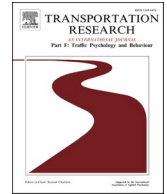




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Assessing the effectiveness of Augmented Reality warnings for improving safety at highway merging zones in a connected environment

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ARTICLE INFO

Keywords:

Driving simulator
Road safety
Merging zone
Safety measures
Augmented Reality
Connected vehicles

ABSTRACT

The merging process of vehicles moving from the on-ramp to the right lane of a highway is quite critical at interchanges for both safety and operational efficiency. Several studies have emphasized the importance of merging zones at interchanges, identifying them as major sites of conflicts between passing and entering vehicles. Incorrect assessment of gaps and precedence in these zones can result in serious collisions and traffic disruptions at interchanges. This study looks at how effective Augmented Reality (AR) solutions in a connected environment are in improving safety at merging zones, helping drivers keep a safe distance from vehicles entering the highway from on-ramps. In a driving simulation study, four different safety measures are evaluated: i) a vehicle-to-vehicle spacing measurement support, which integrates a Variable Message Signs panel (VMS) with a new type of road pavement marking; ii) a Head-Up Display (HUD) that projects a static symbol onto the vehicle windshield, advising the driver to maintain a safe distance from the entering vehicle; iii) a connected vehicle system that integrates AR technology consisting of a dynamic symbol on the road surface, which provides the driver with additional visual cues about the actual longitudinal distance from the entering vehicle; iv) the same AR-based system with an additional audible warning. The driving behavior of forty-four participants in four different configurations with the safety measures was compared with their behavior in a configuration without any measures (baseline condition). The results demonstrated a significant positive impact from all tested measures, with the most effective solution being AR systems, which demonstrated the ability to assist drivers in adjusting their distance from the entering vehicles. This study confirms the high potentialities of AR technologies and connected vehicles in enhancing the overall safety of road networks, particularly in high-risk scenarios and challenging maneuvers.

1. Introduction

The merging maneuvers of vehicles transitioning from the on-ramp to the right lane of a highway are crucial for both operational efficiency and safe driving conditions. Several studies have shown that interchanges, particularly on-ramps, are the pivotal points on highways where vehicular conflicts and interferences are most problematic (Kondyli, 2009). Previous studies (Calvi and De Blasiis, 2011; Yang and Ozbay, 2011; Kononov et al., 2012) demonstrated the high risk in these areas. Lee et al. (Lee et al., 2022) recently confirmed this, finding that 10 % of rear-end crashes in 100-car naturalistic driving studies occurred when drivers encountered a

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<https://doi.org/10.1016/j.trf.2025.103440>

Received 23 November 2024; Received in revised form 4 November 2025; Accepted 4 November 2025

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merging maneuver in a merging zone. However, decelerating in a traffic lane caused 45 % of these rear-end crashes. Besides enhancing traffic flow, merging maneuvers can also cause traffic to slow down due to highway entry maneuvers. Additionally, the authors reported that they deemed the merging maneuvers unsafe, despite their legality, in 33 % of the near-crash incidents and illegal in another 17 %. Driver inattention and following vehicles too closely, either individually or in combination, are the primary causes of rear-end crashes on highways (Knippling et al., 1993). McCartt et al. (McCartt et al., 2004) conducted an analysis on several ramps in Northern Virginia, revealing that 48 % of the crashes happened as vehicles were leaving the highway, 36 % happened as they were entering the highway, and 16 % happened in the middle area of the merging zone.

Hang et al. (Hang et al., 2022) observed that since vehicles on the on-ramp typically travel at a slower speed than those in the right lane of a highway, any interference during the merging zone can result in three potential consequences: 1) The vehicle on the on-ramp enters the highway through the acceleration lane, forcing the vehicle in the right lane of the highway to decelerate rapidly and suddenly, resulting in adverse effects on traffic flow, both in terms of safety and operating conditions. 2) During the merging zone, a crash can occur due to the low safety distance between the entering vehicle and the vehicle on the highway. 3) The vehicle entering from the on-ramp may take longer to complete the maneuver, leading to a significant reduction in the efficiency of the on-ramp traffic flow. Bonnin et al. (Bonnin et al., 2013) demonstrated that the majority of crashes in merging zones were due to drivers' incorrect behavior. Wrong perception of mutual distance or incorrect interpretation of infrastructure's features can negatively influence the decisional process. Despite notable advancements in automotive technology and vehicle design, some safety problems persist at interchanges, particularly concerning acceleration lanes and merging zones. Several crash analyses, such as those conducted by McCartt et al. (McCartt et al., 2004), emphasize that these issues still remain unsolved, and, as previously reported, highway merging zones represent critical areas in terms of road safety, where a high concentration of crashes often occurs.

Several studies have been developed to improve safety and operational efficiency in these areas, but they still remain points of concern within the transportation system. With the advent of new technologies and connected road environments, it is now possible to go further than traditional tolls and measures with innovative systems that leverage technological advancements to provide drivers with timely and useful information aimed at preventing potentially hazardous situations. In this context, the present study is aimed at investigating how effective information systems, such as Augmented Reality (AR) interfaces, can integrate or potentially replace more conventional forms of driver information communications. These emerging technologies are designed to deliver real-time, context-sensitive guidance directly within the driver's field of view, thereby enhancing situational awareness and improving decision-making during complex manoeuvres, such as those typically required in highway merging zones. Indeed, in highway merging zones it is crucial to test measures that can provide timely warnings to drivers regarding potential conflicts with entering vehicles while also supporting their ability to accurately assess relative distances with entering vehicles (Garber and Hoel, 2009). These areas are characterized by vehicle interactions and limited decision time, increasing driver workload and the likelihood of sudden decelerations or lane changes, which may result in congestion and a higher crash risk (Hu et al., 2020).

Due to the dynamic nature of merging scenarios, drivers must simultaneously manage speed coordination and spatial awareness. However, studies have shown that drivers often struggle to perceive and maintain safe distances from vehicles merging from the on-ramp, especially under high traffic conditions or when merging zones are not long enough (Louah et al., 2011; Kondyli and Elefteriadou, 2012; Riener et al., 2013). This difficulty is further compounded by the variability of traffic flow and the need for quick decision-making. Calvi and De Blasii (Calvi and De Blasii, 2011) conducted a driving simulator study that revealed that drivers frequently fail to respond promptly to merging vehicles, leading to abrupt maneuvers as well as a degradation of the overall level of service of highways at interchanges. Several authors (Taieb-Maimon and Shinar, 2001; Taieb-Maimon, 2007; Michael et al., 2000; Risto and Martens, 2013) confirm that drivers commonly experience difficulties in estimating headways and relative speeds, a limitation that can compromise safety and traffic flow (Weng et al., 2015). In this context, technologies that offer both early warnings (visual or auditory) and real-time feedback on spatial relationships, such as distance indicators or AR overlays, may play a key role in enhancing situational awareness and reducing crash risk.

The driving simulator study in this paper looks at how well Augmented Reality (AR) solutions work in a connected environment to make merging areas safer and help drivers keep a safe distance from vehicles entering the highway from on-ramps.

The remainder of the paper is organized as follows: Section 2 gives an overview of various countermeasures that have been suggested and tested in earlier studies to see how well they work in making highway merging zones safer. Section 3 describes the methodology used in this study to investigate the effects of AR-based countermeasures on highway merging zones. Sections 4 and 5 will then present and discuss the results of the study. Finally, Section 6 draws the overall conclusions and proposes directions for future studies.

2. Literature review

2.1. Ramp metering

Ramp metering is a traditional strategy used to improve the safety and operation of merging zones. It employs specialized traffic signals to regulate vehicle flow on highway on-ramps, aiming to minimize conflicts between entering and through traffic flow (Jin et al., 2017). Since 1960, the US has employed the ramp metering-based method to enhance mobility by controlling access to the highway on-ramp through traffic light installations or specific signage (Lee et al., 2006). The overall effects of using such a method include decreasing delays, reducing travel time, and improving travel time reliability (Hourdakakis and Michalopoulos, 2007). Despite the possibility of reducing crashes, only a few studies have analyzed the ramp metering safety effects (Lee et al., 2006; Banks, 2000; Balke et al., 2009; Sun et al., 2013). In fact, another effect of ramp metering consists in improving the safety of the merging zone,

thanks to the lower variance in the speed distribution of the entering vehicles and the reduction of rear-end and sideswipe crashes along the highway main lanes (Cleavenger and Upchurch, 1999). Haule et al. (Haule et al., 2021) showed that ramp metering can reduce the risk of crashes by decreasing the turbulence in the merging zone; the recorded crash risk reduction was between 12 % and 14 %. The authors observed that when ramp metering was in use, there were more noticeable warning signs of potential crashes, like changes in speed, how crowded the traffic was, differences in speed, variations in traffic, and driving behaviors (like sudden stops and quick lane changes), compared to when ramp metering was not used. Indeed, the activation of ramp metering allowed for predicting crash risk based on the difference in average lane speeds between upstream and downstream detectors, the average traffic volume in the lanes at the downstream and upstream detectors, the devices or systems installed on the highway capable of monitoring and collecting real-time traffic data, and the coefficient of speed variation between upstream lane detectors.

Piotrowicz and Robinson (Piotrowicz and Robinson, 1995) found that using ramp metering led to a significant drop in crash rates in several studies they looked at, with reductions of about 24 % to 50 %. Lee et al. (Lee et al., 2006) employed the Asservisement Linéaire d'Entrée Autoroutière (ALINEA) ramp metering strategy, a method widely used in several European countries (Papageorgiou et al., 1991), to instantly determine vehicle critical occupancy (occupancy at capacity) and enhance vehicle integration in merging zones. When using such a ramp metering strategy, the authors observed a crash reduction between 5 % and 37 % compared to the cases without ramp metering. Moreover, it was shown that if a queue already existed downstream of the ramp, the ramp metering's capacity to make significant safety improvements would be limited.

Abdel-Aty and Gayah (Abdel-Aty and Gayah, 2010) analyzed two ramp metering methods: ALINEA, where each ramp meter worked on its own based on the traffic conditions at that ramp, and SCATS, which was a coordinated system where a network of ramp meters worked together. This strategy divided each merging zone into several segments to balance the number of vehicles entering and exiting each segment. The study showed that both SCATS and ALINEA ramp metering methods successfully lower the crash probability in real-time, but coordinated ramp metering (SCATS) usually works better than uncoordinated ramp metering (ALINEA) for reducing crash risk and improving traffic flow. However, the ALINEA method was more restrictive and resulted in a lower crash risk along the single ramp than the SCATS method. Some other studies confirmed the effectiveness of the ALINEA method in reducing the crash risk and improving safety, as well as, in general, the usefulness of the ramp metering methods (Schrock et al., 2015).

The overall results of previous studies conclude that traffic flow management along highway on-ramps effectively reduces crash risk. However, the amount of such reduction depends on the different types of ramp metering applied and significantly varies from case to case. Moreover, this type of traffic strategy based on gap metering systems does not provide any warnings to drivers on the lanes of the main road, as it is not aimed at suggesting to the drivers the right and safe distance to the merging vehicles and offering distance references for a safe headway choice, therefore leaving only to the driver's subjective assessment and judgment the way to adjust the headway to merging vehicles.

2.2. Active gap metering and variable message sign

Reinolsmann et al. (Reinolsmann et al., 2021) proposed an intriguing approach to assist drivers traveling in the right lane of highways in accurately assessing headways with merging vehicles entering the highways from on-ramps at merging zones. Their study introduced an Active Gap Metering (AGM) signalization system, combining pavement markings with an innovative Variable Message Sign (VMS). The findings demonstrated that AGM had a significant impact on driver behaviour. Specifically, drivers progressively increased their following distance from the lead vehicle, thereby establishing safer and more appropriate headways relative to the vehicles merging from the on-ramp. One of the most notable outcomes was the improvement in the minimum time-to-collision with the merging vehicle, which was extended by approximately 1 to 1.5 s compared to scenarios without any intervention. These results suggest that the AGM signalization system has the potential to serve as an effective tool for enhancing driver awareness and interaction in merging areas.

Road markings such as longitudinal and transverse markings, when used as a complementary static traffic control, are particularly effective in providing drivers with guidance to adjust their speeds and lateral positions (Babić et al., 2022). The Federal Highway Administration (Administration, 2009) provides another example of pavement markings in the merging area of highways, proposing a combination of solid and dashed white lines to distinguish the inner lanes from the outer merging lanes. In the marking scheme, the drivers can cross the first dashed line, but not the solid one, to ensure that the lane-changing maneuvers occur only towards the inner lanes of the highway while leaving the right lane as free as possible for the entering vehicles (Reinolsmann et al., 2019).

Some studies have analyzed the behavior of drivers approaching the merging zone while using a VMS, with the aim of ensuring the safety of the maneuver. Despite the drivers' familiarity with the dangers of road merging sections, some authors assert that the VMS's reported message serves as a crucial reminder of correct and safe behavior (Erke et al., 2007; Hössinger and Berger, 2012). In addition, all the tested signals provided similar results in terms of quick and accurate comprehension by the drivers, whether it was a text signal or a static or animated image. However, drivers should prefer pictorial signals over text-only messages due to their lack of linguistic restrictions (Bruyas, 1999; Luoma and Rämä, 2001). Arbaiza and Lucas-Alba (Arbaiza and Lucas-Alba, 2012) reported that when a message includes a pictogram, there is no need to report it in text form to prevent redundancy. On the other hand, Koyuncu and Amado (Koyuncu and Amado, 2008) discovered that when a message incorporates both a pictogram and text within the same panel, the driver's reaction time decreases and their interpretation speed increases (Cristea and Delhomme, 2015). According to another study that used a VMS with both text and graphics, speed dropped by 1–2 km/h and the number of drivers with a time headway under 1.5 s dropped (Reinolsmann et al., 2021). The effect was similar at night and specifically when the sign was illuminated, as it provided the highest effectiveness when its visibility was increased (Rämä and Kulmala, 2000).

