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Driving around bends with or without shoulders: The influence of bend direction

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ABSTRACT

Paved shoulders have long been used to create “forgiving” roads where drivers can maintain control of their vehicles even when as they drift out of the lane. While the safety benefits of shoulders have been well documented, their effects on driver behavior around curves have scarcely been examined. The purpose of this paper is to fill this gap by assessing whether the addition of shoulders affects driver behavior differently as a function of bend direction. Driver behavior in a driving simulator was analyzed on left and right curves of two-lane rural roads in the presence and absence of 0.75-m and 1.25-m shoulders. The results demonstrated significant changes in drivers’ lateral control when shoulders were provided. In the absence of oncoming traffic, the shoulders caused participants to deviate more toward the inner lane edge at curve entry, at the apex and at the innermost position on right bends but not left ones. In the presence of oncoming traffic, this also occurred at the apex and the innermost position, leading participants to spend more time off the lane on right curves. Participants did not slow down in either traffic condition to compensate for steering farther inside, thereby increasing the risk of lane departure on right curves equipped with shoulders. These findings highlight the direction-specific influence of shoulders on a driver’s steering control when driving around bends. They provide arguments supporting the idea that drivers view paved shoulders as a new field of safe travel on right curves. Recommendations are made to encourage drivers to keep their vehicle within the lane on right bends and to prevent potential interference with cyclists when a shoulder is present.

1. Introduction

Driving on curves is a complex locomotor task that requires anticipating the road’s curvature while keeping an adequate distance from the edge lines. This is a critical safety issue in different parts of the world, insofar as the accident rate is much higher on curved than on straight roads (Charlton & DePont, 2007; Glennon et al., 1985; Hummer et al., 2010; Liu & Subramanian, 2009). The most common type of accident on curves is single-vehicle crashes (i.e., run-off-road), particularly in rural areas where these crashes can account for up to 76 % of curve-related fatalities (Torbic et al., 2004). In the European Union, most of the single-vehicle fatalities reported in 2016 occurred in dry weather and in daylight or twilight (ERSO, 2018), indicating that drivers are often confronted with lateral control issues without difficulties related to road perception and pavement grip. Understanding how drivers manage the

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distance from the lane boundaries on curved sections of rural roads thus deserves further research.

One of the most recommended road-design measures for mitigating run-off-road crashes is to install paved shoulders or to increase their width to make bends more "forgiving" (Garber & Kassebaum, 2008; OECD, 1999; SETRA, 2002; Zegeer et al., 1994). The shoulder is the part of the road adjacent to the traffic lane that provides a recovery area for steering errors, and can also serve for bicycle traffic (AASHTO, 2011; Hall et al., 1998). Although the presence and width of shoulders are basic factors in accident-analysis research (e.g., Hadi et al., 1995; Karlaftis & Golias, 2002), studies that have investigated their effects on driver behavior on curves are scarce (Bella, 2013; Ben-Bassat & Shinar, 2011; see also Abele & Møller, 2011; Mecheri et al., 2022). In addition, past studies have not systematically analyzed the effects induced by the presence of a shoulder in relation to curve direction. According to Boer's (1996) model of curve negotiation, drivers move towards the outer edge line as they approach the curve, steer into the curve before its onset, and move towards the inner edge line at the apex of the bend. This behavior, which consists of moving from the outside edge line to the inside edge line when one is approaching the apex, is referred to as corner-cutting (Mars, 2008; Robertshaw & Wilkie, 2008), and allows the driver to reduce the curvature of his/her path on the curve (Kolekar et al., 2020). Since the shoulders are located on the right-hand side of the travel lane, irrespective of curve direction, this additional space may not influence the corner-cutting strategies in the same manner in right and left curves. Drivers could deviate more towards the inner-lane boundary in order to flatten out their path on right curves. Conversely, they may maintain a similar lateral position on left curves, regardless of the presence and width of the shoulder.

Two prior studies have examined the effects of shoulder width (0.50, 1.20, and 3.00 m in Ben-Bassat & Shinar, 2011) and shoulder presence (no-shoulder vs 1.50-m-wide shoulder in Bella, 2013) as a function of roadside configuration (presence or absence of a guardrail) and an overall road-geometry factor (straight, sharp left, shallow left, sharp right, shallow right). Participants have been found to drive faster when shoulders were present (Bella, 2013) and when they were wider but only in the presence of a guardrail (Ben-Bassat & Shinar, 2011). Regarding lateral position, Ben-Bassat and Shinar (2011) showed that participants drove on the left side of the lane when the shoulder was narrow (0.50 m), but moved to the middle and to the right side of the lane when the shoulder was wider (1.20 and 3.00 m, respectively). This effect of shoulder width on drivers' lateral position was found to be amplified when there was a guardrail, but was not affected by the overall road-geometry factor. In the study by Bella (2013), the presence of a shoulder resulted in a position that was 0.20 m farther away from the road center, regardless of the roadside-configuration and road-geometry factors.

These outcomes led to the conclusion that the effects of the shoulder on driver's lateral positioning do not depend on curve direction. However, these two studies did not allow for a systematic analysis of the different road-geometry parameters, since they mixed different curve directions, curve radii, and straight sections within the overall road-geometry factor. A more detailed examination of the lateral-position data suggests a possible differential effect of the shoulder as a function of the direction of the curve. In Bella (2013), the presence of a shoulder resulted in an increase in lateral deviation toward the inner lane boundary on sharp right curves (31 and 70 cm from the lane center in the no-shoulder and shoulder conditions, respectively), whereas the difference between these two conditions was only 5 cm on sharp left curves. Similarly, in the study by Ben-Bassat and Shinar (2011), lateral deviation towards the inner lane boundary was fairly consistent on shallow left curves (32, 43, and 43 cm in the 0.50, 1.20, and 3.00-m shoulder-width conditions, respectively), while it increased substantially with shoulder width on shallow right curves (35, 53, and 70 cm). Thus, by looking at selected road-geometry conditions, it appeared that the presence and widening of the shoulder gave rise to a higher level of corner cutting on right but not on left curves. This raises the question whether the lack of statistically significant differences between bends of different directions is due to a specific experimental design (with an overall road-geometry factor) rather than to a true lack of interaction between the presence of a shoulder and curve direction. Another limitation of previous studies is that they analyzed steering behavior using a mean lateral position calculated over entire bends. In doing so, they did not account for variations in lateral position during the approach and along the curve.

