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An integrated intelligent speed adaptation system for enhanced driver assistance, driving performance and safety

Abrar Hazoor [a,*], Alessandra Lioi [b], Giuseppe Marinelli [a], Marco Bassani [b]

[a] Road Traffic Division, Faculty of Business School, NORD University, campus Stjørdal, Wessels veg 75, 7502 Stjørdal, Norway
[b] Department of Environment, Land, and Infrastructure Engineering, Politecnico di Torino, corso Duca degli Abruzzi 24, 10129 Torino, Italy

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ABSTRACT

Advanced Driver Assistance Systems (ADAS) have become an integral part of modern vehicles, significantly changing the driving experience. Adaptive Cruise Control (ACC) assists drivers in maintaining a constant speed and a safe following distance; however, it does not moderate the speed along curves when sight limitations occur, thus compromising safety. To address these challenges, this study integrates the Intelligent Speed Adaptation for Visibility (V-ISA) system with ACC. The V-ISA system dynamically adjusts the vehicle speed based on real-time visibility conditions, thereby enhancing safety on road curves where sight distance is restricted. Additionally, this study evaluates the impact of the ACC + *V*-ISA system on driver performance, specifically focusing on speed management, lateral vehicle control, and driver experience with assistance systems. The study was conducted in a simulated environment with forty-five participants. The results revealed that the ACC + *V*-ISA system effectively reduced vehicle speed on curves with limited visibility. The ability of the system to regulate speed according to prevailing road conditions highlights its potential to improve road safety. Moreover, the findings suggest that using the V-ISA system integrated with ACC maintains user acceptance and satisfaction while imposing no additional mental workload compared to using ACC alone. These insights are crucial for the future design of ADAS and autonomous vehicles and emphasize the importance of introducing this system into vehicles.

1. Introduction

In recent years, the automotive industry has witnessed significant advancements in technology aimed at enhancing driver safety and improving overall traffic operations [57]. One notable innovation is the development of Advanced Driver Assistance Systems (ADAS) in modern vehicles [7,44,50]. ADAS encompass a wide range of integrated technologies and sensors designed to assist drivers in vehicle operation [1]. These systems include interconnected or stand-alone modules such as collision avoidance, lane-keeping assistance, adaptive cruise control, automated parking, traffic sign recognition, blind spot detection, etc. [16,41].

These advanced technologies represent a paradigm shift in the way vehicles are designed and operated, aiming to mitigate driver errors by providing assistance. However, to achieve the desired effects of ADAS, it is essential that these systems are used correctly and as intended, while considering their limitations. In fact, these systems do not account for all driving, traffic, weather, or road conditions [42]. Even though manufacturers often highlight these limitations in vehicle manuals, a recent study revealed that many drivers remain unaware or fail to fully understand their constraints [35].

1.1. Adaptive cruise control

Adaptive Cruise Control (ACC), categorized as a SAE level 1 driver assistance system, is designed to assist drivers in maintaining a set speed and ensuring a safe distance from the vehicle ahead [46]. It allows vehicles to automatically adjust their speed to keep up with the flow of traffic. Within the ADAS modules, ACC has gained considerable popularity among drivers [26,62–64]. Previous research studies have found that drivers maintain longer following distances when using adaptive cruise control compared to driving without it [12,24]. Maintaining longer headways is crucial, as it enhances the vehicle’s and driver’s response to sudden changes in traffic conditions, such as abrupt stops or slowdowns by the vehicle ahead, thus reducing the likelihood of rear-end collisions [34]. By automating speed and headway adjustments, ACC reduces driver workload and fatigue, resulting in a more comfortable driving experience [10].

* Corresponding author.
E-mail address: abrar.hazoor@nord.no (A. Hazoor).

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To operate safely, users need to understand ACC limitations, especially in managing speed on road curves [49]. Driving through a curve can be risky if the vehicle speed is not adjusted to match the current conditions (e.g., a curve with limited sight distance). Specifically, when no vehicle is present (or not visible) along a curve, the ACC operates as a conventional cruise control (CC) and the ego vehicle (i.e., the vehicle with active ACC) maintains the speed set by the driver regardless of the road conditions [64]. However, the operational speed limit on curves is often lower than on straight sections, which can lead to unsafe vehicle operation. It should be noted that there is no universally adopted practice, and some countries only provide advisory speeds in area of significant risk [3]. Furthermore, national highway codes in line with Vienna Convention on Road Traffic by United Nations Economic Commission for Europe (UNECE) require drivers to maintain full control of their vehicles and adjust their speed according to road, visibility, and traffic conditions to ensure safety and minimize disruptions. They must be prepared to stop promptly within their line of sight and account for hazards, particularly in areas with limited visibility or complex road features [37,39,56].

Due to these limitations, the ACC system may lose the leading vehicle in curves because of roadside sight obstructions, and it may fail to detect small vehicles, such as motorbikes, off-centre vehicles, or unexpected obstacles in the driving lane, unless the vehicle is traveling at a speed suitable for prevailing road conditions [6]. An example of a roadside obstruction that restricts a driver's line of sight and reduces available sight distance is shown in Fig. 1. Furthermore, limited sight distance may prevent drivers from stopping in time to avoid unexpected hazards, such as stationary vehicles [3].

Recent advances in ACC technology allow for speed control on curves according to the posted speed limit (PSL) [65] and/or road curve data extraction [14]. This technology detects vertical signs by using onboard camera sensors or a location-based speed database (i.e., Predictive Cruise Control). However, reliance on PSL alone may not be sufficient to address the potential hazards of driving on curves, particularly in situations where vertical signs are absent or unrecognizable, or the speed database is not updated to reflect current conditions [59]. On curved road segments, particularly those with limited sight distance, drivers are prone to adopting unsafe speed choices. This issue is especially critical on sections where the line of sight is obstructed, either permanently or temporarily, as drivers frequently misjudge the available sight distance and may consequently encounter situations in which the required stopping distance exceeds the available distance to avoid a collision [3]. To mitigate this risk, visibility-based speed adaptation can be employed to ensure that vehicle speeds remain within a safe threshold, defined by comparing the real-time stopping distance (SD) with the available sight distance (ASD).

1.2. Intelligent speed adaptation for visibility (V-ISA)

To address the limitations of ACC, a driver assistance system called Intelligent Speed Adaptation for Visibility (V-ISA) was proposed,

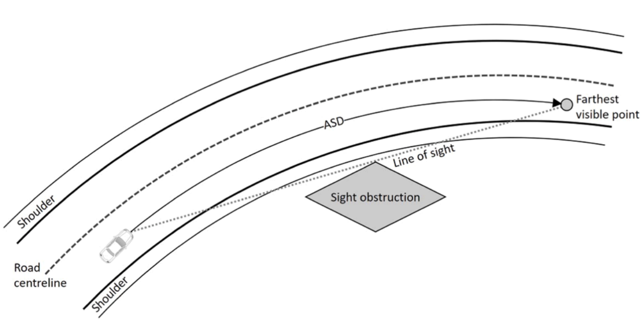

Fig. 1. An example of available sight distance (ASD) from driver point of view along a rightward curve in a two-lane highway.

designed to work alongside ACC. Unlike ACC, the V-ISA adjusts the vehicle speed in real time according to the available sight distance, whether or not there is a vehicle ahead, ensuring safe operation. The V-ISA has been tested in the simulation environment [19,20]. Hazoor et al. [21] assessed longitudinal and transversal driver behaviour on curves with limited sight distance on a two-lane highway and found convincing results, demonstrating that the V-ISA significantly improved driver longitudinal behaviour. Drivers maintained consistent speeds as per sight conditions, without compromising lateral vehicle control. This indicates that drivers were better able to negotiate curves safely when using the V-ISA system. In contrast, without V-ISA, a significant number of drivers misjudged the limited sight distance, resulting in unsafe behaviours (i.e., maintaining the vehicle speed and/or lateral vehicle position in the lane that requires longer stopping distance comparing to available sight distance along curves with limited visibility). Previously, the V-ISA system was proposed in three variants based on the feedback modalities and operating functionalities [20]: (i) the V-ISA Information, which provided drivers with visual feedback on sight conditions via a coloured LED on the lower part of the vehicle's front windshield; (ii) the V-ISA Warning, which alerted drivers with an auditory warning when they were operating under unsafe conditions (i.e., when *SD* exceeds *ASD*); and (iii) the V-ISA Intervening, which actively prevented drivers from exceeding a safe speed threshold (v_L) by controlling the acceleration and brake pedals. Among the different variants tested (i.e., information, warning, and intervening variants), the V-ISA intervening variant was identified as the most effective. In fact, it automatically acts on the vehicle driving controls (e.g., throttle, brakes) to limit the operating speed within a safe threshold. However, the warning variant was rated negatively at the user satisfaction scale. All V-ISA variants effectively reduced speed on curves with limited sight distance, mitigating associated risks [20]. Moreover, all V-ISA variants are highly rated for perceived usability and acceptance, thanks to their intuitive feedback mechanisms and functional effectiveness. These initial findings highlighted the potential of V-ISA systems in enhancing road safety by addressing the specific challenges posed by limited sight distance along road curves. It is important to note that the V-ISA is proposed solely in a simulated environment and has not been implemented in the real world (real vehicles).

As a further development of the aforementioned studies, this new research integrates the intervening variant of V-ISA with Adaptive Cruise Control (ACC). The aim of this study is to investigate the functionality and effectiveness of the new integrated ACC + *V*-ISA system in terms of driving performance and system acceptance. Based on our hypothesis, this integration should not degrade driver performance or increase workload. Moreover, the present study also hypothesized that the V-ISA system should effectively help drivers maintain safe speeds based on real-time sight conditions on curves with limited visibility.

2. Method

2.1. Operating functionality of the integrated system

For the integrated system operation, the driver simulator software (SCANeR Studio®) ran simultaneously with MATLAB Simulink® as a co-simulation environment, following a 'Driver-in-the-Loop' (DIL) model [25]. The co-simulation framework is illustrated in Fig. 2. The vehicle data, road environment data, and sensor inputs were obtained from SCANeR Studio® and transmitted to MATLAB Simulink® in real time. Within Simulink®, the data was processed and analysed before being sent back to SCANeR Studio® to enable system responses. The detailed functionality and operation of both systems (V-ISA and ACC) are described in the following sections.

