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Original Research Paper

Intelligent speed adaptation for visibility technology affects drivers' speed selection along curves with sight limitations

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HIGHLIGHTS

- Sight obstructions along curves increase the risk of crashes.
- V-ISA can inform, warn, or intervene when drivers are travelling at unsafe speeds.
- A driving simulation study to assess the influence of V-ISA on driver behaviour was performed.
- A significant improvement in the longitudinal and lateral behaviour of drivers was observed.
- The intervening variant was the most effective in promoting safer driving conditions.

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ABSTRACT

Sight obstructions along road curves can lead to a crash if the driver is not able to stop the vehicle in time. This is a particular issue along curves with limited available sight, where speed management is necessary to avoid unsafe situations (e.g., driving off the road or invading the other traffic lane). To solve this issue, we proposed a novel intelligent speed adaptation (ISA) system for visibility, called V-ISA (intelligent speed adaptation for visibility). It estimates the real-time safe speed limits based on the prevailing sight conditions. V-ISA comes with three variants with specific feedback modalities (1) visual and (2) auditory information, and (3) direct intervention to assume control over the vehicle speed.

Here, we investigated the efficiency of each of the three V-ISA variants on driving speed choice and lateral behavioural response along road curves with limited and unsafe available sight distances, using a driving simulator. We also considered curve road geometry (curve direction: rightward vs. leftward). Sixty active drivers were recruited for the study. While half of them (experimental group) tested the three V-ISA variants (and a V-ISA off condition), the other half always drove with the V-ISA off (validation group). We used a linear mixed-effect model to evaluate the influence of V-ISA on driver behaviour.

All V-ISA variants were efficient at reducing speeds at entrance points, with no discernible negative impact on driver lateral behaviour. On rightward curves, the V-ISA intervening variant appeared to be the most effective at adapting to sight limitations. Results of the

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current study implies that V-ISA might assist drivers to adjust their operating speed as per prevailing sight conditions and, consequently, establishes safer driving conditions.

1. Introduction

Speed management is essential for smooth traffic operations and safety. A considerable amount of literature has established the strong relationship between speed and crash frequency/severity (Aarts and Van Schagen, 2006; Elvik, 2013). Evidence confirms that when speed increases, the probability of road accidents increases as well due to the increment in the distance required to safely stop a vehicle and avoid a collision with other vehicles and fixed installations. As a consequence, the probability of preventing accidents at higher speeds is lower (Hauer, 2009). In an attempt to overcome this problem, speed detection installations like speed cameras (Li et al., 2020), and roadway interventions, like special horizontal markings and vertical signs, rumble strips, speed bumps and/or acoustic alerts generated from the road pavement surface (Fu and Liu, 2023; Kang and Momtaz, 2018) have been used. Unfortunately, the effectiveness of these safety countermeasures has proved to be limited (Mountain et al., 2005) mainly due to the event migration phenomenon (Smiley and Rudin-Brown, 2020) by which drivers reduce their speed in the vicinity of speed cameras but then compensate for this reduction by increasing their speed after passing them (Mountain et al., 2005). This behaviour could also lead to an increase in road accidents immediately upstream or downstream of the intervention zone (Mountain et al., 2005). In contrast, in-vehicle solutions operate continuously thus improving driving performances and contrasting aggressive behaviour. Intelligent speed adaptation (ISA) systems could have a positive influence on the mind-set of people who drive aggressively and encourage them to reduce their driving speed (Ando and Mimura, 2015). Carsten and Tate (2005) confirmed the benefits of using ISA devices to reduce crash and death/injury rates.

1.1. Problem statement

Through an onboard navigational system (e.g., GPS) interacting with speed databases (i.e., speed limits), and/or cameras to identify speed limits through traffic sign recognition (vertical signs), current onboard ISA systems communicate the posted speed limit for any specific road section to the driver (Young et al., 2010). Extensive research has shown a decrease in the mean speed and a corresponding positive influence on driving performance (Young et al., 2010). However, in some cases, the functionality of current ISAs may be limited due to unreliable traffic signals or outdated databases that cause the posted speed limit to differ from the actual speed limit. Moreover, in road locations affected by permanent or temporary sight obstructions the speed limit does not, in itself, guarantee safe operations.

Previous research conducted by our laboratory (Bassani et al., 2019a, b) reveals that a significant number of drivers when negotiating curves with limited sight distance, limit their driving speed and modulate the lateral position of the vehicle to avoid collisions with unexpected objects along the non-visible part of the curve. They operate the vehicles at low speeds (which reduces the stopping distance) and/or keep a judicious lateral distance from the sight obstruction to benefit in terms of an increase in available sight distance (Fig. 1). Nevertheless, some drivers are not able to accurately judge the risk level associated with curves hampered by limited sight conditions, so they negotiate the curves in unsafe conditions (Bassani et al., 2019b). Evidence indicates that drivers overestimate the sight distance, as a result, they

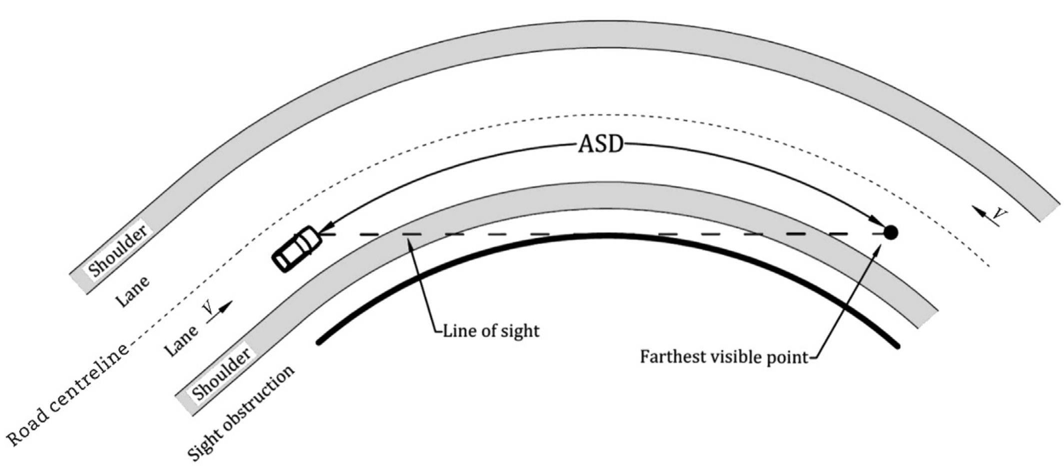


Fig. 1 – Available sight distance along a rightward curve from driver point of view (note: *V* represent direction of traffic flow).

operate at driving speeds that would require longer stopping distances (SD) than the available sight distance (ASD).

