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The Impact of Innovative Lighting Technologies on Driver Performance, Behaviour, Acceptance and Safety

PhD Thesis

Doctoral Program in Civil and Environmental Engineering (36th Cycle)

ALBERTO PORTERA

Doctoral Dissertation
Doctoral Program in Civil and Environmental Engineering (36th Cycle)

The impact of innovative lighting technologies on driver performance, behaviour, acceptance, and safety

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2024

Dedico questa tesi alla mia cara Mamma,

fonte di amore, saggezza e sostegno.

I hereby declare that, the contents and organisation of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

Alberto Portera

Turin, May 3rd, 2024

Summary

Innovative lighting technologies emerged as promising strategies to mitigate the high occurrence of accidents on roads, particularly during night-time when low visibility and driver psychophysical conditions contribute to deteriorate driving capability. Statistics highlight that on urban roads the highest number of accidents involve pedestrians with cars, while rural roads face most accidents of car drivers along curved sections.

This PhD thesis aims to investigate and validate the safety benefits of two innovative lighting technologies, adapted for urban and rural environments in night-time conditions, using a driving simulator.

In rural settings, the study explores the effects of the active LED road studs' colour and layout on horizontal curves, both subjectively and objectively. Results indicate that the presence of white LED road studs, along with configurations facilitating centred trajectories within lane, significantly improved driver behaviour. Drivers perceived road studs as less risky, more pleasant, and less arousing compared to unlit condition, positively accepting their presence. These devices enhance lane perception, allowing drivers to anticipate curve shapes and adjust their trajectories accordingly.

In urban areas, the study investigates the effectiveness of LED strip signals at mid-block crosswalks, activated when pedestrians enter the crosswalk and deactivate upon their exit. The technology aims to alert drivers to pedestrian presence, facilitating prompt reactions. Results demonstrate that this lighting technology improves driver-pedestrian interaction, enabling earlier reactions and undisturbed passage between drivers and pedestrians, even under distracted driving conditions. Drivers showed high trust on the technology, maintaining a workload comparable to conditions without technology.

Overall, the adoption of these innovative lighting technologies in both urban and rural settings enhanced driver behaviour, performance, and overall safety. Driver acceptance underscores the potential usefulness of these technologies in augmenting road safety. Furthermore, the findings highlight the importance of conducting behavioural analyses to determine the optimal configuration of such technologies, ensuring maximal benefit for road users. It is expected that road agencies and transport departments will use the experience gained from this research to reap the maximum benefits in terms of road safety.

Ringraziamenti

Le emozioni che mi travolgono mentre scrivo queste parole sono infinite, e ognuna di esse comprende note di gioia e tristezza al contempo. La felicità e la consapevolezza del raggiungimento di un traguardo tanto desiderato si mescolano inevitabilmente con la tristezza nel pensare che questa avventura stia volgendo al termine. Con queste frasi vorrei ringraziare tutti coloro che mi hanno accompagnato in questo duro percorso, nei momenti più tristi, ma soprattutto in quelli più felici.

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List of Publications

This dissertation is based on the following papers, which will be referred to in the text by their letters. The papers are appended at the end of the thesis.

Paper A Angioi, F., **Portera, A.**, Bassani, M., De Oña, J., & Stasi, L. L. D. (2023). Smart on-Road Technologies and Road Safety: A short overview. *Transportation Research Procedia*, *71*, 395–402. https://doi.org/10.1016/j.trpro.2023.11.100ù

Paper B **Portera, A.,** Angioi, F., Muzzioli, L., Di Stasi, L. L., & Bassani, M. (2023). The influence of LED road stud color on driver behavior and perception along horizontal curves at nighttime. *Transportation Research Part F: Traffic Psychology and Behaviour*, *96*, 66–75. https://doi.org/10.1016/j.trf.2023.06.007

Paper C **Portera, A.,** & Bassani, M. (2024). Examining the Impact of Different LED Road Studs Layouts on Driving Performance and Gaze Behaviour at Night-time. *Transportation Research part F: Traffic Psychology and Behaviour, 103, 430-441.* https://doi.org/10.1016/j.trf.2024.04.024

Paper D **Portera, A.,** & Bassani, M. (2023). Red LED Strip Signalling Pedestrian Presence at Uncontrolled Mid-block Crosswalks. *Transportation Research Procedia, 73, 151-158.* https://doi.org/10.1016/j.trpro.2023.11.903

Paper E **Portera, A.,** Angioi, F., Di Stasi, L. L., & Bassani, M. (2024). Effectiveness of Smart LED strips at mid-block crosswalks under distracted driving conditions. *Submitted reviewed version to Transportation Engineering.*

Chapter 1

Introduction

Every year, around 1.3 million people worldwide lose their lives in road accidents and an estimated 50 million are injured. If the current trajectory persists, road accidents are expected to contribute an additional 13 million deaths and 500 million injuries over the next decade (Ahmed et al., 2023; World Health Organization, 2021). Additionally, it's worth noting that despite conducting only one-quarter of our driving at night, half of traffic fatalities occur during night-time hours (National Safety Council, 2023).

The data from the European Road Safety Observatory on road fatalities (European Commission, 2021), reveals a notable trend when considering the distribution of accidents based on road users and the "main vehicle" involved (Figure 1). Vulnerable road users (VRU, such as pedestrians, cyclists, moped riders, motorcyclists) and car occupants appear to face a higher probability of accidents when colliding with cars. It is worth noting that in many cases car collisions occur without the presence of other vehicles. Therefore, a substantial proportion of accidents stem from human errors or issues related to the road or vehicles themselves (*Highway Safety Manual*, 2010; Petridou & Moustaki, 2000). In addition, the distribution of road fatalities by transport mode (Figure 2) reveals some significant insights into the risks associated with various mode of transportation. A crucial distinction emerges when considering fatalities inside and outside urban areas. Within urban environments, pedestrians are the most vulnerable users, and are involved in 36 % of all fatal crashes. Conversely, outside urban areas, car occupants represent the highest percentage of fatalities (56%). Consequently, it is imperative to discern the specific areas targeted for possible safety interventions. In urban areas, the focus should prioritize the safety of vulnerable road users, while in rural areas, efforts should prioritize the safety of vehicle drivers.

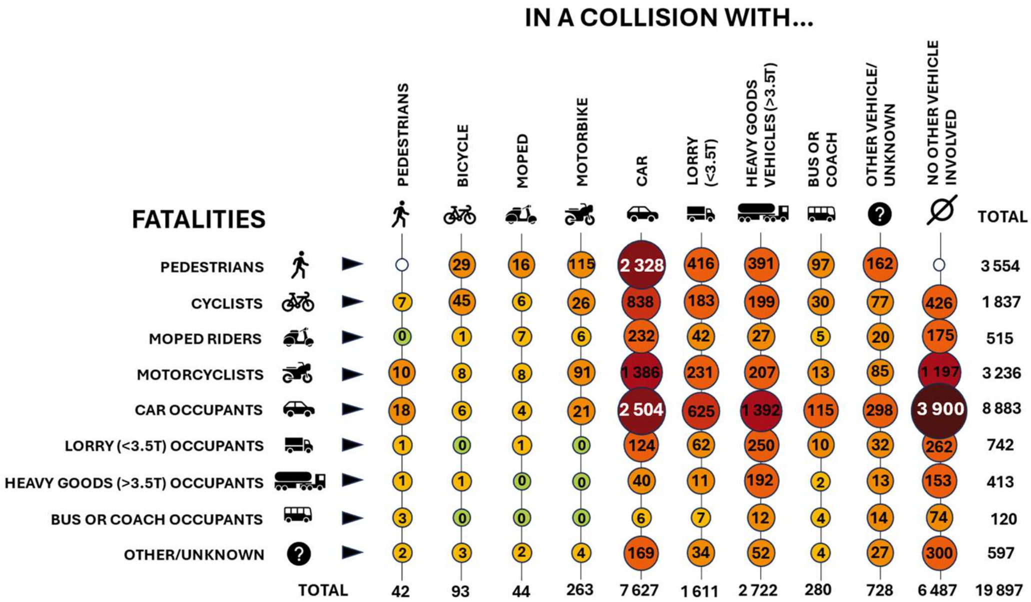


Figure 1: Collision Matrix: Road Traffic fatalities in EU (2021). (Source: European Road Safety Observatory).

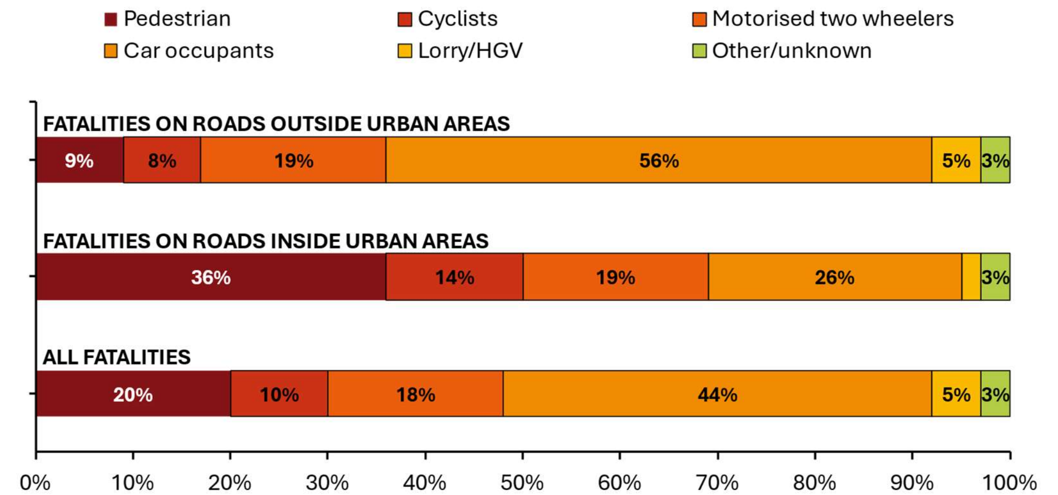


Figure 2: Distribution of fatalities by transport mode and areas. (Source: European Road Safety Observatory).

The Italian trend (ISTAT, 2023) mirrors similar patterns to the EU statistics. Italian data reveals an increase in casualties among vulnerable road users in urban areas. The highest number of fatalities is associated with the category of car occupants. Lastly, there is a nearly equal percentage of fatalities on urban (42.2%) and rural (48.5%) roads, while fatalities on highways account for 9.3%.

Many studies have highlighted that in night-time driving the safety of road users is compromised due to reduced visibility, driver fatigue, and impaired perception (Owens & Sivak, 1996). During night-time, drivers have reduced capacity to distinguish shapes, colours, and objects along the road. Thus, when driving at night on unlit roads, drivers face greater difficulties in identifying the lane, as well as the roadside in the long vision field. This critical issue is underscored and revealed by crash statistics indicating that night-time driving is one of the most dangerous driving conditions for all road users (Johansson et al., 2009; Liu et al., 2019; Wood, 2020), and the probability of road crashes at night is 60% higher than during the day (Owens & Sivak, 1996; Plainis, 2006). Moreover, accident databases show that crash severity is at least two times higher during night hours than during the day (Ackaah et al., 2020; Varghese & Shankar, 2007).

1.1 Safety actions

Recognising the impact of road accidents on human well-being, the United Nations passed a resolution on road safety during the 74th session of the General Assembly. This resolution marked the beginning of the Second Decade of Action for Road Safety (2021-2030), with the goal to achieve at least a 50% reduction in both road fatalities and injuries during this decade (World Health Organization, 2021). To achieve this, it was stipulated that individual countries must take action to prevent accidents, protect people involved in accidents if prevention fails, rescue people after accidents and learn from accidents. The actions are based on the five following pillars: (i) road safety management (also called bridging pillar), (ii) safe user practices, (iii) safe vehicles, (iv) safe road infrastructure, and (v) an efficient post-crash response – with key areas of action including legislation, enforcement, education, and technology (Figure 3). It is worth noting that the sequence of the pillars, particularly safe user practices, safe vehicles, and safe road infrastructure, does not imply any hierarchy; conversely, it emphasises their equal importance and collaborative role in enhancing safety of the entire road system.

The promotion of road safety encompasses several disciplines, such as law, engineering, planning, medicine, and psychology. The scientific initiatives of these disciplines should be integrated and converted into beneficial safety outcomes. Authorities, organizations, and countries must facilitate the opportunity for companies, research centres, and universities to become strongly involved in the validation of proposed solutions and their widespread implementation on a global scale.

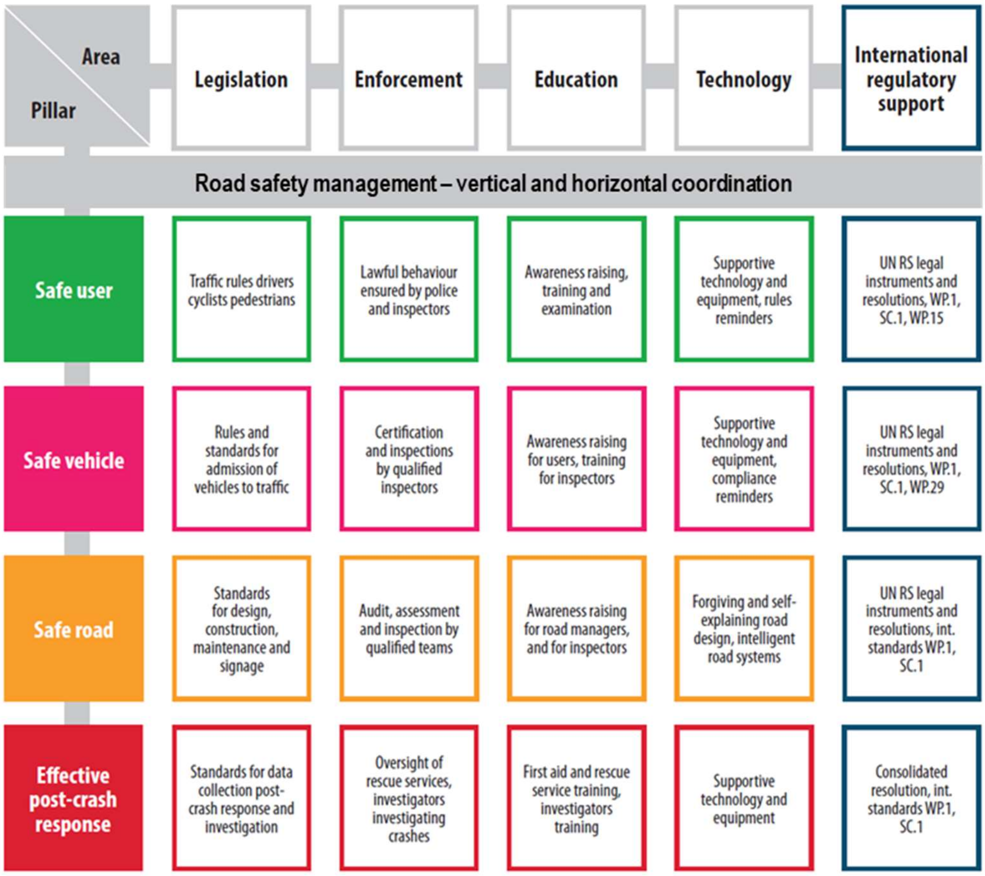


Figure 3: Road safety actions outlined in the Second Decade of Action for Road Safety (2021-2030) (Reproduced from the Global Plan for the Decade of Action for Road Safety 2021-2030).

The *safe user* integrated with the technological key area focuses on promoting assistive technology and equipment, along with reminders of rules, which encompass the following actions:

(1) promote technologies designed to enhance the adherence of road users to traffic regulations, like alcohol ignition interlocks, safety-belt reminders, and mobile phone safety reminders for individuals while driving or walking, etc.; and

(2) develop equipment and technologies for vehicles and road infrastructures that aid drivers and other road users in preventing road accidents and mitigating their impact, like conflicting pedestrian and cyclist detection, emergency steering systems, automated emergency braking systems, safety gear for motorcycle riders, and intelligent traffic light management, particularly in areas like pedestrian crossings and bicycle lanes.

The *safe vehicle* integrated with the technological key area focuses on supportive technology and equipment for increasing protection of all road users. This encompasses a range of technologies, including but not limited to night vision systems, intelligent cruise control, pedestrian and cyclist detection, emergency braking systems, and various automated solutions.

The *safe road* area integrated with the technological key area focuses on forgiving and self-explaining road design. Intelligent road and traffic management systems should encompass the following initiatives:

(1) employ advanced equipment, materials, and technologies in the design and construction of forgiving, self-explanatory roads using elements like lane dividers, emergency lanes, road positioning, school zones, and the design and protection of traffic signs;
(2) utilize state-of-the-art equipment, materials, and technologies for urban street design and construction, using features like pedestrian areas, speed-reducing structures, traffic calming devices, cycling lanes, parking zones, school zones, lanes for individual and public transport, as well as information systems for road users, offering details on waiting times, traffic delays, and alternative routes;
(3) utilize technology to measure, assess, and report on the safety performance of road infrastructures;
(4) employ cutting-edge equipment and technology to objectively evaluate the safety aspects of road design;
(5) foster the development of cost-effective intelligent road systems, which encompass features like variable message signs, systems aimed at enhancing user alertness, and infrastructure-vehicle communication systems;
(6) implement intelligent traffic management systems based on sensor data and traffic forecasts, integrating features like intelligent speed control and dynamic re-routing, among others.

The *effective post-crash response* integrated with the technological key area is intended to cover the following initiatives:

(1) implementation of intelligent systems that assist the work of emergency response centres, rehabilitation facilities, and enhance support for victims;
(2) foster the development of technology that facilitates Motor Vehicle Collision Investigations (MDCI), specifically focusing on crash investigation technologies.

1.2 Research motivation

The unacceptably high number of road accidents still occurring today requires the study of innovative solutions capable of significantly reducing the number of deaths and injuries. Crash statistics provide insight into where investigations should be prioritized. In urban roads, sustainable mobility is increasingly prominent, leading to a grow of vulnerable road users and, consequently, an increase in accidents involving them. On the other hand, a higher frequency of accidents involving car drivers colliding with other vehicles or without another vehicle being involved is observed in rural environments. Finally, a shared aspect among rural and urban settings is that accidents are more severe and frequent during night-time. This is attributed to specific factors, as drivers at night experience diminished abilities to discern shapes, colours, and the information conveyed by the road (Wood, 2020). In addition, drivers are less able to recognise objects in dark conditions, resulting in a significant delay in identifying hazards (i.e., longer reaction times). Consequently, the probability of correcting a potential driving error is reduced in dark conditions (Plainis et al., 2005; Plainis & Murray, 2002).

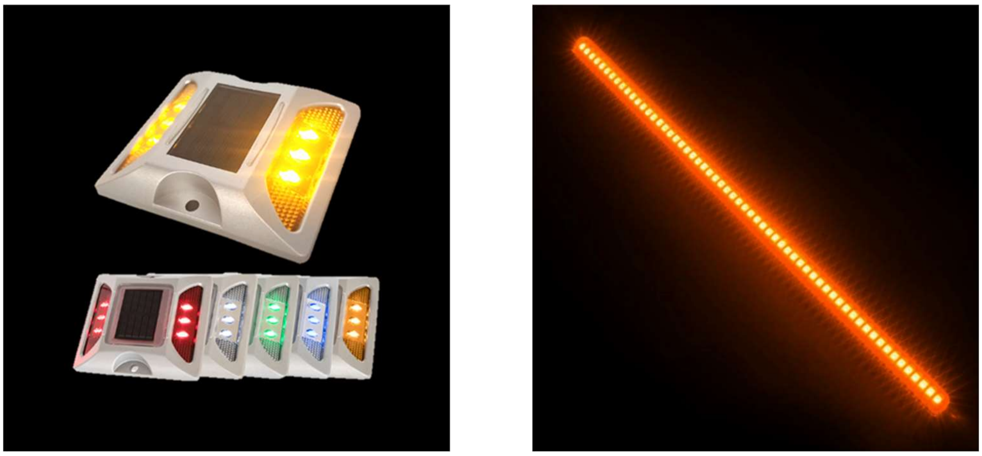
Among the possible solutions, smart roads technologies (SRT) are recommended by the Decade of Actions for Road Safety 2021-2030. SRT may enhance efficiency, sustainability, and safety of roads (Sun et al., 2018). In particular, in dim light conditions, *innovative lighting systems* enhance the visibility of the road thus improving safety (Assum et al., 1999). However, it is essential to conduct research to verify the effects on driver behaviour before their adoption, ensuring their effectiveness at the time of implementation. It is also essential to verify whether road users are able to understand and accept the introduction of these technologies.

1.3 Research objective

How new and innovative *lighting technologies* influence driving performance, behaviour, acceptance, and road safety was the question behind this doctoral research. I delved into the intricate interplay between technologies, road user behaviour, and the safety of the systems where they operate and interact. Through rigorous analyses of data from experiments, and insights based on such analyses, this thesis aspires to understand the impact of such innovations in promoting safer, self-explanatory, and highly efficient roads. This work aimed at contributing to the safety and sustainability of roads for the benefit of society at large. I focused my research on technologies that are installed on roadways and have the potential to influence driver behaviour and enhance road safety during night-time driving.

I studied the effects of *active LED road studs* (Figure 4a) in rural setting to improve the behaviour of drivers along horizontal curves. In the urban context, *LED strip crossings* (Figure 4b) that highlight the crosswalks at night to alert the drivers of the presence of a pedestrian crossing were investigated.
To achieve this objective, firstly, I conducted a literature review to identify existing or conceptual innovative road technologies (see Chapter 2) that may positively influence driver behaviour and enhance road safety. Then, I analysed two lighting technologies for improving safety in night-time conditions on rural and urban roads (see Chapters 4 and 5).

In the first case, I evaluated the effects of using active LED road studs on two-lane highways during night-time. In the urban context, the evaluation was focused on LED strip crossing. The rationale behind the choice and investigation of these two technologies is explored in detail in Chapters 4 and 5.



(a) (b)

Figure 4: Example of (a) active LED road studs and (b) example of red LED strip.

1.4 Thesis organization

This manuscript is organized as follows:

Chapter 2: it focuses on the identification of smart road technologies that currently exist, are under development, or are still in the conceptualization phase. It includes smart technologies aimed at enhancing traffic flow conditions, promoting sustainability, reducing the impact of human factors in crash generation, and overall, elevating road safety standards.

Chapter 3: it describes the experimental methodology used in this thesis including equipment, tools, and statistical methods used.

Chapter 4: it presents the effects of introducing active LED road studs on rural roads. The results obtained from two main experiments are presented and discussed. The first was aimed at evaluating the effects of LED road stud colour on subjective perception and driving behaviour. The second focuses on the effects of road stud layouts on driver and gaze behaviour.

Chapter 5: it presents the results achieved with the introduction of red LED strip at mid-block crosswalks on urban roads with two experiments. The first experiment involved drivers in focused conditions (i.e., non-distracted drivers), while the second involved drivers that were cognitively distracted.

Chapter 6: the final chapter covers the general discussion, contribution of the study, as well as the potential for future works.

The outline of the research conducted in this thesis is shown in Figure 5, where the correspondence between the thesis chapters and the research papers published and submitted to scientific journals is evidenced.

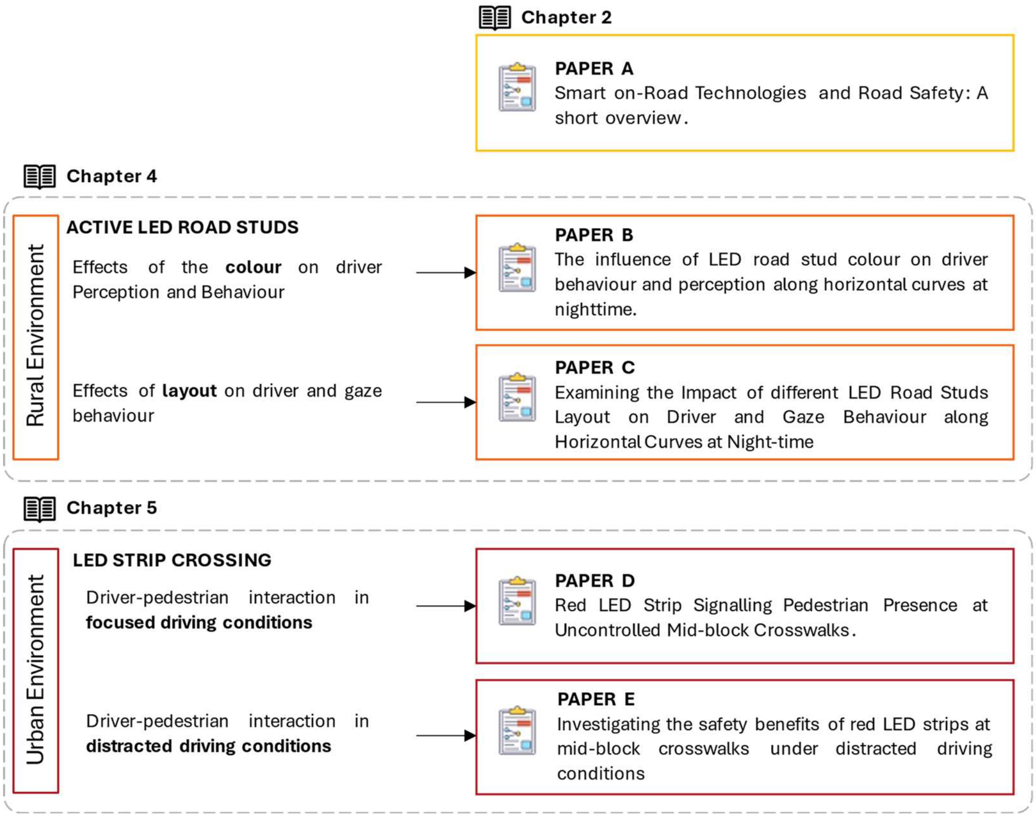


Figure 5: Schematic representation of the connection between the thesis chapters and their respective research papers.

Chapter 2

Smart on-Road Technologies

Smart Road Technologies (SRT) refers to a broad spectrum of technological solutions aimed at enhancing traffic flow conditions, promoting sustainability, reducing the impact of human factors in accident generation, and overall, elevating road safety standards (Pompigna & Mauro, 2022).

The following paragraphs provide an overview of the technologies that currently exist, are under development, or are still in the conceptualization phase. Within this section, our primary focus is on *Smart* ***On-Road*** *Technologies*, which refers to specific technologies installed on roads and, therefore, interact with road users in a passive manner (Angioi et al., 2023). In this context, users are not compelled or controlled by the technology (e.g., there are no systems that automatically reduce a vehicle's speed or prohibit overtaking other vehicles). Instead, they receive passive information that can assist them in enhancing their behaviour and safety. Finally, some of these technologies can have multiple roles, for instance they can self-adapt to the traffic conditions and to the environmental context, reduce energy consumption, and increase user behaviour or improve traffic operations and safety (Pompigna & Mauro, 2022). Specifically, the two technologies analysed in the chapters 4 and 5 of this thesis, are included in the *innovative lighting solutions* (section 2.2). They are intended to influence the behaviour of road users to correct imprudent behaviours such us: over speeding, not centred trajectories, distraction, driver aggressiveness. They are also intended to support drivers in low visibility conditions where drivers are impaired to well distinguish the road geometry, infrastructure, and road signs.

2.1 Smart solutions for improving traffic operations, sustainability and safety

In this section, *smart on-road technologies* dedicated to enhancing traffic management, promoting safety and sustainability are presented. Specifically, these include traffic management systems, roadside sensors, priority charging lanes.

In modern transportation infrastructure, *traffic management systems and roadside sensors* are used to collect information and provide valuable data to improve traffic flow and safety (Guerrero-Ibáñez et al., 2018). These systems consist of sensors, cameras, and laser beams (Figure 6) that work together to detect vehicles and road users and monitor a wide range of parameters related to traffic, environment, and safety. By collecting real-time data, these systems enable authorities to make informed decisions and implement strategies to optimize traffic flow, improve safety, and responding to crashes promptly. The sensors, strategically placed along roadways, highways, and intersections, detect the movement and speed of vehicles, which allows for continuous monitoring of traffic patterns. Cameras provide visual data that can be used to assess the traffic conditions and identify accidents or congestion. Laser beams are used to measure vehicle speed, helping in the enforcement of posted speed limits. In addition to data acquisition, traffic management systems are essential for disseminating information to drivers and commuters. Variable message signs, traffic lights, and mobile applications are used to relay information about traffic conditions, road closures, and alternate routes. By providing real-time updates to drivers, these systems contribute to safer and more efficient travels while reducing the risk of accidents and congestion. The challenge with these sensors lies not in their installation but in their ability to provide accurate and real-time data without latency, which can negatively impact driver responsiveness (Guerrero-Ibáñez et al., 2018). Specifically, if the signal is transmitted inaccurately - either with delays, premature delivery, or incorrect information - it could negatively affect driver behaviour and overall safety.

Road surface condition sensors (Figure 6d) are designed to continuously monitor a range of weather parameters and the quality of the road surface. They collect data such as surface temperature, humidity, water fil height, road grip. This information is invaluable for several reasons. First, it can significantly contribute to the safety of road users (Theofilatos & Yannis, 2014). By constantly assessing the condition of the pavement and the surrounding environment, it is possible to provide real-time insights to vehicles on the road. Through various communication channels, vehicles can receive information about road conditions and adapt their behaviour and driving parameters accordingly. For instance, if the sensors detect a sudden drop in temperature leading to icy road conditions, this information can be immediately transmitted to vehicles, helping drivers to exercise caution and prevent accidents (Veneziano et al., 2014). Experimental results from the California Department of Transportation indicate that the "icy warning system" was effective in prompting drivers to significantly reduce their speed when icy roads were unexpected (Veneziano et al., 2014).

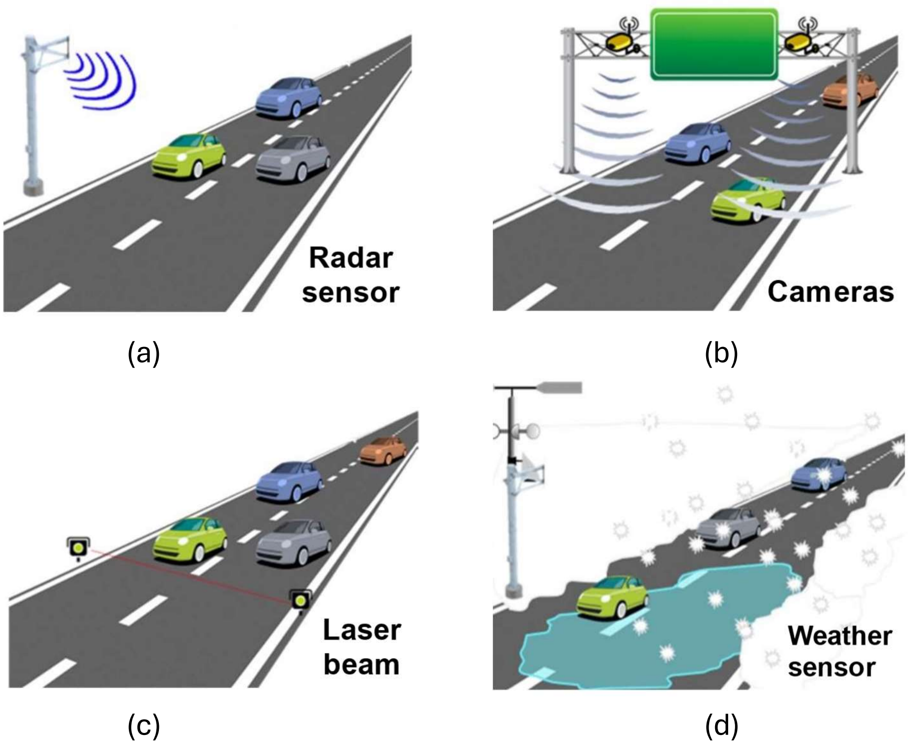


Figure 6: Traffic management systems: (a) radar sensor, (b) video cameras, (c) laser beam, and (d) road weather condition. (Reproduced from Guerrero-Ibáñez et al., 2018).

Priority dynamic charging lanes (Figure 7) are being developed and are currently in the experimental phase. In these lanes, electric vehicles will be able to drive and recharge their batteries simultaneously, potentially extending the range of electric cars indefinitely (Toh et al., 2020). This innovative technology represents a significant step forward in promoting sustainability, as it has the potential to reduce emissions. The concept of dynamic priority battery charging lanes involves providing dedicated lanes on roads with embedded charging infrastructure. Electric vehicles equipped with the necessary technology can access these lanes and receive a continuous charge while driving. This eliminates the need for frequent stops at charging stations and allows electric vehicles to travel longer distances without the limitations imposed by traditional battery range. From a behavioural perspective, the introduction of dynamic charging lanes or, more generally, dedicated lanes (Razmi Rad et al., 2020; Rad R. S. et al., 2024) may raise to issues related to merging and diverging into these lanes, potentially leading to conflicts with other users in regular lanes. There are open questions in behavioural research, such as whether it would be safer to create dedicated entry zones and physically separate the two lanes with a barrier, allowing drivers to enter and exit only at specific points. Alternatively, should drivers be given the flexibility to enter and exit the dynamic charging lanes at their discretion, treating them as regular driving lanes? Moreover, the precise positioning of the vehicle within the electric lane appears to be critical to establish a connection, raising concerns about whether drivers might struggle to maintain the exact central position, leading to increased cognitive load and fatigue. Could this difficulty in precise positioning lead to driving errors? These behavioural considerations highlight the importance of addressing human factors in the design and implementation of dynamic charging infrastructure to ensure both safety and user acceptance. These questions remain still open.

Figure 7: Electric priority lane. (Reproduced from Sazali & Firdaus, 2019).

2.2 Innovative lighting solutions for safety

This section introduces the innovative lighting solutions (i.e., a set of smart on-road technologies) designed to interact with drivers with the aim of enhancing their behaviour and performances, and subsequently reducing the likelihood of road crashes. As already mentioned in this thesis, driving at night poses a series of problems due to the lower visibility thus increasing the likelihood and severity of road crashes (Ackaah et al., 2020; Bella et al., 2014; Castro et al., 2005; Liu et al., 2019; Plainis, 2006). Here, some of the innovative lighting solutions (i.e., smart lighting poles, innovative markings, and smart LED-lighted crosswalks), aimed at overtaking the problem of reduced visibility and perception in low-lighting conditions are explained and discussed.

Smart lighting poles (Figure 8) is a sophisticated technology that utilizes recognition sensors to dynamically adjust luminosity based on environmental and traffic conditions. This innovative approach aims to conserve energy by reducing light intensity in areas devoid of presence of road users following the "less users - less light" (LU-LL) principle, resulting in significant energy savings. However, the implementation of such systems raises intriguing questions about their potential impact on driver behaviour as well as the behaviour of other road users (e.g., two-wheelers and pedestrians) (Gibbons et al., 2014). In particular, there are several aspects that deserve a better comprehension: (i) the impact of new lighting systems on behaviour of road users from a purely objective perspective (i.e., the change in speed, vehicle control, gaze behaviour); (ii) the subjective level of safety perceived by road users dealing with smart lighting poles with different lighting intensity; and (iii) the possible impact on crash severity and frequency of the smart lighting poles in comparison to fixed-light poles. As smart lighting systems dim or brighten in response to users' operations, drivers may unconsciously perceive alterations in road visibility, potentially influencing their speed and overall driving behaviour. To date, no studies have focused on these aspects. Al-Haji suggests that the new generation of street/road lighting is an early technology, the number of accidents is yet too small for a before-and-after study (Al-Haji, 2014). Therefore, it is necessary to implement surrogate safety measures in naturalistic or simulated experiments.

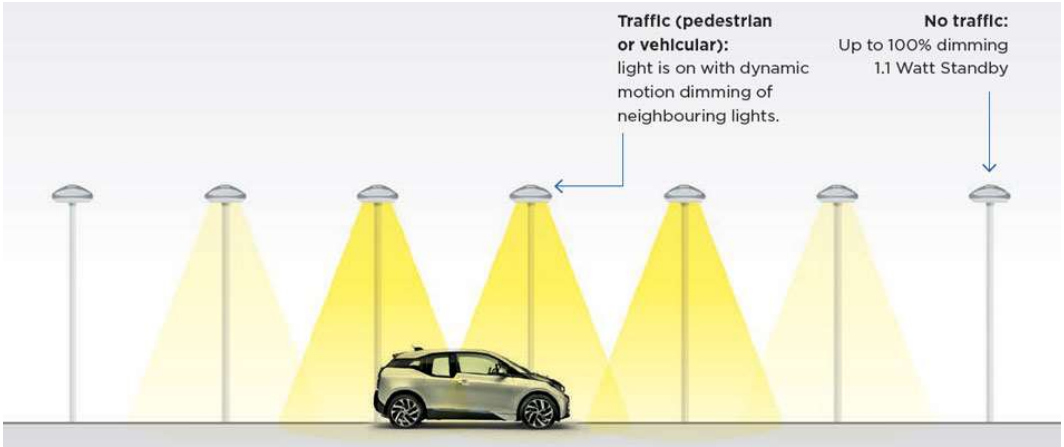


Figure 8: Smart Road lighting (Reproduced from lumenova.net)

Innovative markings aim to enhance driving behaviour by improving road visibility (Wood, 2020), especially during nighttime hours. In recent years solutions like photoluminescent road markings, temperature sensitive pictograms and active LED road studs have been proposed (Figure 9).

Photoluminescent technology (Figure 9a) allows to produce the "glow-in-the-dark" markings by employing materials which accumulate energy during the day to release it as light at night (Bhujbal et al., 2022; Villa et al., 2023; Zhu et al., 2021). From a behavioural perspective, this technology aims to enhance road visibility in dim light conditions and help drivers better understand the road geometry, such as the presence of curves and their radii. Additionally, it is designed to enable drivers to maintain more central trajectories and enhance lateral control of the vehicle. The use of photoluminescent markings contributes to improved safety and a better driving experience, especially during low-light conditions. Some behavioural studies are underway at the University of Granada, Spain.

The *temperature-sensitive pictograms* (Figure 9b) are transparent under normal conditions, but becomes visible under adverse meteorological conditions (e.g., icy conditions) and reveal warning symbols on the road (Dumé, 2008; Studio Roosegaarde, 2013). Their primary objective is to promptly alert drivers, enabling them to adopt safer driving behaviours in response to the changing road conditions. Experimental results on behavioural adaptation are missing.

Active LED road studs are dynamic road safety devices that utilize light-emitting diodes (LED) to enhance visibility and provide real-time guidance for drivers in dark hours, similarly to photoluminescent road markings. In curves, the visibility of the lane is challenging, especially during night-time hours or adverse weather conditions (Bella et al., 2014). Active LED road studs address this issue by highlighting the lane/road geometry providing additional illumination precisely where it's needed. This enhanced visibility helps drivers anticipate the curvature of the road ahead, reducing the likelihood of sudden manoeuvres or late decisions and reactions. This proactive signalling assists drivers in maintaining their lane discipline through the curve, reducing the risk of unintentional lane departures. Moreover, active LED road studs can serve as a dynamic lane management tool, allowing for the real-time adjustment of lane directions based on traffic density. This functionality is showed in Figure 9c, where the studs are strategically employed to dynamically open and close lanes, optimizing traffic flow and accommodating changing demand.

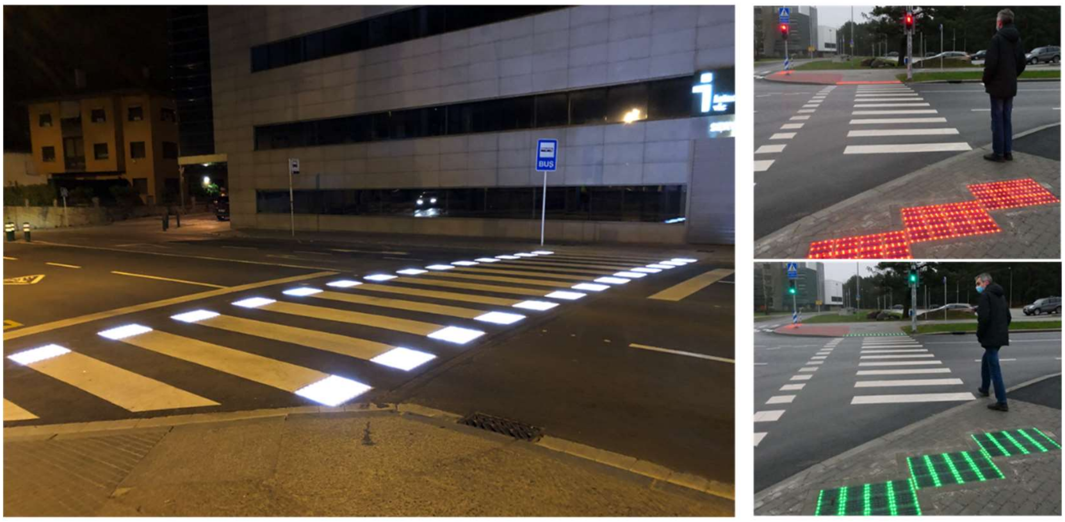
On this technology, some experimental studies have highlighted the possible safety benefits of active LED road studs as countermeasure to increase road visibility. With active road studs, drivers improved their lateral control (Shahar et al., 2018) of the vehicle and maintained safe speeds (Llewellyn et al., 2021). However, information about the impact of road studs' colour and layout (i.e., the different possible disposition onto the pavement) on driver behaviour and perception are missing.

(a) (b) (c)

Figure 9: Innovative markings: (a) photoluminescent road markings, (b) temperature sensitive pictograms and (c) active LED road studs. (Reproduced from: eejournal.com, bbc.com, and cryzal.net)

In urban environments, *smart crosswalks* (Figure 10a) are experiencing significant interest. They leverage sensors and high-intensity lights to alert drivers of the presence of pedestrians that are crossing the road. In such circumstances, the activation of lights indicating a pedestrian crossing should enhance driver awareness, thereby fostering safer interactions between vehicles and pedestrians (Hussain et al., 2023). This innovative technology becomes especially crucial where traditional traffic signals are absent, as it provides a proactive means of communication between pedestrians and drivers. The illuminated indication serves drivers as a visual alert to yield, and acknowledge the pedestrian's right of way, contributing to an overall safer crossing experience. Vice versa, other systems are designed to alert pedestrians to the current signal phase. In these cases, for example, a strip of green or red lights positioned near the crossing provides a clear indication of whether it is safe to cross or not, aligning with the traffic light status (Figure 10b).

Some studies have highlighted potential benefits of smart crosswalks on drivers' behaviour. Indeed, lower speeds and an increased yielding rate have been recorded (Lantieri et al., 2021; Patella et al., 2020). In some cases, vehicle-pedestrian interaction has been measured using surrogate safety measures (Hussain et al., 2023). However, results are lacking on their effectiveness concerning variations in pedestrian aggressiveness (i.e., pedestrian time gap acceptance) and in different urban scenarios (i.e., lane width or number of lanes). Furthermore, there is a gap in knowledge regarding the benefits of smart crosswalks in distracted driving conditions.



a) b)

Figure 10: Smart crosswalks: (a) For driver awareness, (b) for pedestrian awareness. (Reproduced from stepvial.negocio.site and e-pavement.eu/solutions).

Chapter 3

Method

This chapter describes the methods employed throughout this study. It provides information on the equipment used to conduct the experiments and the statistical techniques used for data analysis. Since the method was the same for all the experiments, it is reported in this chapter to avoid redundancy in the manuscript. In this way, common methodological aspects are comprehensively addressed here, while specific features are described in the subsequent sections dedicated to individual studies.

3.1 Driving simulation

In this research, experiments were conducted recurring to driving simulation, which offers many advantages when studying driving behaviour, human factors, and road safety (Winter & Happee, 2012). First, simulations allow for the exploration of realistic driving scenarios and hazardous events without putting participants at risks. Second, simulation enables researchers to fully control the experiments, exerting precise control of the independent variables. Third, accurate and reliable measures are acquired without any noise. Finally, considering the current research trend, a significant advantage of driving simulations is the ability to replicate advanced driver assistance systems (ADAS), connected and automated vehicles (CAVs), smart road technologies, that would be challenging to develop, install and test on real vehicles or roads due to their high costs. This capability allows researchers to examine the effects of technological innovations on driving in controlled conditions, contributing to the development and evaluation of new solutions without the expenses and practical challenges associated with large-scale implementation on real roads. Driving simulators also present some drawbacks that need consideration. These include limited physical, perceptual, and behavioural fidelity which may not fully replicate real-world conditions. Additionally, drivers may experience discomfort during driving simulations, which can affect their engagement and performance. Driving simulation often imposes increased physical and mental demand on drivers (De Winter et al., 2012). However, these disadvantages can be mitigated through a good experimental design and pre-validation of the driving simulator.

This research was conducted with the driving simulator of the Road Safety and Driving Simulation (RSDS) Lab of Politecnico di Torino. The simulator consists of (i) three 32-inch sized monitors with resolution of 1920x1080 pixel and a frequency of 60 Hz which cover 130°×20° of the horizontal and vertical field of view, respectively, a fully equipped driving position including (ii) seat, (iii) instrument panel, (iv) steering wheel with force feedback, (v) pedals, (vi) manual transmission, (vii) vibration pads for returning road roughness, wheel roll and impact. A 5.1 Dolby sound system provides the sound of a realistic car engine and the surrounding environment. SCANeR Studio® simulation software was used to create the driving scenarios, run the simulation, and collect data about the vehicle dynamic and actions of the driver on the steering wheel and pedals. Prior this study, the simulator was validated for longitudinal (Bassani et al., 2018), transversal (Catani & Bassani, 2019), and passing (Karimi et al., 2020) behaviour. It was also validated for tunnel driving (Lioi et al., 2023) achieving both absolute and relative validations (see details in cited papers).

Figure 11: The fixed-base driving simulator (acquired in 2015) at the RSDS Lab is equipped with a visual system that operates using either a three-screen setup or a virtual reality (VR) headset. For the experiments described in this thesis, the three-screen vision system was used.

3.2 Eye-tracking

In paper C, the eye activity was monitored using a wearable (head-mounted) eye-tracking system (Figure 12). The eye-tracking technique is commonly employed in driving simulation experiments as it assesses the visual attention of driver, which is a component of the broader construct of attention (D'Amico et al., 2022). During driving, the eyes play a pivotal role in information processing (Crundall & Underwood, 2011) as they provide continuous input to the brain about the front and surrounding environment. By monitoring eye movements, researchers can understand where drivers' visual attention is focused, how they scan the road and respond to various stimuli. For example, road geometry, lighting, and environment influences gaze patterns, as drivers need to adjust their attention based on curves, traffic signs, and obstacles (Hristov, 2019; Underwood et al., 2002; Vos et al., 2023; Yao et al., 2023). In driving simulation, eye tracking data provides the link between visual attention patterns and driving performance, providing information for enhancing road design, developing lighting systems, and promoting overall safety (Wood, 2020).

The eye-tracking device used for the experiment is Pupil Core from Pupil Labs (https://pupil-labs.com). Specifically, Pupil Core is the eye-tracking platform that includes a suite of open-source software and a wearable eye-tracking device. The device consists of (i) a front-facing camera that captures the individual's field of view (i.e., the world camera) at high resolution (1920×1080@30fps, 1280×720@60fps, 640×480@120fps) with a field of view (FOV) of 100° and a latency of 5.7 ms, and (ii) two binocular cameras for pupil detection using infrared rays (referred to as eye-cameras) operating at 120 Hz with a resolution of 640×480 and a latency of 5.7 ms.

Figure 12: The pupil core eye tracker from Pupil Lab company. (Pictures are reproduced from the company website https://pupil-labs.com/products/core/).

Pupil Capture software was used with the eye-tracking device for real-time data acquisition and other operations. It enables the detection of pupils, tracking of gaze, and identification and tracking of special markers placed in the surrounding environment through videos from the front and eye cameras. After the videos are collected, Pupil Player allows for the visualization, analysis of videos, and extraction of data through specific plugins. During this study, Pupil software version 3.5.1 was used.

3.3 Statistical analyses

To statistically interpret the experimental outcomes, repeated measures analysis of variance (RM ANOVA) were adopted. This statistical technique is well-suited for the within-subject design employed in the experiments. RM ANOVA is particularly advantageous as it accounts for the correlated nature of measurements taken on the same subjects across different conditions. In a within-subject design, each participant is exposed to all levels of the independent variables, making the observations within each subject inherently related. RM ANOVA takes advantage of this by examining the variance within subjects over the various conditions, effectively reducing the error variance associated with individual differences. This approach enhances statistical power, as it considers the systematic variation across measurements within the same subjects. Before running the RM ANOVA analyses, the assumptions of normality, sphericity and causality where checked (see appendix for result). In the RM ANOVA analyses, the significance level (α) was always set to 5%. For multiple comparisons, post-hoc tests were conducted with Bonferroni correction applied.

3.4 Participants

For all experiments, participants were recruited from a list of more than 500 individuals who had expressed their willingness to take part in the driving simulation experiments. To determine the sample size of participants for each experiment, a priori analyses were conducted to guarantee a statistical power of at least 80%. Due to the low availability of females, the distribution between males and females was sometimes unbalanced.

3.5 Questionnaires

In each experiment, questionnaires were administered both before and after the driving simulation (detailed information on dispensed questionnaires are reported in Chapters 4 and 5 and in the attached papers). This was done to gather information about the participants (e.g., physical status) and the simulations they engaged in (e.g., subjective effects of the lighting technologies). The distribution of questionnaires varied based on the experimental design and the purpose of the experiment. For instance, information regarding simulation sickness was consistently collected, but in experiments B, C, and D, it was incorporated in the post-questionnaires, whereas in experiment E, a dedicated and validated questionnaire (e.g., MSAQ; Gianaros et al., 2001) was dispensed.

Chapter 4

Innovative lighting technologies for rural roads

This chapter presents the experimental outcomes obtained with the use of active LED road studs along curves in rural roads. To this aim, the research was divided in two studies. In the first (see **paper B**), the effects of LED road stud colour on subjective perception and driver behaviour were assessed. In the second (see **paper C**), the effects of different road stud layouts on driver and gaze behaviour were evaluated.

4.1 Background

The safety of road users is significantly compromised during night-time driving due to a combination of factors such as reduced visibility, driver fatigue, and impaired perception (Wood, 2020), with crash statistics indicating that the probability of road crashes at night is 60% higher than during the day (Owens & Sivak, 1996; Plainis, 2006). In addition, in rural roads, it is well-established that, curves pose higher risks of accidents compared to straight road segments (Johnston, 1982; Othman et al., 2014).

