Impact on driver behaviour of guardrails of different height in horizontal-vertical coordinated road scenarios with a limited available sight distance

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IMPACT ON DRIVER BEHAVIOUR OF GUARDRAILS OF DIFFERENT HEIGHT IN HORIZONTAL-VERTICAL COORDINATED ROAD SCENARIOS WITH A LIMITED AVAILABLE SIGHT DISTANCE

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ABSTRACT

Drivers consider traffic barriers (e.g., guardrails) a protection system, a hard obstacle and a sight obstruction. Hence, the possibility of using containment level barriers which are higher and superior than the minimum required by current standards should be carefully evaluated. Moreover, research investigations into their impact on driver behaviour should be designed so as to distinguish between the effects associated with each of the three roles cited above.

This driving simulation study investigates how drivers adapt their longitudinal and transversal behaviour when negotiating curves with guardrails of different heights on horizontal-vertical coordinated two-lane rural road settings, with consideration given solely to the sight obstruction effect of the guardrails. Fifty-four participants drove four out of the eighteen possible scenarios obtained when the same horizontal alignment is combined with three vertical profiles with three inner roadside treatments (no guardrails, 0.75 m two-wave and 0.95 m three-wave guardrails) and the two driving directions.

Research outcomes confirm that guardrail height has a significant impact on lateral and longitudinal behaviour. With the minimum standard, i.e., the minimum height, drivers stay closer to the roadside, while higher guardrails result in drivers increasing their lateral distance. Speeds are influenced by the interaction between the guardrail and other geometric and human factors. Male and female drivers adapt differently to the limitation in the available sight distance caused by the guardrail: males increase their speed, adopting a more aggressive behaviour than females. Important safety implications due to the higher speeds and wider trajectories have to be considered at the design stage.

Keywords: Driving simulation, guardrails, available sight distance, driver behaviour, design decision.

1. INTRODUCTION

Traffic barriers alter the driver's subjective risk perception (Wilde, 1998) acting on both the sense of protection and hazard (Michie & Bronstad, 1994). If, in the first case, drivers feel more confident in accepting more risk (i.e., higher speeds and more aggressive manoeuvres), in the second they react by limiting their exposure to the risk of collisions with fixed objects and other vehicles by reducing their speed and aggressiveness (Tay & Churchill, 2007). However, driver reaction to the presence of traffic barriers is a function of many subjective (driving style and levels of risk acceptance) and objective (road geometrics and roadside characteristics) factors.

Along motorways straights, Van Der Horst and De Ridder (2007) observed that drivers tend to move away from roadside barriers if a paved shoulder is not present on the right side of the carriageway, independently of their type or height. Ben-Bassat and Shinar (2011) researched this aspect further by evaluating the effects of the guardrail presence on divided multilane highways including sharp and shallow curves, while also taking into account the influence of the shoulder width and the roadway design. They observed that, when a guardrail marks the edge of the right shoulder, drivers increase their speed as the shoulders become wider. Furthermore, the presence of a guardrail leads to higher speeds along straights and on right-hand curves. Conversely, on leftward curves, the driver's gaze is directed inwards and away from the guardrail on the right side (Shinar *et al.*, 1977), so its presence does not modify driver behaviour. The authors confirmed that the interaction between barriers and the shoulder width affect the lateral position of vehicles in the lane: when the shoulder width reduces, drivers increase their distance from the hard-lateral obstacle.

Recently, in a driving simulation study Bella (2013) mixed design factors such as the presence/absence of shoulders together with three different roadside configurations (i.e., with and without guardrails, and guardrails covered with a red paint) in a two-lane rural highway setting that included straights and curves. Results showed that the roadside configuration did not affect the speed and lateral position of drivers, thus suggesting that behaviours were only affected by the cross-sectional characteristics of the carriageway and lateral shoulders. In the investigation by Ben-Bassat and Shinar (2011) and Bella (2013), guardrails were installed on both carriageway roadsides but only one guardrail type (and height) was considered.

Further recent contributions confirm that along curves, lateral sight obstructions located at different distances from the carriageway alter driver behaviour in terms of both speed and lateral position in the lane

(Bassani *et al.*, 2019a), and that a significant number of drivers compensate for these sight limitations by reducing speed and/or moving laterally to increase their distance from the sight obstructions (Bassani *et al.*, 2019b).

It is worth pointing out that the design of roadside characteristics and installations is subordinate to design policies which establish minimum sight distance requirements (AASHTO, 2018; MIT, 2001; Ministerio de Fomento, 2016). To exclude any negative impacts on traffic operations and safety, policies impose a minimum distance between the safety barrier and the carriageway, and compel designers to provide sight distance levels which are sufficient to guarantee safe emergency braking and, when necessary, overtaking manoeuvres. Furthermore, standards classify safety barriers of different height and robustness levels into classes based on their performance under impact, i.e., vehicle containment levels, lateral deformation, and severity of injuries of occupants (AASHTO, 2011; MIT, 2004; Ministerio de Fomento, 2009, 2014; EN 1317-1/2/4/5).

Although it is common practice to select barriers which satisfy the minimum requirements in the event of a crash, designers can, nevertheless, opt for barriers with superior performances in pursuit of increased protection. Therefore, two roads of identical road category and section type, and operating under the same traffic conditions, could be furnished with different barriers (i.e., different height, and shape), e.g. one satisfying the minimum performance requirements, the other with a higher performance. However, different barrier heights provide drivers with different available sight distances (Lioi *et al.*, 2021; Bassani *et al.*, 2019a), which in turn produce different reactions and behaviours among drivers. At present, there is no design guideline to identify the most appropriate barrier from among those meeting the minimum standard.

To overcome this shortcoming, this driving simulation study aims at evaluating the behavioural effects of guardrails with different heights when they act as a sight obstruction, thus avoiding any behavioural effects in cases where guardrails are perceived as a hard and hazardous obstacle in potential run-off-road situations. As a consequence, in the horizontal-vertical coordinated road scenarios of this experiment guardrails were located on the inside of curves. Vehicle speed and lateral position data were recorded along eighteen road scenarios obtained by combining the same horizontal alignment with (i) three different vertical profiles, (ii) three different inner roadside treatments (without guardrails, with a double one, and with a triple wave guardrail), and (iii) the two directions of travel. The fifty-four drivers involved in the experiment drove in four scenarios which were randomly assigned from the eighteen available.

2. METHODOLOGY

2.1 Experimental design

The inner roadside treatment included: (i) no guardrail (NG) as the baseline condition, (ii) a double wave 0.75 m high (G1), and (iii) a triple wave 0.95 m high (G2). According to EN 1317-2 (2010), the double wave guardrail is an N2 containment level and a W6 working width class (N2W6), while the triple wave guardrail is a H2W5 class. The three different roadside configurations are synthetized in Figure 1. In line with the aims of this study, guardrails were always located on the inner side of both rightward (RW) and leftward (LW) curves to act as a sight obstruction.

Vertical alignments included horizontal grades (G) as the baseline, but also crest (C) and sag (S) curves. Finally, the two travel directions from shallow to sharp horizontal curves (D = direct direction) and from sharp to shallow (R = reverse direction) were also considered. The eighteen road scenarios were created by varying the three independent factors listed in Table 1.

The investigated dependent variables depicting the longitudinal and transversal behaviour of participants include (i) the average speed (*S*), and (ii) the average lateral position in the lane (*LP*) as the distance between the vehicle centre of gravity (CoG) and the lane centreline. Rosey and Auberlet (2012) remarked that in driving simulation studies both speed and lateral position in the lane should be carefully evaluated to understand the effects of roadside features.

Table 1. Factors of the experimental design.