1.2. V-ISA systems

In our previous study (Hazoor et al., 2021)-to assist driver operating speed decisions when negotiating curves with limited sight distance-we proposed and developed a concept for an innovative ISA called "V-ISA", where "V" stands for visibility. It operates by comparing the ASD values with the vehicle stopping distance in the event of an emergency braking manoeuvre. In particular, the system estimates (i) the distance from the driver point of view to the farthest visible point along the driving trajectory, i.e., ASD, and (ii) the distance required to come to a complete stop in the event of an emergency braking manoeuvre, i.e., the SD. At present, V-ISA has been implemented in a virtual simulation environment, in a manner consistent with current road design standards (AASHTO, 2018; MIT, 2001), it operates to guarantee.

$$\mathrm{SD}\ (\upsilon, f, i) \leq \mathrm{ASD}(s) \tag{1}$$

where ASD(s) is the real-time available sight distance at a specific station (s).

$$\mathrm{SD} = \upsilon\tau + \frac{\upsilon^2}{2g(f \pm i)} \tag{2}$$

where υ is the real time vehicle speed, τ is the assumed perception and reaction time (s), SD is estimated in accordance with the Italian highway design policy (i.e., $\tau = 2.8–0.01\upsilon$, with υ in km/h), f is the friction value between tire and road pavement, and i is the longitudinal road grade (MIT, 2001).

V-ISA algorithm can perform a real-time comparison at a frequency of 100 Hz between the ASD and SD values (Fig. 2(a)), assisting or interacting with the driver in three alternative ways (variants).

(i) V-ISA1 assists drivers with visual information on sight conditions through a coloured LED in the lower part of the windscreen (Fig. 2(b)).
(ii) V-ISA2 alarms drivers with an auditory warning when they operate in an unsafe condition (i.e., ASD < SD) finally.
(iii) V-ISA3 actively prevents drivers from exceeding a safe threshold speed limit by acting on both gas (acceleration) and brake pedals.

The functionality, validation, and acceptability of the V-ISA considering the human-machine interaction (HMI) methodology were acquired prior to this study (Hazoor et al., 2021, 2022).

1.3. Objectives

The purpose of the present driving simulation-based study is to examine the efficiency (effectiveness) of three V-ISA variants (i.e., V-ISA1, V-ISA2, and V-ISA3) to assist drivers or speed control as a safety performance measurement (Tarko, 2019); specifically, we focused on the operating speed and lateral driver behaviour (lateral control) when negotiating road curves with limited sight distance.

2. Method

2.1. V-ISA design: functionality and operations

V-ISA was conceived in the SCANeR Studio™ driving simulator environment working in parallel with MATLAB Simulink environment (model) as a co-simulation. In the process of co-simulation, data from the road environment, vehicle dynamics, and virtual advanced driver assistance system (ADAS) sensors on the ego-vehicle were treated in MATLAB Simulink. In this study, the dynamic virtual road sensor points (Fig. 3(a)) were placed in front of the ego vehicle; they had a range of 300 m and were used to measure the distance from the farthest visible point to the driver point of view along the lane centreline (Hazoor et al., 2021). Subsequently, ASD values were detected instantaneously and used to inform (V-ISA1) or warn (V-ISA2) drivers about the safety conditions

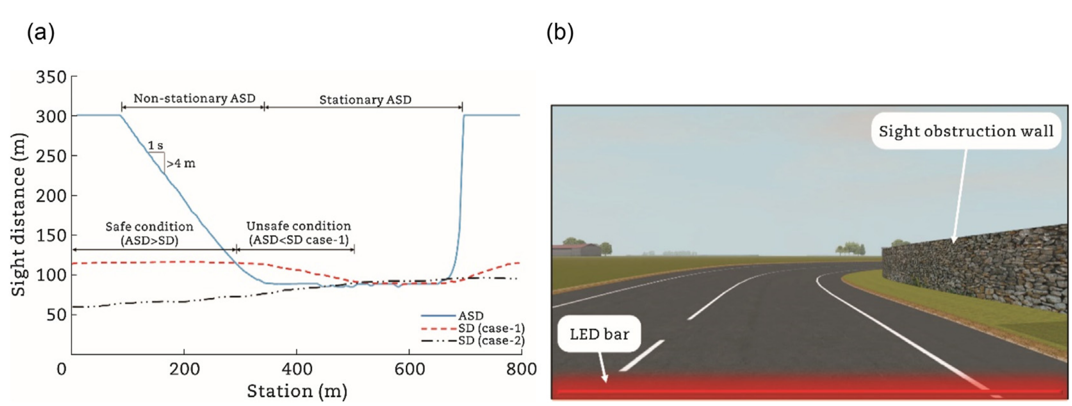
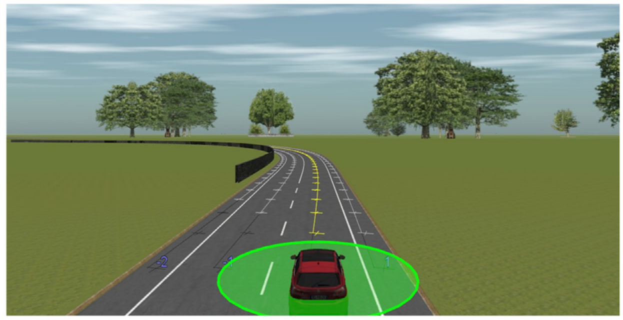


Fig. 2 – An example demonstrating the operational functionality of the V-ISA algorithm. (a) An illustration of ASD profiles in stationary and non-stationary conditions along a rightward curve with a radius of 225 m, a further illustration of SD profiles when the driver approaches the unsafe condition in non-stationary ASD (case-1) and stationary ASD (case-2). (b) An informative LED bar at the bottom of the driver front display when negotiating a rightward curve during the experimental drive (note: LED bar colour depends on the V-ISA variant and on the sight condition as per the synthesis in Table 1).