To enhance safety under these unsafe conditions, road authorities and transportation engineers have devised countermeasures such as retro-reflective road markings and delineators. In the context of smart technologies, active LED road studs have gained prominence due to their luminosity and durability. The key feature of LED road studs is their self-illuminating capability, eliminating the need to be illuminated by car headlights like for the passive road studs.

Until now, various studies have concurred that LED studs potentially enhance driver confidence during night-time driving, as well as safety perception, and driving comfort (Llewellyn et al., 2020; Reed, 2006; Shahar et al., 2018). Nevertheless, the limited research on the effects of LED studs on driving performance has produced contradictory results (Llewellyn et al., 2021; Shahar et al., 2018; Shahar & Brémond, 2014; Zhu et al., 2021). Consequently, the question of whether LED studs can effectively enhance driver performance and road safety remains open.

4.2 Manipulation of LED road stud colour

Although it is widely recognized that colour plays a significant role in shaping driver behaviour (Calvi, 2018) and emotional state (Jalil et al., 2012), rarely specifications on the light colour to be emitted by the LED studs are presented and discussed (Llewellyn et al., 2020; Shahar et al., 2018; Zhu et al., 2021). Indeed, only one study has systematically examined the impact of different stud colours on driver preferences, perceived visibility, legibility and glare (Bacelar, 2004). Findings suggested that bluish/white studs were generally favoured over yellowish or orangish ones by drivers. However, due to concurrent manipulation of variables such as luminous intensity, device surface, spacing, and height of the studs, a straightforward conclusion on the most suitable colour cannot be given.

Therefore, to increase safety on rural roads at night, an experimental study was designed to find the LED road stud colour that better influences driver's behaviour (longitudinal and transversal control of the vehicle) and perception (perceived risk level and emotions) along horizontal curves. We compared the baseline (unlit condition) with white and red colours that are the two prominent colours used for road signs. We opted against choosing blue and green colours as they do not align with the typical colours employed for signals in rural roads. Additionally, yellow/orange was not chosen due to its association with work zones. Since the aim was to increase the visibility of dark curves in nighttime conditions, the LED road studs were installed only along the curves spaced 8 m apart.

We hypothesized that the colour of LED road studs may affect the emotions of participants (from a traffic psychology perspective). Consequently, it is assumed that positive emotions may positively influence safety by enhancing driver's vehicle control along the curve.

4.2.1 Experimental design

Thirty-six participants were involved (11 females) whose ages ranged from 19 to 63 years, with an average age of 31 years and a standard deviation of 11.2. The drivers had a valid Italian driving license.

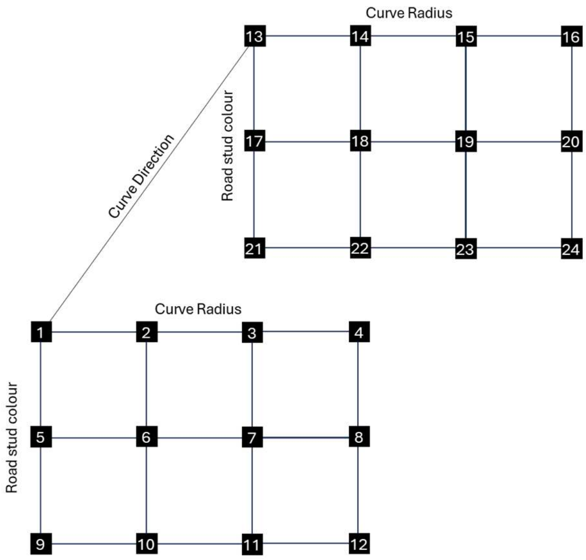
To monitor subjective behaviour of drivers a static perception study was designed and perceived risk, valence and arousal of drivers were collected.

To monitor objective behaviours drivers were engaged in a driving simulation study to collect driving performance (i.e., speed and lateral position).

Both experimental tasks (the static perception and driving simulation) followed a within-subject design with LED Stud (3 levels: unlit, red, and white), Curve Radius (4 levels: 120, 210, 300, and 440 m), and Curve Direction (2 levels: left and right) as independent factors (Figure 13). To this aim, we designed three road scenarios in night-time conditions that were differentiated only by the presence of LED studs (Figure 15). Each scenario included twice the four levels of curve radii (120, 210, 300, and 400 m) and the two levels of curve direction (left and right). The scenarios were designed to represent a two-lane rural highway, with a lane width of 3.75 m and a shoulder width of 1.50 m, observing the road design standards outlined by the Italian policy (MIT, 2001).

In the static perception part, we presented 24 static scenes of the curves taken from the driver point of view (3 LED stud × 4 curve radii × 2 curve directions). After watching the scene, each participant was asked to rate: his/her perceived level of risk with a Likert scale from 1 (not risky) to 9 (extremely risky), and the level of pleasantness (i.e., valence, for a more detailed comprehension see Kensinger, 2004) and the activation (i.e., arousal, for a more detailed comprehension see Kensinger, 2004) using a Self-Assessment-Manikin-Scale (SAM). Figure 14 explains the procedure associated with each scene.

In the driving simulation study participants were asked to drive along the three scenarios containing the curves with different direction (i.e., left vs. right) and radius (i.e., 120, 210, 300, 440 m). Each scenario differed only for the LED road studs present at the edges of each curve (Figure 15). The order of the scenarios was fully counterbalanced to control the order effect (Keppel et al., 2001). We monitored the following dependent variables for each curve of the scenario (Figure 15a and Figure 15b): (i) the longitudinal speed at TS (tangent-to-spiral) and CC (curve centre) termini, (ii) the lateral position (i.e., the distance between the centre of gravity of the vehicle and lane centreline) at TS and CC termini, and (iii) the standard deviation of lateral position (SDLP) between TS and ST (spiral-to-tangent) termini.



Trial	Road Stud Color	Curve Radius [m]	Curve Direction
1	Unlit	120	Left
2	Unlit	210	Left
3	Unlit	300	Left
4	Unlit	440	Left
5	Red	120	Left
6	Red	210	Left
7	Red	300	Left
8	Red	440	Left
9	White	120	Left
10	White	210	Left
11	White	300	Left
12	White	440	Left
13	Unlit	120	Right
14	Unlit	210	Right
15	Unlit	300	Right
16	Unlit	440	Right
17	Red	120	Right
18	Red	210	Right
19	Red	300	Right
20	Red	440	Right
21	White	120	Right
22	White	210	Right
23	White	300	Right
24	White	440	Right

Figure 13: The 3 × 4 × 2 experimental design (paper B).

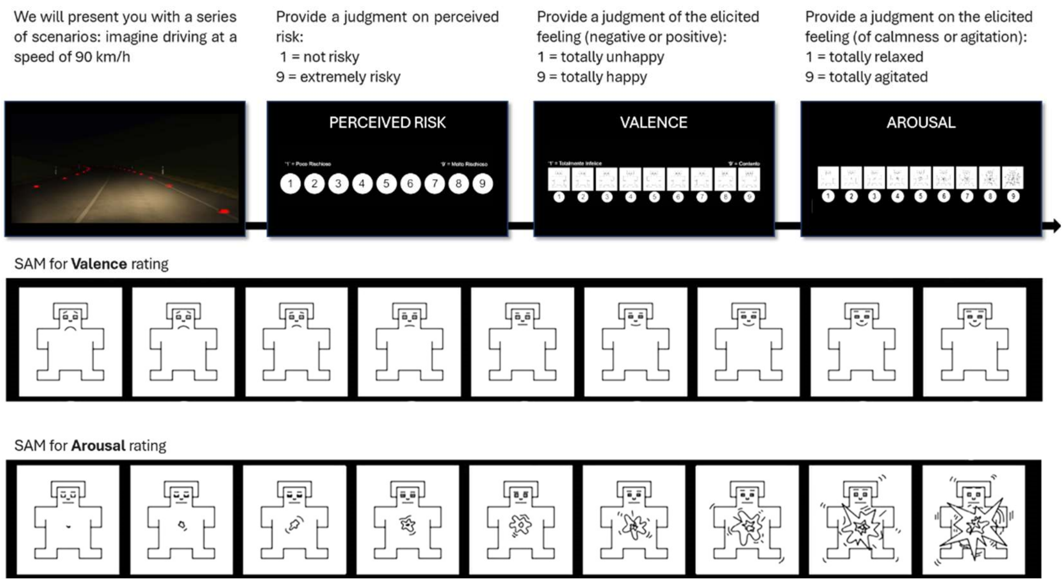


Figure 14: Progress scheme of how each scene was rated. The picture was displayed for 7 seconds, then participants had to rate the perceived risk with Likert scale, Valence, and Arousal with self-assessment-manikin scale (SAM).

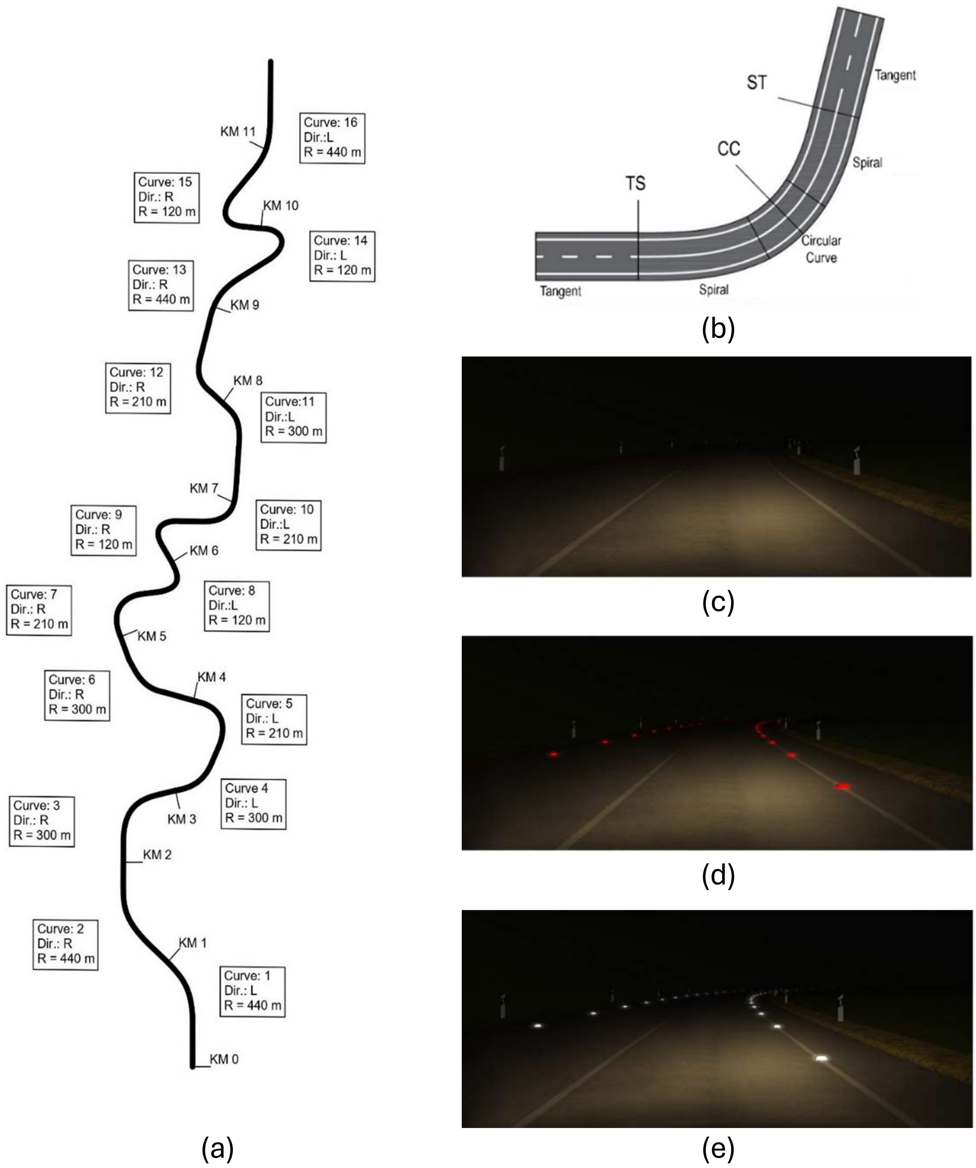


Figure 15: (a) The alignment of the three road scenarios with curve characteristics, (b) indication of sites referred to curve termini: TS (tangent-to-spiral) and ST (spiral-to-tangent), and to circular curve centre (CC) and (c, d, e) examples of scenario for (c) unlit condition, (d) red, and (e) white LED road studs in night-time driving conditions. Road studs were placed 8 m apart at the edges of the lanes.

To analyse the dependent variables in the driving task, we calculated the mean values based on curves with equivalent geometric characteristics.

Two participants were unable to complete the driving task due to simulation sickness. Therefore, the analysis included data from only 34 out of the initial 36 participants.

4.2.2 Subjective measures

The results of the static perception task are shown in Figure 16, Figure 17, and Figure 18. The statistical analysis revealed that risk perception was significantly influenced by the LED stud colour ($F_{2,66}$ = 16.28, p < .001), curve direction ($F_{1,33}$ = 9.44, p = .004), and curve radius ($F_{3,99}$ = 25.91, p < .001). Specifically, the application of the Bonferroni correction uncovered a noteworthy difference between conditions with white LED studs and unlit conditions (mean difference = 1.07, corrected-p <.05). Moreover, participants' valence was statistically influenced by LED stud colour ($F_{2,66}$ = 13.42, p < .001), and curve radius ($F_{3,99}$ = 8.90, p < .001). Post-hoc testing indicated differences between the white and unlit conditions (mean difference = 1.05, corrected-p < .05) and between curves with radii of 120 m and 440 m (mean difference = – 0.48, corrected-p <.05). Additionally, participant arousal was found to be influenced by LED studs ($F_{2,66}$ = 14.120, p < .001), curve radius ($F_{3,99}$ = 6.789, p <.001), and curve direction ($F_{1,33}$ = 11.880, p = .002), with a statistically significant (LED stud × Curve Direction) interaction ($F_{2,66}$ = 3.33, p = .042). Post-hoc tests on this interaction confirmed a significant difference between white and unlit studs for both curve directions. A significant difference between the red LED stud condition on left and right curves was identified too.

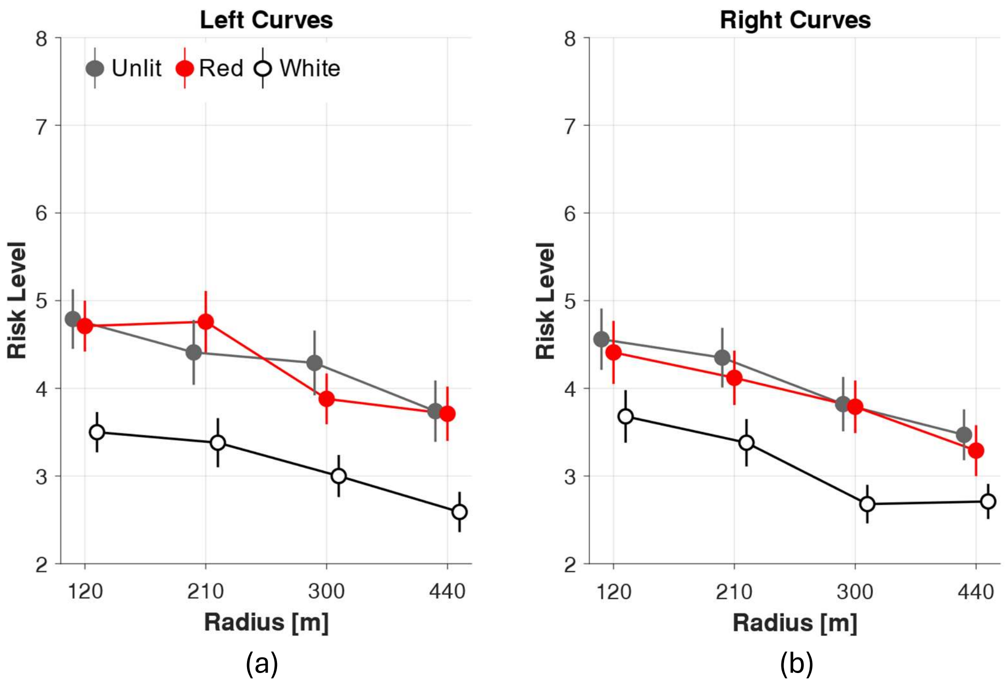


Figure 16: Average perceived risk recorded during the static perception test. Plots are separated for (a) left and (b) right curves. The error bars represent the standard error of the mean (SEM). Note that, for graphic purposes, the range of the y-axis ranges from 2 to 8, while the variables were measured in a scale from 1 to 9.

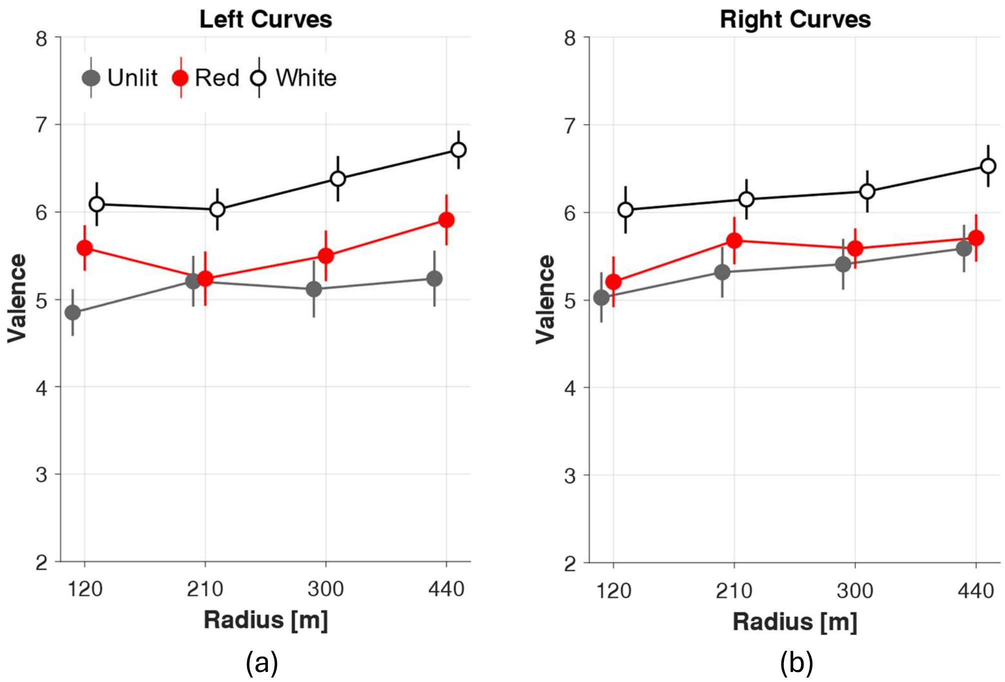


Figure 17: Average valence recorded during the static perception test. Plots are separated for (a) left and (b) right curves. The error bars represent the standard error of the mean (SEM). Note that, for graphic purposes, the range of the y-axis ranges from 2 to 8, while the variables were measured in a scale from 1 to 9.

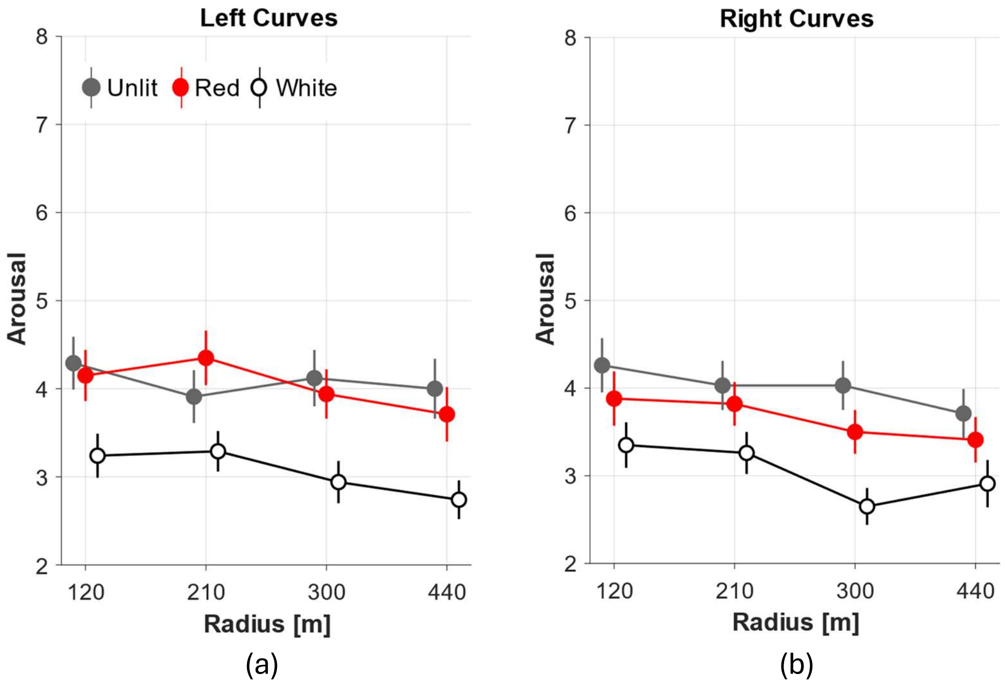


Figure 18: Average arousal recorded during the static perception test. Plots are separated for (a) left and (b) right curves. The error bars represent the standard error of the mean (SEM). Note that, for graphic purposes, the range of the y-axis ranges from 2 to 8, while the variables were measured in a scale from 1 to 9.

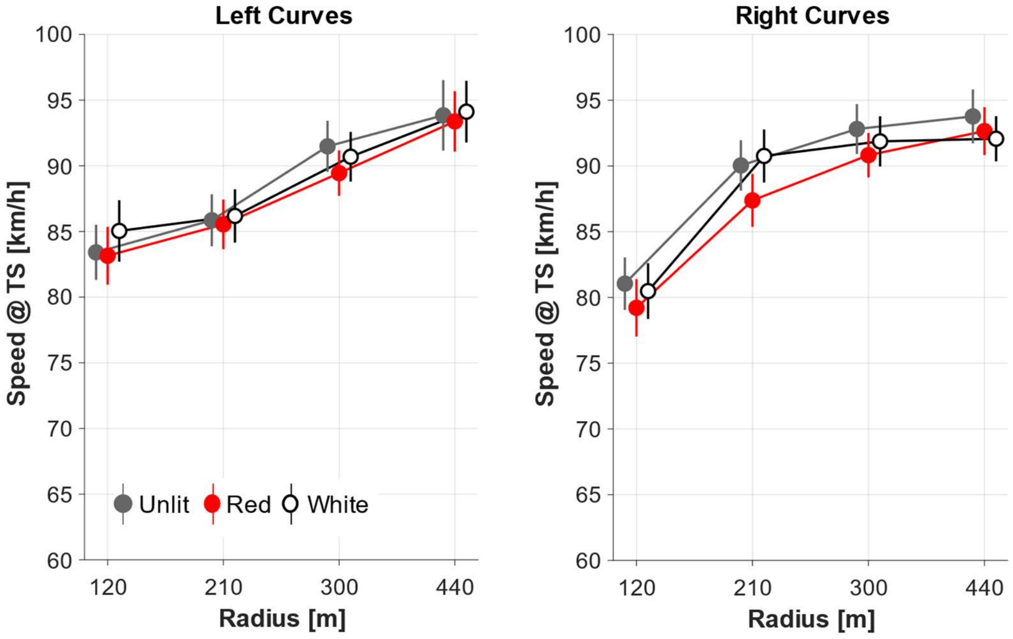
These outcomes revealed an impact of colour on participants' perceptions and emotions. Road studs equipped with LED lights emitting white light were perceived as safer, attributed to a reduced perception of risk compared to the other two conditions. Indeed, as shown in Figure 16, in both left and right curves, the perceived risk with the presence of white LED studs was significantly lower with respect to the red LED studs and unlit conditions. Additionally, the valence associated with white LED lighting was the highest (Figure 17), signifying a more pleasant experience when compared to both red LED and unlit road studs. Notably, the white road studs were also perceived as less arousing (Figure 18), suggesting a state of relaxation (Kensinger, 2004). In contrast, red LED road studs were perceived similarly to the unlit condition and distinctly different from the white LED condition. Our interpretation is that the influence of white LED studs on driver perception contributes to a more pleasant and safer driving experience improving the driving performances (Paxion et al., 2014).

4.2.3 Objective measures

Analysis of results

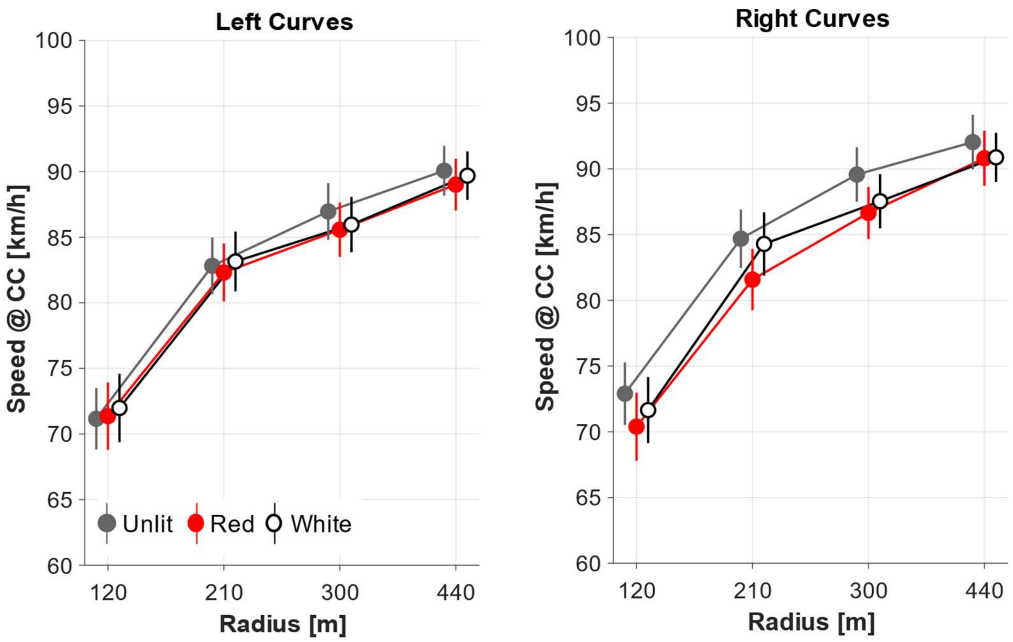
The driver behaviour was monitored by determining the speed (Figure 19 and Figure 20), the lateral position (Figure 21 and Figure 22) and the SDLP (Figure 23). The RM ANOVA results did not find any link between the colour of the road studs and the speed maintained by the drivers ($p > .05$) at the beginning (i.e., TS site) and at the centre of the curves (i.e., CC site). At CC, a significant effect was found for curve radius ($F_{3,99} = 207.08$, $p < .001$) as already highlighted in Bassani et al. (2019) and Calvi (2015).

Concerning the lateral behaviour, at TS site, the LED stud, curve direction and curve radius effect on lateral position was significant ($F_{2,66} = 15.30$, $p < .001$, $F_{1,33} = 6.75$, $p = .015$ and $F_{3,99} = 5.57$, $p = .001$, respectively). At CC site, a significant difference in lateral position arose among the three road stud conditions ($F_{2,66} = 24.74$, $p < .001$). Significant differences were also observed for curve direction ($F_{1,33} = 14.00$, $p < .001$) and curve radius ($F_{3,99} = 6.27$, $p < .001$). Moreover, the second-order interaction (LED stud × Curve Radius × Curve Direction) was found to be statistically significant ($F_{6,198} = 7.47$, $p < .001$). Post-hoc analyses on road studs indicated significant differences between the unlit and white LED conditions (mean difference = – 0.32, corrected-$p < .05$), the red and unlit LED conditions (mean difference = 0.20, corrected-$p < .05$), and the red and white LED conditions (mean difference = – 0.12, corrected-$p < .05$). SDLP was significantly influenced by both LED road stud and curve radius ($F_{2,66} = 4.23$, $p = .019$, $F_{3,99} = 27.28$, $p < .001$), respectively, while curve direction did not exhibit a significant effect. However, the interaction between road stud condition and curve direction was significant ($F_{2,66} = 7.43$, $p = .001$). Post-hoc comparisons between road stud and curve direction revealed noteworthy differences, particularly between the red and unlit conditions (corrected-$p < .05$) and between the white and unlit conditions, specifically on right curves (corrected-$p < .05$).



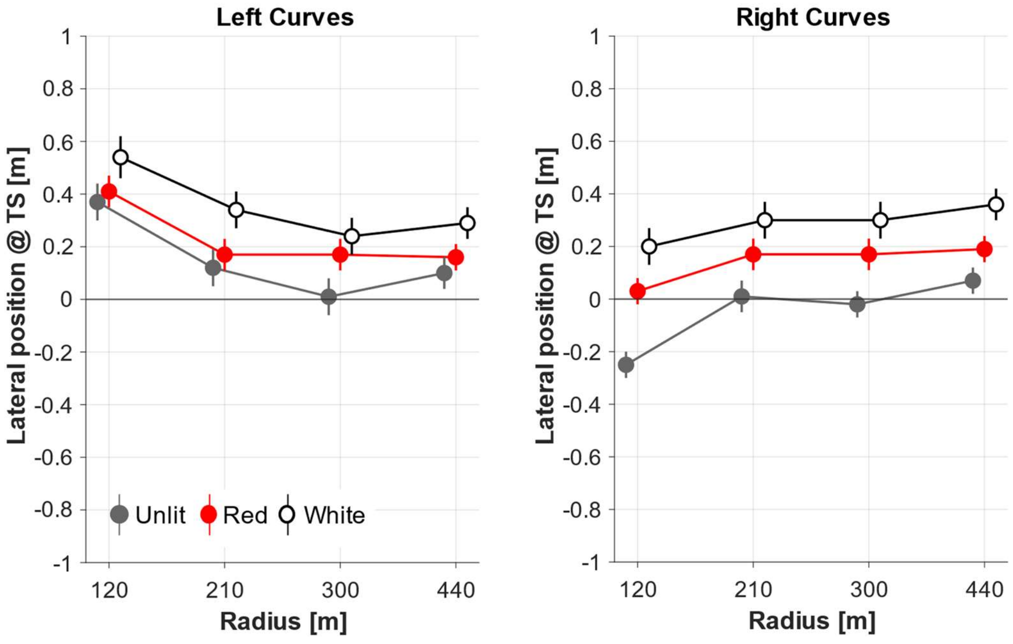
(a) (b)

Figure 19: Average speed recorded at the beginning of the curve (TS site). Graphs are split for (a) left and (b) right curves. The error bars represent the standard error of the mean (SEM).



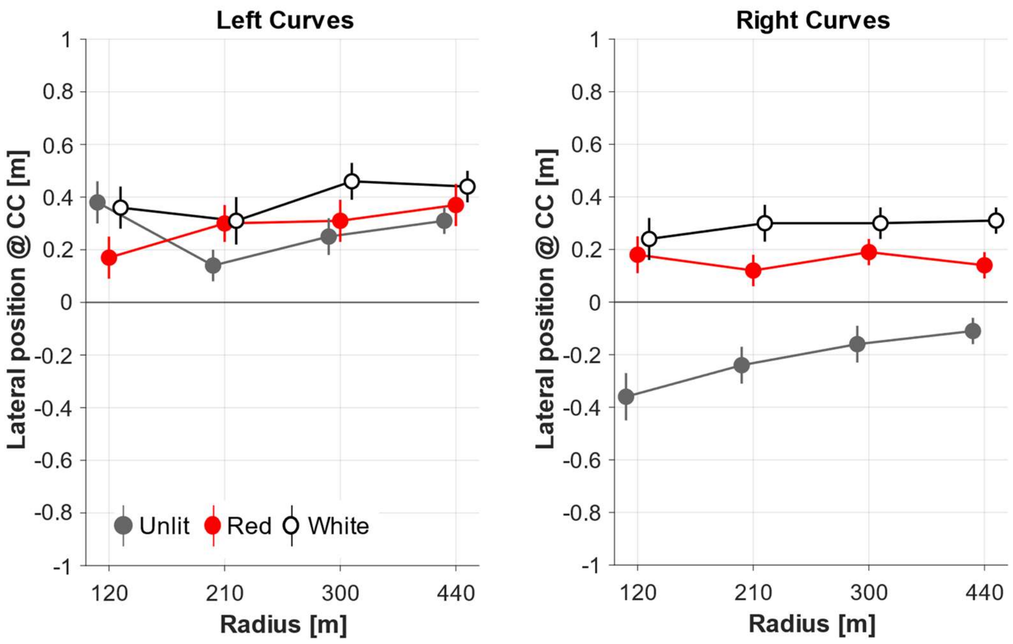
(a) (b)

Figure 20: Average speed recorded at the centre of the curve (CC site). Graphs are split for (a) left and (b) right curves. The error bars represent the standard error of the mean (SEM).



(a) (b)

Figure 21: Average lateral position recorded at the beginning of the curve (TS site). Graphs are split for (a) left and (b) right curves. The horizontal line (LP = 0) represents the lane centreline. Positive values denote a leftward lateral position from the centreline, whereas negative values indicate a rightward lateral position. The error bars represent the SEM.



(a) (b)

Figure 22: Average lateral position recorded at the beginning of the curve (TS site). Graphs are split for (a) left and (b) right curves. The horizontal line (LP = 0) represents the lane centreline. Positive values denote a leftward lateral position from the centreline, whereas negative values indicate a rightward lateral position. The error bars represent the SEM.

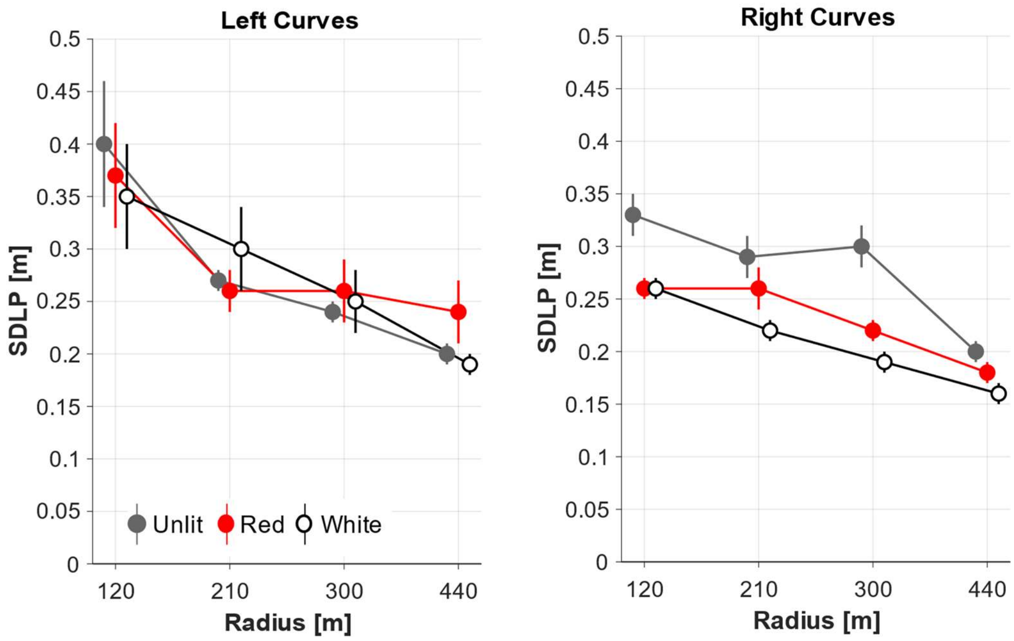


Figure 23: Average SDLP recorded between the TS and ST sites. Graphs are split for left and right curves. The error bars represent the standard error of the mean (SEM).

Discussion of results

The findings related to longitudinal behaviour indicated that the speed values at the beginning and at the centre of the curve (i.e., ST and CC sites) were unaffected by the presence of colour of the LED stud. This outcome is promising and aligns with the results reported by Llewellyn et al. (2021), who similarly found no significant speed variation between LED-studded and unlit conditions on real roads. It suggests that although drivers significantly improved in predicting road curvature (see results on transversal behaviour), this enhancement did not translate into the adoption of riskier behaviours, such as higher speeds. These results agree with earlier research, such as that conducted by Shahar et al. (2018) and Shahar & Brémond (2014), where speed was influenced by LED studs primarily along straight sections only, a condition not considered in our study. Nevertheless, our findings, combined with those of Shahar et al. (2018), clearly indicate that the use of road studs along curved sections does not compromise the longitudinal performance of drivers. Additionally, the study revealed that the radius of the curve had a notable impact on longitudinal behaviour, i.e., the higher the radius the higher the speed, according to Bassani et al. (2019).

The results on lateral behaviour uncovered significant differences when drivers negotiated left and right curves. Specifically, on right curves with red and white road studs, participants tended to drive closer to the carriageway centreline compared to the unlit lateral marking condition. However, no significant differences were observed in the case of left curves, as the lateral positions closely resembled those of the unlit condition. We attributed this variance in behaviour to the specific layout of road studs adopted in our study, positioned solely at the edge of the carriageway. This asymmetry becomes evident when drivers employ the "tangent point" mechanism for lateral control, as noted by Land & Lee (1994) and Lehtonen et al. (2012). These studies observed that drivers typically consider the point of apparent inversion of the inner road marking, aligned with their line of sight, as tangent to the marking itself. Therefore, considering this vision mechanism as predominantly utilized by drivers, in right curves, drivers' gaze precisely fell on the position of the LED studs, while in left curves, their focus landed on the central marking of the carriageway where road studs were not installed. This resulted in drivers encountering essentially identical scenes for left curves, and consequently, the lateral driving behaviour remained consistent across all three LED road stud conditions. Finally, the impact of LED studs on SDLP was significant only on right curves. In line with previous considerations, the enhanced visibility of lane boundaries with LED studs led to fewer trajectory corrections by drivers, resulting in lower SDLP values compared to the unlit condition. Once again, the white LED stud condition exhibited the most effective vehicle control. These outcomes align with the findings of Shahar et al. (2018) and Shahar & Brémond (2014), which also observed lower SDLP values in the studded condition compared to the unlit one. Notably, these prior studies drew differing conclusions for left and right curve manoeuvres, a distinction attributed to the different LED stud layouts. Shahar et al. (2018) observed driver behaviour on two-lane rural roads where road studs, in addition to being positioned at the carriageway's edge, marked the solid line dividing opposing traffic lanes.

By considering both subjective and objective measurements, the implementation of white studs contributed to a more favourable environment, characterized by reduced risk perception and less alarming and more pleasant driving compared to both unlit conditions and curves illuminated red road studs. They also enhanced lateral control, as evidenced by a reduced SDLP and more centred trajectories towards the centre of the road (only along right curves).

These findings should be interpreted in the context of certain limitations. First, the simplicity of the road scenario, characterized by free-flow conditions and favourable weather, may somewhat restrict the external validity of the results. Consequently, further research should address this limitation by exploring more varied driving conditions. Second, while our study primarily focused on psychological (e.g., risk perception, emotional valence, and arousal) and behavioural aspects (e.g., speed, lateral position, and SDLP), it is plausible that physiological factors may have influenced the outcomes. For instance, individual variances in colour perception or physiological responses to light could have played a role.

4.3 Manipulation of LED road stud layout

The previous section provided important insights into the positive effects on transversal driving behaviour with the adoption of the LED studs and the improved benefits using the white colour. However, the study has also showed how the decision to place the LED studs at the edge of the carriageway resulted in different driving behaviour when drivers negotiated left curves compared to right curves. With the study presented in this section, we attempted to overcome this issue by investigating the effects of a different layout of LED stud on the curves. In addition, we were interested in understanding whether the brightness of the LED could catch the gaze of drivers and influence the visual strategies adopted by the driver when negotiating the curve, and consequently influence the driving behaviour.

The studies in the literature that have addressed the topic of LED road studs have focused on the effect of varying brightness (Villa et al., 2015) or on the driving behaviour (Llewellyn et al., 2021; Shahar et al., 2018; Shahar & Brémond, 2014) influenced by the presence of road studs. However, these studies typically employed a single layout without comparing the driving behaviour across different LED stud dispositions.

Thus, since LED stud layout is a feature that can affect driver and gaze behaviour, we designed a new experimental study to compare the baseline condition (unlit) with four different white LED stud layouts (Figure 24). Also in this experiment, we installed the devices only along the curves and spaced 8 m apart.

4.3.1 Experimental design

Thirty-five participants were involved in the experiment including 20 males and 15 females with ages ranging from 21 to 59 (M = 30.8; SD = 9.3). To monitor the driving behaviour, we designed a driving simulation experiment following a within-subject design with LED stud layout (i.e., unlit, edge, centre, edge-centre, and lane), curve radius (120, 210, 300, and 440 m) and curve direction (left and right) as independent variables (Figure 25). To monitor the gaze behaviour, we used an eye tracker. To this aim, we designed five road scenarios in night-time conditions that were differentiated only by the LED stud layout (Figure 24). Each scenario included the four levels of curve radii and the two levels of curve direction. We adopted the same road scenario of the previous experiment, but with one key difference: this time, we displayed each curve only once instead of twice because we expanded the number of driving scenarios from three to five.

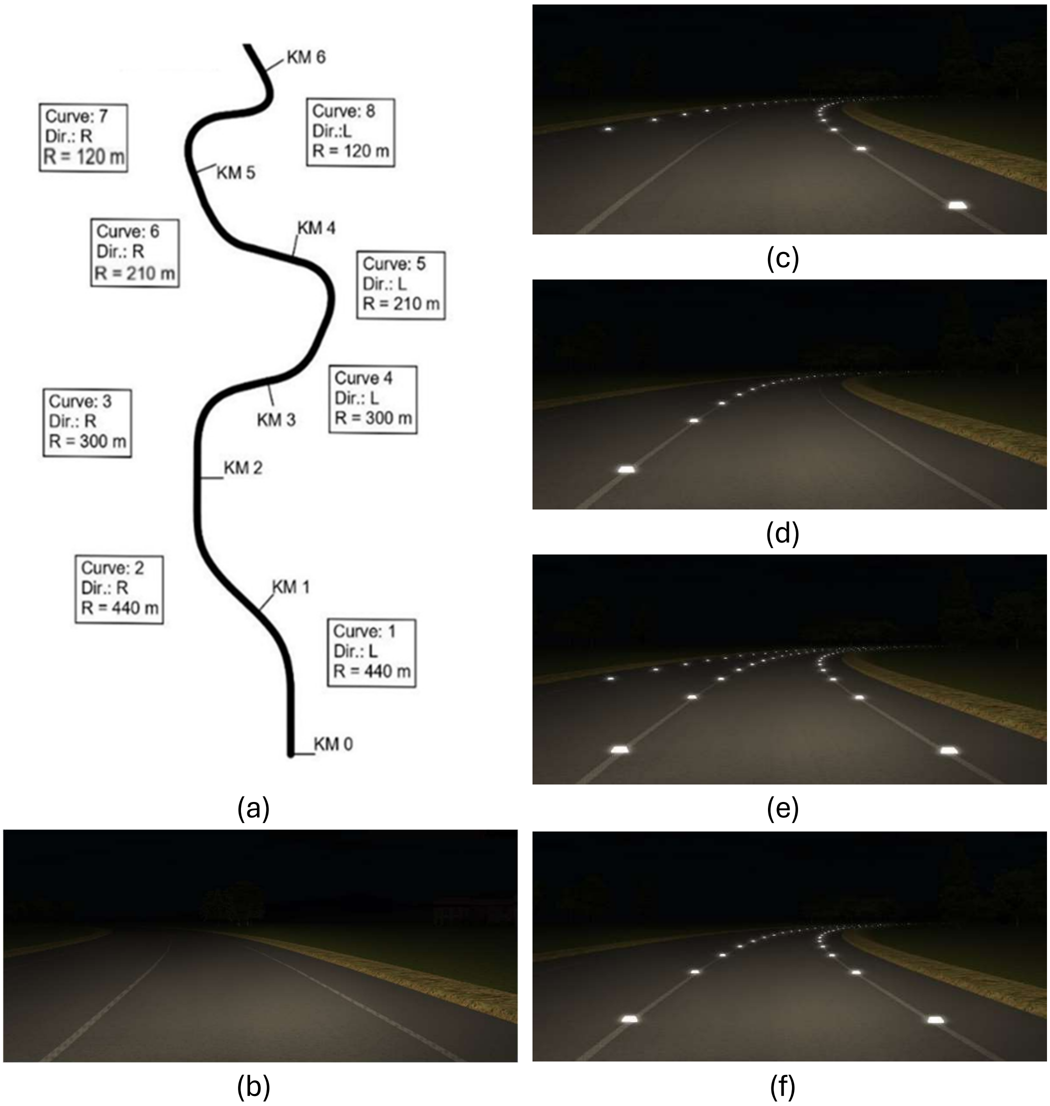
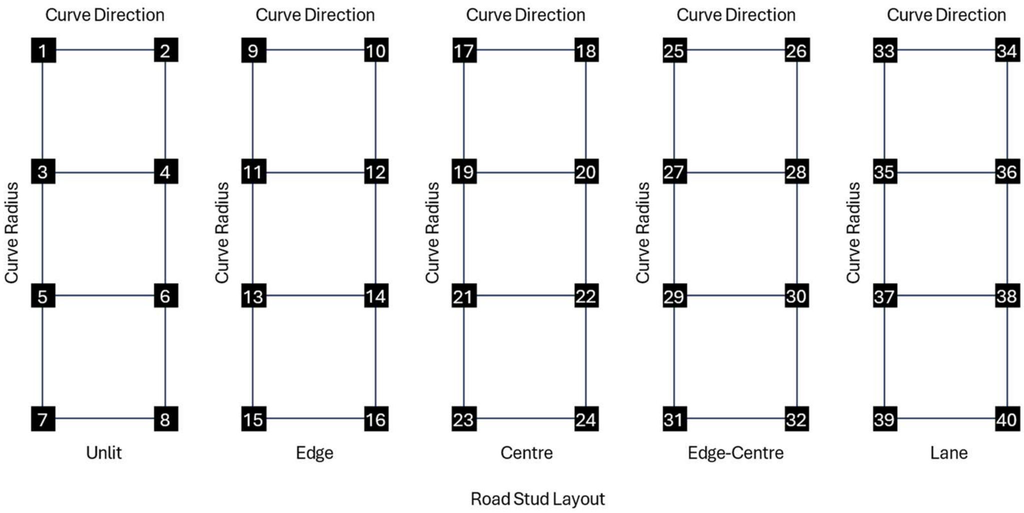


Figure 24: Road alignment (a) with the eight experimental curve (4 radii × 2 directions). Frames taken from the driver point of view representing the five experimental conditions: (b) unlit, (c) studs placed at the edge horizontal markings (edge), (d) studs placed at the central horizontal marking (centre), (e) studs placed both at the external and central horizontal markings (edge-centre), and (f) studs with the light visible in the travel direction only (lane).



Road Stud Layout	Curve Radius	Curve Direction
Unlit	120	Left
Edge	210	Right
Centre	300	
Edge-Centre	440	
Lane		

Figure 25: The 5 × 4 × 2 experimental design (Paper C).

In this within-subject experiment, each participant drove all the scenarios in a randomized order and following a complete balance. The eye tracker was calibrated before starting each driving simulation. We monitored the following independent variables for each curve of the scenario (Figure 24a): the longitudinal speed at TS (tangent-to-spiral) and CC (curve centre) termini, the lateral position at TS and CC termini, and the standard deviation of lateral position (SDLP) between TS and ST (spiral-to-tangent) termini. Moreover, to predict the driver's gaze behaviour, we hypothesized five road elements/areas that the drivers gazed to set his/her trajectory in negotiating the curve: (i) the right edge marking (RM), (ii) the centreline marking (CM), (iii) the far point (FP), (iv) the left edge marking (LM), and (v) the lane centreline (LC) (Figure 26). To obtain the data on the vision strategies adopted by each participant, for each curve, we analysed the gaze heat maps and we associated one of the five vision targets.

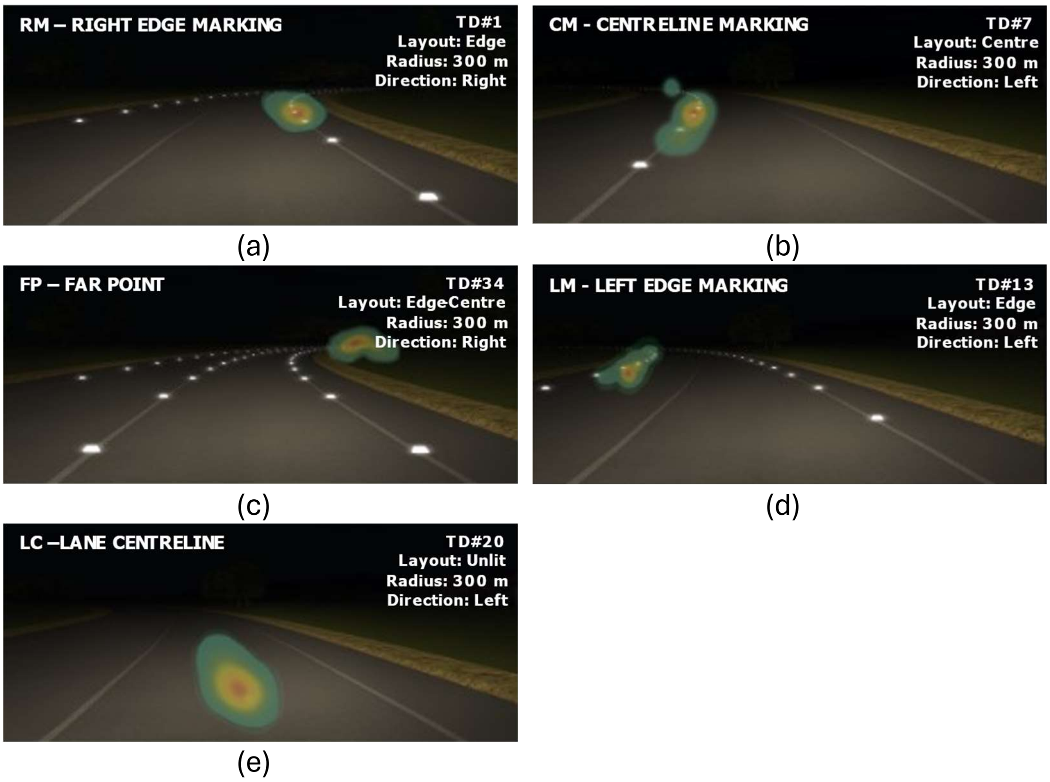


Figure 26. Examples of possible road elements/areas gazed by drivers: (a) the right edge marking (RM), (b) the centreline marking (CM), (c) the far point (FP), (d) the left edge marking (LM), and (e) the lane centreline (LC).

