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Influence of continuous edge-line delineation on drivers' lateral positioning in curves: a gaze-steering approach

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ABSTRACT

Recent research indicates that installing shoulders on rural roads for safety purposes causes drivers to steer further inside on right bends and thus exceed lane boundaries. The present simulator study examined whether continuous rather than broken edge-line delineation would help drivers to keep their vehicles within the lane. The results indicated that continuous delineation significantly impacts the drivers' gaze and steering trajectories. Drivers looked more towards the lane centre and shifted their steering trajectories accordingly. This was accompanied by a significant decrease in lane-departure frequency when driving on a 3.50-m lane but not on a 2.75-m lane. Overall, the findings provide evidence that continuous delineation influences steering control by altering the visual processes underlying trajectory planning. It is concluded that continuous edge-line delineation between lanes and shoulders may induce safer driver behaviour on right bends, which has potential implications for preventing run-off-road crashes and cyclist safety.

Practitioner summary: This study examined how continuous and broken edge lines influence driving behaviour around bends with shoulders. With continuous delineation, drivers gazed and steered in the bend further from the edge line and thus had fewer lane departures. Continuous marking can therefore help prevent run-off-road crashes and improve cyclists' safety.

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Bends; road markings; gaze; steering control; driving simulator

Introduction

Paved shoulders have long been used to create 'forgiving' roads where drivers can maintain control of their vehicles even when they drift out of the lane (Garber and Kassebaum 2008; OECD 1999). However, it has only recently been demonstrated that their installation increases drivers' corner-cutting around bends, leading them to encroach the shoulder, which is not intended for vehicular traffic (Mecheri, Mars, and Lobjois 2022a, 2022b). Here we examine whether the type of edge-line delineation between travel lanes and the adjacent shoulders can prevent drivers from travelling on shoulders while cornering. Edge lines are indeed used to delineate the outer edge of the road normally used by traffic (Migletz, Fish, and Graham 1994) and are a critical roadway characteristic that assists drivers with the control and guidance of their vehicles (Taylor et al. 1972). Indeed, proper delineation can help reduce steering errors (Carlson, Park, and Andersen 2009; Montella 2009), whereas poor delineation may contribute to run-off-road accidents (Ogden 1996; Palamara, Broughton, and Wicks 2014). In the present study, the effectiveness of continuous versus broken edge-line delineation was investigated to determine which would best maintain the driver's trajectory in the lane during right bends equipped with shoulders.

Driving around bends with shoulders

While shoulders have been shown to be effective in reducing run-off accidents on rural two-lane roads (Zegeer et al. 1994; Ogden 1997), little research has been conducted on how they affect driver behaviour around bends. Mecheri, Mars, and Lobjois (2022a) investigated how drivers negotiate left and right bends equipped with shoulders. The drivers deviated more towards the inside edge line and spent more time off the lane throughout right but not left bends in the presence of shoulders (see also Bella 2013; Ben-Bassat and Shinar 2011), but without slowing down to

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compensate for steering further inside. In another study, Mecheri, Mars, and Lobjois (2022b) replicated this effect and showed that shoulders also caused an inward deviation in gaze with a higher proportion of gaze points directed beyond the edge line (i.e. in the shoulder). Given the tight coupling between gaze and steering control (Lappi and Mole 2018), these findings provided evidence that shoulder presence influences the visual processes involved in trajectory planning.

Mecheri, Mars, and Lobjois (2022a, 2022b) thus proposed that drivers perceive the shoulder as a new 'field of safe travel' on right curves (i.e. the actual field within which the car can safely operate on the road, Gibson and Crooks 1938). This field is posited to be a dynamic set of possible paths that is bounded by objects or features that have a negative 'valence'. After installing shoulders, the edge line no longer coincides with the road edge and may thus take on a less negative valence as it no longer indicates the locomotion possibilities and becomes a purely legal limit. Therefore, while shoulders are effective to avoid run-off-road accidents, they present drivers with a compromise between not being allowed to cross the edge line and being able to steer more efficiently (shorter path length through the curve). This can jeopardise the safety of cyclists riding on the shoulder (Abele and Møller 2011), whose numbers are expected to increase as road reallocations and/or shoulder-width recommendations to provide bicycle-friendly shoulders increase (Bella and Silvestri 2017; Mecheri, Rosey, and Lobjois 2020; Rosey et al. 2009). Countermeasures aimed at preserving the safety benefits of shoulders without inducing side effects on lane departures and driver-cyclist interactions thus merit investigation. In particular, continuous delineation that cost-effectively emphasises the separation between the lane and the shoulder is worth testing in countries where the standard edge lines are broken.

