A driving simulation study to examine the impact of available sight distance on driver behavior along rural highways

A DRIVING SIMULATION STUDY TO EXAMINE THE IMPACT OF AVAILABLE SIGHT DISTANCE ON DRIVER BEHAVIOR ALONG RURAL HIGHWAYS

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ABSTRACT

The available sight distance (ASD) is the maximum length of the roadway ahead visible to the driver. It is a fundamental factor in road geometry principles and is used by road designers to ensure safe driving conditions. However, designers do not know how a specific ASD may affect the longitudinal and transversal behavior of drivers engaged in negotiating curves.

This paper focuses on analyzing driver longitudinal behavior along rural highways curves with limited visibility. A number of virtual sight condition scenarios were recreated and tested in the driving simulator. Three tracks were designed with various combinations of radii and sight obstructions (a continuous wall) along the roadside located at various offsets from the lane centerline, combinations which resulted with a minimum ASD of 56.6 m. Roadside factors capable of influencing the risk perception of drivers (e.g., traffic barriers, posted speed limit signs, vegetation) were all excluded from the simulations.

Results indicate that speed and trajectory dispersion from the lane centerline depend linearly on ASD in the investigated range of curve radii (from 120 to 430 m). In general, when ASD increases, so does speed and the trajectories tend to be less dispersed around the lane centerline. As a result, in safety terms, any variation in ASD will have the polar opposite effect on safety related parameters. Furthermore, different curves with similar ASD values resulted in different speed and lateral control behaviors. Analysis from ANOVA support the same findings; in addition, radius, curve direction, and distance from trajectory to sight obstruction have been identified as significant independent parameters. Road designers should adjust the ASD and these parameters when seeking to encourage drivers to adopt appropriate behaviors. To optimize safe driving conditions, ASD should be designed so that it is slightly greater than the required sight distance, since excessive ASD values may encourage drivers to drive at inappropriate speeds.

Keywords: available sight distance, longitudinal driver behavior, transversal driver behavior, driving simulation, vehicle trajectories.

1. INTRODUCTION

Drivers need to be able to see a sufficient length of the roadway ahead in order to (i) avoid hitting a stationary object along the path, (ii) overtake slower vehicles where permitted, and (iii) make appropriate driving decisions at complex locations such as intersections or when coming across traffic diversion signs. To meet these requirements, designers are obliged to adopt appropriate values for the geometric variables that characterize the horizontal and vertical alignments, as well as the cross-section of roads.

In order to translate these needs into standard practices and design decisions, road geometric policies (AASHTO, 2011; MIT, 2001) establish that the length of the road ahead visible to the driver, which is the available sight distance (ASD), must be greater than or at least equal to the required sight distances (RSD) for stopping (SSD), passing (PSD), and taking decisions (DSD); their magnitude depends on the adopted design speed. In accordance with policies, ASD ≥ RSD is a required condition for safe driving operations. Along horizontal curves, the ASD may be limited by the presence of sight obstructions such as vegetation, escarpments, traffic barriers, and buildings which encroach onto the carriageway.

Results from previous studies highlighted the correlation between crash frequency and ASD for specific road sections (Sparks, 1968; Urbanik et al., 1989; Steinauer et al., 2002). From an investigation into more than 100 km of roads on which 500 crash events occurred during the period of investigation, Castro and De Santos-Berbel (2015) found that excessive speed combined with insufficient ASD values may have caused approximately 4% of the crashes recorded. Hence, driving safety is affected by insufficient ASD values, although the limited number of investigations conducted would suggest a need for more researches to be carried out to clarify the relationship between sight conditions and safety (i.e., crash frequency, crash severity.

Road engineers design the horizontal and vertical alignment, as well as the cross section to obtain an ASD which is always greater than the RSD. Alternatively, when permitted by standards, designers impose an appropriate speed limit to encourage drivers to maintain the RSD below the ASD. These design decisions are based on set standards to deter any unintended consequences.

According to the risk compensation theory (Summala, 1996), it is to be expected that a greater ASD leads to a lower perception of risk, and this may induce drivers into taking higher risks by speeding. Conversely, a shorter ASD may encourage people to drive more prudently and within the posted speed limit. In support of such a hypothesis, Weller et al. (2008) observed that ASD affects driver speed behavior and may make a contribution to the categorization of roads. However, these hypotheses need to be confirmed through adequate investigation, and a quantification of any relationship is necessary for professionals and experts involved in the development and improvement of road design standards.

Currently, designers do not question whether decisions that imply ASD > RSD are better (safer) or worse (more dangerous) than cases where the ASD is significantly greater than the RSD. Furthermore, there is a lack of knowledge among practitioners as to how a certain ASD may contextually affect the longitudinal and transversal behavior of drivers engaged in negotiating curves.

In order to address the research questions, the authors carried out experiments using a driving simulator in which road scenarios characterized by different ASD values were established on a two-lane highway designed with horizontal radius curves ranging from 120 to 430 m. On some curves, a sight obstruction in the form of a continuous wall was placed at 0 to 3 m (*d*) from the road edge. The effects of other roadside factors (e.g., safety barriers, vegetation, roadside hazards) that may influence driver risk perception and, consequently, his/her longitudinal and transversal behavior were not included in the simulated road scenarios.

2. RELATED WORK

Past studies identified a linear relationship between operating speed and curvature of the roadway (Transportation Research Circular, 2011), albeit there remain some uncertainties regarding the predominance of curvature with respect to sight distance when it comes to the choice of preferred speed. Furthermore, a combination of the information deriving from road alignment curvature and information deriving from roadside features (i.e., horizontal markings, traffic-calming measures, road pavement conditions, lane width, lateral clearance, etc.), compels drivers to adopt the most appropriate longitudinal and transversal behavior (Martens et al., 1997; Jamson et al., 2010).

From data collected in field observations along four-lane roadways in Indiana (US), Figueroa Medina and Tarko (2004) investigated operating speeds and related models including random effects. Speeds along curves were found to be linearly dependent on both sight distance and curvature: an increase in sight distance leads to an increase in the mean speed, while an increase in the degree of curvature leads to a decrease in the mean speed and an increase in the level of speed dispersion around the mean. However, in the proposed models, other road and environmental factors were also found to be significant. Similarly, Bassani et al. (2014) found that independent variables principally related to cross-sectional characteristics rather than the longitudinal ones (i.e., alignment element) were predominantly significant in the case of urban roads.

In a driving simulation study, Ben-Bassat and Shinar (2011) investigated driver behavior on thirty different road configurations reproduced by varying road element (straights/curves) characteristics, curve radius (sharp/shallow), shoulder width (0.5, 1.2, and 3.0 m), and guardrails (present, absent). They found that the shoulder width along straight sections and rightward curves with guardrails was the most influential factor, since it contributes to an increase in the sense of security while driving. On leftward curves, the effects of lateral elements become non-influential.

Bella (2013) added to the previous variables the presence/absence of shoulders and barriers with trees along a two-lane rural road section reproduced at a driving simulator. Results revealed that driver behavior was only affected by the cross-sections and geometric elements and not by roadside configuration (the presence of trees along the road was not found to be influential even in the absence of barriers). Contrasting results in the work of Ben-Bassat and Shinar (2011) could be a product of the cross-sectional characteristics (four-lane divided carriageways in the case of Ben-Bassat and Shinar vs. two-lane rural roads in the case of Bella).

The effect of vegetation along the roadside was also investigated by Calvi (2015a). Four rural road scenarios with trees spaced apart and at different distances from the road edge were the focus of an experiment using, once again, a driving simulator. When compared to the base condition (i.e., no trees along the roadside), drivers reduced their speeds and moved towards the road centerline when trees were close to the shoulder. When trees were far from the roadway, drivers adopted higher speeds and reduced lateral displacements with respect to the lane axis. Along sharp curves, this behavior was more evident.

Bella (2013) and Calvi (2015a) both supported their inferences by concluding that drivers manage the vehicle trajectory by referring to the visual guidance mechanism provided by road elements in their field of vision. Bella (2013) considered the positive effect of continuous roadside elements such as road markings and/or guardrails, whereas Calvi (2015a) ascribed the guidance effect to trees. Conversely, van der Horst and de Ridder (2007) did not find any guidance effect due to the type of guardrail, although driving behavior changed as a function of its distance from the lane (presence/absence of emergency lane). Although the authors did not seek to explain these results, safety barrier type (flexible or rigid) was regarded as the determining factor.

Another investigation by Calvi (2015b) focused on driving performance for different cross-sections and posted speed limits. Three curve radii (200, 500, and 1000 m), two visibility conditions (restricted/unrestricted), and the presence or absence of transition curves were considered. In particular, visibility conditions were referenced to the relationship between the ASD and the SSD: they were indicated as “unrestricted” when ASD ≥ SSD, and “restricted” when ASD < SSD, with SSD computed according to the Italian Road Design policy (MIT, 2001). Speeds were higher in wider lanes and divided carriageways, and average speed increased when the curve radius was larger. The experiment confirmed that along sharp curves speed was not influenced by the curve direction (right/left); in these driving conditions, the accuracy of the travelled trajectory was greater than that obtained with higher radii of curvature. It should be noted that the highest speeds recorded in this study were for road configurations with guardrails, thus confirming that continuous elements have a guidance effect on drivers. Moreover, speeds adopted on sections with restricted visibility failed to satisfy safe driving conditions since the SSD was not guaranteed.

None of the previous researches evaluated the effects that ASD can have on speeds and related vehicle trajectories when drivers are negotiating curves with known visibility conditions. Consequently, the primary objective of this study is to determine whether this fundamental design parameter, used to assess standard safety conditions, influences drivers when they are deciding the most appropriate longitudinal and transversal behavior along curves, and if the degree of adjustment in their behavior correlates with the magnitude of the variable. In the road design scenarios, no speed limit signs (vertical ones), safety barriers, and vegetation were employed. According to the above literature, they were found to influence driver speed and position choice, so they were excluded as a factor in the design of this experiment.

3. METHODOLOGY

This research used a fixed-base driving simulator to examine road scenarios in which design variables of the horizontal alignment and cross section were manipulated to obtain a variety of ASD values. As already mentioned, no simulated vegetation, trees, speed limit signs, and/or traffic barriers were placed along the roadside in order to provide the subjects involved in the experiment with a level of risk perception which is solely attributable to the limited sight conditions. Accordingly, a continuous wall was placed at different offsets from the road edge to manage ASD values.