4.3.2 Driver and gaze behaviour

Analysis of results

The drivers' speed behaviour approaching the curves (TS termini) and in the middle curve point (CC termini) is illustrated in Figure 27. RM ANOVA revealed significant effects at the TS section due to the road stud layout ($F_{4,136}$ = 7.24, p < .001), curve radius ($F_{3,102}$ = 49.52, p < .001), and curve direction ($F_{1,34}$ = 97.17, p < .001). Additionally, the interaction between Radius × Direction had a significant effect ($F_{3,102}$ = 24.70, p < .001). Post-hoc comparisons showed speed differences between specific road stud layouts (unlit vs. edge, unlit vs. edge-centre, and centre vs. edge-centre) and curve radii (120 vs. 210, 300 and 440 m).

Similarly, at CC termini, road stud layout ($F_{4,136}$ = 9.88, p < .001) and curve radius ($F_{3,102}$ = 188.28, p < .001) significantly impacted driver speeds. Both Layout × Direction ($F_{4,136}$ = 3.09, p = .018) and Radius × Direction ($F_{3,102}$ = 5.84, p < .001) interactions were statistically significant. Post-hoc tests indicated speed variations among different road stud layouts (unlit vs. edge, unlit vs. edge-centre, unlit vs. lane, edge vs. centre, and centre vs. edge-centre) and curve radii (all possible combinations).

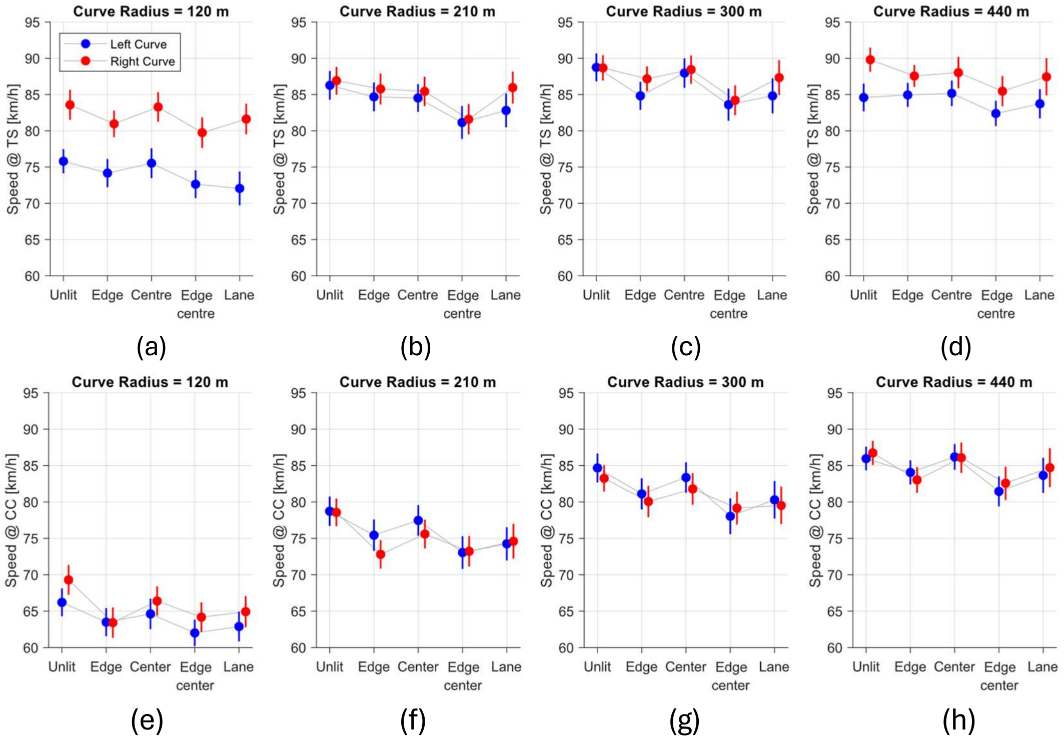


Figure 27. (a,b,c,d) Speed approaching the curve @TS termini, and (e,f,g,h) at the centre of the curve @CC termini across the four road stud layout and the reference (unlit) condition. (a,e) Curves with a 120 m radius; (b,f) curves with a 210 m radius; (c,g) curves with a 300 m radius; and (d,h) curves with a 440 m radius. In all the graphs, the symbol indicates the average value, while the error bars indicate the standard error of mean.

The drivers' lateral behaviour negotiating the curves has been measured through the lateral position at TS and CC termini (Figure 28), while the SDLP between the TS and ST termini is represented in (Figure 29).

At the TS termini section, the lateral position of drivers was significantly influenced by LED road stud layouts ($F_{4,136}$ = 25.79, p < .001), and curve direction ($F_{1,34}$ = 29.34, p < .001). However, curve radius did not have a statistically significant impact (p > .05). The first-order interactions Layout × Radius and Radius × Direction showed significant effects ($F_{12,408}$ = 1.80, p = .046; and $F_{3,102}$ = 14.10, p < .001, respectively). Additionally, the second-order interaction Layout × Radius × Direction influenced the lateral position ($F_{12,408}$ = 2.17, p = .012). The post-hoc comparisons for road stud layouts revealed significant lateral position differences (corrected-p < 0.05) between various combinations including unlit and edge, unlit and centre, edge and centre, edge and edge-centre, edge and lane, centre and edge-centre and between centre and lane.

At CC sites, both road stud layout and curve direction significantly influenced driver lateral position ($F_{4,136}$ = 63.77, p < .001; and $F_{1,34}$ = 25.99, p < .001, respectively). All first and second-order interactions, i.e., Layout × Radius, Radius × Direction, and Layout × Radius × Direction, showed significant effects

($F_{4,136}$ = 28.10, p < .001; $F_{3,102}$ = 10.78, p < .001; and $F_{12,408}$ = 2.92, p < .001, respectively). The post-hoc analyses for road stud layouts showed significant lateral position differences (corrected-p < .05) among the following pairs: unlit and edge, unlit and centre, edge and centre.

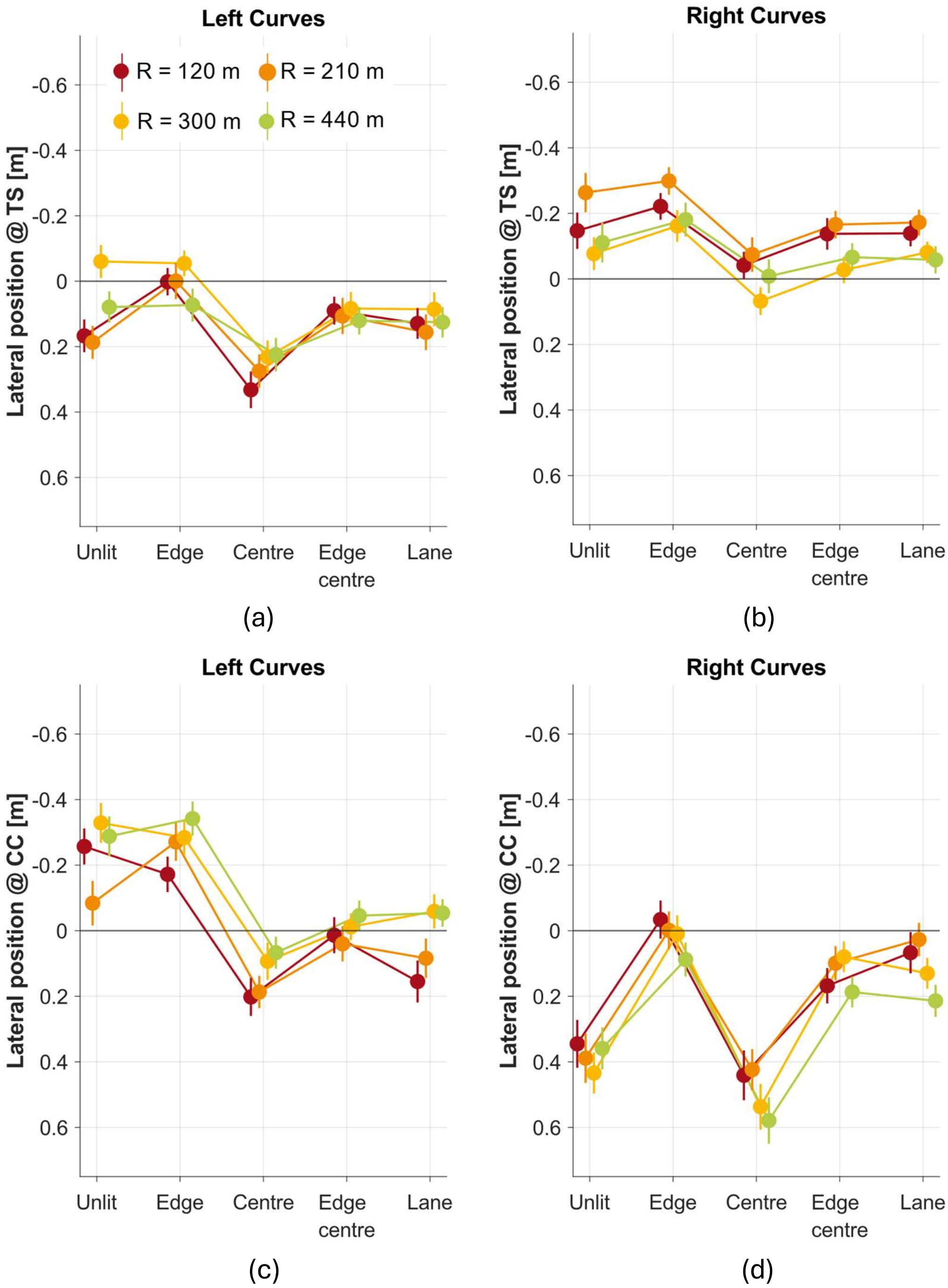


Figure 28. (a,b) Lateral position approaching the curve @TS termini, and (c,d) at the centre curve @CC termini for (a,c) left and (b,d) right curves. Negative values indicate that the vehicle CoG was on the left side of the lane centreline, while positive values indicate that CoG was on the right side of the lane centreline. In all the graphs, the symbol indicates the average value, while the error bars indicate the standard error of mean.

Figure 29 shows the results of SDLP along left and right curves. In left curves, the presence of the LED road studs improves the driver lateral control, especially along the smaller radius curves (120 and 210 m). A similar trend was also observed along right-hand curves, with the sole exception of the case related to road studs placed along the carriageway centreline, where SDLP values are within the domain of the unlit condition case for all the four investigated radii. RM ANOVA reveals that SDLP was influenced by road stud layout ($F_{4,136} = 27.99$, $p < .001$), the curve radius ($F_{3,102} = 33.25$, $p < .001$) and curve direction ($F_{1,34} = 20.14$, $p < .001$). The first order Layout × Direction interaction was also found to be significant ($F_{4,136} = 14.73$, $p < .001$). Post hoc comparisons for road stud layouts indicate significant differences (corrected-$p < .05$) between unlit and edge, unlit and edge-centre, unlit and lane, edge and centre, edge and edge-centre, centre and edge-centre, and between centre and lane. Concerning the effects of curve radii, we observed significant differences (corrected-$p < .05$) for all the possible combinations, except for the comparisons between 120 and 210 m, and between 300 and 440 m.

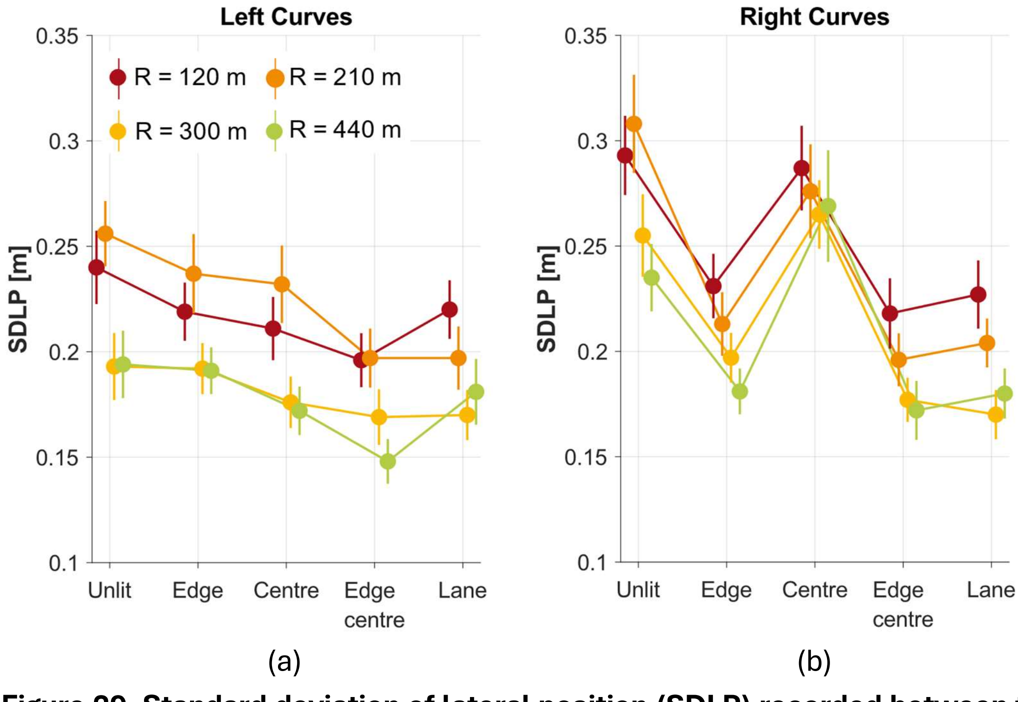


Figure 29. Standard deviation of lateral position (SDLP) recorded between the tangent-to-spiral (TS) and spiral-to-tangent (ST) termini for the different road stud layouts, curve radii and (a) left and (b) right curve directions. In all the graphs, the symbol indicates the average value, while the error bars indicate the standard error of the mean.

The gaze data were analysed conducting a multinomial logistic regression analysis to determine the predominant zone or element fixated upon by drivers when negotiating curves with different LED road stud layout, radius, and direction. The omnibus likelihood ratio test for model calibration indicated a non-significant impact of curve radius on drivers' gaze strategy (p = 0.208). Consequently, a new model focusing on layout and curve direction only was calibrated. The Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) values were lower than those of the model with the curve radius as a factor indicating a better balance between fit and complexity. The model explained 8.2% of the variance (R^2 = .082), with a highly significant global significance test (χ^2 = 241, df = 20, p < .001). While supporting the model's suitability, the limited R^2 suggests potential unaccounted factors. The predicted probability of fixating a specific area or element estimated by the model is reported in Figure 30.

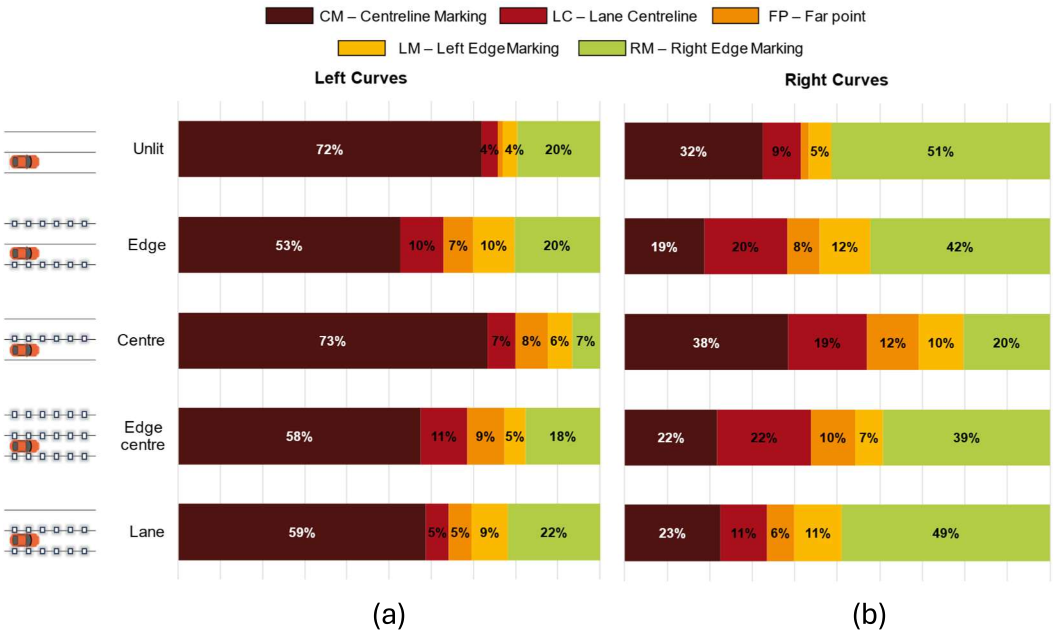


Figure 30. Predicted probability of looking at an area or element across the five different road stud layout for (a) left curves and (b) right curves. (Acronyms indicate: R.M. = right edge marking, C.M. = centreline marking, L.C. = lane centreline, L.M. = left edge marking, F.P. = far point).

Discussion of results

From the results on longitudinal behaviour, we observed significant lower speeds with 'edge-centre' and 'lane' layouts with respect to the unlit layout (the two conditions in which the driver sees the LED studs along both markings of the lane). At TS and CC termini, the edge-centre layout provided the highest and statistically significant speed reduction (mean difference of 4.2 and 5.0 km/h, respectively). We believe that the adoption of 'edge-centre' and 'lane' configurations effectively influenced drivers approaching the curve. The presence of LED studs positioned at the edge of the driving lane may have created the illusion of a slightly narrower lane, prompting drivers to reduce their speed to correctly enter and negotiate the curve. These findings imply that when both markings of the lane are LED lighted, there is an enhancement in the spatial perception of the curve entry section. This prompts drivers to adopt a more cautious behaviour when approaching the curve.

The analysis of lateral behaviour, i.e., lateral position and SDLP, revealed statistically significant differences between the two curve directions and the road stud layouts.

In left curves, when the travelling lane was delimited by a single strip of LED studs (i.e. 'edge' and 'centre'), drivers tended to shy away from the illuminated strip, similar to what Gates et al. (2012) observed when rumble strips were used (see Figure 28). When the travelling lane was delimited on the left and right by the LED studs (i.e., 'edge-centre' and 'lane') drivers tended to maintain an average lateral position closer to the lane centreline. This phenomenon is analogous to the visual "gate" effect as described by Ariën et al. (2013). The placement of road studs along the horizontal markings delimiting the lane appears to compel drivers to adhere to a centred trajectory within the lane boundaries.

On right curves, in the unlit condition drivers maintained a lateral position approximately 0.4 m further to the right than in the centre of the lane (Figure 28d). In the edge configuration, the "shy away" effect had a positive effect, as it moved drivers to the centre of the lane. In the 'centre' layout, the shy away effect worsened performance compared to the unlit condition, moving drivers even further to the right from the lane centreline (about 0.5 m). In the 'edge-centre' and 'lane' cases, the "gate" effect was evident, which had a positive influence on drivers' behaviour by allowing them to keep their trajectories centred in the lane. These observations suggest that the combination of "gate" and "shy away" effects leads to lateral position values closer to null compared to unlit conditions, especially in layouts involving 'edge', 'edge-centre', and 'lane' configurations.

These findings align with previous research (Portera et al., 2023), which explored different lateral behaviours in left and right curves with the 'edge' layout. Consistently with earlier experiments, it was found that the effectiveness of the 'edge' layout varied based on curve direction, with a positive impact only on right curves (trajectories close to the lane centreline). Additionally, these results match with studies by Shahar et al. (2018) and Shahar & Brémond (2014), which demonstrated improvements in lateral position with the 'edge-centre' layout on both left and right curves.

According to the SDLP outcomes (Figure 29), 'edge-centre' and 'lane' layouts are associated with the smallest values. In other terms, when the lane is delineated with LED road studs on both sides, the driver significantly improves the lateral control with respect to the unlit condition. Conversely, with the LED studs along the central marking only, the driver deteriorates his/her lateral control with SDLP values like those recorded in unlit conditions, in particular along right curves.

Finally, the results for lateral position showed safer behaviours when drivers drove along curves with layouts where the lane is fully delineated by LED road studs, i.e., the 'edge-centre' and 'lane' layouts. In these conditions, the lanes were perceived to be narrower (due to the 'gate effect') and drivers reduced their speed to approach the curve and adopted a more central trajectory due to the reduced perceived lateral space.

The gaze behaviour depicted in Figure 30a show that along left 'unlit' curves drivers predominantly (72% of cases) directed their gaze toward the centreline marking (CM), suggesting the use of the tangent point mechanism for negotiating these curves (Land & Lee, 1994), with other road elements or zones being less frequently utilized. Moving from the 'unlit' condition to the 'edge' condition, it can be seen that the percentage of individuals who focused their gaze on CM decreased, this is because in the edge condition, the central marking was not illuminated by LED stud and some drivers were attracted by the presence of LED at the edges of the road, thus choosing to change their gaze from CM to other road elements/zones. The centre layout significantly influenced drivers to focus on the CM, particularly those who initially used the same gaze target in the unlit condition. This indicates that LED road studs influenced gaze behaviour for some drivers, while others maintained their original gaze in unlit conditions. However, edge-centre and lane layouts showed substantial divergence in fixated elements, likely due to multiple visual guidance options.

For right curves in unlit conditions (Figure 30b), the primary gaze target was the right marking (RM) for 51% of cases, activating the tangent point mechanism. However, the CM target was also gazed by a relevant percentage of drivers (32%). Upon transitioning from unlit to edge layout, drivers who initially used the CM as gaze target shifted their gaze behaviour to look at the RM and LM, corresponding to the areas where studs were installed. In the case of the centre layout, percentage of drivers who looked at CM increased significantly (almost two out of five). Finally, as for left curves, the edge centre and lane layouts offered a diversified range of gaze behaviours, with an increment of those who adopting the tangent point mechanism oriented the gaze towards the right marking (RM).

In summary, the results suggest that drivers' gaze behaviours are only partially influenced by LED road stud layouts. Some drivers maintain their gaze on non-illuminated elements of the road space, while others exhibit changes in behaviour that lack a clear explanation. These findings indicate a potential oversight in considering various factors influencing drivers' decisions on where to look along a curve. The complex nature of human behaviour, underlying subjectivity in decision-making during steering, further complicates this matter (Lappi et al., 2013). Along the roadway, both intrinsic and extrinsic factors contribute to shaping driver gaze behaviour. Achieving measures that standardize gaze patterns uniformly proves challenging, even in low-visibility scenarios like the dark driving experiment conducted in this study. Despite the limited visibility of road elements, the complexity of gaze behaviour persists.

Taken as a whole, the findings suggest that, from a behavioural standpoint, both the 'edge-centre' and 'lane' layouts facilitate maintaining centred trajectories along curves and the control the vehicle. Further, this study has allowed to conclude that there is not a specific zone that drivers gazed to set their trajectory along the curve. We believe that the presence of LED studs on both the left and right sides of the lane (as in the case of 'edge-centre' and 'lane' layouts) could support a broader range of drivers, providing more cues to establish their curve trajectory, as demonstrated by the lateral position and SDLP values.

Finally, it is important to acknowledge the absence of oncoming traffic along the horizontal curves as a limitation of the study. The light emitted by oncoming vehicle beams could alter the ambient luminance, which is primarily influenced by the LED road studs, potentially affecting driver behaviour and perception.

Chapter 5

Innovative lighting technologies for urban roads

This chapter shows the experimental outcomes obtained with the implementation of the LED strip crossing on mid-block crosswalks. This research investigated the effects of the LED strip on the interaction between drivers and pedestrians. A first experiment has been conducted in normal driving conditions (**Paper D**), while another experiment has been conducted in distracted driving conditions (**Paper E**).

5.1 Background

In urban settings, pedestrian fatalities represent the 36% of the total road-related deaths (European Road Safety Observatory, 2022). Most accidents typically happen between pedestrian and vehicles around crosswalks. At controlled crosswalks traffic lights govern the flow of traffic and ensure pedestrian safety. In contrast, uncontrolled crosswalks rely on drivers yielding the right of way to pedestrians. Despite these established regulations, the variability of driver behaviour (prudent vs. aggressive) contributes to a higher incidence of accidents at uncontrolled crosswalks. Moreover, in night-time conditions also the visibility and lighting play an important role in increasing the likelihood of accident.

To address these issues, the implementation of smart crosswalks able to alert drivers of the presence of a crossing pedestrian can contribute to safer interaction.

In this context, some researchers have already investigated the effects of smart crosswalk for longitudinal and transversal behaviour, the yielding rate, and the driver-pedestrian interaction using surrogate safety measures. Patella et al., (2020) introduced a crosswalk illuminated with LED panels, consisting of nine panels in total (see paper D for further details), resulting in a 19.3% decrease in the average speed of vehicles, thereby mitigating the risk of conflicts. Another solution has been proposed by Lantieri et al., (2021) using flashing in-curb LED strips and beacons, which significantly enhanced the yield compliance and extended the distance at which pedestrians were detected. The effectiveness of smart detection-based in-pavement LED light units was assessed by Hussain et al. (2021, 2023). The system alerted drivers with a red light upon detecting pedestrians. Authors observed a positive impact on yielding rates and a reduction in the severity of vehicle-pedestrian conflicts. Additionally, augmented reality (AR) technologies integrated into vehicles have been utilized to enhance drivers' awareness of pedestrian presence (Calvi et al., 2020).

In these experiments, the impact of a red LED strip designed to alert drivers to the presence of pedestrians was investigated. The LED was activated when a pedestrian occupied the zebra crossing area, and conversely, turned off when the pedestrian left the area (Figure 33).

5.2 Driver pedestrian interaction in controlled driving conditions

This study aimed to investigate the impact of LED strip crossings on driver behaviour and workload in controlled driving conditions (i.e., not distracted). The experiment involved testing two different types of LED strips, differing only in the mode of light emission. In the first configuration, the light remained fixed, while in the second configuration, the light flashed at a frequency of 2 Hz. The efficacy of this technology was evaluated across two road sections, including one lane and two lanes per direction in urban areas. Additionally, the study examined driver-pedestrian interactions at different time intervals, specifically when the driver was 4, 6, and 8 seconds away from the pedestrian.

5.2.1 Experimental design

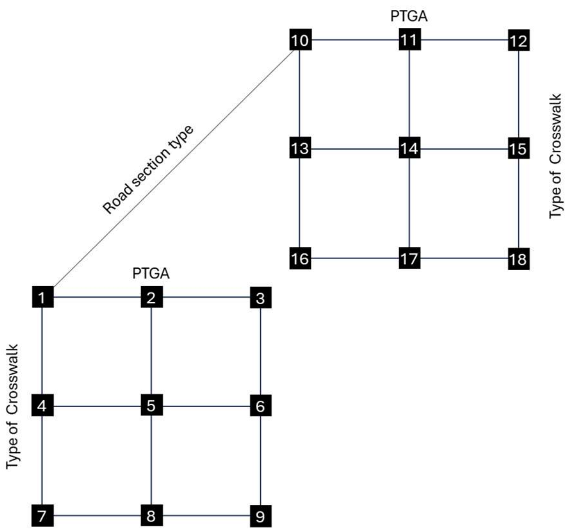
Thirty-six participants were involved (11 females), whose ages ranged from 24 to 51 years, with an average age of 30.7 years and a standard deviation of 6.6. The drivers had a valid Italian driving license.

The experiment followed a within-subject design with type of crosswalk (3 levels: conventional, fixed LED, and flashing LED), pedestrian time gap acceptance *PTGA* (2 levels: 4, 6, and 8 s), and road Section (2 levels: one lane and two lanes per direction) as independent factors (Figure 31). PTGA refers to the time that a pedestrian is willing to wait for a safe opportunity to cross a road in the presence of oncoming vehicles. This variable allowed us to set the distance in time at which the pedestrian started to cross the road with respect to the vehicle.

To combine the three experimental factors, we designed three road scenarios in nighttime conditions that differed by the type of crosswalk. The scenarios were designed to simulate an urban road environment with a posted speed limit of 50 km/h and comprising three segments: two two-lane sections (one for each direction) and one four-lane section (with two lanes per direction separated by a median), for a total length of 7.3 km (Figure 32). Following the Italian standard on geometric design of roads (MIT, 2001), lane widths were set at 3.0 m for the two-lane sections, and 3.5 m for the four-lane section (Figure 35). The horizontal and vertical signs adhered to the rules of the Italian Highway Code (1993). To recreate a realistic urban setting, the scenarios included vehicles and pedestrians moving within the environment without interfering the driving experience.

We included three crosswalks on the section with one lane for direction that were crossed by pedestrian with PTGA 4 s, 6 s, and 8 s (Figure 34). Further, other three crosswalks were included on the section with two lanes for direction, again crossed by pedestrians with PTGA 4 s, 6 s, and 8 s. The crosswalks were presented in a random order. Finally, for each of the three scenarios, each driver encountered 6 pedestrian crossings (2 cross sections × 3 PTGA).

In all cases, the pedestrian consistently crossed from the right side of the road, concealed by a parked car. This is a critical situation for the driver, as the pedestrian is closer to the vehicle when intending to cross. As a result, the driver has less time to react than if the pedestrian was crossing from the left. In addition, being the pedestrian concealed, the driver has even less time to react as they are spotted later. Along the scenario, other crosswalks have been added with or without pedestrians crossing, with the aim of confusing the driver and creating unpredictable situations.



Trial	Type of Crosswalks	PTGA [s]	Road section type
1	Conventional	4	One lane
2	Conventional	6	One lane
3	Conventional	8	One lane
4	Fixed LED	4	One lane
5	Fixed LED	6	One lane
6	Fixed LED	8	One lane
7	Flashing LED	4	One lane
8	Flashing LED	6	One lane
9	Flashing LED	8	One lane
10	Conventional	4	Two lanes
11	Conventional	6	Two lanes
12	Conventional	8	Two lanes
13	Fixed LED	4	Two lanes
14	Fixed LED	6	Two lanes
15	Fixed LED	8	Two lanes
16	Flashing LED	4	Two lanes
17	Flashing LED	6	Two lanes
18	Flashing LED	8	Two lanes

Figure 31. The 3 × 3 × 2 experimental design (paper D).

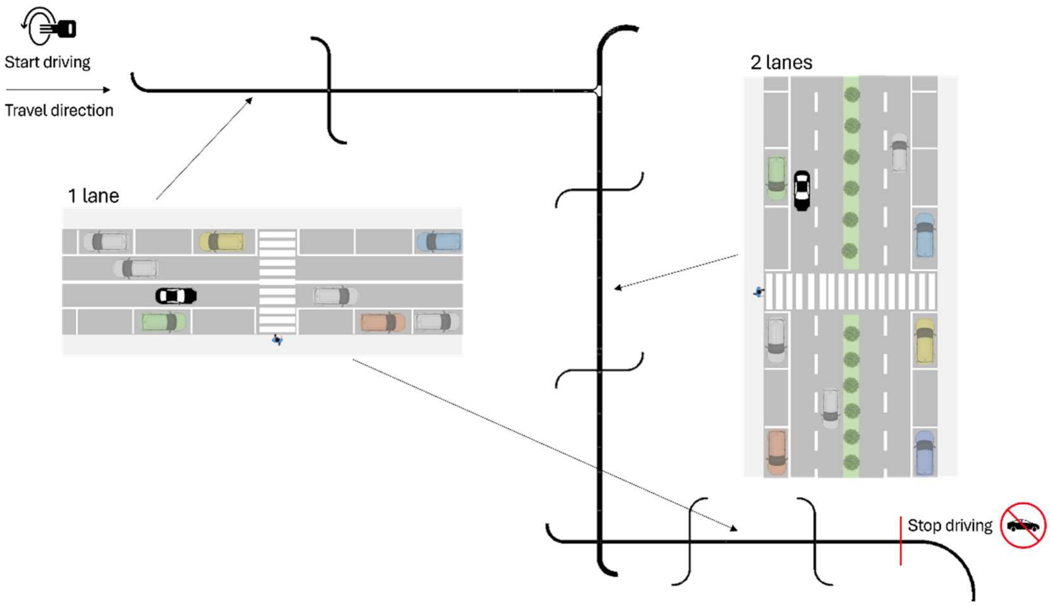


Figure 32. Plan scheme of the urban road scenario.

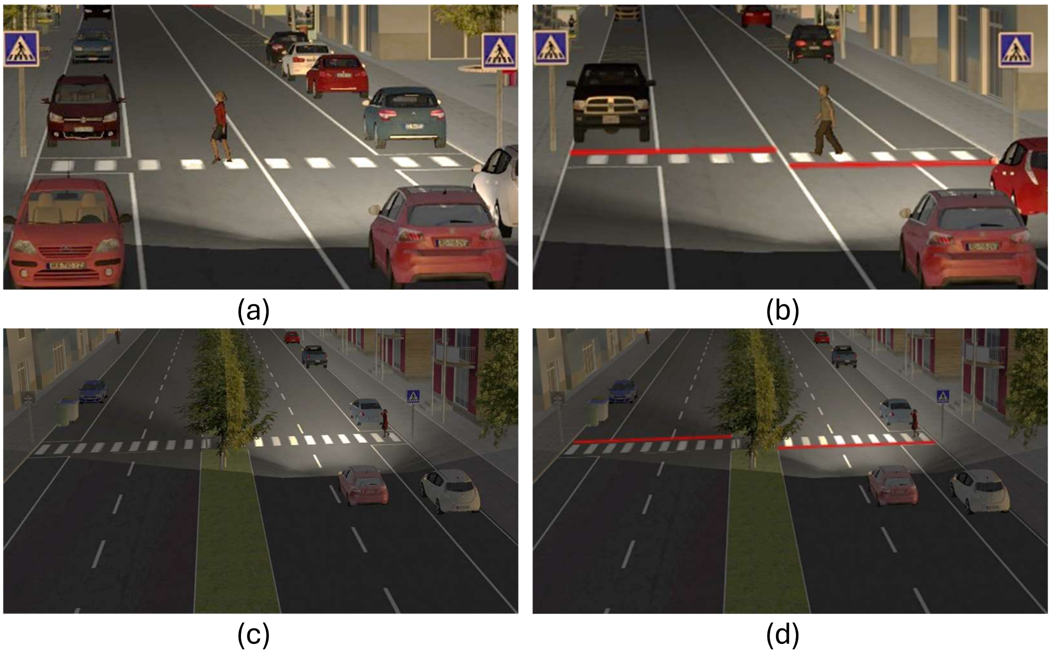
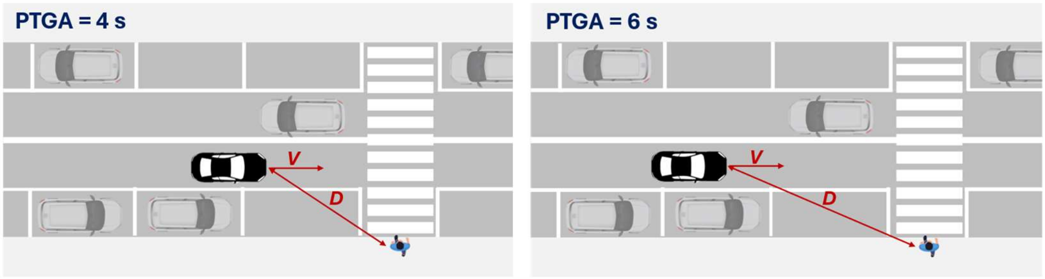
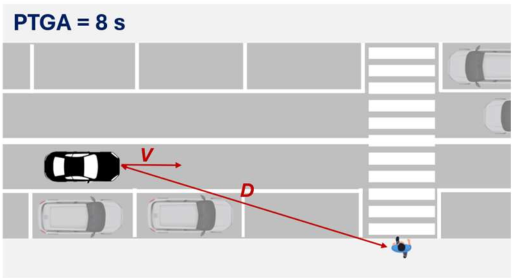


Figure 33. Comparison of crosswalk configurations: (a) conventional one-lane crosswalk, (b) smart crosswalk with fixed/flashing lighting for a single lane, (c) conventional two-lane crosswalk, and (d) smart crosswalk with fixed/flashing lighting for two lanes.



(a) (b)

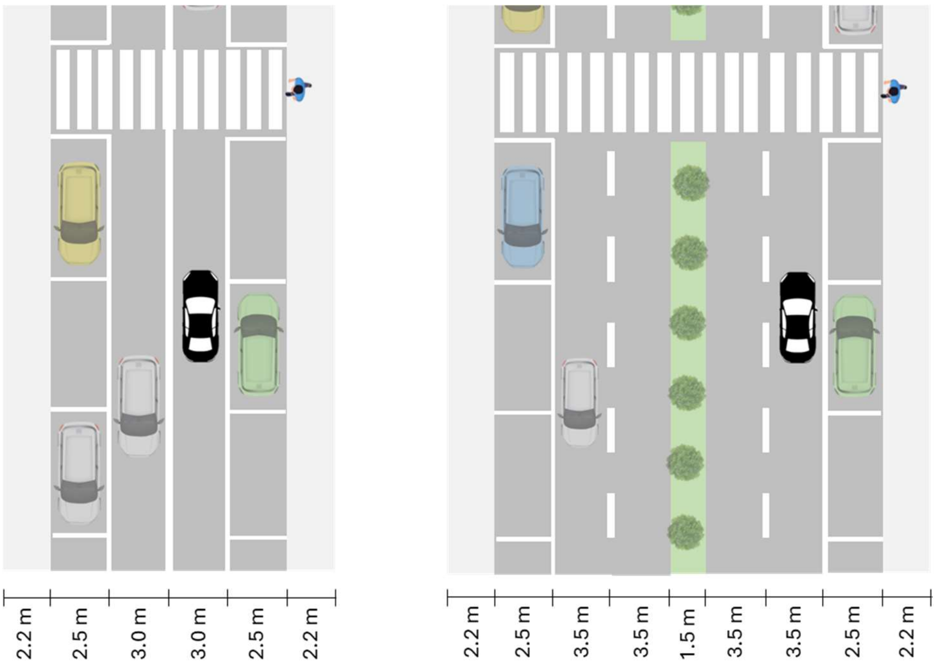


$$PTGA = \frac{D}{V}$$

D: is the distance to the approaching vehicle (in meters),
V: is the speed of the approaching vehicle (in meters per second).

(c)

Figure 34. Pedestrian crossing events triggered with different PTGA values. When the PTGA values, calculated in real time, reached 4 s, 6 s, and 8 s respectively, the pedestrian was activated, initiating the crossing of the road.



(a) (b)

Figure 35. Geometric characteristics of the cross section for (a) single lane and (b) two lanes.

In each driving simulation, various parameters were observed, including (i) the maximum speed of the vehicle recorded 100 meters before the crosswalk, (ii) the distance at which the driver reacts to the presence of the pedestrian (reaction distance) by using the brake pedal, (iii) the minimum time-to-collision (MTTC) between the vehicle and pedestrian, and (iv) the post encroachment time (PET). The impact of LED strips on subjective workload was also assessed using the NASA-TLX questionnaire.

The MTTC is the minimum time remaining before a potential collision between two moving entities following their intended paths with consistent speeds and trajectories (Hayward, 1971). For our study, a MTTC of 3 s was used to distinguish situations where drivers unintentionally enter a hazardous state (conflict) from those where drivers maintain control. PET signifies the time difference between a dynamic entity leaving the encroachment area and another entering the same space (Peesapati et al., 2018). PET can be categorized into (i) undisturbed passage for PET ≥ 5 s, (ii) conflict for 0 < PET ≤ 5 s, and (iii) crash when PET = 0 s, based on Angioi & Bassani, (2022).

5.2.2 Driver behaviour, interaction with pedestrians and workload

Analysis of results

The RM ANOVA revealed that the maximum speed recorded in segment of road 100 m before the crosswalk (Figure 36) was significantly influenced by the type of crosswalk (p = .033), the PTGA (p = .038) and the road section type (p < .001). However, with the Bonferroni multiple comparisons we did not find any statistical differences between the conventional and fixed LED crosswalk and between the conventional and flashing LED crosswalk. The interaction between type of crosswalk and road section type was also significant (p = .028).

The reaction distance (Figure 37) exhibited significant influences from both road section type (p = .028) and PTGA (p < .001). In addition, the interaction type of crosswalk × cross section and type of crosswalk × PTGA also statistical effects on reaction distance (p = .017 for cross section interaction and p = .006 for PTGA interaction). Post-hoc analysis further revealed significant differences in the road section with two lanes, particularly between conventional crosswalks and fixed LED crosswalks, as well as between conventional crosswalks and flashing LED crosswalks.

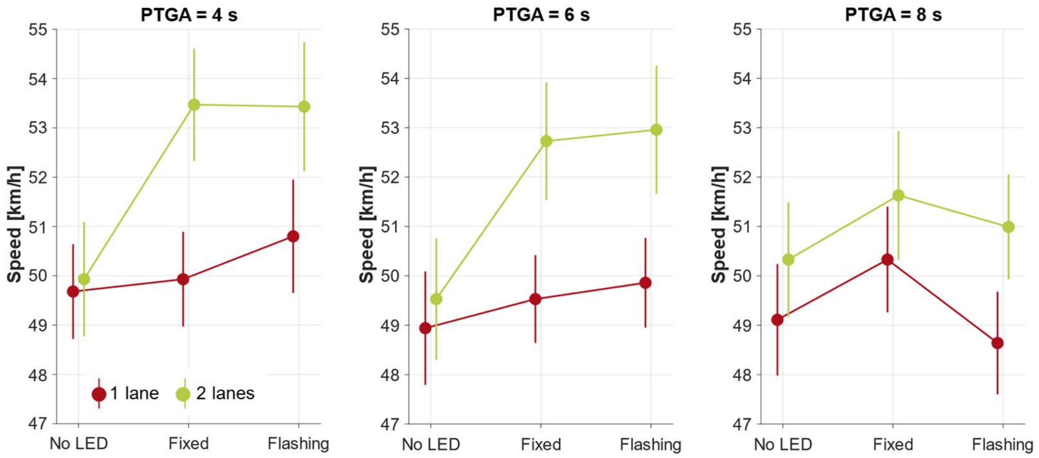


Figure 36: Maximum recorded speeds in the 100 m leading up to the crosswalks. Graphs have been separated for PTGA values of 4, 6, and 8 s. Bars represent the standard error of the mean (SEM).

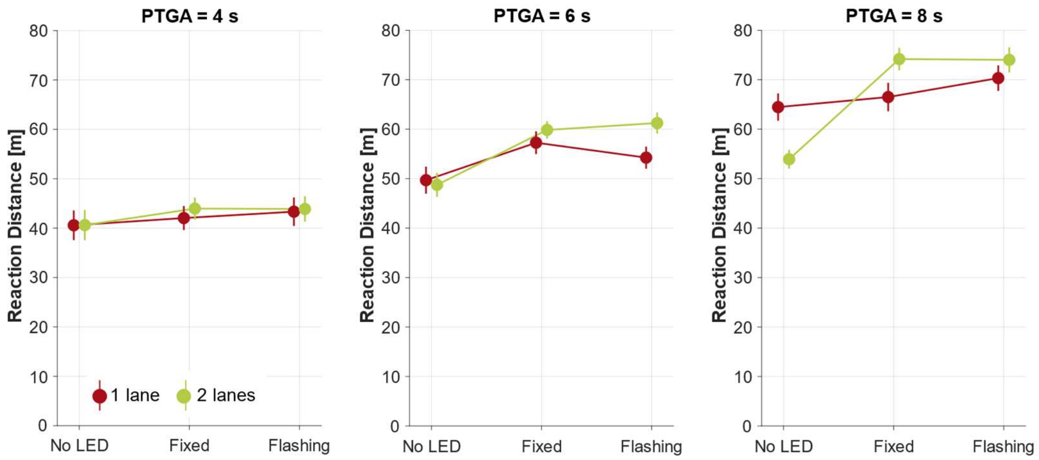


Figure 37: Reaction distance (the distance at which the driver reacts to the presence of the pedestrian by action on the brake pedal). Graphs have been separated for PTGA values of 4, 6, and 8 s. Bars represent the standard error of the mean (SEM).

The MTTC (Figure 38) exhibited a significant dependence on the type of crosswalk (p = .003). Post-hoc analysis confirmed statistical differences between the conventional crosswalk and both the fixed and flashing LED crosswalks. However, no significant differences were observed between the fixed and flashing LED crosswalks. Additionally, the PTGA also exerted a significant influence on MTTC ($p < .001$). The post-hoc test unveiled differences in vehicle-pedestrian interactions with PTGA of 4 and 6 s, 4 and 8 s, and 6 and 8 s.

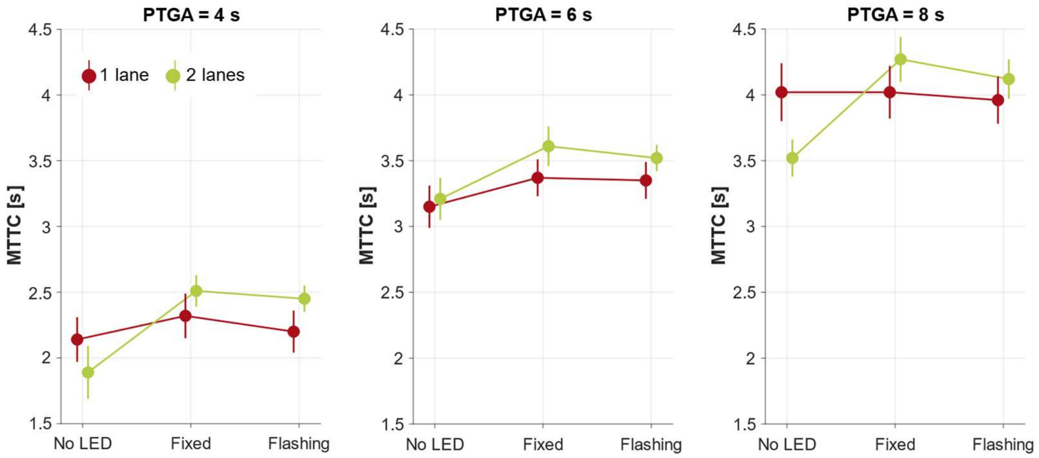


Figure 38: Minimum time-to-collision (MTTC). Graphs have been separated for PTGA values of 4, 6, and 8 s. Bars represent the standard error of the mean (SEM).

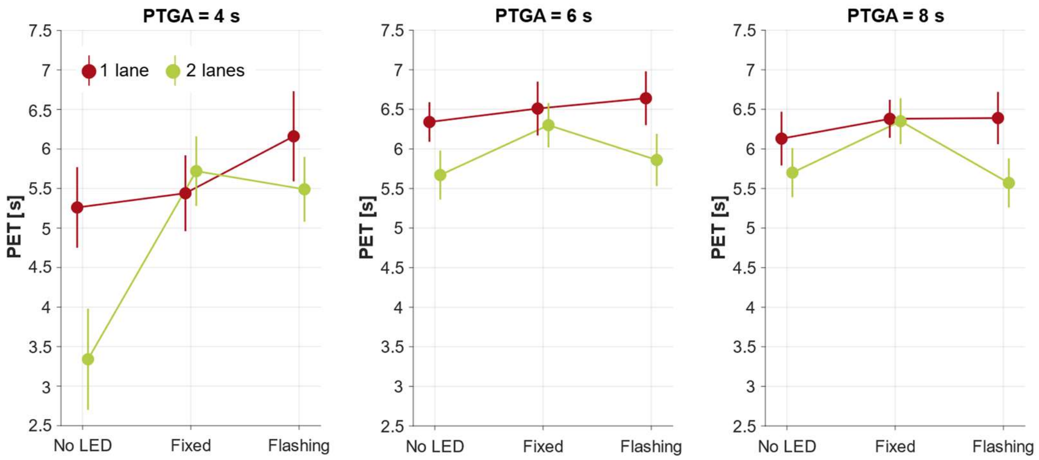


Figure 39: Post encroachment time (PET). Graphs have been separated for PTGA values of 4, 6, and 8 seconds. Bars represent the standard error of the mean (SEM).

The statistical analysis revealed that the different type of crosswalks had a significant influence of the PET values (p = .003, Figure 39). The multiple comparison revealed significant differences between conventional crosswalk and fixed LED crosswalks, and between conventional crosswalk and flashing LED crosswalks. Furthermore, cross section type and PTGA significantly influenced the PET ($p < .001$ and $p < .001$, respectively).

Finally, significant differences in workload (Figure 40) were observed through repeated measures ANOVA for various crosswalk type ($p < .001$). Post hoc analyses revealed a statistical reduction of workload in both the fixed LED condition (*p* = .001) and the flashing condition (*p* = .028) when compared to the baseline (conventional crosswalk). Importantly, there was no significant differences in workload between the fixed and flashing conditions (*p* = .338).

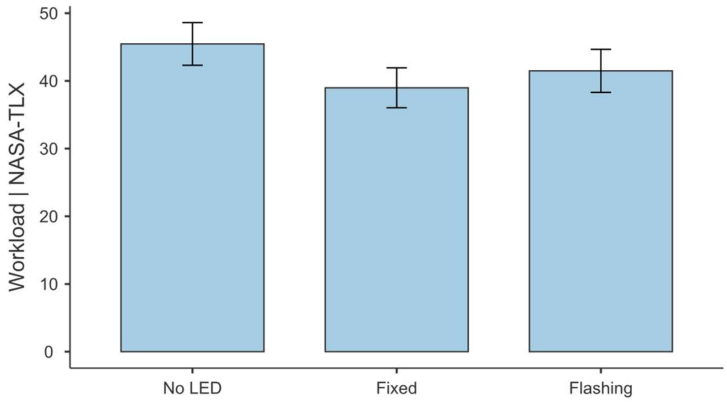


Figure 40: Subjective workload recorded with NASA-TLX in the three experimental crosswalk conditions. Bars indicate the standard error of the mean (SEM).

Discussion of results

The post-hoc comparisons suggest that in road sections both with one lane per direction and two lanes per direction, speed was not significantly influenced by the crosswalk types, and very few variations were recorded. This outcome is consistent with the research of Lantieri et al., (2021), who found no significant differences between the speeds of conventional and smart (i.e., zebra crossing lighted with white LED panels) crosswalks.

Speed was influenced by the type of road section. In road sections with two lanes per direction, speeds were higher than those with one lane per direction. With two lanes available for car movement, drivers may have felt safer due to the wider road space that can be travelled in the same direction (there is no risk of encroaching on a lane travelled in the opposite direction) leading to an increase in speed. Literature confirms that roads with more lanes are travelled at higher speeds (Bassani et al., 2014).

Concerning the PET results, we found a significant increment with the experimental conditions (i.e., fixed, and flashing LED strip). The presence of the red LED strip at the crosswalk may have discouraged drivers from promptly resuming their driving once pedestrians had cleared the portion of the crosswalk where vehicles wait for their crossing. This finding aligns with Hussain et al. (2023), who noticed that the use of the smart detection-based in-pavement LED light units (similar to the ones used in this experiment) led to a significant improvement in PET.