(a)



(b)

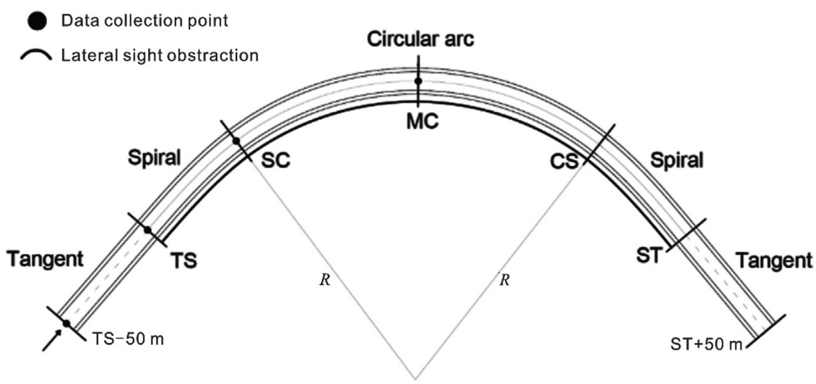


Fig. 3 – Typical curve scenario used in the formation of the 3D simulation modal. (a) Distribution of dynamic road-sensor markers in front of the ego vehicle in the simulation environment to locate the farthest visible point at the centre of the driving lane. (b) Reference points along the generic road curve, considered for the analyses of collected data.

(safe/unsafe), and, if necessary, prompt them to adapt their speed to the prevailing sight conditions (Eq. (1)).

Equating the two members in Eq. (1) and substituting the SD value from Eq. (2), the speed threshold (v_L) that separates safe driving conditions (when $v \leq v_L$, then SD $\leq$ ASD) from unsafe ones (when $v > v_L$, then SD > ASD) is obtained (Hazoor et al., 2021) for the operation of the intervening V-ISA variant. Furthermore, when driving along a curve, the ASD depends on road geometry and the presence or otherwise of sight obstructions. ASD conditions can be distinguished as (i) stationary and (ii) non-stationary as represented in Fig. 2(a). In the case of non-stationary conditions, the reduction in ASD from the preceding time step (1 s) remains 4 m or higher ($ASD_{t-1} - ASD_t \geq 4$ m) where t represents the current/running time of the simulation (Hazoor et al., 2022).

V-ISA can discriminate between safety conditions based on the value of (ASD − SD), distinguishing stationary from non-stationary conditions (Table 1, Fig. 2(a)). If the driver approaches the unsafe condition (ASD < SD) in non-stationary ASD as exemplified by the SD case-1 in Fig. 2(a), V-ISA1, based on the driver's previous behaviour while driving (i.e., speed and lateral position), can react by changing the bottom LED light on the front windscreen from green to yellow, and from yellow to red if the ASD falls below the SD (Fig. 2(b)). Similarly, V-ISA2 alerts the driver to possible danger by changing the acoustic signal from none to low, and from low to loud. The following pre-information in the case of V-ISA1 (yellow) and pre-alert in the case of V-ISA2 (low warning) was assigned to the variant as a rapid reduction in the ASD could be considered riskier and it would be better to encourage drivers to decrease their speeds earlier and, thereby, avoid reaching the unsafe condition. However, if the driver is approaching the unsafe condition in stationary ASD as exemplified by SD case-2 in Fig. 2(a), the system provides information (red LED) or generates an alert (loud warning) only when the driver has actually reached the unsafe condition (ASD < SD) without providing any pre-information and pre-alert in the cases of V-ISA1 and V-ISA2 respectively.

Table 1 – Synthesis of the information, warning and intervention of the three V-ISA variants.

Condition	ASD − SD (m)	V-ISA1 (visual)	V-ISA2 (warn)	$v_L - v$ (km/h)	V-ISA3 (visual)	V-ISA3 (intervention)
Non-stationary	>20	Green	–	>15	Green	–
	≤20, ≥0	Yellow	Low	≤15, >5	Blue	Gas deactivation
	<0	Red	Loud	≤5	Blue	Brake activation
Stationary	≥0	Green	–	>0	Green	–
	<0	Red	Loud	≤0	Blue	Gas deactivation

Table 2 – Minimum ASD values for the combination of curve radius, curve direction, and distance from the road edge to the lateral sight obstruction wall (*d*).

Radius (m)	Leftward curve (m)			Rightward curve (m)		
	$d = 0$	$d = 1.5$	$d = 3.0$	$d = 0$	$d = 1.5$	$d = 3.0$
120	83.8	92.3	100.1	56.6	68.1	78.0
225	114.0	125.5	136.1	77.7	93.5	106.9
300	131.4	144.7	156.8	89.8	108.0	123.5
430	157.1	172.9	187.4	107.6	129.3	148.0

In contrast, V-ISA3 operates in stationary and non-stationary conditions based on the value ($v_L - v$) as described in Table 1. This variant deactivates the gas pedal and activates the brake pedal for drivers with case-1 type behaviour (Fig. 2(a)) so as to maintain a speed below that of the threshold speed limit, while in the case-2 type behaviour (Fig. 2(a)) the variant only deactivates the gas pedal with the intervening function and restricts the speed to below the threshold speed limit. Moreover, during the intervention from the system (on gas and brake pedals), the driver is informed by changing the LED light from green to blue on the windscreen (Table 1).

2.2. *Experimental design and participants*

The study, designed in accordance with the Code of Ethics of the World Medical Association (WMA, 2018), was approved by the Polytechnic of Turin's Institutional Review Board. We designed a factorial, repeated-measures design with (i) V-ISA four level variants (i.e., V-ISA off (baseline), V-ISA1, V-ISA2, and V-ISA3); and (ii) two levels for curve direction, i.e., left and right, as the within-subject factors.

Furthermore, we recruited a validation group (as a control strategy) to ensure that the selected drivers were representative of the general Italian driving population. We used a convenience sampling method to recruit 60 drivers from a database of more than 500 volunteers. The number of participants was considered appropriate based on a previous cohort where statistically significant differences in driving performance metrics were found between different ISA systems (Hazoor et al., 2022) and sight limitations (Bassani et al., 2019a). The sixty participants (34 males and 26 females) were divided into two groups, each consisting of 30 participants (17 males and 13 females) aged between 21 and 59 (for more details see Table 3).