Figure 1 depicts the general method used in this experiment to estimate the ASD from the horizontal radius and the position of sight obstruction(s). According to road design guidelines (AASHTO, 2011; MIT, 2001), the driver line of sight is, by convention, positioned in the center of the travelled lane, and the ASD is calculated as the distance between the driver and the farthest point visible along the future vehicle trajectory.

In Figure 1, the subscript “1” is used to identify the vehicle moving from left to right, while the subscript “2” denotes the one travelling from right to left. Following a circular curved trajectory of radius r_i (with i = 1, 2) with a sight obstruction placed at a constant distance D_i from the same trajectory, drivers who travel along the rightward (i = 1) and the leftward (i = 2) curve benefit from an ASD_i equal to:

$$ASD_i = 2r_i \cdot \arccos\left(1 - \frac{D_i}{r_i}\right) \tag{1}$$

In Figure 1, the two D_i offsets (D_1 for the vehicle turning rightward, and D_2 for the vehicles turning leftward) are equal to:

$$D_1 = d + s_w + \frac{1}{2} \cdot l_w \tag{2}$$

$$D_2 = d + s_w + \frac{3}{2} \cdot l_w \tag{3}$$

where d is the distance of the sight obstruction from the road edge, s_w is the shoulder width, and l_w is the lane width.

It should be noted that eq. 1 provides a conventional estimate of ASD under the simplified hypothesis, supported by current road geometric guidelines, in which the driver moves along the lane axis. In real driving situations, the actual driver position could be shifted laterally away from the lane axis, so the effective ASD changes slightly during the experiment. However, in a preliminary analysis it was observed that the variation in ASD from the driver point of view fell within a range of ± 7 m around the conventional ASD values, assuming different driver positions in the lane, radius values in the range 120 ≤ R ≤ 430 m, and distance of the sight obstruction from the road edge values in the range 0 ≤ d ≤ 3 m. Consequently, the conventional ASD was considered as the dependent factor, and it was kept constant along the entire curve length in order to reflect stationary conditions and allow the drivers adapt to sight conditions.

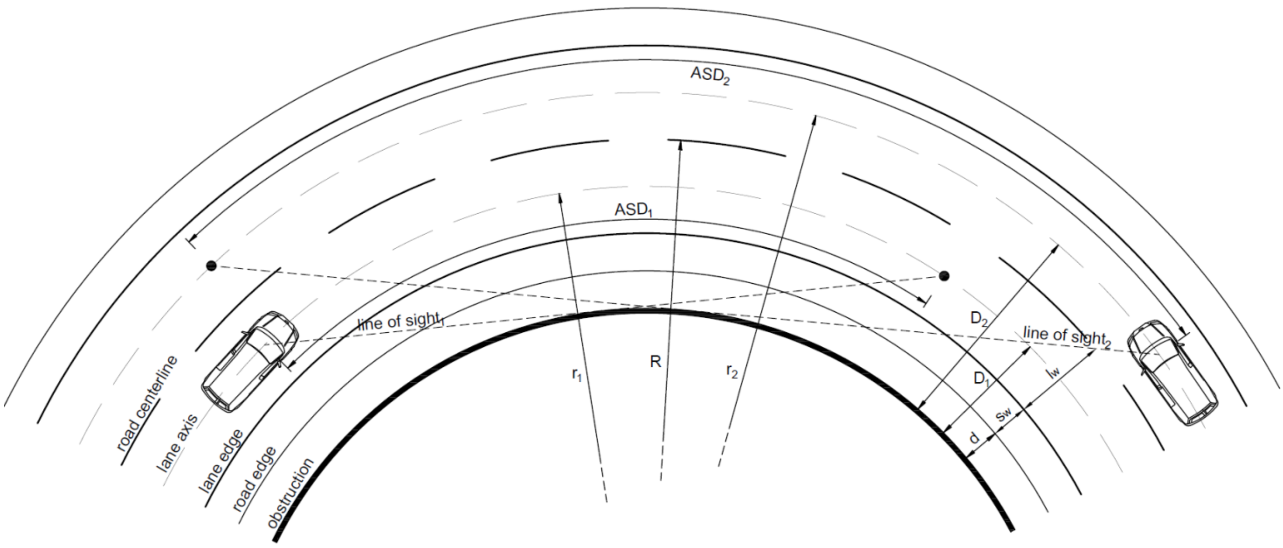


Figure 1. Conventional available sight distance (*ASD*) along a horizontal curve elaborated from road geometric policies (AASHTO, 2011; MIT, 2001). In the figure: *R* is the radius of the road axis; r_1 and r_2 are the radii of the right- and leftward turn trajectories respectively; D_1 and D_2 are the offsets of sight obstruction from the right- and leftward turn trajectories respectively; *d* is the distance of sight obstruction from the road edge; s_w is the shoulder width; ASD_1 and ASD_2 are the available sight distances from the right- and leftward trajectories respectively.

3.1 Apparatus

The fixed-base driving simulator of the Department of Environment, Land and Infrastructure Engineering at the Politecnico di Torino (Italy) was used for this multi-factorial experiment. The hardware consists of a complete cockpit with steering wheel, manual gears, pedals, and dashboard. Three 32-inch full HD screens (1920 × 1080 pixels each) provide a horizontal field of view of 130°. In combination with the video card, the three monitors update the images at a frequency higher than 50 Hz. The speedometer and the rev counter, as well as other in-vehicle displays, are visible on a small monitor attached to the back of the steering wheel and are always visible to drivers during experiments. The steering wheel is furnished with a force feedback sensor to simulate the rolling motion of wheels and shocks. Sound effects are reproduced through five speakers placed behind the screens and beneath the driver's seat, where there is a subwoofer.

The software used to design tracks, generate scenarios, and run experiments was *SCANeR*™*studio*. Data were collected with a frequency of 10 Hz and exported from the same software. The speed and lateral position in this driving simulation experiment were validated prior to data collection (Bassani et al., 2018; Catani and Bassani, 2019).

The same type of vehicle, a family car characterized by the performance levels of a typical vehicle commonly found in Italy (UNRAE, 2016), was used for all the experiments. The dynamic model corresponds to a passenger car powered by a 130 hp gas engine, with six manual gears and automatic clutch and with the brake pedal set to "race regulation". The car model uses a numerical method with a constant time step.

3.2 Scenarios, experimental design and research variables

For this study, two basic alignments of a standard two-lane rural road with lane width (l_w) equal to 3.75 m, and shoulder width (s_w) equal to 1.5 m were designed. Despite obtaining a reduction in the computational size of the model, the two roads included all combinations of the two main variables affecting ASD: (i) the radius of curvature (R), and (ii) the distance from the trajectory to the lateral sight obstruction (D).

Four curve radii (R_1 = 120 m, R_2 = 225 m, R_3 = 300 m, and R_4 = 430 m) were selected in the design speed variation range of 60-100 km/h as per Italian policy (MIT, 2001). For stability reasons, the cross slope along curves was set equal to 7% in accordance with the same policy; spirals were also adopted to enable the transition of cross slope from tangent to curve, and vice versa.

A continuous stone wall with a height of 1.5 m above that of the driver line of sight was employed as a lateral sight obstruction to generate specific ASD values. Walls were placed along the inner sides of curves and at different distances (d) from the road edge (see Figure 2). Three specific distances d were selected equal to 0, 1.5, and 3 m, resulting in six values of D as a function of the hand of the curve. Table 1 lists the ASD values computed from a combination of D and R and, also, of the driving direction according to eq. 1. Curves with deflection angles (ω) greater than 60° were adopted for two reasons: (i) to obtain a constant value for ASD along curves, thus providing stationary sight conditions for a sufficient time (and space) along curves, and (ii) to allow drivers to adjust and stabilize their behavior in terms of speed and lateral position in the lane.

Three tracks were selected to cover all potential combinations of design variables (Figure 2), and to consider the case of unlimited sight conditions (d = infinite) along curves. The first alignment was 12,888 m long, and was used to design the tracks A and A-mod; the differences between these tracks being the absence of sight limitations along certain curves along which drivers enjoyed unrestricted sight conditions. The second alignment was 14,444 m long, and was used to define track B. The lengths of the three tracks were designed to limit the duration of the experiment to below 20 minutes to minimize driver fatigue, sickness, and boredom (Philip et al., 2003). The choice of multiple tracks (and more scenarios) is consistent with techniques used to correct for the confounding effect (McGwin Jr., 2011).

Table 1. Computed available sight distance (*ASD*) values according to eq. 1 for the combinations of curve radius (*R*), typology (right- and leftward), and distance of the lane centerline from the lateral sight obstruction (*D*). The table also includes the distance of the same sight obstruction from the rod edge (*d*).