2.1.1. Intelligent speed adaptation for visibility (V-ISA)

V-ISA was developed in response to the observation that only some drivers adjust their speed based on perceived risks due to limited visi-

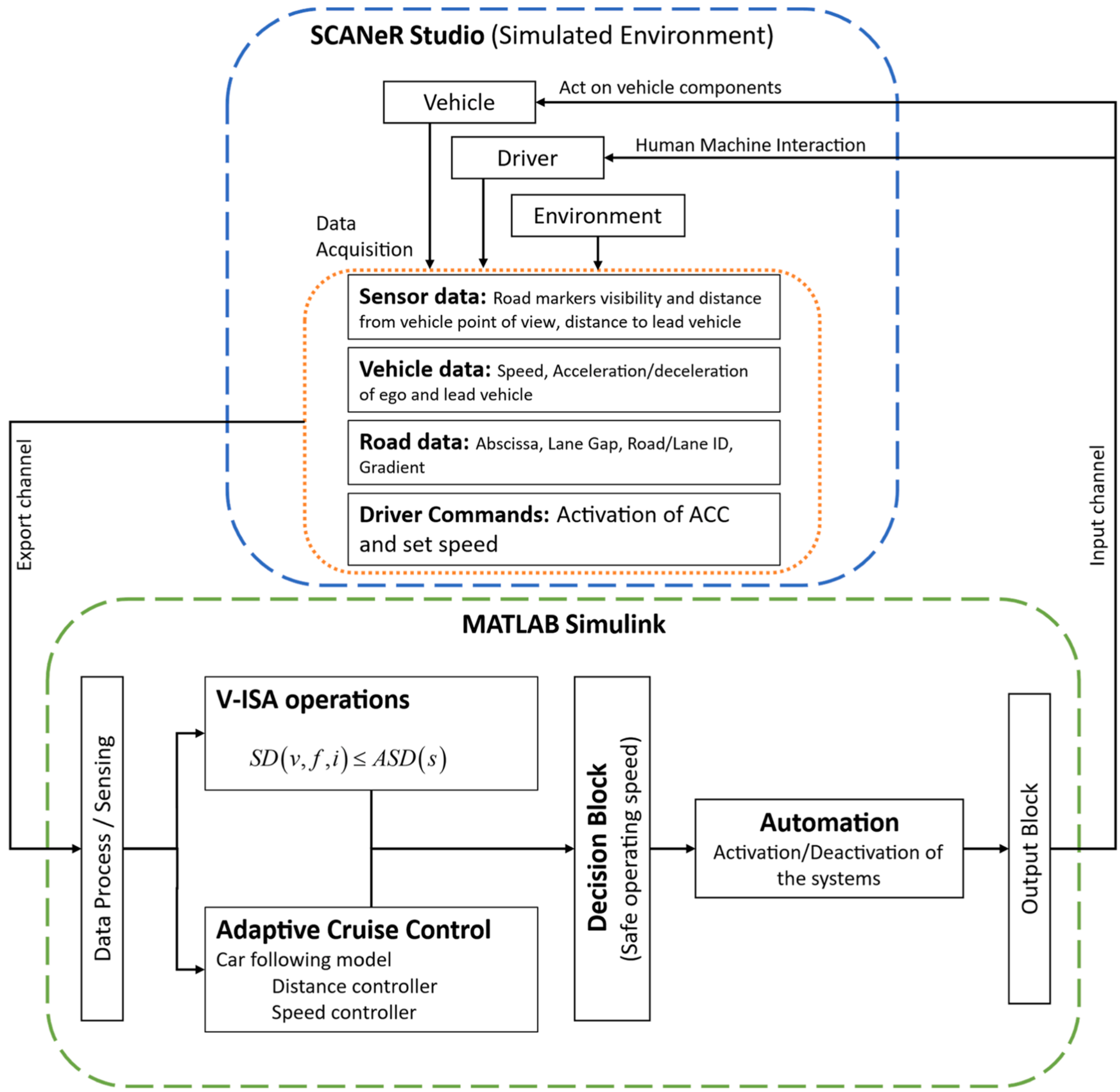

Fig. 2. Integrated system co-simulation framework in SCANeR Studio™ (driving simulator software) and MATLAB Simulink environment.

bility on curves [3]. Drivers frequently misjudge sight distances, resulting in unsafe conditions where the stopping distance (*SD*), i.e., the distance required to bring the vehicle to a complete stop, exceeds the Available Sight Distance (*ASD*), i.e., the distance to the farthest point visible to the driver on their path (see Fig. 1) [3]. This misjudgement, along with the tendency to underestimate the risks associated with poor visibility, can lead to unsafe driving conditions [29]. The V-ISA system addresses this issue by continuously comparing *SD* with *ASD* [19,20], thus ensuring the safety condition as per Eq. (1):

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

where SD is the real-time stopping distance estimated as per Eq. (2) and ASD is the real-time available sight distance at a specific location s. In the initial phase of the V-ISA model, ASD was estimated by processing sensor data in real time using MATLAB Simulink®. A data treatment block within the Simulink model identified the farthest visible point along the centreline of the driving lane. The V-ISA model was validated for accurately calculating ASD using onboard virtual sensors in a simulated environment, alongside an algorithm for calculating real-time stopping distance (SD) [19].

$$SD = v{\cdot}\tau + \frac{v^2}{2g * (f \pm i)} \tag{2}$$

where v is the real time vehicle speed in m/s; τ is the perception and reaction time in seconds, calculated in the V-ISA model using the relation adopted from the Italian road geometric design guidelines: $\tau = 2.8 - 0.0028 \cdot v$, with v in km/h [38]; f is the friction coefficient between the tire and the road surface, the friction values are estimated in the model using regression equations (Eq. (3) and Eq. (4)) as a function of real-time speed in km/h under wet and dry conditions; and i is the longitudinal road gradient, assumed to be zero for flat road alignments [20,38]. It is important to note that, the stopping distance (SD) in the V-ISA model is calculated in real time as a function of the actual operating vehicle speed, road friction, gradient, and driver reaction time (Eq. (2)).

$$f_{wet} = 1.578{\cdot}10^{-5}{\cdot}V^2 - 3.673{\cdot}10^{-3}{\cdot}V + 0.503 \tag{3}$$

$$f_{dry} = 6.349{\cdot}10^{-6}{\cdot}V^2 - 2.216{\cdot}10^{-3}{\cdot}V + 0.716 \tag{4}$$

The real-time safe speed threshold (v_L) was defined by replacing *SD* in Eq. (2) with real-time *ASD* as per safety condition defined in Eq. (1):

$$v_L = \ -g{\cdot}(f+i)\left[\tau - \sqrt{\frac{2{\cdot}ASD}{g{\cdot}(f+i)} + \tau^2}\right] \tag{5}$$

2.1.2. *Integration between ACC and V-ISA*

The ACC model was developed using the MATLAB Simulink environment [54] and co-simulated with driving simulator environment (SCANeR Studio™) as illustrated in Fig. 2. The sensor available in the simulated environment includes a radar mounted on the ego vehicle, which measures the distance and the relative speed to the vehicle ahead. The ACC operates simultaneously based on speed control and distance control, selecting the most critical condition between the two to regulate the ego vehicle speed. Speed control maintains the velocity set by the driver, whereas distance control ensures a safe distance (D_{safe}) is maintained between the ego vehicle and the vehicle ahead. The safe distance D_{safe} is calculated using Eq. (6):

$$D_{safe} = D_f + T_{gap} \cdot V_{ego} \tag{6}$$

In Eq. (6), D_{safe} is in meters, D_f is the standstill distance (safe distance) set at 5 m, T_{gap} is the time gap set at 1.8 s (headway setting), and V_{ego} is the current speed of the ego vehicle in m/s. In modern vehicles, ACC allows drivers to set the following distance to the vehicle ahead based on their driving preferences, typically with three options: Low, Medium, and High. In this study, the D_f and T_{gap} values were fixed, corresponding to the medium-range headway setting in the ACC system [40,45]. Unlike standard ACC systems that let drivers adjust the time gap, participants in this study were not able to modify the headway to the lead vehicle.

An automated subsystem algorithm for the ACC was developed in the MATLAB Simulink environment which allows drivers to control the ACC functions through steering wheel-mounted buttons. This subsystem offers several key features: drivers can (i) activate or deactivate the ACC system, (ii) set a desired travel speed, and (iii) adjust this speed, i.e., increase or decrease it. In most vehicles, adaptive cruise control (ACC) can only be activated once the vehicle reaches a minimum speed, which typically ranges from 20 km/h to 40 km/h, depending on the specific car model and brand [34,49]. Similarly, in this study, ACC activation required the vehicle to be traveling at or above a minimum speed of 30 km/h. An icon was displayed to indicate the status of the ACC activation, along with the set speed as illustrated in Fig. 3. The automated subsystem also integrates with various vehicle components to disengage the ACC system when necessary. For instance, the ACC automatically deactivates when the driver presses the brake pedal, shifts gears, or engages the clutch pedal. When the throttle pedal is pressed, the vehicle speed increases, and once the pedal is released, the vehicle maintains the originally predefined speed set by the driver. All in all, the ACC operating functionalities were meant to be consistent with those found in modern vehicles.

In parallel with the ACC model, the previously developed V-ISA algorithm, i.e., the intervening variant, was integrated into the Simulink environment [19,20]. The input data for the V-ISA model, including sensor, vehicle, and road information, was acquired in real-time from the driving simulator environment (SCANeR Studio™) as illustrated in Fig. 2. This data was processed to estimate the *ASD* and *SD* values based on the prevailing road conditions, and the threshold speed limits (v_L) were modelled as per Eq. (5). Additionally, safety conditions for sight distance were applied using Eq. (1).

As the vehicle approaches a curve, *ASD* values vary in relation to road geometry and the presence of lateral sight obstructions. At the curve entrance, *ASD* decreases from its maximum to the minimum value as the vehicle navigates the curve. Similarly, ASD begins to increase again at the curve exit, reaching infinity once the road straightens. Since ASD is not constant along curves with limited sight distance, the operational parameters for the V-ISA system were classified into two distinct groups based on visibility conditions, (i) unstable sight condition and (ii) stable sight condition [20]. The "unstable sight condition" was defined by a rapid reduction in *ASD*, specifically a decrease of 4 m or more relative to the preceding simulation unit time-step ($ASD_{t-1} - ASD_t \geq 4$ m, where t represents the current simulation time and t-1 represents the time-step one second earlier) [20,21]. Under this condition, V-ISA initially disengages the gas pedal and applies the brakes to reduce the vehicle speed, ensuring that it remains below the threshold speed limit (v_L). During this intervention, the LED bar changes from green to blue, signalling to the driver that the system is actively controlling the speed (Fig. 3). Conversely, the "stable sight condition" is defined by consistent *ASD* values ($ASD_{t-1} - ASD_t \leq 4$ m), particularly when the vehicle is negotiating a curve where the farthest visible point remains within the curve boundaries (Fig. 1). In this case, if the driver accelerates from a safe to an unsafe condition, V-ISA intervenes by releasing the gas pedal and maintaining the vehicle speed below the threshold limit (v_L), as specified in Table 1. It is important to note that during these interventions, drivers do not have the option to override or disable the V-ISA system. A visual feedback modality for the V-ISA using an LED bar positioned at the bottom of the windscreen was adopted as the LED bar effectively captures the driver's visual attention, particularly during critical manoeuvres such as navigating a curve [48,55]. Since the V-ISA system primarily engages when the driver is negotiating a curve, the LED bar should provide relevant information about the system's actions without causing distraction [36].