Edge-line delineation and driver lateral deviation

Pavement-marking delineation defines the roadway operating area for drivers and enables them to control their vehicles within this safe and legal area (Migletz, Fish, and Graham 1994). Research on the behavioural effects of marking delineation has notably focussed on the impact of adding or improving edge lines on vehicle lateral position (van Driel et al., 2004). Steyvers and De Waard (2000) reported that drivers adopted a more central position and approached the edges of the road less frequently in the presence of edge lines. Sun et al. (2007) found that drivers travelled along a more centred and uniform trajectory with edge lines, particularly at night. Tsyganov et al. (2006) reported that edge marking resulted in vehicles moving away from the road edge and having lower lateral-position variability on different roadway geometries, but only on wider lanes. Around curves, edge lining was also demonstrated to elicit more central steering trajectories (Chrysler et al. 2009), up to 30 cm closer to the road axis on sharp curves after adding continuous lines (Havránek et al. 2020). Beyond the effect of the presence or absence of edge marking, a few studies have compared the influence of different types of edge lines on vehicle lateral position. Horberry, Anderson, and Regan (2006) reported lower lateral-position variability and fewer edge-line encroachments with more reflective markings (see also McKnight, McKnight, and Tippetts 1998). Conversely, drivers were found to operate their vehicles more towards the road edge with a more faded edge line (Chang et al. 2019). Surprisingly, very few behavioural studies have focussed on the effect of continuous versus broken edge lines. Zwahlen and Schnell (1995) reported that continuous lines were detected significantly earlier by drivers, whereas Steyvers and De Waard (2000) reported that the two types of edge lines produced similar lateral-position adaptations when compared to an unlined control road.

It is reasonable to conclude from this literature review that continuous edge lines provide more guidance information than broken edge lines, which could help drivers to maintain their vehicles within the lane when negotiating right bends equipped with shoulders. However, no prior research has examined whether driving around bends with continuous rather than broken edge lines elicits safer visual control of steering.

The roles of gaze and Edge-Line information around bends

Influential steering models (Donges 1978; Salvucci and Gray 2004) propose that vehicular locomotion is guided using both a far region that provides anticipatory information about the road ahead to plan a trajectory and a near region that provides feedback information to compensate for lateral-position errors. It has been suggested that gaze picks up anticipatory visual cues—a process that is called guidance (Lappi and Mole 2018)—whereas feedback information comes from peripheral vision of the lane edges (Land 1998; Land and Horwood 1995).

Researchers who have examined how drivers use anticipatory and feedback information have reported a weighted combination depending on the strength of the feedback signal (Frissen and Mars 2014). Robertshaw and Wilkie (2008) required participants to steer around bends in the centre of the lane and investigated whether enforced eccentric fixations would impact their steering trajectories. Overall, steering was biased in the direction of gaze, in accordance with the idea that drivers steer towards where they look and fixate a point on the desired future path (Wann and Swapp 2000; Wilkie and Wann 2003). However, changes in steering trajectories caused by gaze direction did not occur on narrow lanes, suggesting that gaze direction had a greater influence over steering on wider lanes when markings were further into the visual periphery and made feedback information weaker. In another study, Kountouriotis et al. (2012) required participants to maintain a constant lateral position along bends while the strength of the lane-edge information was degraded by fading marking. Similarly, the steering biases caused by eccentric fixation were greater when lane marking was faded, thus providing further evidence that gaze influences steering more when feedback information is weaker.

One can thus contend that the alteration of drivers' gaze caused by the presence of shoulders and its effect on steering can be mitigated by a continuous rather than a broken edge line, as it would provide stronger feedback information. This would particularly occur on narrow lanes, where lateral-position error compensation mechanisms based on the peripheral view of edge line would be more effective.

The present study

This study aimed to investigate the effects of edge-line delineation on drivers' gaze and steering strategies in right-hand bends in the presence of a shoulder. For this purpose, drivers negotiated a series of right bends on simulated two-lane rural roads equipped with shoulders and varying in edge-line delineation (continuous or broken) and lane width (narrow or wide). Based on the above literature, three alternative hypotheses were considered. First, the *planning hypothesis* predicts that a continuous marking will cause the edge line to take on a more negative valence, thereby reducing the driver's field of safe travel (Gibson and Crooks 1938). In this case, the shoulder is seen as a less driveable space, which affects the visual processes involved in path planning. Thus, it is expected that the drivers' gaze will be less directed towards the inside of the bend with a continuous delineation and that steering trajectories will accordingly be further from the edge line. Second, the *feedback hypothesis* predicts that a continuous delineation will not influence the drivers' perception of shoulders but will influence driving behaviour because it provides stronger feedback information for lateral error compensation. In this case, gaze behaviour is expected to be similar for broken and continuous edge lines, but trajectories are expected to differ due to the drivers' compensating lateral deviations more with continuous delineation, particularly on narrow lanes (Kountouriotis et al. 2012; Robertshaw and Wilkie 2008). Last, the *null hypothesis* predicts that type of edge-line delineation has no significant effect on driver behaviour, in line with Steyvers and De Waard (2000), who reported similar influences of broken and continuous edge lines on vehicle lateral position when compared with an unlined control road.