Radius	**Rightward curves**			**Leftward curves**		
	D_1 = 3.375 m d_1 = 0 m	D_2 = 4.875 m d_2 = 1.5 m	D_3 = 6.375 m d_3 = 3 m	D_4 = 7.125 m d_1 = 0 m	D_5 = 8.625 m d_2 = 1.5 m	D_6 = 10.125 m d_3 = 3 m
R_1 = 120 m	56.61	68.11	77.97	83.76	92.25	100.06
R_2 = 225 m	77.72	93.46	106.93	114.02	125.52	136.07
R_3 = 300 m	89.80	107.98	123.53	131.43	144.67	156.81
R_4 = 430 m	107.59	129.34	147.95	157.11	172.91	187.40

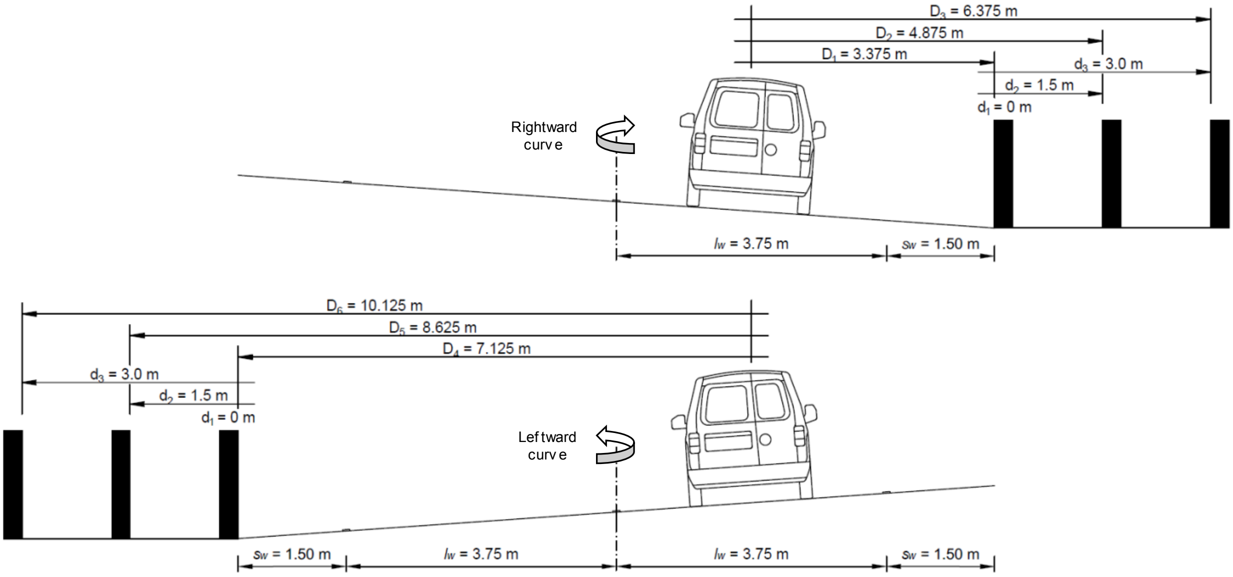


Figure 2. Cross section of the road configuration on right-hand and left-hand curves, with the sight obstructions at different distances (*D*) from the lane centerline and the road edge ($_d$).

Each track included 18 circular curves generated from a combination of *R* and *d* (4 × 3), while other curves were included simply in order to complete the circuits. They were all placed between transition curves (clothoids) with a scale parameter set in a range from *R/3* to *R*. The inclusion of spirals improves the optical perception of the road (Zakowska, 2010). The sequence of left- and rightward curves along both alignments was determined at random. Care was taken to avoid the use of the smallest radius before or after the largest one in order to be consistent with Italian and many other international standards (Brenac, 1996). This procedure is also necessary to avoid an excessive design and/or operating speed variation in two successive curves, and to meet driver expectations when traversing curves of different radii (Leisch and Leisch, 1977; Castro et al., 2011).

Figure 3 provides a curvature diagram of the three tracks, with the variables *R* and *d*, and the scale parameter *A* of the clothoids duly indicated. Tangents between curvilinear elements were designed to guarantee a length (L_t) such that $R > L_t$ for $L_t < 300$ m, and $R \geq 400$ m for $L_t \geq 300$ m (MIT, 2001). Therefore, their length was set in the 110-300 m range. As a result, both tracks consist of 35% of straight sections and 65% of curvilinear elements. To limit the number of design variables, the terrain was kept flat for the two alignments.

Traffic volume consisted of some simulated vehicles moving in the opposite direction and, in a few cases, in the same direction as the test vehicle but sufficiently distant to rule out any impact on speed and sight distances. The simulated vehicles circulated inside the roadway through a secondary network and on set paths so there were always free-flow traffic conditions during the simulation. The three tracks in Figure 3 were driven in both clockwise (CW) and anti-clockwise (CCW) directions, thus generating six different scenarios. Figure 4 provides some frames taken from the simulations that depict the effects of the sight obstruction offset at different *d* from the road edge for right- and leftward curves.

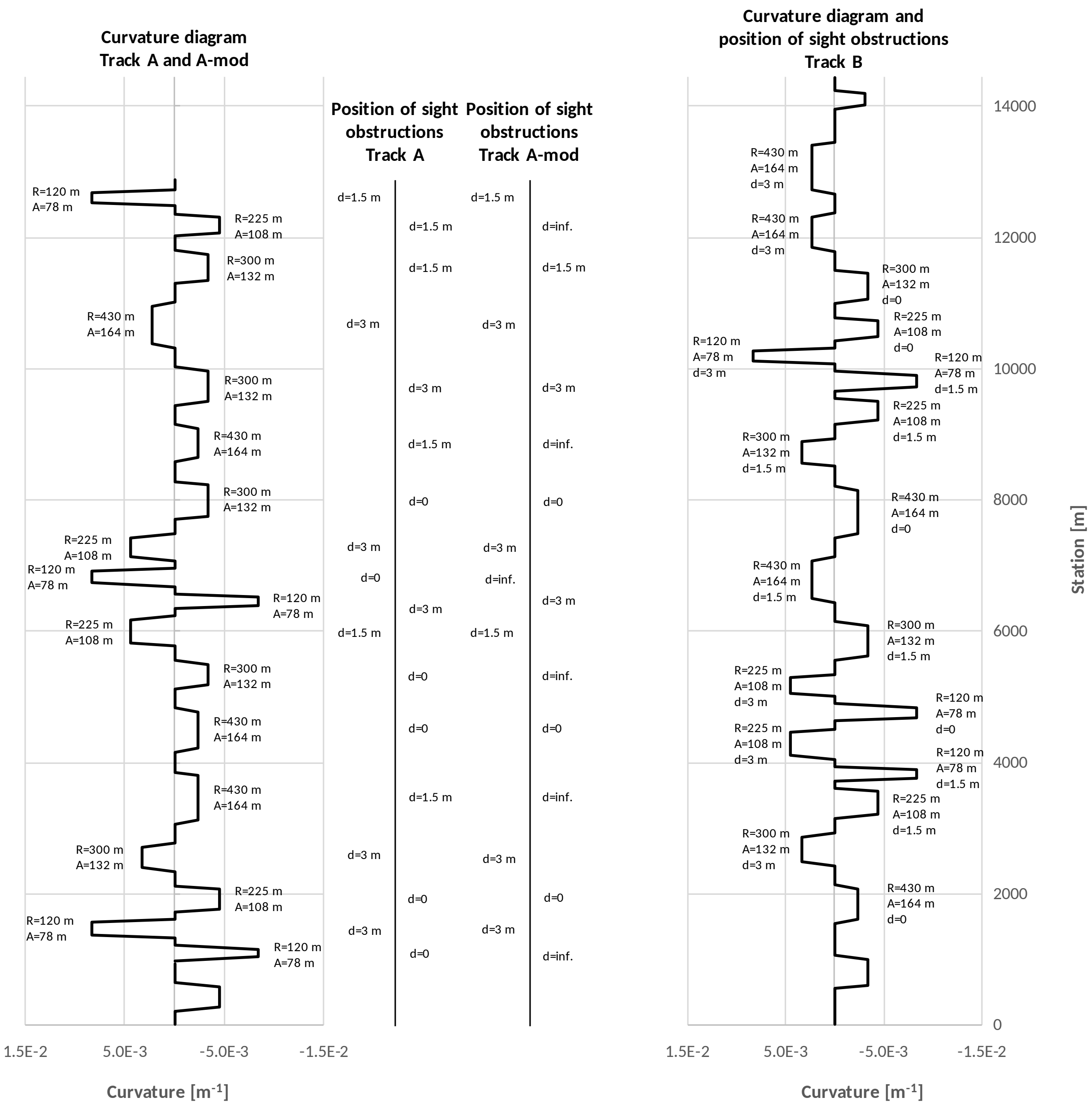


Figure 3. Curvature diagram for the three tracks (A, A-mod, and B), with specification of curve radius *R*, scale parameter *A* of the clothoids, position of sight obstructions, and distance *d* of the lateral obstruction from the road edge.

No vegetation, trees, vertical speed limit signs, and traffic barriers were placed along the roadside to guard the subjects involved in the experiment against any distractions and/or undesirable effects on their driving behavior. However, a few objects (e.g., container, parked vehicle, cones) were positioned on the shoulder, close to the end of a few curves to ensure drivers were being attentive. Some signs provided warnings before curves with R = 120 m only, while right of way signs were positioned at a few intersections to ensure once again that drivers were paying attention.