2.1.3. Decision and automation block

Within the MATLAB Simulink environment, after the speeds are regulated by the V-ISA and ACC blocks, the data is passed to the 'decision block' (Fig. 2). The task of this block is to regulate the operating speed and verify whether the speed provided by the ACC system or manual driving (ACC off) is below the threshold set by the V-ISA system. If the V-ISA system calculates a lower speed, the decision block will

Table 1
Operational functionalities of the V-ISA as per sight conditions and defined threshold speed limits.

Sight condition	$\Delta v = v_L - v_{ego}$ (km/h)	LED bar colour	V-ISA intervention
Unstable	> 15	Green	-
	$5 < \Delta v \leq 15$	Blue	Deactivation of gas pedal
	≤ 5	Blue	Activation of brake
Stable	> 0	Green	-
	≤ 0	Blue	Deactivation of gas pedal

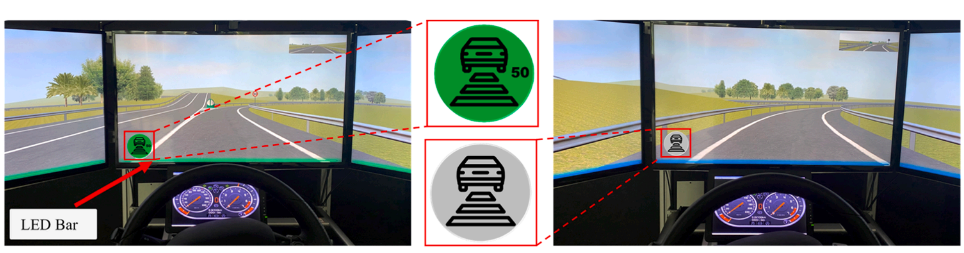

Fig. 3. Illustration of Human-Machine Interface of the Integrated System. (a) The green LED bar indicates a safe sight condition to the driver. (b) The green icon indicates that ACC is on with a driver-set speed of 50 km/h, while the grey colour indicates that ACC is off. (c) The blue LED bar signifies active V-ISA, intervening with the gas and/or brake pedal.

override the ACC system speed regulation. The V-ISA system always remains active while driving, with no option for the driver to deactivate it, while the ACC system can be manually activated or deactivated by the driver.

In Eq. (7), V_{active} represents the speed chosen by the integrated system (ACC + V-ISA) to control the ego vehicle, $V_{ACC\text{-}off}$ denotes the operating speed of the ego vehicle when the ACC is deactivated, $V_{ACC\text{-}on}$ refers to the operating speed when the ACC is activated, which is either the speed set by the driver or the following speed if a lead vehicle is traveling slower than the set speed, and V_L is the threshold speed limit determined by the V-ISA model to ensure safe sight conditions *(SD* $\leq$ *ASD)*.

$$V_{active} = \min\begin{cases} V_{ACC-off} \\ V_{ACC-on} \\ V_L \end{cases} \tag{7}$$

In addition, an 'automation block' was incorporated in the MATLAB Simulink environment, which is responsible for the speed controller and the speed limiter. This block determines acceleration and deceleration rates, ensuring smooth transitions in response to current driving conditions with the help of Model Predictive Control [54]. The output from this block is then used to control vehicle components (driving simulator), including the throttle and brake pedals, to maintain the regulated speed (V_{active}) from the decision block.

2.2. Experimental design

This study evaluated the effectiveness of the integration between ACC and V-ISA systems on driving performance. Additionally, it examined participants' subjective evaluations of the combined system. To minimize learning effects and prevent excessively long driving sessions, a between-subjects experimental design was employed to assess the impact of the assistance systems. This design allows for a comparative analysis of driving performance and subjective evaluations across different levels of system assistance. Moreover, the between-subject experimental design helps minimize familiarity and carryover effects that could arise from repeated exposure to similar driving scenarios and the use of driver assistance systems.

2.3. Participants

Forty-five licensed Italian drivers (21 females) voluntarily participated in the experiment. They were recruited via email, inviting them to fill out an online form to collect information on age, years of driving experience, average annual kilometres travelled, and the number of previous crashes. A prerequisite for participation was familiarity with ACC. To avoid learning effects related to its functionality and use, only those who indicated prior experience using ACC were selected for the study. Additionally, participants completed the Driving Style Questionnaire (DSQ) to assess their self-reported driving attitudes. The questionnaire consisted of 15 items on a six-point Likert scale ranging from 1 (very infrequently or never) to 6 (very frequently or always). These items were combined and categorized into six key dimensions: (i) Speed: items assessing tendencies to drive fast and exceed speed limits, (ii) Calmness: evaluating the ability to remain composed in high-pressure or hazardous situations, (iii) Social Resistance: measuring receptiveness to driving-related advice, (iv) Focus: examining cautious driving habits and the ability to ignore distractions, (v) Planning: considering the extent to which drivers prepare for trips, such as checking maps and planning rest stops, and (vi) Deviance: identifying risky actions like running red lights or overtaking in unsafe conditions [13].

Participants were divided into three groups based on the assistance system they were provided with: (i) Group 1 drove with the system off (i.e., baseline condition), (ii) Group 2 used the ACC system only, while (iii) Group 3 was supported by the integrated system (ACC + V-ISA). Each group consisted of 15 participants (7 females per group), selected based on demographic characteristics and driving style, as detailed in Table 2 and Fig. 4, respectively. The analysis of the pre-driving questionnaires using Student *t*-tests revealed no significant differences in driving styles between the groups ($p > .05$), ensuring homogeneity and facilitating effective comparison of behaviours in the between-subject design. Before the experimental session, all participants provided informed consent by signing a consent form. Each participant had either normal or corrected-to-normal vision and was not informed of the study hypothesis. The study adhered to the ethical standards outlined in the World Medical Association's Declaration of Helsinki [61].

2.4. Equipment

The fixed-base driving simulator located at the Road Safety and Driving Simulation (RSDS) laboratory at Politecnico di Torino (Italy) was used. This simulator, powered by the SCANeR Studio™ simulation software platform from AV Simulation, features a cockpit equipped with a steering wheel, a manual transmission gearbox, pedals, and an adjustable seat. The system includes an active force-feedback steering wheel that realistically simulates wheel spin and impacts, and a seat vibrator to simulate car vibrations and road surface roughness.

The virtual driving environment was displayed on three 32-inch full HD LED monitors (1920 × 1080 pixels), with a horizontal field of view of 130 degrees and a refresh rate of 60 Hz. This setup accurately portrays the car cockpit, including the dashboard and both side and centre rearview mirrors. A surround sound system reproduced the sounds of the car engine, traffic, wind, and various environmental noises. The simulator was previously validated for longitudinal driving performance [2], lateral performance [8] and for passing operations [23].

2.5. Simulated road scenario

In this experimental study, the road track consisted of two different roads, i.e., a two-lane highway and a four-lane motorway, connected by an interchange with ramps and acceleration/deceleration lanes (Fig. 5). The two-lane highway included four horizontal curves with radii ranging from 252 to 450 m (curve 1: 339 m, curve 2: 450 m, curve 3: 252 m, curve 4: 339 m). Conversely, the motorway section also included four horizontal curves with larger radii, ranging from 816 m to 2500 m (curve 5: 816 m, curve 6: 1000 m, curve 7: 2500 m, curve 8: 1000 m). Long straight segments connected these curves to minimize the influence of one curve on the next. The two road sections were connected via merging interchanges (direct ramps) with a radius of 150 m, a speed limit of 50 km/h, and a parallel linear terminal design, in compliance with the Italian road geometric design rules [38]. Furthermore, double-wave guardrails, 0.75 m high, were installed on both sides of the two-lane highway at the outer edge of the shoulder (1.5 m from the outer marking). Similarly, triple-wave guardrails, 0.90 m high, were placed along the motorway section at a distance of 3 m from the outer marking. These guardrails (barriers) obstruct drivers' sightlines, and Lioi et al. [30] found that different barrier heights affect ASD values. Additionally, vegetation was planted along the inner side of curves on the two-lane highway, positioned at the outer edge of the road shoulder (Fig. 5) and it also acts as a sight/visual obstruction. It is important to note that the V-ISA determines ASD values for each driver by considering the vehicle's position along curves. These values are influenced by both the vehicle's position on the roadway and its lateral placement within the lane. Consequently, real-time safety conditions vary for each driver based on ASD and SD. However, the minimum ASD values for each curve, measured from the midpoint of the lane, are indicated in Fig. 5.

The experimental drive began on the two-lane highway, approximately 6.5 km in length, and continued onto the motorway section, which was about 8.7 km long. The scenario concluded with another two-lane highway, connected to the motorway by another direct ramp, allowing the driver to stop in a lay-by. Frames from the driver's point of

Table 2
Demographic characteristics of the participants.

Group	Gender	No. [-]	Age [years]				Driving experience [Years]		Annual mileage [km]		*No. of crashes involved in [-]	
			Min	Mean	Max	SD	Mean	SD	Mean	SD	Mean	SD
G1 (Baseline)	Male	8	23	36.6	58	13.5	15.4	9.86	6106	3473	0.38	1.06
	Female	7	25	30.4	37	5.26	11.6	5.38	3043	3056	1.43	0.98
G2 (ACC)	Male	8	27	32.9	51	7.64	16.4	9.23	12,375	9086	0.50	1.41
	Female	7	24	32.6	39	4.96	14.1	4.95	9714	6075	0.86	1.21
G3 (ACC & V-ISA)	Male	8	25	30.8	39	4.17	10.0	2.62	10,125	9761	0.38	0.52
	Female	7	27	33.9	49	8.91	19.0	9.97	8857	10,383	0.57	0.54

* Note: All road crashes experience in participants' lifetime, including property damage only.