Method

Participants

Thirteen participants between 23 and 48 years old (mean age = 35; *SD* = 10 years; 6 females), all with normal or corrected vision, were recruited for this experiment. The participants had been fully licenced for at least two years. The self-reported total mileage ranged from 22,000 to 410,000 km (mean = 221,782; *SD* = 199,631 km). All participants provided informed consent to be included in the study and did not know about the purpose of the experiment. The experiment was approved by the local ethics committee.

Experimental setup

The experiment was carried out using a low-cost driving simulator equipped with a force-feedback steering wheel (Logitech G25). A virtual full-scale vehicle cab (vehicle width: 1.86 m, including mirrors) was displayed on the screen as this increases the drivers' ability to adjust steering to the lane boundaries in low-cost simulators (Mecheri and Lobjois 2018). Images were displayed on three 1.22×0.70 m screens (60 Hz refresh rate; 3840×2160 pixels), making a $180 \times 37°$ field of view with the participant's head at a distance of 1.05 m from the centre of each screen. Three loudspeakers generated realistic engine and environmental noises. The data were collected at a sampling rate of 50 Hz.

The visual scene represented a two-lane rural road in a traffic-free environment with one lane in each direction. The road surface was textured and marked by lines 0.18 m wide on the edges and another 0.15 m wide in the centre. The surrounding terrain was depicted as a flat rural landscape, excluding unnecessary scene elements that could potentially serve as irrelevant gaze-fixation targets. The participants drove on the right side of the road.

A PERTECH head-mounted monocular eye tracker was used to record the participants' eye movements at a sampling rate of 50 Hz. This monocular eye tracker has an accuracy of 0.25° (according to the manufacturer) and uses pupil-tracking with an image processing algorithm to define ocular direction. It was calibrated using a 7-point grid. Gaze positions were automatically calculated in the image coordinate system and expressed in pixels. Data from the simulator, including the tangent point position (see below) also expressed in pixels in the same coordinate system, were sent to the eye-tracker software. The two data sets were synchronised through a Network Time Protocol server/client application.

Experimental design and task

Four rural roads corresponding to two lane widths (3.50 and 2.75 m) and two edge lines (broken and continuous) were used. These four roads were equipped with 1.25-m shoulders (Figure 1). The broken edge line had 3-m long dashes and 3.50-m intervals, in accordance with marking standards for rural roads in France (IISR, 2016). The lane widths were selected from typical lane designs in France (see Hall et al. 1998; SETRA (Service d'Études sur les Transports and les Routes et leurs Aménagements) 1994). The shoulder width was determined using French regulations for shoulders on rural roads and corresponded to the recommended width.

On each experimental road, the participants had to perform a repetitive cornering task in a right bend that had a radius and arc length of 200 m as measured from the centre of the road. At the beginning of each trial, the participants were positioned in the centre of their (straight) lane 50 m from the bend entry and steered with an initial speed of 90 km/h (i.e. the legal speed limit for two-lane rural roads in France). Their speed was kept constant by the simulator software so that the trajectories in the bend were not influenced by individual speed reduction strategies. Given the constant speed and road portion length (250 m), each experimental trial lasted 10 s.