Before the merging zone begins, it is recommended to place VMS warnings and visual marking guidance to aid drivers in accurately

interpreting the distance to the leading vehicle, allowing them the necessary space and time to adjust it (Reinolsmann et al., 2018). This requirement is crucial, particularly given that the majority of crashes occur when drivers must adjust their behavior near the on-ramp or even during the merging maneuver into the prevailing headway gap. Therefore, the most effective approach is to promptly prepare drivers and inform them to increase their headway before the commencement of the merging maneuver for vehicles entering from on-ramps.

Jin et al. (Jin et al., 2017) proposed another AGM signalization system. The authors viewed gap metering as a non-stopping mainline version of ramp metering, utilizing traffic signals on the highway's right lane to provide ample gaps for vehicles entering the main right lane. This system aimed at facilitating smoother entry of vehicles from the on-ramp without interrupting the traffic flow on the mainline. The results showed a decrease in the average delay of approximately 24 %. Furthermore, using both AGM and traditional ramp metering, the results were enhanced even significantly, showing a marked improvement of the overall traffic efficiency.

According to literature studies that analyzed the effectiveness of integrating gap metering systems with VMS and markings, it is possible to conclude that such a measure is able to improve the safety of merging zones, providing the driver with not only a warning by means of VMS but also visual guidance through the use of chevron markings, which are able to help drivers in the right lane to adjust their headways to the entering vehicle at interchanges. However, according to Reinolsmann et al. (Reinolsmann et al., 2021), although the dynamic component of these systems provides several real-time solutions to manage dynamic and controlled gap spacing for highway merge sections, this additional value is worthy of more in-depth investigation, by using new and advanced technologies within a connected environment that could increase the benefit in terms of driving support and safety.

2.3. Active traffic management and variable speed limits

Ma et al. (Ma et al., 2021) demonstrated that Active Traffic Management (ATM) in merging zones is a useful method to reduce crash risk and improve highway safety, with a crash reduction ranging from 2.8 % to 15.9 % among the investigated case studies. Also, Variable Speed Limit (VSL) makes a big difference by controlling traffic flow and informing drivers about congestion further down the road, which helps manage speeds as they approach merging zones (Kondyli and Elefteriadou, 2012). Germany first introduced VSL in the '80 s, and now many European countries and North America have installed it.

Carlson et al. (Carlson et al., 2010) proposed VSL, which involved imposing different speed limits on different sections of the infrastructure based on current traffic conditions and displaying these speed limits on specific VMSs on the highway. One could argue that the implementation of VSL, in conjunction with traffic control on ramps, enhanced traffic flow and alleviated congestion, potentially leading to a reduction in crash risk. However, the study did not provide specific quantitative data on crash reduction, but it showed that improvements in traffic flow had positive impacts on road safety. Other studies (Papageorgiou et al., 2008; Hellinga and Mandelzys, 2011; Commission, 2020) have found that VSL makes traffic safer by lowering speeds and making them more consistent, which leads to a 15 % faster average travel time, a 20 % decrease in congestion, and a 25 % drop in average delays, all of which are connected to a lower probability of crashes.

Reducing speed limits in congested areas smooths out traffic flow, prevents stop-and-go conditions, and lowers the crash risk. VSL could reduce crash potential (crash frequency divided by some exposure functions) by 5–17 % (Lee et al., 2006). On average, according to the prevalent literature, crash reduction after VSL installation is between 20 % and 30 % (Borrough, 1997; Allaby et al., 2007; Abdel-Aty et al., 2008).

Reinolsmann et al. (Reinolsmann et al., 2019) looked at how well different strategies for dynamically controlling merging zones worked. These strategies included lane control signalization and the potential use of variable speed limits in conjunction. The authors developed a driving simulator study exposing participants to platoon merging zone scenarios with vehicles entering from on-ramps on both urban and rural expressways with four lanes. The results showed that dynamic merge control worked better on rural expressways where traffic moves more quickly. On the other hand, urban expressways did not see any extra safety benefits from dynamic merge control and could choose a cheaper static merge control method instead.

Hayat et al. (Hayat et al., 2014) developed a field test to evaluate the impact of a VSL in a connected vehicle environment, focusing on driver compliance during highway merging zones. The authors examined three conditions with different gaps between vehicles: 40 m (132 feet), 53 m (176 feet), and larger. The results revealed that 68 % of drivers successfully completed the merging maneuver with a gap of 40 m, while only 60 % were able to merge when the gap was larger (53 m and more). This finding contradicts the expectation that drivers change lanes more easily with larger gaps.

In summary, several studies in the literature regarding the application of Variable Speed Limits (VSL) at merging zones demonstrate their effectiveness in enhancing operational efficiency and safety. However, these systems do not directly control the space between vehicles in merging zones, nor do they consider the different perceptions and consequent choices of safe distances that drivers have, which are important for making merging zones safer and more efficient, as noted by Kondyli and Elefteriadou (2012).

2.4. Connected vehicle technology and virtual reality support

These days, the cutting-edge technology of connected vehicles (CV) presents a significant challenge for the near future of active safety technologies. The Human-Machine Interface (HMI) is the heart of the interaction between driver and vehicle and plays a crucial role in enhancing the user driving experience within CV technology. Wang et al. (Wang et al., 2024) developed a driving simulation study to see how well drivers perform when entering a highway from an on-ramp and proposed three different HMI systems that used Augmented Reality (AR) to make merging safer. Three groups of participants were investigated and included: the control group, which

received only basic information; the warning group, which received the addition of the front vehicle icon and real-time headway information; and the guidance group, which also received speed and voice guidance features. The study found that drivers in the guidance group, who used an HMI system with features like speed indicators, lane position tracking, reminders about the front vehicle, real-time distance alerts, speed advice, and voice instructions, were much better at controlling their speed after merging. Additionally, drivers in the guidance group merged closer to the left side of the ramp compared to those in the control group, who merged further from the left. Finally, the three different HMI groups showed no significant difference in mainline vehicle gaps.

Recently, different new systems using AR technology combined with connected vehicle systems have shown they can effectively give warnings to drivers using symbols and signals. These in-vehicle applications have the potential to improve drivers' visual awareness and provide advanced visual feedback, thereby enhancing their driving experience. It is highly recommended to conduct a thorough analysis of behavioral data to assess the impact of these technologies on driving behavior and performance. Some earlier studies using driving simulators have shown that the connected environment and AR technologies can improve driving behavior and road safety in important driving situations (Langlois and Soualmi, 2016; Schwarza and Fastenmeier, 2017; Calvi et al., 2020; Calvi et al., 2020; Calvi et al., 2020; Calvi et al., 2021). However, further studies are needed to see if AR warnings could help drivers during merging maneuvers and accurately estimate safe headways to entering vehicles.

Additionally, some studies were developed to understand the impact of the connected automatic vehicle systems (CAVs) on the ordinary traffic flow. The CAVs facilitate the transition from traditional merging control (e.g., ramp metering) to automated fusion control (Xue et al., 2022). However, as noted by Zhu and Tasic (Zhu and Tasic, 2021), earlier studies on how CAVs affect highway merging areas mainly focused on how well the systems worked in terms of operational efficiency, rather than on the safety of the merging actions. Park and Smith (Park and Smith, 2012) proposed an algorithm that used detailed vehicular and personalized data. The authors reported that the algorithm was able to reduce the conflicts in the merging zone, encouraging the lane changing from the on-ramp to increase the space for the vehicles in the right lane of the highway.

Some other studies on CAVs demonstrated that on-ramp vehicles merged smoothly into the right lane of the highway at the same speed as mainline vehicles (Xue et al., 2022), which can be considered functional for the safety of drivers and also reduces both fuel consumption and travel time of on-ramp vehicles, besides improving passenger comfort.

As concluded by Zhu et al. (Zhu et al., 2022), most of the existing studies on CAVs in the merging zones focus primarily on lower-level control mechanisms, such as trajectory planning, which deals with the precise movement and coordination of individual vehicles during the maneuver. However, the authors highlight that previous studies have not focused enough on higher-level control strategies that oversee traffic flow and the overall system, especially in more complicated situations like multi-lane highways or roads with a mix of traffic of CAVs and human-driven vehicles. While some studies have explored high-level control for single-lane highways using only CAV, there is a lack of comprehensive approaches that can optimize traffic management in environments with multiple lanes and mixed vehicle types, where interactions and merging become more complex. Therefore, more efforts should be made in these areas to enhance robust merge control for multi-lane configurations and mixed traffic, which will become common in the near future.

Only a few studies were found in the literature that analyzed the application of connected vehicle technology and AR in merging zones. In any case, those studies have investigated the behavior and performance of drivers entering a highway from an on-ramp, therefore during their merging maneuver. However, the safety of a merging zone strongly depends also on the behavior of drivers in the main lanes of a highway and their evaluation and assessment of headways with merging vehicles entering from an on-ramp. Augmented Reality integrated into a connected road environment could help drivers by providing them with timely warnings of possible interaction and conflict ahead with merging vehicles and supporting their assessment of headways.

The study presented in this paper is aimed at providing a significant and original contribution to the literature by investigating the potential benefits and behavioural effects that connected and cooperative driving technologies integrated with AR could bring to highway merging zones, both in terms of driver behaviour and overall road safety. Specifically, based on the literature gaps previously discussed for each type of measure proposed and tested in previous studies, the overall objective of this study is to test innovative measures, which introduced the AR interface as an advanced support tool for real-time decision-making, by means of a driving simulator. The AR-based solution visually superimposes information regarding the actual distance to a merging vehicle entering a highway from an on-ramp, directly into the field of view of the driver who is travelling in the main right lane of a highway approaching a merging zone. The system can function either with visual-only feedback or in combination with audio messages, aiming to enhance spatial perception and support hazard anticipation, particularly in high-stress or low-visibility conditions. To evaluate the effectiveness of the proposed AR-based system, the analysis includes a comparison of the results with a baseline condition without any counter-measure. Moreover, in the same scenario, two other, let's say, traditional measures are tested. They are selected because they are implementable on existing roads, with no need for a connected environment to work. The first one was already tested in a previous study (Reinolsmann et al., 2021) and demonstrated its effectiveness in improving the safety of the merging zone: it consists of a VMS combined with pavement markings designed to visually indicate to drivers the recommended minimum safe distance from the vehicle ahead. This measure aims to provide intuitive and easily perceivable visual cues to support drivers' estimations of spacing. The second one is based on a Head-Up Display (HUD) that projects a static warning symbol onto the windshield within the driver's line of sight. This symbol alerts the driver to imminent interference with a merging vehicle and advises him to maintain a safe following distance. This measure is intended to reduce driver distraction and improve reaction times by avoiding the need to look away from the roadway. Both these reference measures can be used without needing a connected environment, which allows for a better assessment of the potential additional benefits offered by the new methods tested in this study that use connected vehicle technologies combined with AR.

3. Methodology

3.1. Driving simulator

The study was carried out using a medium-fidelity, fixed-base driving simulator located at the Department of Civil, Computer Science and Aeronautical Technologies Engineering of Roma Tre University (Fig. 1).

This simulator features a left-hand-drive Toyota Auris car positioned within a curved screen, providing a 180-degree forward view and continuous side image of the driving environment using three overhead HD projectors, along with rear and side mirror displays. It incorporates a force feedback steering wheel and pedal set, seamlessly integrated with the standard controls of a Toyota vehicle. The STISIM software created the driving simulation environment, allowing the collection of different driving data at a rate of up to 60 Hz using a performance measurement system. Previous studies (Calvi et al., 2020; Bella, 2008; Calvi, 2018) have confirmed the validity of this driving simulator, which assessed driving performance in terms of speed, acceleration, and trajectory across diverse driving conditions and road environments (Calvi and D'Amico, 2006; Calvi, 2015; Calvi et al., 2018). The validation studies' results allowed the researchers to investigate complex behaviors that would be challenging, unsafe, or unethical in real-world settings.

3.2. Scenario

The driving scenario reproduced a typical highway segment, considering that, according to literature (Kondyli, 2009; Calvi and De Blasiis, 2011; Yang and Ozbay, 2011; Kononov et al., 2012; Lee et al., 2022; Knippling et al., 1993; McCartt et al., 2004; Hang et al., 2022; Bonnin et al., 2013), this type of road is the one most critical in terms of safety in merging zones. For the aim, the highway section was designed in accordance with Italian design guidelines (MIT – Ministry of Infrastructure and Transport, Italy, 2006; MIT – Ministry of Infrastructure and Transport, Italy, 2011) (Fig. 2) that require a cross-section composed of three lanes in each direction, each measuring 3.75 m wide, complemented by a 3.00 m wide hard shoulder and a 4.00 m wide median. Since the design characteristics of highways worldwide are quite similar, using Italian design guidelines to reproduce the simulated highway scenario does not significantly affect the ability to generalize the results for this type of road environment. It means that for other types of road infrastructures that differ significantly from the one reproduced in this study, it will be necessary to verify a possible confirmation of the results obtained here. Various elements were implemented in the scenario, such as vertical signs, markings, vegetation, barriers, and other vehicles, to enhance realism.