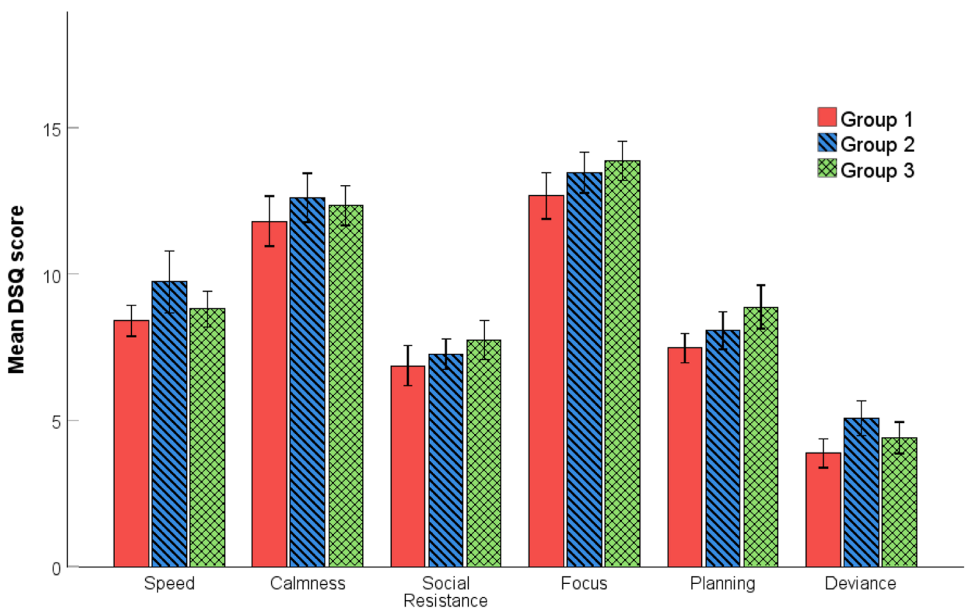

Fig. 4. Mean score provided by the participants on the Driving Style Questionnaire (DSQ). Error bars represent the standard error.

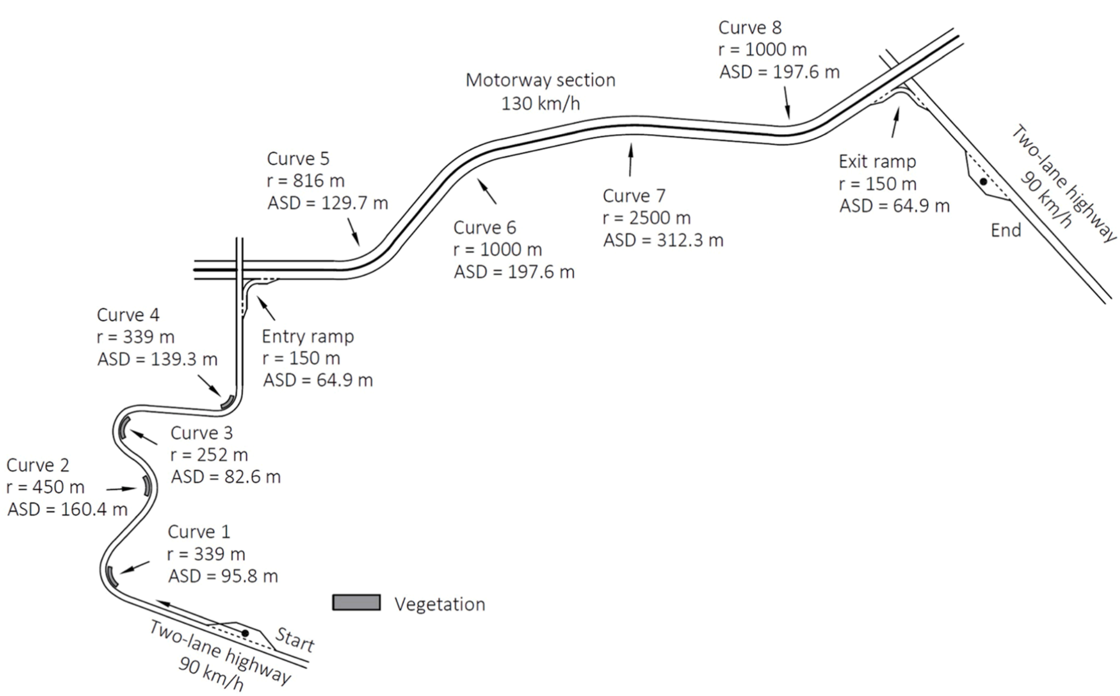

Fig. 5. Layout of the testing track (r: curve radius; ASD = minimum available sight distance).

view are presented in Fig. 6. To mitigate simulator sickness, fatigue, and boredom, the track lengths were designed to limit driving times to 20 min [43]. All experiments were carried out under simulated daylight conditions and in dry weather.

At the beginning of the motorway section, traffic was generated at a constant flow rate of 1500 vehicles per hour, with a maximum posted speed of 130 km/h. On a two-lane highway, no vehicles were present on curves 1 and 2. However, a vehicle traveling at 80 km/h was positioned ahead of the ego vehicle on curves 3 and 4 to create a car-following scenario (Fig. 5). To facilitate this, the lead vehicle maximum speed was set to 80 km/h. Additionally, the lead vehicle adjusted its speed along the curves in response to the road geometry. While the car-following scenario was intended, it was not strictly enforced, as participants could adjust their speed or set their preferred ACC speed based on their driving style. The car-following situation was created along the two-lane highway to allow drivers to experience using the ACC and integrated system (ACC + *V*-ISA) while negotiating curves with a lead vehicle ahead. However, in this road section, drivers remained within the posted speed limit, as overtaking was not permitted due to the continuous centreline marking, although it was still physically possible. No traffic was simulated in the ramps.

2.6. Protocol

Participants were given an overview of the nature and requirements of the experiment and were familiarized with the fundamental components of the driving simulator. Participants in group 2 (ACC) and group 3 (ACC + *V*-ISA) received a one-page manual detailing the functionality of their assigned systems and explaining the defined human-machine interface to familiarize them with the systems. After reviewing the manual, participants drove on a trial track with the assigned system activated to build confidence in both the system's functionality and the driving simulator. Participants were instructed to activate the ACC along the sections where they felt comfortable. On the other hand, participants who used the V-ISA system did not have the option of deactivating the system, as it automatically activated when the driver exceeded safe speed thresholds. Participants in the control group (group 1) underwent a familiarization drive on the same trial circuit for at least five minutes without any assistance, just to enhance their confidence and familiarity with the driving simulator. All participants were instructed to drive as they would in a real-world environment. Following the trial circuit, participants received descriptions of the simulated experimental circuit. Upon completing the experimental drive, participants filled out post-drive questionnaires to provide feedback on the simulation. None of the participants reported experiencing simulator sickness.

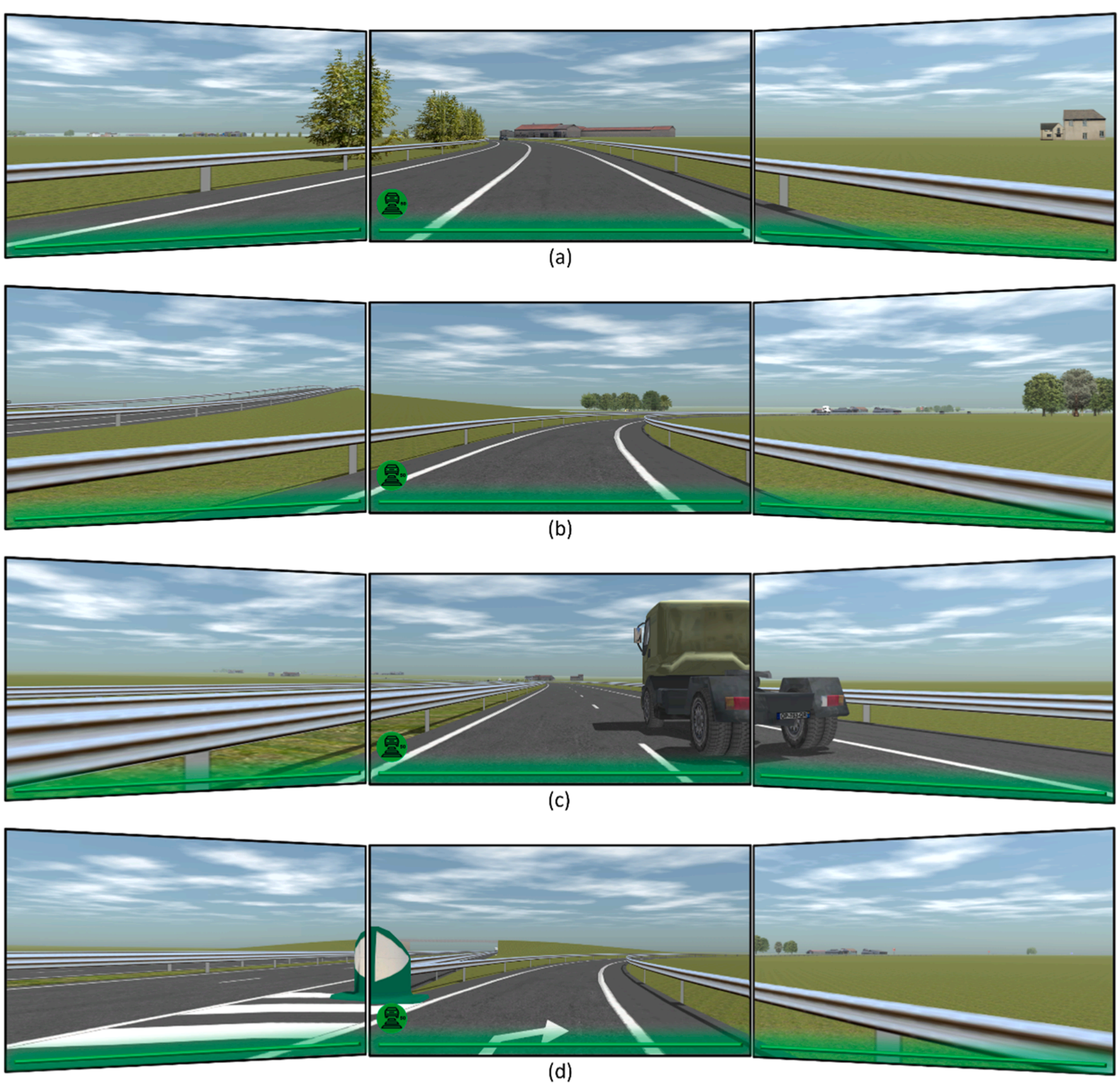

Fig. 6. Frames from driver point of view taken at specific stations along the (a) two-lane highway, (b) the entry ramp, (c) the motorway, and (d) the exit ramp.

2.7. Observed variables

2.7.1. Driving performance

Data from the driving simulator were collected at a sampling rate of 10 Hz, capturing the operating speed and lateral position of the ego vehicle. To assess the impact of the assistance system on driving performance, the mean speed and standard deviation of lateral position (*SDLP*) were analysed along horizontal curves (i.e., circular arcs) in the two-lane rural highway sections, the entry and exit ramps, and in the motorway. Specifically, the mean speed and SDLP were computed based on data collected throughout the circular arcs of the horizontal curves (excluding spirals). The data were recorded continuously as the vehicle travelled along the curve, and the values were then averaged for each driver over the circular arc segment. These individual averages were subsequently averaged across all participants to obtain the overall mean speed and SDLP.