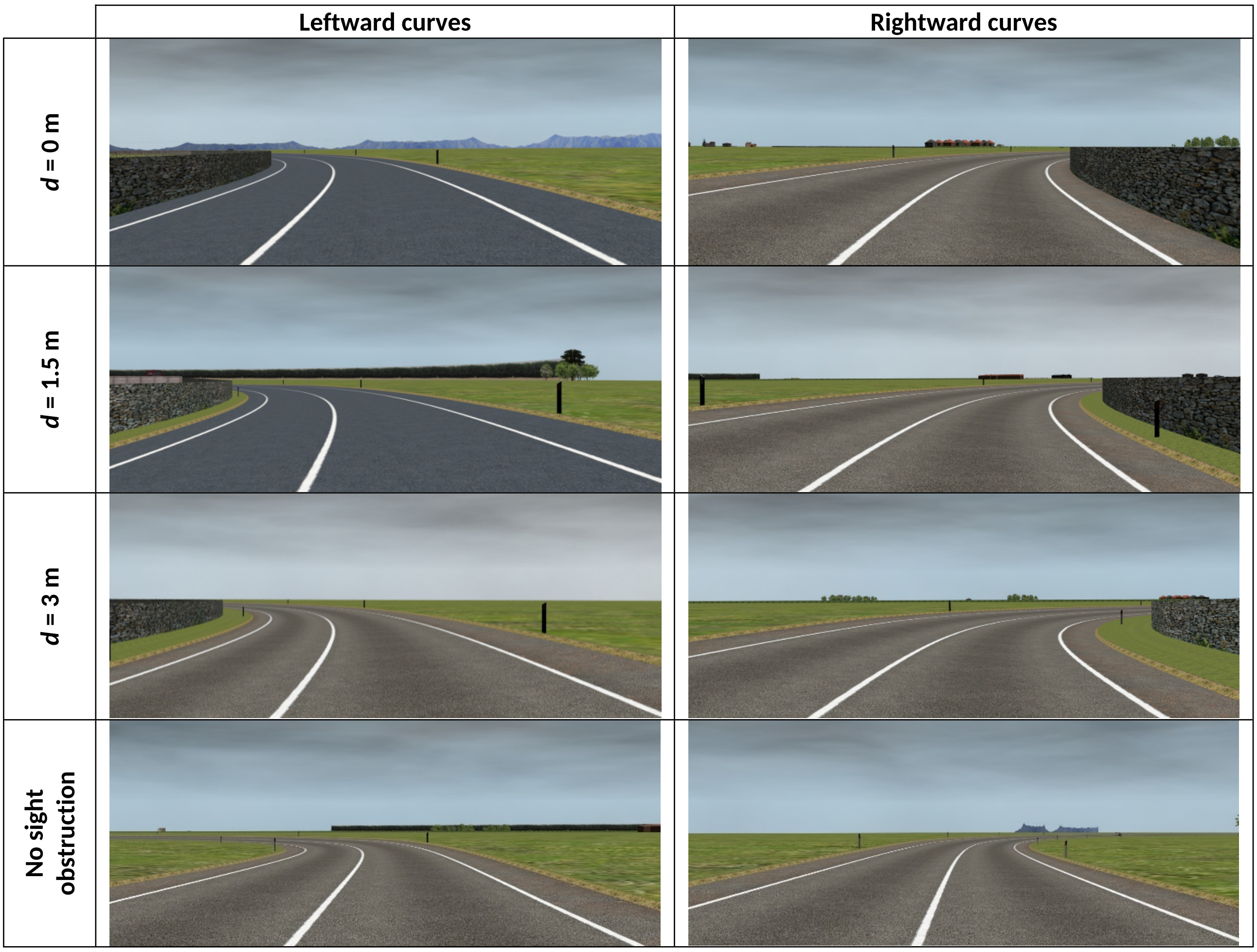


Figure 4. Frames of right-hand and left-hand curves with sight obstructions at a distance *d* equal to 0, 1.5, 3 m, and without the lateral wall. Road delineators were included in accordance with the Italian Highway National Code (MIT, 1992).

3.3 Participants

The simulation experiment involved the recruitment of 41 volunteers, 26 males (63%) and 15 females (37%), aged between 20 and 60 years (Table 2). Drivers were already familiar with the simulator since they had two training sessions (on different days) before starting with the experiments; none of them received any compensation (financial or otherwise) for their participation. None of the drivers experienced any sickness during the training phase or during the experiments. The choice of drivers and their age profile was an attempt to reflect Italian driver population characteristics (MIT, 2016). For the experimental task, participants were instructed to drive as they normally do, and to continue along the same lane for the entire experiment. As previously mentioned, other vehicles were included in the opposite direction and the few which were placed in the same driving direction were sufficiently distant from the simulated vehicles to create realistic conditions while at the same time avoiding the need for any overtaking maneuvers. The duration for the experiment was kept below 20 minutes to avoid any fatigue related effects on drivers.

Table 2. Characteristics of the driver sample set (Notes: M = mean, SD = standard deviation)

	No.	Age			Driving experience		No. accidents involved in	
		Min	M	Max	M	SD	M	SD
	(-)	(yrs)	(yrs)	(yrs)	(yrs)	(yrs)	(-)	(-)
Males	26	20	36.3	60	17.3	11.5	1.1	1.5
Females	15	21	30.6	54	11.7	10.0	0.5	0.5
Total	41	20	34.2	60	15.2	11.2	0.9	1.2

3.4 Experimental protocol, data collection and treatment

The experimental protocol entailed the following steps:

(a) complete a pre-drive questionnaire;

(b) perform pre-drive cognitive tests (visual and auditory);

(c) drive on the first pre-selected track;

(d) rest for at least 10 min;

(e) drive on a second pre-selected track;

(f) perform the same cognitive tests in post-driving; and

(g) complete a post-drive questionnaire.

The pre-drive questionnaire was used to ascertain that drivers were all in good health and were not receiving any medical treatment. Pre- and post-drive cognitive tests were used to determine if any driver(s) suffered from any attention lapses due to simulator induced fatigue (Langner et al., 2010; Zhao et al., 2012). These consisted of measuring reaction times to visual and auditory stimuli by means of an online platform. Driving experiments were performed in two out of the six possible scenarios (three tracks per two driving directions), randomly assigned to all 41 participants; the assignment was regulated to guarantee an equal distribution of drives across each scenario. In the final questionnaire based on a suggestion from Kennedy et al. (1993), drivers were asked to declare if they had experienced any kind of simulation sickness. Their negative responses confirmed the effectiveness of the strategies adopted (i.e., training session, simulation duration, design of road scenarios) to reduce driver discomfort.

Longitudinal and transversal behavior data, in terms of speed and lateral displacement, were collected for each driver involved in the experiment. The lateral position was considered as the transversal distance of the vehicle center of gravity from the lane centerline, also called "lane gap" (*LG*). Data were recorded at the sample rate of 10 Hz, and then filtered in order to consider only free-flow conditions (i.e., excluding overtaking maneuvers, operations influenced by the vehicle ahead). Speed analysis was restricted to the circular arc of curved sections, whereas lane gap was observed across the curve, considering 50 m of the approaching tangent, the entering and exiting spirals, and 50 m of the departure tangent. This measure was employed to compute the dispersion of trajectory (*DT*), a synthetic indicator of the vehicle position in the lane, and along a road segment (Calvi, 2015b). The standardized *DT* (DT^S) considers the discrepancies between the adopted trajectory (red line of Figure 5) and the lane centerline (ideal trajectory) as per the equation:

$$DT^S = \frac{\int_{s=0}^{s=L} \left| LG^*(s) \right| ds}{L} \tag{4}$$

where *s* is the curvilinear abscissa, and *L* is the total length of the element.

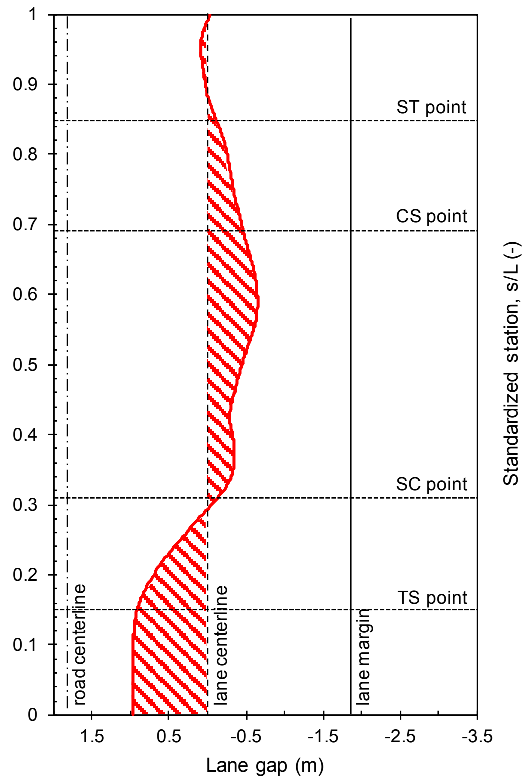


Figure 5. Scheme of DT^S measurement (red area) along the curved elements and adjacent tangents (TS = tangent-to-spiral point; SC = spiral-to-curve point; CS = curve-to-spiral point; ST = spiral-to-tangent point).

Specifically, the DT^S variable evaluates the ability of the driver to select an appropriate steering angle, or to follow the correct geometry of the path. Lower values of DT^S suggest that the geometry of the curve is well perceived (or "read") by the test driver. Such data has safety implication since they describe the tendency of certain road alignments to induce frequent trajectory corrections (i.e., wrong steering wheel control) (McGehee et al., 2004). A pilot study was performed prior to actual data collection to evaluate the consistency of the experimental protocol, the time optimization during the driving sessions, and the methodologies for data manipulation and analysis.

4. RESULTS

4.1 Speed vs. Available Sight Distance

The mean (M) and standard deviation (SD) of all the speed values (n) collected along the circular arcs were estimated and reported in Table 3. The dispersion of speed data around the mean value reflects the variation in the speeds chosen by participants, results which are also evident in the field as noted by the range of behaviors and attitudes exhibited by the driving population (Bassani et al., 2014). Data dispersion was also due to the drivers adjusting their speed along curves.

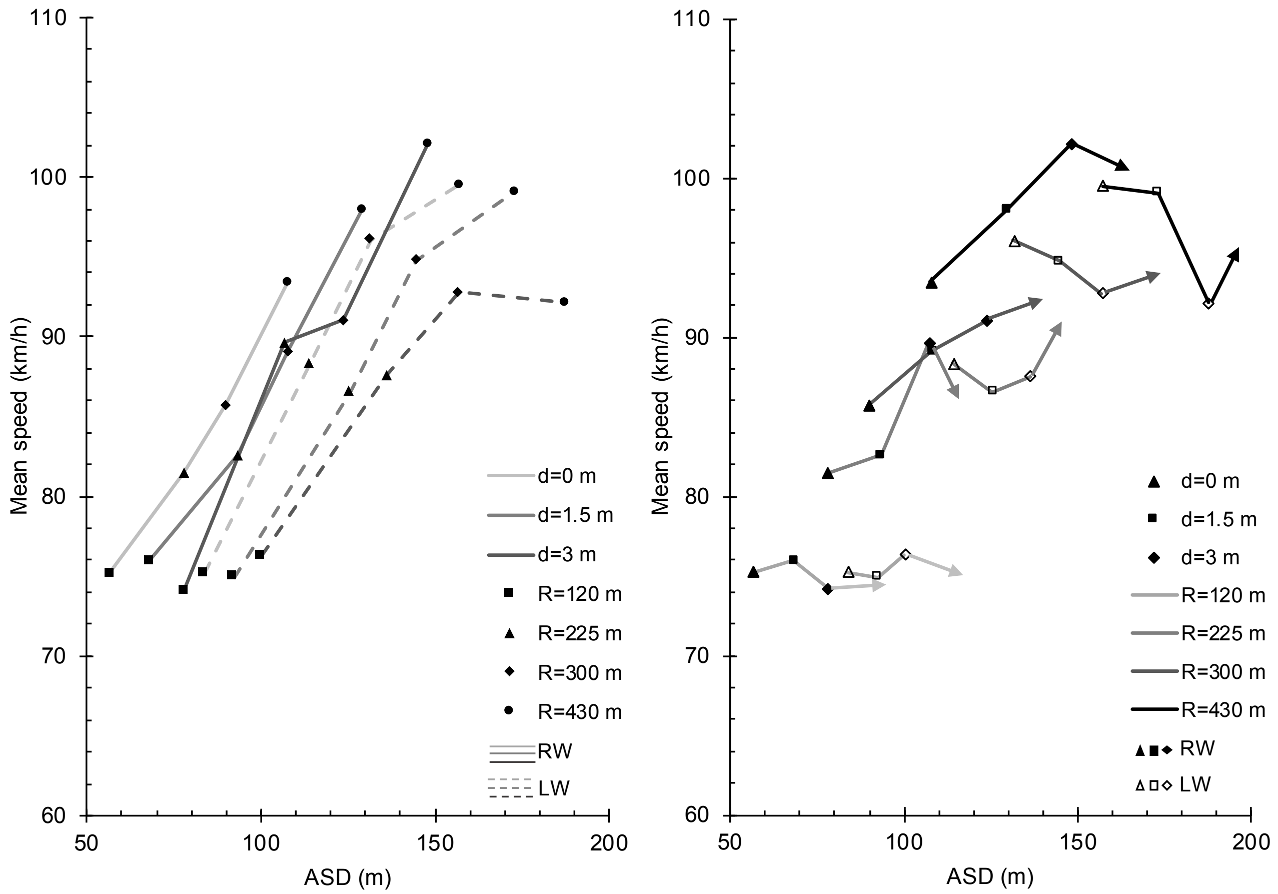
It is worth noting that in the case of *R* equal to 120 m, SD values are, on average, lower than those for higher radii. Lower SD values occur for leftward curves without sight obstructions (11.6 km/h), and the corresponding rightward condition induces a SD of 12.4 km/h, which is close to the lower limit of those recorded on curves with obstructions (ranging from 12.2 to 14.9 km/h).