2.3. *Road scenario and equipment*

We designed a two-lane road alignment was designed with a 3.75 m lane width and 1.5 m shoulder width as per Italian Geometric Design Standards for highways and streets (MIT, 2001). The total length of the road alignment (road segment) was 12.9 km. Combinations of four different curve radii (120, 225, 300, and 430 m) were included in the track in a random order. To change the sight conditions at each curve, a 2 m high stone wall was placed along the inner side of the horizontal curves at different distances from the inner pavement edge (i.e., 0, 1.5, and 3 m). The alignment was manipulated by combining radii (*R*), sight obstruction distances (*d*) from the road edge, and rightward (RW) and leftward (LW) curve directions. The different curve radii were selected in the design speed variation range of 60–100 km/h as per Italian road design policy (MIT, 2001), and a combination of sight obstruction distances to obtain a variation in ASD values (Table 2). To minimize any anticipation strategies, three (out of eighteen) curves had unrestricted sight conditions (i.e., $d = \infty$, no wall). Straight segments in a 110–300 m range were included between curves. Table 2 provides the minimum (stationary) ASD values computed with the combination of curve radii (*R*), sight obstruction distances (*d*), and curve directions. It is important to point out that the ASD values listed in Table 2 are conventional and computed considering the observer's point of view and the farthest visible point along the lane centreline (Fig. 1). However, these ASD can be different for each driver considering the actual lateral position of the vehicle in the lane (i.e., variation in the ASD values caused by lateral distance from the lane centreline) (Bassani et al., 2019b). The V-ISA system is capable of estimating the actual ASD values with respect to the longitudinal as well as lateral position of the vehicle (Hazoor et al., 2021).

Table 3 – Descriptive statistics of the recruited participants.

Characteristic	Gender	Experimental group	Validation group	t-test	
		M (SD)	*M* (SD)	t (df)	*p*
Age (year)	Male	38.8 (12.1)	40.4 (12.7)	−0.387 (32)	0.702
	Female	41.5 (10.2)	38.2 (11.7)	0.787 (24)	0.439
	Total	40.0 (11.2)	39.4 (12.1)	0.177 (58)	0.860
Driving experience (year)	Male	19.5 (11.4)	21.3 (12.3)	−0.445 (32)	0.659
	Female	22.8 (9.4)	19.1 (11.3)	0.905 (24)	0.375
	Total	20.9 (10.6)	20.3 (11.7)	0.203 (58)	0.840
Distance travelled (km/year)	Male	13,219 (13,200)	16,000 (9402)	−0.686 (32)	0.498
	Female	8173 (5427)	6538 (4365)	0.846 (24)	0.406
	Total	10,957 (10,606)	11,759 (8858)	−0.312 (58)	0.756
Crash experience (#)	Male	1.0 (1.5)	1.8 (2.5)	−1.090 (32)	0.286
	Female	0.6 (0.8)	0.8 (0.9)	−0.461 (24)	0.649
	Total	0.8 (1.3)	1.3 (2.0)	−1.160 (58)	0.250

Note: *M* means mean value, SD means standard deviation, df means degree of freedom.

Random traffic was simulated in the opposite oncoming direction, and free-flow driving conditions were guaranteed during the experiments. To enable drivers to adopt speeds consistent with their driving style, no vertical signs with speed restrictions were displayed along the track.

A fixed-base driving simulator (AV Simulation, France) was used to conduct the experimental drives. The driving simulator achieved a relative validation for longitudinal (Bassani et al., 2018; Catani, 2019), transversal (Catani and Bassani, 2019) and driving operations (Karimi et al., 2020). In general, relative validity occurs when experimental factors show a similar pattern of results/effects in both simulated and real environments but differ in magnitude (Wynne et al., 2019).

In this study, the ego vehicle was equipped with a virtual road sensor with a 120° horizontal and a 60° vertical field of view able to quantify the available sight distance values in real-time from the driver's point of view. It recognizes the presence of virtual road markers placed along the lane centreline (Fig. 3(a)). The distance measured from the farthest visible marker to the sensor position was assumed to be the ASD (Hazoor et al., 2021). In Fig. 3, road markers are distributed with a longitudinal gap of 4 m with maximum range of 300 m from the ego vehicle. TS stands for tangent to spiral point, SC stands for spiral to curve point, MC stands for middle of the curve point, CS stands for curve to spiral point, ST stands for spiral to tangent point, *R* stands for radius of the circular arc.

2.4. *Protocol*

The study took place at the Laboratory of Road Safety and Driving Simulation (RSDS Laboratory) at the Department of Environment, Land and Infrastructure Engineering (Politecnico di Torino, Torino, Italy). The experimental group completed two driving sessions. In each session, to prevent simulator sickness or fatigue (Philip et al., 2003), they drove along two pre-selected scenarios (separated by a short 5-min break). The sequence of four scenarios (over the two driving sessions) was randomly assigned. The validation group completed only one driving session with the same scenarios but with the system off (baseline condition). Before the driving task, each test driver completed a pre-drive questionnaire on their health and physical conditioning. The questionnaire was also used to ascertain if the drivers were undergoing any medical treatment that could have had a bearing on their behaviour. The driving simulation was preceded by a test drive to allow the drivers gain familiarity and confidence with the equipment and the virtual environment (Rizzo et al., 2001). The functionality of the three V-ISA variants and the descriptions of the pre-selected scenarios were explained to each participant (in the experimental group only) before the drive. A post-drive questionnaire was designed based on suggestions from Kennedy et al. (1993), to collect information on the driving experience and any possible simulation sickness experienced (Brooks et al., 2010).

2.5. *Observed variables*

Driving data in terms of speed (S) and lateral position (LP) were collected along the road alignment at a frequency of 10 Hz. Further, the following experimental (dependent) variables were analysed at specific points for each road curve as exemplified in Fig. 3(b).

(i) The longitudinal speed (S_{SC}) at the spiral to curve point and the curve entrance speed variation (ΔS) between TS − 50 m (TS stands for tangent to spiral) and MC (middle of the curve) points.