The higher PET with LED strip crosswalks explains the recorded average increase of speed. This could be attributed to some drivers opting to wait longer before proceeding and subsequently compensating for lost time by accelerating between successive crosswalks. Despite the slightly increase in velocity, drivers exhibited an enhanced responsiveness to stimuli generated by the LED lights, thus maintaining safe behaviour.

The results for reaction distance underline the significant influence of PTGA. Our results show a positive correlation between increased PTGA and a corresponding increase in reaction distance. Specifically, as PTGA increased, drivers demonstrated an improved ability to detect crossing pedestrians earlier, resulting in longer reaction distances (Angioi & Bassani, 2022). When examining the influence of the type of crosswalks, LED-illuminated crosswalks were found to have a positive effect on reaction distance. There was a significant increase in reaction distance with LED-illuminated crosswalks. This increased effect can be attributed to the activation of the LED strip, informing drivers of the presence of a pedestrian. As a result, drivers had the advantage of noticing the presence pedestrians earlier than with conventional pedestrian crossings. Finally, this effect was more pronounced on roads with two lanes per direction, where drivers had greater transverse mobility. This increased manoeuvrability, combined with the longer and more visible dimension of the red strips, led to an increased effect on reaction distance.

The analysis indicates an increase in the MTTC values when fixed and flashing LED strips were activated compared to the conventional crosswalk, supporting the hypothesis of reduced collision probability in vehicle-pedestrian interaction. Calvi et al. (2020) also observed increased TTC at the brake pedal pressure when highlighting pedestrian presence with augmented reality. With a PTGA of 4 s, all vehicle-pedestrian interactions resulted in conflicts (MTTC < 3 s), but the LED strip significantly increased MTTC, indicating improved safety. At PTGA 6 and 8 s, interactions no longer conflicted (MTTC < 3 s), yet the LED strip consistently raised MTTC values compared to the unlit condition. Notably, higher MTTC values were observed in the two-lane per direction segments, attributed to the increased lateral space offered to drivers. This enabled them to maintain a greater distance from pedestrians, resulting in higher MTTC.

The subjective perspective, as indicated by the lower perceived workload from the NASA-TLX questionnaire, suggests that LED strips at crosswalks are user-friendly and intuitive, making them likely to be accepted by drivers. The conveyed message is clear and facilitates a prompt response to pedestrian presence. Coupled with positive objective measures, LED strips hold potential for substantial safety improvements. The lowered mental burden on drivers allows them to allocate more attention to their surroundings, enhancing hazard detection.

Finally, our analysis found no significant differences between fixed and flashing LED strips, indicating that the type of light emission did not noticeably affect the objective and subjective driver behaviour.

These findings should be understood within the framework of two limitations. First, the analysis was restricted to scenarios where visibility of pedestrians was obstructed by parked vehicles near the crosswalk. Results may vary under different conditions. Second, the pedestrian behaviour in our study was deterministic and non-dynamic (i.e., a simulated pedestrians crossed the street through a trigger). As a result, they crossed without adjusting to the actual danger of the situation, placing the entire responsibility of collision avoidance on the driver to execute necessary evasive actions.

5.3 Driver-pedestrian interaction in distracted driving conditions

In the previous study (section 5.2), the safety benefits of employing a smart crosswalk equipped with a red LED strip under nighttime driving conditions was demonstrated. Under normal circumstances, drivers are expected to remain sufficiently attentive to detect pedestrians crossing the road, except in situations where pedestrians exhibit high risk acceptance (i.e., low PTGA). However, when drivers engage in non-driving related tasks (NDRT), the mental resources dedicated to vehicle guidance decrease to unacceptable levels (Dingus et al., 2019), thereby elevating the risks of a road accident.

Involvement in NDRT, such as mobile phone use, eating or reading, can be addressed through educational campaigns and police enforcement of stricter driving rules. Nevertheless, drivers may unintentionally find themselves engaged in NDRT such as mind wandering or engaging in conversation, which cannot be easily controlled through regulations alone. Consequently, proactive measures must be implemented to assist drivers in stopping NDRT and refocusing on the primary driving task.

In urban scenarios, the use of the LED strip could serve as a means to force drivers to divert their attention to non-driving related activities (NDRT). The red light emitted by the LED strip could act as an alarm for cognitively inattentive drivers and enables them to react quickly, thus avoiding risky conflicts.

5.3.1 Experimental design

Thirty-six participants (17 females) were involved in a driving simulation experiment, whose ages ranged from 20 to 59 years, with an average age of 28 years and a standard deviation of 10.5. The drivers had a valid Italian driving license.

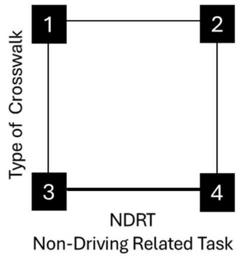
The experiment followed a within-subject design with crosswalk type (2 levels: conventional vs smart), and non-driving related task complexity (2 levels: low vs. high complexity) as experimental factors (Figure 41). The employed smart crosswalk was the same used in the previous experiment (Paper D). We designed four urban scenarios, in nighttime conditions, differentiated by the crosswalk type and the NDRT engagement. We designed a scenario with a straight two-lane (one per direction) urban street segment (~ 2.5 km long). Six crosswalks were included in each scenario, with three used as experimental and three added for confound the participant to avoid learning effect. Participants were randomly assigned three investigated crosswalks, and scenario order was varied to minimize again the learning effect. In the investigated crosswalks, pedestrians started crossing from the right sidewalk with a 4-second pedestrian time gap acceptance (PTGA), which was found to be critical as it involves severe conflicts between driver and pedestrian (Angioi & Bassani, 2022). The NDRT was applied to all crosswalks and began 200 m before each crosswalk. Drivers were intentionally distracted in all crosswalks, preventing them from anticipating pedestrian presence and influencing their behaviour.

We selected two NDRT tasks that involved vocal interactions between the driver and a research assistant. The participants were assigned two mathematical operation tasks of varying complexity levels: Low vs. High complexity. During the Low Complexity NDRT, participants mentally performed a series of two-digit arithmetic operations involving additions without regrouping (Harbluk et al., 2007). The operations were randomly selected from a predetermined set, consistent across all participants (see Figure 42a). In the High Complexity NDRT, participants mentally performed a series of two-digit arithmetical operations involving addition with regrouping. This task was combined with a memory component, where participants were required to sum the number read aloud by the researcher with the second number read in the previous operation (see Figure 42b).

The impact of the smart crosswalk on drivers engaged in NDRT was evaluated by analysing: (i) the maximum speed recorded in the 200 m preceding each crosswalk, (ii) the speed at the brake pedal pressure in response to the presence of a crossing pedestrian, (iii) the reaction distance (i.e., distance between the crosswalk and the moment at which the driver pressed acted on the brake pedal), and (iv) the minimum time-to-collision between vehicle and pedestrian.

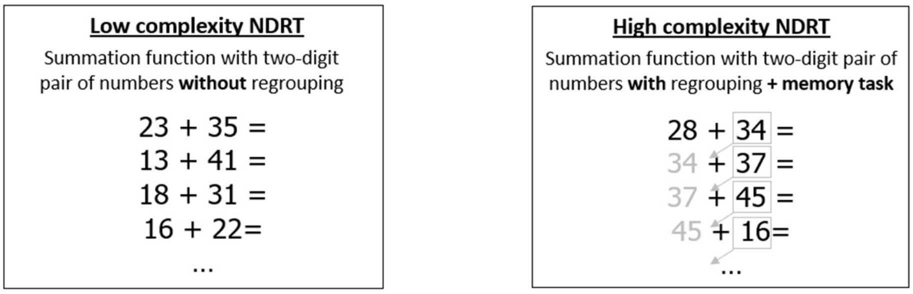
The acceptance of the smart technology was assessed by means of trust in automation (TiA) questionnaire. The TiA questionnaire consisted in 7 brief statements and 3 questions reflecting drivers' opinion about technology's uselessness and stressfulness, and level of trust in technology. The participants evaluated each item through a 7-point Likert scale. Furthermore, we also evaluated the perceived workload produced by NDRT combined with the crosswalk type with

NASA-Task Load Index (Hart, 2006). Finally, we employed the motion sickness assessment questionnaire (MSAQ; Gianaros et al., 2001) to monitor self-reported symptoms of motion sickness.



Trial	Type of Crosswalks	NDRT Complexity
1	Conventional	Low
2	Conventional	High
3	Smart	Low
4	Smart	High

Figure 41. The 2 × 2 experimental design (paper E).



(a) (b)

Figure 42. (a) Examples of mathematical operations of the low complexity NDRT. These operations involve the summation of two-digit pair of number without regrouping; (b) examples of mathematical operations of the high complexity NDRT. These operations involve the summation of two-digit pair of numbers with regrouping and memory task.

For the behavioural (i.e., maximum speed 200 m before the crosswalks, speed at brake pedal pressure, reaction distance at brake pedal pressure, and minimum time to collision) variables, we averaged out the observed values for the three crosswalks in each experimental scenario for each participant.

5.3.2 Driver behaviour, interaction with pedestrians, workload and trust in automation

Analysis of results

The maximum speed recorded in the 200 m leading up to the crosswalks (Figure 43a) was not statistically influenced by crosswalk type or NDRT. The speed recorded at the brake pedal pressure instant (Figure 43b) was significantly different between NDRT conditions (p = .002), indicating that drivers exhibited higher speeds during low complexity compared to high complexity task (M = 45.90 vs 44.20 km/h, SEM = 0.75 vs 0.82 respectively). No significant effect of crosswalk type on speed at the brake pedal pressure instant was observed. Considering reaction distance (Figure 43c), both crosswalk types (p = .012) and NDRT (p = .027) significantly influenced the results. With the smart crosswalk, the reaction distances increased compared to the baseline condition (M = 54.32 vs 50.64 m, SEM = 1.61 vs 1.50), and low complexity NDRT resulted in earlier reactions than high complexity (M = 54.18 vs 50.77 m, SEM = 1.61 vs 1.51). A noteworthy finding was the significant impact of the smart crosswalk on MTTC (Figure 43d) ($p < .001$). The smart crosswalk led to safer driver-pedestrian interactions, reflected in a higher MTTC compared to the conventional solution (M = 3.16 vs 2.88 s, SEM = 0.05 vs 0.07 respectively). NDRT complexity did not significantly affect driver-pedestrian interactions.

In assessing concurrent task performance, NDRT significantly influenced normalized correct answers ($p < .001$), with higher correct answers during low complexity NDRT compared to high complexity (M = 0.93 vs 0.81, respectively). Crosswalk technology did not have a statistically relevant impact on correct answers. The interaction term between crosswalk type and NDRT was not significant for the investigated dependent variables.

The subjective response was assessed by measuring perceived workload using the NASA-TLX and the level of trust in the smart crosswalk through the TiA questionnaire. Concerning workload, it was significantly influenced by the NDRT factor ($p < .001$). Regarding TiA, drivers indicated a reliance on the technology (M = 5.46 out of 7) and believed it would contribute to improving their driving style (M = 4.90 out of 7). General feedback from participants on the system was positive, with suggestions that the implementation of the smart crosswalk would enhance road safety (M = 6.26 out of 7). Participants classified this technology as effective (M = 5.46 out of 7) and useful (M = 5.72 out of 7). Finally, drivers reported that the smart crosswalk did not elicit high-level negative emotions (concern, M = 2.95; stress, M = 2.18) but did evoke a fair level of calmness (M = 4.08).

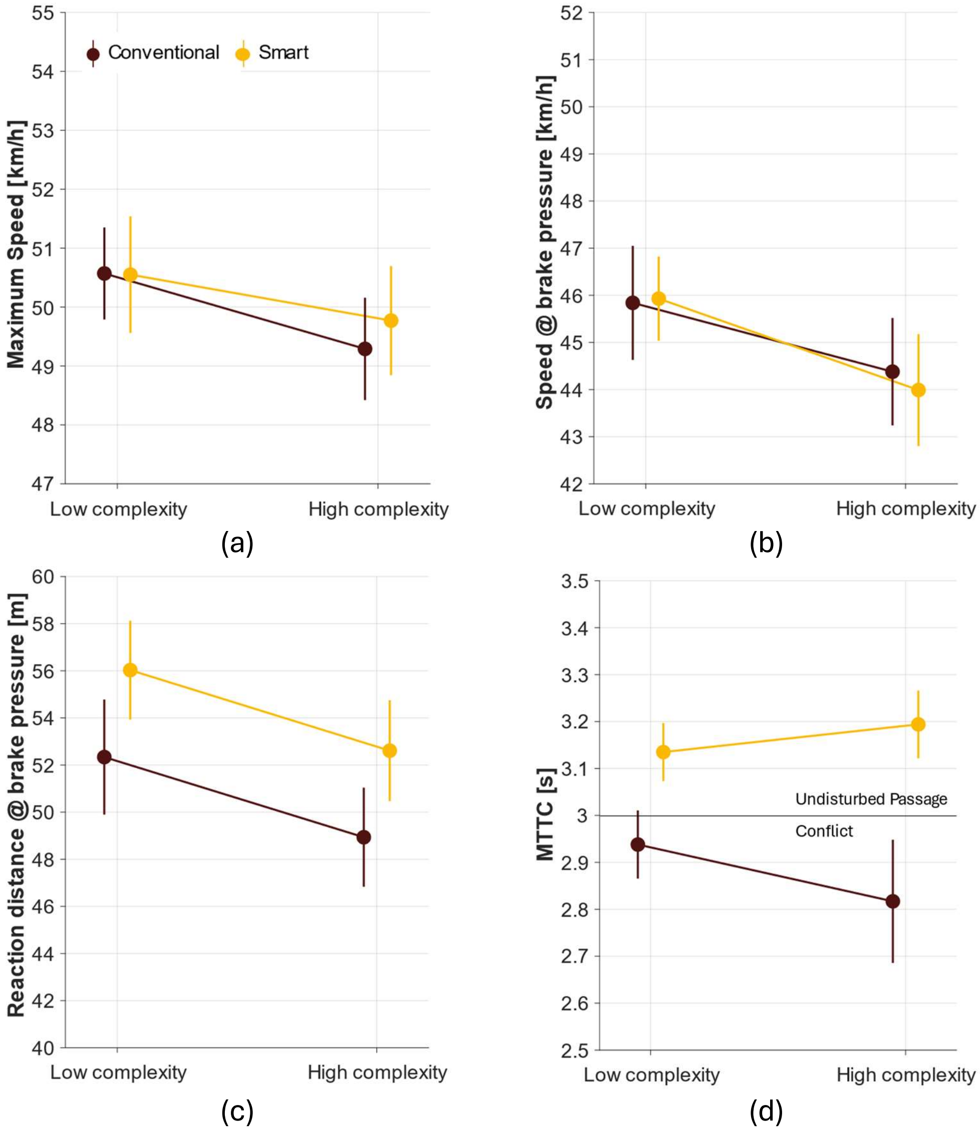


Figure 43. Driver behaviour across the four experimental conditions: 2 crosswalks (conventional vs. smart) × 2 NDRT complexity levels (low vs. high). The following metrics are represented (n = 36): (a) Average maximum speed recorded in the 200 m before the crosswalk; (b) Average speed when drivers engaged the brake pedal in response to the presence of a pedestrian; (c) Average reaction distance; and (d) Average minimum time-to-collision (MTTC); we considered a TTC of 3 s to discriminate cases where drivers unintentionally find themselves in a dangerous situation (i.e., conflict) and cases where drivers remain in control (i.e., undisturbed). Bars indicate the standard errors of the mean (SEM).

Discussion of results

When analysing the longitudinal behaviour, our results indicate that the maximum speed recorded within the 200 m before the crosswalk was not influenced by the crosswalk type and the NDRT complexity. This outcome is reasonable, as the maximum speed was likely recorded at a greater distance from the crosswalk, where the experimental factors may not have had a significant effect. This is probably due to the fact that the smart crosswalk had not yet been activated, and distraction had just been introduced. Regarding the speed at which drivers responded to the brake pedal, the presence of the smart crosswalk did not alter longitudinal behaviour, and drivers maintained similar speeds compared to the traditional crosswalk. However, the NDRT did have a significantly effect on the speed at the brake pedal, as the high-complexity task led to lower speeds. This finding suggests that drivers engaged in a risk compensation strategy, adapting to the increased complexity and perceived risk by regulating their behaviour, such as decreasing driving speed. This is consistent with previous studies (Hoogendoorn et al., 2012; Levym & Miller, 2000; Paire-Ficout et al., 2021; Wilde, 1982) that observed similar behavioural adjustments in response to increased cognitive load. Furthermore, our findings are consistent with previous research, indicating that the introduction of a secondary task can lead to a deterioration in driving performance, despite the observed reduction in speed (Shinar, 2017; Shinar et al., 2005; Strayer & Drew, 2004). In terms of driver-pedestrian interaction, our results suggest that the smart crosswalk improves safety compared to the conventional configuration. With smart crosswalks, we observed increased reaction distance and higher MTTC in both low and high complexity tasks, providing valuable insights into the safety benefits of red LED strip implementation. The presence of smart crosswalks significantly extended the reaction distance, allowing drivers to detect pedestrians earlier and react more promptly. However, task complexity negatively affected drivers' perceptions, leading to reduced reaction distances regardless of crosswalk configuration. In terms of MTTC, the smart crosswalk promoted smoother interactions with pedestrians, resulting in MTTC values consistently above 3 s. In contrast, conventional crosswalks often led to MTTC values below 3 s, indicating the threshold for conflict events (Tarko, 2020). This suggests that conventional crosswalks tend to make interactions more conflict-prone, while smart crosswalks offer a relatively safer environment for pedestrian crossings, even in the presence of NDRT. Importantly, this improvement in safety with smart crosswalks remained consistent regardless of the cognitive difficulty of the secondary task, suggesting a lower risk of driver-pedestrian interaction (lower MTTC) even under conditions of high cognitive load. This significant finding underscores the effectiveness of smart crosswalks in mitigating the negative impact of high cognitive demands on pedestrian safety. From a subjective perspective, participants positively accepted the technology, and perceived workload did not increase compared to the conventional configuration, consistent with findings by Portera & Bassani (2023). This underlines that the introduction of smart crosswalks did not increase the perceived workload of participants, thus preserving their perception and reaction capabilities. Finally, we found a favourable level of technology acceptance among drivers, with the majority finding the technology useful and satisfying to use. This suggests that drivers would be willing to use smart crosswalks, potentially realising the intended safety benefits of this technology (Horberry et al., 2017).

The same limitations as the previous study can be considered. Additionally, given that drivers performed multiple drives with the same driving task, a potential learning effect may have impacted driver behaviour in the later stages of the experiment.

In general, the four experimental studies presented represent the first attempt to validate innovative lighting technologies from a behavioural perspective. While these studies report interesting outcomes, future experiments could consider a larger number of test drivers and explore the influence of innovative lighting on the gender and age of participants. Exploring the effect on gender will help to understand the different reaction on the provided information, as well as the effect of age will help in understanding if lighting technologies have a different effect on younger and older drivers. Such efforts would strengthen and generalize the results obtained so far.

Chapter 6

General Discussion and Conclusions

The aim of this thesis was to investigate the effects of innovative lighting technologies for night-time driving conditions on driver performance, behaviour, acceptance, and safety. Two LED technologies applied to (i) road studs and (ii) strips at pedestrian crossings were specifically investigated. If LED road studs have been used to highlight the presence of horizontal curves on rural roads, LED strip at pedestrian crossings have been used to evidence pedestrians while crossing at unsignalized mid-block crosswalks along urban streets.

The research conducted on LED road studs was aimed at analysing the effects of colour (white and red), and the effects of different layouts (i.e., edge, centre, edge-centre, and lane) on driving and gaze behaviour. In both cases, the unlit condition was assumed as the baseline. The research conducted on LED strips was aimed at investigating how the technology can improve the safety of mid-block crosswalks and the driver acceptance also considering driver's cognitive distraction as a factor.

The work was conducted developing four driving simulation experiments fully descripted in Papers B, C, D, and E (see Appendices). For each experiment a statistically designed sample of participant was recruited, and dedicated road scenarios were designed to test the innovative technologies. Finally, data were statistically analysed through RM ANOVA to interpret the outcomes.

The findings of Paper B indicate that white LED road studs have the best positive impact on nighttime driving behaviour. The use of white studs resulted in a more pleasant, non-hazardous, and less alarming perception compared to unlit and red-lighted curves. This led to improved lateral control for drivers, demonstrated by a significant reduction in steering corrections and more centred trajectories. These results have significant implications for the design and implementation of safety solutions based on smart-lighting technologies, suggesting that the use of white lights may be more favourable than red ones. However, it is worth noting that an asymmetrical behaviour between left and right curves was influenced by the LED stud layout adopted, a factor that was not taken into consideration in this first study. In fact, the benefits of LED studs were predominantly appreciated along right curves.

To further explore this aspect, the impact of LED road stud layout was investigated in Paper C. In this case, we noticed that LED road stud layout controls the driver behaviour while negotiating both left- and right-hand curves. Specifically, with respect to unlit conditions, any LED road stud layout positively assists drivers in adjusting their speed approaching the curve. Furthermore, a significant impact of the layout of road studs was observed on lateral position producing 'shy away' and 'gate' effects. Additionally, although drivers exhibited various gaze behaviours while navigating the curve, the presence of road studs facilitated curve comprehension (as demonstrated by the improved lateral position and vehicle control). Some drivers directly looked at the LED studs, while others relied on peripheral vision. Nevertheless, independently of the gazed area or element for setting the trajectory, drivers were aided by these lights when LEDs were present, thus enhancing driving performance along curves. For both left and right curves, the "edge centre" and "lane" layouts emerge as optimal choices for enhancing driving performance. These layouts enable drivers to maintain a centred trajectory within the lane, thereby reducing the risk of collisions with oncoming vehicles or impacting fixed installations along the roadside.

The results indicate that white is the colour to be preferred because it is the one in which drivers perceived the least risk and the most pleasant driving. Layouts in which the 'gate' effect occurs are preferred, as they allow drivers to control their speed when entering curves and maintain central trajectories, making driving safer.

In this work, LED technology was also tested in urban streets to highlight the presence of pedestrians while crossing the road. In Paper D, the LED strips was used both in fixed and flashing, and the results highlighted that they effectively improved the objective safety of pedestrians at night. By increasing driver responsiveness, improving reaction distances, and providing an increased buffer zone for potential conflicts, LED strips prove to be a tangible and practical measure to reduce the risks of vehicle-pedestrian interactions. From a subjective perspective, the lower perceived mental workload revealed by the NASA-TLX questionnaire suggests that the LED strips at crosswalks are intuitive and user-friendly, thus they are expected to be accepted also by drivers on roads. The reduced mental workload indicates that the message conveyed is clear and helpful and encourages a prompt reaction to the presence of pedestrians. Therefore, the implementation of LED stripes at uncontrolled mid-block crosswalks is recommended as a strategy to improve pedestrian safety and promote the well-being of both pedestrians and drivers.

Paper E contributed to the understanding of the effectiveness of LED strips in mitigating the risks associated with the driver's cognitive distraction at mid-block crosswalks. Our study highlighted the effectiveness of this proactive measure where no legal restriction or educational campaign can be effective due to the inherent nature of cognitive distraction. The results provide valuable insights into the effectiveness of visual warnings (red LED strip) in promoting safer driver behaviour and improving pedestrian safety. Additionally, our research indicates a relevant level of technology acceptance among drivers.

The results obtained encourage the use of this technology because it improves responsiveness to the presence of pedestrians, making their interactions safer. Furthermore, its effectiveness in neutralising cognitively distracted driving conditions and raising the level of safety was proved. The technology was accepted by drivers through measures of workload and trust in automation. This should encourage local authorities to consider the LED technologies as a pivotal strategy for reducing the number of fatalities on urban roads.

In conclusion, the results obtained so far provide extremely positive indications regarding the effectiveness of innovative lighting technologies. The adoption of such technologies can effectively contribute to improving drivers' behavior and, consequently, raise the overall level of safety on road infrastructures. This work confirms how crucial it is to assess drivers' behavior before such technologies are installed on the road. It also highlights the importance of considering the multiple variables that may affect the success of these technologies, and emphasizes the risks associated with a lack of understanding of the effects of their introduction on the road, their incorrect installation, or an improper choice of their mode of operation. This study also showed high acceptability of the technologies by drivers. They were not perceived as harmful, dangerous, or unpopular, but on the contrary improved the driving experience, reduced agitation and were considered useful by all drivers. Furthermore, the mental workload remained at levels comparable to driving without technologies, indicating that their use does not require additional mental effort.

In general, after a preliminary investigation of the behavioural effectiveness of these smart technologies, they could promptly be implemented on our roads as proactive measure to reduce road accidents occurrence. These measures may be included within the possible interventions that the competent body can choose to mitigate the risk at high accident sites. By conducting spatial analysis, it will be possible to identify the locations with the highest accident rates and consider innovative lighting technologies as a proactive measure to reduce accidents. Additionally, a consequent before/after study can be performed in order to estimation of crash modification factors (*CFM*) to demonstrate and validate the real effectiveness of the innovative lighting technologies and facilitating the widespread adoption of these technologies on large scale.

The new challenges are undeniably tied to the adoption of innovative and smart road technologies and autonomous vehicles. In the coming years, the information provided by smart technologies will prove invaluable for drivers to react promptly and exercise better control over their vehicles. As automation progresses in vehicles, particularly reaching SAE levels 4 and 5, the information that was previously given to drivers will be transmitted to the sensors of automated vehicles, guiding them based on received information. Therefore, these technologies will be able to continue to act as a support layer for improved vehicle decision-making capabilities.

Future studies should consider the combined effects of intelligent road technologies in the context of semi-automation or full vehicle automation. In particular, the driver's ability to adapt to intelligent technologies should be carefully assessed, in view of the amount and redundancy of information he/she will have to process.

References

Ackaah, W., Apuseyine, B. A., & Afukaar, F. K. (2020). Road traffic crashes at night-time: Characteristics and risk factors. *International Journal of Injury Control and Safety Promotion*, *27*(3), 392–399. https://doi.org/10.1080/17457300.2020.1785508

Ahmed, S. K., Mohammed, M. G., Abdulqadir, S. O., El-Kader, R. G. A., El-Shall, N. A., Chandran, D., Rehman, M. E. U., & Dhama, K. (2023). Road traffic accidental injuries and deaths: A neglected global health issue. *Health Science Reports*, *6*(5), e1240. https://doi.org/10.1002/hsr2.1240

Al-Haji, G. (2014). The Impact of New Street Lighting Technologies on Traffic Safety. *Journal of Traffic and Logistics Engineering*, *2*(3). https://doi.org/10.12720/jtle.2.3.202-205

Angioi, F., & Bassani, M. (2022). The implications of situation and route familiarity for driver-pedestrian interaction at uncontrolled mid-block crosswalks. *Transportation Research Part F: Traffic Psychology and Behaviour*, *90*, 287–299. https://doi.org/10.1016/j.trf.2022.09.003

Angioi, F., Portera, A., Bassani, M., De Oña, J., & Stasi, L. L. D. (2023). Smart on-Road Technologies and Road Safety: A short overview. *Transportation Research Procedia*, *71*, 395–402. https://doi.org/10.1016/j.trpro.2023.11.100

Ariën, C., Jongen, E. M. M., Brijs, K., Brijs, T., Daniels, S., & Wets, G. (2013). A simulator study on the impact of traffic calming measures in urban areas on driving behavior and workload. *Accident Analysis & Prevention*, *61*, 43–53. https://doi.org/10.1016/j.aap.2012.12.044

Assum, T., Bjørnskau, T., Fosser, S., & Sagberg, F. (1999). Risk compensation—The case of road lighting. *Accident Analysis & Prevention*, *31*(5), 545–553. https://doi.org/10.1016/S0001-4575(99)00011-1

Bacelar, A. (2004). Definition of a Luminous Stud to Improve the Legibility of Expressway for Drivers. *Journal of Light & Visual Environment*, *28*(3), 148–151. https://doi.org/10.2150/jlve.28.148

Bassani, M., Dalmazzo, D., Marinelli, G., & Cirillo, C. (2014). The effects of road geometrics and traffic regulations on driver-preferred speeds in northern Italy. An exploratory analysis. *Transportation research part F: traffic psychology and behaviour,* 25, 10-26.

Bassani, M., Catani, L., Ignazzi, A., & Piras, M. (2018). Validation of a Fixed-Base Driving Simulator to Assess Behavioural Effects of Road Geometrics. *Proceedings of the Driving Simulation Conference 2018 Europe VR*, 101–108.

Bassani, M., Hazoor, A., & Catani, L. (2019). What's around the curve? A driving simulation experiment on compensatory strategies for safe driving along horizontal curves with sight limitations. *Transportation Research Part F: Traffic Psychology and Behaviour*, *66*, 273–291. https://doi.org/10.1016/j.trf.2019.09.011

Bella, F., Calvi, A., & D'Amico, F. (2014). Analysis of driver speeds under night driving conditions using a driving simulator. *Journal of Safety Research*, *49*, 45.e1-52. https://doi.org/10.1016/j.jsr.2014.02.007

Bhujbal, S. A., Bhosure, A. G., Sonawane, G. S., Patel, P. R., Jadhav, V. R., & Dhivare, J. (2022). Study Smart Road with Glowing Lines. *International Journal for Research in Applied Science and Engineering Technology*, *10*(4), 3238–3241. https://doi.org/10.22214/ijraset.2022.41965

Calvi, A. (2015). A Study on Driving Performance Along Horizontal Curves of Rural Roads. *Journal of Transportation Safety & Security*, *7*(3), 243–267. https://doi.org/10.1080/19439962.2014.952468

Calvi, A. (2018). Investigating the effectiveness of perceptual treatments on a crest vertical curve: A driving simulator study. *Transportation Research Part F: Traffic Psychology and Behaviour*, *58*, 1074–1086. https://doi.org/10.1016/j.trf.2018.06.002

Calvi, A., D'Amico, F., Ferrante, C., & Bianchini Ciampoli, L. (2020). Effectiveness of augmented reality warnings on driving behaviour whilst approaching pedestrian crossings: A driving simulator study. *Accident Analysis & Prevention*, *147*, 105760. https://doi.org/10.1016/j.aap.2020.105760

Castro, C., Martínez, C., Tornay, F. J., Fernández, P. G., & Martos, F. J. (2005). Vehicle distance estimations in nighttime driving: A real-setting study. *Transportation Research Part F: Traffic Psychology and Behaviour*, *8*(1), 31–45. https://doi.org/10.1016/j.trf.2004.12.001

Catani, L., & Bassani, M. (2019). Anticipatory Distance, Curvature, and Curvature Change Rate in Compound Curve Negotiation: A Comparison between Real and Simulated Driving. *98th Annual Meeting of the Transportation Research Board, Washington, DC*.

Crundall, D., & Underwood, G. (2011). Chapter 11—Visual Attention While Driving: Measures of Eye Movements Used in Driving Research. In B. E. Porter (A c. Di), *Handbook of Traffic Psychology* (pp. 137–148). Academic Press. https://doi.org/10.1016/B978-0-12-381984-0.10011-6

D'Amico, F., Calvi, A., Ferrante, C., & Ciampoli, L. B. (2022). *Validation of an Eye-Tracking System for Use in Driving Simulator Research*.

De Winter, J., van Leeuwen, P. M., & Happee, R. (2012, August). Advantages and disadvantages of driving simulators: A discussion. In *Proceedings of measuring behavior* (Vol. 2012, pp. 28-31). Utrecht: sn.

Dingus, T. A., Owens, J. M., Guo, F., Fang, Y., Perez, M., McClafferty, J., Buchanan-King, M., & Fitch, G. M. (2019). The prevalence of and crash risk associated with primarily cognitive secondary tasks. *Safety Science*, *119*, 98–105. https://doi.org/10.1016/j.ssci.2019.01.005

Dumé, B. (2008). *Intelligent paint turns roads pink in icy conditions*. https://www.newscientist.com/article/dn13592-intelligent-paint-turns-roads-pink-in-icy-conditions/

European Commission. (2021). *European Road Safety Observatory—European Commission*. https://road-safety.transport.ec.europa.eu/european-road-safety-observatory_en

European Road Safety Observatory. (2022). *Facts and Figures – Urban areas—2022*. https://road-safety.transport.ec.europa.eu/system/files/2022-07/ff_roads_inside_urban_areas_20220707.pdf

Gates, T. J., Savolainen, P. T., Datta, T. K., Todd, R. G., Russo, B., & Morena, J. G. (2012). Use of Both Centerline and Shoulder Rumble Strips on High-Speed Two-Lane Rural Roadways: Impact on Lateral Lane Position and Passing Maneuvers of Vehicles. *Transportation Research Record: Journal of the Transportation Research Board*, *2301*(1), 36–45. https://doi.org/10.3141/2301-05

Gianaros, P. J., Muth, E. R., Mordkoff, J. T., Levine, M. E., & Stern, R. M. (2001). A questionnaire for the assessment of the multiple dimensions of motion sickness. *Aviation, Space, and Environmental Medicine*, *72*(2), 115–119.

Gibbons, R. B., Guo, F., Medina, A., Terry, T. N., Du, J., Lutkevich, P. J., Li, Q., & Virginia Tech Transportation Institute. (2014). *Design Criteria for Adaptive Roadway Lighting* (FHWA-HRT-14-051). https://rosap.ntl.bts.gov/view/dot/35888

Guerrero-Ibáñez, J., Zeadally, S., & Contreras-Castillo, J. (2018). Sensor Technologies for Intelligent Transportation Systems. *Sensors*, *18*(4), Articolo 4. https://doi.org/10.3390/s18041212

Hart, S. G. (2006). Nasa-Task Load Index (NASA-TLX); 20 Years Later. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *50*(9), 904–908. https://doi.org/10.1177/154193120605000909

Hayward, J. (1971). *Near misses as a measure of safety at urban intersections*. Pennsylvania Transportation and Traffic Safety Center.

Highway Safety Manual. (2010). AASHTO.

Hoogendoorn, R. G., van Arem, B., & Hoogendoorn, S. P. (2012). A Neurofuzzy Approach to Modeling Longitudinal Driving Behavior and Driving Task Complexity. *International Journal of Vehicular Technology*, *2012*, 807805. https://doi.org/10.1155/2012/807805

Horberry, T., Regan, M. A., & Stevens, A. (2017). *Driver Acceptance of New Technology: Theory, Measurement and Optimisation*. CRC Press. https://doi.org/10.1201/9781315578132

Hristov, B. (2019). Influence of Road Geometry on Driver's Gaze Behavior on Motorways. *E3S Web of Conferences*, *97*, 01001. https://doi.org/10.1051/e3sconf/20199701001

Hussain, Q., Alhajyaseen, W. K. M., Kharbeche, M., & Almallah, M. (2023). Safer pedestrian crossing facilities on low-speed roads: Comparison of innovative treatments. *Accident Analysis & Prevention*, *180*, 106908. https://doi.org/10.1016/j.aap.2022.106908

Hussain, Q., Alhajyaseen, W. K. M., Pirdavani, A., Brijs, K., Shaaban, K., & Brijs, T. (2021). Do detection-based warning strategies improve vehicle yielding behavior at uncontrolled midblock crosswalks? *Accident Analysis & Prevention*, *157*, 106166. https://doi.org/10.1016/j.aap.2021.106166

ISTAT. (2023). *Road Accidents Year 2022—Italian National Statistics Institute*. https://www.istat.it/it/files//2023/07/REPORT_INCIDENTI_STRADALI_2022_EN.pdf

Jalil, N. Ab., Yunus, R. M., & Said, N. S. (2012). Environmental Colour Impact upon Human Behaviour: A Review. *Procedia - Social and Behavioral Sciences*, *35*, 54–62. https://doi.org/10.1016/j.sbspro.2012.02.062

Johansson, Ö., Wanvik, P. O., & Elvik, R. (2009). A new method for assessing the risk of accident associated with darkness. *Accident Analysis & Prevention*, *41*(4), 809–815. https://doi.org/10.1016/j.aap.2009.04.003

Johnston, I. R. (1982). Modifying driver behaviour on rural road curves - a review of recent research. *Australian Road Research*, (V11, Pt4).

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

Kensinger, E. A. (2004). Remembering emotional experiences: The contribution of valence and arousal. *Reviews in the Neurosciences*, *15*(4), 241–251. https://doi.org/10.1515/revneuro.2004.15.4.241

Keppel, Saufley, Tokunaga, & Violani. (2001). *Disegno sperimentale e analisi dei dati in psicologia*. Edises.

Land, M. F., & Lee, D. N. (1994). Where we look when we steer. *Nature*, *369*(6483), 742–744. https://doi.org/10.1038/369742a0

Lantieri, C., Costa, M., Vignali, V., Acerra, E. M., Marchetti, P., & Simone, A. (2021). Flashing in-curb LEDs and beacons at unsignalized crosswalks and driver's visual attention to pedestrians during nighttime. *Ergonomics*, *64*(3), 330–341. https://doi.org/10.1080/00140139.2020.1834149

Legislative Decree 30 April 1992, No. 285: Public Procurement Code. Retrieved from https://www.gazzettaufficiale.it/eli/id/1994/03/22/093A6158/sg (1993).

Lehtonen, E., Lappi, O., & Summala, H. (2012). Anticipatory eye movements when approaching a curve on a rural road depend on working memory load. *Transportation Research Part F: Traffic Psychology and Behaviour*, *15*(3), 369–377. https://doi.org/10.1016/j.trf.2011.08.007

Levym, D. T., & Miller, T. (2000). Review: Risk Compensation Literature — The Theory and Evidence. *Journal of Crash Prevention and Injury Control*, *2*(1), 75–86. https://doi.org/10.1080/10286580008902554

Lioi, A., Portera, A., Tefa, L., Hazoor, A., & Bassani, M. (2023). Validation of a Driving Simulator for Road Tunnel Behavioural Studies. *Transportation Research Procedia*, *69*, 352–359. https://doi.org/10.1016/j.trpro.2023.02.182

Liu, J., Li, J., Wang, K., Zhao, J., Cong, H., & He, P. (2019). Exploring factors affecting the severity of night-time vehicle accidents under low illumination conditions. *Advances in Mechanical Engineering*, *11*(4), 168781401984094. https://doi.org/10.1177/1687814019840940

Llewellyn, R., Cowie, J., & Fountas, G. (2021). Solar-Powered Active Road Studs and Highway Infrastructure: Effect on Vehicle Speeds. *Energies*, *14*(21), 7209. https://doi.org/10.3390/en14217209

Llewellyn, R., Cowie, J., & Maher, M. (2020). Active Road Studs as an Alternative to Lighting on Rural Roads: Driver Safety Perception. *Sustainability*, *12*(22), 9648. https://doi.org/10.3390/su12229648

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

National Safety Council. (2023). *Driving at Night—National Safety Council*. https://www.nsc.org/road/safety-topics/driving-at-night

Othman, S., Thomson, R., & Lannér, G. (2014). Safety Analysis of Horizontal Curves Using Real Traffic Data. *Journal of Transportation Engineering*, *140*(4), 04014005. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000626

Owens, D. A., & Sivak, M. (1996). Differentiation of Visibility and Alcohol as Contributors to Twilight Road Fatalities. *Human Factors: The Journal of the Human*

Factors and Ergonomics Society, *38*(4), 680–689. https://doi.org/10.1518/001872096778827233

Paire-Ficout, L., Lafont, S., Hay, M., Coquillat, A., Fabrigoule, C., & Chavoix, C. (2021). Relationships Between Cognitive and Driving Self-awareness in Older Drivers. *The Journals of Gerontology: Series B*, *76*(6), Articolo 6. https://doi.org/10.1093/geronb/gbaa224

Patella, S. M., Sportiello, S., Carrese, S., Bella, F., & Asdrubali, F. (2020). The Effect of a LED Lighting Crosswalk on Pedestrian Safety: Some Experimental Results. *Safety*, *6*(2), 20. https://doi.org/10.3390/safety6020020

Paxion, J., Galy, E., & Berthelon, C. (2014). Mental workload and driving. *Frontiers in Psychology*, *5*. https://doi.org/10.3389/fpsyg.2014.01344

Peesapati, L. N., Hunter, M. P., & Rodgers, M. O. (2018). Can post encroachment time substitute intersection characteristics in crash prediction models? *Journal of Safety Research*, *66*, 205–211. https://doi.org/10.1016/j.jsr.2018.05.002

Petridou, E., & Moustaki, M. (2000). Human factors in the causation of road traffic crashes. *European Journal of Epidemiology*, *16*(9), 819–826. https://doi.org/10.1023/A:1007649804201

Plainis, S. (2006). Road traffic casualties: Understanding the night-time death toll. *Injury Prevention*, *12*(2), 125–138. https://doi.org/10.1136/ip.2005.011056

Plainis, S., & Murray, I. J. (2002). Reaction times as an index of visual conspicuity when driving at night. *Ophthalmic and Physiological Optics*, *22*(5), 409–415. https://doi.org/10.1046/j.1475-1313.2002.00076.x

Plainis, S., Murray, I. J., & Charman, W. N. (2005). The Role of Retinal Adaptation in Night Driving: *Optometry and Vision Science*, *82*(8), 682–688. https://doi.org/10.1097/01.opx.0000175559.77853.45

Pompigna, A., & Mauro, R. (2022). Smart roads: A state of the art of highways innovations in the Smart Age. *Engineering Science and Technology, an International Journal*, *25*, 100986. https://doi.org/10.1016/j.jestch.2021.04.005

Portera, A., & Bassani, M. (2023). Red LED Strip Signalling Pedestrian Presence at Uncontrolled Mid-block Crosswalks. *Transportation Research Procedia*.

Razmi Rad, S., Farah, H., Taale, H., van Arem, B., & Hoogendoorn, S. P. (2020). Design and operation of dedicated lanes for connected and automated vehicles on motorways: A conceptual framework and research agenda. *Transportation Research Part C: Emerging Technologies*, *117*, 102664. https://doi.org/10.1016/j.trc.2020.102664

Rad, S. R., Farah, H., Taale, H., van Arem, B., & Hoogendoorn, S. P. (2024). The impact of the presence and utilization policy of a dedicated lane on drivers' preference to use automation and driving behaviour on motorways. *Transportation Research Part F: Traffic Psychology and Behaviour,* 103, 260-272.

Reed, N. (2006). *Driver Behaviour In Response To Actively Illuminated Road Studs: A Simulator Study. Published Project Report 143." Transport Research Laboratory, Crowthorne*.

Sazali, H., & Firdaus, I. M. (2019). Highway infrastructure: Visions & challenges in the next decades. *IOP Conference Series: Materials Science and Engineering*, *512*, 012047. https://doi.org/10.1088/1757-899X/512/1/012047

Shahar, A., & Brémond, R. (2014). *Toward smart active road studs for lane delineation*. 11.

Shahar, A., Brémond, R., & Villa, C. (2018). Can light emitting diode-based road studs improve vehicle control in curves at night? A driving simulator study. *Lighting Research & Technology*, *50*(2), 266–281. https://doi.org/10.1177/1477153516660146

Shinar, D. (2017). Distraction and Inattention. In *Traffic Safety and Human Behavior* (pp. 711–795). Emerald Publishing Limited. https://doi.org/10.1108/978-1-78635-221-720162013

Shinar, D., Tractinsky, N., & Compton, R. (2005). Effects of practice, age, and task demands, on interference from a phone task while driving. *Accident Analysis & Prevention*, *37*(2), Articolo 2. https://doi.org/10.1016/j.aap.2004.09.007

Strayer, D. L., & Drew, F. A. (2004). Profiles in Driver Distraction: Effects of Cell Phone Conversations on Younger and Older Drivers. *Human Factors*, *46*(4), Articolo 4. https://doi.org/10.1518/hfes.46.4.640.56806

Studio Roosegaarde. (2013). *Smart Highway*. https://www.studioroosegaarde.net/project/smart-highway. (accessed 10 February 2023).

Sun, L., Zhao, H., Tu, H., & Tian, Y. (2018). The Smart Road: Practice and Concept. *Engineering*, *4*(4), 436–437. https://doi.org/10.1016/j.eng.2018.07.014

Tarko, A. P. (2020). Chapter 3—Traffic conflicts as crash surrogates. In A. P. Tarko (A c. Di), *Measuring Road Safety Using Surrogate Events* (pp. 31–45). Elsevier. https://doi.org/10.1016/B978-0-12-810504-7.00003-3

Theofilatos, A., & Yannis, G. (2014). A review of the effect of traffic and weather characteristics on road safety. *Accident Analysis & Prevention*, *72*, 244–256. https://doi.org/10.1016/j.aap.2014.06.017

Toh, C. K., Sanguesa, J. A., Cano, J. C., & Martinez, F. J. (2020). Advances in smart roads for future smart cities. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *476*(2233), 20190439. https://doi.org/10.1098/rspa.2019.0439

Underwood, G., Chapman, P., Bowden, K., & Crundall, D. (2002). Visual search while driving: Skill and awareness during inspection of the scene. *Transportation Research Part F: Traffic Psychology and Behaviour*, *5*(2), 87–97. https://doi.org/10.1016/S1369-8478(02)00008-6

Varghese, C., & Shankar, U. (2007). Passenger Vehicle Occupant Fatalities by Day and Night. *A Contrast (No. HS-810 637). NHTSA's National Center for Statistics and Analysis, 1–8*, *51*(4), 443.

Veneziano, D., Ye, Z., & Turnbull, I. (2014). Speed impacts of an icy curve warning system. *IET Intelligent Transport Systems*, *8*(2), 93–101. https://doi.org/10.1049/iet-its.2012.0110

Villa, C., Brémond, R., Eymond, F., & Saint-Jacques, E. (2023). Characterization of luminescent road markings. *Lighting Research & Technology*, *55*(4–5), 459–473. https://doi.org/10.1177/14771535221111052

Villa, C., Bremond, R., & Saint Jacques, E. (2015). Visibility and discomfort glare of LED road studs. *Lighting Research & Technology*, *47*(8), 945–963. https://doi.org/10.1177/1477153514563637

Vos, J., de Winter, J., Farah, H., & Hagenzieker, M. (2023). Which visual cues do drivers use to anticipate and slow down in freeway curve approach? An eye-tracking, think-aloud on-road study. *Transportation Research Part F: Traffic Psychology and Behaviour*, *94*, 190–211. https://doi.org/10.1016/j.trf.2023.01.021

Wilde, G. J. S. (1982). The Theory of Risk Homeostasis: Implications for Safety and Health. *Risk Analysis*, *2*(4), 209–225. https://doi.org/10.1111/j.1539-6924.1982.tb01384.x

Winter, J. D., & Happee, R. (2012). *Advantages and Disadvantages of Driving Simulators: A Discussion*. https://www.semanticscholar.org/paper/Advantages-and-Disadvantages-of-Driving-Simulators%3A-Winter-Happee/b1a70385f980efd993b57142cca100d1e88672b0

Wood, J. M. (2020). Nighttime driving: Visual, lighting and visibility challenges. *Ophthalmic and Physiological Optics*, *40*(2), 187–201. https://doi.org/10.1111/opo.12659

World Health Organization. (2021). *Global plan for the decade of action for road safety 2021-2030 (No. WPR/2022/VNM/001)*. WHO Regional Office for the Western Pacific.

Yao, K., Yan, S., Li, F., Wei, Y., & Chi Tran, C. (2023). Exploring the effects of road type on drivers' eye behavior and workload. *International Journal of Occupational Safety and Ergonomics*, *29*(1), 31–35. https://doi.org/10.1080/10803548.2021.2019427

Zhu, B., Song, C., Guo, Z., Zhang, Y., & Zhou, Z. (2021). Effectiveness of Active Luminous Lane Markings on Highway at Night: A Driving Simulation Study. *Sustainability*, *13*(3), 1043. https://doi.org/10.3390/su13031043

List of Abbreviations

ADAS	-	Advanced Driver Assistance System
CAV	-	Connected and Automated Vehicles
CC	-	Curve Centre
CM	-	Centreline Marking
EU	-	European Union
FP	-	Far Point
ISTAT	-	Istituto Nazionale di Statistica
LED	-	Light Emitting Diode
LC	-	Lane Centreline
MDCI	-	Motor Vehicle Collision Investigation
MIT	-	Ministero delle Infrastrutture e dei Trasporti
MTTC	-	Minimum time-to-collision
NASA-TLX	-	NASA Task Load Index
NDRT	-	Non-driving-related Task
NSC	-	National Safety Council
PET	-	Post Encroachment Time
PTGA	-	Pedestrian Time Gap Acceptance
RSDS	-	Road Safety and Driving Simulation
RM	-	Right Edge Marking
RM ANOVA	-	Repeated Measures Analysis of Variance
SAE	-	Society of Automotive Engineers
SRT	-	Smart Road Technologies
SDLP	-	Standard Deviation of Lateral Position
ST	-	Spiral-to-Tangent
TiA	-	Trust in Automation
TS	-	Tangent-to-Spiral
TTC	-	Time-to-collision
VR	-	Virtual Reality
VRU	-	Vulnerable Road Users

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Appendices

Paper A

Smart on-Road Technologies and Road Safety: A short overview

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Abstract

Smart on-Road Technologies (SRT) are installations on the road, with which drivers interact passively, designed to reduce road accidents by increasing driving performance and/or road network sustainability. Although SRT are a core element of the future Smart Road Infrastructures, as they might significantly improve the road system, they are usually presented just as conceptual models instead of actual solutions. Consequently, evidence on the effectiveness of SRT in increasing driving performance and/or safety are scarce and not conclusive. Here, we present an overview of SRT systems (theoretical or existing) to try to identify their goals and objectives in terms of impact on road safety and driving behavior. More than 100 peer-reviewed articles on SRT, published in the last five years, were screened. Based on their impact on the road transportation system, we classified SRT into two main categories: (i) those that encourage appropriate road users' behaviors and awareness, including active and adaptive road delineator systems such as luminescent horizontal road markings, temperature-sensitive paints, or musical roads, and (ii) those able to reduce the environmental impact of the road transportation system, including technologies such as electrified priority lanes, and smart road lightning. Preliminary empirical evidence has shown the effectiveness of SRT in improving drivers' performance (e.g., vehicle lane positioning) and perceived safety. This result is based on just eight works, however. Overall, our results pointed out that SRT lack dedicated research aimed at evaluating the effects on driving performance and safety (traffic crash/injury prevention). To discourage the misuse of any new SRT, future research investigating the impact of these advanced innovations, using both simulated and real settings, is needed.