In the case of curves with a radius equal to or greater than 225 m, the SD values for unrestricted visibility conditions on rightward curves are lower than those measured in cases where $0 \le d \le 3$ m. The opposite is observed on leftward curves. Finally, as is the case with mean speed (M), the average SD increases with an increase in the radius, both for right- and leftward curves.

Figure 6 exhibits the relationship between the mean speeds (Table 3) and the ASD in curves affected by sight obstruction(s) only. The different connections between points in the two graphs (Figure 6A and Figure 6B) reflect two ways to represent data: linking data obtained from experiments carried out with the same distance *d* (Figure 6A) or linking those obtained from experiments characterized by the same curve radius (Figure 6B).

Table 3. Mean (*M*) and standard deviation (*SD*) of speed data collected along the entire curve length (*n* is the total number of data available for that combination of independent variables) for different combinations of radius (*R*) and distance of the obstruction from the road edge (*d*) and the lane centerline (*D*). Symbol ∞ indicates that no sight obstruction was used, so *ASD* values are assumed to be higher.

R (m)	Leftward curves						Rightward curves					
	d (m)	*D* (m)	*ASD* (m)	Speed (km/h)			*d* (m)	*D* (m)	*ASD* (m)	Speed (km/h)		
				M	*SD*	*n*				*M*	*SD*	*n*
120	0	7.125	83.76	75.2	14.7	41	0	3.375	56.61	75.2	13.9	41
	1.5	8.625	92.25	74.9	12.2	54	1.5	4.875	68.11	76.0	14.9	52
	3	10.125	100.06	76.3	13.6	65	3	6.375	77.97	74.2	13.1	67
	∞	∞	∞	70.9	11.6	26	∞	∞	∞	75.3	12.4	26
225	0	7.125	114.02	88.4	14.1	55	0	3.375	77.72	81.5	16.4	50
	1.5	8.625	125.52	86.6	13.3	49	1.5	4.875	93.46	82.6	14.7	49
	3	10.125	136.07	87.6	13.7	52	3	6.375	106.93	89.6	12.9	53
	∞	∞	∞	97.2	16.4	13	∞	∞	∞	80.3	11.0	14
300	0	7.125	131.43	96.1	14.7	52	0	3.375	89.80	85.7	17.3	53
	1.5	8.625	144.67	94.8	14.1	51	1.5	4.875	107.98	89.1	14.9	52
	3	10.125	156.81	92.8	16.1	61	3	6.375	123.53	91.0	15.7	68
	∞	∞	∞	95.3	17.6	13	∞	∞	∞	93.0	13.3	14
430	0	7.125	157.11	99.5	15.5	52	0	3.375	107.59	93.5	18.2	55
	1.5	8.625	172.91	99.1	14.4	42	1.5	4.875	129.34	98.0	19.4	37
	3	10.125	187.40	92.2	12.4	52	3	6.375	147.95	102.1	15.4	46
	∞	∞	∞	105.9	19.4	26	∞	∞	∞	98.4	13.9	28



(A) (B)

Figure 6. Relationship between *ASD* and average speed: data connected on the basis of distance of sight obstruction from the road edge (A), and data connected on the basis of curve radius (B).

Figure 6A depicts the direct proportionality between speed and ASD. ASD affected the speed decision of drivers, the evidence for which was observed on both left (dashed lines) and right (continuous lines) curves. For the same ASD value, drivers adopted higher speeds as the distance *d* of the sight obstruction from the shoulder decreased; this means that the presence of a continuous element on the roadside has a guidance effect on drivers. Nonetheless, drivers were not able to discriminate between driving scenarios with the same ASD and adjusted their speed accordingly, demonstrating that the visual perception of curvature has a significant impact on driver speed choice. These observations were not evidenced by Moreno et al. (2013), since they used a single curve radius (265 m), and an ASD ranging from 109 to 198 m.

Along curves with R = 120 m, the mean speed remains almost constant even if ASD increases, both on right- and leftward curves (Figure 6B). This confirms that for small radii, there is a strong correlation between speed choice and the curvature captured from the inflection of road markings and roadsides. However, in the case of right curves with radii greater than 120 m, when ASD increases, so does speed while the opposite trend can be observed for left curves. Thus, on curves with the same radius, proximity to the lateral obstruction caused drivers to travel prudently along rightward bends, and faster along leftward ones (only for curves greater than 225 m in radius).

Figure 6B also includes the trend for unrestricted sight conditions (arrows on the right of "*d* = 3 m" series). Without sight obstructions along curves of $R \geq 225$ m, an increase in the average driving speed is evident in the case of left curves. Like previous observations, it is the critical geometry of sharp curves ($R = 120$ m) independently of their ASD values which has the greatest influence over driver speed decisions, a finding which emphasizes once again the relevance of road space guidance elements.

4.2 Dispersion of Trajectory vs. Available Sight Distance

Mean (M) values of DT^S were computed and shown in Table 4, together with the standard deviation (SD) of the values and the number of observations (*n*) for each curve configuration. In general, the higher the radius, the lower the DT^S observed. These results are consistent with findings by Zakowska (2010). In a few cases, this tendency is reversed: e.g., when $d \geq 3$ m on rightward bends, the observed DT^S corresponding to $R = 300$ m was lower than the one on curves with $R = 430$ m. In these conditions, the perceived distance to the lateral wall increased and diminished the guidance effect provided by the sight obstruction. In contrast, leftward bends are characterized by smaller DT^S values with respect to the corresponding rightward curves with the sole exception of curves with $R = 120$ m, $d = 0$ m and infinite (∞). Therefore, the greater the ASD, the smaller the deviation from the ideal trajectory, albeit only when the sight obstruction was present.

Figure 7 exhibits the relationship between the mean dispersion of trajectory and ASD along curves affected by sight obstruction(s), with data presented in Table 4. Data were linked for the same distance *d* (Figure 7A), and for the same curve radius (Figure 7B).

Figure 7A emphasizes the direct proportionality between DT^S and ASD: when ASD increases, the mean dispersion of trajectory decreases. It confirms that a higher ASD leads to an increased tendency to adopt more precise vehicle trajectories, both along leftward (dashed lines) and rightward (continuous lines) curves. It is worth noting that for the same ASD, driver trajectories were characterized by different DT^S: the effect of the radius R on transversal behavior was more evident on right- than on leftward bends. Lower values of DT^S were observed only when the sight limitation was placed near the shoulder ($d = 0$ m) or when the ASD was higher than 150 m. These findings serve to highlight the guidance effect on steering behavior provided by the lateral wall.

Referring to Figure 7B, along rightward curves with $R \leq 225$ m, the mean DT^S increases with a higher slope than on curves with a radius of 430 m. Along left-hand curves where ASD was greater than 120 m, the mean values of DT^S range between 0.3 and 0.4 m.

Table 4. Mean (*M*) and standard deviation (*SD*) of dispersion for trajectories collected along the entire curve length (*n* is the total number of drivers traveling on this kind of curve) for different combinations of radius (*R*) and distance of the obstruction from the road edge (*d*) and lane centerline (*D*). Symbol ∞ indicates that no sight obstruction was used, so *ASD* values are assumed to be higher

R (m)	Leftward curves						Rightward curves					
	d (m)	*D* (m)	ASD (m)	DT^S (m)			*d* (m)	*D* (m)	ASD (m)	DT^S (m)		
				M	SD	n				M	SD	n
120	0	7.125	83.76	0.51	0.19	41	0	3.375	56.61	0.45	0.18	41
	1.5	8.625	92.25	0.50	0.20	52	1.5	4.875	68.11	0.58	0.22	40
	3	10.125	100.06	0.43	0.19	65	3	6.375	77.97	0.66	0.27	26
	∞	∞	∞	0.48	0.20	25	∞	∞	∞	0.46	0.20	26
225	0	7.125	114.02	0.38	0.16	55	0	3.375	77.72	0.43	0.18	23
	1.5	8.625	125.52	0.40	0.19	49	1.5	4.875	93.46	0.54	0.17	12
	3	10.125	136.07	0.36	0.13	52	3	6.375	106.93	0.63	0.21	26
	∞	∞	∞	0.40	0.16	12	∞	∞	∞	-	-	-
300	0	7.125	131.43	0.34	0.13	52	0	3.375	89.80	0.47	0.21	12
	1.5	8.625	144.67	0.38	0.16	51	1.5	4.875	107.98	0.48	0.18	25
	3	10.125	156.81	0.34	0.12	61	3	6.375	123.53	0.46	0.22	41
	∞	∞	∞	0.37	0.16	13	∞	∞	∞	0.45	0.23	14
430	0	7.125	157.11	0.34	0.15	52	0	3.375	107.59	0.36	0.15	41
	1.5	8.625	172.91	0.30	0.14	42	1.5	4.875	129.34	0.42	0.17	26
	3	10.125	187.40	0.34	0.15	52	3	6.375	147.95	0.46	0.21	22
	∞	∞	∞	0.37	0.20	26	∞	∞	∞	0.41	0.20	28