To clarify these issues, the present study investigated how the steering trajectories in left and right curves, described by multiple feature points before and along the curve, are affected by the presence of shoulders of different widths on two-lane rural roads. It was hypothesized that both the presence and width of the shoulder would result a greater amount of corner cutting on right curves but not on left curves. Additionally, the width of the lane was varied to find out whether possible shoulder effects would differ as a function of the maneuvering space afforded by the lane. Since drivers exhibit less corner cutting in narrow than in wide lanes (Raw et al., 2012; Robertshaw & Wilkie, 2008), it was hypothesized that participants would drive farther inside right curves in the presence of shoulders in narrow lanes to reduce the curvature of their path, but that this would result in an increase in the time spent off the lane. The interaction between lane width, shoulder width, and bend direction was examined in two different driving situations: (i) when drivers had to adapt only to the road infrastructure; (ii) when drivers had to cope with a flow of vehicles in the opposite lane. Prior research has shown that the presence of oncoming traffic resulted in drivers shifting their lateral position to the right side of the lane to lessen the risk of head-on collisions (Dijksterhuis et al., 2011; Mecheri et al., 2017). This closer position to the inner lane boundary raises the question of whether drivers increase corner cutting in the presence of shoulders on right curves with oncoming vehicles.

2. Method

2.1. Participants

Thirty participants, with normal or corrected-to-normal vision, volunteered to participate in the study. Participants had had their driving license for a minimum of two years and had at least 20,000 km of driving experience. They were assigned either to the traffic group ($n = 15$; 8 females), in which oncoming traffic was present, or the no-traffic group ($n = 15$; 9 females), in which there was no oncoming traffic. There were no significant differences between the groups in their age, years of driving experience, or kilometers of driving experience (see Table 1). All participants gave their informed consent prior to inclusion in the study and all were unaware of the hypotheses under investigation. The study was approved by the local ethics committee, and the ethical considerations and principles of the Declaration of Helsinki regarding experimentation were respected.

2.2. Experimental setup

The experiment was conducted using a low-cost driving simulator composed of a force-feedback steering wheel, foot pedals, and a gearbox (Logitech G25), mounted in line with a driving seat. The visual environment was displayed on three screens 1.22 m wide and 0.70 m high (refresh rate of 60 Hz, with a resolution of 3,840 × 2,160 pixels). The distance between the participant's head when seated and the center of each screen was 1.04 m. The height of the seat was adjusted for a representative individual so that the viewing angle was aimed at the simulated scene's vanishing point. In this configuration, the visual angle subtended by the three screens was 180° horizontally and 37° vertically. A full-scale virtual model of a vehicle cab was displayed on the screen (simulated vehicle width = 1.86 m, including mirrors), insofar as this enhances the ability of drivers to adjust vehicle-related spatial demands to the width of the lane in low-cost simulators (see Mecheri & Lobjois, 2018). The speedometer was displayed in the dashboard of the virtual cab. Engine sounds and environmental noises were generated by three speakers to enhance the driver's experience. The data were collected at a sampling rate of 60 Hz.

2.3. Stimuli

The simulated route was a two-way rural road, 12.5 km long, with one lane in each direction. The route consisted of a series of 12 randomly ordered curves (6 turning to the right and 6 turning to the left) separated by a 750-m long section of straight road. All the curves had a radius and arc length of 200 m, measured from the center of the road. The radius of curvature was chosen based on literature. Curves with less than 250 m of curvature are considered sharp (Calvi, 2015) and cause more accidents than curves with larger radii on rural roads (Elvik, 2013; Othman et al., 2009). The road surface was textured and marked by a discontinuous line 0.18 m wide on the edges and 0.15 m wide in the center. The surrounding terrain was a flat rural landscape containing trees placed at least 20 m from the side of the road. Tree spacing was random but replicated every 100 m in order to control the number of discontinuities that passed by a fixed point in the driver's visual field. The participants drove the simulated car on the right side of the road. The speed limit was 90 km/h.

2.4. Experimental design

Participants drove on a total of six experimental rural roads (see Fig. 1) created by manipulating two lane widths (3.50 and 2.75 m) and three paved-shoulder widths (0, 0.75, and 1.25 m). Except for the lane and shoulder widths, the six experimental roads were identical in their geometry. The selection of lane widths was based on the typical lane-width design in France (i.e., 3.50 m; see Hall et al., 1998). The shoulder-width range was determined by French regulations for shoulders deemed suitable for cycle use on rural roads, with 0.75 m and 1.25 m corresponding to the minimum and recommended widths, respectively. The edge line was not included in the lane and shoulder widths.

The difference between the participant groups was the absence or presence of oncoming traffic. The traffic condition consisted of passenger cars travelling at 90 km/h with a 6-s time headway (150-m distance headway). All vehicles were identical (width = 1.86 m, including mirrors) and were positioned in such a way that the distance between the sides of the cars (excluding the mirror) and the center of the road was 0.60 m in both lane-width conditions. The no-traffic condition presented no oncoming vehicles in the opposing lane. No vehicles were present in the participant's lane, whatever the traffic condition.

2.5. Procedure

The participants were told that they should drive as if they were driving a real car on a two-way rural road while obeying the speed limit of 90 km/h. After filling out consent forms, the participants were seated in the simulator and asked to adjust their seat position to feel comfortable. They were then given the opportunity to get used to the apparatus and visual environment by driving on a winding rural road consisting of curves of varying lengths and directions, with a curvature radius of 150 or 300 m. Each participant then performed one drive on each experimental road in a random order. Each test drive lasted approximately 8 min, depending on the participant's driving speed. The experiment lasted about 1 h15 in total.

Table 1
Participants' demographic characteristics, by traffic-condition group (mean ± SD).

	Traffic	No-Traffic	*p*-values[a]
Age (years)	34.4 ± 11.4	34.7 ± 9.5	0.92
Years of driving experience	14.6 ± 10.4	15.3 ± 10.9	0.95
Kilometers of driving experience	162,466 ± 207,534	185,667 ± 166,689	0.41

[a] As assessed by Mann-Whitney U-tests.

