive lateral position observations mean that the vehicle moved towards the centerline (left side of the lane axis), while negative values indicate that the vehicle moved towards the edge line [right side of the lane axis]) (see Fig. 2). We also explored the standard deviation of lateral position (SDLP) throughout the whole curve. Finally, the perceived task load was a secondary dependent variable.

2.3. Driving scenarios and simulator

We created six two-lane rural highway scenarios using the SCANeR studio DT 2.5 software (AVSimulation, Boulogne-Billancourt, France). All the scenarios had the same road environment, nighttime lighting conditions, and road alignment replicating a traditional configuration of a Spanish two-lane highway, with 3.5 m-wide lanes and 1.5 m-wide shoulders (Ministry of Transport, Mobility and Urban Agenda, 2020). Each road scenario was 16 km in length and was surrounded by an empty and monotonous grassy meadow. The road alignment included 24 spiraled curves with radii ranging from 120 m and 440 m for both directions (12 right and 12 left curves) to ensure the gradualness of the alignment and comply with the road design standards. We also placed the recommended speed sign 150 m before each curve, according to its radius (e.g., 90 km/h for a 440 m radius curve, 60 km/h for a 120 m radius curve), following the Spanish regulation. No traffic was included in the scenarios.

The six virtual scenarios were obtained by combining the different PRM colors (unlit, smart green, smart red) and width (conventional, wide) of the markings. The PRM technology was only applied to the edge lines. To simulate the self-illuminating property of the technology, we assigned the "emitting" property to those markings in the simulation software, while the brightness and visibility of the markings were designed to be as realistic as possible and controlled by the software's visual module. The simulation software managed the level of luminance