Experimental factors	**Levels**		
	0 (Baseline)	**1**	**2**
Inner Roadside Treatment (IRT)	NG	G1	G2
Vertical Element Type (VET)	G	C	S
Travel Direction (TD)	-	D	R

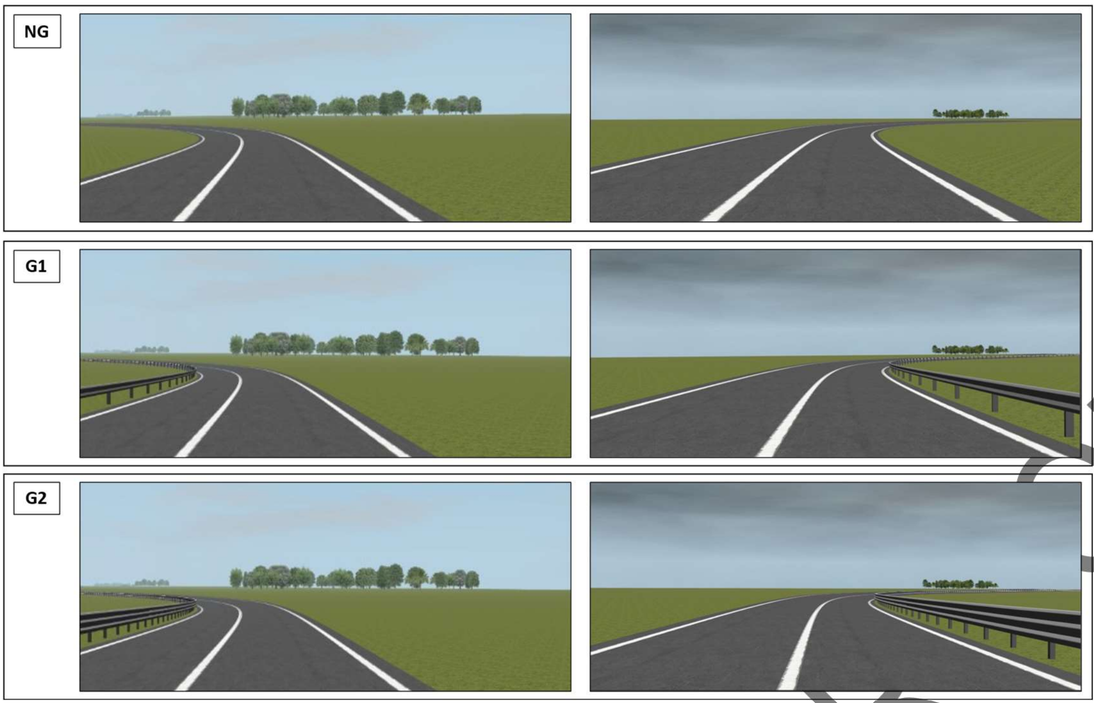

Figure 1. Driver perspective in the three inner roadside treatments for leftward and rightward curves.

2.2 Road scenarios

A 4.125 km long, two-lane rural highway, with lane and shoulder width values of 3.5 and 0.5 m respectively, was designed according to Spanish standards (Ministerio de Fomento, 2016) and then modelled (Figure 2 and Figure 3). The horizontal alignment considered two main segments: in the first, curves with shallow radii ranging from 250 to 700 m were adopted; in the second, sharper curves ranging from 50 to 350 m. A 400 m long, straight section was used to link these two main segments; two tangents were also included at the beginning and at the end of the track where drivers started and stopped the vehicle. Spiral transitions between straights and curves, and reverse spirals between curves with opposite directions were designed as depicted in the curvature diagram in Figure 3. No posted speed limit was provided, so participants were free to adopt their desired speed. A vertical signal indicating a series of sharp curves in the central straight, before entering the sharp curve segment in the direct (D) direction warned the participants of the subsequent significant change in alignment curvature.

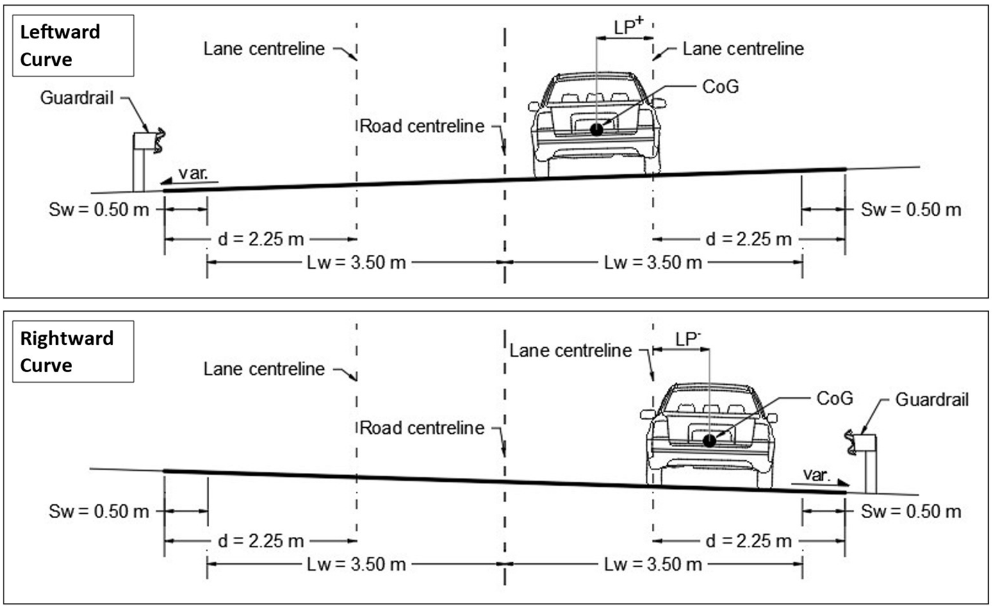

Figure 2. Cross-sections for leftward and rightward curves. (Notes: Lw = Lane width; Sw = Shoulder width; d = distance from the lane centreline to the guardrail; h = guardrail height; CoG = vehicle centre of gravity; LP = lateral position; "var." = variable transversal slope in the curve).

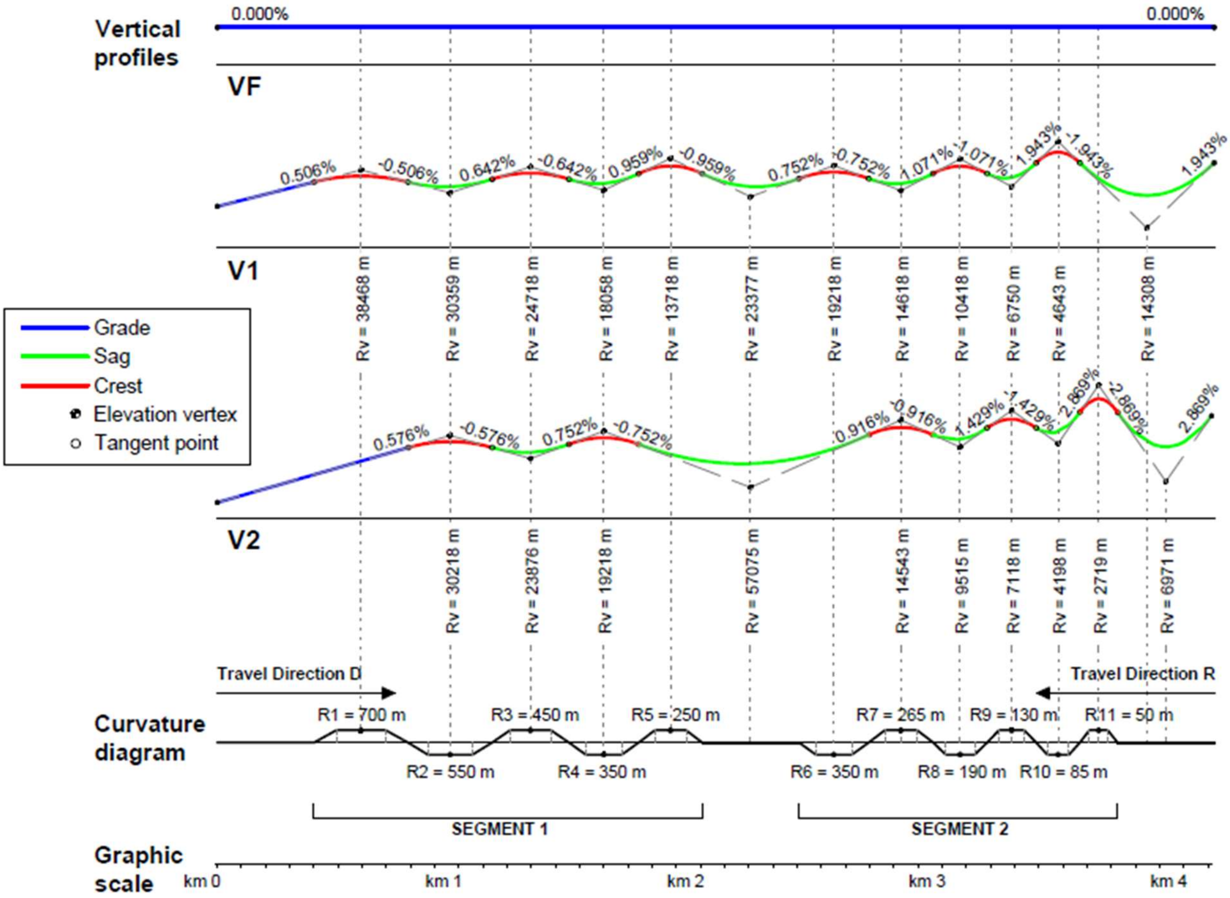

Figure 3. Horizontal and vertical alignments of road scenarios.