2.7.2. Subjective rating

At the end of the experimental drive, participants completed a survey including:

- the *NASA Task Load Index (NASA-TLX) questionnaire* for assessing subjective workload on six dimensions: (i) mental demand, (ii) physical demand, (iii) temporal demand, (iv) frustration, (v) performance, and (vi) effort [17]. Participants rated each dimension on a 10-point Likert scale, ranging from low to high. In this study, the mean ratings for each of these dimensions were calculated across all three groups. It is important to note that the evaluations were relied on the unweighted (raw) ratings of the NASA-TLX, with higher scores indicating higher workload;
- the *System Acceptance questionnaire* for the ACC only and the integrated system (ACC + *V*-ISA) assessed using the System Acceptance Scale developed by Van Der Laan et al. [58]. It included nine items, each rated on a five-point scale from −2 (most negative) to +2 (most positive). These items were grouped into two categories to evaluate participants' perceptions of system usefulness and satisfaction. The items included: (1) useful – useless; (2) pleasant – unpleasant; (3) bad – good; (4) nice – annoying; (5) effective – superfluous; (6) irritating – likeable; (7) assisting – worthless; (8) undesirable – desirable; (9) raising alertness - sleep inducing. Items with odd numbers corresponded to the usefulness sub-scale, while even-numbered items related to satisfaction [58].
- the *Situation Awareness questionnaire* after completing the experimental drives. Participants in groups 2 and 3 were asked to provide their opinions on their experience using the Situation Awareness Rating Technique (SART) [53]. This evaluation involved rating ten items on a 1 – 7 scale, which were further divided into three key dimensions:

  (i) demand (D): instability, variability and complexity of the situation;
  (ii) supply (S): arousal, spare mental capacity, concentration and division of attention;
  (iii) understanding (U): information quantity, information quality and familiarity.

These ratings were then combined to generate the overall Situation Awareness score (SA) using the Eq. (8):

$$SA = U - (D - S) \tag{8}$$

2.8. Statistical analysis

Separate mixed Analysis of Variance (ANOVA) was conducted for each dependent variable (i.e., mean speed and SDLP). The data was subcategorized into three parts based on road alignment (i.e., two-lane highway, motorway and ramps). For the two-lane highway and motorway, we considered curve ID (4 levels) as a within-subject factor and group (3 levels) as a between-subject factor. In the case of ramps, we considered ramp-type (2 levels: on-ramp and off-ramp) as a within-subject factor and group (3 levels) as a between-subject factor. For subjective rating (i.e., NASA-TLX and SART), group (3 levels) was considered as a between-subject factor. A Bonferroni correction was applied for multiple comparisons and significance levels were set at p-value $< .05$. The assumption for homogeneity of variances were checked using Levene's test and for normality K-S test were adopted. In the case of violations of the sphericity assumptions, Greenhouse-Geisser correction was considered. No significant outliers were present in the data. All analyses were performed with IBM SPSS Statistics software (version 29.0).

3. Results

3.1. Activation of ACC and V-ISA

During the experimental drive, participants in groups 2 and 3 had the possibility to activate and deactivate the ACC system and set the cruise speed according to their driving style. Table 3 details the average number of times the ACC was activated/deactivated by the drivers, as well as the duration and distance for which it remained active. Additionally, Table 3 provides similar data for the V-ISA system, but only for group 3. It is worth noting that the V-ISA system was active throughout the experimental drive. However, its intervention with the throttle (gas) and/or brake pedal depended on the driver's speed choice. The V-ISA system automatically reduced speed when unsafe driving was detected, ensuring safe driving conditions (see Eq. (1)). On average, data collection indicated that the V-ISA system intervened over a distance of 1350 m and a duration of 68 s along the track.

The study aimed to understand the influence of the integrated system on driver behaviour, necessitating the activation of ACC while driving. All the participants successfully activated the ACC, therefore, it was possible to further analyse the effects of ACC and the integrated system on driver behaviour by comparing it when the system was off (i.e., the baseline).

3.2. Driving performance

A series of analysis of variance (ANOVA) tests were conducted to assess the impact of the driver assistance system on the dependent variables, specifically speed and the SDLP. Separate ANOVA tests were performed for different roadway types: (i) two-lane highway, (ii) motorway, and (iii) interchange ramp sections. Moreover, the analysis included road curves as a factor (curve ID) to evaluate the influence of the assistance system under various geometric conditions by comparing the three distinct experimental groups. The impact of independent variables on speed is detailed in Table 4, while the SDLP data are shown in Table 5.

3.2.1. Two-lane highway

Mixed ANOVA results for speed indicate that the assistance systems

Table 3
Activation of ACC and V-ISA during the experimental drives for group 2 (ACC) and group 3 (ACC + *V*-ISA). Note: The total length of the circuit was 17,235 m.

	Total activations Mean (SD)	**Activation distance (m)** Mean (SD)	**Activation duration (s)** Mean (SD)
ACC			
Group 2	4.1 (1.96)	12,210 (2342.16)	447 (87.60)
Group 3	4.1 (1.30)	12,849 (1900.12)	469 (73.70)
V-ISA			
Group 3	4.7 (0.90)	1350 (8.45)	68 (14.46)

Table 4
Mixed ANOVA on factors affecting speed along curves in two-lane highway, motorway, and interchange ramps.

	Sum of Squares	*df*	*Mean Square*	*F*	*p-value*	η^2
Two-Lane Highway						
Within Subjects Effects						
Curve ID	4268	3	1422.5	70.06	< .001	.430
Curve ID ✻ Group	474	6	79.1	3.92	.001	.048
Residuals	2539	126	20.1			
Between Subjects Effects						
Group	263	2	131.5	4.50	.012	.027
Residuals	2371	42	56.5			
Motorway						
Within Subject Effects						
Curve ID	3129	3	1042.8	26.37	< .001	.157
Curve ID ✻ Group	253	6	42.1	1.06	.388	.013
Residuals	4983	126	39.5			
Between Subjects Effects						
Group	438	2	219	0.82	.446	.022
Residuals	11,180	42	266			
Interchange ramp						
Within Subjects Effects						
Ramp type	733	1	732.6	38.94	< .001	.086
Ramp type ✻ Group	129	2	64.6	3.43	.042	.015
Residuals	790	42	18.8			
Between Subjects Effects						
Group	687	2	344	4.15	.019	.081
Residuals	6164	42	147			

significantly affect operating speed, $F(2,42) = 4.50$, p-value $= .012$, $\eta^2 = .027$. Additionally, curve ID significantly influence operating speed, $F(3126) = 70.06$, p-value $< .001$, $\eta^2 = .430$. A significant interaction was observed between the assistance system (i.e., group) and curve ID, $F(6126) = 3.92$, p-value $= .001$, $\eta^2 = .048$.

Post-hoc analyses with Bonferroni correction were conducted to examine the differences in more detail. Fig. 7a illustrates the mean operating speeds along four different curves for the three experimental groups. As anticipated, the results indicated that drivers maintained different speed profiles along the different curves (curve ID) due to differences in geometric conditions (p-value $< .05$). Notably, the speed profiles were consistent across the three groups, with no significant differences observed in the presence of the assistance system (groups 2 and 3) compared to the baseline condition (group 1), except for the curve 1 with limited visibility. For curve 1, a significant reduction in speed (p-value $< .05$) was observed in group 3 compared to the other two groups. This reduction is attributed to the activation of the V-ISA system, which compels drivers to limit their operating speed to below the safe speed limit determined by visibility conditions along the curve (sight distance).

In the context of lateral vehicle performance, Mixed ANOVA results from Table 5 indicate that the effect of the assistance systems (ACC and ACC + *V*-ISA) did not show significant differences compared to the baseline condition, $F(2,42) = 0.68$, p-value $= .510$, $\eta^2 = .012$. Vehicle lateral control was consistent across all four curves, with no significant variation detected, $F(3126) = 1.60$, p-value $= .192$, $\eta^2 = .022$. Furthermore, Mixed ANOVA analysis revealed no significant interaction effects between the assistance systems and curve ID, $F(6126) = 0.45$, p-value $= .845$, $\eta^2 = .012$. As illustrated in Fig. 7b, although a reduction in *SDLP* values was observed when drivers used ACC (group 2) along curve 1, this decrease was not statistically significant according to post-hoc analysis (p-value $> .05$).

Table 5
Mixed ANOVA on factors affecting standard deviation of lateral position (SDLP) along curves in two-lane highway, motorway, and interchange ramps.

	Sum of Squares	*df*	*Mean Square*	*F*	*p-value*	η^2
Two-Lane Highway						
Within Subjects Effects						
Curve ID	0.01759	3	0.00586	1.60	.192	.022
Curve ID ✻ Group	0.00985	6	0.00164	0.45	.845	.012
Residuals	0.46059	126	0.00366			
Between Subjects Effects						
Groups	0.00995	2	0.00498	0.68	.510	.012
Residuals	0.30549	42	0.00727			
Motorway						
Within Subjects Effects						
Curve ID	0.0727	3	0.0242	0.66	.577	.010
Curve ID ✻ Group	0.2245	6	0.0374	1.02	.414	.030
Residuals	4.6136	126	0.0366			
Between Subjects Effects						
Groups	0.0762	2	0.0381	0.67	.518	.010
Residuals	2.3996	42	0.0571			
Interchange ramp						
Within Subjects Effects						
Ramp type	0.00187	1	0.00187	0.09	.761	.001
Ramp type ✻ Group	0.0323	2	0.01615	0.81	.450	.017
Residuals	0.83429	42	0.01986			
Between Subjects Effects						
Groups	0.0224	2	0.0112	0.451	.640	.012
Residuals	1.0456	42	0.0249			

3.2.2. Motorway

Table 4 presents the Mixed ANOVA results for speed on the horizontal curves along the motorway section. The results revealed that the assistance systems (ACC and ACC + *V*-ISA) did not significantly impact the operating speed adopted by the drivers, $F(2,42) = 0.823$, p-value $= .446$, $\eta^2 = .022$. However, the curve ID significantly affected the operating speed, $F(3126) = 26.37$, p-value $< .001$, $\eta^2 = .157$. Regarding the interaction between assistance systems and curve ID, Mixed ANOVA showed no significant difference, $F(6126) = 1.06$, p-value $= .388$, $\eta^2 = .013$. To further clarify the Mixed ANOVA results, the outcomes were plotted based on the experimental groups, i.e., groups 1, 2 and 3, and curve ID, as depicted in Fig. 8a. Post-hoc analysis revealed that drivers in each group maintained similar operating speeds ($p > .05$), although the speed profiles differed for each curve. Specifically, drivers travelled at significantly lower speeds on curve 5 compared to the other curves ($p < .001$), whereas the differences in speeds among the remaining three curves (curve IDs: 6, 7, and 8) were not significant ($p > .05$).