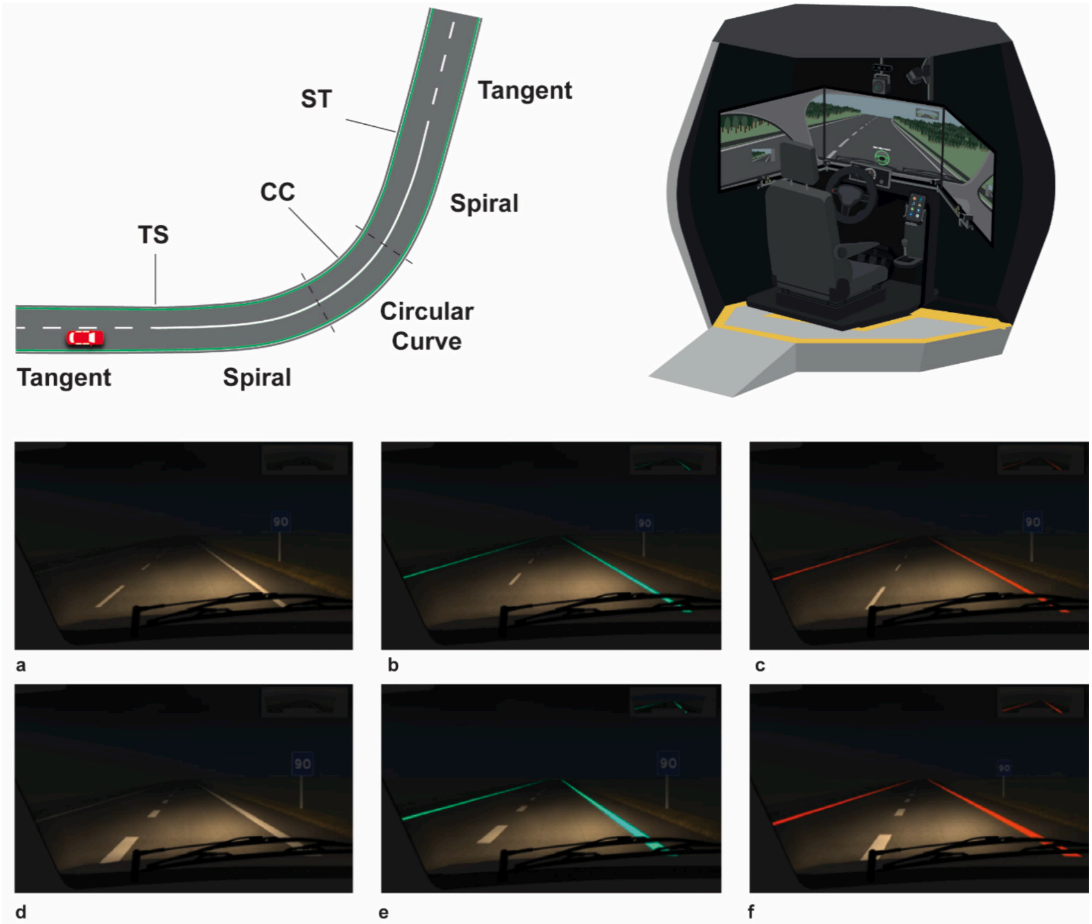

Fig. 1. Schematic representation of the simulated scenarios and the simulator. On the top left, the reference sites which corresponded to the transition point between the tangent and the spiral (TS; tangent-to-spiral), and to circular curve center (CC) are represented. On the top right, an illustration of the HADRIAN semi-dynamic driving simulator (Nervtech™, Ljubljana, Slovenia) used for the simulation task is presented. On the bottom part, images of the six virtual scenarios that were displayed (a, unlit markings; b, smart green markings; c, smart red markings; d, unlit wide markings; e, smart green wide markings; f, smart red wide markings). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

according to the principles of light propagation, reducing the level of luminance when the distance between the driver and the road marking increased (Portera et al., 2023). In terms of visibility, the PRMs were visible throughout the entire scenario, including beyond the vehicle's headlights, due to sufficient self-illumination and the absence of any visual obstructions (e.g., trees, natural terrain). The white retroreflective markings (unlit) were simulated without the "emitting" property, resulting in them being retroflecting (i.e., only illuminated when exposed to vehicle headlights). The wider-than-normal markings were simulated to give the perception of a narrower lane although the actual lane size (3.5 m) did not change.

Participants drove a virtual mid-sized automatic vehicle and were asked to drive in the right lane throughout the experiment and to obey traffic rules. The driving simulator recorded performance indicators at 125 Hz. The experimental scenarios were performed in a semi-dynamic driving simulator (for an illustration see Fig. 1; Di Stasi et al., 2023) situated within a specialized octagonal dome and using a motion platform with four degrees of freedom to replicate the physical sensation and forces (longitudinal, back, and forth; and lateral movements) experienced during real driving. The driving simulator system included three 49″ screens (Samsung Electronics, South Korea) with a 130° field of view, a fully equipped car seat, a dynamic force feedback steering wheel, a digital dashboard, three pedals (gas, brake, clutch), vibration pads to return pavement roughness, wheel rolling, and shocks. A virtual cockpit on the screens allowed drivers to visualize the width of the vehicle and give verisimilitude to the simulation. Moreover, the simulator also incorporated virtual rear-view mirrors and a sound system that reproduced the sounds of the car engine and the surrounding environment. For further information on the features of the simulator, see (Gianfranchi and Di Stasi, 2021).

2.4. Questionnaires

At the beginning of the experimental session, we gathered information about the participants' sociodemographic characteristics (e.g., age, sex, education), health status (e.g., eye impairments, medication use, and alcohol consumption), and driving history (e.g., driving license status, yearly driving frequency) information.

After that, participants completed the SSS (Hoddes et al., 1973) to evaluate their sleepiness level before the driving simulation. The SSS consists of seven statements that reflect the participants' current level of sleepiness ranging from "Feeling active, vital, alert, or wide awake" (rated as 1) to "No longer resisting sleep, on the verge of sleep onset, experiencing dream-like thoughts" (rated as 7).