Three vertical alignments (Figure 3) were adopted to assess driver response to different vertical element types (i.e., grade, crest, and sag): a flat alignment (VF), and two wavy profiles, the first (V1) with a sequence of crest – sag – crest, and the second (V2) with an opposite design sag – crest – sag. Figure 3 provides radii and lengths of horizontal and vertical curves, which were aligned with each other in accordance with geometric design policies (AASHTO, 2018; MIT, 2001; Ministerio de Fomento, 2016).

Guardrails G1 and G2 were included in road scenarios as 3D elements to offer the best visual fidelity to drivers. The 3D guardrail modelling is described in Lioi *et al.* (2021), where a sight analysis was carried out on the same guardrail types to evaluate the available sight distance (ASD) for the stopping manoeuvre with a proprietary GIS algorithm (Castro *et al.*, 2017).

In the analysis, the driver point of view was set at 1.1 m and the target at 0.5 m above the pavement; both were centred, approximately, in the travelled lane (1.5 m from the left lane border). The GIS algorithm was set to evaluate ASD to a maximum of 500 m, so any higher values were indicated as equal to 500 m (Table 2). In line with expectations, the results listed in Table 2 indicate that G2 generally provides lower visibility levels than G1. In some cases, the difference in ASD reaches relevant values, e.g. in curve n.2, V1 profile, and R direction it was 135 m (= 345 – 210).

Table 2. Minimum available sight distance values (in m) along the eleven horizontal curves influenced by Vertical Profile (VF, V1, V2), Vertical Element Type (G, S, C), Travel Direction (D, R), and Inner Roadside Treatment (NG, G1, G2).

Segment no.			**1**					**2**					
Curve no.			**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
VF	Vertical Element Type		G	G	G	G	G	G	G	G	G	G	G
	D direction	NG	500	500	500	500	500	500	500	500	500	500	500
		G1	190	190	135	140	95	150	105	105	70	65	40
		G2	120	110	95	85	70	90	75	60	50	40	30
	R direction	NG	500	500	500	500	500	500	500	500	500	500	500
		G1	260	155	210	120	115	115	160	90	110	55	70
		G2	210	105	125	85	100	85	100	60	75	40	55
V1	Vertical Element Type		C	S	C	S	C	C	S	C	S	C	S
	D direction	NG	500	500	500	500	500	500	500	420	225	215	500
		G1	155	140	120	105	90	215	125	160	85	65	45
		G2	120	110	95	85	70	95	75	65	60	40	30
	R direction	NG	500	500	500	500	500	500	500	500	500	500	180
		G1	225	345	180	285	135	500	190	270	135	205	70
		G2	195	210	155	165	112	500	150	235	105	180	55
V2	Vertical Element Type		G	C	S	C	S	S	C	S	C	S	C
	D direction	NG	500	500	395	410	500	500	500	500	500	500	500
		G1	255	200	225	160	500	190	220	155	170	110	400
		G2	185	175	150	135	500	155	190	125	145	85	400
	R direction	NG	500	500	500	500	385	500	345	355	500	305	500
		G1	405	135	165	105	130	120	215	105	190	70	150
		G2	400	85	145	125	190	155	500	135	150	175	185

2.3 Participants

The study was conducted in accordance with the Code of Ethics of the World Medical Association (2018). Based on the decision to have each participant complete 4 driving tasks, a total of 54 drivers were required in order to get 12 replications for each of the 18 scenarios (4 × 54 = 12 × 18). Drivers were randomly selected from a database of more than 500 volunteers to form a stratified sample in three age groups including class I (≤ 25 years), class II (between 26 and 44), and class III (≥ 45). The number of drivers in each age group was determined in line with the age distribution of the Italian population of licenced drivers (www.mit.gov.it/comunicazione/news/patenti-dataset-online). A synthesis of participant characteristics (age, driving experience and crash history) is given in Table 3.

Table 3. Descriptive statistics (mean and standard deviation between brackets) of participants' characteristics. (Notes. Crash history = includes all road accidents involving the participant even property damage only crashes)

Age class (years)	Gender	Age	Number of drivers	Driving experience (years)	Driving experience (km/years)	Crash history
I	M	20.7 (2.1)	3	1.0 (0.0)	5667 (4041)	0.3 (0.6)
(≤ 25)	F	21.0 (1.4)	2	2.0 (1.4)	4000 (1414)	0.0 (0.0)
II	M	32.3 (7.1)	12	14.3 (7.4)	12292 (11833)	0.5 (0.7)
(> 26, < 44)	F	33.2 (5.2)	11	15.0 (5.4)	8280 (7444)	0.6 (0.8)
III	M	52.1 (8.0)	14	32.9 (8.2)	20769 (10001)	2.0 (1.7)
(≥ 45)	F	52.9 (3.5)	12	33.1 (3.8)	8200 (8349)	1.8 (2.8)
All	-	41.1 (12.9)	54	22.3 (12.5)	12069 (10504)	1.2 (1.8)

2.4 Equipment

The experiment was carried out at the Road Safety and Driving Simulation (RSDS) Laboratory of Politecnico di Torino. A fixed-base driving simulator manufactured by AV Simulation (France) was used to build road scenarios, perform tests, and collect data using SCANeR Studio® software (Figure 4). This simulation software includes a module on vehicle dynamics, which allows the driver to perceive vehicle movements and rotations that are very realistic. According to Milleville-Pennel (2008) the simulated vehicle rotation helps the driver to negotiate curves, and to slow down when the subjective perceived risk is high.

The simulator was equipped with a vision system made up of three 32-inch full HD monitors with a 130° field of vision, a steering wheel that returns active force feedback to simulate the rolling motion of wheels, the pavement roughness, and any shocks absorbed. The hardware also included a manual gearbox, three pedals (including a clutch), and an instrument panel. Vibration pads simulated vehicle vibrations on the seat and pedals. A sound system reproduced the sounds of the engine and surrounding environment. Prior to the test, this simulator was subjected to behavioural validation for longitudinal (Bassani *et al.*, 2018; Catani, 2019), transversal (Catani & Bassani, 2019), and passing (Karimi *et al.*, 2020) behaviours. According to Törnros (1998), behavioural relative validation is sufficient to bring the phenomena observed in the simulation back to reality.

Figure 4. Fixed-base driving simulator of the experiment (Road Safety and Driving Simulation Laboratory, Politecnico di Torino).

2.5 Protocol

Each participant faced the 50-minute, three-step protocol shown in Figure 5, with a pre- and a post-simulation phase. The protocol included: (i) a pre-drive questionnaire; (ii) a pre-drive cognitive test (visual and auditory); (iii) the driving simulation session; (iv) a post-drive cognitive test; and finally (v) a post-drive questionnaire. The pre-drive questionnaire was designed to assess the health conditions of participants. With the pre- and post-cognitive tests, the reaction times of the participants to visual and auditory stimuli were measured using an online tool (www.cognitivefun.net) to detect any changes in cognitive performances during the driving session. A pre-drive session on a different circuit was also included to enable drivers to become familiar with the simulator (C-TEST phase, Figure 5). In the simulation session, four different circuits (D1, D2, D3, and D4) were dispensed (Figure 5) and participants were asked to drive as they do in real driving. Some rest periods were included to change scenarios. The post-drive questionnaire was used to gather information on the experience of participants in the simulation.

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During the experiment, no test driver experienced debilitating discomforts to a degree which would have invalidated the experiment. The responses indicated that only some individuals exhibited slight symptoms, mostly related to visual fatigue (almost 35%), headaches (around 15%), and general fatigue (around 30%). The accuracy of the scenario was judged as being generally good. In an effort to exclude secondary effects on participants' response only a few vehicles in the opposite direction (along tangents only) were included, and speed limit signs were omitted.

Cognitive test results were evaluated through the Kolmogorov-Smirnov (KS) test for normality, and they were found to be normally distributed. Visual reaction times were longer than auditive ones (before: $t_{53} = 18.56$, $p < .001$; after: $t_{53} = 21.43$, $p < .001$), due to the different brain processes used to elaborate the signals, with the process being longer in the case of visual stimuli (Kemp, 1973). These results confirm previous observations by Thompson *et al.* (1992) and Pain and Hibbs (2007) with no significant variation in visual ($t_{53} = -0.41$, $p = .684$) and auditory ($t_{53} = 0.16$, $p = .870$) reaction times before and after the test. As a result, the experimental protocol adopted did not alter the auditory or the visual performances of participants.