Procedure

Upon their arrival, the participants filled out biographical and consent forms and were then invited to sit down in the simulator. They were told that they

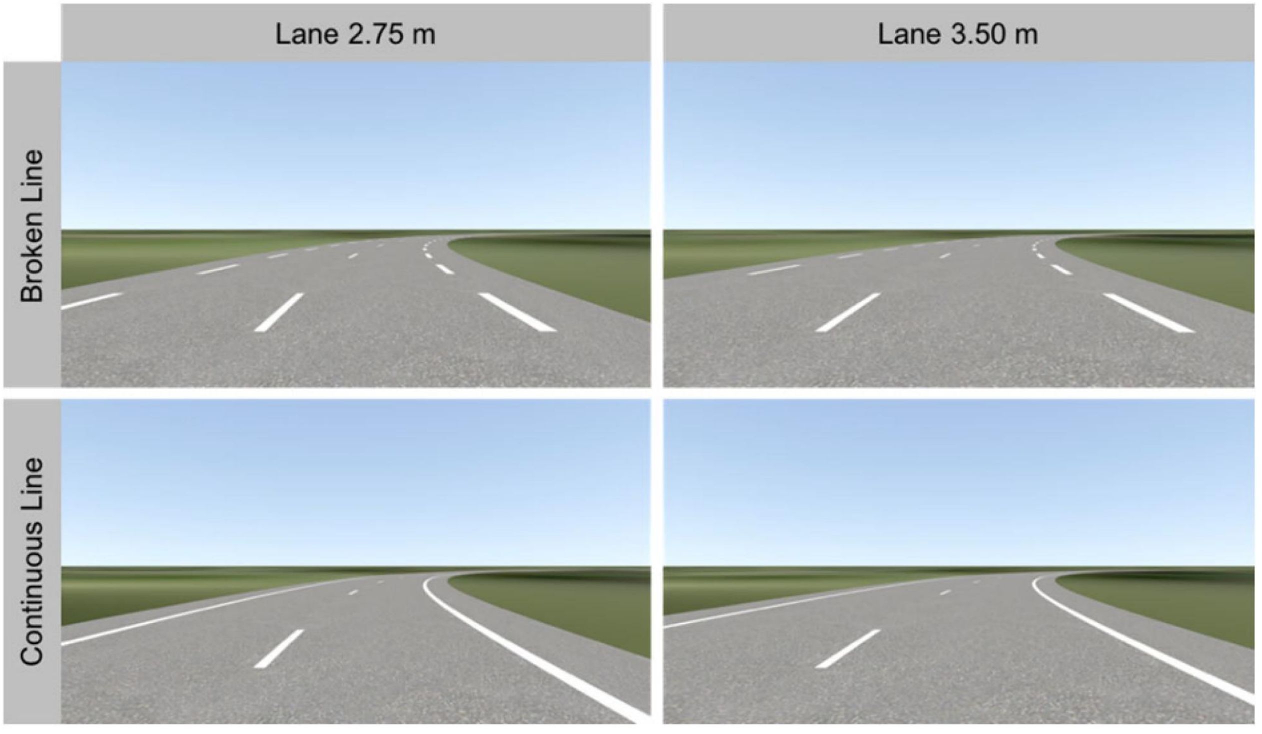

Figure 1. Screenshots of the four experimental roads used in the edge-line delineation analysis. The point of view is that of the participants at the beginning of the curve.

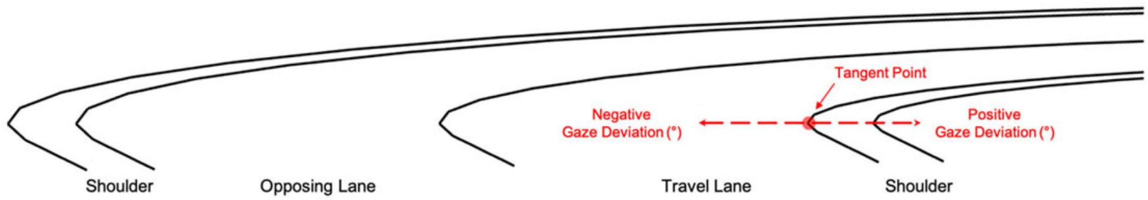

Figure 2. Schematic representation of gaze behaviour analysis as the horizontal angular deviation from the TP. As an approximation, gaze deviation was considered to be either in the lane (negative angular deviations) or beyond the edge line (positive angular deviations).

would have to drive around a series of right bends on a two-lane rural road, with the speed held constant. Despite this constraint, their instruction was to adopt a trajectory as close as possible to the one they would adopt spontaneously, while obeying traffic rules. They were then informed that each trial would begin with a black screen, which would be replaced with the visual scene. At this point, they had to drive until they reached the end of the bend (where the black screen reappeared). The participants were then familiarised with the simulator by driving on a winding rural road and subsequently with the experimental task by carrying out six practice trials. After that, they were equipped with the eye tracker, and the device was calibrated. During the experiment proper, the participants completed eight successive trials on each randomly presented experimental road. They took a short break after two roads, during which they were free to leave the simulator. The experimental session lasted about 45 minutes.