Regarding lateral performance, Mixed ANOVA indicated no significant differences in SDLP values among the three groups, $F(2,42) = 0.668$, p-value $= .518$, $\eta^2 = .010$, nor was the effect of curve ID significant, $F(3126) = 0.662$, p-value $= .577$, $\eta^2 = .010$, as presented in Table 5. Fig. 8b illustrates that drivers maintained consistent lateral control across the three groups and along all four motorway curves.

3.2.3. Ramps

Table 4 presents the Mixed ANOVA results for on-ramp (two-lane highway to motorway) and off-ramp (motorway to two-lane highway) curves. The analysis revealed a significant difference between the groups, $F(2,42) = 4.15$, p-value $= .019$, $\eta^2 = .081$. Additionally, the ramp

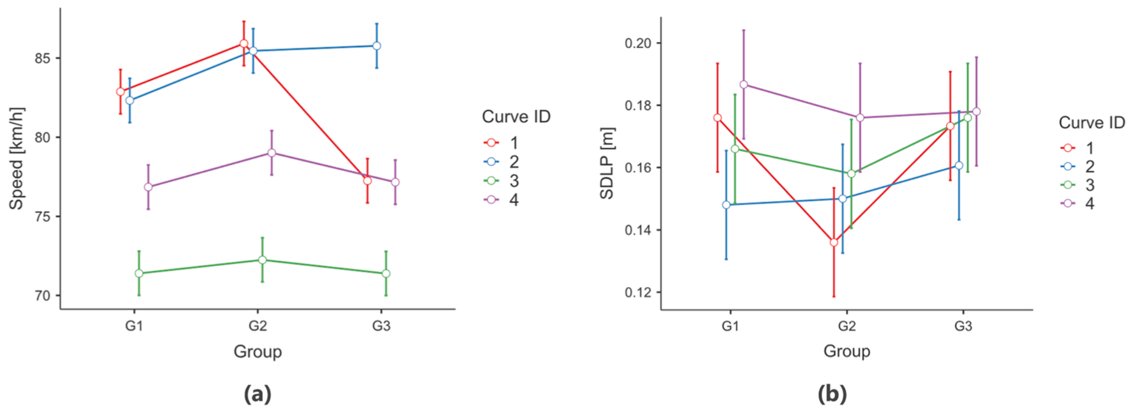

Fig. 7. Comparison of estimated marginal means of (a) speed and (b) SDLP along horizontal curves in two-lane highway section. Error bars represent the standard error. Note: G1 = baseline condition; G2 = ACC; G3 = ACC + *V*-ISA. Note: Data points are slightly offset vertically from G1, G2, and G3 to enhance readability and prevent overlap.

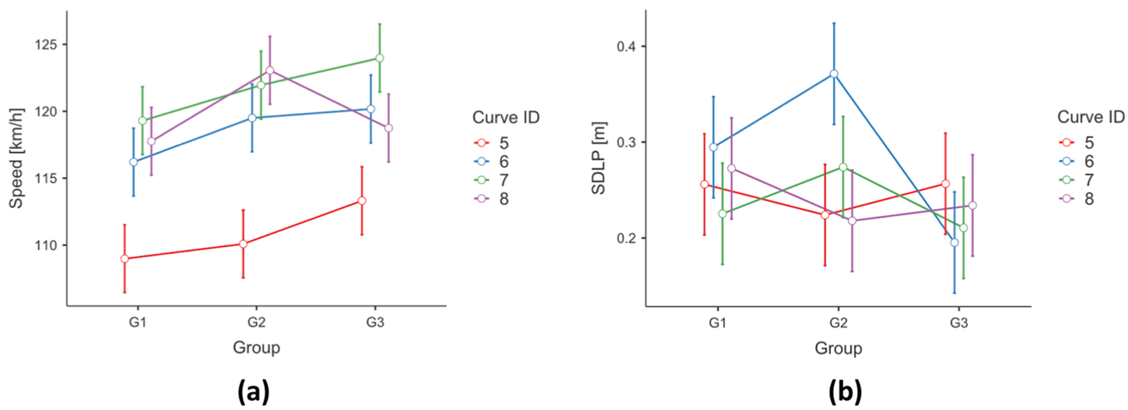

Fig. 8. Comparison of estimated marginal means of (a) speed and (b) SDLP along horizontal curves in motorway section. Error bars represent the standard error. Note: G1 = baseline condition; G2 = ACC; G3 = ACC + *V*-ISA. Note: Data points are slightly offset vertically from G1, G2, and G3 to enhance readability and prevent overlap.

type (on-ramp vs. off-ramp) had a significant effect on operating speed, $F(1,42) = 38.94$, p-value = < .001, $\eta^2 = .086$. The interaction between group and ramp type was also significant, $F(2,42) = 3.43$, p-value = .042, $\eta^2 = .015$. Post-hoc tests indicated that drivers in group 3, i.e., using the ACC + *V*-ISA system, drove at lower speeds compared to those in the baseline condition (group 1) and ACC only (group 2). This reduction in speed was particularly notable on the off-ramp, where drivers exited the motorway with a posted speed limit of 130 km/h, compared to the on-ramp, where the posted speed limit was 90 km/h ($V_{G1,\ off\text{-}ramp}$ - $V_{G3,\ off\text{-}ramp}$ = 6.973 km/h, p = .039; $V_{G2,\ off\text{-}ramp}$ - $V_{G3,\ off\text{-}ramp}$ = 7.896 km/h, p-value = .020), as illustrated in Fig. 9a. The primary reason for the significant speed reduction in group 3 is attributed to the activation of the V-ISA along curves with limited sight distance.

On the other hand, the activation of assistance systems does not impact vehicle lateral control as no significant effect was found,

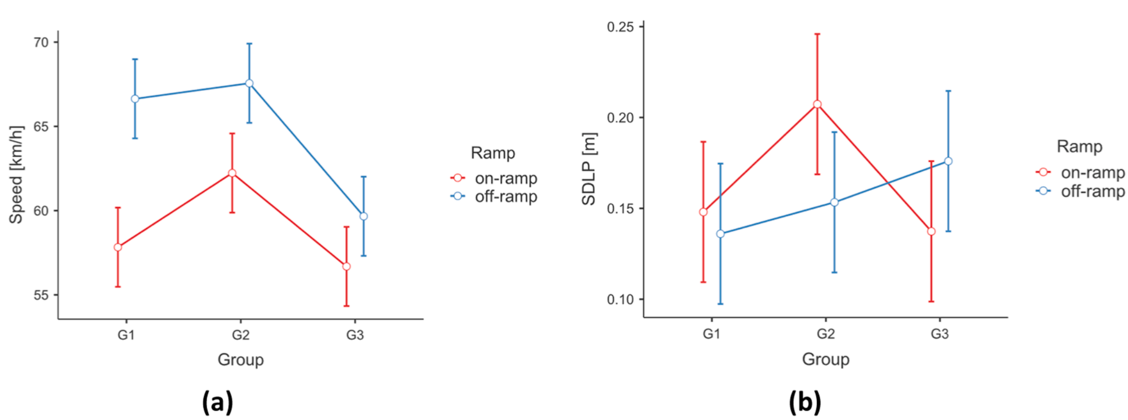

Fig. 9. Comparison of estimated marginal means of (a) speed and (b) SDLP along merging and diverging ramps. Error bars represent the standard error. Note: G1 = baseline condition; G2 = ACC; G3 = ACC + *V*-ISA. Note: Data points are slightly offset vertically from G1, G2, and G3 to enhance readability and prevent overlap.

$F(2,42) = 0.451$, p-value $= .640$, $\eta^2 = .012$. Similarly, the type of ramp (on-ramp vs. off-ramp) was found to be insignificant, $F(1,42) = 0.094$, p-value $= .761$, $\eta^2 = .010$, as were the interactions between group type and ramp type, $F(2,84) = 0.8129$, p-value $= .450$, $\eta^2 = .017$, according to the Mixed ANOVA results presented in Table 5 and illustrated in Fig. 9b These findings indicate that the use of assistance systems (ACC only and ACC + *V*-ISA) does not adversely affect lateral driving performance.

3.3. Subjective evaluation (post-drive questionnaire)

After the experimental drive, the participants were provided with a post-drive questionnaire to evaluate the overall subjective workload using (i) NASA-TLX, (ii) System Acceptance and (iii) Situation Awareness. The results of the subjective evaluation are presented in the following sub-sections.

3.3.1. NASA task load index

To analyse the impact of driving assistance systems on workload, *one-way ANOVA* were conducted on all six subscales of NASA-TLX among the three groups and also considering the overall workload score. The one-way ANOVA showed no significant differences in workload between the groups, Mental demand: $F(2,44) = 0.332$, p-value $= .719$, $\eta^2 = .016$; Physical demand: $F(2,44) = 1.214$, p-value $= .307$, $\eta^2 = .055$; Temporal demand: $F(2,44) = 0.031$, p-value $= .970$, $\eta^2 = .001$; Effort: $F(2,44) = 0.787$, p-value $= .462$, $\eta^2 = .036$; Performance: $F(2,44) = 0.214$, p-value $= .808$, $\eta^2 = .010$; Frustration: $F(2,44) = 0.778$, p-value $= .466$, $\eta^2 = .036$; Overall: $F(2,44) = 0.619$, p-value $= .544$, $\eta^2 = .029$. The high ratings on the performance subscale (> 7.5) in all three groups suggest that participants felt they had successfully completed the driving task, as illustrated in Fig. 10. This indicates that neither the ACC system nor the ACC + *V*-ISA system had a substantial impact on the drivers' self-reported workload. One possible explanation for this finding is the drivers' prior familiarity with the ACC, which likely minimized any additional cognitive load during the experiment.

Furthermore, before the experiment, drivers underwent a training session on a trial scenario to familiarize themselves with the systems being tested. This preparation likely contributed to the observed lack of significant differences in workload. The ACC system is designed to be user-friendly, which probably explains why drivers did not experience increased mental demand when using it. Similarly, the V-ISA system operates automatically, which indicates that drivers in group 3 did not experience higher mental activity compared to those in group 2, who were only using the ACC system.

3.3.2. System acceptance

The acceptance of the ACC and the integrated system ACC + *V*-ISA was assessed using the System Acceptance Scale (SAS) developed by [58]. This scale was employed to measure participants' perceptions in two specific areas: (i) system usefulness and (ii) driver satisfaction. Participants from groups 2 and 3 were asked to complete a detailed questionnaire focusing on these two subscales.