(ii) The lateral position (LP_{SC}) at spiral to curve point and variation of lateral position (ΔLP) between TS and SC points.

(iii) The standard deviation of lateral position (SDLP), which is the standard deviation of the distances between the vehicle centre of gravity and the lane centreline, measured from TS − 50 m and MC sections.

2.6. *Statistical analysis*

A series of linear mixed-effect models (LMMs) (Woltman et al., 2012) were used to estimate the influence of the contributing (experimental) factors on driver behaviour. The LMM assumption for the normality of residuals was assured using the Kolmogorov-Smirnov (KS) test. However, in the case of SDLP that condition was not satisfied, and the generalized linear model (GLM) was used to determine the effects on the dependent parameter. Furthermore, as a control strategy to ensure that our experimental group was representative of the general driving population, we performed several one-way analysis of variance (ANOVAs), comparing the behaviour of the group (while driving with the system off) to that of the validation group (a group that did not experience the V-ISA1-3 variants). Finally, to ensure that both groups (experimental and validation) shared the same characteristics (i.e., age, driving experience in years, distance travelled per year, and total number of crashes) we used several independent *t*-test samples. Statistical data analysis and model calibration was carried out with Jamovi software (version 2.2.2.0). In the case of data analysed using a within-subject design, (comparing each driver to himself/herself), the variability among drivers was part of the error term. For multiple comparisons, we applied the Bonferroni alpha-inflation correction with significance levels set at 95%.

3. Results

3.1. *Sample characteristics*

Both groups exhibited similar characteristics in that they did not differ in their mean age, years of driving experience, distance travelled per year, and number of crashes (all p-values > 0.05, Table 3).

3.2. *Group assessment*

Drivers from both groups assumed the same longitudinal behaviour along curves with the same geometrical characteristics ($p > 0.05$). These results are consistent with the initial hypothesis and therefore confirm that, despite repeated exposure to the driving environment, road familiarity and

Table 4 – Linear mixed model and generalized linear model outputs on significant factors influencing speed at SC point (S_{SC}), speed variation (ΔS), lateral position at SC (LP_{SC}) and variation of lateral position (ΔLP).

Factors, covariates, and cluster	Effect	Estimate (significance level)				
		LMM				GLM
		S_{SC}	ΔS	LP_{SC}	ΔLP	SDLP
Fixed effects						
Intercept		89.09***	6.15***	−0.35**	0.07***	0.34***
V-ISA	V-ISA1-base	−4.70***	2.99***	0.05*	−0.08**	−0.03**
	V-ISA2-base	−6.93***	2.92***	–	–	–
	V-ISA3-base	−11.87***	6.03***	−0.08**	–	–
CD	RW-LW	−11.44***	4.10***	−0.64***	1.20***	0.06***
Gender	M-F	–	–	–	0.09*	0.04***
V-ISA × Gender	V-ISA1-base × M-F	−9.99***	–	–	–	–
	V-ISA2-base × M-F	−4.97***	–	–	–	–
	V-ISA3-base × M-F	−9.19***	–	–	–	–
V-ISA × CD	V-ISA1-base × RW-LW	–	2.81*	0.20***	−0.23***	–
	V-ISA2-base × RW-LW	–	2.93*	–	–	–
	V-ISA3-base × RW-LW	−11.45***	8.72***	−0.15**	–	–
Random effects		(<0.001)	(<0.001)	(<0.001)	(<0.001)	–
Test driver ID						

Note: CD means curve direction, RW means rightward, LW means leftward, M means male, F means female; significance level * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

interaction with V-ISA variants did not have a significant influence on longitudinal behaviour. Moreover, the same comparison was made for transversal behaviour considering the lateral position of the vehicle from the lane centreline. A significant difference between the two groups was observed for one RW curve with $R = 430$ m, $d = 3$ m ($LP_{SC,experimental} - LP_{SC,validation} = 0.31$ m, $F_{1,58} = 11.35$, $p = 0.001$), in five curves the one-way ANOVA revealed a marginal difference between the two groups, while in other comparisons no significant difference was observed. A possible explanation for this slight difference between the groups may be attributable to the driving styles of individual participants. Unfortunately, we did not investigate this variable. Hence, it could be inferred that the assignment of scenarios in random order for repeated measurement has a negligible learning effect on the transversal behaviour of drivers. This evidence can be used to assess the results for the experimental group considering repeated measure design including the baseline (system off) and V-ISA variants assigned in random order, and it will be further addressed in sections 3.3 and 3.4.

3.3. Speed

To address the first research objective which was to determine how effective V-ISA variants are in reducing speed along curves and, hence, in improving driving performance and safety, operating speed values were examined and compared with the baseline scenario (system off) by considering within-subject design. Speed at SC for the base condition remains higher than with the V-ISA variants ($S_{SC,base} - S_{SC,V\text{-}ISA1} = 4.70$ km/h, $p < 0.001$; $S_{SC,base} - S_{SC,V\text{-}ISA2} = 6.93$ km/h, $p < 0.001$; $S_{SC,base} - S_{SC,V\text{-}ISA3} = 11.87$ km/h, $p < 0.001$). A Bonferroni adjusted post-hoc comparison between the V-ISA variants shows statistically significant differences ($S_{SC,V\text{-}ISA1} - S_{SC,V\text{-}ISA2} = 2.23$ km/h, $p = 0.005$; $S_{SC,V\text{-}ISA1} - S_{SC,V\text{-}ISA3} = 7.17$ km/h, $p < 0.001$; $S_{SC,V\text{-}ISA2} - S_{SC,V\text{-}ISA3} = 4.94$ km/h, $p < 0.001$) with the V-ISA3 (intervening variant) having the lowest values.

Moreover, any variation in speed (ΔS) between the entrance to the curve (TS−50 m) and the middle of the curve (MC), significant differences were observed with a reduction in speed when drivers were assisted with the V-ISA variants ($S_{\Delta S,V\text{-}ISA1} - S_{\Delta S,base} = 2.99$ km/h, $p < 0.001$; $S_{\Delta S,V\text{-}ISA2} - S_{\Delta S,base} = 2.92$ km/h, $p < 0.001$; $S_{\Delta S,V\text{-}ISA3} - S_{\Delta S,base} = 6.03$, $p < 0.001$) (Tables 4 and 5).