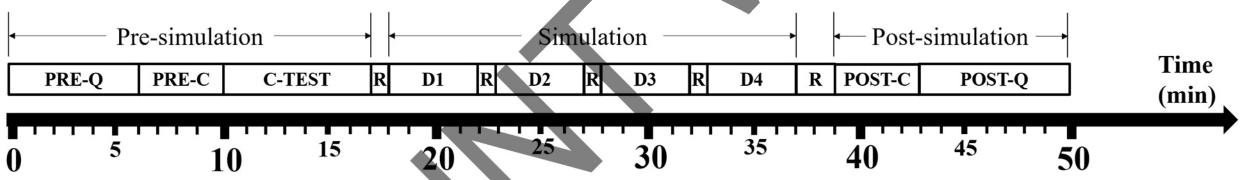


Figure 5. Experimental protocol dispensed to participants consisting of the following stages: pre-drive questionnaire (PRE-Q), pre-cognitive tests (PRE-C), test circuit (C-TEST), driving on the experimental scenarios (D1, D2, D3, D4), rest time (R), post-cognitive tests (POST-C), post-drive questionnaire (POST-Q).

2.6 Data analysis

Speed (*S*) and lateral position data (*LP*) for each test driver were collected with a frequency of 10 Hz. Data were first analysed by conducting the KS normality test every 100 m along the track. In all the investigated scenarios, values of speed and lateral position at each station were found to be normally distributed. Afterwards, the average *S* and *LP* of the twenty values extracted at equally spaced stations along the circular arc of horizontal curves were calculated for each driver. As a result, a database of 2376 rows (= 11 curves × 18 circuits × 12 drives) was obtained for both *S* and *LP*.

The linear mixed-effect model (LMM) fit by restricted maximum likelihood estimates (REML) was chosen to analyse the influence of the experimental factors on the behavioural response of drivers. LMMs are appropriate for experiments with repeated measurements (West *et al.*, 2014), use both categorical and continuous variables, and consider random effects that cannot be controlled in the experiment. Furthermore, Type I error probability is low (Jashami *et al.*, 2019). In the model equation:

$$y = X \cdot b + Z \cdot u + e \tag{1}$$

y are the observations of the measured dependent variable (i.e., speed and lateral position), *b* is the vector of unknown coefficients of fixed effects, *u* is the vector of the unknown coefficients associated with the random effects (normally distributed, with zero mean), *X* and *Z* represent the vectors for the independent variables, continuous covariates and/or categorical factors for fixed and random effects respectively, and finally *e* is the normally distributed with zero mean error term (i.e., the residuals).

The LMM was calibrated by using *Jamovi* for Windows (The Jamovi Project, 2021). All categorical variables and covariates were initially included, but statistically insignificant variables and relative interactions were removed one at a time according to the backward elimination technique minimizing the Bayesian Information Criterion (BIC). The BIC was monitored at each step: the lower the BIC, the more powerful the model performance. Post-hoc tests with Holm correction were performed when statistically significant effects were found. In the analysis, the significance level was always set at 5%.

3. RESULTS

3.1 Descriptive statistics

Table 4 provides the descriptive statistics (mean and the standard deviation) of data split up into the subsamples obtained for the three inner roadside treatments, the three vertical element types, and the two travel directions. Negative *LP* values indicate that the CoG was on the right side of the lane centreline, while positive *LP* values indicate that it was on the left side.

Higher speed values were measured along grades with G1, along crests with G2, and along sags with NG. Speeds in the direct direction were higher than in the reverse one, except once again for G2. Regarding lateral position, drivers stay more to the left with the triple wave guardrail (G2) than they do with the other inner roadside treatments.

Table 4. Mean (and standard deviation) of speed (*S*) and lateral position (*LP*).
(Notes. Inner Roadside Treatment: NG = no guardrail, G1 = double wave guardrail, G2 = triple wave guardrail; Vertical Element Type: G = grade, C = crest, S = sag; Horizontal Curve Direction: RW = rightward, LW = leftward).

Inner Roadside Treatment (IRT)	Vertical Element Type (VET)	Travel Direction (TD)	*S* [km/h]	*LP* [m]
NG	G	D	80.8 (15.1)	-0.149 (0.416)
		R	77.0 (17.9)	-0.102 (0.400)
	C	D	74.7 (16.6)	-0.130 (0.476)
		R	67.8 (16.9)	-0.175 (0.584)
	S	D	81.5 (17.0)	-0.148 (0.436)
		R	77.9 (17.1)	-0.091 (0.463)
G1	G	D	89.3 (22.8)	0.072 (0.397)
		R	75.0 (17.9)	-0.131 (0.404)
	C	D	82.9 (12.1)	-0.154 (0.347)
		R	82.0 (13.4)	0.031 (0.310)
	S	D	74.9 (14.1)	-0.066 (0.399)
		R	62.8 (14.5)	-0.048 (0.452)
G2	G	D	78.7 (14.4)	-0.033 (0.369)
		R	73.0 (18.2)	0.049 (0.406)
	C	D	84.3 (17.4)	-0.040 (0.306)
		R	87.8 (17.0)	0.071 (0.329)
	S	D	74.7 (15.2)	-0.064 (0.338)
		R	67.5 (15.2)	0.007 (0.438)

3.2 Model outcomes

Table 5 summarizes the LMM outputs for the two dependent variables investigated. The Inner Roadside Treatment (NG - baseline, G1, G2), the Vertical Element Type (G, C, S), the Travel Direction (D, R), the Horizontal Curve Direction (RW, LW), and the gender of participants (M = males, F = females) were assumed as factors in the LMM. The Horizontal Curve Radius and the Vertical Curvature (i.e., the inverse of the vertical radius), age, driving experience and crash history were assumed as continuous variables and included in LMM as covariates. Finally, the Participant ID was included as a cluster variable. As mentioned above, insignificant factors and interactions were excluded from the model through the minimization of BIC. Covariates such as age, driving experience in years, and crash history were not statistically significant, so they were excluded in the step-by-step process.

Table 5. Significant factors and covariates, and summary statistics of LMM for speed (*S*) and lateral position (*LP*). (Notes: * for p < .05, ** for p < .01, and * for p < .001, symbol "-" means not statistically significant).**

Variables	Effect	Estimate (significance)	
		S [km/h]	*LP* [m]
Fixed Effects			
(significant main factors and interactions)			
Intercept		76.498 (***)	-0.060 (**)
Inner Roadside Treatment (IRT)	G1 – NG	-	0.089 (***)
	G2 – NG	-	0.140 (***)
Vertical Element Type (VET)	C – G	2.601 (***)	-
	S – G	2.521 (***)	-
Travel Direction (TD)	R – D	-6.057 (***)	-
Horizontal Curve Direction (HCD)	LW – RW	-	0.432 (***)
Test Driver Gender (TDG)	F – M	-9.914 (**)	-
Horizontal Curve Radius		0.035 (***)	-
Vertical Curvature		$-4.906 \cdot 10^{-5}$ (***)	-
IRT * VET	(G1 – NG) * (C – G)	-4.592 (**)	-
	(G1 – NG) * (S – G)	-6.791 (***)	-
	(G2 – NG) * (S – G)	-3.378 (*)	-
IRT * TD	(G1 – NG) * (R – D)	2.632 (*)	-
	(G2 – NG) * (R – D)	-	0.118 (***)
IRT * HCD	(G1 – NG) * (LW – RW)	-	-0.230 (***)
	(G2 – NG) * (LW – RW)	-	-0.317 (***)
IRT * TDG	(G2 – NG) * (F – M)	-2.983 (**)	-0.105 (**)
(other significant interactions)			
VET * HCD	(C – G) * (LW – RW)	-3.001 (**)	-
	(S – G) * (LW – RW)	-3.011 (**)	-
TD * VET	(R – D) * (C – G)	3.606 (**)	-
	(R – D) * (S – G)	-2.528 (*)	-
TD * HCD	(R – D) * (LW – RW)	-5.141 (***)	-
TD * TDG	(R – D) * (F – M)	2.022 (*)	-
HCD * TDG	(LW – RW) * (F – M)	-	-0.224 (***)
Random effects			
Participant ID		(***)	(***)
Summary statistics			
AIC		17729.0	1329.5
BIC		17852.7	1502.0
Marginal R^2		.379	.378
Conditional R^2		.718	.514
ICC for random components		.545	.218
Observations		2376	
Drivers		54	
Observations/driver		44	
KS test on residual (p-value)		.092	.030

In Table 5, the proportion of variance explained by the fixed factors alone (marginal R^2) and the proportion of variance explained by both fixed and random effects together (conditional R^2) are reported. In the LMM for speed, 72% of the variance in the data was explained by the model, half of which was due to fixed effects. In the LMM for lateral position, 51% of the variance was explained by the model, approximately 70% of which attributable to fixed factors. This result evidences the high impact of subjectivity on the data. Referring to the random effects of these two models, the intraclass correlation coefficients (ICC) for speed (.545) and lateral position (.218) were greater than the cut-off value of .1, thus indicating that individuals in the group resemble each other (Barlow *et al.*, 2019). Although *LP* residuals did not pass the normality test ($p = .03$), according to Schielzeth *et al.* (2020) this violation is not critical for LMMs when the calibration is carried out on a large sample size ($N = 2376$). According to the central limit theorem, the non-normality of residuals does not adversely affect the inferential procedures.