The collected data were analysed to look for any potential differences in acceptance ratings between the two groups. Specifically, one-way ANOVA was performed to compare the scores of participants using the ACC system alone (group 2) with those using the integrated system (group 3). The analysis revealed no statistically significant differences between the two groups in the usefulness ratings ($F(1,29) = 1.488$, p-value $= .233$, $\eta^2 = .050$), and for satisfaction ratings ($F(1,29) = 0.329$, p-value $= .571$, $\eta^2 = .012$). Participants from both groups reported similar level of acceptance, indicating that both systems were perceived as useful and satisfying, as illustrated in Fig. 11. This suggests that the addition of V-ISA to the ACC system did not negatively impact user acceptance.

3.3.3. Situation awareness

The ratings for the three subscales demand (D), supply (S), and understanding (U) were analysed. The results indicated that both driving assistance systems had a positive impact on drivers. For the demand dimension, participants reported that neither system imposed excessive cognitive or operational demands, which allowed them to maintain focus and control. This was reflected in the lowest ratings among the three subscales (Fig. 12), with no significant difference observed between the two groups, $F(1,29) = 2.066$, p-value $= .162$, $\eta^2 = .069$).

Regarding the supply dimension, participants felt that both systems adequately provided the necessary information and support to manage

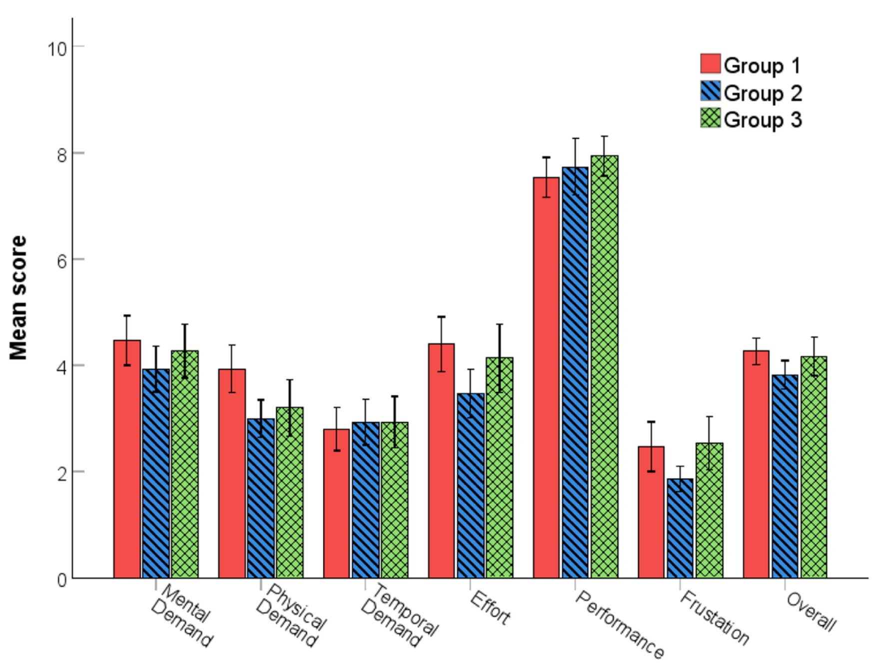

Fig. 10. Comparison of self-reported workload dimensions of NASA-TLX questionnaire between three groups (G1 = baseline condition; G2 = ACC; and G3 = ACC + *V*-ISA). Error bars represent the standard error.

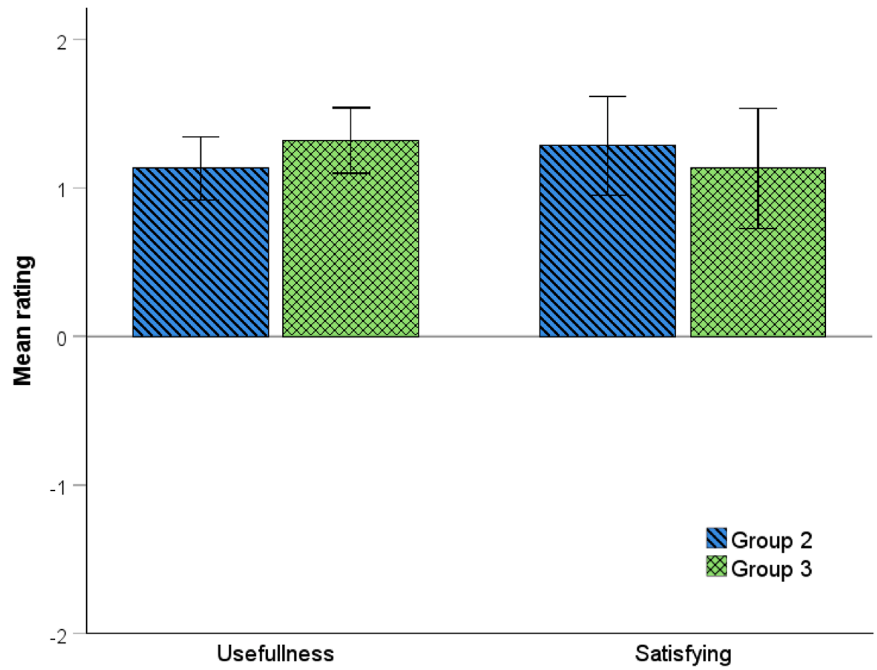

Fig. 11. Average system acceptance rating on two subscales: usefulness and satisfying for ACC (group 2) and integrated system (ACC + *V*-ISA, group 3). Error bars represent the standard error.

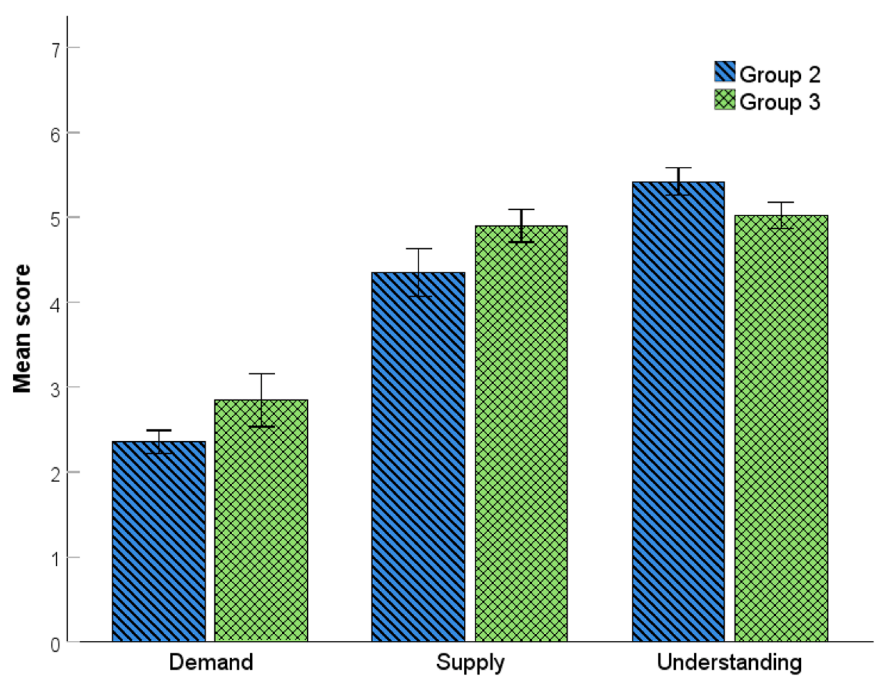

Fig. 12. Mean scores of situational awareness rating on three sub-scales for group 2 (ACC) and group 3 (ACC + *V*-ISA). Error bars represent the standard error.

the driving task effectively, again with no significant difference between the groups, ($F(1,29) = 2.585$, p-value = .119, $\eta^2 = .085$. For the understanding dimension, participants from both groups reported a clear comprehension of the driving situation, with higher ratings observed in the ACC-only group, where values exceeded 5 (Fig. 12). However, this difference was not statistically significant, ($F(1,29) = 3.090$, p-value = .090, $\eta^2 = .099$).

In addition, the overall situation awareness (SA) was estimated using Eq. (8). For group 2 (ACC only), the mean score was 26.60, while for group 3 (ACC + *V*-ISA), the mean score was 26.13, with standard deviations of 5.30 and 5.50, respectively. The situational awareness analysis revealed that participants in both the ACC-only group and the integrated ACC + *V*-ISA group exhibited similar levels of situation awareness. This finding was statistically confirmed, ($F(1,29) = 0.056$, p-value = .815, $\eta^2 = .002$). These results suggest that the integration of the V-ISA system with the ACC system does not adversely affect drivers' situation awareness.

4. Discussion

The aim of this study was to evaluate the effects of assistance systems on driver performance, specifically focusing on speed control, lateral vehicle control, and driver experience. The assistance systems evaluated were Adaptive Cruise Control (ACC only) and an integrated system combining ACC with Intelligent Speed Adaptation for Visibility (V-ISA).

4.1. Driving performance

The results demonstrate that the integration of the ACC + *V*-ISA system significantly influences vehicle speed on two-lane highways and ramps, with particular emphasis on curves with limited visibility. On the two-lane highway section, the significant reduction in speed observed in the ACC + *V*-ISA group (G3) on a curve with a small radius (i.e., curve 1) demonstrates the effectiveness of the V-ISA system in enforcing the operating speed below the threshold speed limit estimated based on visibility conditions and stopping distance (*ASD* and *SD*). The absence of a leading vehicle on curve 1 significantly affected operating speeds, as most drivers struggled to judge the appropriate safe speed limit. In the case of Group 3, the V-ISA system was activated, enforcing speed reduction based on safety conditions when drivers exceeded the threshold speed limit. This finding is consistent with previous studies which highlighted the role of V-ISA in adjusting vehicle speed according to sight distance [20,21]. The outcome is particularly relevant for enhancing safety on roads with complex geometric conditions, where sight distance is limited and poses a risk of crash when drivers operate with only ACC [65].

While the integrated system ACC + *V*-ISA effectively reduced speed on the most challenging curve (i.e., curve 1), the absence of significant speed differences between the groups on the other curves suggests that the system influence is most pronounced in situations where the driver's speed choice could exceed safe limits due to reduced visibility [3]. This underscores the role of the V-ISA as a safeguard in specific hazardous conditions rather than a tool for uniformly altering driving behaviour across all road environments. Such a context-sensitive response aligns with prior research highlighting the value of adaptive systems that respond to specific situations [9] and supports the integration of the V-ISA with ACC for improved performance.