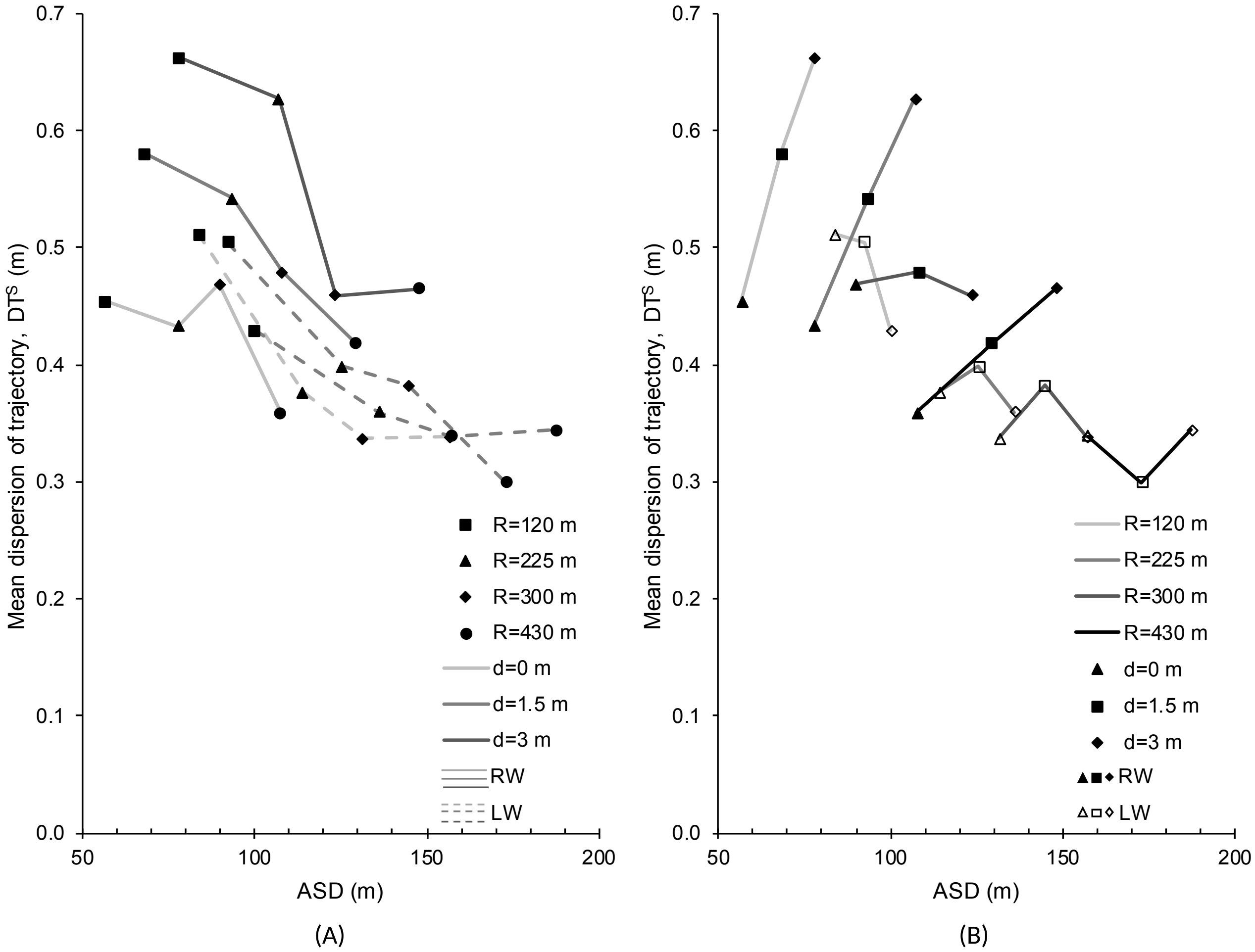


Figure 7. Relationship between *ASD* and trajectory dispersion: data connected on the basis of sight obstruction distance from the road edge (A), and data connected on the basis of curve radius (B)

4.3 Significant variables and interactions

To support the inferences drawn from Figure 6 and Figure 7, ANOVA was performed by using R software (v3.1.1) to evaluate the significance of the investigated variables for the observed data (R Core Team, 2016). In this analysis, the mean speed along each investigated circular curve and the values of the standardized dispersion of trajectory (DT^S) were repeatedly used as measurement variables for drivers.

The ANOVA was performed in two different ways: a 3-way ANOVA in which the main variables were curve direction (*dir*), radius (*R*) and offset of the lateral obstruction from the road edge (*d*); and a 2-way ANOVA with radius (*R*) and the distance between the lane centerline and the sight obstruction (*D*) regarded as the principal variables. The two ANOVAs were carried out to determine whether *d* or *D* had more influence on the driver speed and track behavior; it is worth considering that D values include the effects of d and curve direction. In the two ANOVAs, eta-squared (η^2) was computed to determine the magnitude of the effects of individual variables. It measures the degree of variance in dependent variables explained by the different groups defined for independent variables (Richardson, 2011). In general, η^2 is more conservative than the partial coefficient since it returns smaller or equal values.

In both cases, the statistical analysis required that datasets be normally distributed, and variances be homogeneous. These assumptions were checked by means of the K-S test and Levene's test, respectively.

4.3.1 Driving speeds

Data shown in Table 3 were subjected to the Chi-squared test assuming a confidence level of 95% (χ^2_{crit} = 5.99). Results revealed datasets were normally distributed (29 of 32 groups for 3-way ANOVA; 26 of 28 groups for 2-way ANOVA). The results of Levene's tests for the 3-way (DoF = 31, F = 1.24; p = .174) and the 2-way (DoF = 27, F = 1.38, p = .096) ANOVAs showed that variances are homogeneous among the dataset.

Table 5 lists the results of the 3-way ANOVA on driving speeds, clearly indicating both the radius ($F(3,1377)$ = 154.57, p < .001, η^2 = .243) and the direction of travel ($F(1,1377)$ = 9.33, p = .002, η^2 = .005) as the variables with the greatest influence on the operating speed, while the offset of the lateral sight obstruction (*d*) was found to be insignificant ($F(3,1377)$ = 1.24, p > .05, η^2 = .002). In fact, the radius accounts for 24.3% of the variation in speed values, with the direction of travel and distance *d* of lateral sight obstruction contributing less than 1%. The offset *d* becomes significant in the interaction with the direction of travel ($F(3,1377)$ = 5.14, p = .002, η^2 = .008), which means that the position of the sight obstruction plays a different role when evaluated on left- or right-hand curves. Other interactions between influencing factors are less significant. Lastly, the proportion of speed variance that cannot be explained by design variables is 72%.

In the wake of previous outcomes, the aggregated distance *D* was used instead of the distinguished effects *direction* and *d* to perform a 2-way ANOVA, with the results listed in Table 6. In this case, speed samples were grouped as a function of the four radii and the seven road configurations (six with sight obstructions and one without). The outcomes confirmed the high significance of both *R* ($F(3,1381)$ = 153.57,

$p < .001$, $\eta^2 = .243$) and D ($F(6,1381) = 4.07$, $p < .001$, $\eta^2 = .013$), while their interaction proved to be fairly significant ($F(18,1381) = 1.64$, $p < .05$, $\eta^2 = .016$). Results confirm the relative contributions of the radius (24.3%) and the effective distance D from the sight obstruction (1.3%) to speed variance. The results from the 2-way ANOVA suggest that the distance between the sight obstruction and driving trajectory was the significant factor rather than the offset of the same obstruction from the roadway. This outcome reaffirmed the relevance of ASD when assessing driver behavior.

Table 5. Results of 3-way ANOVA on driving speeds

Principal Effects	Degree of Freedom	Sum of Squares	Mean of Squares	*F* value	Pr(>*F*)	η^2
Direction (left/right hand), *dir*	1	2052	2052	9.334	0.00229	0.005
Radius, *R*	3	101946	33982	154.567	< 2.2e-16	0.243
Distance, *d*	3	820	273	1.243	0.29267	0.002
Interaction Effects						
*dir*R*	3	1952	651	2.960	0.03129	0.005
*dir*d*	3	3387	1129	5.136	0.00156	0.008
*R*d*	9	2089	232	1.056	0.39308	0.005
*dir*R*d*	9	4643	516	2.347	0.01259	0.011
Residuals	1377	302738	220			0.721

Table 6. Results of 2-way ANOVA on driving speeds

Principal Effects	Degree of Freedom	Sum of Squares	Mean of Squares	*F* value	Pr(>*F*)	η^2
Radius, *R*	3	101985	33995	153.5676	< 2.2e-16	0.243
Distance, *D*	6	5408	901	4.0715	0.00047	0.013
Interaction Effects						
*R*D*	18	6525	362	1.6375	0.04445	0.016
Residuals	1381	305710	221			0.729

4.3.2 Dispersion of trajectories

Once again, data shown in Table 4 were subjected to the Chi-squared and Levene's tests (level of significance of 5%). Results revealed datasets were normally distributed (28 of 31 groups for 3-way ANOVA; 27 of 28 groups for 2-way ANOVA); and variances were homogeneous among the dataset ($DoF = 30$, $F = 2.01$, $p = .111$ for 3-way ANOVA; $DoF = 27$, $F = 2.14$, $p = .066$ for 2-way ANOVA).