Data and statistical analysis

Driving measures

Driver behaviour was assessed in terms of lateral position (LP) defined as the distance in centimetres between the centre of the participant's vehicle and the centre of the lane. To obtain a straightforward view of the trajectories taken by the participants along the curve, we computed the LP at three key points in the bend: at curve onset (LP_{Entry}), at the apex of the curve (LP_{Apex}) and when drivers reached the innermost position in the curve (LP_{Max}). Positive values indicated deviation towards the inside edge line. The amplitude of corner-cutting was also calculated as the difference between LP_{Max} and LP_{Entry}. Last, we computed the total number of lane departures, defined as the number of bends in which a vehicle left the lane out of all the bends negotiated by all the participants. A departure was counted when any part of a wheel touched the edge line.

Gaze measures

Gaze behaviour was examined by computing the deviation of the gaze on the horizontal axis relative to the tangent point (TP), the point in the bend where the direction of the inside edge line seems to reverse from the driver's viewpoint (see Figure 2; Kandil, Rotter, and Lappe 2009; Land and Lee 1994). The TP was used as a dynamic spatial reference to analyse visual strategies, as gaze points in the vicinity of the TP capture a large proportion of guiding fixations, whether they are future path fixations (e.g. Robertshaw and Wilkie 2008) or fixations to the TP itself (e.g. Kandil, Rotter, and Lappe 2009). As the TP was located on the inner edge of the edge line, this provided a straightforward view of gaze direction as being either in the lane space or beyond. In practical terms, the visual scene was divided into 20 intervals of 1° of angular deviation from the TP (from $-10°$ to $+10°$), and the proportion of gaze points falling within each interval was computed for each bend (the straight-line approach was excluded). Gaze points that fell beyond 10° of eccentricity were distributed between two additional classes ($< -10°$ or $> +10°$).

The effects of lane width and delineation on lateral-position measures were assessed using 2 (lane width: 2.75, 3.50) $\times$ 2 (delineation: broken, continuous) repeated-measures ANOVAs. For gaze distribution, a three-way repeated-measures ANOVA (lane width $\times$ delineation $\times$ angular deviation from the TP) was conducted on the proportion of gaze points. Chi-square tests on lane departure (yes, no) $\times$ delineation (broken, continuous) were also performed for each lane width in order to determine whether the frequencies of lane departures significantly differed across delineations. All tests were done with p set at .05. The family-wise error rate for the 4 ANOVAs on lateral-position variables was controlled using the Holm step-down procedure (Holm 1979) by ranking the p-values from smallest to largest and comparing them to a sequentially adjusted alpha (p_{adj}). Mauchly's test of sphericity was conducted to determine whether the sphericity assumption was violated (Greenhouse-Geisser correction was reported in cases of violation). Post-hoc analyses were conducted with Bonferroni-corrected pairwise comparisons. For each effect, partial eta-squared (η_p^2) was calculated to determine the proportion of total variability accounting for the effect. Descriptive statistics are reported using means and standard deviations (mean ± *SD*).

Results

Driving measures

Averaged lateral positions at the three key points in the bend are depicted in Figure 3. The 2 (lane) × 2 (delineation) ANOVA revealed a main effect of delineation only for LP_{Entry} ($F_{1,12}$ = 10.29, p = .008, p_{adj} =.017, η_p^2 = .46) and LP_{Max} ($F_{1,12}$ = 5.11, p = .043, p_{adj} =.050, η_p^2 = .30). With the continuous line, drivers operated their vehicles further away from the inside edge line at curve entry (broken = 3 ± 35 cm; continuous = −9 ± 29 cm) and for the innermost position (broken = 46 ± 34 cm; continuous = 36 ± 32 cm). Although the lateral deviation also decreased at the apex with the continuous line, the difference was not significant.

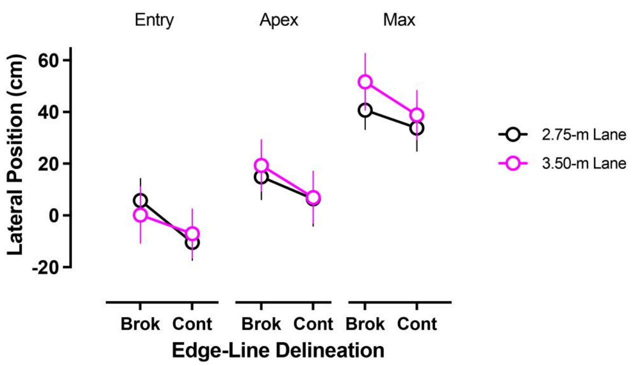

Figure 3. Lateral position at the three measurement points with broken and continuous edge lines. Zero represents the centre of the lane. Positive values correspond to a deviation towards the inside edge of the bend.