After completing each of the six experimental scenarios, the drivers verbally filled in the NASA Task Load Index (NASA-TLX; Hart and Staveland, 1988) questionnaire. The NASA-TLX questionnaire aims at assessing the perceived task load of each experimental scenario across six bipolar dimensions: Mental demand, Physical demand, Temporal demand, Effort, Performance, and Frustration level. Participants

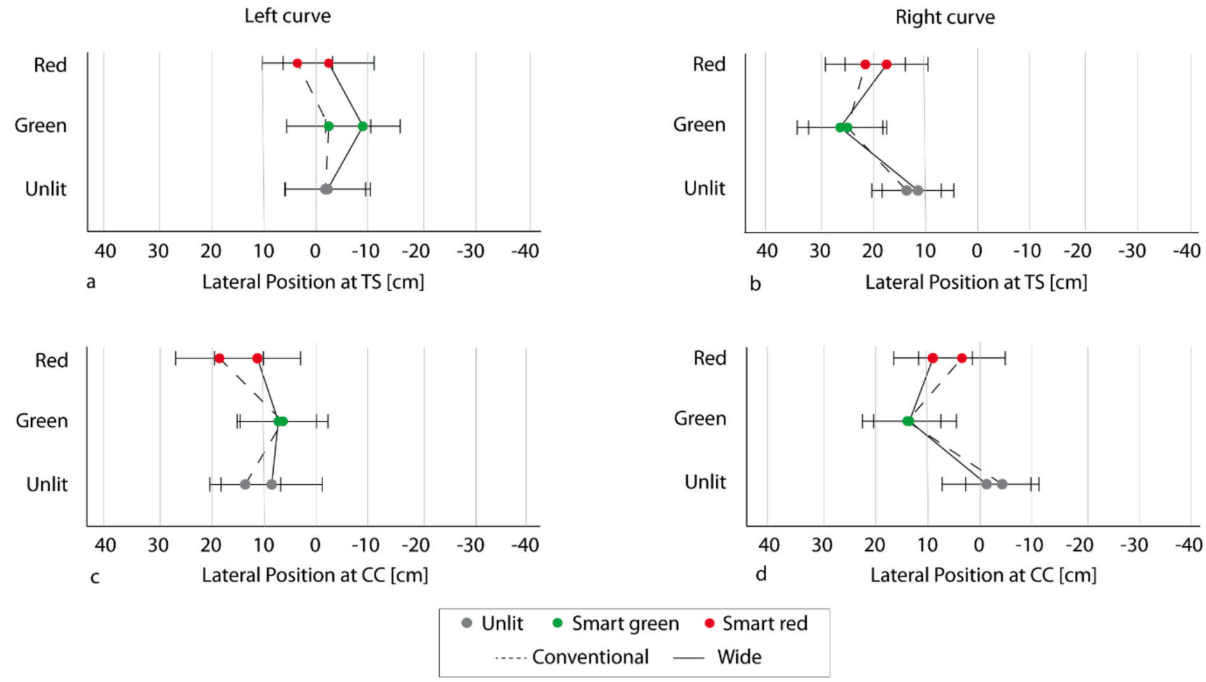

Fig. 2. The effect of PRM, marking width, and curve direction on vehicle lateral position. Data refers to the estimated average observations at the beginning of the spiral (TS section; top part of the figure [a], [b]), and at the center of the curve (CC section; bottom part of the figure [c], [d]). Zero on the x-axis represented the lane center (reference line). Grey dots referred to unlit markings, green dots to the smart green, and red dots to the smart red ones. The dashed lines referred to the conventional markings, while the continuous ones were to the wider-than-normal markings. Graphs [a], [c] refer to left curves, graphs [b], [d] the right ones. The error bars indicate the 95% confidence interval. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

provided their assessment on an interval scale ranging from 0 to 100 (higher values indicate a higher perceived task load).

Upon completion of the final scenario, participants completed the Motion Sickness Assessment Questionnaire (MSAQ; Gianaros et al., 2001) to evaluate simulation sickness symptoms. The MSAQ includes 16 statements outlining the most common symptoms of motion sickness (e.g., "I felt dizzy"). For each statement, participants were required to provide their response using a Likert scale that ranged from "not at all"(1) to "severely" (9) (overall motion sickness scores were scaled from 0 to 100).