Results for the same analyses with values of DT^S are presented in Table 7 and Table 8. The outcomes for the 3-way ANOVA clearly indicate that the direction ($F(1,1072) = 69.31$, $p < 2.6 \cdot 10^{-16}$, $\eta^2 = .053$) and radius ($F(3,1072) = 31.47$, $p < 2.2 \cdot 10^{-16}$, $\eta^2 = .072$) are the variables which have the most significant influence on dispersion of trajectory. Distance (d) is less significant ($F(3,1072) = 2.92$, $p = .033$, $\eta^2 = .007$). Once again, the radius of curvature is the variable which contributes most to the outcome (7.2%), whereas the direction of travel influences only 5.3% of the dispersion of trajectory variance. The interaction between the direction of travel and the distance has high significance ($F(3,1072) = 10.17$, $p = 1.3 \cdot 10^{-6}$, $\eta^2 = .023$), which means that the position of the sight obstruction plays a different role when evaluated on left- or rightward curves. Furthermore, there is an influence on interaction between the radius and the direction of the curve

($F(3,1072)$ = 3.34, p < .02, η^2 = .008). The proportion of variance not explained by the considered variables is about 82%.

In light of previous outcomes, the 2-way ANOVA confirms the high significance of both R ($F(3,1075)$ = 32.90, $p < 2 \cdot 10^{-16}$, η^2 = .075) and D ($F(6,1075)$ = 17.87, $p < 2 \cdot 10^{-16}$, η^2 = .082), while their interaction proved to be fairly significant ($F(18,1075)$ = 1.65, p < .05, η^2 = .023). In this case, the DT^S variance is associated more with the variation in D (8.2%) than with the variation in R (7.5%). The results of this 2-way ANOVA are the same as those relating to the driving speed, evidencing that R and D influence longitudinal and transversal driver behavior. Once again, these results show the relevance of ASD to driver performance.

Table 7. Results of 3-way ANOVA on dispersion of trajectory (DT^S)

Principal Effects	**Degree of Freedom**	**Sum of Squares**	**Mean of Squares**	***F* value**	**Pr(>*F*)**	**η^2**
Direction (left/right hand), *dir*	1	2.224	2.22388	69.309	2.542e-16	0.053
Radius, *R*	3	3.029	1.00962	31.466	< 2.2e-16	0.072
Distance, *d*	3	0.281	0.09357	2.916	0.03330	0.007
Interaction Effects						
*dir*R*	3	0.321	0.10704	3.336	0.01885	0.008
*dir*d*	3	0.979	0.32617	10.165	1.325e-06	0.023
*R*d*	9	0.308	0.03426	1.068	0.38403	0.007
*dir*R*d*	8	0.483	0.06035	1.881	0.05945	0.011
Residuals	1072	34.397	0.03209			0.819

Table 8. Results of 2-way ANOVA on dispersion of trajectory (DT^S)

Principal Effects	**Degree of Freedom**	**Sum of Squares**	**Mean of Squares**	***F* value**	**Pr(>*F*)**	**η^2**
Radius, *R*	3	3.164	1.05481	32.8994	< 2e-16	0.075
Distance, *D*	6	3.438	0.57294	17.8699	< 2e-16	0.082
Interaction Effects						
*R*D*	18	0.952	0.05291	1.6503	0.04238	0.023
Residuals	1075	34.466	0.03206			0.820

5. DISCUSSION

Previous studies investigated the effects of horizontal alignment and cross-sectional factors on the longitudinal behavior of drivers (Ben Bassat and Shinar, 2011; Bella, 2013; Calvi, 2015b). These works did not measure the effects associated with variations in the available sight distance (ASD) along curves with limited visibility; their experimental designs also included roadside elements which have great influence on risk perception and, consequently, longitudinal and transversal driver behaviors.

The main aim of this work was to evaluate if the ASD on its own could influence driver behavior in terms of preferred speed and trajectory. Weller et al. (2008) postulated that the available sight distance is a key factor when it comes to driver perception of road type, which in turn has a great influence on driver preferred speeds and trajectories. In this experiment, ASD values were generated by the placement of a continuous sight obstruction at different offsets from the lane centerline along curves of different radii (R)

within a range from 120 to 430 m (Figure 1). As a result, *R* and *D* were the main design factors in the experiment.

Driving speeds were examined by computing the mean speed adopted by participants in the simulation experiment along the circular arc of the curves (which also included spiraled transitions). Results confirmed that the road curvature had the most significant impact on driver preferred speed. However, on sharp curves, the speed choice was affected more by the curvature of the segment than by the ASD (Figure 6b). For higher radii, the effect of the distance from the sight obstruction is also evident on driving speed, leading to increasing values when it (sight obstruction) was moved further away from the vehicle trajectory (for rightward curves only). Conversely, on leftward bends, the speed decreased even when the sight distance increased. Along the investigated interval of alignment radii, results indicated that the relationship between the mean driving speed and the ASD tends to be linear – the greater the ASD, the higher the speed. This result is consistent with the results from field observations by Figueroa Medina and Tarko (2005).

The 3-way ANOVA confirmed the influence of the radius on driving speed. As documented in previous studies (Said et al., 2009; Van Winsum and Godthelp, 1996), low curvatures facilitate the adoption of higher speeds since they generate reduced lateral accelerations. Although lateral acceleration cannot be detected on a fixed-base driving-simulator, drivers, drawing on real-life past driving experience, limited their speed on sharp curves. Furthermore, the second factor affecting speeds is curve direction (Table 4); the influence of direction is reduced in the case of sharp curves while it becomes dominant for wider radii, revealing the significance of the interaction between direction and radius.

Bella (2013) found significant differences in speed between left - and right-hand curves in the 200 to 400 m range, consistent with the findings of this study. Conversely, Calvi (2015b) stated that only radius magnitude affected driver speed choice. The findings from this study confirm the conclusions reached by Bella (2013). However, with respect to Calvi (2015b), any difference with respect to this investigation are attributed to roadside elements used in the various driving scenarios, which influence driver perceived safety levels and trigger specific visual mechanism strategies. In the present study, roadside elements were excluded in order to concentrate solely on the influence of sight obstruction.

The results from this work confirmed the hypothesis of the influence of ASD on driver preferred speed along medium and shallow curves. The 3-way ANOVA carried out in this research revealed that the distance of the lateral wall from the road edge did not affect driver preferred speed. In this case, a sight obstruction was placed at three different offsets from the same 1.5 m wide shoulder. In the investigation of Ben-Bassat and Shinar (2011), the traffic barrier was offset by increasing the shoulder width. The average speed on rightward curves increases with an increase in the distance of the barrier from the road edge, while it remained almost constant with different shoulder width values, albeit without the barrier.

Driver transversal behavior was analyzed in terms of the lane gap (*LG*) between the travelled path (center of gravity of the vehicle) and the lane centerline, which allows the computation of the trajectory dispersion along the investigated curves. Data were considered across the analyzed bends (including 50 m of approaching and departure tangents, spirals, and circular arc) to investigate the entire curve negotiation. The computation of the standardized dispersion of trajectory (DT^S) confirmed that the accuracy of the trajectory increased for greater radii, and for leftward curves (Van Winsum and Godthelp, 1996; Calvi, 2015b). The trends for DT^S also evidenced the guidance role of the lateral sight obstruction on rightward bends. Specifically, for the same radius of curvature, reduced values were observed when the obstruction was close to the vehicle trajectory. The distance of the driver from the lateral wall (D) had less of an effect than the radius of curvature when negotiating leftward bends. A direct proportionality was also observed between the dispersion of trajectory and the ASD: the greater the ASD, the lower the DT^S.

The high values for trajectory dispersion along tight curves could suggest a tendency for participants to "cut" curves (Ben Bassat and Shinar, 2011; Bella, 2013). Although the movement toward the roadside (on rightward curves) is risky for drivers, moving leftward is no less so since it may lead to a head-on collision with vehicles traveling in the opposite direction. This is also in line with previous observations by Boer (1996) and Coutton-Jean et al. (2009), who stated that drivers are prone to adopt the path with the lowest maximum curvature to minimize the centrifugal forces on the vehicle. However, this experiment evidenced that drivers tended to "cut" the leftward bends since this maneuver did not significantly limit their perceived ASD, while they adopted trajectory curvatures close to the design ones thereby not compromising their restricted sight distance. These outcomes derive from an analysis of several sight distance values provided by test drivers, which the previously mentioned works omitted. These results affirm the relevance of visual information that drivers process when negotiating curves, although the simulator used in this experiment did not return any acceleration to participants.

The statistical analysis with the ANOVA highlighted the contextual significance of the radius and the offset of the sight obstruction from the lane centerline (D), both on driving speed and on dispersion of trajectory. The 3-way ANOVA confirmed that the offset of the sight obstruction from the road edge (d) did not affect the speed choices, while a limited but nevertheless significant influence was found in the case of dispersion of trajectories only.

6. CONCLUSIONS AND RECOMMENDATIONS

This study examined the longitudinal and transversal behavioral response of drivers travelling along curves with limited and unlimited available sight distance (ASD). The road scenarios were designed to produce a constant ASD value along each curve so that the driver response could be evaluated under stationary sight conditions.

This investigation demonstrates that drivers adjust their longitudinal behavior and vehicle trajectory under different visibility conditions. From a road designer perspective, a knowledge of the range of possible driver behaviors would help with the adoption of consistent design decisions. It has also been demonstrated that driver behavior can be anticipated and manipulated with a proper geometric design of sight conditions (resulting from the combination of geometric factors associated with road alignment and cross-sectional characteristics), and plausible driving errors and unexpected/undesired behaviors deterred. Consequently, the results of this investigation provide a new insight into the operational and behavioral effects of road geometrics, and more specifically the effects attributable to ASD variations.

It is worth noting that the results of this investigation are consistent with the risk compensation theory (Summala, 1996): a greater ASD induces drivers to take higher risks by speeding, which also means that their risk perception changes when ASD changes. Furthermore, the results reported here are consistent with the "self-explaining road" concept and framework (Theeuwes and Godthelp, 1995). In fact, ASD can be modulated to convey a specific message to drivers, for example to compel drivers to assume behaviors consistent with the road category and surrounding environment.

Road geometric policy makers should consider ASD as a fundamental parameter and integrate it into operational and road safety analyses. Since ASD affects speed choice along horizontal curves, this variable should be included in future versions of operating speed models (Transportation Research Circular, 2011) currently used in road design consistency analyses.