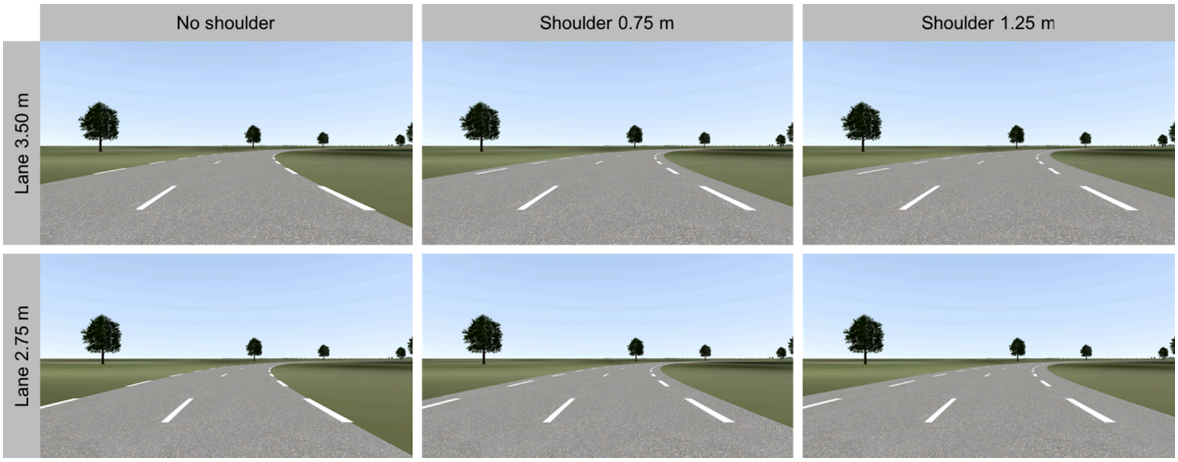

Fig. 1. The six experimental roads used for the experiment.

2.6. Data and statistical analysis

The participants' speed and lateral position were recorded. The speed variable corresponded to the mean speed along the curve. The lateral position was defined as the distance in centimeters between the center of the participant's vehicle and the center of his/her driving lane. Irrespective of the curve direction, positive values corresponded to a deviation toward the inside edge of the curve, and negative values corresponded to a deviation toward the outside edge of the curve.

In line with Boer's (1996) model of curve negotiation, we calculated the lateral positions (LP) at three points on the curve: when approaching the curve ($LP_{Approach}$), at curve entry (LP_{Entry}), and at its apex (LP_{Apex}). $LP_{Approach}$ was recorded 25 m before curve entry, a distance at which the upcoming bend is known to influence steering control (given a 90 km/h speed; see Wilkie & Wann, 2003). LP_{Entry} was recorded at curve onset and LP_{Apex} was recorded when the driver reached the apex of each curve (100 m into the curve).

To complete our understanding of how participants negotiated the curves, two other variables were calculated: the maximal lateral position (LP_{Max}) and the lane-departure duration. LP_{Max} corresponded to the closest position of the vehicle to the inside edge along the entire curve. Lane-departure duration was defined as the percentage of the total time that any part of the vehicle crossed the inner lane boundary (i.e., the time spent in the opposing lane on left curves, and on or beyond the edge line on right curves).

The traffic and no-traffic conditions were analyzed separately because they have been shown to induce very different lateral-positioning strategies (see Dijksterhuis et al., 2011; Mecheri et al., 2017). Thus, for each traffic condition and each dependent variable, 2 (lane width: 2.75, 3.50) × 3 (shoulder width: 0, 0.75, 1.25) × 2 (direction: left, right) repeated-measures analyses of variance (ANOVAs) were conducted. All statistical tests were performed with a p-level of 0.05. Mauchly's test of sphericity was conducted to determine whether the sphericity assumption was violated. In cases of violation, the Greenhouse-Geisser correction was used to adjust the degrees of freedom. Post hoc comparisons were made to follow up on significant effects using Tukey's honestly significant difference procedure. For each effect, partial eta-squared (η_p^2) was calculated to determine the proportion of total variability accounting for the effect. Descriptive statistics were reported using means and standard deviations (mean ± SD).

3. Results

Fig. 2 displays the mean lateral position adopted by participants when approaching the curve and along the curve in the no-traffic (top) and traffic (bottom) conditions. The statistical results for lateral-position variables are summarized in Table 2.

3.1. No-Traffic condition

Speed. The driving speed was not affected by lane width ($F_{1,14} = 2.71$, $p = .122$), shoulder width ($F_{2,28} = 0.04$, $p = .958$), or curve direction ($F_{1,14} = 0.18$, $p = .676$). No significant interactions were observed. Participants averaged a driving speed of 85 ± 7 km/h throughout the experiment.

$LP_{Approach}$. The ANOVA for $LP_{Approach}$ revealed significant main effects of lane width and shoulder width. The lane × direction and shoulder × direction interactions were also significant. Participants approached left curves in a similar way in the two lanes (–32 ± 29 cm and –32 ± 36 cm in the 2.75 and the 3.50-m lane, respectively), while they approached right curves significantly closer to the outside edge in the 3.50-m lane (-29 ± 35 cm) than in the 2.75-m lane (-15 ± 28 cm). Regarding the shoulder × direction interaction, participants approached left curves with significantly more lateral deviation toward the outside edge in the presence of shoulders (0.75 m = -36 ± 34 cm; 1.25 m = -37 ± 33 cm) than in the no-shoulder condition (-24 ± 30 cm). In contrast, when the participants were approaching right curves, the lateral deviation toward the outside edge was significantly lower in the 1.25-m shoulder condition (-16 ± 30 cm) than in the 0.75-m shoulder (-25 ± 33 cm) and no-shoulder (-25 ± 33 cm) conditions.