1. Introduction

In line with the European "Vision Zero" policy (European Commission, 2021), the installation of (Smart) technology on road infrastructure is a promising technique for reducing road accidents. In this context, the term Smart usually refers to technologies that self-adapt to the traffic and environmental context, aim to increase sustainability of the road network, reduce road accidents, and eliminate the negative impact of human factors on road safety (e.g., Pompigna & Mauro, 2022). In this overview, we defined on-road Smart Road Technologies (hereafter SRT) as fixed installations on the road surface with which the drivers passively interact. To date, SRT have been mostly classified into two categories based on their main functions: (i) reducing the environmental impact of the road transport system, and (ii) promoting appropriate road user behavior and awareness. For instance, while the first category includes technologies such as electrified priority lanes, and smart road lighting (Toh et al, 2020), the second one comprises active road delineator systems (e.g., luminescent markings, active road studs), and traffic sensitive markings (Zhu et al. 2021; Llewellyn et al., 2020). Even though SRT are reshaping road and city concepts (Savithramma et al., 2020), in most of cases, they are only a concept without scientific evidence supporting their effectiveness. Besides, evidence suggest new technological innovation may have a negative impact on safety due to changes in risk perception and acceptance by drivers (Wilde, 1998; 1982), and general technophobia may influence users' intention to use new technologies (Koul and Eydgahi, 2020). Thus, it is utterly relevant to understand the effects of these new technologies on drivers' behavior and attitude toward SRT.

Our overview aims to explore the existing research on SRT (theoretical and currently used) to map the current state of evidence and identify knowledge gaps for further studies. The key objectives of this work are twofold: (i) identifying the SRT and their purpose, and (ii) assessing the impact of SRTs on road safety and driving behavior.

2. Search Methodology

In this overview, we summarize the state of the art of on-road SRT reporting technologies and their evolution, their goal, impact on the road transportation system, driving behavior, performance, and acceptance. We conducted a comprehensive search including peer-reviewed articles, technical reports, and news (from websites/newspapers) in any context that included, at least, one on-road SRT. We used four electronic bibliographic databases: Scopus, ProQuest One Academic, MedLine, and Web of Science. Moreover, Google Scholar online tool was used to broaden the search. We included English and non-English (Spanish and Italian) scientific literature published before January 2023. The keywords included terms such as smart and intelligent, which are often used in the literature when referring to innovations within road technologies. Moreover, the terms active and dynamic are usually associated with technologies capable to self-adapt to different traffic situations (e.g., variability in traffic flow and/or road visibility). As we focused on technologies applied on the road surface, we included road, pavement, and horizontal terms in the search strategy. Finally, we used truncation, and phrase searching to search in a broad range of databases (e.g., smart AND (road OR pavement OR horizontal) AND (technology* OR marking*), (active OR dynamic) AND (road OR pavement OR horizontal) AND (marking*).

3. Smart Road Technology

We extracted 267 studies from the databases. After removing duplicates (n = 55), two reviewers (authors: FA and AP) independently screened 212 studies. To assess the eligibility of documents, the reviewers independently performed first a title and abstract screening, and then a full-text screening of the included records. We found 31 studies that met the eligibility criteria and were used to identify the SRT. Afterward, we assigned each SRT to the respective category according to their main goal (for a schematic representation see Fig. 1). Finally, we analyzed whether the studies included any results on drivers' behavior, performance, and acceptance using objective (e.g., speed, lateral position) and/or subjective (e.g., self-reported measures, questionnaires) indicators.

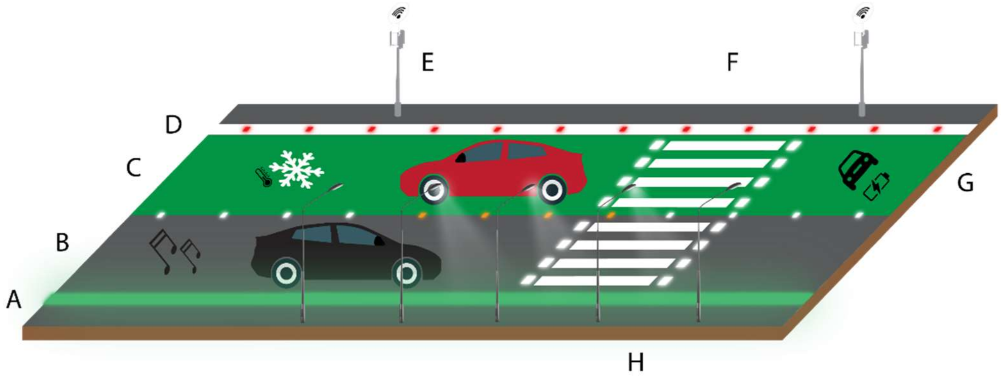

Figure 1. Schematic representations of SRT on the road surface. In this figure we represent photoluminescent road markings (A), musical roads (B), temperature-sensitive paint (C), dynamic road markings (D), multifunctional posts (E), smart crosswalk (F), electric vehicles charging lane (G), smart street lightning (H).

3.1. SRT improving sustainability of the road network

We identified four types of SRT aimed to enhance the sustainability of the road network: (i) the solar road, (ii) piezoelectric road, (iii) smart road lighting, and (iv) electric priority lanes. Most of these SRT are just proof-of-concept designs which are in development and testing phases (i.e., not currently installed on road) or employed in a few road stretches. The solar road concept combines road infrastructure with photovoltaic technology that converts sunlight into electricity to provide clean energy (Solar Impulse Foundation, 2019). This SRT can be installed on shoulders, cycle paths, car parks and urban areas, and can also empower the street lighting. Piezoelectric roads consist of piezoelectric devices and a stainless-steel substrate installed underneath the road pavement which collect the kinetic energy coming from the movement of road users (Giudici & Pèrez-Fortes, 2022). This smart energy-harvesting system is expected to reduce or eliminate the black ice problem by measuring the temperature of the road surface (Do Hong et al., 2022). Smart road lighting technology may exploit those energy sources. It can sense the environment and react accordingly by providing different lighting conditions, focusing on specific users, or illuminating specific sections of the road when a car is approaching (Mao et al., 2021; Todorović & Samardžija, 2017; Samardžija et al., 2010). This strategy saves a significant amount of electricity and is expected to improve driver visibility and reduce the number of accidents. However, while the payback in terms of energy consumption has been demonstrated for all three SRT, their influence on drivers' performance is still unclear. Finally, the increasing uptake of electric vehicles (EVs) requires the development of a charging network to support the transition to the new generation of low-emission vehicles (for a recent review, see Hemavathi & Shinisha, 2022). Therefore, SRT such as electric priority lanes will soon be introduced in the European road network, allowing cars and trucks to charge using magnetic field or contact with rail technologies (Toh et al., 2020). Nevertheless, it is worth noting that the introduction of these lanes will probably lead to an increased number of lane-changing maneuvers, but the effect on longitudinal and lateral driving behavior has not been investigated yet.

3.2. SRT encouraging safe driving behaviour

We identified four types of SRT aimed to enhance driving behavior and promote road safety: (i) active road markings, (ii) musical roads, (iii) multifunctional posts, and (iv) temperature-sensitive paints. Firstly, active road markings aim to support driver's vision in low-visibility traffic scenarios by making the horizontal markings visible beyond the vehicles' headlamps beams during the night, which represents the main improvement with respect to conventional passive (retroreflective) markings. These SRT can be divided into two categories: photoluminescent road markings, and electric luminous road markings (for a recent review see, Lin et al., 2023). Photoluminescent technology allows to produce the "glow-in-the-dark" markings by employing materials which accumulate energy during the day to release it as light at night (Bhujbal et al., 2022; Zhu et al., 2021). The results obtained with different materials are promising and this solution does not require any changes in the road structure (Villa et al., 2021; Yanqiu et al., 2020). However, factors such as daily color variations, painting formula, and temperature make it complicated to define material service life and a standard characterization methodology (Lin et al., 2023; Villa et al., 2021). On the other hand, electric luminous markings employ light emitter devices which are empowered by an electric energy supply or solar energy (Llewellyn et al., 2021; Grabinsky, 2019). Electric energy supply is mainly used by dynamic road markings, active road studs, and smart crosswalks. Dynamic road markings consist of a series of LED sensors (without painted markings) integrated with intelligent transport system devices aiming to improve traffic management and safety (Wiafe et al., 2020; Nguyen, 2018; Le Roux, 2013). Then, active road studs consist of self-illuminating LED devices applied in combination with existing painted lanes, which aim to control drivers' over-speeding behavior, improve lateral vehicle control, and provide light-based traffic guidance (Tao et al., 2022; Llewellyn et al., 2020; Shahar et al., 2018; Shahar & Bremond, 2014; Samardzija et al., 2012; Birk & Osipov, 2008). Finally, smart crosswalks aim to improve driver behavior (e.g., longitudinal speed) and the interaction with pedestrian at night. They are mainly composed of detection system (optical or integrated), and an alerting unit which mainly consists of a set of high-brightness LED (Lozano Domínguez et al., 2021; Patella et al., 2020; Lozano Domínguez & Sanguino, 2018). Although electric luminous markings are a remarkable leap forward in road safety, lightening intensity management, system reliability, and high cost of implementation and maintenance require further research (Ram et al., 2021; Villa et al., 2015a; 2015b). We identified also SRT exploiting auditory stimulus, such as musical road, to induce appropriate speed behavior and warn drivers of hazardous situations (Toh et al., 2020). Musical road technology has been mostly adopted in Japan and consists of a series of grooves and rumble strips applied to the road pavement that produce different tones as vehicle pass, depending on their speed (Zhou et al., 2018). Finally, we found other two proof-of-concept SRT, which are multifunctional posts, and temperature-sensitive paints. Multifunctional posts will wirelessly detect incoming environmental conditions and dangerous situations (e.g., passing vehicles, wildlife, and pedestrians in poor visibility conditions) and alert drivers by displaying the information on an external screen with a simple visual interface installed on the post (National Highway Authority [ANAS], 2021; Agafonovs et al., 2013). The temperature-sensitive paint is transparent under normal conditions, but becomes visible under adverse meteorological conditions (e.g., icy conditions) and reveal warning symbols on the road (Studio Roosergaarde, 2013; Dumé, 2008).

4. Effectiveness of SRT on driving behavior and road safety

In this section we present studies reporting results on the effects of existing SRT on driving behavior, performance, and acceptance, and/or road safety. We found that only 26% of the included studies (i.e., 8 out of 31) showed specific outcomes on SRT effectiveness (see Table 1). To assess the impact of the SRT studies on road safety and driving behavior, we extracted information on the population, the investigated conditions (comparison, if applicable), and the research outcomes. Four of the included studies do not report any information on population characteristics (Patella et al., 2020; Hakkert et al. 2002; Llewellyn, 2015; Llewelyn et al., 2021). When reported, the mean age of the drivers recruited was about 37 years old (SD from ±10.2 to ±11 years), with the number of participants ranging from twelve to thirty-one (Zhu et al., 2021; Shahar et al., 2018; Shahar & Bremond, 2014). Finally, Llewellyn and colleagues (2020) considered respondents to a survey older than 18 years old (Llewellyn et al., 2020). Regarding the study settings, we found three driving simulation studies, four naturalistic (on-road) studies, and one survey. Three driving simulation studies explored the effectiveness of active road markings (i.e., LED studs or continuous markings) on driving behavior showing mixed results, however. Factors such as illumination, road section, and light color were investigated (Zhu et al., 2021; Shahar et al., 2018; Shahar & Bremond, 2014). Active road studs seem to induce a similar speed along curved sections as the passive conventional markings condition, but a higher speed was detected along straight sections on rural roads (Shahar et al., 2018; Shahar & Bremond, 2014). Moreover, active LED markings induced lower speed variance than conventional markings, suggesting a positive effect on drivers' vehicle speed control (Shahar et al., 2018). However, Zhu and colleagues (2021) observed higher vehicle speeds with active road markings when compared to passive road markings along highways. Thus, results on the effect on drivers' longitudinal behavior are inconclusive. Regarding lateral behavior, active road studs were effective in improving lateral control (Zhu et al., 2021; Shahar et al., 2018; Shahar & Bremond, 2014). In addition, a comprehensive driving performance indicator combining physiological (i.e., pupil area change rate) and driving performance variables (i.e., steering wheel speed, brake pedal force, gas pedal, lane departure, speed), showed that yellow LED active road markings were more effective than white and continuous active markings along highways (Zhu et al., 2021). Finally, roads including active road studs were perceived to be safer, more comfortable, and allow better vehicle control (Shahar et al., 2018; Shahar & Bremond, 2014). Concerning the naturalistic (on-road) studies, we identified four observational studies that investigated the effects of smart crosswalks (Patella et al., 2020; Hakkert et al., 2002), and active road stud (Llewellyn et al., 2021; Llewellyn, 2015) which reported results on driving behavior and/or road safety. Smart crosswalks showed beneficial effects on driving behavior, performance, and pedestrian safety as the mean speed of vehicles was significantly decreased at the smart crosswalk with and/or without pedestrian (Patella et al., 2020; Hakkert et al., 2002). Although outcomes are promising for road safety, findings must be interpreted with caution as some results appeared to be site dependent (Hakkert et al., 2002). On the other hand, the application of active road studs on rural road and spiral-marked roundabout showed beneficial effects on driving behavior. Llewellyn and colleagues (2021; 2020) observed a positive influence on driver confidence and a significant decrease in mean speeds immediately after installation of the road studs and in low-light condition (speed limit 70 mph). However, long term beneficial effects of SRT were not demonstrated and change in mean speed by road sites and light condition were mixed both in direction and magnitude (Llewellyn et al., 2021). The implementation of active road studs on spiral-marked roundabout induced a better drivers' lane discipline (i.e., reduction in lane transgression) which means lower probability of vehicle conflicts and more predictable drivers' behavior (Llewellyn, 2015). Nevertheless, it is not clear whether this SRT can effectively reduce collisions and if the beneficial effects will be durable and sustainable.

Table 1. Review of previous studies reporting outcomes on impact of SRT on driving behaviour, performance, and acceptance and/or road safety.

SRT	Participants	Study setting	Observed indicators	Results	Ref.
Active road markings (yellow/white and stud/continuous)	N = 31 Age (M, SD) = 37.5, 10.2 years 45.2% female	Driving simulation, highway	Pupil area change rate (%) Steering wheel speed (°/s) Brake pedal force (N) Gas pedal (%) Lane departure (m) Speed (km/h)	A comprehensive indicator showed that yellow active road stud with a moderate blinking (40 times per min) was the best SRT in promoting safer driving behavior.	Zhu et al., 2021
Active road stud	N = 20 Age (M, SD) = 37.0, 11.0 years 25.0% female	Driving simulation, rural	Speed (km/h) Lane positioning (m) Crossover (s) Questionnaire (3 items)	On straights, participants drove faster with SRT, and closer to the lane centerline. Drivers also had better vehicle lateral control along curve with SRT.	Shahar et al., 2018
Active road stud	N = 12 Age (M, SD) = 37.9, 10.2 years 33.3% female	Driving simulation, rural	Speed (km/h) Lane positioning (m) Questionnaire (3 items)	Participants drove faster on straights with SRT. Drivers had better vehicle lateral control along curves with SRT, and considered this scenario safer, more comfortable and allowing better control.	Shahar & Bremond, 2014
Active road stud	ND	On road, rural	Vehicle speed (mph)	SRT was effective in reducing speed immediately after installation and in dark condition (limit = 70 mph).	Llewellyn et al., 2021
Active road stud	ND	On road, roundabout	Lane transgressions (-)	SRT reduced lane transgression rate for almost all vehicle types and maneuvers during daytime.	Llewellyn, 2015
Active road stud	N = 698 ≥18 years 35.8% female (N = 589)	Survey, rural	Survey (16 items, and open-ended questions)	Drivers reported a positive level of confidence both during hours of daylight (87%) and nighttime (52%).	Llewellyn et al., 2020
Smart crosswalk	ND	On road, urban	Speed (km/h) Deceleration (m/s2)	SRT was effective in reducing speed both with pedestrian absence, while decelerations were higher.	Patella et al., 2020
Smart crosswalk	ND	On road, urban	Speed (km/h) Yield to pedestrian (%) User conflicts (-) Pedestrian crossing (%)	Reduction in vehicle speeds near the crosswalk zone of 2–5 km/h in mean speeds, and in the conflict rates to less than 1%. Increased rate of giving way to pedestrians.	Hakkert et al., 2002

5. Conclusions

We aimed to map the existing and theoretical SRT solutions and investigate their influence on road safety and driving behavior, performance, and acceptance. The overview highlighted that most of the literature dealt with technical issues, while few studies have investigated the fallouts of these technologies on traffic operation and safety, as well as on drivers' behavior and acceptance. SRT effectiveness on driving behavior and road safety have been rarely targeted by previous research, while others are only futuristic concepts that are not yet ready to be implemented and tested. Although technological innovations such as active road markings and smart crosswalks have shown promising positive effects on driving behavior and road safety, there are few studies reporting research results, and those outcomes are not always consistent. Finally, as SRT are being slowly introduced on European public roads, it is essential to fill these gaps and avoid any costly mistakes before their widespread implementation.

References

Agafonovs, N., Skageris, A., Strazdins, G., Mednis, A., 2013. IMilePost: Embedded solution for dangerous road situation warnings, in: Proceedings - 1st International Conference on Artificial Intelligence, Modelling and Simulation, AIMS 2013. https://doi.org/10.1109/AIMS.2013.88.

Bhujbal, S.A., Bhosure, A.G., Sonawane, G.S., Patel, P.R., Jadhav, V.R., Dhivare, J., 2022. Study Smart Road with Glowing Lines. Int. J. Appl. Sci. Eng., 10(4). https://doi.org/10.22214/ijraset.2022.41965.

Bi, Y., Pei, J., Chen, Z., Zhang, L., Li, R., Hu, D., 2021. Preparation and characterization of luminescent road-marking paint. Int. J. Pavement Res. Technol., 14(2), 252-258. https://doi.org/10.1007/s42947-020-0229-3.

Birk, W., Osipov, E., 2008. On the design of cooperative road infrastructure systems, in: Proceedings of Reglermöte 2008.

Dumé, B., 2008. Intelligent paint turns roads pink in icy conditions. https://www.newscientist.com/article/dn13592-intelligent-paint-turns-roadspink-in-icy-conditions/ (accessed 10 February 2023).

European Commission, 2021. Report on the EU road safety policy framework 2021-2030 – Recommendations on next steps towards 'Vision Zero'. https://www.europarl.europa.eu/doceo/document/A-9-2021-0211_EN.html#_ section 2. (accessed 23 February 2023).

Giudici, H., Pérez-Fortes, A.P., 2022. How recent developments in smart road technologies and construction materials can contribute to the sustainability of road infrastructure. J. Infrastruct. Syst., 28(4), 02522002. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000711.

Grabinski, S., 2019. Improved visibility - Solar powered road markers on polish roads. IOP Conf. Ser.: Mater. Sci. Eng., 661(1). https://doi.org/10.1088/1757-899x/661/1/012150.

Hakkert, A.S., Gitelman, V., Ben-Shabat, E., 2002. An evaluation of crosswalk warning systems: Effects on pedestrian and vehicle behaviour. Transp. Res. F: Traffic Psychol. Behav., 5(4), 275–292. https://doi.org/10.1016/S1369-8478(02)00033-5.

Hemavathi, S., Shinisha, A., 2022. A study on trends and developments in electric vehicle charging technologies. J. Energy Storage, 52, 105013. https://doi.org/10.1016/j.est.2022.105013.

Hong, S.D., Ahn, J. H., Kim, K.B., Kim, J. H., Cho, J.Y., Woo, M. S., Song, Y., Hwang, W., Jeon, D. H., Kim, J., 2022. Uniform stress distribution road piezoelectric generator with free-fixed-end type central strike mechanism. Energy, 239(4), 121812. https://doi.org/10.1016/j.energy.2021.121812.

Koul, S., Eydgahi, A., 2020. The impact of social influence, technophobia, and perceived safety on autonomous vehicle technology adoption. Period. Polytech. Transp. Eng., 48(2), 133–142. https://doi.org/10.3311/PPtr.11332.

Le Roux, J.H., Barnard, A., Booysen, M.J., 2013. Remotely controllable wireless road stud network, in: 16th International IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC. https://doi.org/10.1109/ITSC.2013.6728323.

Lin, H., Chen, F., Zhang, H., 2023. Active luminous road markings: A comprehensive review of technologies, materials, and challenges. Constr. Build. Mater., 363, 129811. https://doi.org/10.1016/j.conbuildmat.2022.129811.

Llewellyn, R., 2015. Lighting the way: the use of intelligent road studs at spiral-marked roundabouts, in: Proceedings of the 43rd European Transport Conference, AET 2015.

Llewellyn, R., Cowie, J., Maher, M., 2020. Active road studs as an alternative to lighting on rural roads: Driver safety perception. Sustainability, 12(22), 9648. https://doi.org/10.3390/su12229648.

Llewellyn, R., Cowie, J., Fountas, G., 2021. Solar-powered active road studs and highway infrastructure: effect on vehicle speeds. Energies, 14(21), 7209. https://doi.org/10.3390/en14217209.

Lozano Domínguez, J. M., Sanguino, M., 2018. Design, modelling, and implementation of a fuzzy controller for an intelligent road signaling system. Complexity, e1849527. https://doi.org/10.1155/2018/1849527.

Lozano Domínguez, J. M., Al-Tam, F., Sanguino, M., Correia, N., 2021. Vehicle detection system for smart crosswalks using sensors and machine learning, in: 18th International Multi-Conference on Systems, Signals and Devices, SSD 2021.

Mao, G., Hui, Y., Ren, X., Li, C., Shao, Y., 2021. The internet of things for smart roads: A road map from present to future road infrastructure. IEEE Intell. Transp. Syst. Mag., 14(6), 66–76. https://doi.org/10.1109/MITS.2021.3115126.

National Highway Company (ANAS), 2021. Smart road book. https://www.stradeanas.it/sites/default/files/pdf/Smart_Book_%28eng%29.pdf. (accessed 18 February 2023).

Nguyen, T., 2018. Ahead of the curb: Smart roads, in: 2018 IEEE International Smart Cities Conference, ISC2 2018, 1–2. https://doi.org/10.1109/ISC2.2018.8656667.

Patella, S. M., Sportiello, S., Carrese, S., Bella, F., Asdrubali, F., 2020. The effect of a LED lighting crosswalk on pedestrian safety: Some experimental results. Saf., 6(2), 20. https://doi.org/10.3390/safety6020020.

Pompigna, A., Mauro, R., 2021. Smart roads: A state of the art of highways innovations in the smart age. Eng. Sci. Technol. an Int. J., 25 (2). https://doi.org/10.1016/j.jestch.2021.04.005.

Ram, M., Bhandari, A. S., Kumar, A., 2022. Reliability evaluation and cost optimization of solar road studs. Int. J. Reliab. Qual., 29(1). https://doi.org/10.1142/S0218539321500418.

Samardzija, D., Kovac, E., Isailovic, D., Miladinovic, B., Teslic, N., Katona, M., 2010. Road nail: Intelligent road marking system testbed, in: 2010 IEEE Vehicular Networking Conference, VVNC 2010. https://doi.org/10.1109/VNC.2010.5698254.

Samardzija, D., Teslic, N., Todorovic, B., Kovac, E., Isailovic, D., Miladinovic, B., 2012. Road nail: Experimental solar powered intelligent road marking system. J. Electr. Eng., 63(2), 65. https://doi.org/10.2478/v10187-012-0010-1.

Savithramma, R. M., Ashwini, B. P., Sumathi, R., 2022. Smart mobility implementation in smart cities: A comprehensive review on state-of-art technologies, in: 2022 4th International Conference on Smart Systems and Inventive Technology, ICSSIT 2022. https://doi.org/10.1109/ICSSIT53264.2022.9716288.

Shahar, A., Brémond, R., 2014. Toward smart active road studs for lane delineation, in: Transport Research Arena: Transport Solutions: From Research to Deployment-Innovate Mobility, Mobilise Innovation!.

Shahar, A., Brémond, R., Villa, C., 2018. Can light emitting diode-based road studs improve vehicle control in curves at night? A driving simulator study. Light. Res. Technol., 50(2), 266–281. https://doi.org/10.1177/1477153516660146.

Solar Impulse Foundation, 2019. Solar road: Wattway, on the road to renewable energy. https://solarimpulse.com/news/wattway-on-the-road-to-renewable-energy. (accessed 10 February 2023).

Studio Roosegaarde, 2013. Smart Highway. https://www.studioroosegaarde.net/project/smart-highway. (accessed 10 February 2023).

Tao, Z., Quan, W., Wang, H., 2022. Innovative smart road stud sensor network development for real-time traffic monitoring. J. Adv. Transp, 8830276. https://doi.org/10.1155/2022/8830276.

Todorovic, B. M., Samardzija, D., 2017. Road lighting energy-saving system based on wireless sensor network. Energy Effic., 10(1), 239–247. https://doi.org/10.1007/s12053-016-9447-6.

Toh, C. K., Sanguesa, J. A., Cano, J. C., Martinez, F. J., 2020. Advances in smart roads for future smart cities. Proc. R. Soc. A., 476(2233), 20190439. http://doi.org/10.1098/rspa.2019.0439.

Villa, C., Brémond, R., & Saint-Jaques, E., 2015a. Smart intensity management of LED road studs, in: Proceedings of 28th CIE Session, 883–891.

Villa, C., Bremond, R., Saint Jacques, E., 2015b. Visibility and discomfort glare of LED road studs. Light. Res. Technol., 47(8), 945–963. https://doi.org/10.1177/1477153514563637.

Villa, C., Bremond, R., Eymond, F., Saint-Jacques, E., 2021. Characterization of luminescent road markings. Light. Res. Technol., 1-15. https://doi.org/10.1177/14771535221111052.

Wiafe, I., Abdulai, J.-D., Katsriku, F., Kumi, J. A., Koranteng, F. N., Boakye-Sekyerehene, P., 2020. Controlling driver over-speeding with a persuasive and intelligent road marking system. Adv. Transp. St., 50, 19–30. https://doi.org/10.4399/97888255317322.

Wilde, G. J. S., 1982. The theory of risk homeostasis: implications for safety and health. Risk Anal., 2(4), 209-225. https://doi.org/10.1111/j.1539-6924.1982.tb01384.

Wilde, G. J. S., 1998. Risk homeostasis theory: an overview. Inj. Prev., 4(2), 89-91. https://doi.org/10.1136/ip.4.2.89.

Zhou, M., Huang, D., Hu, Y., Zhou, L., An, L., 2018. Musical road: design, construction and potential economic and safety benefits. Transp., 75(1),

34-42. https://doi.org/10.1680/jtran.18.00136.

Zhu, B., Song, C., Guo, Z., Zhang, Y., & Zhou, Z., 2021. Effectiveness of active luminous lane markings on highway at night: a driving simulation

study. Sustainability, 13(3), 1043. https://doi.org/10.3390/su13031043.

Paper B

The Influence of LED Road Stud Color on Driver Behavior and Perception along Horizontal Curves at Night-time

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Abstract

Scotopic lighting conditions (reduced level of natural light or presence of artificial lighting) may impair driving performance and, therefore, impact on road safety. Thanks to technological developments, low-cost light emitting diode (LED) studs are now being considered as an alternative and affordable pavement marking solution to assist drivers in these conditions. By helping them to maintain their vehicle within the marked lane, the studs should prevent any deterioration in driver performance when negotiating curves at nighttime. However, the few studies that investigated the impact of LED studs on driving performance produced inconsistent results, and the question of whether they actively improve driver performance remains open. Furthermore, while international road regulations allow the use of LED studs, they do not provide consistent prescriptions for their lighting color. Here, we assessed the influence of different LED lighting colors (red, white, and unlit) on longitudinal and transversal driver behavior when negotiating road curves with different radii and sense of direction. In the study, thirty-six drivers drove a dynamic virtual scenario featuring twenty-four curves. After the driving simulation, participants completed a static perception test in which they assessed each curve in terms of the perceived levels of risk, pleasantness, and arousal they experienced while driving on it. In comparison with the unlit and red lit curves, those marked with white lighting LED studs were perceived as less risky, less arousing, and more pleasant independently of the radii and curve direction. Furthermore, when entering these curves, participants tended to shift their driving trajectories towards the center of the road. This effect was most evident on the central part of the curve. Further studies are expected to corroborate these results by focusing on different road geometries and LED stud layouts, as well as testing driving behavior in controlled road field studies.

1. Introduction

Road fatalities per vehicle-miles driven are significantly higher at nighttime than during daytime, with a crash rate difference of around 60% (Owens & Sivak, 1996; Plainis, 2006). Furthermore, road crashes occurring at nighttime are typically more severe than those in daytime (Elvik, 1995; Goswamy et al., 2018). Consequently, the introduction of innovative solutions is of paramount importance when it comes to improving road safety while driving with reduced levels of natural light or in the presence of artificial light (i.e, scotopic lighting conditions; Babi ́c & Brijs, 2021; Bassani et al., 2022; Calvi et al., 2019; Charlton, 2007; Plainis, 2006; Raimondo et al., 2022). Light Emitting Diode (LED) technology is commanding considerable attention as a road lighting solution (Lin, Chen, & Zhang, 2023; Pagden et al., 2020; Vicente et al., 2023; Ylinen et al., 2011).

LED active road studs are among the considerable number of LED devices available on the market. The major technological advantage of these active LEDs compared to current retro–reflective (passive) raised horizontal markers is that they do not need to be illuminated by the light of the vehicle's headlights. Active road studs offer a clear advantage in terms of visibility as they can increase forward visibility by up to 800 m more than passive retroreflective studs (Reed, 2006). Thus, active LEDs are able to provide better visibility of the road ahead in low light (e.g., night) conditions, giving drivers greater visibility over longer sections of horizontal curves and a keener perception of the curvature. Indeed, LED studs are currently used as alternative horizontal road delineators to enhance the visibility of the carriageway in low-light conditions (Villa et al., 2015), especially in non-urban curved sections (Bhatnagar, 1994; Johnston, 1982; NHTSA, 2008).

To date, several studies have agreed that LED studs might increase driver confidence at nighttime, perceived safety, and comfort (Llewellyn et al., 2020; Reed, 2006; Shahar et al., 2018). However, the few studies that investigated the impact of LED studs on driving performance produced inconsistent results (Llewellyn et al., 2021; Shahar et al., 2018; Shahar & Br´emond, 2014; Zhu et al., 2021). Thus, the question of whether driver performance and road safety could be improved through these solutions remains open. Furthermore, although it is well known that color affects driver behavior (for a review, see Calvi, 2018) and emotional state (for a review, see Jalil et al., 2012), requirements for the design of LED studs almost never include definitive specifications on the choice of color lighting to be displayed (Llewellyn et al., 2020; Shahar et al., 2018; Zhu et al., 2021). Indeed, to date, only one study has parametrically manipulated the color of studs (among other factors) and measured their effects on driver personal preference and perceived visibility, legibility and level of glare (Bacelar, 2004). Results indicated that drivers preferred bluish/white studs to yellow(ish) or orang(ish) ones. However, because other factors – such as luminous intensity, device surface, spacing, and stud height – were simultaneously manipulated, a straightforward conclusion is not possible. Thus, starting from Bacelar's pioneering observations (ibidem), we designed an experimental simulator–based study to investigate the influence of LED road stud color on driver behavior and perception.

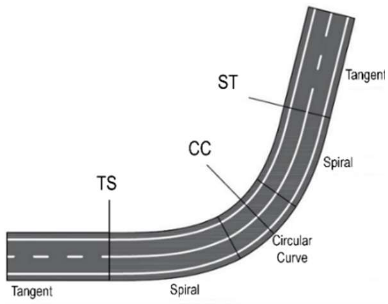
Here, we evaluated the effects of two different colored LED studs (red vs. white, and a control condition: unlit) on driver performance and driver subjective perception. Participants performed two experimental tasks: (i) a driving simulation and (ii) a static perception test. The first task aimed to evaluate the effects of colored LED studs on vehicle longitudinal and transversal behavior, while the second one was intended to investigate their effect(s) on the levels of risk, pleasantness, and arousal perceived by drivers. Since red is commonly used to convey danger in traffic signs and lights (Chapanis, 1994; Pravossoudovitch et al., 2014), we expected that red LED studs – perceived as a warning signal – would induce a safer driving style (i.e., a more stable longitudinal and transversal control). In addition, it was also expected that driver perception of risk, pleasantness and arousal would reflect this red–danger association.

2. Method

2.1. Participants

Thirty-six participants (11 females) took part in the study. This sample included drivers with ages ranging from 19 to 63 (Mean [Standard Deviation, SD] = 31 [11.2] years). All participants had normal or corrected–to–normal vision and were asked to abstain from caffeine–based beverages in the 2 h before the experimental sessions. None of the drivers were aware of the hypotheses being investigated nor did they receive any monetary compensation. The experiment was conducted in compliance with the Code of Ethics of the World Medical Association (WMA, 2013).

(a)

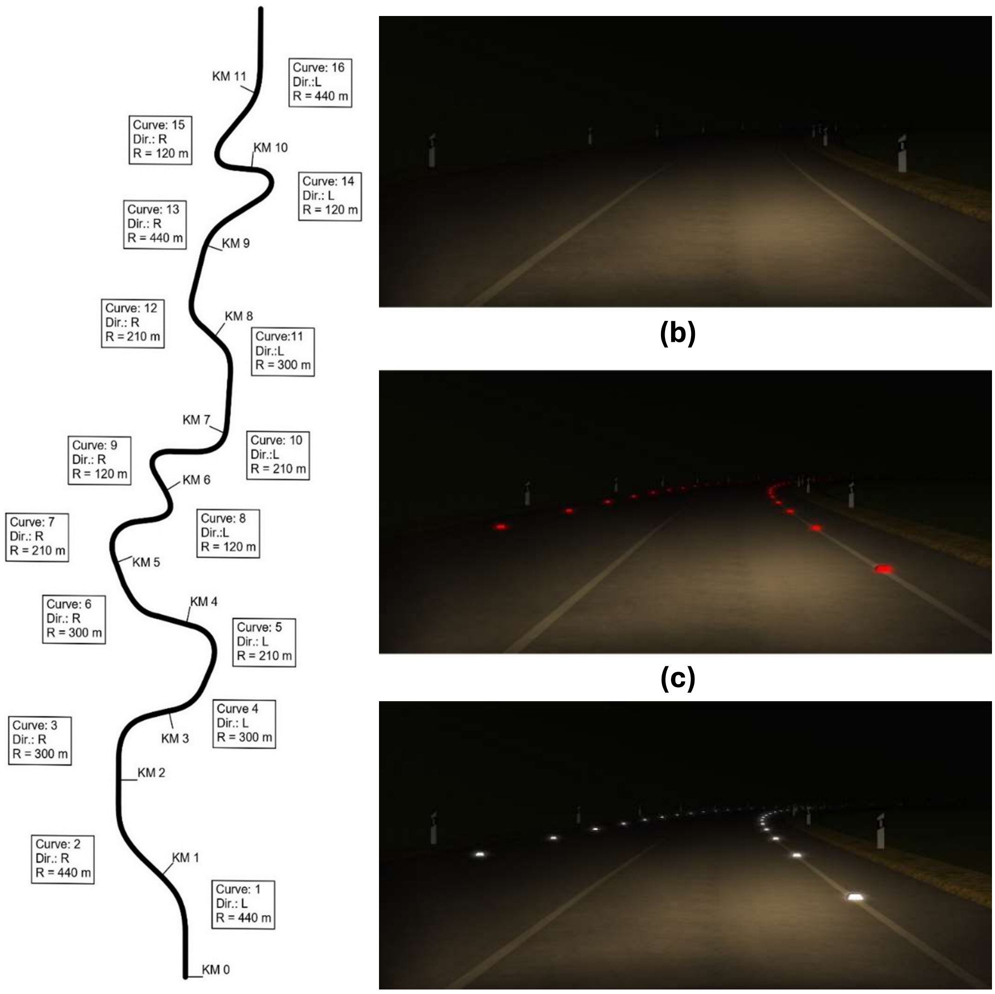


(b)

Figure 1. (a) The fixed-base driving simulator used for the simulation task; (b) Reference sites correspond to curve termini TS (tangent-to-spiral) and ST (spiral-to-tangent), and to circular curve center (CC).

2.2. Experimental design

Both experimental tasks (the driving simulation and the static perception) followed a within-subject design with LED Stud (3 levels: unlit, red, and white), Curve Radius (4 levels: 120, 210, 300, and 440 m), and Curve Direction (2 levels: left and right) as independent factors. It is worth noting that the four radius values were chosen so as to enable the participants negotiate the curves at different speeds. Therefore, to explore design speed interval, we selected the four values permitted by the Italian technical standards (MIT, 2001) for two–lane rural roads, which are 60, 75, 85, and 100 km/h. During the driving simulation task, we recorded the following longitudinal and transversal variables (Fig. 1b) for each investigated curve: (i) the longitudinal speed at TS (tangent-to-spiral) and CC (curve center) termini, (ii) the lateral position (i.e., the distance between the center of gravity of the vehicle and the lane centerline) at TS and CC termini, and (iii) the standard deviation of lateral position (SDLP) between TS and ST (spiral-to-tangent) termini (Fig. 1b). During the static perception test, we recorded participants' (i) perceived level of risk, (ii) the degree of pleasantness, and (iii) degree of arousal. We used three separated 9-point Likert scales (from 1, very low, to 9, very high), see 2.3 section).



(a) **(d)**

Figure 2. Plan scheme (a) of the experimental track with curve details (16 curves: 2 curve directions × 4 radii × 2 repetitions), and frames taken from the driver point of view for (b) unlit condition, (c) red, and (d) white LED road studs in night-time driving conditions. Road studs were placed 8 m apart at the edges of the lanes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.3. Equipment, simulated scenario, and stimuli

For the driving simulation task, we used a fixed-base driving simulator (AV Simulation, France) located at the Road Safety and Driving Simulation lab (RSDS, Politecnico di Torino, Italy). The simulator is composed of three monitors with a 130° field of view, a fully equipped driving position with seat, dashboard, steering wheel with force feedback, pedals, manual gearbox, vibration pads to replicate pavement roughness, wheel rolling, and shocks (Fig. 1a). A sound system reproduced the sounds of the engine and the surrounding environment. The data acquisition frequency was set to 100 Hz. The SCANeR Studio® simulation software (https://www.avsimulation.com/scanerstudio/) was employed to develop the driving scenarios, run the simulation, and record the dependent variable values. The simulator had previously been validated for longitudinal (Bassani et al., 2018), transversal (Catani & Bassani, 2019), and passing (Karimi et al., 2020) behavior.

Three driving scenarios were designed to simulate the road alignment of a two–lane, 11.63 km long rural highway (Fig. 2a). The road cross-section presented one lane per direction, with a lane width of 3.75 m and a shoulder width of 1.50 m, in accordance with the Italian policy for road design (Ministero delle Infrastrutture e dei Trasporti, 2001). For all scenarios, we simulated a low volume of traffic on tangents to reflect real conditions as much as possible (Michael et al., 2014; Pinto et al., 2008), while free-flow conditions were simulated along curves. The scenarios were differentiated by the presence of LED studs at the curve roadside: (i) unlit, i.e., no LED studs (Fig. 2b), (ii) red (Fig. 2c), and (iii) white LED studs (Fig. 2d). Each scenario had the same characteristics in terms of landscape, environment, nighttime lighting conditions, and road geometric elements. The road alignment consisted of 16-spiraled curves, with different radii (120, 210, 300, and 440 m) and curve directions (left and right). Each condition was repeated twice (4 radii × 2 directions × 2 times = 16 curves). For the statistical analysis, we averaged out the observed values by referring to those curves having equal geometric characteristics (see Section 2.5). The length of the tangent was set in a range of 110 to 330 m. The road studs were placed on the left and right sides of the curves (Fig. 2), spaced 8 m apart, and not installed on tangents. We decided to install the active road studs exclusively at the edges of the carriageway because our objective was to support the passive retroreflective delineators, which are traditionally placed there to guide motorists and enhance safety.

The luminance and visibility of the simulated active road studs were managed by the SCANeR Studio software and were simulated to be as realistic as possible (i.e., light intensity of the studs decreased as the distance from the driver observation point increased). Furthermore, the road studs were visible along the entire length of the curve thanks to the adequate luminance of the studs and the absence of any sight obstructions (Fig. 2c and d).

For the static perception task, we randomly presented 24 images (obtained from the combination of 3 LED stud condition types × 4 radii × 2 curve directions) on a 24'' monitor positioned about 60 cm from the driver's face. Each image was displayed for 7 s. After seeing each image, participants assessed the perceived risk level of the driving scene using a 9-point Likert rating scale from 1 (not risky) to 9 (extremely risky). Then, they were asked to rate the levels of pleasantness (i.e., valence) and arousal (i.e., activation) they had experienced while viewing the image. We used a digital version of the Self-Assessment-Manikin-Scales – SAM – (Lang, 1980). Drivers were instructed to rate the level of pleasantness (i.e., valence), as positive or negative on a 9-point rating scale (e.g., one is the lowest valence and nine corresponds to the highest valence). For the arousal evaluation, drivers had to describe the activation induced by the presented image, from "lowest activating" to "highest activating" again on a 9-point rating scale (one is the lowest arousal while nine corresponds to the highest arousal).

2.4. Procedure

The experiment took place at the RSDS lab (Politecnico di Torino, Italy) during a one-day session organized as follows: (i) a predrive questionnaire, (ii) simulator training session, (iii) the three driving simulations, (iv) the static perception test, and, finally, (v) the post-drive questionnaire.

First, participants filled in a pre-drive questionnaire to collect demographic data, driving information, and information related to their health and physical condition. Subsequently, they conducted a five-minute training test at the driving simulator. After a 2-min rest period, participants were asked to drive the three experimental scenarios, which were fully counterbalanced to control the order effect (Keppel et al., 2001). Participants were given a 1-min rest time between driving scenarios. To increase the truthfulness of nighttime driving conditions, the experiment took place in a dimly lit laboratory. That is, the displayed image/simulation on the screen/s provided the only light inside the room. After that, we conducted the static perception test on the dedicated PC. Finally, the participants filled in a post-drive questionnaire about their driving simulation experience and any motion sickness experienced.

2.5. Statistical analysis

All the dependent variables were analyzed with a (3 × 4 × 2) repeated measures analysis of variance (RM ANOVA). For the dependent variables in the driving task, we averaged out the observed values by referring to those curves having equal geometric characteristics. The significance level (α) was always set to ≤ 0.05. The Bonferroni correction for multiple comparisons was applied. Two participants failed to complete the driving task because of simulation sickness. As a result, only data from 34 out of the 36 participants were analyzed.

3. Results

This study explored the effects of different LED stud colors on driver behavior and perceived levels of risk, levels of pleasantness, and arousal experienced, using both a simulator-based technology and a static perception test. To investigate the influence of the color manipulation on driver behavior, we first analyzed the outcomes of the second task (static perception task), after which we analyzed the driver performance results from the first task (driving simulation task).

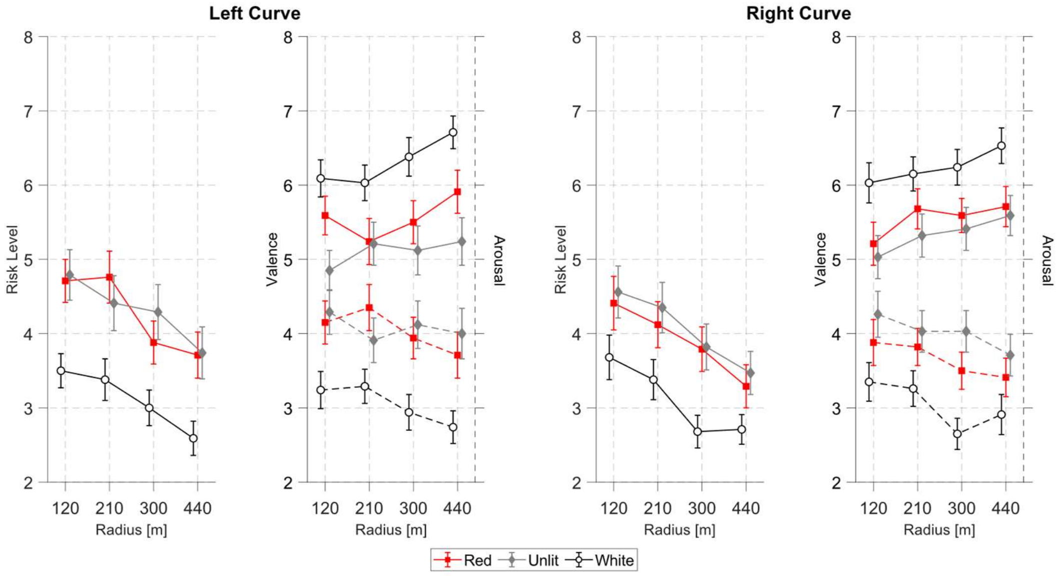
3.1. Subjective measures

The risk perception of participants was affected by the color of LED studs, $F(2,66) = 16.28$, $p < .001$, as well as by curve direction, $F(1,33) = 9.44$, $p = .004$, and curve radius, $F(3,99) = 25.91$, $p < .001$. No significant interactions between these independent factors were found. Bonferroni post-hoc tests on the LED stud variable revealed a significant difference between the white and unlit conditions (mean difference = 1.07, corrected–p <.05), while the other comparisons did not prove to be significant (see Fig. 3).

The valence level of participants was significantly influenced by LED studs, $F(2,66) = 13.42$, $p < .001$, and curve radius, $F(3,99) = 8.90$, $p < .001$, albeit no significant interactions were found. Post-hoc comparisons revealed a difference between the white and unlit condition (mean difference = 1.05, corrected-p <.05). A post-hoc test on curve radius showed a significant difference between the sharper radius (120 m) and the wider (440 m) one (mean difference = –0.48, corrected-p <.05).

Participant arousal levels were significantly influenced by the LED studs, $F(2,66) = 14.120$, $p < .001$, as well as by curve direction, $F(1,33) = 11.880$, $p = .002$, and curve radius, $F(3,99) = 6.789$, $p < .001$. The interaction between LED studs and curve direction was statistically significant, $F(2,66) = 3.33$, $p = .042$. The post-hoc tests on the interaction (LED stud*Curve Direction) confirmed a significant difference between white and unlit studs for both directions of the curve. Moreover, no significant differences between the red and unlit conditions were detected. A significant difference between the red LED stud condition on left and right curves was found (mean difference = 0.38, corrected-p <.05).

Overall, the manipulation of the color had a marginally significant effect on the participants' subjective perception of the road. The white LED condition was perceived as less risky, less arousing, and more pleasant than the unlit condition. The red LED condition was perceived as similar to the unlit LED condition, while also tending to be perceived as different from the white LED condition (see Fig. 3). We did not find significant differences between the red and unlit conditions.



(a) (b) (c) (d)

Figure 3. Average perceived risk, valence, and arousal levels recorded during the static perception test. Graphs are split for curve direction (i.e., left, and right). Solid lines refer to valence, the dashed ones refer to arousal. The error bars represent the standard error of the mean (SEM). Valence and arousal are represented on the same scale. Note that, for graphic purposes, the range of the y-axis always ranges from 2 to 8, while the variables were measured in a scale from 1 to 9.

3.2. Lateral and longitudinal driver behaviour

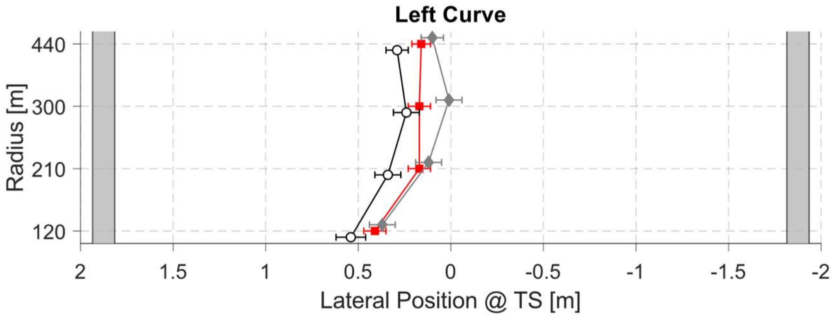
The transversal behavior of the drivers was measured by determining the lateral position (Fig. 4) and the SDLP (Fig. 5) of the vehicle. At the TS section, the LED stud effect on lateral position was significant, $F(2,66) = 15.30$, $p < .001$, as well as the curve direction and radius, $F(1,33) = 6.75$, $p = .015$ and $F(3,99) = 5.57$, $p = .001$, respectively. The second-order interaction (LED Stud * Curve Radius * Curve Direction) was also found to be significant, $F(6,198) = 2.65$, $p = .017$. The post-hoc test of the second order interaction revealed significant differences between the lateral position with left curves and a sharp radius (120 m) and the other three curves (210, 300, and 440 m), for the same road stud condition (corrected–$p < 0.05$). No significant differences were found among lateral positions in the lane on left curves with 210, 300, and 440 m, for the same road stud condition. On left curves, there were significant differences between the unlit condition and that of the white LED stud even though the mean difference was small (-0.20 m).

At the CC section, the lateral position differed significantly across the three road stud conditions $F(2,66) = 24.74$, $p < .001$. Significant differences were also found for curve direction, $F(1,33) = 14.00$, $p < .001$, and curve radius, $F(3,99) = 6.27$, p <.001. The second-order interaction (LED Stud*Curve Radius*Curve Direction) was also found to be significant, F(6,198) = 7.47, p <.001. A post–hoc comparison of road studs showed significant differences between the unlit and white LED conditions (mean difference = - 0.32, corrected-p <.05), the red and unlit LED conditions (mean difference = 0.20, corrected-p <.05), and the red and white LED conditions (mean difference = - 0.12, corrected-p <.05).

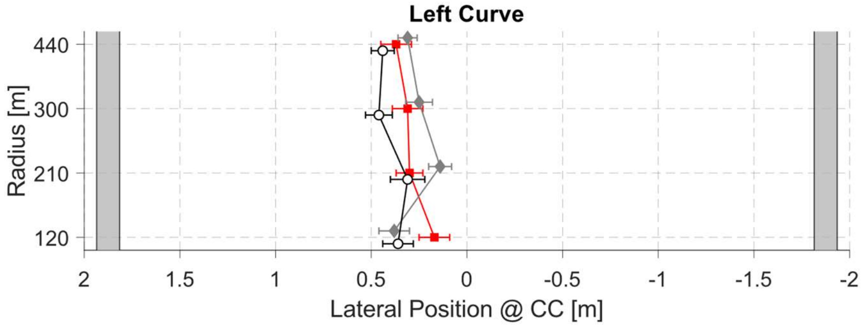
SDLP was significantly affected by LED road stud and curve radius, F(2,66) = 4.23, p =.019, F(3,99) = 27.28, p <.001, respectively, while the curve direction was non–significant. Nevertheless, the interaction between road stud condition and curve direction was significant, F(2,66) = 7.43, p =.001. Post–hoc comparisons between road stud and curve direction revealed significant differences between the red and unlit condition (corrected-p <.05) and between the white and unlit conditions albeit only on right curves (corrected-p <.05).