3.3 Longitudinal behaviour

Among the independent factors affecting longitudinal behaviour, the LMM indicates that the Inner Roadside Treatment (IRT) did not affect speed (Table 5). Speed values (*S*) under the influence of G1 ($M_{G1} = 77.0$ km/h, $SE_{G1} = 1.50$ km/h) were only slightly higher than those with the other two treatments ($M_{NG} = 76.4$ km/h, $SE_{NG} = 1.46$ km/h; $M_{G2} = 76.1$ km/h, $SE_{G2} = 1.50$ km/h).

The Travel Direction (TD) proved to be statistically significant ($p < .001$). Drivers adopted lower Speed values in the reverse direction ($M_R = 73.5$ km/h, $SE_R = 1.47$ km/h) than in the direct one ($M_D = 79.5$ km/h, $SE_D = 1.47$ km/h), since they first had to negotiate sharp curves with a lower ASD (Table 2) and, thus, required greater longitudinal control. As expected, *S* values were higher in the direct direction, where drivers initially negotiated shallow curves with higher ASD values. Furthermore, the Horizontal Curve Direction (HCD) did not impact on speed as a single factor ($p = .160$), but only in combination with the TD ($p < .001$) and the Vertical Element Type ($p = .001$).

S values were also influenced by the Vertical Element Type (VET). The estimated marginal means revealed that speeds were higher along both crests ($M_C = 77.4$ km/h, $SE_C = 1.50$ km/h) and sags ($M_S = 77.3$ km/h, $SE_S = 1.49$ km/h) compared to the baseline, i.e., the grades ($M_G = 74.8$ km/h, $SE_G = 1.49$ km/h). The statistical significance of these results is confirmed by the estimated LMM coefficients reported in Table 5 for a comparison between crests and grades ($p < .001$) and between sags and grades ($p < .001$). A post-hoc test revealed no statistical differences in longitudinal behaviour between crests and sags ($S_C - S_S = 0.1$ km/h, $t_{2294} = 0.128$, $p_{Holm} = .898$).

It is worth noting that LMMs consider the random effects associated with the participant ID separately and these were deemed to be highly statistically significant in the speed model ($p < .001$). Therefore, the LMM outcomes attributable to fixed effects (i.e., all categorical factors and continuous covariates) were purged of any participant subjectivity.

The LMM analysis synthetized in Table 5 revealed other important results. The Test Driver Gender (TDG) was found to be statistically significant, with males driving at higher speeds than females ($p = .001$). The covariates in the LMM, i.e., the Horizontal Curve Radius ($p < .001$) and the Vertical Curvature ($p < .001$) were both significant. It is well known that in real driving conditions when the horizontal curve radius decreases, drivers increase the steering wheel angle, at which point they perceive an uncomfortable lateral acceleration, so they react by reducing their speed to more comfortable levels (Van Winsum and Godthelp, 1996). Furthermore, the lower the radius, the lower the ASD from the driver point of view (Table 2); when the ASD falls below a subjective threshold, the driver slows down so as to reduce the distance necessary to stop the vehicle in the case of an emergency (Bassani *et al.*, 2019b). In this experiment, S also decreased along vertical elements with higher curvature (i.e., lower vertical radii) for the same two reasons indicated above.

The LMM model exhibited several significant two-way interactions, three of which included the Inner Roadside Treatment (IRT), the main experimental factor. The interaction between the IRT and the Travel Direction (TD) is shown in Figure 6a. Post-hoc test results confirm that when approaching shallow curves at the beginning of the track (direct direction, D), no significant differences in speed were evident between the three IRTs. Conversely, a slight IRT effect was detected in the reverse direction when drivers started by negotiating sharper curves. In this case, post-hoc tests indicate that the differences in speed between NG and G1 ($S_{NG,R} - S_{G1,R}$ = -1.9 km/h, t_{2306} = -2.48, p_{Holm} = .066) and between G1 and G2 guardrails ($S_{G1,R} - S_{G2,R}$ = 2.5 km/h, t_{2306} = 2.65, p_{Holm} = .048) were moderately relevant. These can be explained by the higher significance of the travel direction and the more attentive behaviour of drivers when they first negotiated curves with lower radius and ASD values.

The interaction between IRT and the Test Driver Gender (TDG) is evidenced in Figure 6b. It confirms that higher speeds were adopted by males, while the roadside configuration only influenced female drivers. Their S was moderately lower in the presence of the G2 guardrail than with the G1 ($S_{G1,F} - S_{G2,F}$ = 2.4 km/h, t_{2301} = 2.59, p_{Holm} = .058). Conversely, male drivers exhibited speed values with no significant differences between all the various roadside treatments. Considering males and females separately, a post-hoc test revealed a significant effect on S with the G2 guardrail ($S_{G2,M} - S_{G2,F}$ = 11.8 km/h, $t_{59.5}$ = 3.98, p_{Holm} = .003).

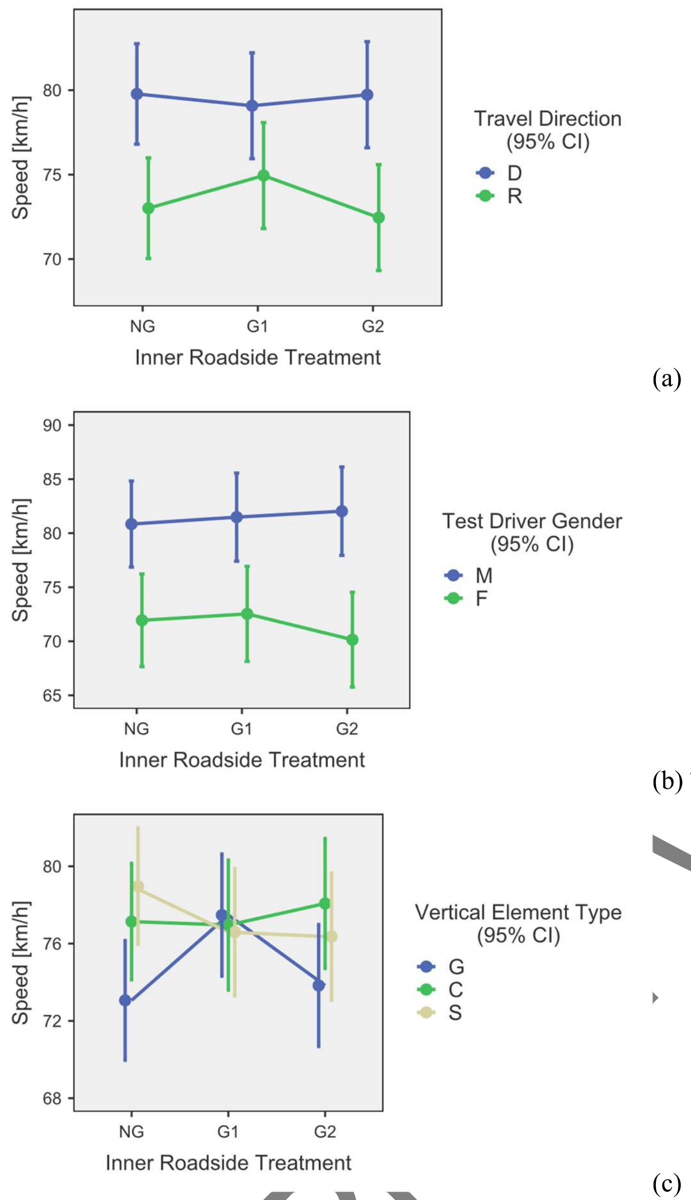


Figure 6. Interaction between inner roadside treatment and (a) travel direction, (b) gender of test drivers, and (c) vertical element type for speeds.
(Notes. Inner Roadside Treatment: NG = no guardrail, G1 = double wave guardrail, G2 = triple wave guardrail; Travel Direction: D = direct direction, R = reverse direction; Test Driver Gender: M = males, F = females; Vertical Element Type: G = grade, C = crest, S = sag).

Since the Vertical Element Type (VET) has a significant impact on ASD (Table 2), different S values were observed for the same VET with different IRT as depicted in Figure 6c. A post-hoc test revealed that significant differences were only recorded along grades between NG and G1 ($S_{NG,G} - S_{G1,G}$ = -4.4 km/h, t_{2314} = -4.95, $p_{Holm} < .001$) and G1 and G2 ($S_{G1,G} - S_{G2,G}$ = 3.6 km/h, t_{2315} = 3.88, p_{Holm} = .003). The model outcomes also indicate that a statistically significant difference was evident for the G2 guardrail between grades and crests ($S_{G2,G} - S_{G2,C}$ = -4.2 km/h, t_{2303} = -3.69, p_{Holm} = .007).