The ANOVA on the amplitude of corner-cutting highlighted a main effect of lane width ($F_{1,12}$ = 18.54, p = .001, p_{adj} =.013, η_p^2 = .61) and an interaction effect between lane width and delineation ($F_{1,12}$ = 7.80, p = .016, p_{adj} =.025, η_p^2 = .39). The amplitude of corner-cutting was significantly larger on the 3.50-m (52 ± 13 cm) than on the 2.75-m (35 ± 13 cm) lane with the broken line, but it was similar between lane widths with the continuous line (44 ± 16 and 46 ± 15 cm in the 2.75-m and 3.50-m lane width conditions, respectively). Regarding lane departures, the chi-square revealed similar frequencies of lane departures between delineations on the 2.75-m lane (see Figure 4, left). On the 3.50-m lane, the frequency of lane departures was significantly lower with continuous edge lines than with broken edge lines ($\chi^2(1)$ = 5.32, p = .021, Cramer's V = .16).

For a finer perspective on lane departures, we visualised the maximum distances reached by the right edge of the vehicle relative to the lane boundary (which amounted to a recalculation of LP_{Max}) in Figure 4 (right). This allowed for an examination of the extent to which participants entered or kept away from the shoulder on every negotiated bend. Interestingly, inspection of the data revealed that lane departures on the 2.75-m lane with continuous marking were not of smaller magnitude (mean = 29 cm)

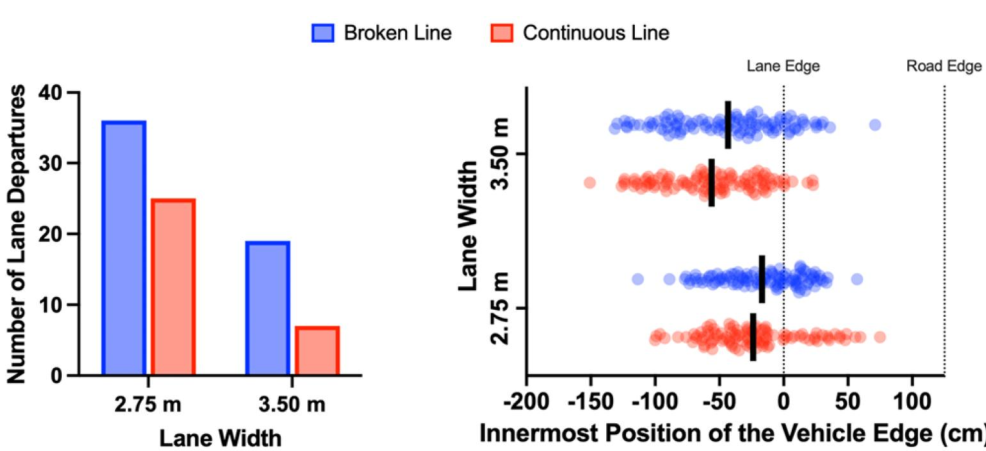

Figure 4. Left: Total number of lane departures on 2.75-m and 3.50-m lanes with broken and continuous edge lines. A total of 104 bends were negotiated by all participants in each of the four conditions. Right: Innermost position of the right edge of the vehicle as a function of lane width and delineation conditions (points represent individual trial values, bars are means). The vertical dashed lines represent the lane edge (i.e. the inner edge of the edge line, 0 cm) and the road edge (125 cm). Negative values mean that the right edge of the vehicle is within the lane.