2.5. Procedure

We conducted the study in conformity with the Code of Ethics of the World Medical Association (Declaration of Helsinki) (World Medical Association, 2013). The experimental protocol was approved by the University of Granada's Institutional Review Board (IRB approval #1528). The study took place at the Mind, Brain, and Behavior Research Center (CIMCYC; University of Granada). After obtaining a signed informed consent, we recorded sociodemographic, health, and driving history data, as well as initial sleepiness level. Participants were then informed that they would drive on a two-way rural highway. They were instructed to follow the usual traffic rules and keep the car in the right lane, with a general speed limit of 90 km/h. Participants had a 5-minute driving training phase with the simulator to familiarize themselves with the apparatus and virtual environment.

The training scenario had the same characteristics as the experimental ones in terms of the type of roads (two-lane rural highway) and lighting conditions (night), but we presented a different color for the road marking (yellow retroreflective). After the training phase, participants completed the six experimental scenarios (~ 12 min on average for each scenario). To prevent the learning and the order effects, road scenarios were randomly administered to the participants, in terms of color, width, and starting point (from start-to-end or end-to-start). The NASA-TLX questionnaire was administered between each scenario (by voice) through the microphone of the simulation system. After completing the final scenario, participants filled out the MSAQ to evaluate simulation sickness (MSAQ mean score = 23; see Section 2.4 for further details). Finally, participants were not informed about the exact duration of the driving simulation to prevent the end-spurt effect, which occurs when people know they are approaching the end of a task (Bergum and Lehr, 1963). Instead, they were told that the overall duration of the experiment was approximately 2 h (on average the experiment lasted 1.5 h).

3. Analysis and results

We investigated the effects of *PRM* and *marking widths* on both longitudinal (i.e., speed and acceleration) and transversal (i.e., lateral position) driving behavioral indices along horizontal curves (in both directions) on two-lane rural highways. Prior to the analysis, we averaged out the observed values by grouping curves with equal experimental characteristics (i.e., in terms of the independent variables). We then analyzed all the behavioral variables (i.e., lateral position, speed, and acceleration) using a 3 (*PRM*) × 2 (*marking width*) x 2 (*curve direction*) repeated measures analysis of variance (RM ANOVA). Furthermore, we analyzed the perceived task load for each driving scenario (NASA-TLX scores) with a 3 (*PRM*) x 2 (*marking width*) RM ANOVA. The significance level was set at $\alpha \leq 0.05$. We used the Greenhouse–Geisser correction when the sphericity assumption was not met. We used the Holm-Bonferroni adjustment to correct for multiple comparisons.

3.1. Transversal driving behavior indices

At the TS section (Fig. 2a; 2b), all main effects were significant. *PRM* influenced the lateral position, $p = 0.006$. Overall, both the smart green (average [M] lateral position = 9.41 cm) and the smart red (M = 9.48 cm) markings induced drivers to maintain a greater lateral distance from the edge line than with the unlit (M = 4.62 cm) markings, corrected-*p-values* < 0.05. Both *marking width* and *curve direction* also had significant main effects on lateral position, $p = 0.05$, $p < 0.001$. With conventional markings, drivers kept the vehicle at a greater lateral distance from the edge line (M = 9.35 cm) than with wider-than-normal ones (M = 6.33 cm). The first-order interactions between *PRM* and *curve direction, PRM* and *marking width,* and *marking width* and *curve direction*, were found to be significant, $p < 0.001$, $p = 0.028$, and $p = 0.044$ respectively. On the left curves (Fig. 2a), smart red markings prompted the drivers to maintain a larger lateral gap from the edge line than with smart green ones (mean difference = 6.4 cm), corrected-$p < 0.05$. On the right curves (Fig. 2b), the smart green markings induced the drivers to keep the vehicle at a greater lateral distance from the edge line than both unlit and smart red markings (mean differences = 13.4 cm and 6.3 cm respectively), corrected-*p-values* < 0.05. No other interactions were significant.