The other significant interactions between experimental factors explain the influence of road geometrics in horizontal-vertical coordinated road settings. These outcomes are not commented on here because they are not relevant to the aims of the study.

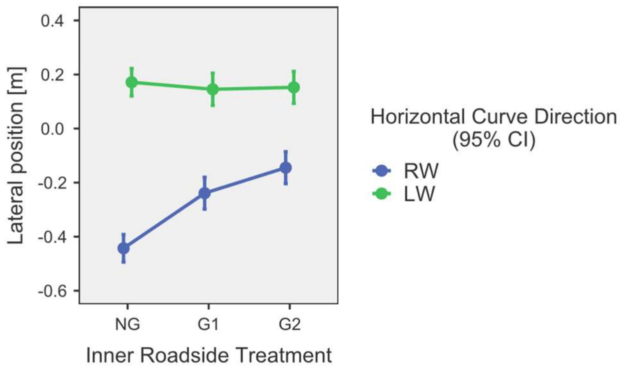
3.4 Transversal behaviour

In contrast to the case with speed, the impact of Inner Roadside Treatment (IRT) on the Lateral Position (*LP*) is significant. The positive estimated model coefficients in Table 5 indicate that in response to the presence of the two guardrails, drivers moved laterally away from the roadside. In particular, a CoG closer to the lane centreline was observed in the presence of the G2 guardrail (M_{G2} = 0.004 m, SE_{G2} = 0.026 m), while drivers maintained a position slightly closer to the right lane edge without a guardrail (M_{NG} = -0.136 m, SE_{NG} = 0.024 m) and in the presence of the G1 guardrail (M_{G1} = -0.047 m, SE_{G1} = 0.026 m). A post-hoc test with Holm correction showed that the higher guardrail (G2) resulted in vehicle positions closer to the centre of lane ($LP_{G1} - LP_{G2}$ = -0.051 m, t_{2337} = -2.54, p_{Holm} = .011).

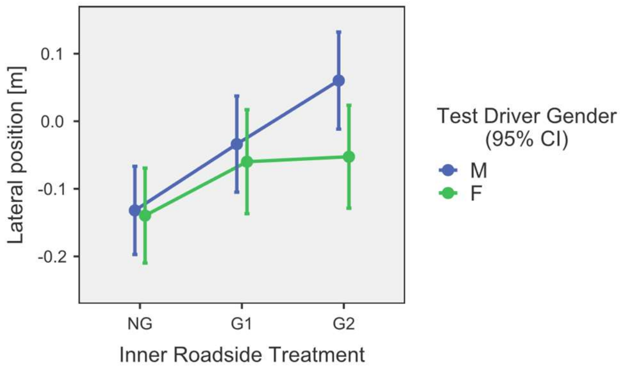
In this study (Table 5), the Horizontal Curve Direction (HCD) was also deemed to be extremely significant ($p < .001$). Participants maintained the vehicle CoG on the left side of the lane centreline in leftward curves (M_{LW} = 0.163 m, SE_{LW} = 0.025 m) and on the right side in rightward ones (M_{RW} = -0.276 m, SE_{RW} = 0.025 m) as confirmed by the estimated marginal means analysis.

As was also the case for longitudinal behaviour, random effects associated with the Participant ID had a significant impact on *LP* model outputs ($p < .001$), which means that results were heavily affected by subjective driving habits and styles. This result confirms the need to separate the subjective component from the objective influence of factors in the interpretation of experimental data.

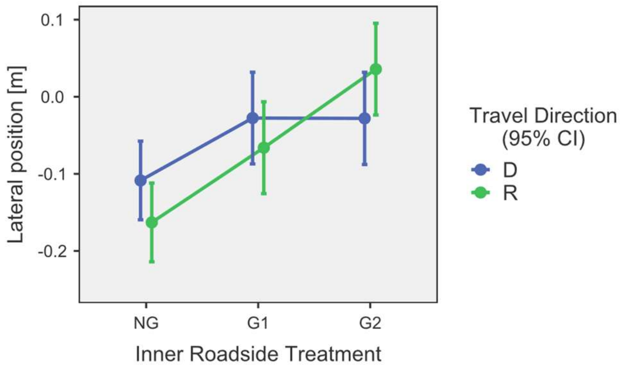
Three interactions involving the IRT were also found to be statistically relevant in the LMM on Lateral Positions (Table 5). The first is with the HCD, which is shown in Figure 7a. In right-hand curves, drivers moved toward the left side when the inner roadside was treated with a G1 guardrail ($LP_{RW,NG} - LP_{RW,G1}$ = -0.204 m, t_{2335} = -8.60, $p_{Holm} < .001$) or with a G2 guardrail ($LP_{RW,NG} - LP_{RW,G2}$ = -0.298 m, t_{2335} = -12.54, $p_{Holm} < .001$) with respect to inner roadsides without guardrails (NG). In the same right-hand curves, the higher the guardrail, the further left the position of the CoG in the lane ($LP_{RW,G1} - LP_{RW,G2}$ = -0.094 m, t_{2328} = -3.39, p_{Holm} = .003). Conversely, in left-hand curves the inner roadside treatment did not prove to be statistically significant. This outcome is due to the greater distance of the vehicle from the barrier which significantly increased the available sight distance (ASD).



(a)



(b)



(c)

Figure 7. Interaction between inner roadside treatment and (a) horizontal curve direction, (b) test driver gender, and (c) travel direction for lateral positions.
(Notes. Inner Roadside Treatment: NG = no guardrail, G1 = double wave guardrail, G2 = triple wave guardrail; Horizontal Curve Direction: RW = rightward, LW = leftward; Test Driver Gender: M = males, F = females; Travel Direction: D = direct, R = reverse. Positive *LP* values indicate that the CoG was on the left side of the lane centreline, while negative *LP* on the right side).

The Test Driver Gender (TDG) interacted with the IRT to affect the driver transversal behaviour as clearly depicted in Figure 7b. Post-hoc test results show a statistically significant difference between male drivers interacting with G1 ($LP_{M,NG} - LP_{M,G1}$ = -0.098 m, $t_{2334.4}$ = -4.34, $p_{Holm} < .001$) and G2 roadside treatments ($LP_{M,NG} - LP_{M,G2}$ = -0.192 m, $t_{2333.4}$ = -8.29, $p_{Holm} < .001$), and when they interact with the NG (baseline) condition. Moreover, a significant shift to the left of the *LP* was maintained with G2 with respect to G1 guardrail ($LP_{M,G1} - LP_{M,G2}$ = -0.094 m, $t_{2339.7}$ = -3.42, p_{Holm} = .007). Figure 7b also highlights that females react similarly to guardrails of different heights and shapes, adopting a lane position closer to the lane centreline with respect to the baseline condition (NG).

Finally, IRT also interacted with the Travel Direction (TD) as shown in Figure 7c. In the direct direction, drivers behave differently under the influence of G1 ($LP_{NG,D} - LP_{G1,D}$ = -0.081 m, t_{2341} = -3.37, p_{Holm} = .007) and G2 ($LP_{NG,D} - LP_{G2,D}$ = -0.081 m, t_{2348} = -3.31, p_{Holm} =.007) with respect to NG (baseline) condition. When drivers encountered the sharp curve segment before the shallow curves (i.e., reverse direction), the differences between the *LP* recorded under the influence of the three inner roadside treatments were even more accentuated. With respect to the baseline condition, both types of guardrails resulted in the trajectory being significantly closer to the road centreline. In particular, the highest one, i.e., the G2 ensured an *LP* which was further from the roadside than the G1 ($LP_{G1,R} - LP_{G2,R}$ = -0.102 m, t_{2352} = -3.50, p_{Holm} = .005).

4. DISCUSSION

This study aimed at investigating the effects on driver behaviour of guardrails of different heights along two-lane rural highways. To avoid any behavioural effects due to the perceived subjective risk of the vehicle leaving the road, guardrails were located along the inner roadsides of curves to differentiate between the sight conditions experienced by participants.

Evidence from literature indicates that the higher the barrier, the lower the available sight distance (Lioi *et al.*, 2021). Furthermore, with an ASD restricted by the presence of sight obstructions along the roadside, most drivers react by adapting their longitudinal and transversal behaviour in order to reduce the stopping distance and/or increase the ASD. This change in behaviour is intended to reduce the perceived risk due to unknown road conditions along that part of the curve which is not visible to the driver (Bassani *et al.*, 2019b).