A speed limit of 130 km/h was required throughout the scenario, across a total length of 40 km. To enhance driving realism and drivers' perceptions of approaching an interchange, seven interchanges were integrated along the highway. Each interchange included a deceleration lane with an exit ramp (170 m long), followed by an acceleration lane (210 m) where vehicles entered the highway from the on-ramp into the right lane of the highway. This configuration, based on Italian design guidelines for interchanges (MIT – Ministry of Infrastructure and Transport, Italy, 2006); created a merging zone for each interchange with interactions between the driver and the entering vehicles. Additionally, at the interchanges, a platoon of vehicles was implemented in the middle lane of the highway, with speeds higher than the driver's speed and a short headway between them, to deter the right-lane driver (i.e., the participant in the experiment) from moving to the left lanes and overtaking the entering vehicle.

Five of the seven interchanges of the study were used to observe how drivers behaved when approaching the merging area and interacting with vehicles entering the highway from the on-ramp. Each interchange had its own specific measure, which will be explained later in the paper. In the other two interchanges, no vehicles entered the highway, which meant drivers couldn't expect a



Fig. 1. Roma Tre driving simulator.



Fig. 2. Simulated scenario.

merging vehicle at all the interchanges, reducing any learning effects that might change their behavior and affect the results. Moreover, the seven interchanges were strategically positioned at different locations along the highway within the sample of drivers to eliminate any further biasing effects caused by the order of interchanges in the scenario.

In addition to simulating a platoon of vehicles in the middle lane of the highway, an audio message was reproduced inviting the driver to stay in the right lane, approximately 1.5 km before the appearance of the tested measure defining each interchange. Furthermore, to provide drivers with the opportunity to switch lanes only when they were far from the merging zone and to guarantee the accurate coordination of the simulated vehicles in the scenario, the following features were implemented, as shown in Fig. 3:

1. In the center lane, there was a platoon of vehicles proceeding with a mutual distance between 25 m and 15 m and a speed 30 % higher than the driver's speed to prevent drivers from moving to the middle lane along the merging zone.
2. In the left lane only "intelligent" vehicles were introduced, capable of performing automatically some specific activities, like maintaining the safety distance from the other vehicles in the scenario or maintaining the safety distance with the driver's vehicle, and ensuring at the same time a more realistic scenario;
3. In the right lane there were no other vehicles than the participant's one; only along the merging zone one "intelligent" vehicle (the entering one) moved from the on-ramp to the right lane of the highway.

3.3. Countermeasures

Each of the five interchanges being studied for evaluating driver behavior had one of four different safety countermeasures (in addition to the baseline condition) designed to improve safety during vehicle merging and help drivers maintain a safe distance from entering vehicles. Fig. 4 illustrates and describes the following countermeasures:

1. The baseline condition, referred to in the paper as countermeasure B (Fig. 4a), did not have any countermeasures, just the standard highway signs showing the next exit, placed according to Italian design guidelines for interchanges (MIT – Ministry of Infrastructure and Transport, Italy, 2006), which were found at all the interchanges in the scenario.
2. The paper describes gap metering signalization as countermeasure C₁ (Fig. 4b), which means placing a VMS 400 m before the on-ramp. The sign showed the message "Keep the distance from the entering vehicle" along with a picture of the chevron markings painted on the right lane. The distance between these chevrons was 50 m, following the half-distance rule that suggests a safe space of at least half the speed (CEDR, 2010) for vehicles going 100 km/h. Before the test, the chevron markings were illustrated to the drivers, who were trained to maintain a distance of two chevrons (100 m) from the entering vehicle, in accordance with a previous study where the same countermeasure (VMS + chevrons markings) was designed and tested (Reinolsmann et al., 2021) according to

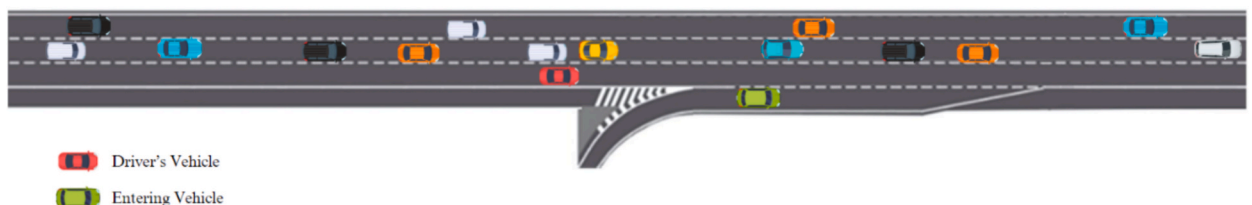


Fig. 3. Representation of the merging zone and traffic management.

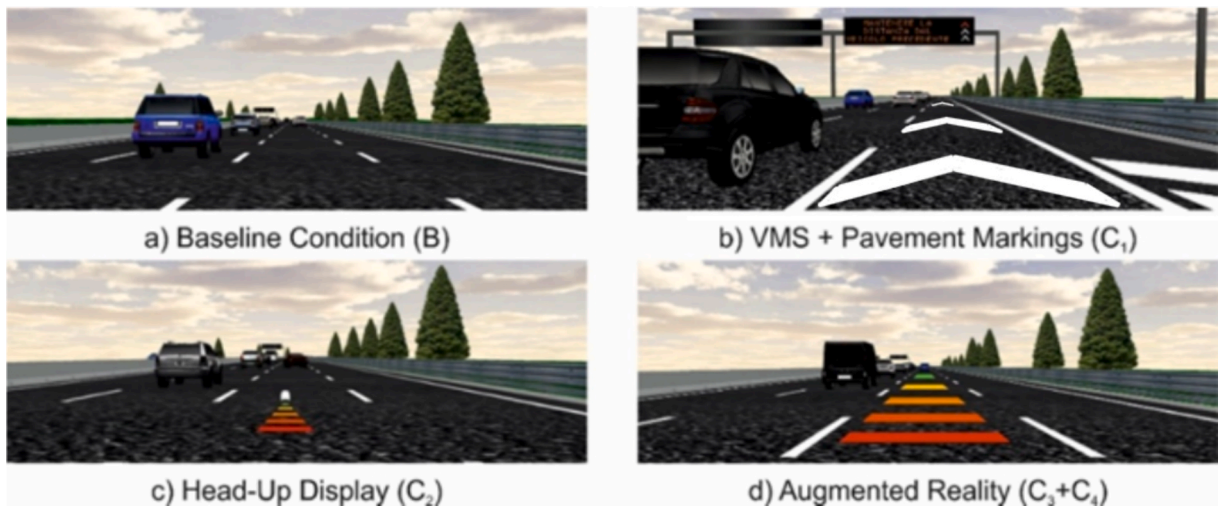


Fig. 4. Scenario and countermeasures.

European standards (*Agentschap wegen en verkeer (AWV), 2019*) that suggest a minimum distance of two chevron markers for highway speeds (for a total of 100 m), which roughly corresponds to the stopping distance when traveling at 100 km/h. That operating speed was selected with reference to the entering vehicle, which executes the merging maneuver at a speed of 100 km/h, according to the results of previous studies (*Calvi and De Blasiis, 2011; Calvi et al., 2020*). This configuration compels the driver to adjust speed accordingly, thereby adopting the same speed (100 km/h) throughout the analysis segment.

- The paper reports a static symbol as countermeasure C₂, as shown in Fig. 4c. This symbol is projected onto the vehicle’s windshield using a Head-Up Display (HUD), and it remains visible for 25 s, starting from 400 m before the on-ramp, which approximately corresponds, at a speed of 100 km/h, to the entire analysis segment. During the training step, each driver received an illustration of the symbol’s meaning, reminding them to maintain a safe distance from the entering vehicle.

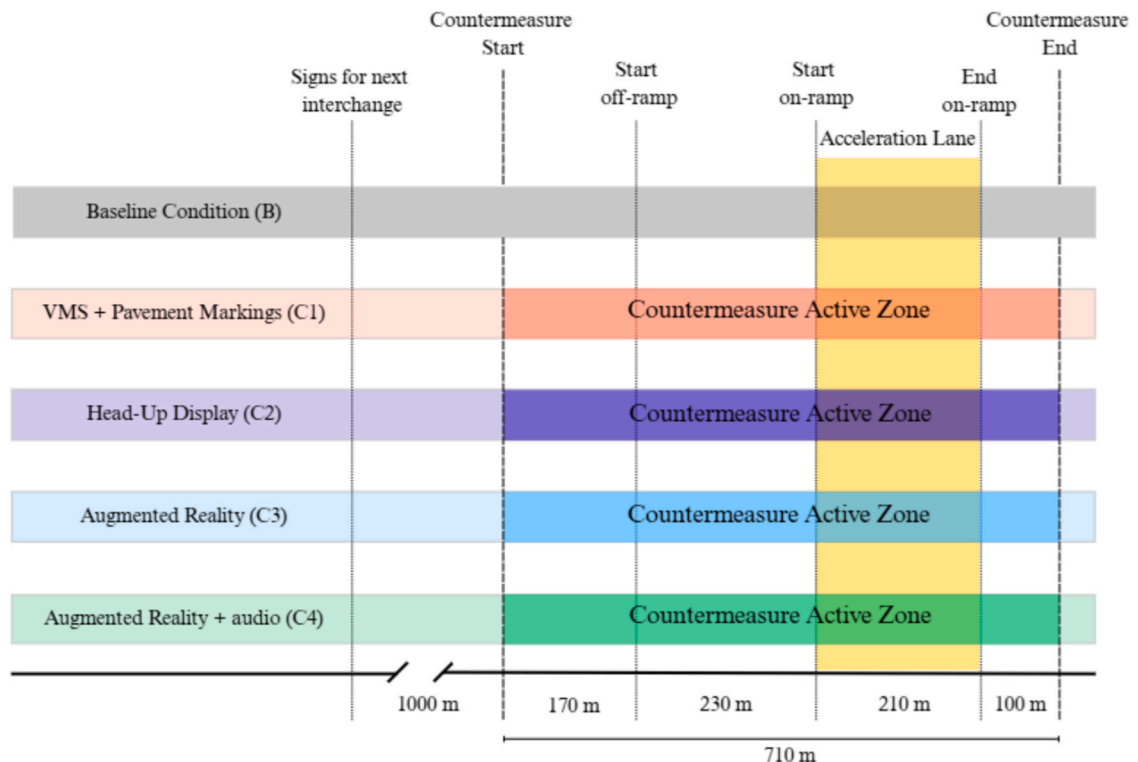


Fig. 5. Countermeasures position into scenario.

4. The dynamic symbol, reported in the paper as countermeasure C₃ (Fig. 4d), uses AR technology integrated with connected vehicle systems to provide real-time visual information to the driver about the current headway of his vehicle to the entering vehicle and the safe headway to maintain. Similar to the static symbol, the dynamic symbol projected horizontal lines ranging from red to green on the right lane of the highway, indicating the safe distance to maintain. If the entering vehicle was before the last green line (therefore, within the symbol), it signaled an unsafe driving condition, with the color representing the risk level of the car-following condition. Conversely, a safe car-following condition was the one in which the vehicle in front of the driver was located after the green line of the dynamic symbol. The total length of the symbol, from the first red line to the green one, was 100 m, which roughly corresponds to the stopping distance when traveling at 100 km/h.
5. The paper also evaluated the AR system with an additional audio warning, known as countermeasure C₄ that conveyed the message, “Keep the distance from the entering vehicle”.

Therefore, all the countermeasures start 400 m before the on-ramp, namely 170 m before the off-ramp (indeed, 230 m was the interchange design distance between the start of the off-ramp and the on-ramp, respectively), which, considering an operating speed of 100 km/h, provides the drivers with 6 s of travel time before the beginning of the interchange. This experimental design's decision complies with human factors guidelines (World Road Association (PIARC) and Committee, 2016; World Road Association (PIARC) and Committee, 2008) and specifically with “the 6-seconds rule: the road should give the driver enough time to react” which recommends providing the drivers with the necessary time to adapt their behaviour to new and unexpected situations, allowing them to perceive and process the upcoming road situation adequately and reorganize their driving program.

As shown in Fig. 5, countermeasures were placed approaching and along merging zones, covering a total length of 710 m from the start of the countermeasure to 100 m beyond the end of the on-ramp, where the entering vehicle increased its speed from 100 km/h to 130 km/h, thereby minimizing any further interference with vehicles in the main lanes.

The speed of the entering vehicle during the merging maneuver was based on the results of previous observational and simulation studies that analyzed the driving performance of vehicles entering a highway (Calvi and De Blasiis, 2011; Hang et al., 2022; Calvi et al., 2020) and observed they typically travel at a slower speed than those in the right lane of a highway. All the entering vehicles in the simulated scenario were designed to execute the same maneuver for each one of the interchanges of investigation, both in terms of speed profile, trajectory, and lateral position, and started their maneuver when the driver's vehicle reached a fixed position on the highway. More precisely, the entering vehicle followed a fully preprogrammed trajectory and speed profile, the same for all the entering vehicles in all the tests, with fixed spatial reference points.

The order of countermeasures was randomized to avoid effects that could bias the results.