At the CC section (Fig. 2c; 2d), only the main effect of *PRM* influenced the lateral position, $p < 0.001$. Both the smart green (M = 9.79 cm), and smart red (M = 10.05 cm) markings prompted the drivers to maintain the vehicle at a greater lateral distance from the edge line with respect to unlit ones (M = 3.52 cm), corrected-*p-values* < 0.05. The first-order interactions between *PRM* and *curve direction*, and *marking width* and *curve direction,* were found to be significant, $p < 0.001$ and $p = 0.002$ respectively. On the left curves (Fig. 2c), the smart red markings induced drivers to maintain a greater lateral distance from the edge line with respect to the smart green ones (mean difference = 8.2 cm), corrected-$p < 0.05$. On the right curves (Fig. 2d), with both the smart green and smart red markings, the drivers maintained the vehicle at a larger distance from the edge line compared to unlit markings (mean differences = 16.9 cm and 9.2 cm respectively), corrected-*p-values* < 0.05. No other interactions were significant.

The SDLP was only affected by *PRM* and *marking width* factors, $p < 0.001$ and $p = 0.032$ respectively. The smart green markings induced greater lane deviation (M ± SD = 30.7 ± 13 cm) than both unlit (M ± SD = 28.5 ± 13 cm), and smart red (M ± SD = 28.7 ± 13 cm), corrected-*p-values* < 0.05. Wider-than-normal markings led to slightly poorer lateral control (M ± SD = 29.9 ± 13 cm) with respect to conventional ones (M ± SD = 28.7 ± 14 cm). No other interactions were significant.

3.2. Longitudinal driving behavior indices

While, at the TS section, *PRM* and *marking width* did not affect speed and acceleration, the *curve direction* only affected speed, ($p = 0.003$, see Fig. 3). As expected, users drove at higher speed when approaching right curves (average [M] speed = 86.3 km/h) than left curves (M = 85.2 km/h). No significant interactions were found.