In this study, outcomes from data modelling confirmed that in horizontal-vertical coordinated road scenarios designed by varying horizontal and vertical characteristics, the presence/absence of the guardrail as well as its height did not directly affect longitudinal driver behaviour in their own right, but rather in combination with other experimental factors, i.e., the vertical element type, the travel direction, and the driver gender. Results are consistent with those from Ben-Bassat and Shinar (2011), who stated that drivers are affected by the presence of a guardrail along the roadside in combination with the shoulder width. Despite the different experimental design and scenario settings, this study provides different outcomes with respect to Bella (2013), who affirmed that driver longitudinal behaviour is only influenced by the cross-sectional characteristics of the paved section (carriageway and shoulders) rather than the roadside conditions. Of course, differences can be attributed to the factors considered in the experimental design, so the outputs of this study should be viewed as an extension of those from Bella (2013).

This study evidences that the inner roadside treatment interacted with the vertical element type to affect speed. It is worth noting that along horizontal and vertical curves, both the radius and guardrail height affect the ASD, as quantitatively evidenced by Table 2. However, the benefits of a greater ASD do not explain why speeds were found to be higher with the guardrail than without. In curves along grades, speeds are higher with the double wave guardrail than without, while with triple wave guardrails the speeds were higher along crests rather than along grades. These results can be explained by considering that in the road scenarios investigated, the guardrail marked the road geometry, thus helping drivers to anticipate the future road alignment. The visual guidance provided by the guardrails was also possible thanks to the absence of other sight obstructions along the inner roadside like vegetation, escarpments, fences, buildings all of which can be found in real road scenarios. Experimental results indicate that, without guardrails, speeds are higher along sags: a finding explained by the longer ASD (Table 2) in scenarios where drivers do not need any visual guidance to maintain their preferred speed. Furthermore, along horizontal curved crests speeds were higher with higher and more visible triple wave guardrails, which provided the necessary visual guidance in this scenario with a low ASD value. Finally, along horizontal curved grades, drivers were better visually guided by double wave guardrails that provide ASD values which are superior to those provided by triple wave ones (Table 2).

In the horizontal-vertical coordinated road scenarios investigated here, other factors affected longitudinal behaviour. The fact that the travel direction proved to be statistically significant in the model implies that drivers adjusted their behaviour on the basis of their past experience along the road. If drivers first negotiate sharper curves, the speed along a successive shallow one is significantly lower than the speed that drivers will adopt if they first drive along shallow curves only. This means that drivers had memorized the recent driving experience, which they then used to negotiate the successive road segments. The role that the memory of previous driving experience plays and which is evident here is consistent with findings by Cafiso and Cerni (2012), who developed a continuous speed model to predict longitudinal behaviour along two-lane rural highways taking the memory effect into account. In interaction with the inner roadside treatment, the reverse direction confirmed higher speeds with the double wave guardrail. There were no effects detected for the direct direction due to the inner roadside treatment.

Finally, males drove at higher speeds than females, thus confirming previous findings by Li *et al.* (2015), who observed that males drive more aggressively than females in hazardous situations, and of Fountas *et al.* (2019), who evidenced that males exhibit various patterns of aggressive driving compared to females.

Differently from speed behaviour, data modelling revealed that the guardrail height had a significant direct impact on the lateral behaviour of drivers. The lower guardrail induced drivers to maintain their vehicle farther from the roadside with respect to the baseline condition. As the guardrail is increased in height, drivers increase their lateral position thus moving further away from the roadside. These results are in line with those from Van der Horst and de Ridder (2007), who observed that drivers tended to move away from a guardrail in the absence of an emergency lane. In our case, the shoulder width was 0.50 m, so quite narrow compared to that of similar roads in real contexts (e.g., in Italy, the shoulder width is between 1.25 and 1.50 m in two-lane rural highways). However, Van der Horst and de Ridder (2007) did not observe any change in driver behaviour attributable to the guardrail type or height, which does not correspond to the findings of this study. It should be pointed out that Van der Horst and de Ridder (2007) included a combination of other influencing (and probably confounding) cross-sectional factors like vegetation, shoulders of different width, and roadside geometry.

The higher the guardrail, the further away the drivers remain from it. This behaviour confirms the previous findings in Bassani *et al.* (2019b), which revealed that most drivers adopt a compensation mechanism in response to sight limitations. In Bassani *et al.* (2019a, 2019b), most drivers moved laterally to benefit from a longer ASD when restricted by walls of the same height located at different lateral distances from the lane. The novelty here is that different guardrail heights (and shapes, with two vs. three rail waves) also influence the lateral behaviour. It should be pointed out that the horizontal curve direction led to statistically significant differences in the average positions of the CoG in the lane: drivers operated on the left side of the lane along leftward bends, and on the right side of the lane along right-hand bends.

The interaction between the roadside configuration and gender was significant for both speed and lateral position, in particular with the triple wave guardrail. When exposed to this inner roadside treatment, female drivers significantly reduced their speed and drove closer to the roadside; in contrast, males drove more centred in the lane to compensate for the higher speeds adopted. This study points out the relevant behavioural differences associated with driver gender, which should always be considered in driving studies including human factors.

What emerges from the analysis of modelled data is that the higher triple wave guardrail is correctly perceived as a more limiting sight obstruction with respect to the lower double wave guardrail. This leads to speeds influenced by other geometric and human factors, but always more centred trajectories, i.e. farther from the roadside and nearer to the lane centreline. On the other hand, the double wave guardrail encourages trajectories which are closer to it than those with the higher guardrail. It is also important to point out that males and females react differently to the same roadside treatment. More uninhibited male drivers compensate differently for a higher guardrail and consequently lower ASD (Table 2) compared to females. Females correctly perceive and compensate for the sight impairments associated with higher guardrails, so they adapt their driving style to unfavourable ASD conditions by reducing their speed with respect to the other roadside treatments.

5. CONCLUSIONS

Traffic barriers (e.g., guardrails) are protection systems that serve to redirect the vehicle along the carriageway. They must be installed along those stretches of roadside where the consequences of a vehicle leaving the road would be more hazardous for the vehicle occupants than if the vehicle were redirected back into the roadway. For this reason, they are perceived as a hard and hazardous obstacle. Along curves, this effect is evident when barriers are installed on the outer roadside. According to this concept, driver risk perception can vary: they may be inclined to accept more risk (i.e., increasing speed) or they can react by limiting their exposure to the risk of a possible crash. However, traffic barriers and/or guardrails also limit the available sight distance when installed along the inner side of curves, with drivers assuming different longitudinal and transversal behaviours in response to this limitation.

This triple perceptual role of barriers (i.e., safety system, dangerous rigid item, sight obstruction) is reflected in the two main approaches to national road design standards. While in some countries traffic barriers are used sparingly and installed only where the safety benefits outweigh the negative impact on traffic operations and the cost of installation (AASHTO 2011, 2018; Lay, 2009), in other countries (e.g., Italy and Spain) barriers are used extensively with a view to ensuring higher levels of safety. Furthermore, designers can choose between a barrier type that meets the minimum requirements and one that offers superior performance. Unfortunately, no guidelines indicate which of the two options results in better operational and safety performances.

This study confirms that when located along the inner roadside of two-lane rural highways, guardrails have a significant impact on both longitudinal and transversal driver behaviour. When the minimum standard is adopted (i.e., the minimum height), drivers stay closer to the roadside, while higher guardrails force drivers to increase their lateral distance from same. As regards longitudinal behaviour, a higher guardrail reduces the available sight distance thus leading to reductions in speed, but it also acts as a visual guidance element that, conversely, favours an increase in speeds.

The safety implications due to increased speeds and wider trajectories need to be carefully considered in locations where the use of guardrails is mandatory. This study helps designers to take the most appropriate decision in the interests of safety.

However, some limitations are the consequence of decisions taken at the experimental design stage. This investigation evaluated the impact of guardrails as a sight obstruction only. Guardrails of different height were used along the inner side of the curve only, so future research must evaluate the behavioural effects when guardrails are placed on the outer side of the curve, where they become possible hard obstacles in the case of a lane departure. New experiments are expected to provide a more complete knowledge of the behavioural response to these protection systems on both roadsides, evaluating their effects on road safety.

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REFERENCES

AASHTO (2011). *Roadside design guide*. American Association of State Highway and Transportation Officials, Washington D.C., US.

AASHTO (2018). *A Policy on Geometric Design of Highways and Streets*. American Association of State Highway and Transportation Officials, Washington D.C., US.

Barlow, Z., Jashami, H., Sova, A., Hurwitz, D. S., & Olsen, M. J. (2019). Policy processes and recommendations for Unmanned Aerial System operations near roadways based on visual attention of drivers. *Transportation research part C: emerging technologies*, *108*, 207-222, https://doi.org/10.1016/j.trc.2019.09.012.

Bassani, M., Catani, L., Ignazzi, A. A., & Piras, M. (2018, September). Validation of a Fixed Base Driving Simulator to Assess Behavioural Effects of Road Geometrics. In Proceedings of the DSC 2018 EUROPE VR Driving Simulation Conference & Exhibition (pp. 101–108). Antibes, France.