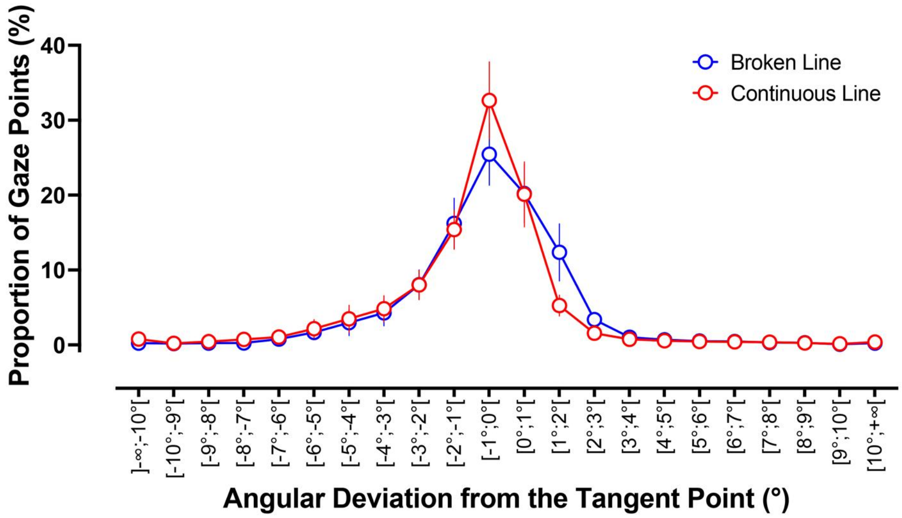

Figure 5. Proportion of gaze points (%) as a function of edge-line delineation and angular deviation from the TP on the horizontal axis. Negative angular deviations indicate that drivers' gaze is directed towards the lane. Positive angular deviations indicate that drivers' gaze is directed towards the shoulder.

than with broken marking (mean = 17 cm). In contrast, on the 3.50-m lane, lane departures were significantly fewer with continuous edge lines, as already reported, and were also made with smaller magnitudes (means of 10 and 17 cm for the continuous and broken edge lines, respectively).

Gaze measures

The 2 (lane) × 2 (delineation) × 22 (angular deviation) ANOVA on the proportion of gaze points revealed a main effect of angular deviation ($F_{21,252} = 21.93$, $p < .001$, $\eta_p{}^2 = .65$), and significant interactions between lane width and angular deviation ($F_{21,252} = 2.50$, $p < .001$, $\eta_p{}^2 = .17$) and between delineation and angular deviation ($F_{21,252} = 2.10$, $p = .004$, $\eta_p{}^2 = .15$). The lane width × angular deviation interaction revealed a higher proportion of gaze points in the [−1°; 0° [interval in the 3.50-m lane than in the 2.75-m lane. The delineation × angular deviation interaction revealed a higher proportion of gaze points in the [−1°; 0° [interval with the continuous line than with the broken line. Conversely, a higher proportion of gaze points was observed within the [1°; 2° [interval with the broken line than with the continuous line (Figure 5).

Discussion

This study examined whether continuous as opposed to broken edge-line delineation would affect drivers' gaze and steering strategies around right-hand bends equipped with shoulders. Three possible outcomes of this experiment were formulated. First, according to the *planning hypothesis,* a shoulder separated from the driving lane by a continuous line would be perceived as a less driveable space. Drivers would therefore direct their gaze and steer their vehicles further away from the edge line. Conversely, the *feedback hypothesis* predicted that a continuous delineation would not influence drivers' gaze but would lead to a more centred path because the stronger feedback information would reinforce compensatory control. Last, the *null hypothesis* stated that there would be no effect of delineation type on gaze orientation or trajectory, which is consistent with a previous study showing that continuous and broken edge lines produced similar effects on vehicle lateral position as compared to an unlined control road (Steyvers and De Waard 2000). Overall, the results support the planning hypothesis, as discussed in more detail below.

Negotiating right bends with a continuous rather than a broken edge line was found to significantly influence drivers' visual sampling of the road. With the continuous line, participants looked comparatively more at the travel lane (corresponding to the [−1°; −0° [interval) and less at the shoulder beyond the lane edge line (corresponding to the [1°; 2° [interval). Consistent with the 'steer where you look' strategy (Lappi and Mole 2018; Wann and Swapp 2000; Wilkie and Wann 2003), participants steered through bends with a more conservative path in the presence of a continuous edge line compared to a conventional broken edge line. This agrees with the planning hypothesis: the continuous delineation influenced steering control at the guidance level, i.e. the processes fed by distant visual information to plan a trajectory (Lappi and Mole 2018).

The question remains as to whether the changes in gaze direction induced by the continuous marking are strictly due to symbolic factors (a continuous line must not be crossed) or whether visibility factors (higher visibility of the edge line) also played a role. Given that the participants were unfamiliar with continuous marking on the lane edges, it is likely that continuous lines took on a more negative valence in the determination of the field of safe travel (Gibson and Crooks 1938). Yet, continuous marking may also facilitate the extraction of the TP visual motion compared to broken marking, as suggested in previous studies (e.g. Kountouriotis et al. 2012; Mestre et al. 2005). In line with this idea, several participants declared in a post-experiment informal conversation that driving with the continuous edge lines was more 'comfortable'. This agrees with the idea that continuous edge lines provide stronger guidance cues and possibly facilitate the process of extracting relevant information from the road ahead to specify the desired future path. One can note that this is a plausible explanation for the lower workload reported by drivers with enhanced markings compared to standard markings (Horberry, Anderson, and Regan 2006; Steyvers and De Waard 2000). Further investigation regarding mental workload would help to determine whether continuous delineation, in addition to inducing safer trajectory planning, facilitates the extraction of relevant guidance information.