Although the assistance systems did not significantly alter overall operating speeds compared to the baseline (group 1) on motorways, the significant reduction observed on curve 5, a curve with a smaller radius, indicates that road geometry still plays a crucial role in speed management, even in the presence of ACC [33]. In contrast, the absence of significant group differences on the motorway sections can be attributed to the characteristics of these environments, which include higher visibility with sight distances ranging from 197 to 312 m, gentler curvature with radii from 1000 to 2500 m, and more predictable driving conditions, which reduce the need for system intervention and lead to similar speed choices across groups. This interpretation is consistent with earlier studies that reported minimal effects of assistance systems in motorway contexts with favourable driving conditions [5,52].

For ramps, the significant speed reduction in group 3 (ACC + *V*-ISA), particularly on off-ramps, emphasizes the role of the system in managing speed transitions during deceleration phases. This finding is crucial, as it suggests that V-ISA effectively supports drivers by enforcing speed levels according to sight conditions when transitioning from high-speed motorways to slower-speed sections, such as off-ramps [18]. The statistically significant differences in speed on off-ramps between the groups further indicate that assistance systems (i.e., V-ISA) can play a vital role in mitigating speed-related risks during complex driving tasks like merging and diverging. These findings are consistent with the literature on ramp safety, which highlights the importance of speed control during these critical transitions [28,47].

The analysis of lateral vehicle control, measured through the *SDLP* revealed no significant differences across all road environments (two-lane highways, motorways, and ramps) among the baseline, ACC only and integrated system (ACC + *V*-ISA). The absence of an effect on lateral control is likely explained by the functionality of the integrated system, which regulates longitudinal control (i.e., speed reduction) in response to visibility limitations. Since the system does not interfere with lateral control mechanisms, drivers are able to maintain their natural steering behaviour. This suggests that the activation of the integrated systems does not compromise lateral control, a critical consideration for ensuring that safety enhancements in one domain (i.e., speed regulation) do not introduce new risks in another domain (i.e., lateral control) as discussed by Rudin-Brown and Parker [45]. These findings align with previous research, which found no adverse effects of V-ISA on lateral control alone [21], suggesting that such an integrated system can enhance driving safety without impairing the driver's ability to maintain lane position.

4.2. Driving experience

The NASA-TLX assessment showed no significant differences in perceived workload among the groups, indicating that neither the ACC system nor the ACC + *V*-ISA integrated system added extra effort. Similarly, Dragutinovic et al. [11] found in their review study that driving with ACC did not increase self-reported workload and in some instances, it was perceived as less demanding. This suggests that the proposed integrated system is user-friendly and does not increase mental workload, thereby preserving its safety benefits in terms of risk reduction [20]. The high-performance ratings in all three groups further support that the drivers felt effective in completing the primary task, regardless of the system used. This aligns with research showing that well-designed assistance system can improve safety without increasing driver workload [27].

System acceptance, measured by the System Acceptance Scale (SAS), was rated similarly by participants in both group 2 (ACC only) and group 3 (ACC + *V*-ISA). The integration of the V-ISA to ACC did not reduce user satisfaction, with no significant differences in acceptance ratings between the groups as observed in a previous study, when drivers were assisted with only V-ISA [20].

Situation awareness in driving involves understanding how the driver's goals, the vehicle condition, the road environment, and the actions of other road users are connected at any given moment [51]. This becomes particularly important when the vehicle operates with some level of autonomy, requiring the driver to monitor the systems that control the vehicle. As these systems take over more driving tasks, there is a risk that the driver's understanding of the system status may not match the actual status of the system [4]. In this study, situation awareness remained unaffected when assisted with the integrated system compared to ACC only. Participants reported adequate support from both systems without excessive cognitive demands. The lack of significant differences in situation awareness between the groups suggests that the integrated system improves the driving experience without compromising control or understanding of the driving environment. Overall, findings on workload, system acceptance, and situational awareness indicate that the integrated system performs comparably to other groups, while aligning operating speed with stopping distance to maintain safe sight conditions (i.e., SD $\leq$ ASD).

4.3. Implications and limitations

The findings of this study have important implications for road safety and the design of future ADAS and autonomous vehicles. One of the overall objectives was to demonstrate that the working algorithm (model) of the V-ISA can be integrated with other ADAS modules. In this case, the V-ISA was integrated with Adaptive Cruise Control (ACC). As demonstrated in this and previous studies [20,21], V-ISA effectively regulates speed in specific high-risk scenarios, such as sharp curves with limited visibility, which underlines its potential as a targeted intervention for maintaining appropriate speeds based on road conditions, both as a standalone assistance system and as part of an integrated system. Importantly, this speed management by V-ISA does not increase driver workload, so V-ISA can enhance safety without compromising driver comfort or engagement. Moreover, the system acceptance observed in this study suggests a positive trajectory for the adoption of ADAS technologies. As drivers become more familiar with ADAS, their comfort and trust in the technology are likely to increase, since user confidence and familiarity are key factors in the successful implementation of ADAS into everyday driving [15].

While this study provides valuable insights, it is important to acknowledge its limitations. The study was conducted in a controlled experimental setting within the simulated environment, which may not fully capture the variability and unpredictability of real-world driving conditions. However, the simulator allows for controlled experiments and ensures that all participants experience the same conditions, enabling reliable comparisons across groups. Although a Poisson distribution is typically employed to model actual traffic flow, the traffic in this study was generated at a constant rate due to limitations in the simulation software. Additionally, the study involved a limited sample of participants, and we acknowledge that driving styles and risk perception may vary across regions. Future studies should therefore include larger and more diverse participant samples to validate the generalizability of the findings across different cultural and infrastructural contexts. Furthermore, this study only considered the mean speed across the circular arc of the curve. This may overlook differences between entry and mid-arc speeds [60]. Future work should address these aspects to better capture how drivers anticipate safe speed and adapt within the curve. In addition, further studies should incorporate other key performance measures (such as distance to the leading vehicle under car-following conditions and acceleration/deceleration patterns) to gain a more comprehensive understanding of the influence of the integrated assistance system on driver performance, behaviour, and subjective perceptions. This study utilized a fixed-base driving simulator for the experiments; therefore, future research should consider conducting field studies to validate these findings in real-world driving conditions. Moreover, the study focused on a specific ADAS module (ACC + *V*-ISA). Exploring the effects of other ADAS combinations and V-ISA variants could provide a more comprehensive understanding of the V-ISA effectiveness. Finally, while the study examined immediate behavioural responses to the integrated ACC + *V*-ISA system, long-term effects were not considered. Future research should investigate how drivers' interactions with this system evolve over time.

The real-time measurement of available sight distance (ASD) in this study was determined using sensors, (i.e., road markers), but was limited to a simulation environment. However, ongoing research on dynamic ASD evaluation using Light Detection and Ranging (LiDAR) technology suggests the potential for integrating this functionality into real vehicles. LiDAR-based perception systems are currently among the most effective for measuring sight distance, as they can detect stationary objects and generate high-resolution 3D environmental maps. These sensors are typically mounted at heights different from the driver's eye, which can alter the available sight distance (ASD) compared to the driver's line of sight. Jung et al. [22] analysed driver sight distances using LiDAR point cloud data, reconstructing the visible three-dimensional (3D) space as the area accessible through an unobstructed line of sight from a moving observer. Additionally, Ma et al. [32] developed a real-time visualization framework for estimating sight distances on existing highways using LiDAR data. In another study, Ma et al. [31] introduced a method for detecting obstacles that obstruct a driver's view on highways using Mobile Laser Scanning (MLS) data. Their approach processes and analyses point cloud data to accurately identify sight obstructions along roadways, achieving high efficiency with a detection time of approximately 0.2 s per sight point. These studies contribute to the advancement of this technology, paving the way for its integration into the next generation of ADAS and automated vehicles.

It is important to note that the perception–reaction time (PRT) adopted in this study ($\tau = 2.8 - 0.0028 \cdot v$, with v in km/h) represents the response behaviour of a human driver, as defined in the Italian road geometric design guidelines [38]. However advanced driver-assistance or intelligent speed adaptation systems may possibly produce substantially shorter PRT values due to faster response times. If these shorter reaction times were considered, the required SD would decrease correspondingly, implying that the speeds selected by human drivers might still be within safe limits when assisted by automated systems. Future research should therefore further investigate the influence of varying PRT assumptions on SD estimation.

5. Conclusions

This simulator-based study assessed the integration of Intelligent Speed Adaptation for Visibility (V-ISA) with Adaptive Cruise Control (ACC). The ACC + *V*-ISA integration effectively moderated vehicle speed on curves where visibility was constrained, aligning with the system design to manage speed according to sight distances. The observed reduction in speed on critical curves, particularly where sight conditions were poor, highlights the role of the system in mitigating the risk of crashes in such locations. This finding supports previous research on the benefits of V-ISA in adapting speed to sight conditions as a standalone system. Importantly, the V-ISA + ACC integration did not compromise lateral vehicle control or increase driver perceived workload, as evidenced by consistent standard deviation of lateral position and NASA-TLX ratings across all groups. This finding is crucial, as it suggests that improving speed control through integrated systems does not introduce new risks or increase mental demands on drivers. The high acceptance ratings and stable situational awareness further indicate that drivers perceived the V-ISA + ACC integrated system as a valuable enhancement.

These findings have significant implications for the design and implementation of future ADAS. The operational functionality (algorithm) of the V-ISA and its ability to effectively integrate with ACC and manage speed under limited sight conditions highlight its potential as a critical tool for improving road safety. This study also asserts that the integration of ACC and V-ISA technologies equips drivers with the necessary tools to maintain correct distances from the vehicle in front (i.e., by ACC) and the correct speed when driving isolated (i.e., by V-ISA), thereby ensuring compliance with national highway codes, such as the Italian and Norwegian regulations. These regulations state that drivers must always maintain control of their vehicle and be able to perform all necessary manoeuvres safely, particularly to stop the vehicle within the field of vision and in front of any obstacles [37,39]. The functionality of the V-ISA ensures compliance with the sight conditions ($SD \leq ASD$), by aligning vehicle speed with the SD the system directly mitigates one of the most critical risk factors in curve negotiation. However, the valid concern that enforcing lower speeds relative to the expectations of other drivers could introduce local speed differences, particularly in curves with limited sight distance. Such differences may influence traffic flow and interaction safety. Future research should therefore investigate not only the safety benefits of V-ISA at the individual vehicle level but also its potential impacts on surrounding traffic. Moreover, further studies are required to explore the comparison between the integrated system (ACC + *V*-ISA) and modern ACC (e.g., predictive ACC) or other ADAS modules. However, continued research and development are essential to optimize these systems for different driving conditions and to ensure their effectiveness and reliability in real-world applications.

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CRediT authorship contribution statement

Abrar Hazoor: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Alessandra Lioi:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Giuseppe Marinelli:** Writing – review & editing, Writing – original draft, Conceptualization. **Marco Bassani:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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