3.4. Participants

The experiment involved a total of 44 participants, consisting of 21 males and 23 females, with an average age of 30.1 years and a standard deviation of 5.3 years. The average driving experience of the sample was 10.4 years, with a standard deviation of 3.6 years. 60 % of the sample had held a driving license for between 5 and 10 years, while 22 % had held it for more than 10 years. Participants evenly divided their annual kilometers traveled into four main classes: 26 % of the sample confirmed that they travel less than 4000 km annually; this percentage held true for both the range of 4000 km to 8000 km and the range of 8000 km to 12000 km. The remaining 22 % of the participants traveled more than 12,000 km per year. Furthermore, 53 % of the sample indicated that they primarily drive on urban roads, whereas 43 % stated that they typically drive on all types of roads. All participants were from the Department of Civil, Computer Science and Aeronautical Technologies Engineering of Roma Tre University, including students, staff, and professors, and 21 % of the sample had already participated in other driving simulation tests. ITS technology is not widely known, with only 28 % of the sample having knowledge of this type of tool and technology and only 16 % having knowledge of HUD. On the other hand, the knowledge of AR technology is slightly more widespread, with 58 % of the drivers reporting that they were familiar with it. Therefore, a homogeneous sample of subjects was selected and the same standard simulation protocol was used to make sure the results were not influenced by drivers' attitudes, experience, age, stress, emotional state, or other factors. The authors' choice of sample homogeneity is based on the fact that many studies have shown that driving performance is primarily affected by age (Dixit et al., 2017) and driving experience (World Health Organization, 2018). In this study, to evaluate how well AR-based measures improve driving performance in merging areas, the authors chose a homogeneous sample of participants to minimize any differences that could affect the results. Accordingly, the drivers' sample was correctly composed according to selection criteria of homogeneity in terms of demographic characteristics and driving experience.

The experiments excluded one participant due to simulation sickness. Moreover, a statistical analysis was used to identify possible outliers among the simulation results. In particular, the speed values of the drivers were recorded 400 m before the on-ramp, where all the countermeasures were implemented in the driving scenario. Only for countermeasure C₁ the drivers' speeds were recorded 900 m before the on-ramp, as the VMS was visible up to 500 m before its location. Using the Chauvenet criterion (Taylor, 1997) applied to the sample of speed data recorded in each countermeasure, after confirming that the samples of data followed a normal distribution, a driver was considered an outlier and consequently removed, if his speeds recorded at the chosen spots showed a probability of obtaining a deviation from the mean that was less than the inverse of twice the number of measurements. As a result, two drivers were excluded from the analysis as they resulted outliers for all the countermeasures. Moreover, an additional analysis was performed along

the investigation site in other point of measurements, both in terms of speeds and lateral positions and resulted in no further outliers to be removed.

Accordingly, the final sample consisted of 41 participants, 19 males and 22 females, with ages ranging from 22.8 to 39.3 years and an average age of 29.7 (standard deviation of 5.1).

3.5. Procedures

Each participant carried out the same experimental protocol. Initially, participants were instructed on the study's overall objective without providing details to avoid bias and were trained on the designed countermeasures, including their operation and usage. The experimental procedure was designed to provide the participants with all the necessary information to conduct the tests correctly and understand all the proposed countermeasures. The test protocol was structured as follows:

- a. Information about the experiment: following a brief introduction to driving simulation technology, participants were shown the objective of the driving simulator study;
- b. Each participant received a pre-test questionnaire to gather characteristics of the study sample;
- c. Participants received training on countermeasures, which included illustrations and explanations, along with guidance on how to handle them;
- d. Participants drove a training scenario for approximately 10 min to familiarize themselves with the driving simulator;
- e. Test scenario: following the training, each participant completed the test scenario, which included the four countermeasures and the baseline condition located along five of the seven interchanges of the scenario;
- f. Post-test questionnaire: following the completion of the test, participants were asked to complete an additional questionnaire to evaluate any potential symptoms of simulation sickness and their severity. Besides information on eventual symptoms of simulation sickness, participants had to reply to some questions related to their opinions about the comprehension and effectiveness of the tested countermeasures.

3.6. Data collection

To study how drivers behaved and interacted with the entering vehicles as they approached and drove along each merging zone, the following variables were collected and investigated:

1. Longitudinal acceleration of the driver;
2. Longitudinal speed (S) of the driver;
3. Accelerator pedal input counter;
4. Stop pedal input counter.

Also, the interaction between the driver and the merging vehicle was analyzed for each vehicle entering from the on-ramp, using:

1. Distance between the driver and the entering vehicle (d);
2. Time headway between the driver's vehicle and the entering vehicle (TH).

The literature widely recognizes some of these variables as key measures for characterizing drivers' behavior in merging zones, particularly when assessing interactions between through and entering vehicles. Indeed, Time Headway (TH) represents the time interval between the front of the leading vehicle passing a specific point on the lane and the front of the following vehicle passing the same point. It serves as a crucial indicator for measuring the severity of traffic conflicts. Some countries, like the Netherlands and France, recommend that drivers maintain a TH of more than 2 s (Michael et al., 2000). Similarly, in the US, various driver training programs emphasize the importance of keeping a TH of more than 2 s (Taieb-Maimon, 2007). Additionally, the literature commonly accepts 2 s as the minimum TH for safe car-following conditions, often referred to as the "two-second rule" (Shinar, 2007). Another relevant example is provided by the study of Taieb-Maimon and Shinar (2001), which found that when the speed of the lead vehicle was varied in a simple car-following situation from 50 km/h to 100 km/h, drivers adjusted their distance headways in relation to speed while maintaining constant time headways. Moreover, the study indicated that drivers' behavior did not appear to be influenced by speed in the definition of time headway but rather by temporal perception. According to literature, TH less than 2 s was considered an unsafe condition in this study.

The driver's speed was recorded at five specific points along the scenario (for each interchange/countermeasure):

1. when the driver first noticed the countermeasure, it was 400 m before the on-ramp for countermeasure C_2 , C_3 and C_4 (the same point was selected also for countermeasure B), exactly in the location they are activated, while for countermeasure C_1 it was 900 m before the on-ramp, being the VMS visible to the driver up-to 500 m before its location;
2. when the entering vehicle started to move on the on-ramp and was visible to the driver;
3. when the entering vehicle initiated the merging maneuver;
4. once the entering vehicle completed the merging maneuver;

5. at the end of the investigation site, which was 100 m after the end of the on-ramp (i.e., 310 m after the beginning of the on-ramp, being the acceleration lane 210 m long).

Furthermore, the distance and TH between the driver’s vehicle and the entering vehicle were recorded at points 3, 4, and 5, as well as the average values of the distance between vehicles, and TH between points 3 and 5 (called d_{3-5} and TH_{3-5} , respectively) were computed for each driver and for each merging zone. Finally, for each one of the four countermeasures and the baseline condition, the number of drivers traveling at a distance from the entering vehicle less than the stopping distance and the number of drivers with a TH less than 2 s from the entering vehicle were counted.

The driver’s lateral position along the merging zone was also collected to just verify that the platoon of vehicles in the center lane played exactly their role in the experiments, meaning to ensure that drivers could not move on it and change the lane, keeping the right lane. The analysis on drivers’ lateral positions demonstrated the effectiveness of the platoon in preventing drivers from changing lanes and ensuring interaction with the merging vehicle. Accordingly, drivers’ lateral position was not used as a variable of investigation but only for being sure that drivers kept the right lane and did not move to the left one. Indeed, the aim of this study was to examine the interaction between the driver in the right lane and the vehicle entering from the on-ramp, not the merging vehicle’s maneuver.

A statistical analysis was developed to evaluate the effectiveness of the countermeasures in improving driving performance and safety in the highway merging zone. One-way ANOVA analysis of variance with repeated measures and non-parametric tests were used to achieve the aim. Specifically, a one-way ANOVA (5x1) was performed for each dependent variable mentioned earlier (after confirming that the sample data met the ANOVA assumptions of normality and homoscedasticity), considering the different countermeasures (B, C₁, C₂, C₃, and C₄) as independent variables. The effects of the countermeasures on each dependent variable, including speed, distance, and TH, were examined and compared among the different countermeasures. We adopted a significance level (*p-value*) of 0.05 for the tests. In cases where data distribution failed to meet the ANOVA assumptions of normality and homoscedasticity, non-parametric tests were used. Specifically, the Brown-Forsythe test was used when the data were normally distributed but did not meet the homoscedasticity assumption; the Kruskal-Wallis test was used when the data did not follow a normal distribution but met the homoscedasticity assumption; finally, the median test was applied when the data were neither normally distributed nor homoscedastic.

In case the analysis of variance resulted in significant differences among the configurations, post-hoc tests were used to determine which specific group means were significantly different from each other. Specifically, post-hoc Tukey test, also known as Tukey’s Honest Significant Difference (HSD) test, was used in case the data distributions met the assumption of homoscedasticity. Conversely, the Games-Howell nonparametric post-hoc test was used for the pairwise comparisons between configurations.

For each variable studied (drivers’ speed S, distance d, and TH with the entering vehicle), mean, standard deviation (SD), and standard error of the mean (SEM) were reported for each measurement point and each countermeasure. The results of statistical analyses are presented in the next section of the paper.

4. Results

4.1. Driver’s speed

In Table 1, a summary of the statistical analyses is presented, reporting the mean values and standard deviations of the observed speeds along with the SEM of each distribution. The analysis of variance reveals significant differences in driving speed for each of the five measurement points, with the exception of S₁ ($p = 0.146$), where all the configurations exhibit similar speed values. This outcome was expected because the first measurement point was positioned 400 m before the on-ramp (900 m for countermeasure C₁), where the countermeasures first appeared to the driver, thereby avoiding or at least limiting their influence on driving speed as demonstrated by the statistical analysis performed on drivers’ speeds at the first measurement point. Table 2 summarizes the results of post-hoc test used for pairwise comparisons between speed distributions at each measurement point.

Moreover, the mean speed profiles of the sample of drivers approaching the interchange and along the merging zone were collected and compared across the different configurations (B, C₁, C₂, C₃, and C₄), as shown in Fig. 6, where the beginning of the on-ramp corresponds to longitudinal position “0”.

Specifically, the mean speed profiles were derived by extrapolating the individual drivers’ speed values every 5 m and averaging them across the sample of drivers for each interchange. The mean speed profile of the baseline condition (B) shows a constant trend

Table 1
Speed values and statistical analysis results.

Variable	Configuration										ANOVA		
	Baseline (B)		VMS (C ₁)		HUD (C ₂)		AR (C ₃)		AR + audio (C ₄)		F	p	
	Mean (SD)	SEM	Mean (SD)	SEM	Mean (SD)	SEM	Mean (SD)	SEM	Mean (SD)	SEM			
Speed [km/h]	S ₁	128.02 (13.30)	2.08	130.94 (12.98)	2.03	130.34 (12.02)	1.88	124.76 (12.01)	1.88	126.46 (13.11)	2.05	1.726	0.146
	S ₂	127.69 (13.06)	2.04	112.91 (16.64)	2.60	120.29 (11.87)	1.85	126.77 (10.07)	1.57	118.48 (16.18)	2.53	7.723	<0.001
	S ₃	105.58 (13.63)	2.13	98.80 (12.39)	1.93	96.69 (10.26)	1.60	91.58 (12.03)	1.88	91.97 (12.06)	1.88	9.180	<0.001
	S ₄	98.39 (11.87)	1.85	93.77 (11.83)	1.85	93.66 (9.77)	1.53	89.79 (11.39)	1.78	90.5 (11.66)	1.82	3.708	0.006
	S ₅	109.25 (11.24)	1.76	104.05 (12.60)	1.97	108.93 (12.47)	1.95	111.97 (8.58)	1.34	114.21 (9.54)	1.49	4.996	<0.001

Table 2
Results of post-hoc test on speed values.

p-value	Configuration	Baseline (B)	VMS (C ₁)	HUD (C ₂)	AR (C ₃)	AR + audio (C ₄)
S ₂	Baseline (B)	–	<0.001	0.065	0.997	0.045
	VMS (C ₁)	–	–	0.068	<0.001	0.201
	HUD (C ₂)	–	–	–	0.112	0.857
	AR (C ₃)	–	–	–	–	0.075
	AR + audio (C ₄)	–	–	–	–	–
S ₃	Baseline (B)	–	0.138	0.011	<0.001	<0.001
	VMS (C ₁)	–	–	0.741	0.046	0.049
	HUD (C ₂)	–	–	–	0.226	0.289
	AR (C ₃)	–	–	–	–	0.998
	AR + audio (C ₄)	–	–	–	–	–
S ₄	Baseline (B)	–	0.399	0.290	<0.001	0.026
	VMS (C ₁)	–	–	0.999	0.417	0.537
	HUD (C ₂)	–	–	–	0.438	0.561
	AR (C ₃)	–	–	–	–	0.996
	AR + audio (C ₄)	–	–	–	–	–
S ₅	Baseline (B)	–	0.184	0.998	0.705	0.373
	VMS (C ₁)	–	–	0.401	0.012	<0.001
	HUD (C ₂)	–	–	–	0.519	0.219
	AR (C ₃)	–	–	–	–	0.711
	AR + audio (C ₄)	–	–	–	–	–

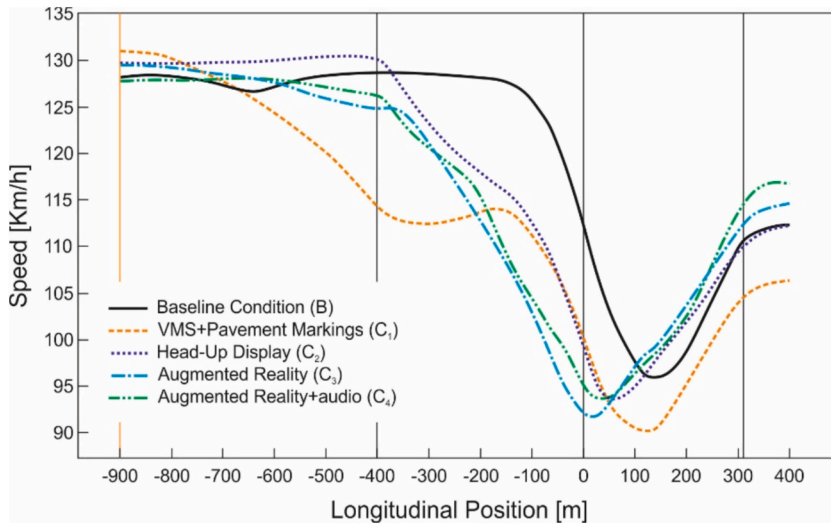


Fig. 6. Mean speed profiles of drivers for all countermeasures.