Bassani, M., Catani, L., Salussolia, A., & Yang, C. Y. D. (2019a). A driving simulation study to examine the impact of available sight distance on driver behavior along rural highways. *Accident Analysis & Prevention*, *131*, 200-212, https://doi.org/10.1016/j.aap.2019.07.003.

Bassani, M., Hazoor, A., & Catani, L. (2019b). What's around the curve? A driving simulation experiment on compensatory strategies for safe driving along horizontal curves with sight limitations. *Transportation research part F: traffic psychology and behaviour*, *66*, 273-291, https://doi.org/10.1016/j.trf.2019.09.011.

Bella, F. (2013). Driver perception of roadside configurations on two-lane rural roads: Effects on speed and lateral placement. *Accident Analysis & Prevention*, *50*, 251-262, https://doi.org/10.1016/j.aap.2012.04.015.

Ben-Bassat, T., & Shinar, D. (2011). Effect of shoulder width, guardrail and roadway geometry on driver perception and behavior. *Accident Analysis & Prevention*, *43*(6), 2142-2152, https://doi.org/10.1016/j.aap.2011.06.004.

Cafiso, S., & Cerni, G. (2012). New approach to defining continuous speed profile models for two-lane rural roads. *Transportation Research Record*, *2309*(1), 157-167, https://doi.org/10.3141/2309-16.

Castro, M., De Santos-Berbel, C., & Iglesias, L. (2017). A comprehensive methodology for the analysis of highway sight distance. In *Transport Infrastructure and Systems* (pp. 193-200). CRC Press.

Catani, L. (2019). *A Simulation Based Study on Driver Behavior when Negotiating Curves with Sight Limitations*. Doctoral dissertation, Politecnico di Torino, Turin, Italy.

Catani, L., & Bassani, M. (2019, January). Anticipatory distance, curvature, and curvature change rate in compound curve negotiation: a comparison between real and simulated driving. In Proceedings of the 98th Transportation Research Board Annual Meeting, Washington, DC.

EN 1317-1 N. Road restraint systems - Part 1: Terminology and general criteria for test methods. 2010.

EN 1317-2 N. Road restraint systems - Part 2: Performance classes, impact test acceptance criteria and test methods for safety barriers including vehicle parapets. 2010.

EN 1317-4 N. Road restraint systems - Part 4: Performance classes, impact test acceptance criteria and test methods for terminals and transitions of safety barriers. 2001.

EN 1317-5 N. Road restraint systems - Part 5: Product requirements and evaluation of conformity for vehicle restraint systems. 2012.

Fountas, G., Pantangi, S.S., Hulme, K.F., & Anastasopoulos, P.C. (2019). The Effects of Driver Fatigue, Gender, and Distracted Driving on Perceived and Observed Aggressive Driving Behavior: A Correlated Grouped Random Parameters Bivariate Probit Approach. *Analytic Methods in Accident Research*, *22*, 100091, https://doi.org/10.1016/j.amar.2019.100091.

Jashami, H., Hurwitz, D. S., Monsere, C., & Kothuri, S. (2019). Evaluation of driver comprehension and visual attention of the flashing yellow arrow display for permissive right turns. *Transportation Research Record*, *2673*(8), 397-407, https://doi.org/10.1177/0361198119843093.

Karimi, A., Bassani, M., Boroujerdian, A. M., & Catani, L. (2020). Investigation into passing behavior at passing zones to validate and extend the use of driving simulators in two-lane roads safety analysis. *Accident Analysis & Prevention*, *139*, 105487, https://doi.org/10.1016/j.aap.2020.105487.

Kemp, B. J. (1973). Reaction time of young and elderly subjects in relation to perceptual deprivation and signal-on versus signal-off conditions. *Developmental Psychology*, 8(2), 268-272, https://doi.org/10.1037/h0034147.

Lay, M. G. (2009). *Handbook of road technology*. CRC Press.

Li, G., Eben Li, S., & Cheng, B. (2015). Field Operational Test of Advanced Driver Assistance Systems in Typical Chinese Road Conditions: The Influence of Driver Gender, Age and Aggression. *International Journal of Automotive Technology*, *16*(5), 739–750, https://doi.org/10.1007/s12239-015-0075-5.

Lioi, A., De Santos-Berbel, C., Bassani, M., Castro, M. (2021). 3D modelling of highway guardrails for sight distance assessment. *Journal of Transportation Engineering, Part A: Systems*, *147*(11), 04021078, https://doi.org/10.1061/JTEPBS.0000593.

Michie, J. D., & Bronstad, M. E. (1994). Highway guardrails: Safety feature or roadside hazard? *Transportation Research Record*, *1468*, 1-9.

Milleville-Pennel, I. (2008). A visual sign of lateral acceleration for steering assistance. *International Journal of Human-Computer Studies*, *66*(3), 145-157, https://doi.org/10.1016/j.ijhcs.2007.01.003.

Ministerio de Fomento (2009). *Orden circular 28/2009 sobre criterios de aplicacion de barreras de seguridad metálicas* (in Spanish). Madrid, Spain.

Ministerio de Fomento (2014). *Orden Circular 35/2014 sobre criterios de aplicacio´n de sistemas de contencio´n de vehículos* (in Spanish). Madrid, Spain.

Ministerio de Fomento (2016). *Instrucción de Carreteras* (in Spanish). Norma 3.1-IC, Madrid, Spain. Available at: http://www.boe.es

Ministero delle Infrastrutture e dei Trasporti - MIT (2001). *Norme funzionali e geometriche per la costruzione delle strade* (in Italian). D.M. no. 6792 of November 5th (2001).

Ministero delle Infrastrutture e dei Trasporti - MIT (2004). *Aggiornamento delle istruzioni tecniche per la progettazione, l'omologazione e l'impiego delle barriere stradali di sicurezza e le prescrizioni tecniche per le prove delle barriere di sicurezza stradale* (in Italian). D.M. no. 2367 of June 21st (2004).

Pain, M. T., & Hibbs, A. (2007). Sprint starts and the minimum auditory reaction time. *Journal of sports sciences*, *25*(1), 79-86, https://doi.org/10.1080/02640410600718004.

Rosey, F., & Auberlet, J. M. (2012). Trajectory variability: Road geometry difficulty indicator. *Safety science*, *50*(9), 1818-1828, https://doi.org/10.1016/j.ssci.2012.04.003.

Schielzeth, H., Dingemanse, N. J., Nakagawa, S., Westneat, D. F., Allegue, H., Teplitsky, C., ... & Araya-Ajoy, Y. G. (2020). Robustness of linear mixed-effects models to violations of distributional assumptions. *Methods in Ecology and Evolution*, *11*(9), 1141-1152, https://doi.org/10.1111/2041-210X.13434.

Shinar, D., McDowell, E.D., Rockwell, T.H., 1977. Eye movements in curve negotiation. *Human Factors 19*, 63–72, https://doi.org/10.1177/001872087701900107.

Tay, R., & Churchill, A. (2007). Effect of different median barriers on traffic speed. *Canadian Journal of Transportation*, *1*(1).

The Jamovi Project (2021). *Jamovi* (Version 1.6) [Computer Software]. Retrieved from https://www.jamovi.org

Thompson, P. D., Colebatch, J. G., Brown, P., Rothwell, J. C., Day, B. L., Obeso, J. A., & Marsden, C. D. (1992). Voluntary stimulus-sensitive jerks and jumps mimicking myoclonus or pathological startle syndromes. *Movement disorders: official journal of the Movement Disorder Society*, *7*(3), 257-262, https://doi.org/10.1002/mds.870070312.

Törnros, J. (1998). Driving Behaviour in a Real and a Simulated Road Tunnel - A Validation Study. *Accident Analysis & Prevention*, *30*(4), 497–503.

Van Der Horst, R., & De Ridder, S. (2007). Influence of roadside infrastructure on driving behavior: driving simulator study. *Transportation Research Record*, *2018*(1), 36-44, https://doi.org/10.3141/2018-06.

Van Winsum, W., & Godthelp, H. (1996). Speed choice and steering behavior in curve driving. *Human factors*, *38*(3), 434-441, https://doi.org/10.1518/001872096778701926.

West, B. T., Welch, K. B., & Galecki, A. T. (2014). *Linear mixed models: a practical guide using statistical software*. Crc Press.

Wilde, G. J. (1998). Risk homeostasis theory: an overview. *Injury prevention*, *4*(2), 89-91, http://dx.doi.org/10.1136/ip.4.2.89.

World Medical Association, 2018. WMA Declaration of Helsinki–Ethical Principles for Medical Research Involving Human Subjects, 9 July 2018. https://www.wma.net/what-we-do/medical-ethics/declaration-of-helsinki/.