An important practical implication of this research is related to the design of new roads as well as the analysis (and re-design) of existing ones. In both cases, designers should avoid situations in which the ASD is much greater than the RSD. Based on the study results, limiting the ASD to the lowest possible value (but ensuring that ASD > RSD according to standards) is strongly recommended. This design decision will discourage motorists from driving at inappropriate or excessive speeds. However, drivers maintain a greater control of their trajectory at superior ASD values. Accordingly, limitations to the ASD could be used in conjunction with other environmental factors in the quest for a more prudent longitudinal behavior and safer vehicle control.

Reliability analysis is, nowadays, one of the solutions promoted as a response to the uncertainties in geometric design and to evaluate the risk(s) associated with particular design choices (Hussein et al., 2014). Thus, the results of this work could be employed in the validation of a risk-based reliability analysis to assess the effectiveness of design guides.

This investigation reveals a number of limitations that have to be considered before these results can be transformed into practical applications: (i) the selected road type corresponds to a two-lane highway in a rural environment; (ii) the range of curvature radii employed only considers curves in the 120-430 m; (iii) the range of ASD investigated is greater than 56.6 m; (iv) the road tracks were developed on a flat terrain. As a result, other road types, curve radii, shorter ASD, and vertical alignment design should be examined in future investigations. Furthermore, the contextual presence in the road environment of other road features (i.e., vertical signals with speed limits, traffic barriers, hazardous elements in the roadside) which were demonstrated in past studies to influence driver behavior in combination with visibility conditions should be carefully evaluated. Despite the significant potential of simulation technology in the performance of experiments where the independent variables are fully controlled, the risk perception with this system is different from that of real driving conditions, so the results of this investigation have to be carefully evaluated in terms of their transferability to real -life driving situations.

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REFERENCES

AASHTO (2011). *A policy on geometric design of highways and streets, 6th edition*. American Association of State Highway, and Transportation Officials, Washington, D.C. ISBN: 978-1-56051-508-1

Bassani, M., Catani, L., Ignazzi, A.A., Piras, M. (September, 2018). 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 and Exhibition (pp. 101 108). Antibes, France*. ISBN: 978-2-85782-734-4

Bassani, M., Dalmazzo, D., Marinelli, G., Cirillo, C. (2014). The effects of road geometrics and traffic regulations on driver-preferred speeds in northern Italy. An exploratory analysis. *Transportation Research Part F: Traffic Psychology and Behaviour*, *25*, 10-26. doi: 10.1016/j.trf.2014.04.019

Bella, F. (2013). Driver perception of roadside configurations on two-lane rural roads: Effects on speed and lateral placement. *Accident Analysis and Prevention*, *50*, 251-262. doi: 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 and Prevention*, *43*, 2142-2152. doi: 10.1016/j.aap.2011.06.004

Boer, E. R. (1996, September). Tangent point oriented curve negotiation. In *Proceedings of the Intelligent Vehicles Symposium* (pp. 7-12). IEEE. doi: 10.1109/IVS.1996.566341

Brenac, T. (1996). Safety at curves and road geometry standards in some European countries. *Transportation Research Record: Journal of the Transportation Research Board*, *No. 1523*, 99-106. doi: 10.1177/0361198196152300112

Calvi, A. (2015a). Does Roadside Vegetation Affect Driving Performance? Driving Simulator Study on the Effects of Trees on Drivers' Speed and Lateral Position. *Transportation Research Record: Journal of the Transportation Research Board*, *No. 2518*, 1-8. doi: 10.3141/2518-01

Calvi, A. (2015b). A study on driving performance along horizontal curves of rural roads. *Journal of Transportation Safety and Security*, *7*(3), 243-267. doi: 10.1080/19439962.2014.952468

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 TRB Annual Meeting. Washington, D.C.

Castro, M., Sánchez, J. F., Sánchez, J. A., Iglesias, L. (2011). Operating speed and speed differential for highway design consistency. *Journal of Transportation Engineering*, *137*(11), 837-840. doi: 10.1061/(ASCE)TE.1943-5436.0000309

Castro, M., De Santos-Berbel, C. (2015). Spatial analysis of geometric design consistency and road sight distance. *International Journal of Geographical Information Science*, *29*(12), 2061-2074. doi: 10.1080/13658816.2015.1037304

Coutton-Jean, C., Mestre, D. R., Goulon, C., Bootsma, R. J. (2009). The role of edge lines in curve driving. *Transportation Research Part F: Traffic Psychology and Behaviour*, *12*(6), 483-493. doi: 10.1016/j.trf.2009.04.006

Figueroa Medina, A. M., Tarko, A. P. (2005). Speed factors on two-lane rural highways in free-flow conditions. *Transportation Research Record*, 1912(1), 39-46. doi: 10.3141/1912-05

Hussein, M., Sayed, T., Ismail, K., Van Espen, A. (2014). Calibrating road design guides using risk-based reliability analysis. *Journal of Transportation Engineering*, *140*(9), 04014041. doi: 10.1061/(ASCE)TE.1943-5436.0000694

Kennedy, R. S., Lane, N. E., Berbaum, K. S., Lilienthal, M. G. (1993). Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The International Journal of Aviation Psychology*, *3*(3), 203-220. doi: 10.1207/s15327108ijap0303_3

Jamson, S., Lai, F., Jamson, H. (2010). Driving simulators for robust comparisons: A case study evaluating road safety engineering treatments. *Accident Analysis and Prevention*, *42*(3), 961-971. doi: 10.1016/j.aap.2009.04.014

Langner, R., Steinborn, M. B., Chatterjee, A., Sturm, W., Willmes, K. (2010). Mental fatigue and temporal preparation in simple reaction-time performance. *Acta Psychologica*, *133*(1), 64-72. doi: 10.1016/j.actpsy.2009.10.001

Leisch, J. E., Leisch, J. P. (1977). New concepts in design-speed application. *Transportation Research Record*, *No. 631*, 4-14.

Martens, M. H., Compte, S., Kaptein, N. A. (1997). The effects of road design on speed behaviour: a literature review. Deliverable D1 (Report 2.3.1), *MASTER Project*.

McGehee, D. V., Lee, J. D., Rizzo, M., Dawson, J., Bateman, K. (2004). Quantitative analysis of steering adaptation on a high performance fixed-base driving simulator. *Transportation Research Part F: Traffic Psychology and Behaviour*, *7*(3), 181-196. doi: 10.1016/j.trf.2004.08.001

McGwin Jr, G. (2011). “Independent Variables: The Role of confounding and effect modification”. In: Fisher, D. L., Rizzo, M., Caird, J., Lee, J. D. (2011). In *Handbook of driving simulation for engineering*, *medicine*, *and psychology*. CRC Press, 15:1-8. ISBN: 978-1-4200-6100-0

MIT (1992). Nuovo codice della strada (in Italian). D.L. n.285 of April 30th, 1992, 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 5^{th}, 2001, Ministero delle Infrastrutture e dei Trasporti.

MIT (2016). *Conto Nazionale delle Infrastrutture e dei Trasporti: Anni 2014-2015*, Ministero delle Infrastrutture e dei Trasporti, Istituto Poligrafico e Zecca dello Stato S.p.A., Roma, Italy.

Moreno, A. T., Garcia, A., Camacho-Torregrosa, F. J., Llorca, C. (2013). Influence of highway three-dimensional coordination on drivers’ perception of horizontal curvature and available sight distance. *IET Intelligent Transport Systems*, *7*(2), 244-250. doi: 10.1049/iet-its.2012.0146

Philip, P., Taillard, J., Klein, E., Sagaspe, P., Charles, A., Davies, W. L., Guilleminault, C., Bioulac, B. (2003). Effect of fatigue on performance measured by a driving simulator in automobile drivers. *Journal of Psychosomatic Research*, *55*(3), 197-200. doi: 10.1016/S0022-3999(02)00496-8

R Core Team (2016). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/

Richardson, J. T. (2011). Eta squared and partial eta squared as measures of effect size in educational research. *Educational Research Review*, *6*(2), 135-147. doi: 10.1016/j.edurev.2010.12.001

Said, D., Abd El Halim, A., Hassan, Y. (2009). Desirable spiral length based on driver steering behavior. *Transportation Research Record: Journal of the Transportation Research Board*, *No. 2092*, 28-38. doi: 10.3141/2092-04

Sparks, W. J. (1968). The influence of highway characteristics on accident rates. *Public Works*, *99*(3), 101-103.

Steinauer, B., Trapp, R., Böker, E. (2002). Verkehrssicherheit in Kurven auf Autobahnen. *Straßenverkehrstechnik*, *8*, 389-393.

Summala, H. (1996). Accident risk and driver behaviour. *Safety Science*, *22*(1), 103-117. doi: 10.1016/0925-7535(96)00009-4

Theeuwes, J., Godthelp, H. (1995). Self-explaining roads. *Safety science*, *19*(2), 217-225. doi: 10.1016/0925-7535(94)00022-U

Transportation Research Circular (2011). Modeling operating speed. E-C151 synthesis report. Washington, DC: Transportation Research Board of the National Academies.

Unione Nazionale Rappresentanti Autoveicoli Esteri – UNRAE (2016). *L’auto 2015: Sintesi Statistica. Il Mercato Italiano negli ultimi 10 anni* (in Italian).

Urbanik II, T., Hinshaw, W., Fambro, D. B. (1989). Safety effects of limited sight distance on crest vertical curves. *Transportation Research Record*, *No. 1208*, 23-35.

van der Horst, R., de Ridder, S. (2007). Influence of roadside infrastructure on driving behavior: driving simulator study. *Transportation Research Record: Journal of the Transportation Research Board*, *2018*, 36-44. doi: 10.3141/2018-06

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

Weller, G., Schlag, B., Friedel, T., Rammin, C. (2008). Behaviourally Relevant Road Categorisation: a Step Towards Self-explaining Rural Roads. *Accident Analysis and Prevention*, *40*(4), 1581-1588. doi: 10.1016/j.aap.2008.04.009

Zakowska, L. (2010). Operational and safety effects of transition curves in highway design-A driving simulator study. In *4th International Symposium on Highway Geometric Design*, *Polytechnic University of Valencia*, *Transportation Research Board*.

Zhao, C., Zhao, M., Liu, J., Zheng, C. (2012). Electroencephalogram and electrocardiograph assessment of mental fatigue in a driving simulator. *Accident Analysis and Prevention*, *45*, 83-90. doi: 10.1016/j.aap.2011.11.019