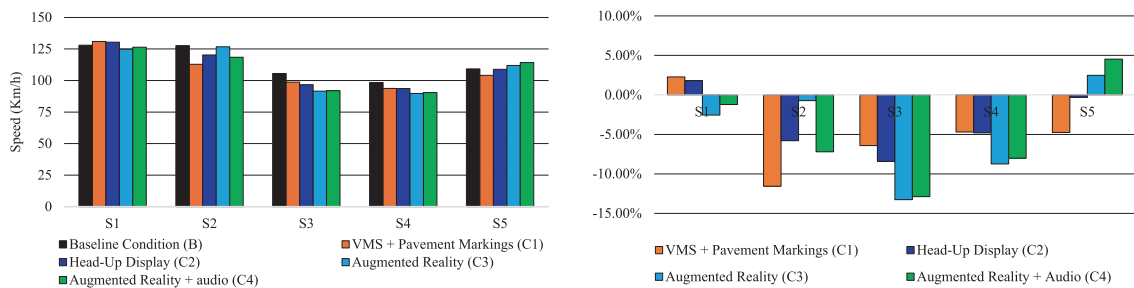


Fig. 7. a – mean speed at measurement points. b – Speed reductions at measurement points in comparison with the baseline condition.

until 100 m before the on-ramp, meaning that drivers did not change their speeds until that point; after that, the trend linearly decreases until 150 m after the on-ramp, resulting in a speed reduction of about 30 km/h in 250 m. In the VMS + pavement markings configuration (C_1), the mean speed profile is quite variable, with a relative minimum value located near 300 m before the on-ramp and an absolute minimum value recorded at 100 m after the on-ramp. In the HUD (C_2) configuration, the speed trend is approximately horizontal until 400 m before the on-ramp, and then the speed profile decreases until 50 m after the beginning of the on-ramp; afterwards, speed increases. In both AR configurations, without and with the additional audio warning (C_3 and C_4 , respectively), the driver's speed behavior is quite similar, with an approximately constant linear trend until 350 m before the beginning of the on-ramp and a following speed reduction until the beginning of the on-ramp.

Compared to the baseline condition, drivers' decelerations begin earlier in all countermeasure scenarios. This behavior happens because drivers want to help vehicles coming from the on-ramp merge more easily, which leads to less sudden slowing down compared to the baseline condition, where the highest speeds were seen up to 100 m after the on-ramp (Fig. 7a).

In the configuration with VMS + pavement markings (C_1), the mean speed reduction at the five measurement points in comparison with the corresponding speed recorded in the baseline condition (B) resulted in 5.0 %, with the maximum speed reduction recorded at the second measurement point (11.6 %), as shown in Fig. 7b and statistically confirmed by the post-hoc analysis ($p < 0.001$). In the configuration with the implementation of countermeasure HUD (C_2), the mean speed reduction was 3.5 %, with a maximum value recorded at the third measurement point (8.4 %) also revealed by the post-hoc analysis ($p = 0.011$). The mean speed reductions measured in configuration with the AR countermeasure (C_3) were 4.6 %, with the maximum value (13.2 %) recorded at the third measurement point ($p < 0.001$). Lastly, the configuration incorporating the AR countermeasure and the additional audio warning (C_4) yielded an average speed reduction of 5.0 %, with the third measurement point recording the highest value of 12.9 % ($p < 0.001$).

Consequently, the implementation of all tested countermeasures results in a significant reduction in driver speed compared to the baseline condition, as demonstrated by the results of the statistical analysis. This is attributed to the advanced warnings and information provided to drivers about the entering vehicle and the safe following distances to maintain. The implementation of AR countermeasures (C_3 and C_4) at the end of the merging zone led to an increase in speeds, reaching 2.5 % and 4.5 % at the fourth measurement point, respectively. Conversely, these countermeasures resulted in the significantly lowest speeds recorded during the merging maneuver, as demonstrated by the results of the statistical analysis reported in Table 2.

In summary, the countermeasures, although not primarily aimed at reducing speed but rather at providing drivers with preventive information, allowing them to have more time and space to manage interactions with merging vehicles, are found to encourage drivers to adjust their speed to maintain a safe distance from the vehicle in front, thereby enhancing their ability to handle any potential collisions.

This effect on speed, although representing the most appropriate way to ensure a high level of safety, could nonetheless raise concerns regarding the possibility of abrupt and rapid deceleration during the manoeuvre. To evaluate these potential negative effects, which could increase the risk of rear-end collisions with vehicles following the driver's vehicle, the driver's deceleration behaviour was analysed, and the results are presented in the following section.

4.2. Driver's deceleration

Drivers' deceleration behaviors approaching each interchange and along the merging zone were evaluated to understand how they reduced and modulated their speed to cope with the interference from the entering vehicle. For the analysis, the speed and deceleration data for each driver at each interchange were split into four sections, based on the measurement points defined earlier: section 1 (St1) was between points 1 and 2, section 2 (St2) was between points 2 and 3, section 3 (St3) was between points 3 and 4, and section 4 (St4) was between points 4 and 5. The driver's pressure on the stop pedal was investigated along each section, dividing the sample of drivers into three groups:

1. drivers who did not reduce their speed;
2. drivers who braked using the stop pedal;
3. drivers who braked without using the stop pedal, only using the engine brake.

For the analysis, it was considered that drivers did not reduce their speed along a section if the variation of the speed within the section itself was less than 5 km/h.

During the first section in the baseline condition (B), drivers did not reduce their speed. More than 70 % of drivers in configuration with VMS and pavement markings (C_1) slowed down in the first section by simply releasing the accelerator pedal, demonstrating a soft and non-aggressive deceleration.

In the second section, minor variations in the behavior of drivers across various configurations were observed. Only with countermeasures HUD (C_2) and AR (C_3), 25 % of drivers started to decelerate only by releasing their foot from the accelerator pedal.

In the third section, it was observed that under the baseline condition (B) and countermeasure C_1 , over 30 % of drivers braked by using the stop pedal, whereas 40 % braked by simply releasing their foot from the acceleration pedal. In the case of countermeasure C_2 , the percentage of drivers that used the stop pedal was 27.0 %. When countermeasure AR + audio message (C_4) assisted drivers during the merging zone, more than 75 % of them did not reduce their speed.

In the fourth section, in the case of the baseline condition (B) and with countermeasure C_1 , approximately 30 % of drivers decelerated using the stop pedal. Conversely, when countermeasures C_2 and C_3 assisted drivers, 81.0 % of them did not alter their behavior.

Moreover, the mean decelerations of the drivers' sample were analyzed along the different sections to determine whether the braking was gentle or aggressive. The results showed that the mean deceleration was greatly influenced by the countermeasures, as seen in Fig. 8, which compares the mean deceleration profiles of the drivers' sample approaching the interchange and in the merging zone across different configurations (B, C₁, C₂, C₃, and C₄). The baseline condition (B) recorded the majority of the relevant deceleration, with the first deceleration occurring later than in configurations with the countermeasures. Specifically, in the baseline condition B, the drivers began decelerating only 35 m before the on-ramp began, and their mean deceleration was the highest recorded among all the other configurations (-1.82 m/s^2). Configuration using C₁ recorded a first gentle deceleration from the point where the countermeasure started, followed by an increase in the mean deceleration value from 200 m before the on-ramp began. As shown in Fig. 9, the maximum value of deceleration recorded in configuration C₁ was located only at 30 m before the beginning of the on-ramp; that is almost the same position recorded in the baseline condition (B), but its value was lower and equal to -1.29 m/s^2 .

In configuration with countermeasure C₂, similar to the previous case, drivers initially decelerated quickly when the countermeasure first appeared, but they then decelerated more gently. Subsequently, the deceleration reached the maximum mean value (-1.31 m/s^2) at 35 m before the beginning of the on-ramp. With AR countermeasure (C₃), drivers first adopted an aggressive deceleration when the countermeasure first appeared, equal to -1.18 m/s^2 , but after that, deceleration decreased more gently from 100 m before the beginning of the on-ramp, with a relative peak of -0.82 m/s^2 . AR + audio configuration (C₄) yielded similar results, showing a first peak in deceleration equal to -0.72 m/s^2 and a second peak of -1.11 m/s^2 , 215 m before the on-ramp began.

4.3. Distance between vehicles

In Table 3, a summary of the statistical analyses is shown, which includes the mean and standard deviations in the distances between vehicles, along with the SEM for each data distribution. The analysis of the longitudinal distance between drivers and the entering vehicle revealed significant differences across the various countermeasure configurations (B, C₁, C₂, C₃, and C₄) for all the measurement points, as well as for the mean distance during the car-following condition calculated from measurement point 3 to point 5. Table 4 summarizes the results of post-hoc test used for pairwise comparisons between the distributions of distance between vehicles at each measurement point. Fig. 10 illustrates the profiles of drivers' distance to the entering vehicle along the interchange for all configurations. As can be observed, while using the countermeasures, distance initially decreased when approaching the merging zone. In the baseline condition (B), this reduction in distance between vehicles continued until 100 m after the start of the on-ramp. Conversely, with all countermeasures, the reduction stopped a few meters after the beginning of the on-ramp. The greatest distance between the driver's vehicle and the entering vehicle was recorded when using AR countermeasure C₃ (particularly at measurement point 3 and 4, according to the results of post-hoc comparisons reported in Table 4), followed by AR combined with audio (C₄), then the HUD (C₂), and finally the VMS with pavement markings (C₁). With countermeasure C₂, drivers increased distance after a first reduction, more than with all other countermeasures. When adopting the countermeasures, drivers maintained longer distances to the entering vehicle, up to +60 m compared to the baseline condition (B), as shown in Fig. 11. At all measurement points, in the baseline condition (B), drivers kept a distance to the entering vehicle equal to, or less than, 100 m. When using countermeasure C₂, drivers maintained a longer distance at all measurement points, approximately 25 m longer, resulting in a mean distance of about 125 m. In this analysis, the most effective countermeasures that suggested the drivers keep a longer and safer distance from the entering vehicle were those based on AR (C₃ and C₄) as confirmed by the results of pairwise comparisons in Table 4.

This finding suggests that the tested countermeasures could significantly enhance the safety of the merging zone. Particularly remarkable is the observation that the number of drivers keeping a distance to the entering vehicle shorter than the stopping distance

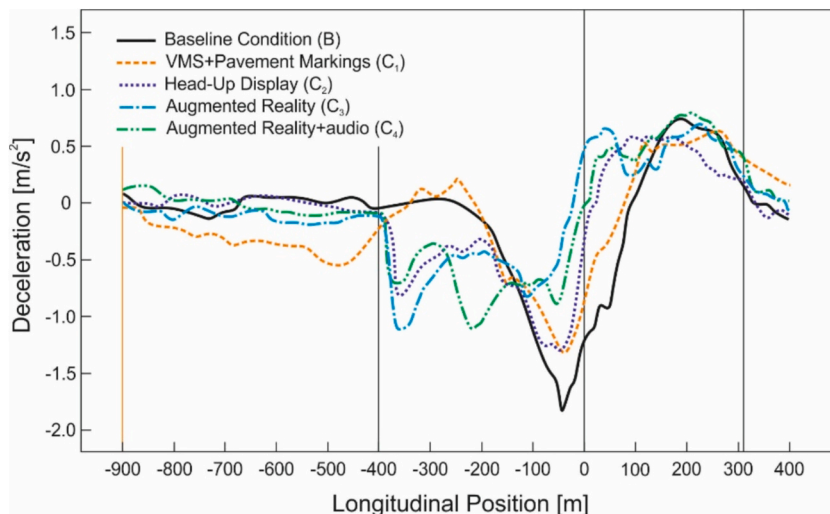


Fig. 8. Mean deceleration profiles of drivers for all countermeasures.