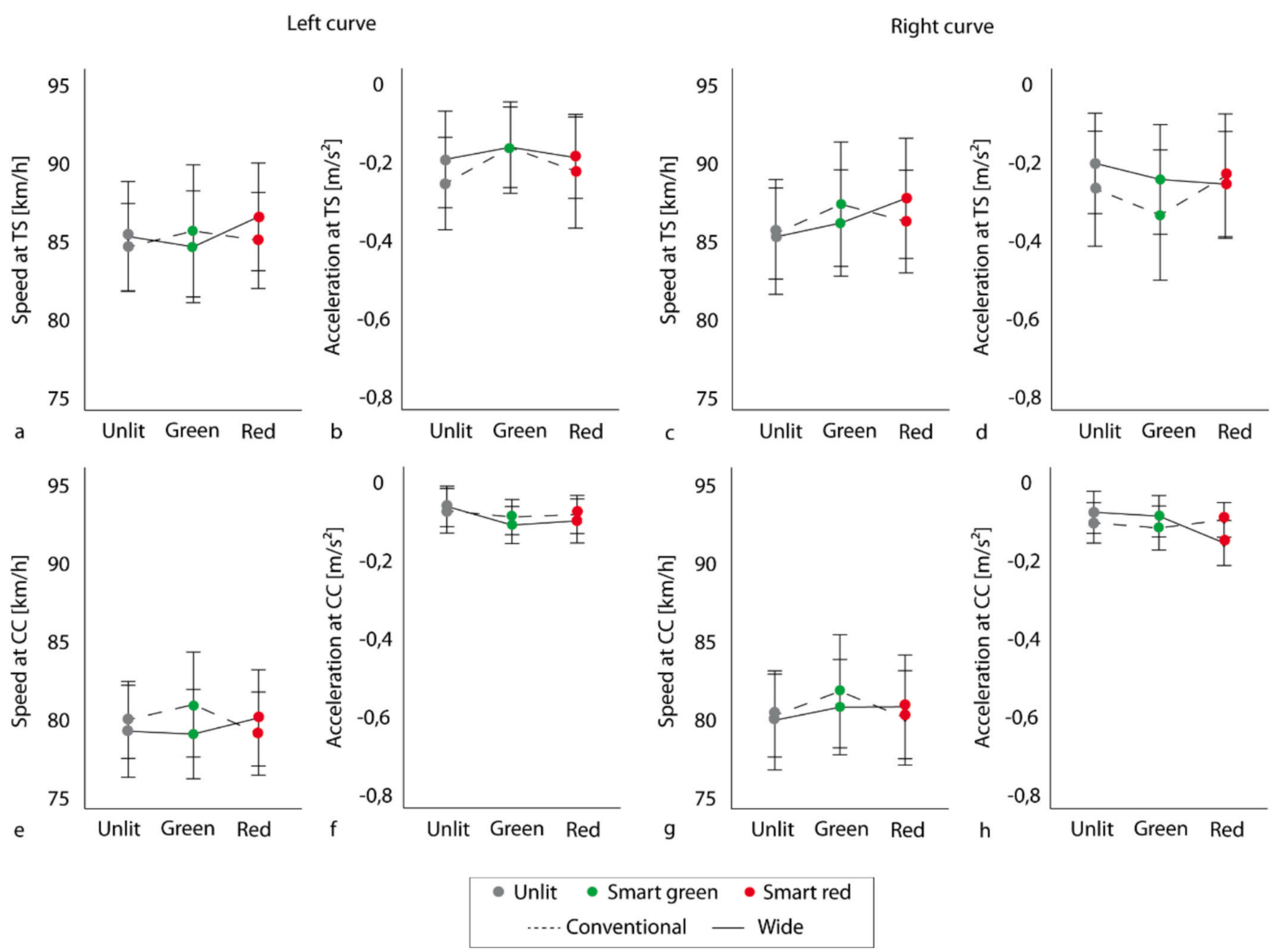

Fig. 3. The effects of PRM, marking width, and curve direction on speed and acceleration. Data refers to the estimated average observations at the beginning of the spiral (TS section; top part of the figure [a], [b], [c], [d]), and at the center of the curve (CC section; bottom part of the figure [e], [f], [g], [h]). Grey dots referred to unlit markings, green dots to the smart green, and red dots to the smart red ones. The dashed lines referred to the conventional markings, while the continuous ones were to the conventional size of the markings. Graphs [a], [b], [e], [f] refer to left curves, graphs [c], [d], [g], [h] to the right ones. The error bars indicate the 95% confidence interval. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Similarly, at the CC section, *PRM* and *marking width* did not affect speed and acceleration. Also, for this section, the curve direction only affected speed, $p = 0.013$: users drove at higher speed when along right curves (M = 80.3 km/h) than left curves (M = 79.4 km/h). No significant interactions were found.

3.3. Perceived task load index

Perceived task complexity, as measured by NASA-TLX scores, was similarly low between the driving scenarios, all *p-values* > 0.05 (mean values range = 34–38) (Grier, 2015).

4. Discussion

We evaluated the effects of PRM technology (i.e., unlit [white retroreflective], smart green, and smart red) and widths (i.e., conventional, and wide) on driving behavior while negotiating horizontal curves on two-lane rural highways in nighttime lighting conditions. Furthermore, we also considered the curve direction. We analyzed both longitudinal (speed and acceleration) and transversal (lateral position) driving behaviors at TS and CC sections as well the SDLP throughout the whole curves. Perceived task load was a secondary dependent variable.