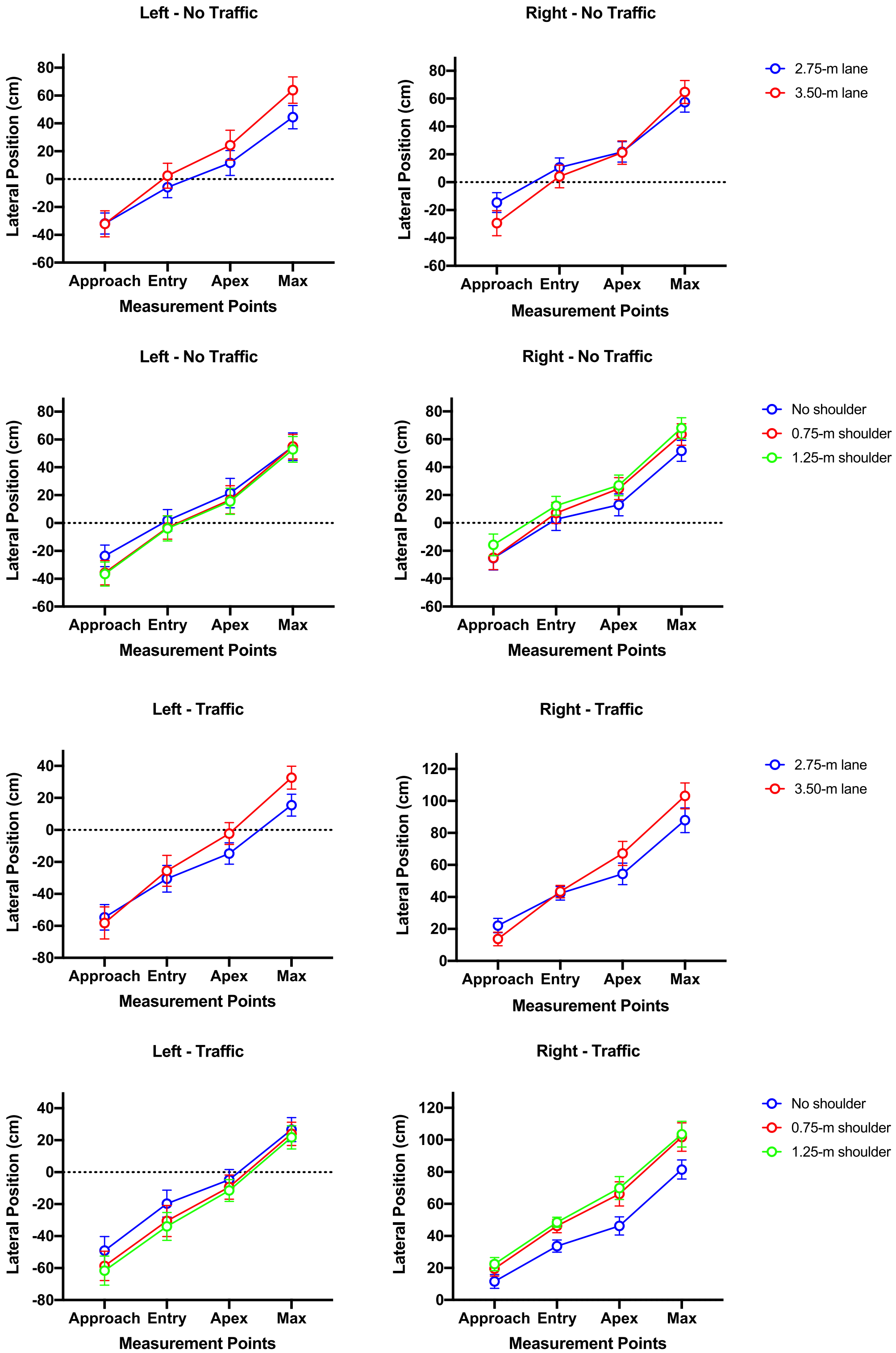

Fig. 2. Lateral position at the four measurement points on left and right curves. The top four graphs and the bottom four graphs plot the lane × direction interaction and the shoulder × direction interaction in the absence of traffic and in the presence of traffic, respectively. Zero represents the center of the lane and positive values correspond to a deviation toward the inside edge of the curve. The bars represent the standard error of the mean.

Table 2
Main effects and interactions on lateral-position (LP) variables and lane-departure duration in the no-traffic (top) and traffic (bottom) conditions.

	$LP_{Approach}$			LP_{Entry}			LP_{Apex}			LP_{Max}			Lane-Departure Duration		
Variables – No Traffic	*F*	*p*	η_p^2	*F*	*p*	η_p^2	*F*	*p*	η_p^2	*F*	*p*	η_p^2	*F*	*p*	η_p^2
Lane	**21.22**	**<0.001**	**0.60**	0.25	0.62	0.02	**6.53**	**0.02**	**0.32**	**174.4**	**<0.001**	**0.93**	**12.45**	**0.003**	**0.47**
Shoulder	**5.58**	**0.009**	**0.29**	1.10	0.35	0.07	1.96	0.16	0.12	**7.92**	**0.002**	**0.36**	3.35	0.05	0.19
Direction	0.53	0.48	0.04	0.51	0.49	0.04	0.06	0.81	0.00	0.25	0.62	0.02	**9.66**	**0.008**	**0.41**
Lane × Shoulder	2.82	0.08	0.17	0.02	0.98	0.00	0.84	0.44	0.06	0.57	0.57	0.04	2.63	0.09	0.16
Lane × Direction	**7.86**	**0.01**	**0.36**	**8.89**	**0.009**	**0.39**	**9.44**	**0.008**	**0.41**	**5.95**	**0.03**	**0.30**	**12.01**	**0.004**	**0.46**
Shoulder × Direction	**11.25**	**<0.001**	**0.45**	**6.33**	**0.006**	**0.31**	**6.11**	**0.006**	**0.31**	**6.56**	**0.005**	**0.32**	3.34	0.05	0.19
Lane × Shoulder × Direction	1.16	0.33	0.08	2.21	0.13	0.14	0.38	0.69	0.03	1.34	0.28	0.09	2.64	0.09	0.16
	$LP_{Approach}$			LP_{Entry}			LP_{Apex}			LP_{Max}			Lane-Departure Duration		
Variables – Traffic	*F*	*p*	η_p^2	*F*	*p*	η_p^2	*F*	*p*	η_p^2	*F*	*p*	η_p^2	*F*	*p*	η_p^2
Lane	**12.99**	**0.003**	**0.48**	3.42	0.09	0.20	**27.59**	**<0.001**	**0.66**	**55.82**	**<0.001**	**0.80**	**40.91**	**<0.001**	**0.75**
Shoulder	0.16	0.85	0.01	0.16	0.85	0.01	**7.32**	**0.003**	**0.34**	**10.68**	**<0.001**	**0.43**	**20.61**	**<0.001**	**0.60**
Direction	**49.90**	**<0.001**	**0.78**	**48.38**	**<0.001**	**0.78**	**51.62**	**<0.001**	**0.79**	**53.79**	**<0.001**	**0.79**	**30.05**	**<0.001**	**0.68**
Lane × Shoulder	0.45	0.64	0.03	0.15	0.86	0.01	0.04	0.96	0.00	0.08	0.93	0.01	1.12	0.34	0.07
Lane × Direction	1.76	0.21	0.11	1.29	0.28	0.08	0.02	0.90	0.00	0.93	0.35	0.06	**38.05**	**<0.001**	**0.73**
Shoulder × Direction	**11.77**	**<0.001**	**0.46**	**22.43**	**<0.001**	**0.62**	**20.81**	**<0.001**	**0.60**	**17.05**	**<0.001**	**0.55**	**19.18**	**<0.001**	**0.58**
Lane × Shoulder × Direction	0.27	0.77	0.02	0.52	0.60	0.04	1.15	0.33	0.08	1.02	0.37	0.07	2.00	0.16	0.12