The speed results (S_{SC} and ΔS) are also coherent with the curve direction (CD) ($S_{SC,RW} - S_{SC,LW} = -11.44$ km/h, $p < 0.001$; $S_{\Delta S,RW} - S_{\Delta S,LW} = 4.10$ km/h, $p < 0.001$), as in the case of rightward curves (RW) for which visibility is more limited, thereby leading to lower ASD values and, consequently, more frequent interaction between the driver and the system (Bassani et al., 2019b; Hazoor et al., 2022). However, in the case of leftward (LW) curves with higher ASD values, a Bonferroni corrected post-hoc comparison revealed no significant differences in speed variation (ΔS) among V-ISA variant levels including the baseline condition ($p > 0.05$).

Table 5 – Summary statistics.

Summary statistics	Estimate (significance level)				
	LMM				GLM
	S_{SC}	ΔS	LP_{SC}	ΔLP	SDLP
AIC	14,145	13,363	1935	1693	−1676
BIC	14,195	13,425	2031	1831	−1599
R^2 marginal	0.225	0.106	0.366	0.704	0.079
R^2 conditional	0.560	0.230	0.435	0.715	–
ICC	0.433	0.139	0.109	0.037	–
Observations	1800	1800	1800	1800	1800
Drivers	30	30	30	30	30
Observations/driver	60	60	60	60	60
KS test for normality of residuals (p-value)	0.098	0.215	0.408	0.486	–

Another important outcome refers to the speed at S_{SC} and speed variation (ΔS) values. Both variables are not influenced by gender. The LMM output with V-ISA and gender interaction for S_{SC} supported with Bonferroni adjusted post-hoc comparison at a significance level of 95% (for most cases $p < 0.001$) reveals that male and female drivers adopted the same behaviour when using the system with V-ISA3 being the most effective variant followed by V-ISA2 and V-ISA1 in terms of operating speed at curve entrance and speed variation. The output implies that the workability/functionality of the V-ISA variants are effective for both male and female drivers. However, the differences in groups under V-ISA variant and gender interaction (V-ISA × Gender, Table 4) are based on the different driving styles for males and females, with females being more prudent (Degraeve et al., 2015).

3.4. *Lateral position*

A comparison of V-ISA1 and the baseline condition for dependent variable LP_{SC} reveals a significant difference between the groups ($LP_{SC,V\text{-}ISA1} - LP_{SC,base} = 0.048$, $p < 0.001$). The positive value of the estimates in the case of LP_{SC} suggests that drivers tended to drive more in the centre of the lane than they do with the baseline condition. In terms of lateral shift, lower values of ΔLP were observed for V-ISA1 ($\Delta LP_{V\text{-}ISA1} - \Delta LP_{base} = -0.08$, $p < 0.001$), which implies that drivers assisted by the information variant require less correction to their trajectory while negotiating curves.

In the case of V-ISA2 no statistically significant difference was found in a comparison with the baseline condition for the transversal dependent variable LP_{SC} and the output also suggests that drivers maintain the same lateral position without any significant difference in ΔLP. However, V-ISA3 provides negative values for the model estimates at SC ($LP_{SC,V\text{-}ISA3} - LP_{SC,base} = -0.08$, $p = 0.002$) which indicates that most drivers drove along the left side of the lane in contrast to how they drove with the base condition. Further on, it was observed in the post-hoc analysis that most of the drivers along rightward curves tend to drive on the right side of the lane without any lateral shift (ΔLP) ($LP_{SC,\ RW,V\text{-}ISA3} - LP_{SC,\ RW,\ base} = -0.16$, $p < 0.001$) and no differences were detected between the baseline condition and V-ISA3 on leftward curves.

The geometrical curve direction factor (CD) reveals a significant difference between leftward and rightward curves ($LP_{SC,RW} - LP_{SC,LW} = -0.64$, $p < 0.001$). These outcomes were expected as drivers travelling along curves occupy different lane positions for leftward and rightward directions and results are consistent with previous studies focusing on the geometrical parameters of the road (Bassani et al., 2019a, b). Furthermore, the interaction between V-ISA variants and gender shows no statistically significant difference between groups for LP_{SC} and ΔLP (Table 4). The effect(s) of the system on both male and female transversal behaviour remains the same for the respective variants. However, interaction with the curve direction (CD) yielded significant differences for LP_{SC}.

Turning now to the other interesting output related to from generalized linear model (GLM) for the lateral performance for lane-keeping measured in terms of the SDLP in the event of external/internal disruptions (Zhou et al., 2008). When assisted with V-ISA1 (information variant), as provided in Table 4, lower values for SDLP were observed when compared with the baseline (system off) condition ($SDLP_{V\text{-}ISA1} - SDLP_{base} = -0.03$, $z = -2.60$, $p = 0.009$). The decrease in SDLP values indicates that drivers have more lateral control and stability over the vehicle along the curves (Calvi, 2015). On the other hand, when compared to the baseline condition, V-ISA2 (warning) and V-ISA3 (intervening) did not show any statically significant difference (Table 4).

4. Discussions

This study reflects the capability of the intelligent speed adaptation for visibility (V-ISA) variants to play a significant role in road safety improvement in terms of crash mitigation, while also ascertaining their impact on driver behaviour. In this study, drivers were given driving tasks which necessitated interaction with the three V-ISA variants (V-ISA1 information, V-ISA2 auditory, and V-ISA3 intervening) together with the system off included as the baseline condition. We studied the effect(s) of V-ISA variants on drivers' longitudinal behaviour (speed) and lateral behaviour (lateral position) in a simulated driving environment.