Concerning the influence of delineation on steering, the continuous marking resulted in a reduction in lateral deviation at the three key points in the bend (although it was not significant at the apex), altering the steering path upon entering the curve. Crucially, on the 3.50-m lane, participants steered further away from the edge line with continuous delineation to the point of significantly reducing lane-departure frequency. It is also worth noting that fewer participants made lane departures in this lane-width condition: seven out of 13 participants departed the lane with broken lines, whereas only three of them did so with continuous lines. This significant difference in lane-departure frequency was nevertheless not observed in the 2.75-m lane. Plausibly, the restricted manoeuvring space in the narrow lane led drivers to limit their lateral deviation with continuous marking – but not to the point of avoiding crossing the edge line—in order to keep a minimal level of steering efficiency (reducing path length). Results also revealed that the delineation influenced the amplitude of corner-cutting, which increased with lane width only when driving with broken edge lines. The increase in corner-cutting typically observed with wider lanes (e.g. Raw et al. 2012; Robertshaw and Wilkie 2008) was thus mitigated with continuous delineation. Overall, the steering results suggest that continuous edge-line delineation on roads with wide lanes and equipped with shoulders can prompt drivers to take a more conservative path during right-hand bends, to the point of avoiding crossing the edge line. In this sense, continuous edge-line delineation in bends may preserve the safety benefits of shoulder installation by minimising the changes it produces on drivers' lateral position. This will bring them closer to the position they would adopt to negotiate a right bend in the absence of shoulders (Mecheri, Mars, and Lobjois 2022a, 2022b) and therefore would not increase the risk of head-on collisions with oncoming traffic compared to driving conditions without shoulders. For left bends, there is no reason to expect steering to be altered by continuous edge-line delineation, as one previous study has shown that manipulations of the outside lane edge marking were not impactful on drivers' trajectory (see Kountouriotis et al. 2012).

The present study has several limitations that warrant consideration. First, although the number of participants in our study is typical of many investigations exploring the relationship between gaze and steering in driving (e.g. Kountouriotis et al. 2012; Mole et al. 2016; Mole et al. 2021; Tuhkanen et al. 2019; Wilkie et al. 2010), this relatively small sample size limits the statistical power of our analyses and increases the risk of type II error. Future studies should include a larger sample to enable more confident statistical comparisons of gaze and steering data between different edge-line delineations. Another note of caution is that drivers' speed was kept constant, preventing them from adjusting their speed to negotiate bends. While this method is commonly used to study the visual control of steering and facilitate rigorous comparisons between experimental conditions (e.g. Kountouriotis et al. 2012; Robertshaw and Wilkie 2008; Schnebelen et al. 2019), it limits the ecological validity of the study and makes it important to replicate this experiment with free speed. Last, the effects of edge-line delineation were tested on bends of only one radius of curvature, which limits the generalisability of the results to different rural roads configurations. It would be worthwhile to extend the analysis to curves of various radii, this time incorporating lateral positioning measures that take into account differences in curve geometry (Bongiorno et al. 2022).

Conclusion

To conclude, this study showed that, for negotiating right-hand bends equipped with shoulders, continuous as opposed to broken edge lines significantly impacted the way drivers visually sampled the road and steered. Drivers looked more towards the lane centre and shifted their trajectories accordingly. The changes in steering behaviour led to a significant reduction in the number and severity of lane departures when driving on the wider lane. This coordination between gaze and steering behaviour provides compelling evidence that the benefits of continuous delineation stem from the visual processes involved in trajectory planning. In terms of recommendations, these findings suggest that it would be beneficial to assess continuous edge lines (in conjunction with lane width) in countries currently using broken edge lines on roads equipped with shoulders. This may promote safer driving behaviour during cornering, especially on rural roads where cyclists are particularly expected. Given that continuous edge delineation did not eliminate shoulder encroachment on the narrower lane, driver education about the dangers of using the shoulder to cut corners may also help reduce this behaviour. Further investigation is needed to examine whether continuous edge-line delineation around right bends would produce undesirable side effects. For instance, improved visual guidance and/or a lower workload might result in increased speed. It would also be worthwhile to test different shoulder widths and lighting conditions to confirm the observed effects and assess their magnitude at night, when pavement marking is more salient in the visual field.

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Data availability statement

The data that support the findings of this study are available upon request.

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