Our study did not establish any link between the color of LED studs and curve direction, and speeds at the TS section of curves under white, red, and unlit conditions. However, we did find that the curve radius had a significant effect on speed, F(3,99) = 77.76, p <.001. We also found the first order interaction between curve direction and radius to be significant F(3,99) = 15.97, p <.001.

At the CC section, color LED studs did not statistically affect drivers' speed behavior. Significant differences were found for curve direction, F(1,99) = 9.51, p =.004, and radius, F(3,99) = 207.08, p <.001. We found the first order interaction between road stud condition and direction to be significant too, F(2,66) = 5.72, p =.005. Post hoc comparisons between color LED stud and curve direction revealed significant differences only for the unlit condition between left and right curves (corrected-p <.05). The outcomes for speed are shown in the Supplementary Material 1.



(a)



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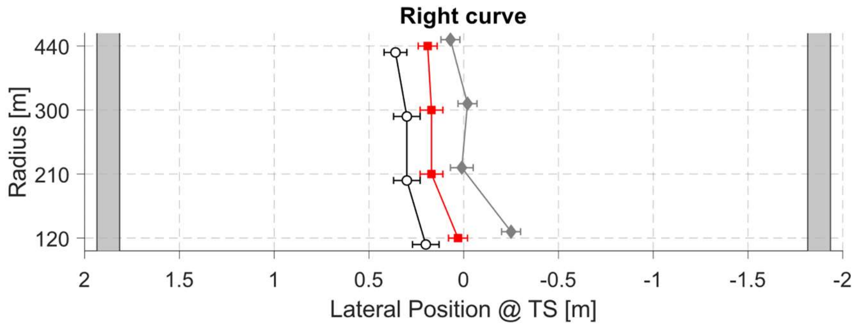

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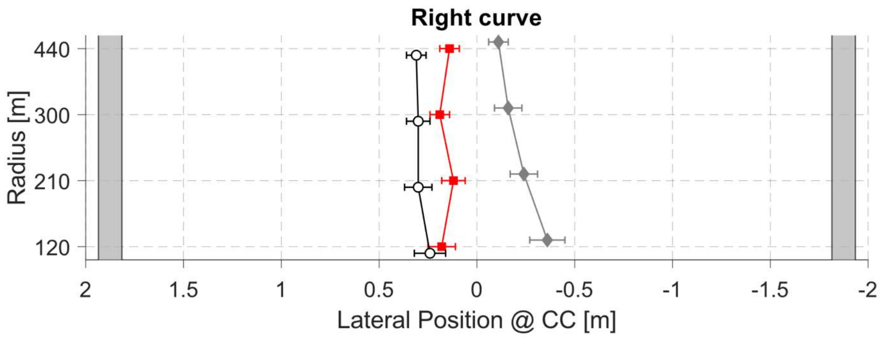


(d)

Figure 4. Average lateral position maintained by drivers at (a, c) the beginning of the curve (TS section), and (b, d) at the center of the curve (CC section). (a, b) figures show the behavior on left curves, (c, d) figures show the right curves. The two grey vertical bars in each graph represent the horizontal road markings, and the white area is the lane width. The error bars indicate the standard error of the mean (SEM).

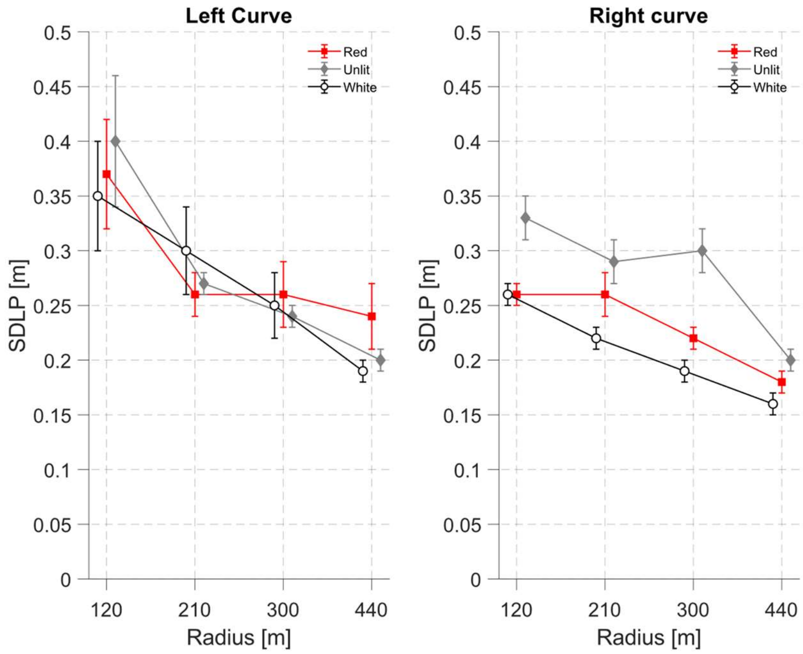


Figure 5. Average standard deviation of lateral position (SDLP) between the beginning of the curve (TS) and the transition end (TE) sections for (a) left and (b) right curves. The error bars indicate the standard error of the mean (SEM).

4. Discussion and Conclusions

We examined the effect(s) of the color (unlit, red, and white) of LED road studs, placed at curve carriageway edges in correspondence with the horizontal markings visible in nighttime driving conditions, on subjective measures and driver performance. We considered curves with four different radii (120, 210, 300, and 440 m) and in both directions (left and right).

Based on the results we obtained from the static perception task, the white LED studs induced a lower perception of risk than the words, white LED studs induced a less aroused (activating) state (Kensinger, 2004). In contrast, the red and unlit stud conditions produced comparable valence and arousal levels. Therefore, in terms of a subjective response, white LED studs are perceived as non–hazardous, pleasant, and less alarming delineators of the carriageway when driving at nighttime. We contend that the effect of white LED studs on driver perception enables the driver to benefit from a more pleasant and safer driving experience (Paxion et al., 2014). Moreover, our results indicate that the greater the radius, the lower the perceived level of risk. This result (from a subjective measurement) reflects the actual behavior of drivers (Bassani et al., 2019; Chen et al., 2007; Othman et al., 2009), as the authors determined that a decrease in the radius of the curve was accompanied by an increase in the objective level of risk. We also found significant differences in the perceived levels of risk between left and right curves. Although we cannot extrapolate too much from a single result, our findings provide further support for the hypothesis that a difference in risk perception can influence driving behavior (Jing et al., 2022; Song et al., 2021).

The analysis of lateral position revealed significant differences in driving behavior along curves of different directions. On right curves with red and white road studs, participants drove closer to the carriageway centerline compared to the unlit condition of the lateral marking (Fig. 4). However, we found no significant differences in the case of left curves, as the lateral positions were all close to the unlit condition (Fig. 4a). We conjecture that this different behavior is a consequence of the specific road stud layout we adopted. We only put the road studs at the edge of the carriageway, which inevitably makes the behavior asymmetrical when the driver uses the "tangent point" mechanism for lateral control. Land & Lee (1994) as well as Lehtonen et al., (2012) observed that most drivers regard the point of apparent inversion of the inner road marking, and towards which the driver's line of sight is oriented, to be tangent to the marking itself. Since they were almost visible to the driver (see Fig. 2), all left curves in the three scenarios offered the same visual support to drivers, as the road centerline was always free of LED studs.

The analysis of SDLP also produced relevant results, used here as an indicator of the vehicle's lateral control capability through the steering wheel (Verster & Roth, 2011). Based on previous considerations, it is not surprising that the effect of LED studs on SDLP was significant on right curves only. As previously said, the LED studs render the lane boundaries more visible to drivers who, consequently, performed fewer trajectory corrections, resulting in lower SDLP values with respect to the unlit condition. Once again, the white LED stud condition resulted in the best vehicle control. These results are consistent with those of Shahar et al. (2018) and Shahar & Bremond (2014), who observed lower SDLP values in the studded condition than in the unlit one. In these previous works, different conclusions were drawn for left and right curve maneuvers with respect to this study, again due to the different LED stud layout. Shahar et al., (2018) observed driver behavior on two-lane rural roads where, in addition to being placed on the edge of the carriageway, road studs were also used to mark the solid line dividing the two opposing traffic lanes. Moreover, as expected, the SDLP decreased as the radius increased. This result reflects that of Portera & Bassani (2021) who also established an inverse correlation between curve radius and SDLP.

Results for longitudinal behavior revealed that speed values entering and along the curve were not influenced by the presence nor by the color of the LED stud. This is certainly a good result in favor of the use of road studs and is in line with the results obtained by Llewellyn et al. (2021) who did not find a significant variation in speed between the LED studded and unlit conditions on real roads. This implies that although the drivers' ability to predict road curvature improved dramatically, it did not translate into the adoption of riskier behavior in terms of higher speeds.

Our results are also consistent with previous studies (e.g., Shahar et al., 2018; Shahar & Bremond, 2014) in which speed was influenced by the presence of LED studs along straight sections only, a condition which we did not consider in this study. Nevertheless, our results combined with those from Shahar et al. (2018) clearly indicate that the longitudinal performance of drivers does not deteriorate with the use of road studs along curved sections only. In addition, the radius had an impact on longitudinal behavior. As the radius increased the speed increased too. This result was already found by Bassani et al. (2019).

Finally, the presence of red LED studs during nighttime driving in free-flowing conditions produces perceptions of hazard, pleasantness, and arousal similar to those of the unlit condition. Moreover, along right curves with red LED studs, the lateral control of drivers improved with respect to the unlit LED studs but regressed with respect to the white ones. While this result is neither positive nor negative, it does suggest that it might be preferable to avoid the use of any red(ish) color which is typically used to signal work zones and/or situations of danger (Bacelar, 2004; Chapanis, 1994; Pravossoudovitch et al., 2014).

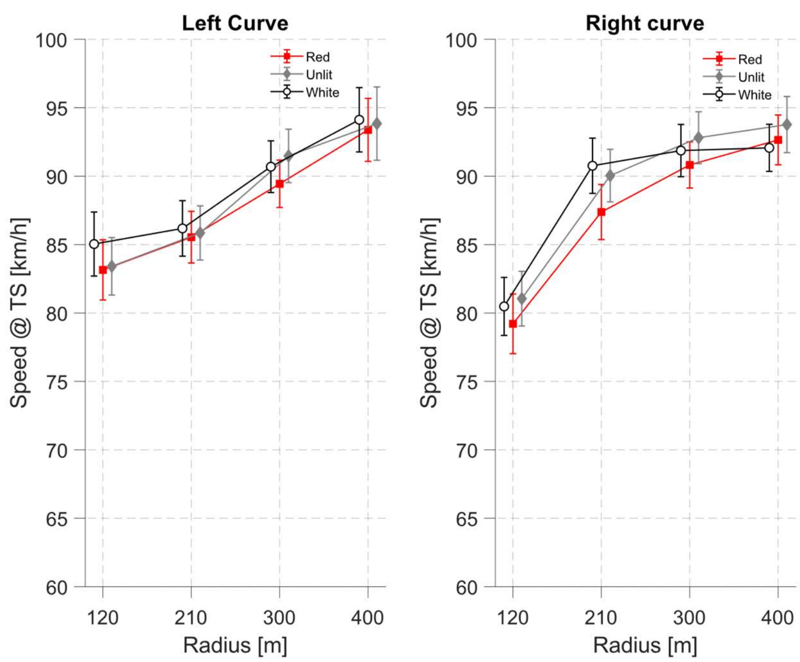
Taken together, our results demonstrate that white LED studs have a positive influence on nighttime driving. We found that a more pleasant, non-hazardous, and less alarming perception enabled the driver to exercise better lateral control, with significantly fewer steering corrections. This result appears to be extremely relevant for the design and implementation of road lighting solutions and would seem to favor the use of white devices over red ones. However, we also observed an asymmetrical behavior which was certainly influenced by the LED stud layout that we did not consider here. Therefore, we were able to appreciate the benefits of LED on right curves only.

Notwithstanding the above, our results should be viewed in the context of four shortcomings. First, LED studs were installed along the carriageway edges only. Our outcomes confirm that this decision led to a difference in results between right and left curves. Future research should compare all possible layouts resulting from a different arrangement of LED studs along the available lane markings. Second, the simplicity of our road scenario (free-flow conditions involving only horizontal curves) with constant meteorological and favorable visibility conditions (e.g., dry road surface, no fog, see Villa et al. 2015) could in part limit the external validity of our results, so further studies should address our research hypothesis in a more ecological way. Third, the explication based on the tangent point vision mechanism is just an assumption based on relevant previous studies. Future studies must also include eye–tracking measurements to confirm the effective adoption of this mechanism. Finally, although the study aimed at analyzing psychological (i.e., level of risk, valence, and arousal) and behavioral (i.e., speed, lateral position and SDLP) aspects, there is a possibility that the results were also influenced by physiological factors outside of our control, e.g., individual differences in color perception or in physiological responses to light (Boyce, 2009). Indeed, we did not specifically check the environmental levels across the different experimental conditions.

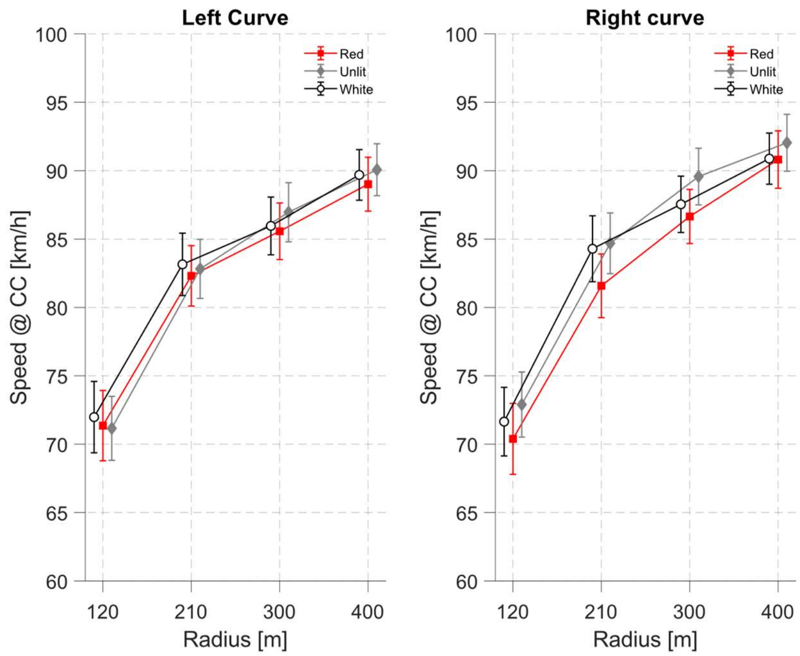
Considering the absence of any oncoming vehicles or other road lighting devices, the variation in environmental luminance was determined by the led emitting lights themselves. Therefore, the findings should be interpreted with caution and future studies should aim to address this potential limitation by reducing the impact of confounding variables.

To conclude, our study on the influence of LED road stud color on driver behavior and attitude yielded promising results when white was used to provide guidance while driving at nighttime. Our investigation can offer transportation engineers, as well as road designers, some guidance on how to enhance traffic lighting developments, which serve to increase driver awareness of the conditions of oncoming curves, and to improve traffic safety.

Supplemental material 1



[1]



[2]

Figure. [1] Average speed maintained by drivers at the beginning of the curve (TS section, on the left), [2] and at the center of the curve (CC section). The error bars represent the standard error of the mean (SEM).

References

Babic, D., & Brijs, T. (2021). Low-cost road marking measures for increasing safety in horizontal curves: A driving simulator study. *Accident Analysis & Prevention, 153*, Article 106013. https://doi.org/10.1016/j.aap.2021.106013

Bacelar, A. (2004). Definition of a luminous stud to improve the legibility of expressway for drivers. *Journal of Light & Visual Environment, 28*(3), 148–151. https://doi. org/10.2150/jlve.28.148

Bassani, M., Catani, L., Ignazzi, A., & Piras, M. (2018). Validation of a Fixed-Base Driving Simulator to Assess Behavioural Effects of Road Geometrics. *Proceedings of the Driving Simulation Conference 2018 Europe VR*, 101–108.

Bassani, M., Hazoor, A., & Catani, L. (2019). What's around the curve? A driving simulation experiment on compensatory strategies for safe driving along horizontal curves with sight limitations. *Transportation Research Part F: Traffic Psychology and Behaviour, 66*, 273–291. https://doi.org/10.1016/j.trf.2019.09.011

Bassani, M., Portera, A., & Raimondo, G. (2022). Longitudinal and transversal driver behavior with innovative horizontal markings along curved motorway on-ramps and terminals. *Transportation Letters, 1–11*. https://doi.org/10.1080/19427867.2022.2035121

Bhatnagar, Y. S. (1994). *OBSERVATIONS ON THE USE OF CHEVRON ALIGNMENT MARKERS*. 17TH ARRB CONFERENCE, GOLD COAST, QUEENSLAND, 15-19 AUGUST 1994; PROCEEDINGS; VOLUME 17, PART 5. https://trid.trb.org/view/414045.

Boyce, P. R. (2009). *Lighting for driving: Roads, vehicles, signs, and signals*. CRC Press.

Calvi, A. (2018). Investigating the effectiveness of perceptual treatments on a crest vertical curve: A driving simulator study. *Transportation Research Part F: Traffic Psychology and Behaviour, 58*, 1074–1086. https://doi.org/10.1016/j.trf.2018.06.002

Calvi, A., D’Amico, F., Bianchini Ciampoli, L., & Ferrante, C. (2019). Evaluating the effectiveness of perceptual treatments on sharp curves: A driving simulator study. *Traffic Injury Prevention, 20*(sup2), S13–S19. https://doi.org/10.1080/15389588.2019.1669789

Catani, L., & Bassani, M. (2019). Anticipatory Distance, Curvature, and Curvature Change Rate in Compound Curve Negotiation: A Comparison between Real and Simulated Driving. *98th Annual Meeting of the Transportation Research Board, Washington, DC*.

Chapanis, A. (1994). Hazards associated with three signal words and four colours on warning signs. *Ergonomics, 37*(2), 265–275. https://doi.org/10.1080/ 00140139408963644

Charlton, S. G. (2007). The role of attention in horizontal curves: A comparison of advance warning, delineation, and road marking treatments. *Accident Analysis & Prevention, 39*(5), 873–885. https://doi.org/10.1016/j.aap.2006.12.007

Chen, S., Rakotonirainy, A., Loke, S. W., & Krishnaswamy, S. (2007). A crash risk assessment model for road curves. *Proceedings of the 20th International Technical Conference on the Enhanced Safety of Vehicles*. Mira Digital Publishing, 2007.

Elvik, R. (1995). Meta-analysis of evaluations of public lighting as accident countermeasure. *Transportation Research Record*, *1485*. https://trid.trb.org/view/451827.

Goswamy, A., Hallmark, S., Litteral, T., & Pawlovich, M. (2018). Safety Evaluation of Destination Lighting Treatment at Stop Controlled Cross-Intersections. *Transportation Research Record: Journal of the Transportation Research Board, 2672*(16), 113–121. https://doi.org/10.1177/0361198118774747

Jalil, N. A., Yunus, R. M., & Said, N. S. (2012). Environmental Colour Impact upon Human Behaviour: A Review. *Procedia - Social and Behavioral Sciences, 35*, 54–62. https://doi.org/10.1016/j.sbspro.2012.02.062

Jing, L., Shan, W., & Zhang, Y. (2022). Risk preference, risk perception as predictors of risky driving behaviors: The moderating effects of gender, age, and driving experience. *Journal of Transportation Safety & Security, 1–26*. https://doi.org/10.1080/19439962.2022.2086953

Johnston, I. R. (1982). Modifying driver behaviour on rural road curves-a review of recent research. *Australian Road Research, Articolo, 11*, Pt4. https://trid.trb.org/ view/186373.

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

Kensinger, E. A. (2004). Remembering Emotional Experiences: The Contribution of Valence and Arousal. *Reviews in the Neurosciences, 15*(4). https://doi.org/10.1515/ REVNEURO.2004.15.4.241

Keppel, Saufley, Tokunaga, & Violani. (2001). *Disegno sperimentale e analisi dei dati in psicologia*. Edises. Lang, P. J. (1980). Behavioral treatment and bio-behavioral assessment: Computer applications. *Technology in mental health care delivery systems*, 119–137.

Lehtonen, E., Lappi, O., & Summala, H. (2012). Anticipatory eye movements when approaching a curve on a rural road depend on working memory load. *Transportation Research Part F: Traffic Psychology and Behaviour, 15*(3), 369–377. https://doi.org/10.1016/j.trf.2011.08.007

Lin, H., Chen, F., & Zhang, H. (2023). Active luminous road markings: A comprehensive review of technologies, materials, and challenges. *Construction and Building Materials, 363*, 129811. https://doi.org/10.1016/j.conbuildmat.2022.129811

Llewellyn, R., Cowie, J., & Fountas, G. (2021). Solar-Powered Active Road Studs and Highway Infrastructure: Effect on Vehicle Speeds. *Energies, 14*(21), 7209. https:// doi.org/10.3390/en14217209

Llewellyn, R., Cowie, J., & Maher, M. (2020). Active Road Studs as an Alternative to Lighting on Rural Roads: Driver Safety Perception. *Sustainability, 12*(22), 9648. https://doi.org/10.3390/su12229648

Michael, D., Kleanthous, M., Savva, M., Christodoulou, S., Pampaka, M., & Gregoriades, A. (2014). *Impact of Immersion and Realism in Driving Simulator Studies: International Journal of Interdisciplinary Telecommunications and Networking, 6*(1), 10–25. https://doi.org/10.4018/ijitn.2014010102

Ministero delle Infrastrutture e dei Trasporti. (2001). *Norme Funzionali e Geometriche per la Costruzione Delle Strade (in Italian). D.M. no. 6792 of November 5th*. Roma, Italy: Istituto Poligrafico dello Stato.

Nhtsa. (2008). Fatality Analysis Reporting System General Estimates System: 2008 Data Summary: (625002012–001). *American Psychological Association*. https://doi. org/10.1037/e625002012-001

Othman, S., Thomson, R., & Lann´er, G. (2009). Identifying critical road geometry parameters affecting crash rate and crash type. In *Annals of advances in automotive medicine/annual scientific conference, 53* p. 155). Association for the Advancement of Automotive Medicine.

Owens, D. A., & Sivak, M. (1996). Differentiation of Visibility and Alcohol as Contributors to Twilight Road Fatalities. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 38*(4), 680–689. https://doi.org/10.1518/001872096778827233

Pagden, M., Ngahane, K., & Amin, M. S. R. (2020). Changing the colour of night on urban streets—LED vs. *Part-night lighting system. Socio-Economic Planning Sciences, 69*, Article 100692. https://doi.org/10.1016/j.seps.2019.02.007

Paxion, J., Galy, E., & Berthelon, C. (2014). Mental workload and driving. *Frontiers in Psychology, 5*. https://doi.org/10.3389/fpsyg.2014.01344 Pinto, M., Cavallo, V., & Ohlmann, T. (2008). *The development of driving simulators: Toward a multisensory solution: Le travail humain, 71*(1), 62–95. https://doi.org/ 10.3917/th.711.0062

Plainis, S. (2006). Road traffic casualties: Understanding the night-time death toll. *Injury Prevention, 12*(2), 125–138. https://doi.org/10.1136/ip.2005.011056

Portera, A., & Bassani, M. (2021). Experimental Investigation into Driver Behavior along Curved and Parallel Diverging Terminals of Exit Interchange Ramps. *Transportation Research Record: Journal of the Transportation Research Board, 2675*(8), 254–267. https://doi.org/10.1177/0361198121997420

Pravossoudovitch, K., Cury, F., Young, S. G., & Elliot, A. J. (2014). Is red the colour of danger? Testing an implicit red–danger association. *Ergonomics, 57*(4), 503–510. https://doi.org/10.1080/00140139.2014.889220

Raimondo, G., Lioi, A., Hazoor, A., Portera, A., Tefa, L., & Bassani, M. (2022). Alternative Horizontal Markings along Curved Exit Ramp Terminals to Improve Driver- Safety-Related Performance. *Transportation Research Record: Journal of the Transportation Research Board, 036119812210764*. https://doi.org/10.1177/ 03611981221076443

Reed, N. (2006). *Driver Behaviour In Response To Actively Illuminated Road Studs: A Simulator Study., 76*.

Shahar, A., & Br´emond, R. (2014). Toward smart active road studs for lane delineation. *In TRA2014-Transport Research Arena: Transport Solutions: from Research to Deployment-Innovate Mobility, Mobilise Innovation!*, 11.

Shahar, A., Br´emond, R., & Villa, C. (2018). Can light emitting diode-based road studs improve vehicle control in curves at night? A driving simulator study. *Lighting Research & Technology, 50*(2), 266–281. https://doi.org/10.1177/1477153516660146

Song, X., Yin, Y., Cao, H., Zhao, S., Li, M., & Yi, B. (2021). The mediating effect of driver characteristics on risky driving behaviors moderated by gender, and the classification model of driver's driving risk. *Accident Analysis & Prevention, 153*, Article 106038. https://doi.org/10.1016/j.aap.2021.106038

Verster, J., & Roth, T. (2011). Standard operation procedures for conducting the on-the-road driving test, and measurement of the standard deviation of lateral position (SDLP). *International Journal of General Medicine, 359*. https://doi.org/10.2147/IJGM.S19639

Vicente, E. G., Matesanz, B. M., Rodríguez-Rosa, M., S´aez, A. M., Mar, S., & Arranz, I. (2023). Effect of Correlated Color Temperature and S/P-ratio of LED Light Sources on Reaction Time in Off-axis Vision and Mesopic Lighting Levels. *LEUKOS, 19*(1), 4–15. https://doi.org/10.1080/15502724.2021.1970580

Villa, C., Bremond, R., & Saint Jacques, E. (2015). Visibility and discomfort glare of LED road studs. *Lighting Research & Technology, 47*(8), 945–963. https://doi.org/ 10.1177/1477153514563637

Wma. (2013). World Medical Association Declaration of Helsinki: Ethical principles for medical research involving human subjects. *JAMA, 310*(20), 2191–2194. https://doi.org/10.1001/jama.2013.281053

Ylinen, A.-M., T¨ahk¨am¨o, L., Puolakka, M., & Halonen, L. (2011). Road lighting quality, energy efficiency, and mesopic design – LED street lighting case study. *LEUKOS, 8*(1), 9–24. https://doi.org/10.1582/LEUKOS.2011.08.01.001

Zhu, B., Song, C., Guo, Z., Zhang, Y., & Zhou, Z. (2021). Effectiveness of active luminous lane markings on highway at night: A driving simulation study. *Sustainability, 13*(3), 1043. https://doi.org/10.3390/su13031043

Paper C

Examining the Impact of Different LED Road Stud Layouts on Driving Performance and Gaze Behaviour at Night-time

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Abstract

The risks associated with night-time driving on dimly lit roads are substantial and are attributable to the limitations of human visual abilities. As a result, drivers often struggle to distinguish road geometry from ordinary road markings, thus increasing the likelihood of mistakes. These circumstances contribute to a 60% higher likelihood of road crashes compared to daytime conditions. To mitigate these risks, active LED road studs, which previous studies have shown to have a positive influence on driving performance, can be used. However, there remains a gap in research regarding the optimal arrangement of these studs along road markings for an improvement in driver behaviour and traffic safety. In this study, we assessed the influence of five different LED road stud layouts (unlit, edge, centre, edge-centre, and lane) during night-time driving on two-lane rural highways with curves of different radii (120, 210, 300, 440 m) and directions (left, right). Following a within subject design, thirty-five participants drove in a simulator along a road track with 8 spiralled curves (4 radii × 2 directions) linked to straights. We monitored the longitudinal (i.e., speed), transversal (i.e., lateral position and standard deviation of lateral position) and gaze behaviours.

Our findings indicate that the presence of LED road studs promotes safer driving, by helping drivers to adjust their speed when negotiating curves. Transversal behaviour analysis revealed layout-dependent effects on lateral position. The presence of road studs both at the lane centreline and edge allows drivers to maintain centred trajectories and improve steering control. Gaze behaviour analysis uncovered interesting patterns, demonstrating a strong correlation between road stud layout and the driver's focus on specific road targets. Illuminated markings prompt drivers to concentrate their gaze on distinct points, subsequently altering their transversal behaviour.

1. Introduction

Driving at night on dimly lit roads poses risks to drivers (Johansson et al., 2009) because of their limited ability to detect any movements ahead and discern the shape, colour, and texture of objects along the road. This is due to the limited performance of human vision under low environmental luminance conditions (Liu et al., 2019; Wood, 2020), i.e., scotopic vision (Boyce, 2008). Thus, when driving at night, drivers face greater difficulties in identifying the boundaries of the lane they are moving in, as well as those of adjacent lanes. This, combined with factors such as fatigue, distraction, and driving under the influence, underscores why the probability of a road crash is 60% higher at night than during the day (Chen et al., 2016; Zhang et al., 2016; Plainis, 2006; Owens & Sivak, 1996). Since speeds are higher when traffic density is low, crash severity is also at least two times higher during night hours than during the day (Ackaah et al., 2020; Johansson et al., 2009; Varghese & Shankar, 2007).

To enhance driving performance and safety in dark conditions, solutions like retro-reflective road markings and roadside delineators have been installed on roads for years. In this context, road studs have recently gained prominence as they enhance visibility and accurately delineate the lane and the carriageway.

Although traditional (passive) road studs have been widely used, light emitting diode (LED) road studs have become increasingly popular in recent years thanks to their superior performance (Angioi et al., 2023; Shahar et al., 2018). A key feature of LED road studs is that they are self-illuminating, that is, they emit light on their own, unlike passive road studs, which must first be hit by light from vehicle headlamps before they return the reflected beam into the driver's field of view. Therefore, LED road studs have a superior performance since they are active and visible even in haze and fog. In ordinary visibility conditions, the distance at which they are visible increases from 100 m for passive devices to about 900 m for active LED devices (Reed, 2006). Active road studs provide visual guidance to drivers helping them to achieve greater control of their vehicle trajectories, especially on those curved stretches of road that are recognized as unsafe at night-time (NHTSA, 2008).

The effectiveness of road studs on driving performance has been confirmed with a few research activities in naturalistic and simulated studies. In a driving simulation experiment, Shahar et al. (2018) and Shahar & Brémond, (2014) observed that drivers exhibited centred trajectories within the lane and made fewer steering corrections under studded conditions than they did in unlit conditions without studs. Drivers stated that they perceived roads with studs to be safer and more comfortable than roads without. While the presence of road studs does not result in any significant changes in mean driving speeds (Llewellyn et al., 2021), it increases the confidence levels of drivers at night (Llewellyn et al., 2020).

In a preliminary study (Portera et al., 2023), we investigated the effects of red and white coloured LED road studs placed along the two carriageway edge strips (indicated here as edge layout). Results revealed that white studs performed better in terms of pleasantness and perceived risk. Also, driving performance levels were significantly improved with the white LED studs. However, we observed different behaviours when drivers negotiated left- and right-hand curves. We conjecture that this was a consequence of the specific layout adopted. According to Figure 1, road studs were installed along the two lateral roadway strips only. As a result, when drivers focus on the inner marking line using the tangent point as an aid to steer the vehicle (Land & Lee, 1994), an asymmetric condition was tested. On left curves (Figure 1a), the driver's gaze is guided by lane markings of low optical quality. In contrast, on right curves (Figure 1b), the driver's gaze is aligned with the line of LED road studs, providing an enhanced vision of the curve geometry. Based on this evidence, we inferred that the layout of road studs (i.e., the different combinations of LED road stud positions along the three marking strips) may influence the gaze behaviour and overall performance of drivers.

To the best of our knowledge, no one had ever previously investigated driver gaze behaviour when subjected to different road stud layouts, both passive and active, and the effects of such layouts on night time driving performance. In this study, we used eye-tracking technology to establish whether a brighter marking delineation could capture the drivers' gaze. We hypothesised that if the driver's gaze was directed toward the markings made brighter by the LED road studs, this would improve his/her ability to control the vehicle longitudinally and laterally along curves.

(a) (b)

Figure 1. Road stud layout adopted in Portera et al. (2023). Assuming the tangent point mechanism is used (Land & Lee, 1994), in the case of a left turn (a) the gaze is directed toward a road sign without LED studs, which is in contrast with the case for right turn (b).

2. Method

2.1. Experimental design

The experiment followed a repeated measures approach with (i) road stud layout, (ii) curve radii, and (iii) curve direction as experimental factors. Together with the reference “unlit” condition (Figure 2b), four different LED road stud layouts were investigated: (i) the two carriageway edges (“edge” in Figure 2c), (ii) the carriageway centreline (“centre” in Figure 2d), (iii) both carriageway edges and centreline (“edge-centre” in Figure 2e), and (iv) the lane edges (i.e., the LED are visible only along the travelled lane, “lane” in Figure 2f). It is worth noting that the edge layout depicted in Figure 2c had already been considered in our previous study in order to evaluate the effects of colour on driving performance (Portera et al., 2023).

Consistent with Portera et al. (2023), we set the white LED as the only road stud colour. Four different spiralled curves with radii equal to 120, 210, 300, and 440 m, and the two directions, right and left, were considered for the design of the road track. A total of five different scenarios were reproduced with the same road geometry, each including only one road stud layout. In each scenario, all possible combinations of radii (4) and curve directions (2) were reproduced, for a total of (4 × 2 =) 8 curves. Three behavioural outcomes were considered in the data analysis: (i) the speeds at tangent to spiral (TS) and at the curve centre (CC) termini (Figure 2a); (ii) the lateral distances between the vehicle centre of gravity (CoG) of the vehicle and the lane centreline at TS and CC termini; and (iii) the standard deviation of lateral position (SDLP) along the entire curve, i.e., between TS and spiral-to-tangent (ST) termini. An eye tracker was employed to record the gaze behaviour of participants while negotiating the curves. The eye fixation value (period of stable gaze) was recorded for each curve from the TS to curve-to-spiral (CS) termini, i.e., along the segment in which the driver gaze was directed on the curve, with heatmaps as the outcome (see Section 2.3 for more details).

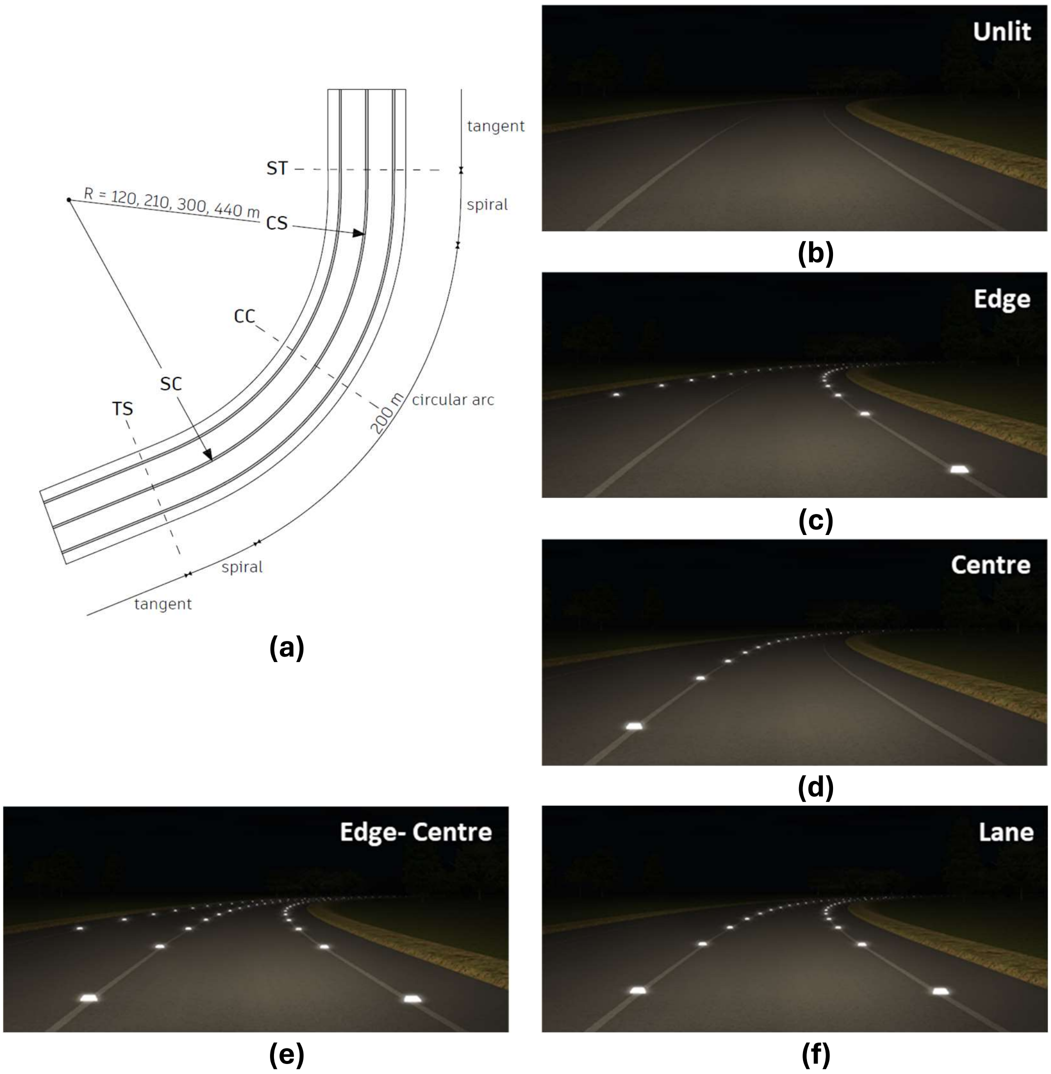


Figure 2. Plan scheme (a) of the geometric factors of curves and curve termini. Frames taken from the driver point of view for (b) unlit condition, (c) edge, (d) centre, (e) edge-centre, and (f) lane road studs. Road studs were always placed 8 m apart.

2.2. Equipment and road scenarios

The experiment was carried out with the fixed-base driving simulator (AV Simulation, France) in the Road Safety and Driving Simulation Laboratory (RSDS Lab) at the Politecnico di Torino. The simulator was equipped with three 32-inch monitors (resolution 1920×1080 pixels, frequency 60 Hz, 130°×20° field of view), a fully equipped driving position including seat, instrument panel, steering wheel with force feedback, pedals, manual transmission, and vibration pads for returning road roughness, wheel roll and impact. In the course of the experiments, the image of the cockpit on the screens allowed drivers to visualise the width of the vehicle and lend verisimilitude to the simulation. A Dolby Surround 5.1 sound system provided a realistic reproduction of the car engine, nearby traffic and the surrounding environment. SCANeR Studio® simulation software was used to build the driving scenarios, run the simulation, and acquire the driving data. The simulator had previously been validated for longitudinal (Bassani et al., 2018) and transversal behaviour (Catani & Bassani, 2019). Pupil Labs Core eye tracker (https://pupil labs.com/products/core/) was used to collect the driver gaze data.

All five scenarios were based on the same road alignment of a two-lane rural highway. The road alignment was designed in accordance with the Italian standards for road geometric design (Ministero delle Infrastrutture e dei Trasporti, 2001) and the Italian Highway Code (Legislative Decree 30 April 1992, No. 285) and featured 3.75 m wide lanes and 1.5 m wide shoulders (Road type C as per the Italian standard). The total length of the road was 6.9 km including 8 spiralled curves obtained by combining four radii (120 m, 210 m, 300 m, 440 m) and the two directions (left and right). We selected four radius values to collect behavioural data at different speeds. In accordance with Italian standards (Ministero delle Infrastrutture e dei Trasporti, 2001), the four radii correspond to design speeds of 60, 75, 85, and 100 km/h respectively. Each circular arc of curves was 200 m long (from SC to CS in Figure 2a), but the spiral length (L) was calculated from the radius (R) in accordance with Italian geometric design rules (L = R/9) (Ministero delle Infrastrutture e dei Trasporti, 2001). To ensure that the experience of preceding curves did not influence the speed adopted on successive ones, straight segments of sufficient length were introduced between two consecutive horizontal curves. The lengths of the straight segments varied between 110 m, used to connect curves with larger radius, and 330 m, used to connect curves with a sharper radius. Finally, the alignment was designed so that the curve radius gradually changed within the range 120 440 m curve by curve.

All scenarios shared the same landscape, environment, and road geometry. As already mentioned, they differed only in the layout of the white LED road studs. The few vehicles travelling in the opposite direction were only encountered along tangents to mimic realistic conditions, and to preclude any influence on driver behaviour along curves. In accordance with Portera et al. (2023), all LED road studs were spaced 8 m apart along curves.

2.3. Eye tracking

The eye-tracker revealed the driver's gaze behaviour following extraction of the gaze heatmaps. From an examination of these outcomes and in line with previous works (Fiolić et al., 2023; Land & Lee, 1994; Lappi, 2014; Lappi et al., 2013), we observed that drivers tended to focus their gaze on a specific element of the road while driving along the curve. Therefore, we established the five gaze targets showed in Figure 3 that indicate where each driver generally oriented his/her gaze: (i) the right edge marking (RM), (ii) the centreline marking (CM), (iii) the far point (FP), (iv) the left edge marking (LM), and (v) the lane centreline (LC). We calibrated a multinomial logit model to predict the probabilities of the various possible outcomes of a categorically distributed dependent variable, given a set of independent (real-, binary-, or categorical-valued) variables (see section 3.3).

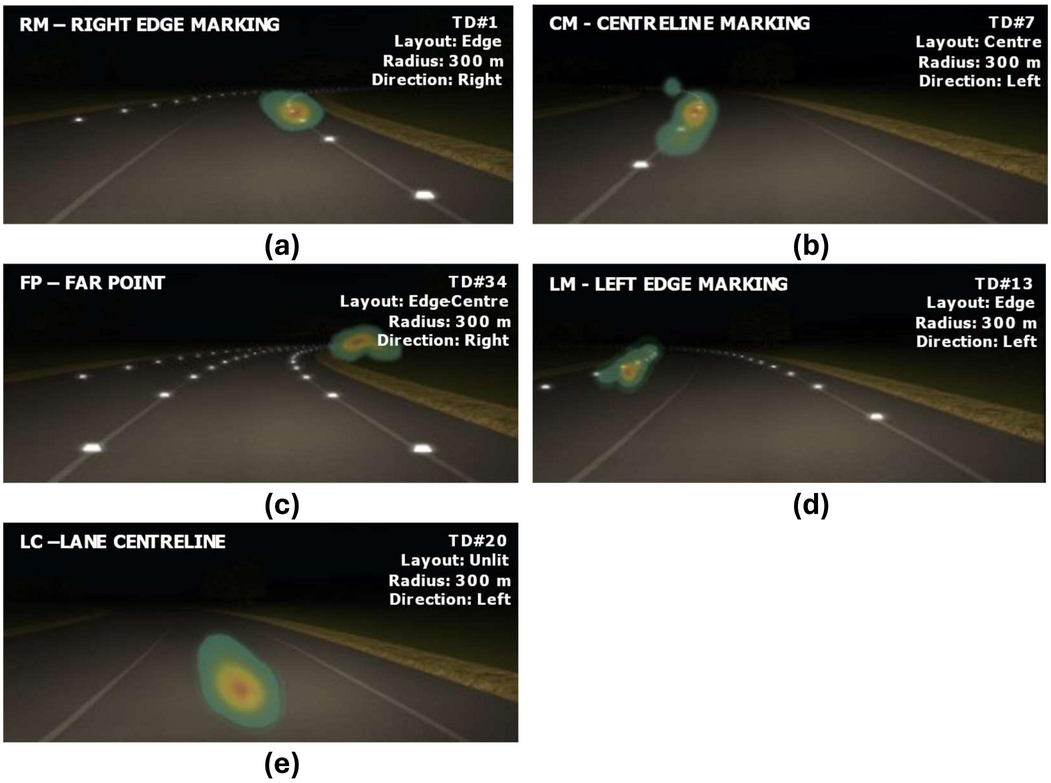


Figure 3. Pictures provide examples of gaze heatmaps retrieved from different test drivers (TD), which indicate the different road elements gazed at along the tests: (a) right edge marking (RM), (b) centreline marking (CM), (c) far point (FP), (d) left edge marking (LM), and (e) lane centreline (LC).

2.4. Participants

Participants were recruited by email from a list of more than four hundred volunteers who had already been involved in previous studies. Of those who accepted the invitation, thirty-five were randomly selected and took part in this repeated measure, within-subject fully randomized experiment, including males (20) and females (15) with ages ranging from 21 to 59 (M = 30.8; SD = 9.3). All drivers were required to have held a driving license for more than one year. Driving experience was adjudged by the kilometres travelled per year (M = 12,209; SD = 11,767) and the number of years in possession of a driver's license (M = 13; SD = 7.8). The participants signed an informed consent in accordance with the European General Data Protection Regulation form prior to the experimental session, and they did not receive any benefits or payments. The experiment was conducted in compliance with the Code of Ethics of the World Medical Association (WMA, 2013). The sample size was determined by G-power (Kang, 2021) setting the effect size at .25, the significance level (α) at .05, and the power at 95%.

2.5. Procedure

Participants were tested individually with a four-step protocol, consisting of (i) a pre-drive questionnaire, (ii) the driving simulator training, (iii) the eye tracker calibration, and (iv) the five simulations. Participants filled out a pre-questionnaire to collect personal information (age, driving story, general health state). Thereafter, they were introduced to the training session where they were shown the functions of the simulated vehicle; then they took part in a practice trial on a test circuit for at least 3 min to familiarize themselves with the simulator. After that, the eye tracker was fitted and calibrated. Finally, the simulation started, with the five scenarios employed following a complete balance design to minimize the potential confounding effects of treatment order, making the results more robust and generalizable, and ensuring a fair distribution of experimental conditions among participants. Between every two drives, a rest time of 1 min was administered. Before driving any new scenario, the eye tracker was recalibrated to maintain accuracy during the acquisition. To ensure an authentic reproduction of night driving conditions, the study was conducted in a completely dark room.

2.6. Statistical Analysis

Numerical data were analysed as per the repeated measures analysis of variance (RM-ANOVA). The significance level (α) was always set to .05. The Bonferroni correction for multiple comparisons was also applied. For the gaze data (categorical variable), the multinomial logistic regression model was used (Kwak &

Clayton-Matthews, 2002) to understand what factors influenced gaze behaviour. It extends the binary logistic regression model to handle categorical outcomes with more than two unordered categories. It estimates the probability of an observation belonging to each category as a function of independent variables.

3. Results

3.1. Speed behaviour

The speeds observed when approaching (TS termini) and in the middle of curves (CC termini) are shown in Figure 4. The figure evidences that right curves were always travelled at higher speeds than the corresponding left ones, and that drivers adopted higher speed values in the absence of road studs. The sharper the radius, the higher the speed reduction between the approaching zone (TS) and the curve centre (CC). Most importantly, it is evident that the presence of LED road studs resulted in lower speeds (when compared to unlit conditions) in all the layouts considered.

RM-ANOVA revealed that at a TS section the layout of road studs significantly influenced the speed ($F_{4,136} = 7.24$, $p < .001$), as well as the curve radius ($F_{3,102} = 49.52$, $p < .001$) and curve direction ($F_{1,34} = 97.17$, $p < .001$). Furthermore, the first-order interaction *Radius × Direction* revealed a significant effect ($F_{3,102} = 24.70$, $p < .001$). The post-hoc comparisons on road stud layouts revealed significant speed differences between unlit vs. edge (corrected-$p = .049$), and unlit vs. edge-centre (corrected-$p = .006$). Regarding curve radius, significant differences (corrected-$p < .05$) emerged between the sharpest radius (120 m) and the other radii (210, 300, and 440 m), with the lowest speed recorded along the sharpest one.

At CC termini, road stud layout and curve radius influenced driver speeds ($F_{4,136} = 9.88$, $p < .001$; and $F_{3,102} = 188.28$, $p < .001$, respectively). Two out of three two-way first-order interaction, i.e., the *Layout × Direction*, and *Radius × Direction*, were statistically significant ($F_{4,136} = 3.09$, $p = .018$; and $F_{3,102} = 5.84$, $p < .001$, respectively). Post hoc comparisons for road stud layouts revealed significant differences between unlit vs. edge (corrected-$p < .001$), unlit vs. edge-centre (corrected-$p < .001$), and unlit vs. lane (corrected-$p = .042$). As for curve radius, we observed significant differences across all the possible combinations (corrected-$p < .05$).

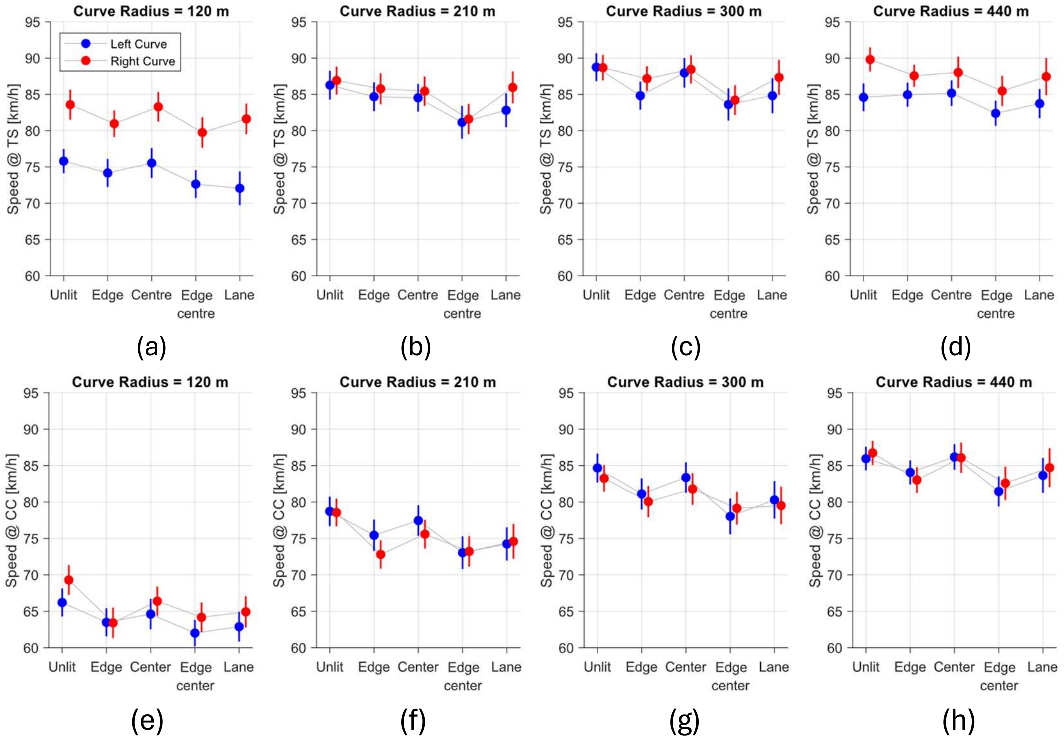


Figure 4. Speeds approaching the curve @TS termini (a,b,c,d), and at the centre of the curve @CC termini (e,f,g,h) across the four road stud layouts and the reference (unlit) condition. (a,e) Curves with a 120 m radius; (b,f) curves with a 210 m radius; (c,g) curves with a 300 m radius; and (d,h) curves with a 440 m radius. In all the graphs, the symbol indicates the average value, while the error bars indicate the standard error of mean.