4.1. *Influence of V-ISA on longitudinal behaviour*

The results for speed indicated that the use of the V-ISA variants could indeed enhance safety along sections with limited sight distances. The continuous visual feedback (LED bar) in the case of V-ISA1 was effective in influencing drivers' longitudinal behaviour and in assisting them to adopt safe driving practises (Fig. 4). This finding is consistent with that of Laquai et al. (2011) and Meschtscherjakov et al. (2020) who showed that the LED bar offers a viable way to attract the driver's attention particularly when he/she is negotiating a curve. Providing acoustic alerts (V-ISA2) when the driver approaches or operates in an unsafe condition (SD < ASD) had a significant effect on driver speed choice compared with the baseline scenario (system off). In terms of operating speed at curve entrance (Fig. 4(a)) and speed variation along the curve (Fig. 4(b)), a Bonferroni-corrected post-hoc did not reveal any significant difference in the effectiveness of the two V-ISA variants (V-ISA1 and V-ISA2). In reviewing the literature, drivers usually found the sound warning system annoying and if possible, they kept the warning systems off after multiple activations (Braitman et al., 2010; Wiese and Lee, 2004). Similarly, in our previous study (Hazoor et al., 2022), most drivers were dissatisfied with the use of V-ISA2 due to the associated acoustic alerts while driving.

As described in the previous section, the V-ISA3 (intervening variant) acts on the vehicle gas and brake pedals when the driver approaches unsafe sight conditions (i.e., ASD < SD) and limits the operating speed under the safe speed limit. In line with the V-ISA3 functionality, we observed lower operating speed values (S_{SC}) as compared to the other two variants (V-ISA1 and V-ISA2) as shown in Fig. 4(a). Considering the functionality and robustness of the V-ISA3 variant in preventing drivers under safe threshold speed limits, makes the variant most effective compared to other variants in

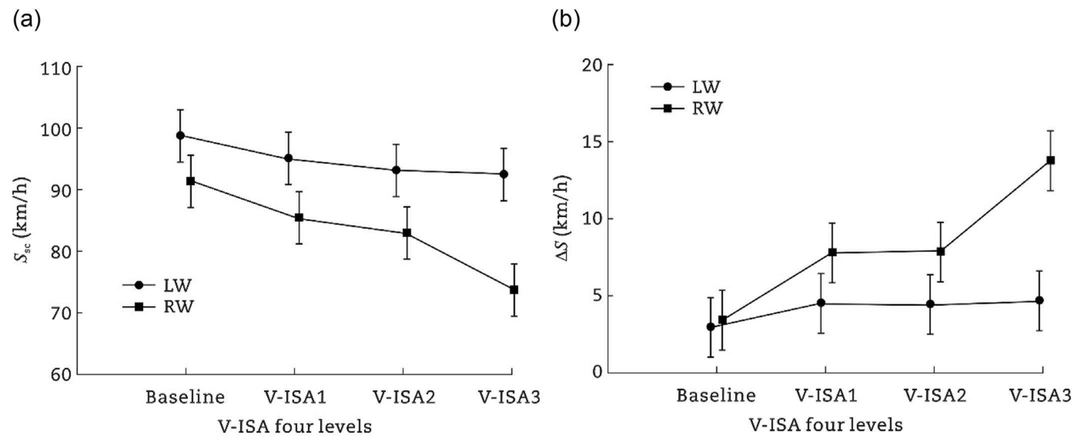


Fig. 4 – Graphs presents estimated marginal means. (a) Speed at spiral to curve point (S_{SC}). (b) Speed variations (ΔS), from all participants (note: $n = 30$, for leftward (LW) and rightward (RW) curves, ΔS (+) represents a reduction in speed, error bars represent 95% confidence interval).

terms of safety. Nevertheless, it should be highlighted that V-ISA1 and V-ISA2 were also capable of communicating or assisting the drivers efficiently vis-à-vis visual information and acoustic alerts respectively (Fig. 4(a)). These results are in accordance with previous studies on the use and impact of intelligent speed adaptation systems on longitudinal driver behaviour (Spyropoulou et al., 2014). The significant reduction in variable ΔS implies that the V-ISA variants encourage/oblige the driver to maintain a safe operating speed at the curve entrance in contrast to what happens with the baseline condition where most of the drivers were not able to accurately judge what speed levels would be appropriate and safe (Bassani et al., 2019a, b).

4.2. *Influence of V-ISA on lateral behaviour*

The in-vehicle assistance system with visual display or acoustic alerts can attract the driver's attention and influence lane-keeping performance (Kircher et al., 2014). We found no significant evidence that V-ISA feedback modalities (visual and acoustic) or the intervening functionality resulted in driver distraction or had other negative consequences. As noted earlier in the results section, there were no significant differences between groups for leftward curves in terms of lateral position at curve entrance (LP_{SC}) and variation of lateral position (ΔLP) as illustrated in Fig. 5(a) and (b). The V-ISA variant effects were mostly evident with the rightward curves (Fig. 5). The reason is apparent when one considers that leftward curves result in less interaction and use of the system as a result of higher sight distances compared to rightward curves (Bassani et al., 2019a, b). Drivers when assisted with V-ISA1 tend to move towards the centre of the lane compared to the baseline condition at curve entrance (Fig. 5(a)). Drivers compensated for this transversal behaviour along the curve with lower lateral position variation values (ΔLP) as illustrated in Fig. 5(b). In Fig. 5, LP (+) means vehicle on the left side of the lane centreline, LP (–) means vehicle on the right side of the lane centreline, ΔLP (+) means rightward shift, ΔLP (–) means leftward shift, error bars represent 95% confidence interval.

It is worth mentioning that no significant difference ($p > 0.10$) was observed for LP_{SC} and ΔLP when considering the baseline condition and V-ISA2 (warning) variant along rightward and leftward curves (Fig. 5). One possible reason is that in both cases (scenarios) no visual information was provided to the drivers during the experimental drive, and the V-ISA2 (warning) variant may be viewed as an effective speed