The presence of the PRM affected the drivers' transversal behavior along horizontal curves. Overall, both smart green and red markings induced drivers to adopt greater lateral distances from the edge line compared to the unlit ones. This finding is consistent with previous simulation studies on smart technologies having similar purposes to PRMs (i.e., smart LED; see Portera et al., 2023). The effects of the PRM on lateral position varied depending on the direction of the curve. On left curves, drivers approached the curves maintaining the vehicle close to the lane axis (TS section). When moving at the center of the curve (CC section), the smart red marking induced drivers to maintain the vehicle at a greater lateral distance from the edge line than the smart green marking. On right curves, drivers' transversal behavior was the same at the TS and CC sections. Both smart green and red markings induced drivers to maintain larger lateral distances from the edge line compared to the unlit ones. Lateral behavior differences based on curve direction are consistent with prior simulation studies on smart LED technologies (i.e., Portera et al., 2023). This difference is likely due to PRM technology being solely on the edge lines. On right curves, drivers would perceive the smart marking as an obstacle, which led them to "shy away" from the edge line (Portera and Bassani, 2024). It is worth noting that, along the right curves, the smart green markings led to larger lateral distances from the edge line. This result suggests that smart green markings provide better visual support to drivers who anticipated the road design (Lehtonen et al., 2012) and would be useful in preventing roadway departure (running-off-road) events. Notably, the maximum displacement towards the centerline of the carriageway caused by the smart markings was only about 26 cm at the TS section (smart green markings on right curves) and about 19 cm at the CC section (smart red markings on left curves), posing no risk for head-on collisions.

Our results demonstrated that the color of the smart markings did influence vehicle lateral control, as measured by Standard Deviation of Lateral Position (SDLP). Specifically, smart green markings resulted in higher SDLP values compared to the red markings. Since the SDLP is an indicator of the drivers' capability to properly control the lateral position of the vehicle (Verster and Roth, 2011), it is reasonable to infer that brighter markings (i.e., smart green) led to greater lateral corrections and reduced vehicle control. This finding suggests that it would be preferable to use smart red markings in specific situations, such as work zones and/or situations of danger (Pravossoudovitch et al., 2014; Studio Roosegaarde, 2013). However, the mean difference resulting from the color difference was about 2 cm.

In our study, at the TS section, the marking width influenced the drivers' lateral behavior. On left curves, wider-than-normal smart (green and red) markings induced drivers to slightly reduce the lateral distance from the edge line with respect to the baseline scenario (conventional markings). The reduction in the lateral distance from the edge line caused by the markings widening is consistent with previous studies (for a systematic review see Babić et al., 2020). However, our results showed that the effect of the marking width was not significant in CC section nor throughout the whole curve in terms of SDLP. On right curves, we did not find any difference between wider-than-normal-markings and conventional markings. Overall, our results suggest that while wider-than-normal markings are intended to improve lane visibility and road safety, their effect on lateral positioning might be minimal. A possible reason why wider markings had a poor effect on the lateral position of the vehicle could be attributed to the drivers' perception of the road environment. Although wider-than-normal markings lead to perceive a narrower lane, wider markings may not provide additional benefits that influence lateral positioning, as drivers might primarily rely on other visual cues, such as the illumination given by the smart markings, for maintaining their lane position (Portera et al., 2023).

Our findings on longitudinal behavior indicated that the speed and acceleration were not affected by the PRM and marking width at the TS and CC sections. Whatever the reason for the lack of effects on driving speed of the smart markings in our study, it is worth noting that this finding aligns with those that studied the smart LED technology along horizontal curves in simulated (Portera et al., 2023; Shahar et al., 2018; Shahar and Bremond, 2014) and real (Llewellyn et al., 2021) road settings. The lack of effect of the PRM compared to unlit markings could be seen as a beneficial aspect, as it suggests that while the drivers' ability to anticipate road curvature improved, it did not lead to riskier behavior in terms of higher speeds. Furthermore, while wider-than-normal markings were expected to reduce driving speed, our study showed that this is not always the case. The marking width did not have a significant effect on driving speed, which is not consistent with previous findings on a real two-lane rural highway (Calvo-Poyo et al., 2020). Other road safety countermeasures for managing driving speed, such as longitudinal speed reduction markings and optical speed bars, induced a speed reduction with respect to a conventional solution (Boodlal et al., 2015; Ding et al., 2016; Zhao et al., 2018), emphasizing the need for further research. The lack of effect of the wider-than-normal markings could be due to the reduced effectiveness of such countermeasures at nighttime compared to daytime (Calvo-Poyo et al., 2020). Another possible explanation for the differences between ours and previous findings in this regard might be linked to the different experimental settings employed in each case (i.e., on a real road vs simulation studies). The curve direction had a significant effect on driving speed. Our result is consistent with a previous simulation study on a two-lane rural road (Bella, 2013). Bella and colleagues (Bella, 2013) pointed out that the right side of the roadway would have a guidance effect, allowing drivers to adopt higher speeds than left turns. As for acceleration, it was observed that drivers did not exhibit abrupt acceleration/deceleration either when approaching the curve or at its midpoint in any of the studied scenarios, which is a positive outcome in terms of road safety (Ariën et al., 2017). Finally, perceived task complexity levels, as measured by NASA-TLX scores, did not show any significant differences between the experimental scenarios. The low scores obtained from the questionnaire would reflect the low complexity and monotony of the driving situation (in terms of traffic density) used in our experiment (Morales et al., 2017; Fallahi et al., 2016).