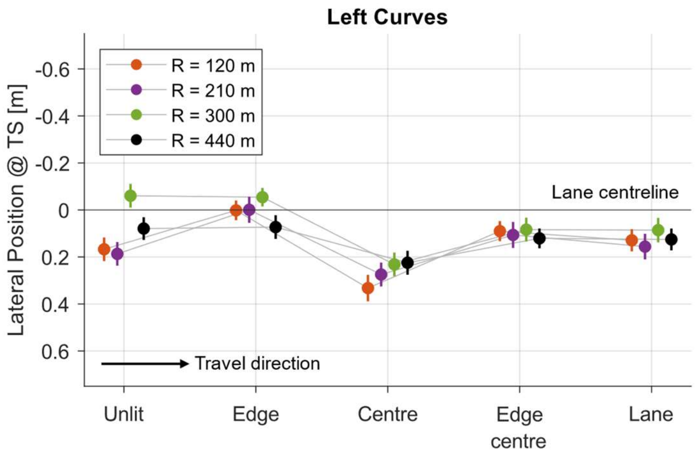
3.2. Lateral behaviour

Driver lateral behaviour along curves was measured through the lateral position and TS and CC termini in Figure 5, while the SDLP between the TS and ST termini is represented in Figure 6. We fixed the reference point in the middle of the lane, so positive lateral position values are on the right side of the lane centreline. The figure evidences that when entering the curve, the presence of LED road studs (used in the centre, edge centre, and to delimit the lane) prompts drivers to move toward the right side of the lane. A similar trend was observed for left curves at the CC termini, while a different trend was observed for right curves.

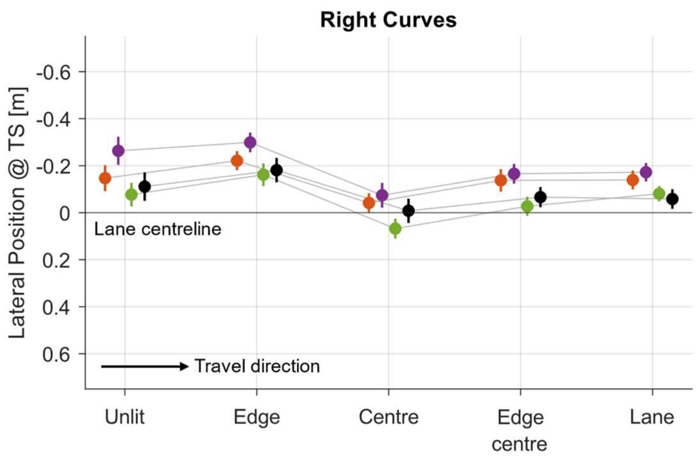
Approaching the curve (TS termini), LED road stud layouts significantly influenced the lateral position of drivers ($F_{4,136} = 25.79$, $p < .001$); additionally, curve direction was also found to have an influence ($F_{1,34} = 29.34$, $p < .001$). However, curve radius did not statistically influence the lateral position ($p > .05$). The layout × radius and radius × direction first order interaction revealed significant effects ($F_{12,408} = 1.80$, $p = .046$; and $F_{3,102} = 14.10$, $p < .001$, respectively). Finally, the second order interaction between the three experimental factors layout × radius × direction had an influence on lateral position ($F_{12,408} = 2.17$, $p = .012$). The post-hoc comparisons for road stud layouts revealed significant lateral position differences between unlit vs. edge (corrected-p = .024), and unlit vs. centre (corrected-p < .001).

At the CC site, road stud layout, and curve direction statistically influenced the driver's lateral position ($F_{4,136}$ = 63.77, p < .001; and $F_{1,34}$ = 25.99, p < .001, respectively). All the first and second order interactions, i.e., layout × radius, the radius × direction, and layout × radius × direction, revealed significant effects ($F_{4,136}$ = 28.10, p < .001; $F_{3,102}$ = 10.78, p < .001; and $F_{12,408}$ = 2.92, p < .001, respectively). The post-hoc analyses for road stud layouts showed significant lateral position differences between the following pairs: unlit vs. edge (corrected-p < .001), and unlit vs. centre (corrected-p < .001).

Figure 6 shows the results of SDLP along left and right curves. On left curves, the presence of LED road studs improves driver lateral control, especially along the smaller radius curves (120 and 210 m). A similar trend was observed along right curves, with the sole exception of the case related to road studs placed along the carriageway centreline, where SDLP values are within the domain of the unlit condition case for all the four investigated radii.



(a)



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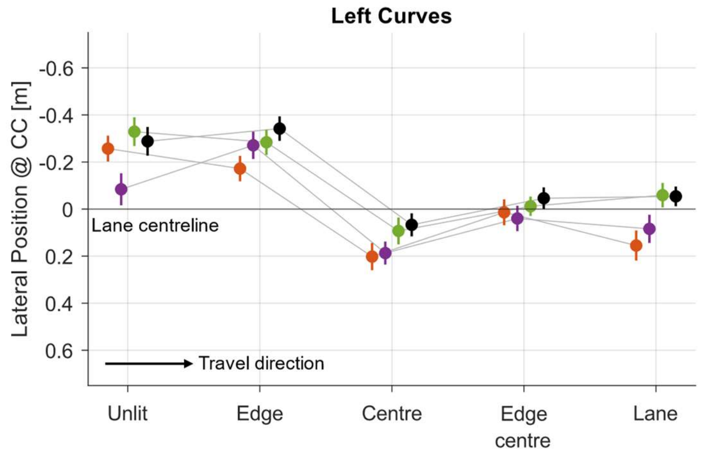
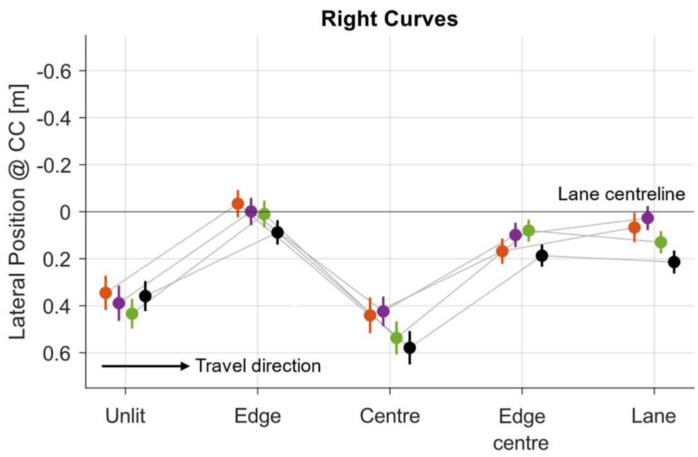


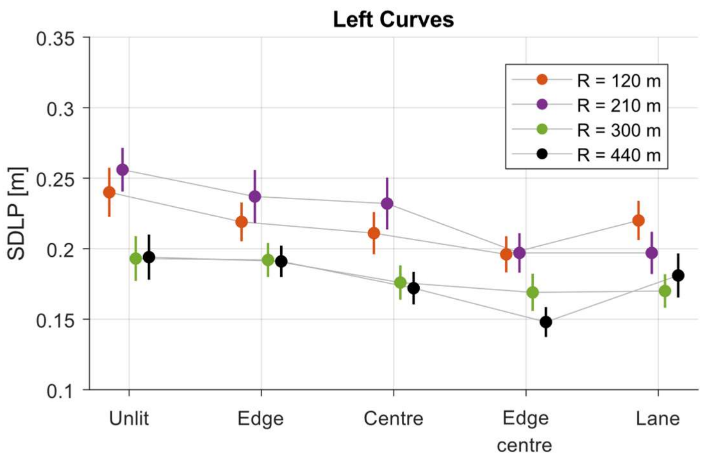
(c)



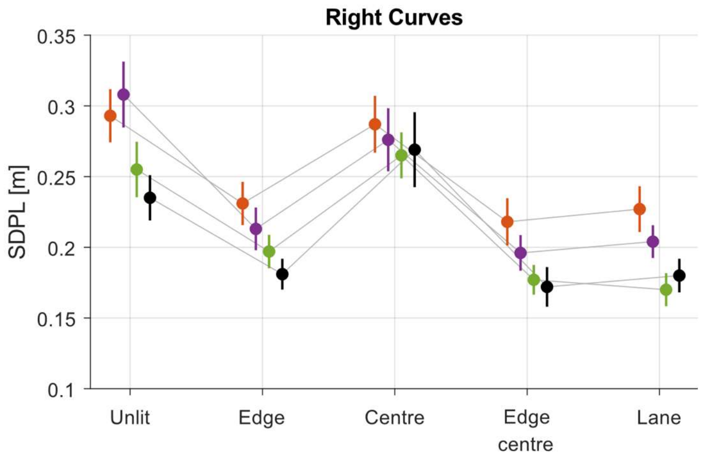
(d)

Figure 5. (a,b) Lateral position approaching the curve @TS termini, and (c,d) at the centre curve @CC termini for (a,c) left and (b,d) right curves. Negative values indicate that the vehicle CoG was on the left side of the lane centreline, while positive values indicate that the CoG was on the right side of the lane centreline. In all the graphs, the symbol indicates the average value, while the error bars indicate the standard error of mean.

RM-ANOVA reveals that SDLP was influenced by road stud layout ($F_{4,136} = 27.99$, $p < .001$), the curve radius ($F_{3,102} = 33.25$, $p < .001$) and curve direction ($F_{1,34} = 20.14$, $p < .001$). The first order *layout* × *direction* interaction was also found to be significant ($F_{4,136} = 14.73$, $p < .001$). Post hoc comparisons for road stud layouts indicate significant differences (corrected-$p < .05$) between unlit and edge, unlit and edge-centre, and unlit and lane. Concerning the effects of curve radii, we observed significant differences (corrected-$p < .05$) for all the possible combinations, except for the comparisons between 120 and 210 m, and between 300 and 440 m.



(a)



(b)

Figure 6. Standard deviation of lateral position (SDLP) recorded between the tangent-to-spiral (TS) and spiral-to-tangent (ST) termini for the different road stud layouts, curve radii and (a) left and (b) right curve directions. In all the graphs, the symbol indicates the average value, while the error bars indicate the standard error of the mean.

3.3. Gaze behaviour

The gaze data were analysed by conducting a multinomial logistic regression analysis to determine the predominant zone or element fixated upon by drivers when negotiating curves with different road stud layout, radius, and direction. The results of the omnibus likelihood ratio test performed to calibrate the model revealed that the *p*-value associated with the curve radius was .208, i.e., the curve radius did not impact on the gaze strategy adopted by drivers. We then calibrated a new model considering layout and curve direction as factors influencing drivers' gaze behaviour. A good model-data agreement (Deviance = 2699), and a favourable balance between goodness of fit and model complexity (AIC = 2747, BIC = 2866) were achieved. The global significance test using the chi-square statistic was highly significant ($\chi^2 = 241$, df = 20, $p < .001$), underscoring the statistical superiority of the model over a null model.

These results collectively support the suitability of the multinomial logit model for elucidating the relationships between predictor variables and response variable categories. However, it is noteworthy that the value of $R^2 = .0820$ accounts for a limited proportion of the explained variance, implying the potential influence of unaccounted factors (e.g., gender, age, driving experience, speed, visibility). The predicted probability of fixing a specific area or element estimated by the model is provided in Figure.

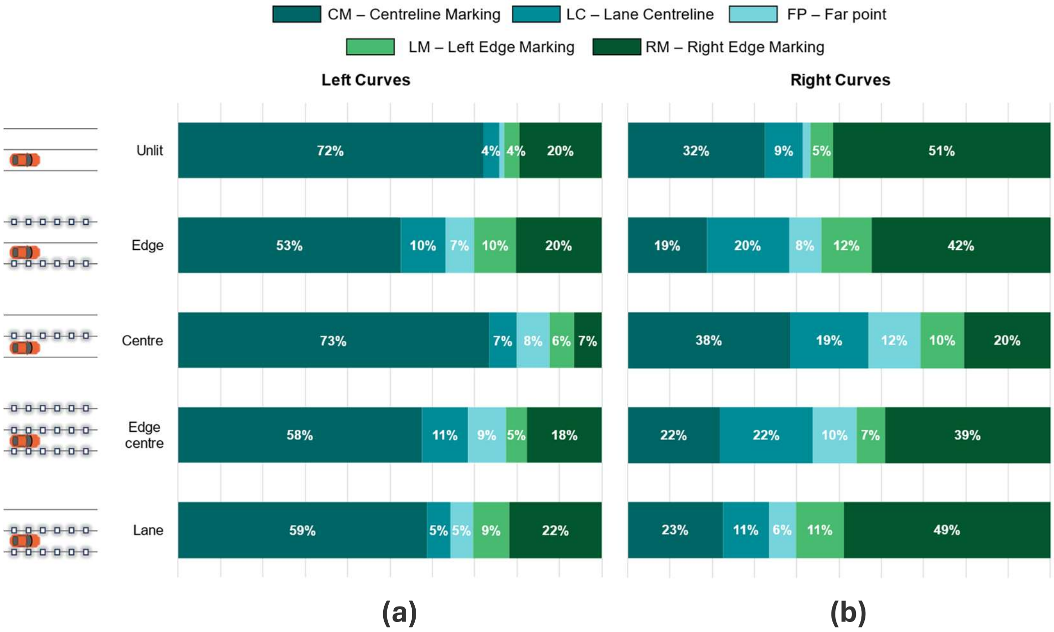


Figure 7. Predicted probability of looking at an area or element across the five different road stud layouts for (a) left curves and (b) right curves.

4. Discussion

4.1. Longitudinal behaviour

Regarding the effects of layout on speeds, we observed that the presence of LED road studs led to a reduction in speed compared to the unlit condition (Figure 4). It is worth noting that a reduction in speed resulting from the implementation of a road treatment is considered beneficial in safety terms, since it suggests greater prudence when negotiating curves, reduces the risk of a collision, and may lower the severity in the event of a crash. In our experiment, we observed significantly lower speeds with respect to the unlit (reference) conditions when we adopted a layout in which the driver sees the LED studs along both the edge and centre of the carriageway. In fact, in both TS and CC termini, the edge centre layout provided the highest and most statistically significant speed reduction (mean difference of 4.2

and 5.0 km/h, respectively). We argue that this arrangement improves drivers' awareness of the position of their vehicle, while also prompting a reduction in speed to provide more lateral control as the vehicle approaches the curve. The driver therefore needs to adopt and maintain a lower speed to better negotiate the curve while steering the vehicle into the lane, as evidenced well in Figure 4 (lower speed values in the CC section are evidenced in comparison to the TS section).

Other positive results for speeds come from the edge-centre and the lane layouts at the CC sections (mean difference of 3.7 and 3.6 km/h, respectively). With these two layouts, the driver is forced to adopt the appropriate speed required to maintain the vehicle within the boundaries of the marked lane. Conversely, the centre layout exhibited no statistically significant differences with respect to the unlit condition. Taken together, the results suggest that when the lane or the carriageway are fully delimited, the spatial perception of the curve entry section improves, and also that drivers react with a greater degree of caution when approaching the curve. We also believe that this result is related to the specific distribution of the LED road studs along the track, since they were installed on the curved sections only. We would anticipate that a uniform distribution on both straight and curved sections of a track could produce different effects on speed, but this implies higher installation and maintenance costs.

Differences and similarities between this and other studies related to identical or similar safety countermeasures, e.g., retroreflective markings, should also be viewed in light of the differences in the environmental visibility conditions at night-time (i.e., normal vs. reduced visibility), and the distribution of the treatments along the road (i.e., uniform vs. along curves only). Our findings on speed are aligned with our previous research (Portera et al., 2023) where the use of white and red LED road studs with the edge layout did not lead to an increase in vehicle speed compared to the unlit condition. The results also resonate with the outcomes reported by Llewellyn et al. (2021) on real roads, and Shahar et al. (2018) on simulated roads, who recorded no relevant before/after variations in speed between unlit and uniformly LED studded road segments including both straights and curves, as well as approach stretches to intersections. Conversely, Fiolić et al. (2023) observed that an improvement in the quality of horizontal road strips vis-à-vis the use of high-performance retroreflective marking results in an increase in driving speed. However, it should be noted that this increase was a modest one at 2% only albeit it occurred along both curves and straights. In conclusion, we believe that when LED road studs are installed along curves, drivers negotiate the same curves more cautiously, as their perception of the geometry of the road ahead is improved by the delimitation of the space within which to drive the vehicle.

4.2. Lateral behaviour

It is widely accepted that the implementation of a road treatment improves the lateral behaviour of vehicles when drivers (i) stay closer to the lane centreline, as this minimizes the risk of collision with both oncoming vehicles and potential fixed roadside installations (Bassani et al., 2019), and (ii) decrease the number of steering wheel corrections performed in order to maintain their intended trajectory (Verster & Roth, 2011). In this study, the analysis of lateral behaviour, i.e., lateral position and SDLP, revealed statistically significant differences between the two curve directions and the four road stud layouts. Considering the influence of gaze on the transversal behaviour of drivers, the analysis and interpretation of lateral behaviour was conducted in light of the results obtained through the observation of gaze behaviour (see previous Section 3.3). Additionally, it is worth noting that the vehicle cockpit was displayed on the vision system during the simulations (Fisher et al., 2011). The presence of the cockpit influences the visibility of road markings and studs in the immediate surroundings of the vehicle.

Figure 7a shows that on left curves in unlit conditions the majority of drivers (i.e., three out of four) direct their gaze at the central marking, relying on this line for visual guidance. It is worth noting that drivers seem to react to the sight of the studded lateral marking by shying away from the studs (Figure 5c). We believe that this behaviour is the same as that observed by Gates et al. (2012) in the case of rumble strips. Indeed, rumble strips are perceived as an obstacle to be avoided and this behaviour was replicated in our experiment when drivers cautiously kept a certain distance from the LED road studs to avoid contact with the wheels. With the presence of the visual guidance offered by the stud delineation on the right marking (i.e., edge, edge centre, and lane), the average lateral position fell close to the lane centreline (i.e., around the 0 value). In this scenario, a visual "gate" effect was observed (Ariën et al., 2013). The road studs placed along the two horizontal markings delimiting the lane helps the driver to maintain a centred trajectory within said lane.

Along right curves in unlit conditions, two out of four drivers look at the right edge marking (Figure 7b). Again, in studded conditions, more drivers stayed further to the left in the lane as a reaction to the augmented perception of the marking. Figure 5b and Figure 5d illustrate this behaviour, with data referred to edge, edge centre and lane layouts, with lateral position values smaller (around the null value) than those for the unlit condition and a centre layout resulting from a combination of the “gate” and “shy away” effects.

These results also concur with our earlier observations (Portera et al., 2023) in which different lateral behaviours with the edge layout for left and right curves were evaluated. As in previous experiments, we found that the edge layout was only effective on right curves. Moreover, this finding agrees with that of Shahar et al.

(2018) and Shahar & Brémond (2014), who found that the edge-centre layout improved the lateral position on both left and right curves.

Viewed as a whole, the results for lateral position indicate better lateral behaviour and safer outcomes in favour of layouts where the lane is fully delineated by LED road studs, i.e., the edge centre and lane layouts. Accordingly, the SDLP outcomes indicate that these two layouts are associated with the smallest values for this behavioural parameter. In other words, when the lane is delineated with LED road studs on both sides, drivers significantly improve their lateral control with respect to the unlit condition. In contrast, when LED studs are installed along the central marking only, there is a deterioration in driver lateral control with SDLP values similar to those recorded in unlit conditions, in particular along right curves.

4.3. Gaze behaviour

The gaze behaviour depicted in Figure 7a indicates that along left curves drivers generally oriented their gaze towards the centreline marking (CM). Our analyses on heatmaps suggest that drivers normally negotiated left curves by adopting the tangent point mechanism (Land & Lee, 1994), with other road elements being less frequently utilized. As drivers switched driving scenario from unlit to edge layout, some individuals shifted their gaze from CM to alternative approaches aligned with the placement of studs. Similarly, the centre layout appeared to have a significant impact on drivers' gaze behaviour, prompting a majority to focus on the centreline marking (CM), particularly those who initially had the same gaze target in the unlit condition. These findings suggest that the different LED road stud layouts influenced the gaze behaviour of some drivers only, while others maintained the gaze already exhibited in unlit conditions. Conversely, in the cases of edge centre and lane layouts, the fixated elements exhibited substantial divergence. This discrepancy is likely attributable to the abundance of delineations which means drivers can choose from a number of road elements for visual guidance.

For right curves in unlit conditions (Figure 7b), the predominant gaze target was the RM (51% of the cases). In this case, RM activates the tangent point mechanism. However, the CM target was also gazed at by a relevant percentage of drivers (32%). Upon transitioning from unlit to edge layout, drivers who initially used the CM as their gaze target shifted to look at the RM and LM, corresponding to the areas where studs were installed. In the case of the centre layout, the percentage of drivers who looked at CM increased significantly (to almost two out of five). Finally, as for left curves, the edge centre and lane layouts offered a diversified range of gaze behaviours, with an increment in those adopting the tangent point mechanism to orient their gaze towards the right marking (RM).

Overall, these results reveal that any change in driver gaze behaviour is only partly conditioned by the roadway delineation systems. Some drivers keep their gaze directed toward elements of the road space that are not illuminated, while others modify their behaviour seemingly without explanation. While these results may highlight our failure to consider other factors that might influence the decision on what to look at along a curve, it does highlight the complex and subjective nature of the human decision-making process in terms of what we choose to look at when behind the steering wheel (Lappi et al., 2013). Along the roadway, a series of intrinsic and extrinsic factors may play a role in influencing driver gaze behaviour. Finding measures that harmonize the gaze patterns of all drivers in a uniform manner is challenging and the complexity of gaze behaviour was evident even in the dark driving scenario we dispensed to participants in which few road elements were clearly visible. In conclusion, our results illustrate the complex nature of the gaze behaviour adopted by drivers during curve negotiation, but do not identify the particular gaze patterns predominantly used in each layout. Nevertheless, the behavioural results do indicate that the presence of LED road studs improves curve negotiation behaviour, particularly in terms of vehicle transverse position and trajectory control. The variability in visual behaviour is, therefore, attributable to the driving habits of individual drivers. While the presence of LEDs benefited drivers (by providing them with the necessary optical guidance to accurately negotiate the curves), this effect was not uniform across all drivers.

4.4. Layout-curve direction interaction

The three RM-ANOVAs carried out on the dependent variables of this study, i.e., speed, lateral position and SDLP, evidenced that the two way first order interaction between the road stud layout and the curve direction was always significant (see Section 3 for more details). The three variables shown in Figure 8 confirm that the edge centre and lane layouts performed better overall since they help drivers to negotiate the curves at a lower speed (Figure 8a), to maintain a central trajectory in the lane (Figure 8b), and enable better lateral control of the vehicle within the lane (Figure 8c). It is worth noting that the differences between the performances of the two above-mentioned layouts with the unlit condition are always statistically significant (corrected-$p < .05$). These results are consistent with (Charlton, 2007), who demonstrated how marking treatments that delineate the curve and increase the momentary perception of speed induce drivers to enter the curve at a lower speed. In this work, we confirm and extend the outcomes from Charlton (2007) also for night-time driving conditions.

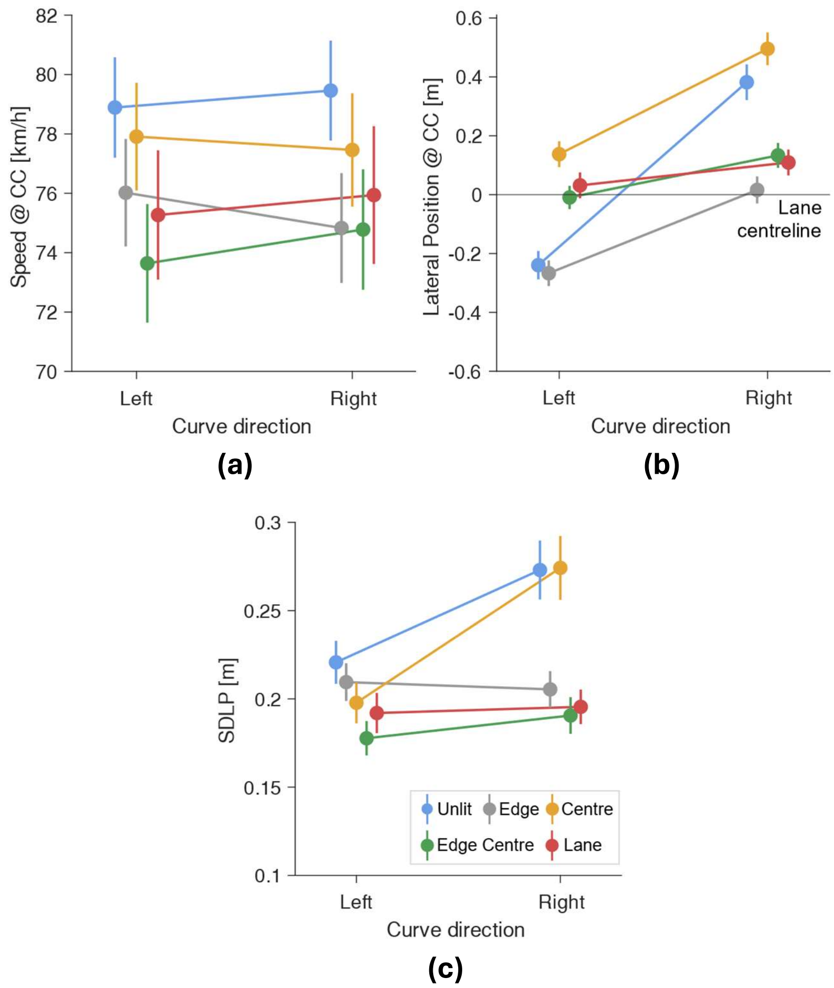


Figure 8. Two-way first-order interaction between the road stud layout and the curve direction for (a) speed, (b) lateral position, and (c) standard deviation of lateral position (SDLP). Points indicate average values, while bars the standard error of the mean.

5. Conclusions

In this study, we assessed the effects of four different white LED road stud layouts along horizontal curves on driving performance and gaze behaviour. From data analyses, we concluded that the presence of LED road studs enabled drivers to maintain a more safety-oriented behaviour with respect to the unlit condition. In particular, the use of LED road studs encourages drivers to adopt appropriate speeds when approaching and negotiating curves. An analysis of transversal behaviour revealed that at the centre of the curve, the road stud layout had a significant impact on lateral position, and this effect varied between left and right curves. Notably, certain layouts promoted better lateral control on left curves, while others were more effective on right curves.

Furthermore, our investigation into gaze behaviour revealed interesting patterns. Although the results did not reveal a common tendency in gaze behaviour, we observed that the vision system of drivers was positively influenced by LED stud illuminated curves, enabling drivers to improve their transversal behaviour.

Taken together, our findings highlight the link between the significant and positive improvement in driver behaviour during night time conditions and the adoption of LED road studs. Furthermore, when choosing a particular road stud layout, it is imperative to consider the curve direction. For both left and right curves, the "edge centre" and “lane” layouts emerge as the optimal choice for improving driving performance. They allow drivers to maintain control of a central trajectory within the lane, reducing the likelihood of a collision with oncoming vehicles or fixed installations along the roadside. These two layouts involve different installation and maintenance costs. It is worth noting that the “lane” layout requires the same number of road studs as the “edge-centre” one, considering that the same curve requires road studs in both directions. However, road studs on the centreline that direct the light beam in the two opposite directions are only necessary in the “lane” layout, while along the two marking strips delimiting the carriageway road studs equipped with a unidirectional beam would suffice.

The simplicity of our road scenarios, characterized by free-flow conditions involving only horizontal curves, together with weather conditions that favour visibility (dry road surface, no fog), may somewhat limit the external applicability of our findings. For this reason, it is recommended that future research efforts examine the solutions proposed here while also considering the influence of other environmental factors. It is important to note that our study lacked the presence of oncoming vehicles or other road lighting devices, resulting in changes in ambient luminance determined primarily by LED lights. Therefore, the results should be interpreted with caution, and future studies should mitigate the influence of other potentially confounding variables. It should be noted that the effect of simulated LED road studs may differ from that observed on real roads due to potential differences in brightness perceived by drivers. Therefore, future research should include a validation study to determine whether any difference in visual perception between real and simulated LED road studs may result in differences in behaviour on the road and in the driving simulator. Another aspect to consider in future studies is the relationship between gaze strategies and driving performance for different types of road markings (unlit vs. studded) and ambient lighting conditions (daytime vs. night-time). A greater understanding of this relationship would help us understand whether prompting drivers to adopt specific gaze patterns is beneficial for road safety. Finally, field tests are recommended to validate the results obtained here and ensure the real world applicability of our research outcomes.

References

Ackaah, W., Apuseyine, B. A., & Afukaar, F. K. (2020). Road traffic crashes at night-time: Characteristics and risk factors. International Journal of Injury Control and Safety Promotion, 27(3), 392–399. https://doi.org/10.1080/17457300.2020.1785508

Angioi, F., Portera, A., Bassani, M., De Oña, J., & Stasi, L. L. D. (2023). Smart on-Road Technologies and Road Safety: A short overview. Transportation Research Procedia, 71, 395–402. https://doi.org/10.1016/j.trpro.2023.11.100

Ariën, C., Jongen, E. M., Brijs, K., Brijs, T., Daniels, S., & Wets, G. (2013). A simulator study on the impact of traffic calming measures in urban areas on driving behavior and workload. Accident Analysis & Prevention, 61, 43-53.

Bassani, M., Catani, L., Ignazzi, A., & Piras, M. (2018). Validation of a Fixed-Base Driving Simulator to Assess Behavioural Effects of Road Geometrics. Proceedings of the Driving Simulation Conference 2018 Europe VR, 101–108.

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

Boyce, P. R. (2008). Lighting for Driving: Roads, Vehicles, Signs, and Signals (1st ed.). CRC Press. https://doi.org/10.1201/9781420008159

Catani, L., & Bassani, M. (2019). Anticipatory Distance, Curvature, and Curvature Change Rate in Compound Curve Negotiation: A Comparison between Real and Simulated Driving. 98th Annual Meeting of the Transportation Research Board, Washington, DC.

Charlton, S. G. (2007). The role of attention in horizontal curves: A comparison of advance warning, delineation, and road marking treatments. Accident Analysis & Prevention, 39(5), 873–885. https://doi.org/10.1016/j.aap.2006.12.007

Chen, H., Chen, Q., Chen, L., & Zhang, G. (2016). Analysis of risk factors affecting driver injury and crash injury with drivers under the influence of alcohol (DUI) and non-DUI. Traffic injury prevention, 17(8), 796-802.

Fiolić, M., Babić, D., Babić, D., & Tomasović, S. (2023). Effect of road markings and road signs quality on driving behaviour, driver's gaze patterns and driver's cognitive load at night-time. Transportation Research Part F: Traffic Psychology and Behaviour, 99, 306–318. https://doi.org/10.1016/j.trf.2023.10.025

Fisher, D. L., Rizzo, M., Caird, J., & Lee, J. D. (Eds.). (2011). Handbook of driving simulation for engineering, medicine, and psychology. CRC press.

Gates, T. J., Savolainen, P. T., Datta, T. K., Todd, R. G., Russo, B., & Morena, J. G. (2012). Use of both centerline and shoulder rumble strips on high-speed two-lane rural roadways: Impact on lateral lane position and passing maneuvers of vehicles. Transportation Research Record, 2301(1), 36-45. https://doi.org/10.3141/2301-05

Legislative Decree 30 April 1992, No. 285: Public Procurement Code. Retrieved from https://www.gazzettaufficiale.it/eli/id/1994/03/22/093A6158/sg, (1993).

Johansson, Ö., Wanvik, P. O., & Elvik, R. (2009). A new method for assessing the risk of accident associated with darkness. Accident Analysis & Prevention, 41(4), 809–815. https://doi.org/10.1016/j.aap.2009.04.003

Kang, H. (2021). Sample size determination and power analysis using the G*Power software. Journal of Educational Evaluation for Health Professions, 18, 17. https://doi.org/10.3352/jeehp.2021.18.17

Kwak, C., & Clayton-Matthews, A. (2002). Multinomial Logistic Regression. In Nursing Research (Nursing Research 51(6):p 404-410, Vol. 51, Fascicolo 6, pp. 404–410). https://journals.lww.com/nursingresearchonline/fulltext/2002/11000/multinomial_logistic_regression.9.aspx

Land, M. F., & Lee, D. N. (1994). Where we look when we steer. Nature, 369(6483), 742–744. https://doi.org/10.1038/369742a0

Lappi, O. (2014). Future path and tangent point models in the visual control of locomotion in curve driving. Journal of Vision, 14(12), 21–21. https://doi.org/10.1167/14.12.21

Lappi, O., Lehtonen, E., Pekkanen, J., & Itkonen, T. (2013). Beyond the tangent point: Gaze targets in naturalistic driving. Journal of Vision, 13(13), 11–11. https://doi.org/10.1167/13.13.11

Liu, J., Li, J., Wang, K., Zhao, J., Cong, H., & He, P. (2019). Exploring factors affecting the severity of night-time vehicle accidents under low illumination conditions. Advances in Mechanical Engineering, 11(4), 168781401984094. https://doi.org/10.1177/1687814019840940

Llewellyn, R., Cowie, J., & Fountas, G. (2021). Solar-Powered Active Road Studs and Highway Infrastructure: Effect on Vehicle Speeds. Energies, 14(21), 7209. https://doi.org/10.3390/en14217209

Llewellyn, R., Cowie, J., & Maher, M. (2020). Active Road Studs as an Alternative to Lighting on Rural Roads: Driver Safety Perception. Sustainability, 12(22), 9648. https://doi.org/10.3390/su12229648

Ministero delle Infrastrutture e dei Trasporti - MIT. (2001). Norme funzionali e geometriche per la costruzione delle strade (in Italian). D.M. no. 6792 of November 5th. Istituto Poligrafico dello Stato Roma,, Italy.

NHTSA. (2008). Fatality Analysis Reporting System General Estimates System: 2008 Data Summary: (625002012-001) [dataset]. American Psychological Association. https://doi.org/10.1037/e625002012-001

Owens, D. A., & Sivak, M. (1996). Differentiation of Visibility and Alcohol as Contributors to Twilight Road Fatalities. Human Factors: The Journal of the Human Factors and Ergonomics Society, 38(4), 680–689. https://doi.org/10.1518/001872096778827233

Plainis, S. (2006). Road traffic casualties: Understanding the night-time death toll. Injury Prevention, 12(2), 125–138. https://doi.org/10.1136/ip.2005.011056

Portera, A., Angioi, F., Muzzioli, L., Di Stasi, L. L., & Bassani, M. (2023). The influence of LED road stud color on driver behavior and perception along horizontal curves at nighttime. Transportation Research Part F: Traffic Psychology and Behaviour, 96, 66–75. https://doi.org/10.1016/j.trf.2023.06.007

Reed, N. (2006). Driver Behaviour In Response To Actively Illuminated Road Studs: A Simulator Study. Published Project Report 143." Transport Research Laboratory, Crowthorne.

Shahar, A., & Brémond, R. (2014). Toward smart active road studs for lane delineation. In TRA2014-Transport Research Arena: Transport Solutions: from Research to Deployment-Innovate Mobility, Mobilise Innovation!

Shahar, A., Brémond, R., & Villa, C. (2018). Can light emitting diode-based road studs improve vehicle control in curves at night? A driving simulator study. Lighting Research & Technology, 50(2), 266–281. https://doi.org/10.1177/1477153516660146

Varghese, C., & Shankar, U. (2007). Passenger Vehicle Occupant Fatalities by Day and Night. A Contrast (No. HS-810 637). NHTSA's National Center for Statistics and Analysis, 1–8, 51(4), 443.

Verster, J. C., & Roth, T. (2011). Standard operation procedures for conducting the on-the-road driving test, and measurement of the standard deviation of lateral position (SDLP). International journal of general medicine, 359-371.

WMA. (2013). World Medical Association Declaration of Helsinki: Ethical principles for medical research involving human subjects. JAMA, 310(20), 2191–2194. https://doi.org/10.1001/jama.2013.281053

Wood, J. M. (2020). Nighttime driving: Visual, lighting and visibility challenges. Ophthalmic and Physiological Optics, 40(2), 187–201. https://doi.org/10.1111/opo.12659

Zhang, G., Yau, K. K., Zhang, X., & Li, Y. (2016). Traffic accidents involving fatigue driving and their extent of casualties. Accident Analysis & Prevention, 87, 34-4

Paper D

Red LED Strip Signalling Pedestrian Presence at Uncontrolled Mid-block Crosswalks

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Abstract

A relevant number of collisions between vehicles and pedestrians occur at night because of the reduced capacity of a driver to perceive and react to the presence of pedestrians at crosswalks. To reduce this risk of collision, new smart road technologies have been introduced. This study aims to evaluate the effectiveness of a red LED strip that warns the driver of the presence of pedestrians at unsignalized mid-block crosswalks at night-time. The technology consists of LED strips installed near the crosswalk on the side of oncoming vehicles. The LED is activated when a sensor detects a pedestrian approaching the crosswalk. In this driving simulation experiment, three different urban mid-block crosswalks were evaluated: (i) without an LED strip (baseline), (ii) with a fixed LED strip, and (iii) with a flashing LED strip. Each scenario was tested for three different levels of pedestrian time gap acceptance (PTGA) (i.e., 4, 6, 8 s) and two road sections (i.e., 1 lane vs. 2 lanes). Thirty-six participants took part in a within subjects' design. During the experiment, the minimum time to collision (mTTC), the post encroachment time (PET), maximum vehicle speed, and reaction distance were monitored to quantitatively compare the different levels of vehicle pedestrian interaction. Compared to the baseline, the LED strip resulted in a safer driver-pedestrian interaction, with an average increase in mTTC of 1.13 s, PET of 0.66 s and a longer average reaction distance of 7.9 m. However, a slight (albeit not statistically significant) increase in speed was observed following installation of the LED strip. Furthermore, no significant differences were observed between fixed and flashing LED strips. Overall, these results confirm the LED strips effectiveness in alerting the driver to the presence of a pedestrian, thus increasing the safety of their interaction. Further studies should confirm these findings in a more ecological way, e.g., evaluating the safety impact of this technology under different weather and distracted driving conditions.

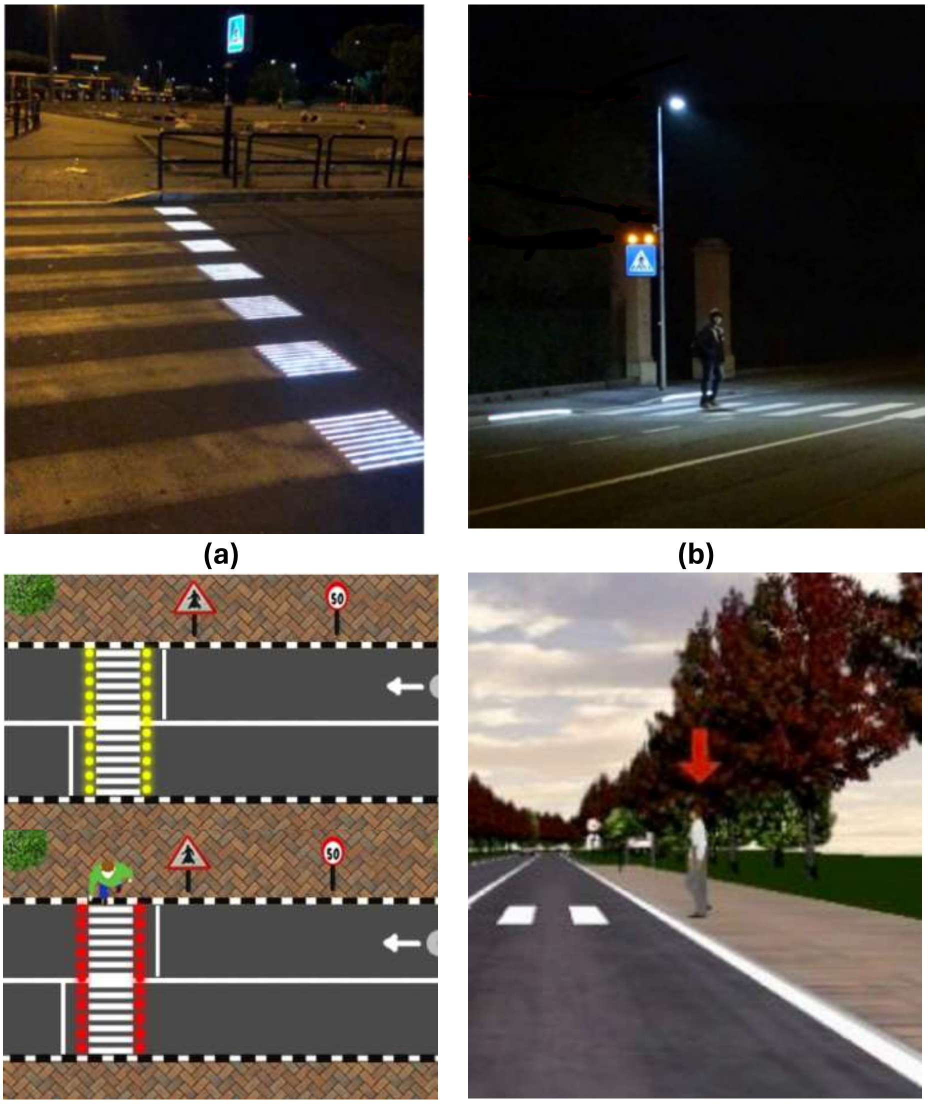
1. Introduction

The Decade of Action for Road Safety 2021-2030 (WHO, 2021) sets the ambitious target of preventing at least 50% of road traffic deaths and injuries by 2030. Worldwide, road traffic crashes cause more than 1.3 million preventable deaths and an estimated 50 million injuries every year – making it the leading cause of death for children and people aged 5-29 worldwide. Within these statistics, vulnerable road users (VRU), i.e., pedestrians, cyclists, two-wheelers and persons with disabilities, account for more than 50% of all road traffic deaths, with many of these occurring in urban areas. Another aspect meriting careful consideration is the number of collisions at night between vehicles and VRU, mainly due to poor visibility and insufficient lighting conditions that negatively affect the braking reaction of drivers (Owens and Sivak, 1996; Plainis, 2006; Sullivan and Flannagan, 2002).

Literature has paid special attention to pedestrian safety at mid-block crosswalks where they are most at risk of colliding with vehicles. In recent years, research has focused on using smart technologies as a safety countermeasure. Some technologies are able to detect the presence of conflicting road users and alert drivers in advance. A solution has been proposed by Patella et al., (2020) with the LED-lit pedestrian crossing. They installed and tested this technology in Rome (close to the "Anagnina" subway). The smart crossing, consisting of panels containing 9 LED stripes (Fig. 1a), contributed to a 19.3% reduction in average vehicle speed, reducing the hazardousness of the conflict. Flashing in-curb LED strips and beacons (Fig. 1b) installed and tested in Bologna (Italy) at unsignalized pedestrian crossings have been proposed by Lantieri et al., (2021). This solution significantly increased the yield compliance and pedestrian detection distance. Hussain et al., (2023, 2021) tested the effectiveness of a system called ITS_LED (Fig. 1c) and observed a positive increment in yielding rates and a reduction in the vehicle-pedestrian conflict severity. Augmented reality (AR) in-vehicle technologies have also been used to increase driver awareness of the presence of pedestrians. A study by Calvi et al., (2020) tested the effectiveness of an AR system alerting the driver to a pedestrian ahead by placing a red arrow on the head of the pedestrian (Fig. 1d). The results were positive with drivers starting to slow down well before the crossing when the AR was active, with high time-to-collision and time-to-zebra values.

Although smart crosswalks have been explored in literature, the majority remain purely conceptual with little information on their impact on the behaviour, acceptance, and mental workload of drivers with a notable lack of information on the safety effectiveness of LED strip crosswalks. LED strips are installed along crosswalks and alert drivers to the presence of crossing pedestrians. It is worth noting that any smart technology, including LED strips, should not replace basic road safety hardware such as lighting, road markings, and pedestrian signs, which should be considered standard safety installations.

In this study, we evaluated the effectiveness of red LED strips at uncontrolled mid-block crosswalks on urban roads at night. In this regard, the LED strip was tested with two light configurations. i.e., fixed and flashing at a 2Hz frequency, and then compared with a traditional uncontrolled crosswalk (the baseline). The proposed technology was aimed at reducing the hazardousness of conflicts between vehicles and pedestrians.



(a) (b) (c) (d)

Figure 1. Case (a) crosswalks was proposed by Patella et al., 2020, with crosswalk delimited by LED panels installed at the edges of each zebra crossing. The LED lights switch on when a pedestrian passes under the optical sensor. Case (b) was proposed by Lantieri et al., 2021, with in-curb LED strips that were activated by a movement sensor, a "yield here to pedestrians" sign, orange beacons positioned above the sign, and LED lamps. Case (c) was proposed by Hussain et al., (2023), with a smart detection-based-in-pavement LED light unit. This system warned drivers when a pedestrian was detected along the road. In the first situation (without pedestrians), the yellow LED light flashes. When a pedestrian is detected at the edge of the crosswalk the same strip changes to flashing red lights. Case (d) was proposed by Calvi et al., (2020), with AR warning systems implemented in the driving simulator to alert drivers to a pedestrian on the sidewalk. The visual warning system consisted of a red arrow above the pedestrian which tracks the pedestrian during the crossing.

2. Method

2.1. Participants

Thirty-six participants (11 females) were randomly selected from a database of more than 500 available participants recruited with a message disseminated through the social media of the Politecnico di Torino. The sample included drivers aged between 24 and 51 (mean = 30.7, SD = 6.6). All drivers voluntarily took part in the activity without receiving any monetary compensation. The experiment was conducted in compliance with the World Medical Association's Code of Ethics (WMA, 2013). The drivers were unaware of the hypothesis under investigation.

2.2. Experimental design

The experiment was conducted following a within-subject design with 3 experimental factors: (i) LED strip, (ii) pedestrian time gap acceptance (PTGA), and (iii) the road section type. The LED strip was the main factor and was tested under three different conditions: (i) no LED strip along the crosswalk (baseline), (ii) LED strip with fixed lights and (iii) LED strip with flashing lights. For the PTGA, the three values of 4, 6 and 8 s already used by Angioi and Bassani (2022) were adopted. PTGA is the time gap from when the pedestrian started crossing the road to when the vehicles reached the conflicting point in the crosswalk. PTGA can be viewed as an indicator of pedestrian aggressiveness: the smaller the PTGA, the higher the risk assumed by the pedestrian in traversing the road in front of the oncoming vehicle. Finally, to account for the change in driver behaviour on different road types, measurements were taken along road segments with (i) one and (ii) two lanes per direction.

From a combination of these factors, three urban scenarios were designed. The first involved crosswalks with no LED strip and a combination of the other experimental factors (3 PTGA × 2 road sections). The second scenario included crosswalks with fixed LED strips and the same combination of the other two factors. The third scenario consisted of crosswalks with flashing LED strips and, again, the same combination of the two other experimental factors.

We monitored surrogate measures of safety like the (i) maximum speed of vehicle recorded from 100 m before the crosswalk, (ii) the distance from the crosswalk at which the driver reacts to the presence of the pedestrian (reaction distance) by acting on the brake pedal, (iii) the minimum time to collision (mTTC) between vehicle and pedestrian, and (iv) the post encroachment time (PET). We also evaluated the effects of the LED strips on subjective mental workload using the NASA-TLX questionnaire.

mTTC is the minimum time (i.e., the most critical) remaining before a collision between two moving entities that occurs if they continue on their intended path with the same speeds and trajectories (Hayward, 1971). In our study, we considered a TTC of 3 s to discriminate between cases where drivers unintentionally find themselves in a dangerous situation (i.e., conflict) and cases where drivers remain in control.

PET represents the time difference between a dynamic entity leaving the area of encroachment and another dynamic entity entering the same area (Peesapati et al., 2018). Three categories for PET can be identified according to Angioi and Bassani, (2022): (i) undisturbed passage for PET ≥ 5 s, (ii) conflict 0 < PET ≤ 5 s, and (iii) crash when PET = 0 s.

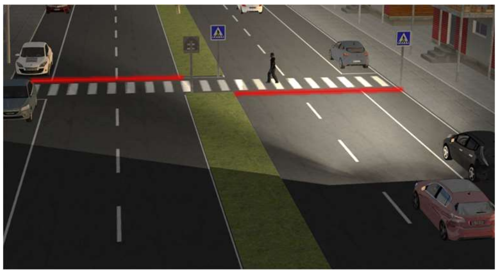
2.3. *Equipment and simulated scenarios*

The experiment was conducted at fixed-base driving simulator of the Road Safety and Driving Simulation (RSDS) Lab of Politecnico di Torino. The Scenario and simulations were designed using SCANeR Studio (https://www.avsimulation.com/scanerstudio/).

We designed an urban road setting with a speed limit of 50 km/h with three segments, two two-lane (one per direction) and one four lane (two per direction with median), for a total length of 7.3 km. A number of crosswalks, spaced 600 m apart on average in the two-lane and 400 m in the four-lane segments, were included. Lane width was set at 3.0 m for the two-lane section, and 3.5 m for the four-lane section. The horizontal and vertical signs conformed to the rules of the Italian Highway Code, (1993). To reproduce a realistic urban environment, we also included vehicles, and pedestrians moving around without interfering with the driver. In all three scenarios, other mid-block crosswalks with and without pedestrians were included with the purpose of confusing the driver and creating unpredictable situations for them.