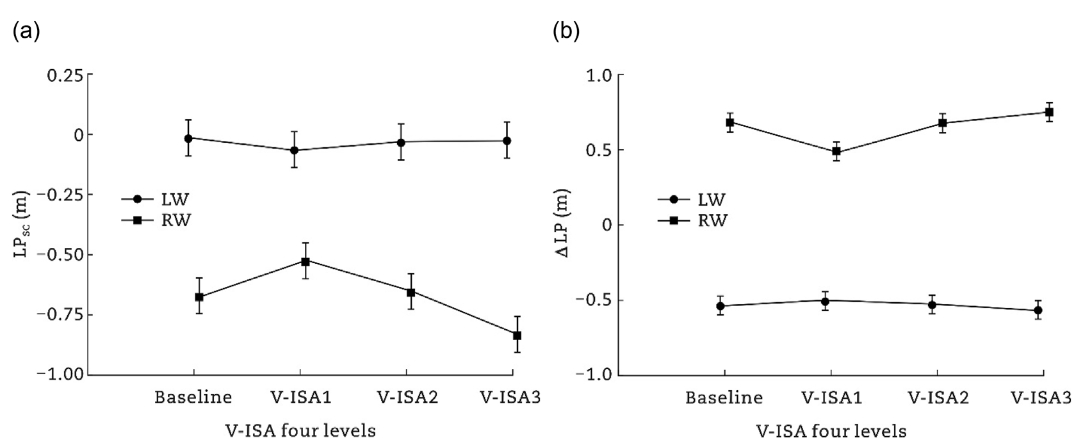


Fig. 5 – Graphs presents estimated marginal means (note: error bars represent 95% confidence interval). (a) Lateral position at spiral to curve point (LP_{SC}). (b) Variation of lateral position (ΔLP) at the entrance of the curve, from all participants ($n = 30$) for leftward (LW) and rightward (RW) curves.

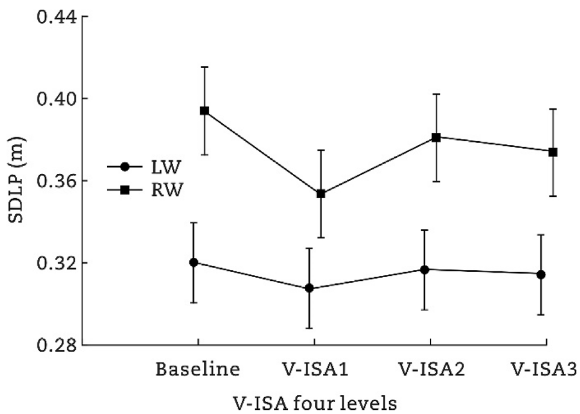


Fig. 6 – Graph presents estimated marginal means of standard deviation of lane position (SDLP) at the entrance of the curve, from all participants ($n = 30$) for leftward (LW) and rightward (RW) curves (note: error bars represent 95% confidence interval).

reduction measure with the warning/alert sound emitted not having a negative influence on driver transversal behaviour.

The transversal driving behaviour on the right side of the lane is adjudged to be positive in safety terms during passing manoeuvres and is likely to be related to the left side lateral shift compensation mechanism to increase the ASD along rightward curves for safe manoeuvres (Bassani et al., 2019b). However, in the case of V-ISA3, the speed was controlled autonomously, and drivers were visually informed, so they maintained their trajectory on the right side of the lane without the need for a lateral shift compensation mechanism. The V-ISA3 (intervening) variant was determined to be the most effective at maintaining the operating speed within safe limits as discussed in the previous section. Overall results for driver transversal behaviour suggest that the use of V-ISA variants discourages drivers from adopting a lateral shift manoeuvre to increase ASD. It should be noted that this manoeuvre is deemed a hazardous risk in road safety (Bassani et al., 2019b).

Drivers' lateral control of the vehicle or lane-keeping performance (SDLP) was consistent across all V-ISA variants and the baseline condition (Fig. 6). V-ISA variants did not show any adverse reaction and there was no evidence of a deterioration in driving performance. It is important to point out that the SDLP was measured along the road sections where the possibility of driver interaction with the V-ISA variants were higher (i.e., at curve entrances). A significant difference was observed only for V-ISA1 compared to the baseline condition. In this case, lane-keeping performance increased (reduction in SDLP) when drivers were assisted with the continuous visual information variant (V-ISA1).

5. Conclusions, implications, and future needs

The use of V-ISA variants has a significant effect on driver speed choice at the curve entrance. When receiving continuous visual information (V-ISA1), drivers adopt safer speed profiles with a corresponding and noticeable reduction in speed. Hence, the provision of visual information proved effective and encouraged the driver to maintain a safe driving behaviour which was appropriate for the prevailing visibility conditions. In previous studies, it was found that these displays of information could be a source of distraction for drivers. Conversely, the SDLP indicates that drivers were more in control and improved their driving performance while using V-ISA1 with drivers also managing to adopt a more central position in the lane. Similar speed decisions were observed in the case of V-ISA2, although sound alerts were provided when drivers operated at speeds associated with unsafe sight conditions (ASD <SD). Interestingly, drivers did not show any significant differences in their transversal behaviour when subjected to acoustic alerts (waring V-ISA variant) and maintained the same lateral position as for the baseline condition (system off).

As expected, V-ISA3 was superior to the other two variants in terms of safety, as speed choice along the curves was controlled by the system vis-à-vis the intervening function. Interestingly, the intervening operation (in which drivers had to relinquish control over driving speed) did not appear to affect their lateral behaviour with the same analysed values of SDLP and ΔLP as a baseline condition. In addition, it was noted that drivers reacted in a positive manner by driving more towards the inner side of the lane.

Overall, this study reinforces the concept that vehicles should be equipped with a system that assists drivers with real-time safe speed limits along road sections (i.e., curves) where sight distance is limited due to the presence of temporary or permanent obstructions in the driver line of sight. Although the study provides promising results in terms of V-ISA performance, the transferability of results from the driving simulator to real traffic conditions may require a redefining of the V-ISA functional thresholds/conditions (for information, warning, and intervening variants). The major limitation of this study is the conduct of driving experiments on a simple road alignment having only horizontal curves in free-flow conditions. The study should be extended to analyse driver behaviour in complex road scenarios involving multiple road configurations and traffic flow conditions. As V-ISA technology has not been installed on real vehicles yet, field tests are required for full validation and general implementation. More broadly, research is also needed to ascertain the long-term effects of the V-ISA on driver behavioural adaptation phenomena and performance. In summary, the V-ISA can work as a standalone driver assistance system or can be integrated with already available ADAS for vehicles.

Conflict of interest

The authors do not have any conflict of interest with other entities or researchers.

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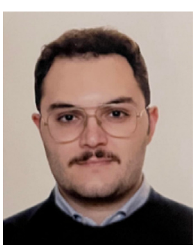

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