In summary, our findings shed light on the complexities of road marking interventions and highlight the need for considering various factors, such as visibility conditions, when implementing such road safety measures.

Although relevant, our results must be interpreted carefully, taking into consideration some limitations. First, we did not consider external elements, such as traffic or adverse weather conditions (e.g., fog/rain), which may limit the generalizability of our findings. Further studies should explore the impact of traffic flow in the opposite direction (e.g., head-on collision) and/or adverse conditions on the effectiveness of the PRM. Second, our study only considered a standard size for the lateral shoulder (1.5 m) and PRMs were installed along the edge lines only, but different shoulder and marking layouts could influence the drivers' performance (e.g., larger/smaller/inexistent shoulder and PRM on the centerline). Third, no sight obstructions were included in our scenarios (i.e., trees, mountains). Reduced sight distance could affect the effectiveness of the smart markings in improving visibility and driving behavior. Last, it is worth noting that driving behavior and perception are profoundly influenced by cultural and social factors, so caution should be taken in assuming the universal applicability of our results (Di Stasi et al., 2020; Özkan et al., 2006).

5. Conclusions

The introduction of smart road technologies, such as PRMs, may help drivers to discern the forthcoming road layout and to adapt vehicle speed and position accordingly. Thus, we evaluated the effects of PRM colors and marking widths on driver performance in nighttime lighting conditions. Our findings show that smart markings positively influence driving behavior in terms of lateral position. The results indicate that, independently from the green or red color, PRMs would induce drivers to adopt a greater distance from the edge line. Therefore, PRMs would represent a potential effective prevention tool for roadway departure (running-off-road) events along horizontal curves. Furthermore, smart green markings would lead to poorer vehicle control compared to red ones, suggesting that red markings could be preferable along sharper curves or in dangerous zones. Additionally, the wider markings would replicate the effects of conventional ones on driving behavior. The presence of wider markings might be compensated by other visual cues, such as the self-illumination of the smart markings, resulting in no significant change in lateral position. Our results encourage the use of the conventional marking width when the photoluminescent technology is used. Overall, this study offers valuable information on driving behavior with unconventional road markings colors and novel technology that transportation engineers and road designers could use when implementing PRMs to improve road safety.

CRediT authorship contribution statement

Francesco Angioi: Conceptualization, Methodology, Investigation, Visualization, Writing – original draft, Writing – review & editing, Data collection, Formal analysis, Data curation. **Juan de Oña:** Conceptualization, Investigation, Writing - original draft, Writing - review & editing, Supervision. **Carolina Díaz-Piedra:** Conceptualization, Methodology, Writing - review & editing. **Rocío de Oña:** Writing - review & editing, Funding acquisition. **Leandro L. Di Stasi:** Conceptualization, Investigation, Writing - original draft, Writing - review & editing, Funding acquisition, Supervision.

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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.

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Data availability

Data will be made available on request.

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