LP_{Entry}. At curve entry, only the lane × direction and shoulder × direction interactions were significant. The post-hoc tests for lane × direction revealed no significant pairwise comparisons. The shoulder × direction interaction indicated that drivers entered left curves in the same way regardless of whether there was a shoulder (no shoulder = 2 ± 30 cm, 0.75 m = -3 ± 33 cm; 1.25 m = -4 ± 35 cm), but adopted significantly more lateral deviation toward the inside edge in the 1.25-m shoulder condition (12 ± 26 cm) than in the no-shoulder condition (3 ± 31 cm) when entering right curves.

LP_{Apex}. The ANOVA on LP_{Apex} indicated a significant main effect of lane width, indicating more lateral deviation toward the inside edge in the 3.50-m lane (23 ± 37 cm) than in the 2.75-m lane (17 ± 32 cm). The lane × direction and the shoulder × direction interactions were also significant. Participants deviated significantly more in the 3.50-m lane (24 ± 42 cm) than in the 2.75-m lane (12 ± 35 cm) on left curves, while no significant difference was found between the two lane-width conditions on right curves (2.75 m = 22 ± 28 cm; 3.50 m = 21 ± 32 cm). Regarding the shoulder × direction interaction, participants did not deviate from the lane center differently in the three shoulder-width conditions on left curves (no shoulder = 22 ± 41 cm; 0.75 m = 17 ± 39 cm; 1.25 m = 16 ± 36 cm), whereas LP_{Apex} was significantly greater on right curves in the presence of shoulders (0.75 m = 25 ± 31 cm; 1.25 m = 27 ± 29 cm) than in the no-shoulder condition (13 ± 30 cm).

LP_{Max}. The ANOVA revealed significant main effects of lane width and shoulder width on the innermost position on the curve. The lane × direction and the shoulder × direction interactions were also significant. The lateral deviation on left curves was significantly higher in the 3.50-m lane (64 ± 37 cm) than in the 2.75-m lane (44 ± 32 cm), while no significant difference was found between the two lane-width conditions on right curves (2.75 m = 57 ± 27 cm; 3.50 m = 65 ± 32 cm). Regarding shoulder × direction, similar LP_{Max} values were found for the three shoulder-width conditions on left curves (no shoulder = 55 ± 38 cm; 0.75 m = 55 ± 34 cm; 1.25 m = 53 ± 36 cm), whereas participants drove on right curves significantly closer to the inside edge in the presence of shoulders (0.75 m = 64 ± 30 cm; 1.25 m = 68 ± 29 cm) than in the no-shoulder condition (52 ± 29 cm).

Lane-departure duration. The lane departure duration (see Fig. 3) was significantly affected by lane width, direction, and the interaction between these two factors. This duration was similar in the two lane-width conditions on left curves (2.75 m = 0.2 ± 0.3 %; 3.50 m = 0.0 ± 0.0 %), but was significantly longer in the 2.75-m lane (17.0 ± 20.9 %) than in the 3.50-m lane (4.6 ± 10.1 %) on right curves.

3.2. Traffic condition

Speed. Driving speed was significantly affected by lane width ($F_{1,14}$ = 6.24, p =.026, η_p^2 = 0.31), and by a significant lane × shoulder interaction ($F_{2,28}$ = 6.24, p =.036, η_p^2 = 0.21). Participants drove significantly faster on the widest road (3.50-m lane, 1.25-m

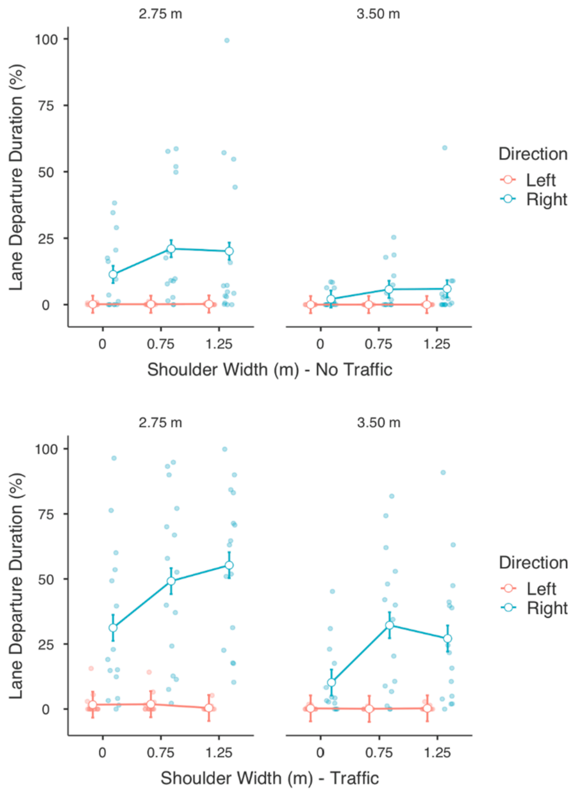

Fig. 3. Percentage of time spent off the lane in each shoulder-width condition as a function of curve direction and lane width in the absence (top) and in the presence (bottom) of traffic. Points represent individual means. The bars represent the standard error of the mean.

shoulder = 85 ± 6 km/h) than in the narrowest road (2.75-m lane, no shoulder = 83 ± 8 km/h).