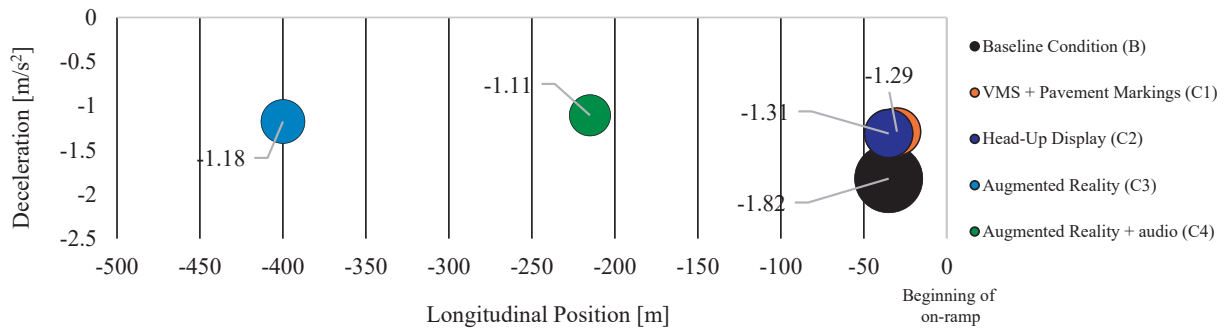


Fig. 9. Maximum decelerations and their positions for all countermeasures (The diameter of circles represents deceleration value).

(unsafe condition) varied significantly among configurations, with the highest numbers recorded in the baseline condition, as it will be presented later in the paper. This highlights the effectiveness of countermeasures in improving the safety of the interactions between drivers and entering vehicles, especially those based on AR and connected vehicle technology (C₃ and C₄).

4.4. Time headway

In Table 5, a summary of the statistical analyses is presented, reporting the mean and standard deviations in Time Headway (TH), along with the SEM for each distribution. Besides the analysis of the distance between the drivers and the entering vehicle, time headways were also analyzed for all countermeasures. The overall results confirm that countermeasures are able to enhance safety during the merging maneuver of the entering vehicles and for the subsequent car-following conditions. Table 6 summarizes the results of post-hoc test used for pairwise comparisons between TH distributions at each measurement point. The baseline condition (B) recorded the lowest TH values, while all countermeasure configurations showed significantly higher time headway until +2.5 s at all measurement points, as confirmed by the post-hoc analysis, particularly at measurement point 3 for all the configurations and at all the measurement points for AR countermeasure (C₃) and VMS (C₁). Fig. 12 reports the TH profiles for all countermeasures, while Fig. 13 shows the mean TH at measurement points. All configurations with a countermeasure show a first reduction in TH when drivers approach the on-ramp and the entering vehicle; in the baseline condition (B), this reduction continues until 100 m after the beginning of the on-ramp. The TH profiles recorded in the baseline condition (B) and using HUD (C₂) were quite similar, although configuration C₂ recorded higher TH values. A different TH trend was observed using countermeasure C₁, which initially reduced TH until the on-ramp began and then, unlike the other countermeasures, increased TH along the section. For both AR countermeasures (C₃ and C₄), TH profiles decreased slowly, with higher values recorded when using countermeasure C₃.

4.5. Risk analysis

To evaluate the safety of drivers' interactions with entering vehicles, data on the number of drivers maintaining a distance from the entering vehicle that was less than the visibility distance required for stopping was collected. Moreover, the relevant literature (Taieb-Maimon and Shinar, 2001; Sadeghhosseini and Benekohal, 1997; Vogel, 2003; Bella, 2011) has previously reported that cases with a time headway of less than 2 s are considered risky conditions. Consequently, the number of drivers traveling with TH less than 2 s was also collected.

4.5.1. Distance between vehicles

The distance between the driver and the entering vehicle was analyzed in the merging zone, and the number of drivers who kept a distance shorter than the safety distance (equal to 100 m, which roughly corresponds to the visibility distance for stopping at 100 km/h), was noted. Fig. 14 displays the analysis results, securing the longitudinal progressive "0" at the on-ramp's beginning. It is evident that, in the baseline condition (B), 42.5 % of the drivers did not maintain the safe distance to the entering vehicle during the merging zone. On the other hand, the application of countermeasures resulted in fewer participants driving below the unsafe threshold. Only 4.5 % of drivers underestimated the stopping distance when using countermeasure HUD (C₂). In the case of AR configuration (C₃), the percentage of such drivers was 17.4 %, while for AR + audio configuration (C₄), it was 11.8 %.

Finally, in the VMS + pavement markings configuration (C₁), the percentage was 13.0 %. Consequently, it was found that countermeasure C₂ was the most effective in encouraging drivers to maintain a distance longer than the stopping distance from the entering vehicle.

The mean safety distance significantly increases at measurement points, demonstrating the positive impact of countermeasures on drivers' behavior. In the VMS + pavement markings configuration (C₁), the increase in distance during the car-following condition was 42.7 % in comparison with the baseline condition (B) at the fifth measurement point. The countermeasure with HUD (C₂) registered an increase of 29.4 % in the mean distance at the measurement points, while the countermeasure with AR (C₃) achieved its maximum value of +53.8 %. Finally, in the AR + audio configuration (C₄), the average increase in distance was 42.8 %.

Table 3
Distance values and statistical analysis results.

Variable		Configuration										Non-parametric Test		
		Baseline (B)		VMS (C ₁)		HUD (C ₂)		AR (C ₃)		AR + audio (C ₄)		Test	F, St, c ²	p
		Mean (SD)	SEM	Mean (SD)	SEM	Mean (SD)	SEM	Mean (SD)	SEM	Mean (SD)	SEM			
Distance [m]	d ₃	101.05 (22.68)	3.54	129.44 (32.31)	5.05	126.14 (23.11)	3.61	148.14 (23.58)	3.68	137.88 (33.40)	5.22	Brown Forsythe	F = 16.796	<0.001
	d ₄	93.04 (24.77)	3.87	123.23 (35.28)	5.51	120.50 (24.77)	3.87	143.38 (26.18)	4.09	133.29 (35.93)	5.61	Brown Forsythe	F = 16.415	<0.001
	d ₅	97.38 (34.17)	5.34	157.49 (54.23)	8.47	128.03 (49.26)	7.69	152.36 (45.32)	7.08	139.93 (65.27)	10.2	Median	c ² = 25.484	<0.001
	d _{3,5}	92.09 (27.41)	4.28	136.87 (45.64)	7.13	121.53 (35.67)	5.57	145.55 (33.82)	5.28	136.03 (51.32)	8.01	Median	c ² = 43.045	<0.001

Table 4
Results of post-hoc test on distance values.

p-value	Configuration	Baseline (B)	VMS (C ₁)	HUD (C ₂)	AR (C ₃)	AR + audio (C ₄)
d ₃	Baseline (B)	–	<0.001	<0.001	<0.001	<0.001
	VMS (C ₁)	–	–	0.984	0.030	0.772
	HUD (C ₂)	–	–	–	<0.001	0.513
	AR (C ₃)	–	–	–	–	0.498
	AR + audio (C ₄)	–	–	–	–	–
d ₄	Baseline (B)	–	<0.001	<0.001	<0.001	<0.001
	VMS (C ₁)	–	–	0.994	0.035	0.704
	HUD (C ₂)	–	–	–	<0.001	0.623
	AR (C ₃)	–	–	–	–	0.596
	AR + audio (C ₄)	–	–	–	–	–
d ₅	Baseline (B)	–	<0.001	0.014	<0.001	0.004
	VMS (C ₁)	–	–	0.021	0.816	0.439
	HUD (C ₂)	–	–	–	0.086	0.714
	AR (C ₃)	–	–	–	–	0.681
	AR + audio (C ₄)	–	–	–	–	–
d _{3,5}	Baseline (B)	–	<0.001	0.008	<0.001	<0.001
	VMS (C ₁)	–	–	0.542	0.757	0.999
	HUD (C ₂)	–	–	–	0.107	0.613
	AR (C ₃)	–	–	–	–	0.782
	AR + audio (C ₄)	–	–	–	–	–

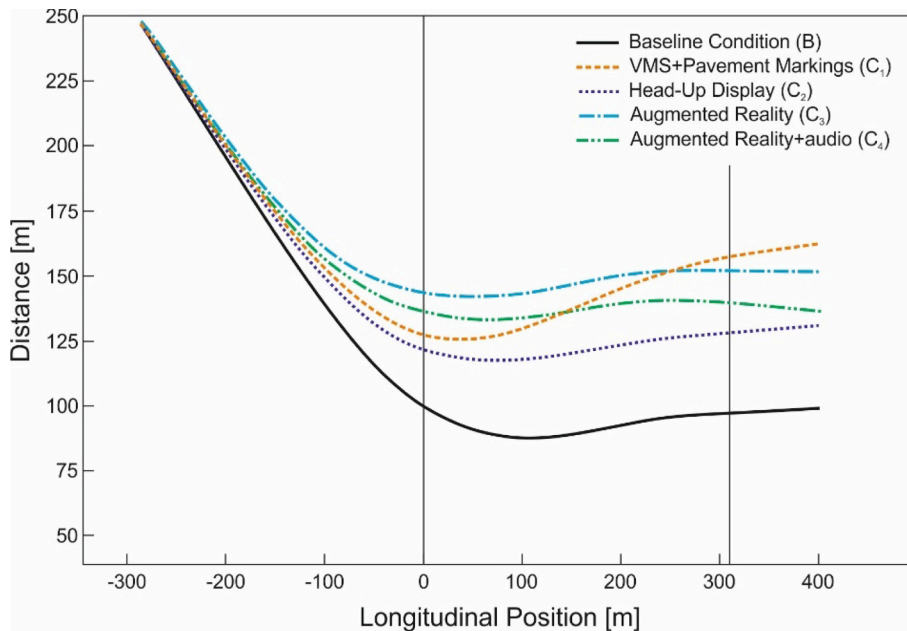


Fig. 10. Profiles of mean distance between vehicles for all countermeasures.

4.5.2. Time headway

TH values of all drivers were obtained to identify those who traveled using a TH to the entering vehicle lower than 2 s. Fig. 15 shows the results of the analysis performed on collecting the number of drivers who traveled with TH less than 2 s; the longitudinal progressive “0” was fixed at the beginning of the on-ramp. The results confirmed those obtained in the previous analysis of drivers’ distance to the entering vehicle. Indeed, the baseline condition (B) had the highest percentage of drivers with TH less than 2 s (8.3 %). Using countermeasure C₁, the percentage of drivers with TH less than 2 s was 1.7 %, while for HUD countermeasure (C₂), it was 2.8 %. Moreover, it is intriguing to note that using AR technology (C₃), no drivers adopted TH less than 2 s for all the sections of analysis. In the AR + audio configuration (C₄), only 1.0 % of drivers had TH lower than 2 s.

When using HUD countermeasure (C₂), the average increase in TH at measurement points compared to the baseline condition (B) was 51.7 %; the drivers maintained an average TH of 3.4 s at all measurement points during the baseline condition (B). Using HUD (C₂), TH increased at all the measurement points, with an average increase of 4.6 s, representing an increase of 1.2 s compared to the baseline condition. It was countermeasures C₃ and C₁ that were able to push the driver to keep their THs higher. They had an average

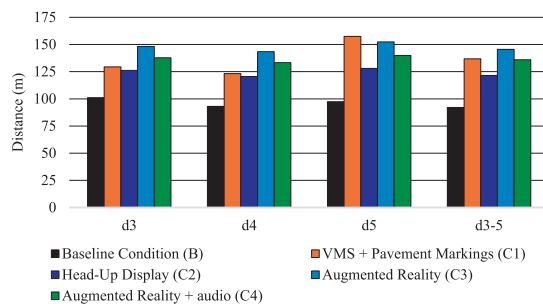


Fig. 11. Mean distance between vehicles at measurement points.

TH of 5.6 s (C_3) and 5.2 s (C_1), with an average increase with respect to the baseline condition equal to 62.7 % and 51.7 %, respectively. Finally, using countermeasure C_4 , the average TH was 5.2 s, with an average increase of 50.4 %.

In conclusion, the differences in the number of drivers adopting TH to the entering vehicle lower than 2 s, considered an unsafe driving condition, varied significantly among configurations. Specifically, the percentages of drivers with TH lower than 2 s were 8.3 %, 1.7 %, 2.8 %, 0.0 %, and 1.0 % for configurations B, C_1 , C_2 , C_3 , and C_4 , respectively. As previously discussed, this result indicates that all countermeasures were effective in making interactions between drivers and entering vehicles safer. This conclusion is especially true for those based on AR and connected vehicle technology (C_3), where no drivers used TH lower than 2 s.

4.5.3. Post-test questionnaire results

A post-test questionnaire was submitted to participants to understand their perceptions of the effectiveness of countermeasures, their effects on drivers' behavior, their level of complexity, and an evaluation of immersion and the effectiveness of virtual reality simulation.

The drivers' opinion regarding the usefulness of countermeasures is quite clear; only 19 % of drivers believed that VMS + pavement markings (C_1) had no effect on their driving behavior. Fig. 16a shows that only 9 % of the participants thought the driving help from countermeasure C_2 was not effective, and an even smaller 5 % said that the AR-based countermeasures (C_3 and C_4) did not affect their driving perception, choices, or behavior.

The participants' evaluation of countermeasures was very positive and encouraging, as reported in Fig. 16b. The participants expressed a positive opinion about the effectiveness of all countermeasures, particularly the AR-based ones (C_3 and C_4), with 93 % rating the AR + audio (C_4) and 91 % rating the AR (C_3) countermeasures as highly or extremely effective, respectively. The other countermeasures also received positive ratings, with 88 % of the sample judging the HUD (C_2) as moderately to highly effective and 75 % giving the same rating to the VMS + pavement markings (C_1).