$LP_{Approach}$. The ANOVA for $LP_{Approach}$ yielded a significant main effect of lane width indicating significantly more deviation toward the outside edge in the 3.50-m lane (–22 ± 47 cm) than in the 2.75-m lane (-16 ± 46 cm). There was also a significant main effect of direction, and a significant shoulder × direction interaction. Lateral-position differences between left and right curves were significantly different at each shoulder width, due to participants approaching left curves in the outer lane (no shoulder = -49 ± 34 cm; 0.75 m = -59 ± 35 cm; 1.25 m = -62 ± 35 cm), and approaching right curves in the inner lane (no shoulder = 12 ± 17 cm; 0.75 m = 20 ± 18 cm; 1.25 m = 22 ± 16 cm). On left curves, the lateral deviation toward the outside edge was significantly greater in the presence of shoulders than in the no-shoulder condition. On right curves, the lateral deviation toward the inside edge was significantly greater in the 1.25-m shoulder condition than in the no-shoulder condition.

LP_{Entry}. The observed differences in the curve approach resulted in a significant main effect of direction for LP_{Entry}, and a significant shoulder × direction interaction with almost the same statistical pattern. Lateral-position differences between left and right curves were significantly different at each shoulder width. Drivers entered curves to the left with significantly more deviation toward the outside edge in the presence (0.75 m = -31 ± 38 cm; 1.25 m = -34 ± 34 cm) than in the absence (-20 ± 33 cm) of shoulders, and curves to the right with significantly more deviation toward the inside edge in the presence (0.75 m = 46 ± 16 cm; 1.25 m = 49 ± 12 cm) than in the absence (34 ± 15 cm) of shoulders.

LP_{Apex}. The ANOVA for LP_{Apex} revealed a significant main effect of lane width, showing a significantly greater lateral deviation in the 3.50-m lane (32 ± 45 cm) than in the 2.75-m lane (20 ± 43 cm). The analysis also revealed significant main effects of shoulder width and direction, and a significant shoulder × direction interaction. On left curves, LP_{Apex} was similar in the three shoulder-width conditions (no shoulder = -5 ± 25 cm; 0.75 m = -9 ± 29 cm; 1.25 m = -11 ± 26 cm), whereas it was significantly greater on right curves in the presence of shoulders (0.75 m = 66 ± 29 cm; 1.25 m = 70 ± 28 cm) than in the no-shoulder condition (46 ± 22 cm). Again, the lateral-position differences between left and right curves were significant at each shoulder width.

LP_{Max}. The ANOVA results for LP_{Max} strictly paralleled those of LP_{Apex}, with significant main effects of all factors, and a significant shoulder × direction interaction. The main effect of lane width revealed significantly higher lateral deviation in the 3.50-m lane (68 ± 46 cm) than in the 2.75-m lane (52 ± 46 cm). The shoulder × direction interaction revealed a similar lateral deviation in all three shoulder-width conditions on left curves (no shoulder = 27 ± 29 cm; 0.75 m = 24 ± 28 cm; 1.25 m = 22 ± 28 cm), whereas on right curves, participants drove significantly closer to the inside edge in the presence of shoulders (0.75 m = 102 ± 34 cm; 1.25 m = 104 ± 31 cm) than in the no-shoulder condition (81 ± 23 cm). Again, the differences between left and right curves were significant at each shoulder width.

Lane-departure duration. Finally, lane-departure duration was significantly higher in the narrow lane, in the presence of shoulders, and on right curves. A significant lane × direction interaction revealed that this duration was similar in the two lane-width conditions on left curves (2.75 m = 1.3 ± 3.3 %; 3.50 m = 0.2 ± 0.6 %), and was significantly longer in the 2.75-m lane (45.2 ± 31.6 %) than in the 3.50-m lane (23.2 ± 24.8 %) on right curves. A significant shoulder × direction interaction also revealed a similar lane-departure duration in all three shoulder-width conditions on left curves (no shoulder = 1.0 ± 3.0 %; 0.75 m = 1.0 ± 2.8 %; 1.25 m = 0.4 ± 1.1 %), and a significantly longer lane-departure duration on right curves in the presence (0.75 m = 40.7 ± 31.0 %; 1.25 m = 41.2 ± 30.9 %) than in the absence (20.7 ± 25.1 %) of shoulders.

4. Discussion

The purpose of this study was to determine whether having paved shoulders on two-lane rural roads causes driving around curves to vary as a function of curve direction. The overall results indicate that speed is marginally affected and lateral control is strongly affected by the presence of a shoulder on right bends in both traffic conditions.

4.1. Speed

In the absence of traffic, the participants kept their speed unchanged in all conditions. This result does not align with studies showing changes in speed with lane width on bends (Godley et al., 2004; Lewis-Evans & Charlton, 2006). However, those studies were not entirely conclusive. First, the speed adaptation reported by Godley et al. (2004) and Lewis-Evans and Charlton (2006) was not systematic: speed decreased significantly on narrow roads in comparison to the control condition, but did not increase significantly on wide roads. Second, on straight sections of rural roads, drivers were found to increase their speed as a function of lane width in certain studies (De Waard et al., 1995; Godley et al., 2004; Lewis-Evans & Charlton, 2006) but not in others (Lum, 1984; Mecheri et al., 2017; Rosey et al., 2009). With regard to the shoulder effects, our results are in line with Ben-Bassat and Shinar's (2011) findings showing that widening shoulders from 0.50 m to 1.20 m and 3.00 m did not increase speed (in the absence of guardrails), but are at variance with those of Bella (2013) showing higher speeds with 1.50-m wide shoulder. Given that the participants were driving below the speed limit in the present study, our results are unlikely to be due to a ceiling effect, and thereby reinforce the limited body of evidence showing that widening shoulders does not affect speed choice on bends.