The countermeasures primarily help drivers maintain a safe and correct distance from merging vehicles. Fig. 17 shows that drivers well perceived the overall objective of countermeasures, particularly for the AR countermeasure (C_3) (49 %) and HUD (C_2) (56 %). The main opinion of participants regarding countermeasure VMS + pavement markings (C_1) is that it was advantageous in maintaining an appropriate speed, as expressed by 49 % of them. Finally, according to participants' replies, the AR-based countermeasure (C_3) was also useful to better understand the distance between vehicles (34 %).

As shown in Fig. 18, participants reported that countermeasures had a very low level of complexity and were well-designed for quick understanding. The countermeasures using AR technology (C_3 and C_4) were easy to understand, with drivers rating their complexity as none, low, or very low in 86 % of the cases. For HUD (C_2) and VMS + pavement markings (C_1), the percentages were slightly lower (80 % and 77 %, respectively).

5. Discussion

The purpose of this study was to evaluate the effectiveness of AR-based countermeasures in warning drivers of potential interferences with vehicles entering the highway from the on-ramp and assisting them in maintaining a safe and correct distance, thereby enhancing road safety. For the aim, other countermeasures based on VMS + markings and HUD that did not need a connected environment to work and were easily implementable on roads and vehicles were analyzed to have a comparison of the effects of AR-based countermeasures not only with a baseline condition (with no warnings and support to the driver) but also with, let's say, more traditional countermeasures. The following sections of the paper will discuss the overall results (summarized in Table 7) separately for each countermeasure.

5.1. Variable message sign and pavement markings (C_1)

Variable Message Sign (VMS) is a widely used traditional technology for communicating with drivers. However, nowadays, this tool is not commonly used to provide drivers with the kind of information proposed in this study. In this study, the variable message sign is combined with a pavement marking to suggest to the driver the distance to keep from the vehicle ahead, similar to the

Table 5
Time Headway values and statistical analysis results.

Variable		Configuration										Non-parametric Test		
		Baseline (B)		VMS (C ₁)		HUD (C ₂)		AR (C ₃)		AR+audio (C ₄)		Test	F, St, c ²	p
		Mean (SD)	SEM	Mean (SD)	SEM	Mean (SD)	SEM	Mean (SD)	SEM	Mean (SD)	SEM			
TH [s]	TH ₃	3.57 (1.15)	0.18	4.92 (1.83)	0.29	4.80 (1.24)	0.19	6.02 (1.70)	0.27	5.63 (2.14)	0.33	Median	c ² = 49.719	<0.001
	TH ₄	3.52 (1.27)	0.20	4.94 (1.99)	0.31	4.74 (1.33)	0.21	5.95 (1.80)	0.28	5.54 (2.27)	0.35	Median	c ² = 44.990	<0.001
	TH ₅	3.28 (1.36)	0.21	5.56 (2.16)	0.34	4.40 (2.05)	0.32	4.98 (1.71)	0.27	4.53 (2.55)	0.40	Kruskal Wallis	St = 33.169	<0.001
	TH ₃₋₅	3.39 (1.17)	0.18	5.40 (2.01)	0.31	4.52 (1.61)	0.25	5.47 (1.60)	0.25	5.03 (2.41)	0.38	Median	c ² = 43.045	<0.001

Table 6
Results of post-hoc test on Time Headway values.

p-value	Configuration	Baseline (B)	VMS (C ₁)	HUD (C ₂)	AR (C ₃)	AR + audio (C ₄)
TH ₃	Baseline (B)	–	<0.001	<0.001	<0.001	<0.001
	VMS (C ₁)	–	–	0.945	0.045	0.531
	HUD (C ₂)	–	–	–	0.003	0.213
	AR (C ₃)	–	–	–	–	0.891
	AR + audio (C ₄)	–	–	–	–	–
TH ₄	Baseline (B)	–	0.002	<0.001	<0.001	<0.001
	VMS (C ₁)	–	–	0.946	0.127	0.728
	HUD (C ₂)	–	–	–	0.008	0.308
	AR (C ₃)	–	–	–	–	0.896
	AR + audio (C ₄)	–	–	–	–	–
TH ₅	Baseline (B)	–	<0.001	0.040	<0.001	0.057
	VMS (C ₁)	–	–	0.067	0.719	0.137
	HUD (C ₂)	–	–	–	0.734	0.928
	AR (C ₃)	–	–	–	–	0.811
	AR + audio (C ₄)	–	–	–	–	–
TH ₃₋₅	Baseline (B)	–	<0.001	0.071	<0.001	<0.001
	VMS (C ₁)	–	–	0.142	0.993	0.812
	HUD (C ₂)	–	–	–	0.129	0.805
	AR (C ₃)	–	–	–	–	0.894
	AR + audio (C ₄)	–	–	–	–	–

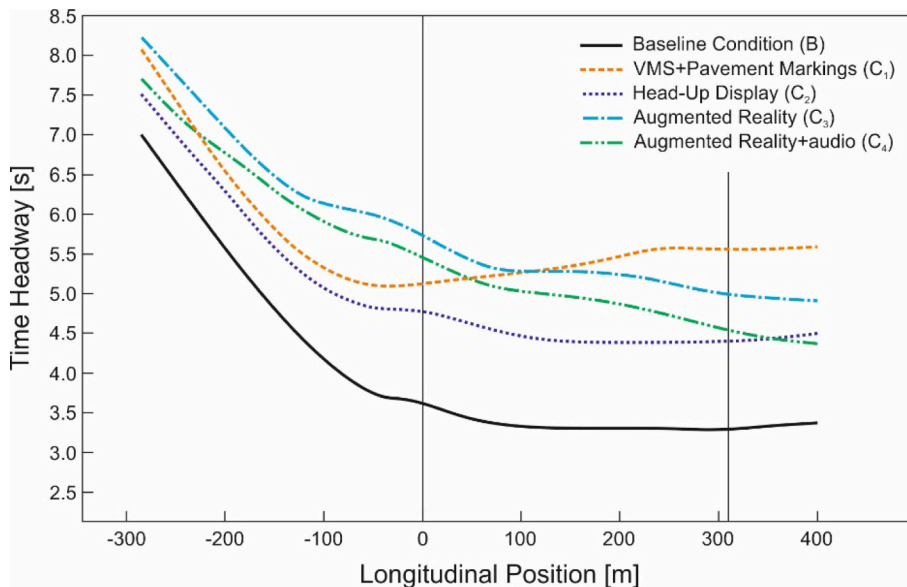


Fig. 12. Profiles of the mean Time Headway for all countermeasures.

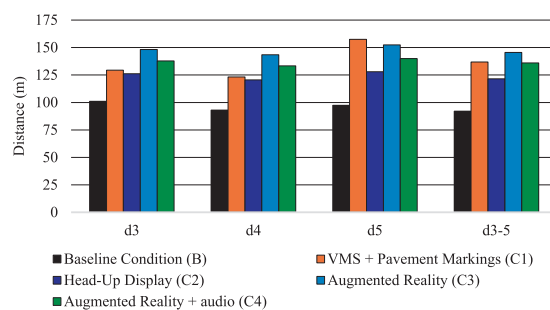


Fig. 13. Mean TH at measurement points.

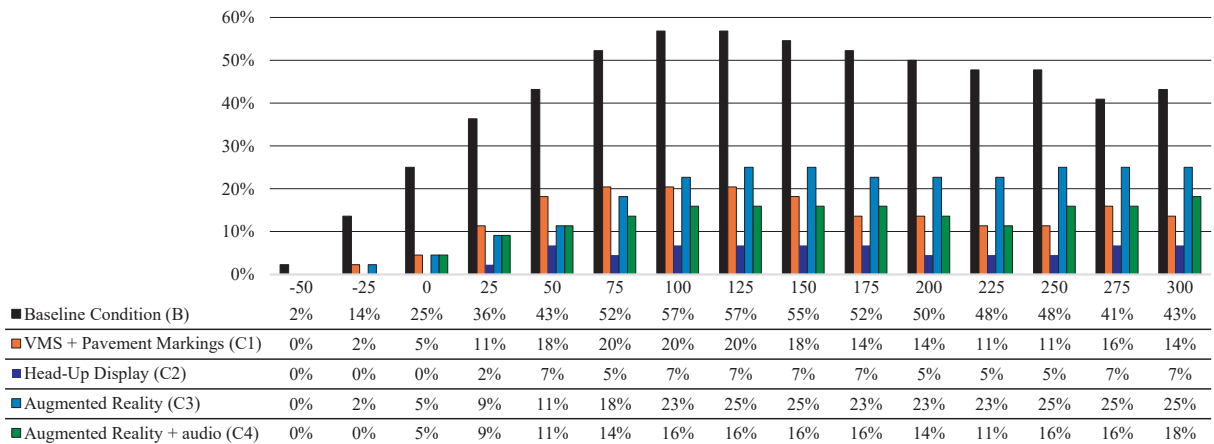


Fig. 14. Percentage of drivers traveling in unsafe conditions (distance to entering vehicle lower than stopping distance).

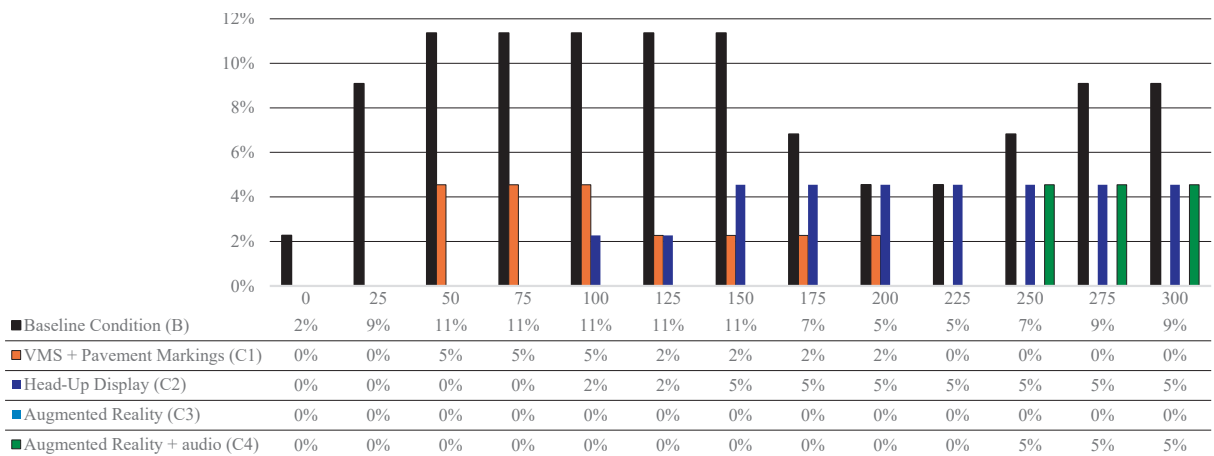


Fig. 15. Percentage of drivers traveling in unsafe conditions (TH lower than 2 s).

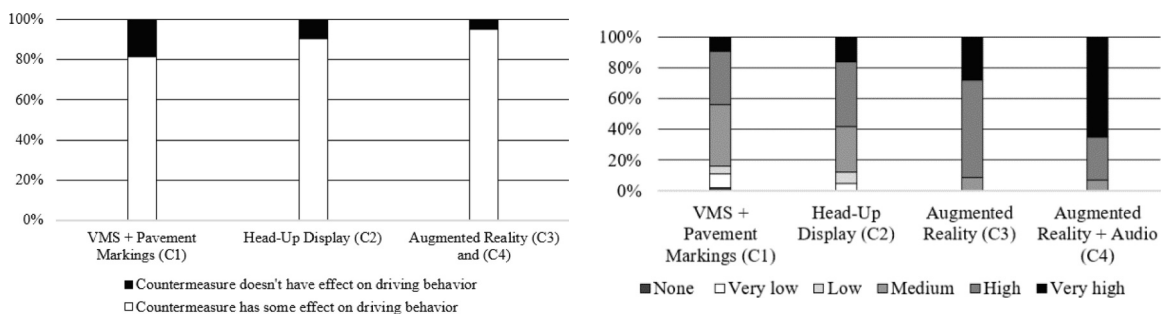


Fig. 16. a – Drivers' opinion on countermeasures' usefulness. b – Drivers' evaluation of countermeasures' effectiveness.

investigation developed by Reinolmann et al. (Reinolmann et al., 2021) in a previous study. Specifically, countermeasure C₁ recommends that drivers maintain a distance of two pavement markings (chevrons), equivalent to 100 m, from the approaching vehicle. According to the results of the study by Koyuncu and Amado (Koyuncu and Amado, 2008), the majority of participants reported no difficulties in understanding and correctly interpreting the sign, and they evaluated the countermeasure positively. However, the analysis of speed, distance, and TH data from the driving simulation tests revealed that the effectiveness of countermeasure C₁ was not as high as other countermeasures, despite its contribution to improve driving conditions in the merging zone. The mean distance between the driver and the entering vehicle significantly increased compared to the baseline condition (B), with an average increase of 40.9%. The increased distance ensured that more than 80% of drivers had the necessary space for stopping. Moreover, no significant

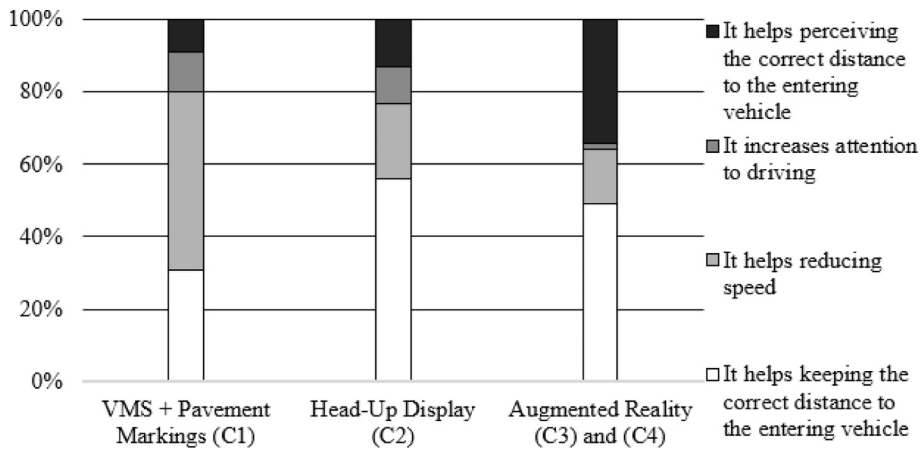


Fig. 17. Effects of countermeasures on driving perception and behavior.