In the presence of traffic, driving speed underwent a significant decrease of 2 km/h on the narrowest (2.75-m lane, no shoulder) as compared to the widest (3.50-m lane, 1.25-m shoulder) road cross-section. In the absence of lane and shoulder main effects, this speed adaptation is most likely a consequence of driving on a narrow road, close to the edge line, with no recovery area. In such driving conditions, more attention must be paid to lateral control of the vehicle to avoid swerving off the edge of the road (Dijksterhuis et al., 2011). Plausibly, participants were unable – or unwilling for reasons of comfort – to provide the extra effort needed to drive closer to the edge of the road while keeping their speed constant. Thus, the observed decrease in speed is most likely the result of a compensatory mechanism consisting of slowing down.

4.2. Lateral position and shoulder width

In the absence of traffic, participants exhibited a very similar pattern of curve negotiation on left and right curves in the no-shoulder condition. They moved toward the outer lane edge during the approach, entered curves close to the center of the lane, and then moved toward the inner lane edge. Except when approaching the curve where lateral position was affected in both directions, the presence of shoulders had an impact on the trajectories taken by participants on right curves only. On left curves, similar lateral deviations were found in the three shoulder-width conditions at entry, apex, and for LP_{Max}. On right curves, however, participants steered significantly farther inside at curve entry in the presence of the widest shoulder, and did so at the apex and for LP_{Max} in the presence of both shoulders. Importantly, these lateral-position changes in the presence of shoulders were not compensated for by slowing down, in such a way that the time-to-line-crossing was reduced (Godthelp, 1988).

In the presence of traffic, participants generally shifted to the right of their lane in both bend directions to move away from oncoming vehicles, consistent with previous findings (Dijksterhuis et al., 2011; Mecheri et al., 2017). Despite the participants' greater proximity to the inner edge line, the influence of shoulders on drivers' lateral positioning was very similar to that in the no-traffic condition: participants steered farther inside on right curves but not on left curves. However, in contrast to the no-traffic condition, the more off-centered trajectories led to significantly more time outside the lane during driving with shoulders (41% of the time). This suggests that drivers see the shoulder as an extra lane for travelling and increasing their safety margin against oncoming vehicles on right curves, even at the cost of lane departure. It is worth noting that oncoming vehicles maintained a constant lateral position rather than adopting a racing line, which could have made drivers encroach further onto the shoulder. Therefore, it would be appropriate to replicate this experiment by varying the behavior of oncoming vehicles.

At this point, it should be noted that a study by Mecheri & Lobjois (2018), which examined the reliability of lateral control data obtained from the simulator used in the current study, showed that drivers' lateral positioning was similar along left and right curves when driving on rural roads. The presence of a virtual vehicle cab, such as the one used in the current study, greatly reduced the difficulty in estimating the distance between the right edge of the car and the lane boundary. Therefore, although a validation study comparing the simulator to real-world driving would be worth conducting (e.g., Bella, 2008; Faschina et al., 2021), the design of the simulator cannot account for the increased lateral deviation observed when negotiating right bends with shoulders.

In sum, participants increased their lateral deviation toward the inner lane edge in the presence of shoulders on right but not on left curves, in both traffic conditions, confirming our hypothesis that the shoulder effect on drivers' lateral control is direction-specific. These results extend and clarify those of previous studies that have examined an overall road-geometry factor (Bella 2013; Ben-Bassat & Shinar, 2011). Another important finding is that shoulder width had almost no impact on drivers' lateral control in either traffic condition.

4.3. Lateral position and lane width

In the absence of traffic, participants adapted their lateral position to the lane width, but on left curves only. Recently, Oka et al. (2015) found differences in brain activity suggesting that driving on left curves requires more visual attention than it does on right curves. This increased difficulty of left-bend driving may have led participants to keep a greater distance from the centerline in the narrow lane so as to limit the risk of encroachment. Conversely, the possibility of reducing the trajectory's curvature for negotiating right curves could explain why drivers overstepped the limits of the narrow lanes. Possibly, this occurred because, while there is a concrete disadvantage in real conditions of driving too far to the left (running into oncoming traffic), the disadvantage of driving too far to the right is only implicit (lane departure). This was especially true since there was no roadside element (e.g., trees close to the road edge or guardrails) that can be perceived by drivers as potentially dangerous in the event of a crash (Stamatiadis et al., 2010) and minimize lateral deviations from the road center (Bella, 2013; van der Horst & De Ridder, 2007). This methodological choice was made in order not to confuse the effect of the shoulder and the effect of the roadside elements, two properties of the road that can have effects in opposite directions. However, a replication of the experiment jointly studying the two factors would allow to better understand their interaction.

In the presence of traffic, lateral adaptation to the lane width was observed in both directions, which is consistent with prior findings (Raw et al., 2012; Robertshaw & Wilkie, 2008). On left curves, the participants increased their lateral deviation in the wide lane, as expected. On right bends, they also increased their lateral deviation in the wide lane despite being close to the inner edge. It is striking that, while participants did not deviate as much in the narrow lane as in the wide lane, they did drive outside the lane for a substantial portion of the bends. Crossing the inner-lane boundary thus appears to be motivated by the need to reduce path curvature throughout the curve.

Importantly, the non-significant interaction between the lane and shoulder factors, whether or not oncoming vehicles were present, revealed that the impact of the shoulder did not depend on the width of the lane. Thus, the hypothesis of a greater effect of shoulders on the narrow lane was not confirmed. From a practical standpoint, this outcome is important since no previous research has examined whether lane and shoulder width interact to influence drivers' lateral deviation on right curves. This finding, however, remains to be tested with other shoulder dimensions like those found in other countries (such as the 3.00-m wide shoulders used by Ben-Bassat & Shinar, 2011).

4.4. Shoulder influence and steering control processes

Because this study provides evidence that driving with and without shoulders leads to changes in drivers' lateral control on right curves, an important question concerns the processes responsible for the observed differences in lateral positioning.

Influential theoretical accounts (Donges, 1978) have proposed that the steering control relies on both anticipatory open-loop control (guidance level) and compensatory closed-loop control (stabilization level). The guidance level is responsible for anticipating changes in the road ahead in order to plan the trajectory. The stabilization level serves to maintain lane position against unpredictable perturbations by tracking and nullifying lateral position errors to compensate for deviations from the planned trajectory. Since the visual input coming from the lane-marking boundaries in the so-called near region, which provides compensatory closed-loop information (see Salvucci & Gray, 2004), was unaffected by the presence of a shoulder, it is likely that the compensatory processes were very similar in all shoulder conditions. In support of this idea, driving on straight roads with and without shoulders of different widths has been shown to produce differences in lateral position but not in lateral-position variability (Mecheri et al., 2017).

The trajectory differences we observed in the presence and absence of shoulders can therefore be ascribed to anticipatory processes, via which the driver plans where to drive on the road ahead (Donges, 1978). Early driver models (Gibson & Crooks, 1938) proposed that individuals manage risk according to safety margins and a perceived "field of safe travel", i.e., the actual field within which the car can safely operate on the road. Field-of-safe-travel theory posits that this field is a continuously changing set of possible paths that center on attractive openings and is bounded by surrounding objects or features of the terrain that have a negative "valence" from the driver's viewpoint (obstacles). In the present context, the inside edge line, which coincided with the edge of the road in the absence of a shoulder on right bends, can be seen as an obstacle. In the presence of a shoulder, however, the inside edge line may take on a less negative valence and no longer be seen as an obstacle insofar as the shoulder opens up a new road space. In this view, the inner edge line may no longer be an objective indicator of the locomotion possibilities on right curves with shoulders and thus become a purely legal limit. In support of this idea, Ben-Bassat and Shinar (2011) demonstrated, using static views of road scenes, that drivers sense that there is more space and feel safer in the presence of wide rather than narrow shoulders, and in right rather than left bends equipped with shoulders. One can assume, then, that steering changes that depend on the provision of shoulders reflect a compromise, from the driver's point of view, between the legal prohibition of crossing the edge line and the possibility of steering more efficiently (shorter path length through the curve) via the use of a new and extended field of safe travel.

4.5. Practical implications of Direction-Specific shoulder influence

In accounting for the direction-specific effect of shoulders, this study provided a more accurate prediction of driver behavior around bends on rural roads equipped with shoulders. Some recommendations can be made based on this finding.

The first recommendation is to combine the installation of shoulders with features known to encourage drivers to keep their vehicles in the lane. For instance, drilling rumble strips next to the edge line has proven effective in helping drivers keep their vehicles in the center of their lane (Khan et al., 2015; Räsänen, 2005). Perceptual countermeasures such as herringbones have also been found to induce more central lateral positions on bends without altering corner-cutting behavior (Awan et al., 2019; Charlton, 2007; for contradictory findings, see Ariën et al., 2017). The purpose of such delineations would be to cause the edge line to take on a more negative valence with respect to the space the driver will deem safe to travel on the bend (Gibson & Crooks, 1938). This would prevent drivers from steering farther inside at the same speed with shoulders, thus reducing the time available before crossing the lane boundary, a robust predictor of lane departures (Mammar et al., 2004, 2006).

The second recommendation is to act upon shoulder width to mitigate the negative impact of vehicle lane departures on cyclist safety. Insofar as our results indicate that the shoulder effect depended very little on shoulder width, providing larger shoulders should increase the lateral distance between driver and cyclist (assuming that the cyclist is riding in the middle of the shoulder), without inducing an increase in driver corner cutting. Installing the widest possible shoulders on two-lane rural roads must therefore be recommended in order to keep cyclists at a safer distance from drivers during right-bend overtaking.

Lastly, our findings suggest that the frequency of close overtaking on two-lane rural roads can also be reduced through driver education. Indeed, one can argue that drivers' susceptibility to perceive shoulders as a new field of safe travel does not result from conscious steering control but rather from implicit processing of the road environment, as evidenced by road-width manipulation studies (Lewis-Evans & Charlton, 2006; see also Coutton-Jean et al., 2009). Furthermore, drivers are known to "unconsciously" overtake cyclists when they are riding on the shoulder. This is because a clear forward lane renders unnecessary the guesswork associated with the proper lateral clearance, so they pass them with little leeway as a result (Beck et al., 2019; Parkin & Meyers, 2010; Mecheri et al., 2020). In short, providing novice drivers in driver education with explicit knowledge of increased corner cutting when negotiating right curves with shoulders is a potentially effective countermeasure.

5. Conclusion

The present study assessed whether paved shoulders on two-lane rural roads causes driving around bends to vary as a function of bend direction. The findings provided clear evidence that shoulders had a distinct effect on drivers' lateral positioning on left and right curves, whether or not oncoming vehicles were present. Providing shoulders made drivers deviate more toward the inside edge line when cutting across right but not left curves. Importantly, these effects were independent of the adjacent lane's width. Therefore, while it is well established that shoulders are associated with a significant reduction in run-off-road events on two-lane rural roads (Zegeer & Council, 1995; Ogden, 1997), their influence on steering control around curves must also be considered in deciding to install them. On one hand, providing shoulders allows vehicles to recover without having a serious crash in cases of lane departures caused by a loss of control. On the other, providing shoulders exposes drivers to an increased risk of crossing the inner lane edge, which can have detrimental effects on the safety of cyclists riding on the shoulder. Countermeasures aimed at preserving the safety benefits of shoulders for drivers, without inducing riskier driver-cyclist interactions on rural roads, must therefore be promoted.

This work should be extended to generalize its findings. The question of the interaction between the presence of a shoulder, oncoming traffic and roadside configuration needs to be clarified, as discussed earlier. The question of the effectiveness of this type of design in relation to the age and profile of the drivers can also be investigated. For example, while relatively young drivers, such as those in this study, may exhibit risk-taking when driving around a bend (Borowsky et al., 2010; Mayhew et al., 2003), older drivers compensate for their loss of motor skills by staying closer to the middle of the lane (Raw et al., 2012). In addition, it would be worthwhile to examine the drivers' steering trajectories when overtaking cyclists riding on the shoulder in right-hand bends to assess the potential adverse effects on cyclist safety. Future research should also investigate more thoroughly (e.g., using dynamic rather than static road scenes, see Ben-Bassat & Shinar, 2011) how drivers perceive shoulders during rural road bends using questionnaires. This would allow to assess whether the subjective dimension of the field of safe travel is altered by the presence or width of shoulders.

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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