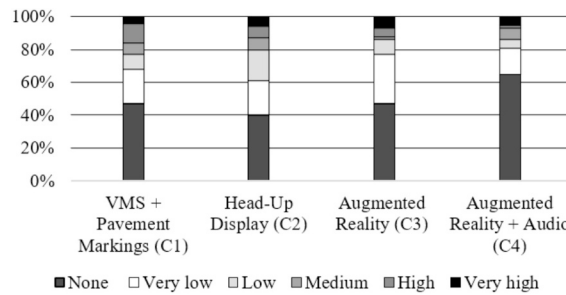


Fig. 18. Level of complexity in drivers' interpretation of countermeasures.

Table 7

Summary of the overall results of the study.

	Configuration				
	Baseline (B) reference value	VMS + Pavement Markings (C ₁)	Head-Up Display (C ₂)	Augmented Reality (C ₃)	Augmented Reality + Audio (C ₄)
Mean distance to the entering vehicle	95.9 m	136.8 m (+40.9 m)	124.1 m (+28.2 m)	147.5 m (+51.6 m)	136.9 m (+41.0 m)
% drivers with $d < d_{stop}$	42.5 %	13.0 %	4.5 %	17.4 %	11.8 %
Mean TH to the entering vehicle	3.4 s	5.2 s (+1.8 s)	4.6 s (+1.2 s)	5.6 s (+2.2 s)	5.2 s (+1.8 s)
% driver with TH < 2 s	8.3 %	1.7 %	2.8 %	0.0 %	1.0 %

changes in the location of the maximum deceleration were recorded, very near the on-ramp as in the baseline condition, but with a smoother deceleration, mainly achieved without the use of the brake pedal.

In comparison to the baseline condition (B), lower mean speeds were observed during the merging zone and a 1.78 % increase in TH. A speed reduction of approximately 10 km/h was recorded, which was higher than the 1–2 km/h reported in the study by Reinolmann et al. (Reinolmann et al., 2021). Using the countermeasure, only 5 % of drivers kept TH lower than 2 s. This result perfectly agrees with the finding of Reinolmann et al. (Reinolmann et al., 2021). Furthermore, every speed recorded at the five measurement points showed a significant decrease compared to baseline condition (B). This result could also make it easier for vehicles coming from the on-ramp, which usually go slower than those in the right lane of the highway (Calvi and De Blasiis, 2011), to find available gaps in the flow of passing vehicles in the right lane of the highway.

5.2. Head-up display (C₂)

Despite the widespread use of HUD tools in automotive technology today, only 16 % of participants reported familiarity with this technology. As previously reported, the tool's symbol encouraged drivers to maintain a safe distance from other vehicles, but it did not specify a minimum spatial headway. Although the participants reported no difficulties in understanding the countermeasure's message, they expressed doubts about its effectiveness. This conclusion contrasts with the findings of a study by Li et al. (Li et al., 2024),

which found that drivers preferred HUD over other types of in-vehicle displays placed in various parts of the cockpit, despite considering the countermeasure to be very effective. When using HUD-based countermeasure, only 7 % of drivers underestimated the safety distance to the entering vehicle in the merging zone, and a mere 5 % used TH for less than 2 s. In comparison to the baseline condition (B), the maximum deceleration location remained relatively close to the on-ramp, but it occurred with a smoother deceleration. The number of drivers using the brake pedal during deceleration was slightly higher than in the previous case. Moreover, a significant difference in the distance to the entering vehicle was observed, with an average increase of approximately 25 % compared to the baseline condition and an average increase of 1.2 % for TH. The results are undoubtedly encouraging for this countermeasure, despite its lower safety effects compared to other countermeasures, particularly those utilizing AR (C₃ and C₄).

5.3. Augmented Reality (C₃ and C₄)

The study proposes a countermeasure that reflects the near future of technological progress and links the equipment to the future implementation and innovation of transport infrastructures. More than 80 % of participants sincerely believed that using AR technology for driving assistance could enhance their perception and interpretation of distance, thereby maintaining a safe distance from other vehicles. Furthermore, participants reported to not have experienced any difficulties when interpreting the shared information.

As previously reported, the AR-based countermeasure recommends using a multicolor stripe symbol to maintain a distance of 100 m to the entering vehicle in the merging zone. The results showed that only 3 out of 41 drivers underestimated the target. In comparison to the baseline condition (B), mean speed was significantly lower, and both mean TH and mean distance to the entering vehicle were, respectively, higher than 2.2 % and 51.5 %. The drivers' reaction to the information was also clear; when the countermeasure appeared, every participant experienced the most incisive deceleration, although it was lower than the deceleration values recorded when using other countermeasures. This finding indicates that drivers were able to better modulate speed before the merging zone without using the brake pedal immediately after the appearance of the countermeasure, located 400 m before the beginning of the on-ramp. This condition can limit disturbances in the merging zone's travel speed, which can be significant in identifying slowdowns in traffic flow caused by passing vehicles on the highway. These slowdowns can be major obstacles to road operation and safety, as noted by Lee et al. (Lee et al., 2022). Furthermore, in both the AR and AR + audio countermeasures (C₃ and C₄), no driver used TH lower than 2 s.

Using AR + audio (C₄) significantly increased the efficacy. Over 90 % of participants expressed their satisfaction with the countermeasure's clarity and efficiency, stating that all drivers were able to maintain the safety distance to the entering vehicle. Compared to the baseline condition (B), the mean TH increase was 1.7 %, and the mean distances to the entering vehicle exceeded 40.9 %. All drivers achieved the greatest deceleration, although lower than that recorded for all the other tested countermeasures, and were able to modulate their speed properly before the merging zone and 200 m before the beginning of the on-ramp. The use of the brake pedal was even less common, and the speed profile trend in the section where the countermeasure was present was significantly more linear than in baseline condition (B).

6. Conclusions

This driving simulator study shows that AR warnings and connected vehicle technologies can greatly help reduce potential vehicles conflicts between through and entering drivers in the merging zones of highways. Specifically, the tested AR alerts (countermeasures C₃ and C₄) demonstrated a significant positive impact on driving performance and road safety during the merging maneuver of vehicles entering the highway from on-ramps directly in front of the driver. Observations included reducing the driver's speed to accommodate the merging maneuver, increasing longitudinal distance between the driver and the entering vehicle under car-following conditions, and increasing TH between the vehicles. In addition, there was a significant decrease in the number of drivers operating within the merging zones under unsafe conditions compared to the baseline condition (B). The warning from AR (C₃) helped drivers slow down and use the brake pedal less often and less harshly; this made their slowing down more steady, which reduced problems with sudden stops and slow speeds when getting on and off the highways. The other countermeasures tested in the study (C₁ and C₂) also showed positive effects, although lower than those observed for AR-based countermeasures, on the safety of merging zones. The implementation of a variable message sign (VMS) with chevron markings (C₁) produced results consistent with the findings of previous studies on similar countermeasures, especially regarding speed reduction and the percentage of drivers traveling with inadequate TH. HUD (C₂) projected a static symbol onto the vehicle windshield, resulting in a higher distance and TH between the driver and the entering vehicles compared to the baseline condition (B), surpassing the users' expectations and predicted effectiveness.

This study also shows the effectiveness of driving simulations for understanding how AR technologies and safety measures affect driving performance and behavior, and overall road safety. These results have important implications for the development of driver warning systems in the automotive industry, potentially improving the effectiveness of in-vehicle crash prevention systems.

The limitations of this study should be recognized, especially how participants' background may affect their driving behavior, merging, and use of technologies tested in this experiment. For the purposes of this study, young and middle-aged drivers were deliberately selected, as many studies have suggested that speeding and risky behavior are generally associated with males, particularly young males (World Health Organization, 2018). In this context, it has been noted that AR warnings have a positive impact on these "hard-to-reach" road users. However, the effectiveness of AR warnings should also be studied using a different sample of drivers in terms of age and gender distribution. Also, Dixit et al. (Dixit et al., 2014; Dixit et al., 2017) conducted a controlled laboratory experiment using a driving simulator to examine how risk attitudes and personal beliefs affect driver decisions and the likelihood of crashes, finding that personal beliefs change with experience and driving skills (Domeyer et al., 2013). Therefore, to improve the

external validity of our experiments and to test whether the causal relationships and results obtained here can be generalized to other contexts, additional samples of heterogeneous drivers will be tested to investigate behavioral descriptors of driving choices.

Another limitation is where the Variable Message Signs (VMS) and road markings are located, as well as all the other safety measures, which were set up to make sure drivers get the information far enough away from the merging zone. This placement was determined in accordance with established human factors guidelines (World Road Association (PIARC) and Committee, 2016; World Road Association (PIARC) and Committee, 2008), and more specifically with the widely adopted “6-seconds rule,” which states that drivers should be given at least six seconds to perceive, process, and react to new or unexpected stimuli. However, a valuable direction for future studies would be to investigate the optimal timing and positioning for delivering alerts or driver support information. Different road geometries, traffic densities, and user characteristics may require adaptive or personalized timing strategies to maximize the effectiveness of both traditional and connected guidance systems. Studying how early or late warnings are given could help create clear guidelines for when to share information, making road safety measures in merging areas more accurate and effective.

Moreover, it is also important to underline that in this study the authors used the drivers’ lateral position data just to verify lane-keeping behavior during the experiment, where any possible lane-changing maneuver was limited by the implementation in the simulation of a platoon of vehicles in the middle lane of the highway, able to deter the right-lane driver from moving to the left lanes and overtaking the entering vehicle. While this controlled setup helped isolating the desired interactions in the right lane, that was the core of this study aimed at evaluating the effectiveness of AR countermeasures in assisting drivers to keep a safe distance from vehicles entering the highway from on-ramps, in real-world traffic conditions drivers could respond to merging vehicles by performing a lane change when possible. In a future study, we will replicate the analysis by varying the characteristics of the platoon of vehicles, leaving the drivers free to decide their action when facing an entering vehicle.

Another future study will analyze the impact of demographic factors such as age, gender, driving experience, technological confidence, etc., on both equipment and tool usage and on the merging maneuver itself. It would also be useful to see how people with different levels of experience with the technology used in the experiment respond to the proposed countermeasures. Furthermore, this study’s objective does not delve deeply into the real-world application of AR, and conducting a practical study on its implementation would certainly be of interest. Another thing that was not fully looked at in this study was the possible side effects of the tested warnings, like distracting drivers. Eye-tracking systems could test these effects by observing where drivers focus their visual attention during the merging zone. Such findings would give useful information for improving AR design warnings and help find more variables worthy of further investigation.

Moreover, this study was focused on an analysis in a highway environment, as literature reported this type of road as one of the most critical in terms of safety in merging zones. The design characteristics of highways around the world are quite similar, and selecting Italian design guidelines does not significantly affect the ability to generalize the results for this specific type of road environment. It means that for other types of road infrastructures that differ significantly from the one reproduced in this study, it will be necessary to verify a possible confirmation of the results obtained here.

Future studies could investigate the different types and features of information that drivers should share when approaching merging zones and explore additional countermeasures to promote safer merging on highways, thereby lowering the risk of crashes. Moreover, another future study could focus on the interaction between different vehicle types, such as vehicle-truck or vehicle-motorcycle interactions, which were not covered in this paper, and compare these interactions with the vehicle-vehicle dynamics observed in this study. Future studies could also explore the interaction between a vehicle on the right lane and potential merging vehicles in a platoon with different gaps, a topic particularly relevant to connected and autonomous driving, by varying the gap size within the platoon. It may be possible to analyze the reactions of both the vehicle in the right lane and the entering vehicle, as well as the entering vehicle’s decision to merge based on available gaps. In both cases, it would be useful to find out what information is most helpful to drivers and which countermeasure features best promote safer maneuvers and interactions.

Lastly, using metaverse-based driving co-simulation technologies, future studies might look at how different vehicles affect each other (Louah et al., 2011). Additionally, this approach could help determine which countermeasures are the most effective for ensuring safety during the merging process. These future studies could adopt a co-simulation approach where multiple users interact with the environment and each other at the same time and within the same merging zone, analyzing simultaneously the perspectives of both merging and passing vehicles. This approach may also suggest new types of safety countermeasures, offering opportunities for further studies in this field.

CRedit authorship contribution statement

Alessandro Calvi: Writing – original draft, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Andrea Vennarucci:** Writing – original draft, Validation, Investigation.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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