We monitored only those crosswalks where pedestrians arrived from the right side. In this experiment this was the most hazardous situation because of (i) the shorter arrival time to the potential conflict zone and (ii) the obstructed visibility of pedestrians from the driver point of view due to parked cars close to the crosswalks (see Figure 1). In this experiment, pedestrians started crossing at PTGA values of 4, 6, or 8 s distributed randomly across the events. Experimental factors were randomly generated not only between scenarios but also between participants to prevent any learning effect bias. In the two scenarios with LED strips, the LED switched on when the driver neared the crosswalk and the pedestrian started to cross. The colour red was adopted since it conveys danger in traffic signs and lights (Chapanis, 1994). Fig. 2 shows three examples of the road scenarios featuring a pedestrian crossing the road.

(a) **(b)**



(c)

Figure 2. Crosswalks (a) without, (b) with fixed LED strips and road section with one lane per direction, and (c) with fixed LED strips and road section with two lanes per direction. In the fixed LED condition, the pedestrian crossed the road with the led bar always on. In the flashing condition, the bar operated with a flashing light at a frequency of 2 Hz. The light was activated when the pedestrian stepped inside an area monitored by a set of virtual cameras.

2.4. *Procedure and statistical analysis*

The procedure included the following steps: (i) a pre-drive questionnaire, (ii) a pre drive test of 5 min, (iii) the three driving simulations, (iv) the NASA-TLX questionnaire between each drive, and (v) the post-drive questionnaire. The pre-drive questionnaire collected demographic data, driving information, and health condition status. Subsequently, participants underwent a trial scenario to gain familiarity with the simulator. After a rest period of 2 minutes, the participants were then asked to drive the three experimental scenarios, which were administered in a different order following the complete counterbalance method (composed of six possible combinations (3!)), in order to avoid any familiarity bias. At the end of each drive, participants completed the NASA-TLX questionnaire followed by a rest time of at least one minute before starting the next drive. The experiment ended with a post-drive test collecting information on the driving experience at the simulator and the state of health after completing the experiment.

Statistical analyses on the collected data were performed using Jamovi software version 2.2.5. Five repeated ANOVA measurements were taken. We checked the normality, sphericity, and randomness assumptions. The significant threshold (α) was set equal to 0.05. When a significant effect was found, Bonferroni post-hoc tests were performed.

3. Results

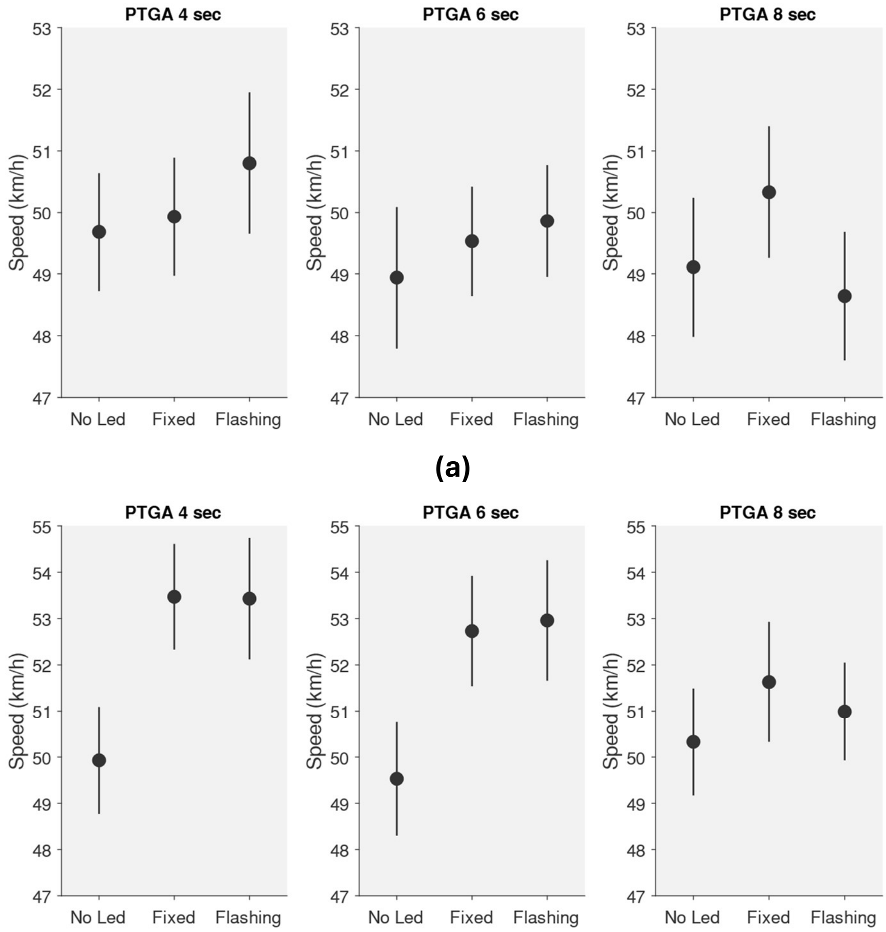
The RM-ANOVA results are reported in Table 1. The statistical analysis of the NASA-TLX questionnaire is reported in section 3.5. The results for each analysis are commented on in the following sections.

Table 1. RM-ANOVA results on max vehicle speed 100 m before the crosswalks (Speed), reaction distance, minimum time to collision (mTTC), and post encroachment time (PET); depending on LED, Lane, PTGA and interactions.

	Speed [km/h]			**Reaction distance [m]**		
	F	df	*p*	F	df	*p*
LED	3.58	(2,70)	**.033**	3.11	(2,34)	.058
Cross section	18.81	(1,35)	**<.001**	5.78	(1,17)	**.028**
PTGA	3.44	(2,70)	**.038**	72.12	(2,34)	**<.001**
LED × Cross section	3.78	(2,70)	**.028**	4.58	(2,34)	**.017**
LED × PTGA	1.11	(4,140)	.356	3.92	(4,68)	**.006**
Cross section × PTGA	0.41	(2,70)	.668	0.21	(2,34)	.809
LED × Lane × PTGA	1.31	(4,140)	.271	0.77	(4,68)	.546
	mTTC [s]			**PET [s]**		
	F	df	*p*	F	df	*p*
LED	6.52	(2,70)	**.003**	6.46	(2,70)	**.003**
Cross section	1.58	(1,35)	.217	16.31	(1,35)	**<.001**
PTGA	130.5	(2,70)	**<.001**	11.79	(2,70)	**<.001**
LED × Cross section	6.75	(2,70)	**.002**	4.59	(2,70)	**.013**
LED × PTGA	0.07	(4,140)	.990	3.01	(4,140)	**.020**
Cross section × PTGA	0.63	(2,70)	.538	0.38	(2,70)	.686
LED × Lane × PTGA	0.78	(4,140)	.537	1.81	(4,140)	.131

3.1. *Max speed in the 100 m leading up to the crosswalk*

The maximum speed recorded (Figure 3) in the 100 m leading up to the crosswalk was significantly affected by LED ($p = .033$), as well as by PTGA ($p = .038$). There was also a significant main effect for the cross section ($p < .001$) with participants driving slower with one lane (-2.01 km/h) compared to two lanes. In addition, the interaction between LED and cross section was significant ($p = .028$). However, Bonferroni-corrected post hoc analysis did not reveal significant differences between the baseline and fixed LED ($p = .107$), and between the baseline and flashing LED conditions ($p = .066$). For the post hoc comparisons on PTGA, we found significant differences between PTGA of 4 s and 8 s (*mean difference* 1.057, $p = .046$).

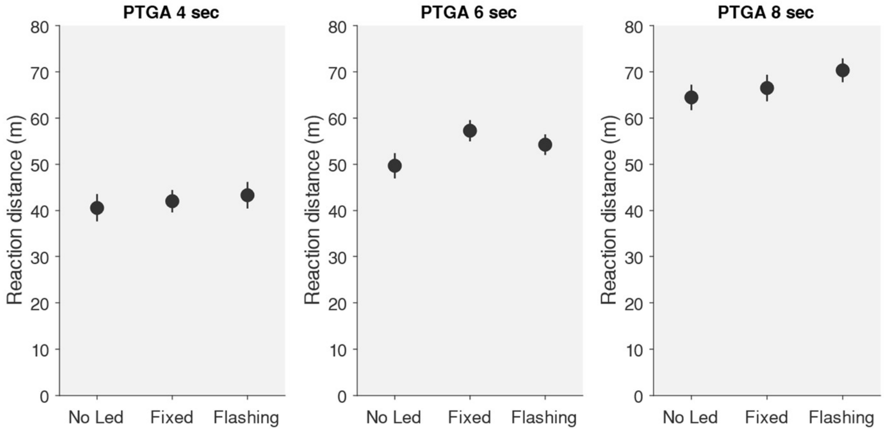


(b)

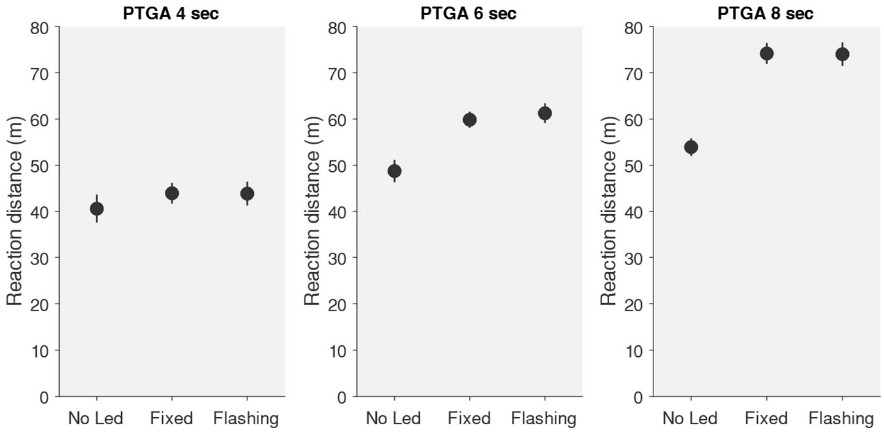
Figure 3. Maximum recorded speeds in the 100 m leading up to the crosswalks. (a) corresponds to data collected in the road cross-section featuring one lane per travel direction, while (b) corresponds to data from the road cross-section with two lanes per travel direction. Graphs have been separated for PTGA values of 4, 6, and 8 seconds. Error bars in both subfigures represent the standard error of the mean (SEM).

3.2. *Reaction distance*

The reaction distance of participants (Figure 4) was significantly influenced by cross section ($p = .028$) and PTGA ($p < .001$). The LED had a significant effect on the interaction with cross section ($p = .017$) and PTGA ($p = .006$). Post-hoc comparisons revealed significant differences in the 2 Lane configuration between baseline and Fixed LED (*mean difference* = - 11.0 m, $p = .015$) and between baseline and flashing LED (*mean difference* = - 11.4 m, $p = .031$).



(a)



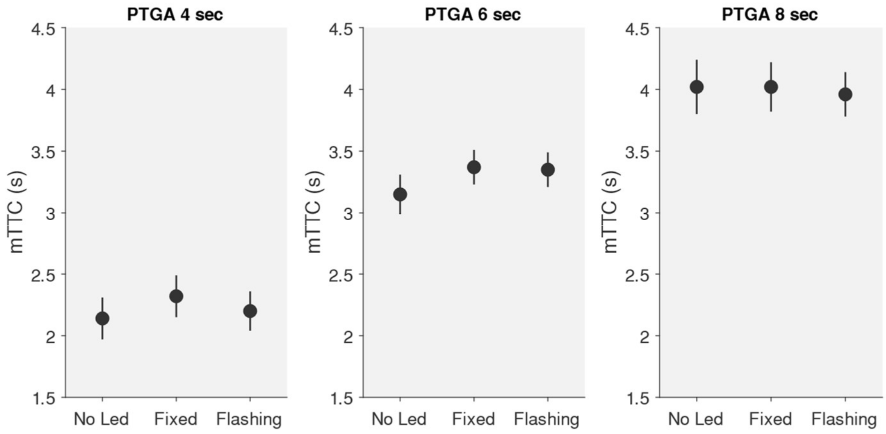
(b)

Figure 4. Reaction distance (the distance at which the driver reacts to the presence of the pedestrian by action on the brake pedal). (a) corresponds to data collected in the road cross-section featuring one lane per travel direction, while (b) corresponds to data from the road cross-section with two lanes per travel direction. Graphs have been separated for PTGA values of 4, 6, and 8 seconds. Error bars in both subfigures represent the standard error of the mean (SEM).

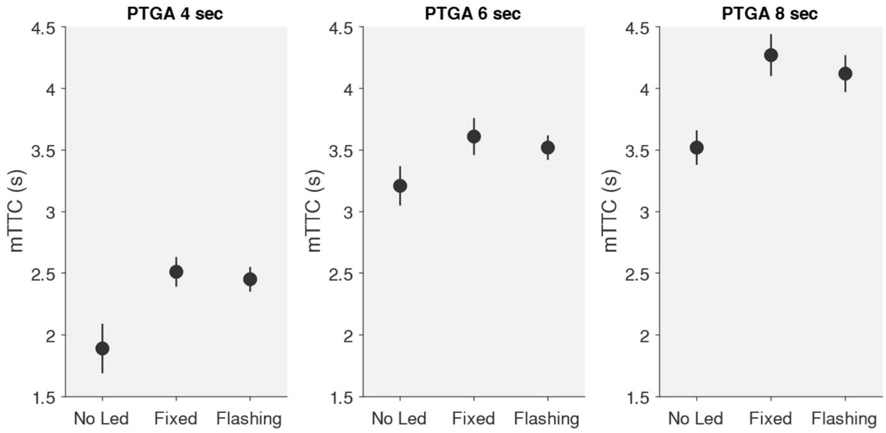
3.3. *Minimum time-to-collision (mTTC)*

The minimum time to collision between vehicle and pedestrian (Figure 5) was significantly influenced by the LED factor (p = .003), indicating that the LED conditions had a significant impact on the observed outcomes. Post hoc comparisons revealed further significant differences between the baseline and fixed LED (*mean difference* = -0.3620, p = .009) as well as between the baseline and flashing LED (*mean difference* = -0.2790, p = .032). However, no significant difference was found between the fixed and flashing LED strips. There was also a significant main effect for the factor PTGA (p < .001). Post hoc comparisons for

PTGA revealed significant differences between the 4 s and 6 s interaction (*mean difference* = -1.116, $p < .001$) as well as between 4 s and 8 s (*mean difference* = -1.732, $p < .001$). Additionally, a significant difference was observed between the 6 s and 8 s conditions (*mean difference* = -0.616, $p < .001$).



(a)

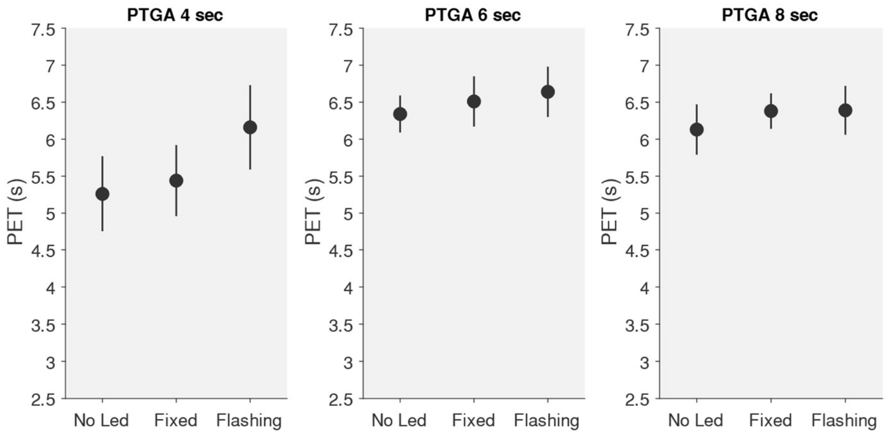


(b)

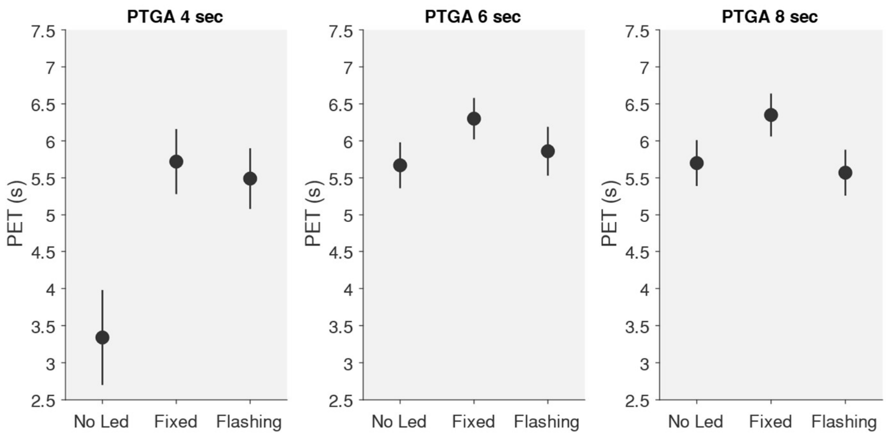
Figure 5. Minimum time-to-collision (mTTC). (a) corresponds to data collected in the road cross-section featuring one lane per travel direction, while (b) corresponds to data from the road cross-section with two lanes per travel direction. Graphs have been separated for PTGA values of 4, 6, and 8 seconds. Error bars in both subfigures represent the standard error of the mean (SEM).

3.4. *Post encroachment time (PET)*

The analysis revealed that the different LED conditions had a significant impact on PET outcomes (p = .003, Figure 6). Post hoc comparisons for LED demonstrated significant mean differences between the baseline and the fixed LED conditions (*mean difference* = -0.7061, p = .007), as well as between the baseline and the flashing conditions (*mean difference* = -0.6124, p = .033). Moreover, the analysis revealed a significant main effect of cross section (p < .001), and of the PTGA (p < .001). Post hoc comparisons for PTGA revealed significant mean differences between the 4 and 6 s interaction between the driver and the pedestrian (*mean difference* = -0.983, p = .003), as well as between 4 and 8 s (*mean difference* = -0.851, p = .003).



(a)



(b)

Figure 6. Post encroachment time (PET). (a) corresponds to data collected in the road cross-section featuring one lane per travel direction, while (b) corresponds to data from the road cross-section with two lanes per travel direction. Graphs have been separated for PTGA values of 4, 6, and 8 seconds. Error bars in both subfigures represent the standard error of the mean (SEM).

3.5. *NASA-TLX questionnaire*

Repeated ANOVA measurements revealed a significant main effect of LED on mental workload ($F(2,70) = 8.96$, $p < .001$). Post hoc comparisons indicated a significantly lower mental workload in the Fixed LED condition ($p = 0.001$) and in the Flashing condition ($p = 0.028$) compared to the baseline (unlit crosswalk). No significant difference in mental workload was found between the fixed and flashing conditions ($p = 0.338$).

4. Discussion and Conclusions

The results indicate that the LED strips led to a slight increase in the maximum speed in the 100 m before the crosswalks: while this increment was not significant on the one-lane road and drivers remained close to the posted speed limit (50 km/h), it was more pronounced on the two-lane road, with an average speed increment of 2.6 km/h. These results are consistent with those of Lantieri et al. (2021), who found no significant differences between the speed values observed with the standard and LED crosswalks (Figure 1c). The PET results showed that drivers waited longer before resuming their driving after stopping at a pedestrian crossing with LED strips. This is in accordance with the results of a study conducted in Qatar which found a significant improvement in PET with the ITS_LED solution (Hussain et al., 2023). We believe that this result is explained by the higher speed of certain drivers who, especially in the case of the crosswalks marked with LED strips, waited longer before driving away, and then tried to make up for lost time by increasing their speed between consecutive crosswalks. However, the slight increase in speed did not undermine the overall level of safety, as the drivers exhibited enhanced responsiveness to the stimuli generated by the LED lights. Despite their marginally higher velocity, they demonstrated a heightened ability to react promptly, thereby maintaining a safe behaviour.

The analysis of the reaction distance highlighted the significant impact of PTGA. As the PTGA increases, so does the reaction distance, allowing the driver to perceive the crossing pedestrian earlier and to react in time. This finding is consistent with the study by Angioi and Bassani, (2022), who observed an increase in reaction distance as the PTGA increased. It is important to note that the effect of LED strips was more pronounced when PTGA increases because the LED strip itself lights up earlier as the pedestrian begins crossing. In this case, the driver immediately notices the light signalling the presence of the pedestrian and reacts earlier. Vice versa, when the PTGA was set to 4 s, the driver had already seen the pedestrian when the lights turned on to signal their presence on the crossing. Therefore, in that case, the LED strip did not have a significant impact.

The analysis of mTTC revealed an increase in mTTC when the fixed and flashing LED strips were active compared to the case of unlit crosswalks. This outcome supports the hypothesis of a reduced probability of collision in vehicle-pedestrian interactions thanks to the investigated technology. The results of Calvi et al., (2020) corroborate our conclusions, since they observed that when the presence of a pedestrian is highlighted the values of TTC increase with respect to the baseline condition. When the pedestrian time gap acceptance (PTGA) was set to 4 s, all interactions resulted in conflicts with mTTC < 3 s. However, with the LED strip, the mTTC increased significantly thus indicating a relevant improvement in safety. With PTGA set to 6 and 8 s, the interactions no longer constituted conflicts as the mTTC was always greater than 3 s. Even in those situations, the LED strip had a strong influence, increasing the mTTC values compared to the unlit condition. The interaction between LED lighting and cross-section revealed a significant difference between the baseline and LED strips in the two-lane segments. This outcome can be explained by the fact that drivers on two-lane roads benefited not only from the LED strips, which influenced their longitudinal behaviour, but also from the wider lateral space within the roadway. This additional space enabled them to maintain a greater distance from potential conflicts.

From the subjective perspective, the lower perceived mental workload revealed by the NASA-TLX questionnaire suggests that the LED strips at crosswalks are intuitive and user-friendly, thus they could be accepted by drivers on roads. The reduced mental workload indicates that the message conveyed is clear and helpful and encourages a prompt reaction to the presence of a pedestrian. Together with the positive response from surrogate safety measures already discussed, the LED strips have the potential to significantly improve safety at crosswalks. Indeed, when drivers are less mentally burdened, they can devote more attention to their surroundings, and identify other potential hazards. Finally, our analysis revealed no significant differences between fixed and flashing LED strips, suggesting that the presence of emitting lights did not exert any discernible influence on the perceived mental workload.

Taken together, the results of this study strongly support the conclusion that LED strips, both fixed and flashing, effectively improve the safety of pedestrian crossings at night. By increasing driver responsiveness, improving reaction distances, and providing an increased buffer zone for potential conflicts, LED strips prove to be a tangible and practical measure to reduce the risks associated with vehicle-pedestrian interactions. Therefore, the implementation of LED stripes at uncontrolled mid-block crosswalks is recommended as a strategy to improve pedestrian safety and promote the well-being of both pedestrians and drivers. It is important to acknowledge that further studies are required to validate the results obtained and strengthen the conclusions drawn from this research. New studies could evaluate the potential effectiveness of the LED strips in mitigating the risks associated with more challenging situations. Additionally, it would be beneficial to explore other conditions, such as driving in fog or when distracted. These conditions represent real-world challenges on roads, and investigating the impact of LED strips under such circumstances would provide further insights into their overall effectiveness in improving road safety.

References

Angioi, F., Bassani, M., 2022. The implications of situation and route familiarity for driver-pedestrian interaction at uncontrolled mid-block crosswalks. Transportation Research Part F: Traffic Psychology and Behaviour 90, 287–299. https://doi.org/10.1016/j.trf.2022.09.003

Calvi, A., D'Amico, F., Ferrante, C., Bianchini Ciampoli, L., 2020. Effectiveness of augmented reality warnings on driving behaviour whilst approaching pedestrian crossings: A driving simulator study. Accident Analysis & Prevention 147, 105760. https://doi.org/10.1016/j.aap.2020.105760

Chapanis, A., 1994. Hazards associated with three signal words and four colours on warning signs. Ergonomics 37, 265–275. https://doi.org/10.1080/00140139408963644

Hayward, J., 1971. Near misses as a measure of safety at urban intersections. Pennsylvania Transportation and Traffic Safety Center.

Hussain, Q., Alhajyaseen, W.K.M., Kharbeche, M., Almallah, M., 2023. Safer pedestrian crossing facilities on low-speed roads: Comparison of innovative treatments. Accident Analysis & Prevention 180, 106908. https://doi.org/10.1016/j.aap.2022.106908

Hussain, Q., Alhajyaseen, W.K.M., Pirdavani, A., Brijs, K., Shaaban, K., Brijs, T., 2021. Do detection-based warning strategies improve vehicle yielding behavior at uncontrolled midblock crosswalks? Accident Analysis & Prevention 157, 106166. https://doi.org/10.1016/j.aap.2021.106166

Italian Highway Code, 1993. Legislative Decree 30 April 1992, No. 285: Public Procurement Code. Retrieved from https://www.gazzettaufficiale.it/eli/id/1994/03/22/093A6158/sg.

Lantieri, C., Costa, M., Vignali, V., Acerra, E.M., Marchetti, P., Simone, A., 2021. Flashing in-curb LEDs and beacons at unsignalized crosswalks and driver's visual attention to pedestrians during nighttime. Ergonomics 64, 330–341. https://doi.org/10.1080/00140139.2020.1834149

Owens, D.A., Sivak, M., 1996. Differentiation of Visibility and Alcohol as Contributors to Twilight Road Fatalities. Hum Factors 38, 680–689. https://doi.org/10.1518/001872096778827233

Patella, S.M., Sportiello, S., Carrese, S., Bella, F., Asdrubali, F., 2020. The Effect of a LED Lighting Crosswalk on Pedestrian Safety: Some Experimental Results. Safety 6, 20. https://doi.org/10.3390/safety6020020

Peesapati, L.N., Hunter, M.P., Rodgers, M.O., 2018. Can post encroachment time substitute intersection characteristics in crash prediction models? Journal of Safety Research 66, 205–211. https://doi.org/10.1016/j.jsr.2018.05.002

Plainis, S., 2006. Road traffic casualties: understanding the night-time death toll. Injury Prevention 12, 125–138. https://doi.org/10.1136/ip.2005.011056

Sullivan, J.M., Flannagan, M.J., 2002. The role of ambient light level in fatal crashes: inferences from daylight saving time transitions. Accident Analysis & Prevention 34, 487–498. https://doi.org/10.1016/S0001-4575(01)00046-X

WMA, 2013. World Medical Association Declaration of Helsinki: ethical principles for medical research involving human subjects. JAMA 310, 2191–2194. https://doi.org/10.1001/jama.2013.281053

World Health Organization, 2021. Decade of Action for Road Safety 2021-2030. Retrieved from https://www.who.int/publications/m/item/global-plan-for-the-decade-of-action-for-road-safety-2021-2030.

Paper E

Effectiveness of Smart LED Strips at Mid-Block Crosswalks Under Distracted Driving Conditions

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Abstract

Unsignalized crosswalks pose a significant safety challenge for pedestrians and drivers, particularly during night-time conditions and when drivers are distracted. While smart road technologies have been employed in recent years as a countermeasure to improve safety at these crosswalks, no studies have explored their impact under distracted driving conditions.

Here, we investigated the effectiveness of an LED-based smart crosswalk system in mitigating the detrimental effects of engaging in non-driving-related tasks (NDRTs) on behavioural, performance, and subjective measurements. We designed a 2 (Crosswalk: smart vs conventional) by 2 (Task complexity: low vs. high NDRT) within-subjects experiment. Thirty-six drivers drove along four urban scenarios in a static driving simulator (~5 minutes each; night-time conditions). Each scenario included six crosswalks, in which the drivers performed the assigned NDRT. In each scenario, the driver-pedestrian interactions were simulated in 50% of the cases (i.e., 3 crosswalks out of 6). We collected data on driving behaviour (speed, reaction distance), and safety (minimum time-to-collision [MTTC]), as well as subjective driver ratings on the perceived task load and their trust in the technology used, and performance levels achieved while conducting the NDRTs.

Behavioural and performance observations showed that the smart crosswalk resulted in greater reaction distances and MTTC values when drivers interacted with pedestrians, thus indicating improved safety. Remarkably, the results also revealed that increased NDRT complexity does not negatively affect the smart crosswalk effectiveness in terms of driver-pedestrian collision probability (i.e., MTTC does not decrease significantly). However, the NDRT complexity influenced driving performance in terms of speed and reaction distance at brake pedal pressure, with drivers exhibiting lower speeds and lower reaction distances with higher task loads. Moreover, the subjective ratings and performance levels while performing a NDRT reflected the experimental manipulation, with drivers perceiving higher task loads and performing worse in the higher NDRT complexity condition. Overall, the smart crosswalk led to a safer driver-pedestrian interaction compared to conventional crosswalks and achieved a good acceptance level both of which augur well for the widespread future installation of this technology.

1. Introduction

Pedestrian safety is of paramount public health and road safety importance, as pedestrian fatalities account for 36% of total urban-road-related deaths in Europe (European Road Safety Observatory, 2022). A major factor in collisions involving pedestrians is driving distraction, which negatively affects drivers' ability to interact safely with other road users (e.g., pedestrians) or to anticipate and respond effectively to potential hazards (Drews & Strayer, 2008). A driver is considered distracted when engaged in Non-Driving Related Tasks (hereafter NDRTs) while driving (i.e., primary task), as NDRTs divert the driver's attention from the road and traffic conditions (Dingus et al., 2019). Crash statistics showed that distracted driving was the most common contributing factor in road collisions (ISTAT, 2023), and that in distraction-affected crashes many of the non-occupant victims were pedestrians (National Center for Statistics and Analysis, 2023). In recent decades, several successful countermeasures have been developed, e.g. (Bassani et al., 2023; Mase et al., 2020; Reagan et al., 2018) to mitigate the adverse effects of NDRTs. Nevertheless, the incidence of fatalities among vulnerable road users (e.g., pedestrian) still remains a major road safety issue. Thus, it is imperative to find alternative strategies to address the problem. One of the latest strategies to enhance the driving experience and reduce driving risks involves the use of smart on-road technologies (Angioi et al. 2023). Specifically, in the context of driver-pedestrian interaction at mid-block crosswalks, previous naturalistic and simulated studies tested the effectiveness of different Smart on-Road Technologies in reducing the level of human error and improving road safety with results that were positive, but sometimes site-dependent (Angioi et al., 2023). For example, naturalistic studies revealed how the installation of smart LED-based crosswalk technologies on the road surface was effective in improving the drivers' longitudinal behaviour, as drivers slowed down in order to yield to pedestrians at significantly greater distances from the crosswalk (Lantieri et al., 2021) and significantly (20%) reduced their speed compared to conventional pedestrian crossings (Patella et al., 2020). Further driving simulation studies supported the effectiveness of the smart LED-based crosswalks in improving drivers' yielding behaviour and inducing safer interactions with respect to conventional solutions (Hussain et al., 2021, 2023; Portera & Bassani, 2023).

Although existing literature has demonstrated the effectiveness of smart technologies at crosswalks, no study to date has examined their impact in the context of distracted driving. Here, we investigated the effectiveness of a smart LED based crosswalk on driving behaviour while drivers were simultaneously engaged in a NDRT (with the possibility of two different task loads). Participants drove in a static driving simulator undergoing four driving simulations with different crosswalk configurations and task loads. We adopted the minimum time-to-collision (MTTC) as the primary safety-index for assessing driver-pedestrian interactions (Hayward, 1971). Additionally, we collected data on driver speed behaviour to evaluate longitudinal performance and measured reaction distance to assess how drivers reacted to the presence of pedestrians. Finally, we collected subjective ratings of the task load and trust in automation. We hypothesized that the smart crosswalk would induce safer driver-pedestrian interactions, and that the improvement would be modulated by the NDRT complexity (i.e., the smart solution would produce a greater improvement with a low complexity NDRT than it would with a high complexity one).

2. Method

2.1. *Participants*

Thirty-six participants took part in the experiment (mean [M] age = 28 years ± standard deviation [SD] = 10.5, age range = 20-59 years; 19 males). All the participants held an Italian car driving license and they had normal or corrected-to-normal vision. We screened the participants for their level of arousal with the Stanford Sleeping Scale (SSS; Hoddes et al., 1973). All the participants scored lower than 4 (SSS = 1.55, 1-3 range) indicating no fatigue or drowsiness (Diaz-Piedra et al., 2019). Finally, none of the drivers were aware of the hypotheses being tested.

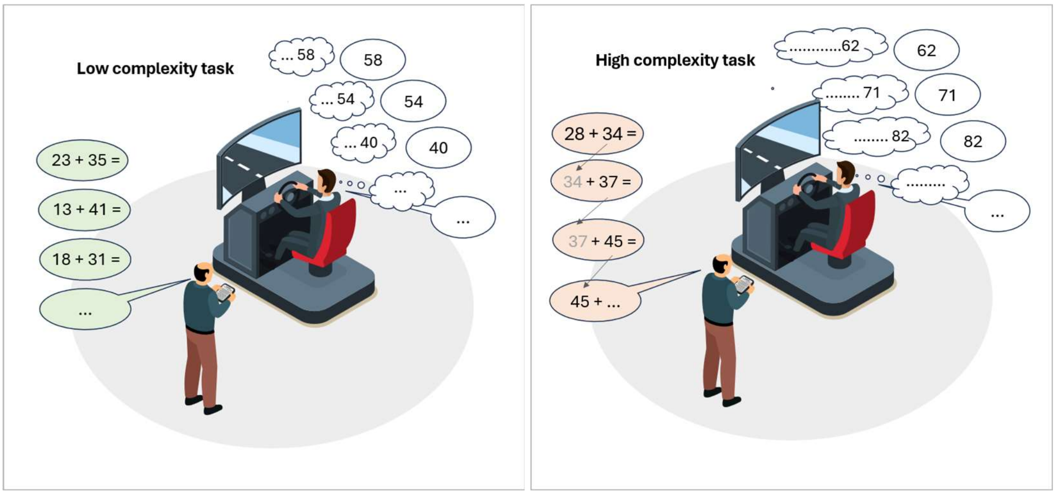
2.2. *Experimental design*

We carried out a 2 (Crosswalk: smart vs. conventional) × 2 (Task complexity: low vs. high NDRT) within-participants experiment. Participants drove along four 2-lane (one per direction) urban road scenarios (~5 minutes each) in night-time conditions. Each scenario included six crosswalks, and there was an interaction with one or more pedestrians at three of them (randomly presented to limit the learning effect). In each scenario, we presented a crosswalk configuration (smart or conventional) and the drivers performed a concurrent NDRT (see section below). The NDRTs (low or high) were administered for all the crosswalks to avoid giving participants any indication of the crosswalks being investigated. The distraction period (i.e., engagement in the NDRT) started 200 m before each crosswalk. The pedestrians always crossed from the right side and with a time gap acceptance of 4 s (Angioi & Bassani, 2022). The order of the administration of the scenarios was randomized.

2.3. *Non-Driving Related Tasks*

We selected two NDRTs that involved vocal interactions between the driver and the researcher, with the former performing a number of mathematical operations ranging in complexity (Di Stasi et al., 2023) to reproduce a cognitive distraction.

During the low complexity NDRT (Figure 1a), participants performed a series of two-digit mental arithmetic operations involving additions without regrouping (Harbluk et al., 2007) while in the high complexity NDRT (Figure1b), they performed the same type of exercise but with regrouping. This task was combined with a memory component, in which participants were required to sum the number read aloud by the researcher with the second number read in the previous operation. The operations were randomly selected from a predetermined set, which was employed for all participants. For both tasks, we considered the total number of answers as the performance index.



(a) (b)

Figure 1. Non-driving related task (NRDT) involving mathematical operations: (a) low complexity NDRT, with the summation of two-digit pairs of number without regrouping; (b) high complexity NDRT, with the summation of two-digit pairs of numbers with regrouping and memory task.

2.4. *Driving simulation and performance*

We developed four two-lane (each 3.0 m wide) urban road scenarios using the SCANeR Studio® (version 1.9; AV Simulation, Boulogne-Billancourt, France). Each road scenario was 2.5 km long with a parking lane and sidewalks which were 2.5 m and 2 m wide respectively. The smart crosswalk was simulated by introducing a red LED bar on the road surface before the crosswalk (Figure 2b). We chose the colour red for its association with danger in signalling (Pravossoudovitch et al., 2014). As soon as a pedestrian steps onto the road surface, the LED bar is activated and emits a fixed red light; when the pedestrian leaves the crossing area, the LED bar is disactivated and turned off. The carriageway was surrounded by several buildings to simulate a typical urban environment. Throughout the scenario, we randomly placed parked cars to increase the verisimilitude of the scene. To deliberately create a critical situation for the driver, we consistently placed a parked car on the right side just before each crosswalk, effectively obscuring the pedestrian who was crossing. We included a low level of traffic in the opposite travelling direction, while no traffic was simulated in the direction of the ego-vehicle. Participants were asked to respect the traffic rules throughout the duration of the experiment, with the posted speed limit set to 50 km/h.

To perform the driving simulation task, we used a fixed-base driving simulator (model CDS650; AV Simulation, Boulougne-Billancourt, France). The simulation system was composed of three 32-inch monitors with a 130°×20° field of view, a fully equipped driving position with seat, dashboard, steering wheel with force feedback, pedals, manual gearbox, and vibration pads to replicate pavement roughness, wheel rolling, and shocks. We reproduced the car cockpit on screen to ensure that driving conditions were as realistic as possible. A sound system reproduced the sounds of the engine and the surrounding environment. The simulator had previously been validated for longitudinal (Bassani et al., 2018), and transversal behaviour (Catani & Bassani, 2019).

The driving performance indicators were recorded with a frequency of 100 Hz. Specifically, we measured the speed and the reaction distance between the car and the crosswalk when the driver pressed on the brake pedal to stop the car before the crosswalk, and the maximum speed and the MTTC in the 200 m before the crosswalk. In our study, we considered a TTC of 3 s to discriminate between cases where drivers unintentionally find themselves in a dangerous situation (i.e., conflict) and cases where drivers remain in control (i.e., undisturbed) (Portera & Bassani, 2023).

(a)

(b)

Figure 2. (a) Conventional, and (b) Smart crosswalks. In the smart crosswalk, the red LED light is activated when the pedestrian steps onto the crossing area.

2.5. *Questionnaires*

We assessed the perceived workload produced by the NDRT combined with the crosswalk type for each scenario with the NASA Task Load Index (NASA-TLX; Hart & Staveland, 1988). The NASA-TLX assesses task loads through six bipolar dimensions: mental, physical, and temporal demand, own performance, effort, and frustration, using a score between 0 and 100 (higher values indicate higher perceived task loads). Finally, we employed the Motion Sickness Assessment Questionnaire (MSAQ; Gianaros et al., 2001) to monitor self-reported symptoms of motion sickness, and a customized Trust in Automation (TiA) questionnaire to evaluate the level of trust in this smart technology and drivers' willingness to rely on it. The MSAQ includes 16 brief statements describing the most common motion sickness symptoms (e.g., "I felt sick to my stomach"). The participants must respond to each statement on a Likert scale ranging from 1 ("not at all") to 9 ("severely"). The TiA questionnaire consisted of 7 brief statements and 3 questions reflecting drivers' opinions on the utility (or otherwise) and stressfulness of technology and their level of trust in it (partially readapted from Verberne et al., 2012). The participants evaluated each item on a 7-point Likert scale.

2.6. *Procedure*

The study was conducted in compliance with the Code of Ethics of the World Medical Association (WMA, 2013). The experiment took place in the Road Safety and Driving Simulation lab at the Politecnico di Torino (Italy). To recreate night-time driving conditions, the experiment took place in a dark room, with the only source of light being the visual system (i.e., three screens).

First, participants were asked to fill out the SSS questionnaire to self-evaluate their scale of sleepiness. All participants were considered eligible for the experiment. Next, participants underwent a short (~5 minutes) training session to gain confidence with the driving simulator equipment. Before starting the first experimental scenario, the researcher (AP, the same for all the experimental sessions) explained the study's procedures and the NDRTs the participant would undertake. Afterward, the experiment began, with participants completing the four experimental scenarios and engaging in the non-driving related task when instructed to do so. After each scenario, participants filled out the NASA-TLX questionnaire. At the end of the experimental session participants completed the MSAQ and TiA questionnaires. Finally, participants were informed of the overall duration of the experiment (circa 30 mins), but they were unaware of the exact duration of the driving simulation to avoid the end-spurt effect (Morales et al., 2017).

2.7. *Statistical analysis*

To assess the effectiveness of the smart crosswalk on behavioural, performance, and subjective metrics we performed a separate 2 × 2 repeated measures ANOVA, with the Crosswalk (smart vs conventional) and Task complexity (low vs high) as independent variables. For the behavioural (i.e., maximum speed 200 m before the crosswalks, speed and reaction distance when pressure applied on brake pedal, and MTTC) variables, we averaged out the observed values for the three crosswalks in each experimental scenario for each participant. The significance level (α) was always set to 5%.

3. Results

Our study used simulator-based technology to investigate the impact of a smart LED-based crosswalk on road safety in the context of distracted driving. To investigate how this technology affected driver behaviour, we analysed the driver's longitudinal behaviour and the driver-pedestrian interactions when vehicles approached the crosswalk. Finally, we presented the results of subjective measures related to the workload produced by the two NDRTs and the level of driver trust in the smart technology used.

3.1. *Behavioural measurements*

We presented the results on driving behaviour when approaching the crosswalks, focusing on: (a) maximum speed 200 m before the crosswalks, (b) speed at brake pedal pressure, (c) reaction distance at brake pedal pressure, and (d) minimum time to collision, across the various experimental conditions (see Figure 3).

The maximum speed recorded in the 200 m before the crosswalks was not significantly influenced by either the type of crosswalk or the complexity of the NDRT. At the brake pedal pressure, the observed speed differed significantly across the NDRT conditions, $F(1,35) = 10.75$, $p = .002$, $\eta^2_p = .235$ with drivers adopting higher speeds when performing a low complexity NDRT than they did with a high complexity one (*M* = 45.9 vs 44.2 km/h respectively). The effect of the crosswalk on speed was not found to be significant at the brake pedal pressure moment. Considering the same instant, the reaction distance was significantly influenced by both the crosswalk, $F(1,35) = 7.02$, $p = .012$, $\eta^2_p = .167$, and the NDRT, $F(1,35) = 5.33$, $p = .027$, $\eta^2_p = .132$. The smart crosswalk was more effective than the baseline condition in making the drivers start the braking manoeuvre at a greater distance from the crosswalk (*M* = 54.32 vs 50.64 m). Moreover, drivers were found to react earlier while performing a low complexity NDRT than they did with a high complexity one (M = 54.18 vs 50.77 m). From our study, the smart crosswalk was also determined to have a significant effect on MTTC, $F(1,35) = 22.14$, $p < .001$, $\eta^2_p = .387$.

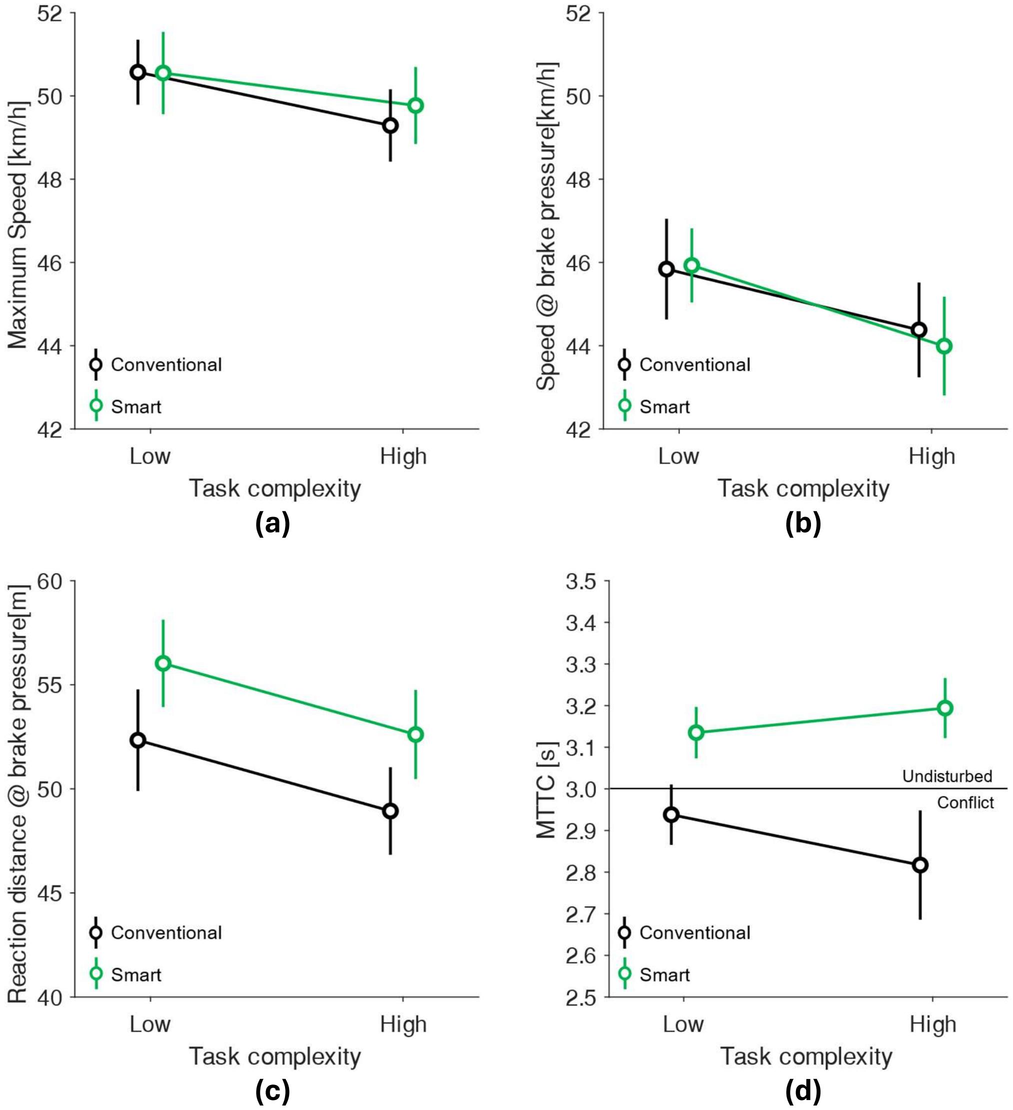


Figure 3. Driver behaviour across the four experimental conditions: 2 crosswalks (conventional vs. smart) × 2 NDRT complexity levels (low vs. high). The following metrics are represented (n = 36): (a) Average maximum speed recorded in the 200 m before the crosswalk; (b) Average speed when drivers engaged the brake pedal in response to the presence of a pedestrian; (c) Average reaction distance; and (d) Average minimum time-to-collision (MTTC); we considered a TTC of 3 s to discriminate between cases where drivers unintentionally find themselves in a dangerous situation (i.e., conflict) and cases where drivers remain in control (i.e., undisturbed). The green line refers to the smart crosswalk configuration, while the black one to the conventional configuration. Error bars on the graphs represent standard errors of the mean (SEM).

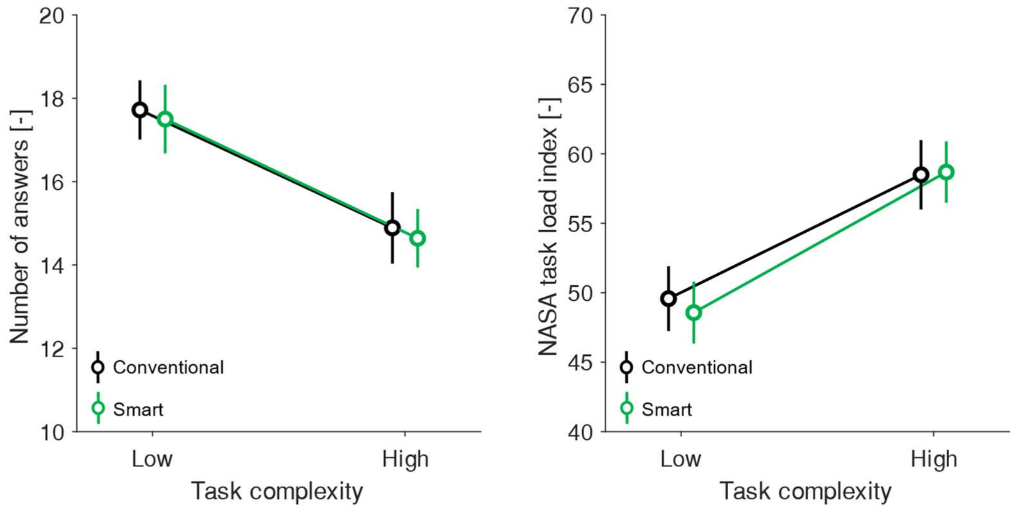
The proposed smart countermeasure led to safer driver-pedestrian interactions, resulting in a higher MTTC with respect to the conventional solution (M = 3.16 vs 2.88 s respectively); while the same variable (MTTC) was not significantly affected by NDRT complexity. We were able to observe that the smart crosswalk was more effective than conventional ones in facilitating conflict free interactions between pedestrians and drivers (MTTC > 3 s; for further detail see Angioi & Bassani, 2022). Finally, as a general outcome, we observed that the crosswalk × NDRT interaction term was not significant for the dependent variables investigated.

3.2. *Performance and subjective measurements*

For the performance of the concurrent task (Figure 4a), we found the NDRT had a significant effect on the total number of answers, $F(1,35) = 69.29$, $p < .001$, $\eta^2_p = .750$ resulting in a higher number of answers with the low complexity than with the high complexity NDRT ($M = 17.61$ vs 14.76 respectively). On the other hand, the crosswalk did not have a statistically relevant impact on the number of answers.

Concerning the perceived workload (Figure 4b), the effect of the NDRT was deemed to be significant, $F(1,35) = 27.16$, $p < .001$, $\eta^2_p = .437$. As hypothesised, drivers judged the driving tasks to be more demanding when they were undertaking a high complexity NDRT rather than a low complexity one ($M = 58.59$ vs 49.07 respectively). Neither crosswalk nor crosswalk × NDRT interaction terms were found to be significant.

Regarding the level of trust in this smart solution (evaluated on a Likert scale with ratings ranging from 1 to 7 by participants), the drivers had to declare their level of trust in the technology (*Median [Mdn]* = 5) and whether it would help to improve their driving style (*Mdn* = 5). The general feedback on the system was positive since they suggested that the implementation of the smart crosswalk would be useful for road safety (*Mdn* = 6), and they classified this technology as effective (*Mdn* = 5) and useful (*Mdn* = 6). Finally, the drivers reported that the smart crosswalk did not evoke any high-level negative feelings (concern, *Mdn* = 2 stress, *Mdn* = 2), whilst it evoked a fair level of calmness (*Mdn* = 4).



(a) **(b)**

Figure 4. Performance and subjective measurements across the four experimental conditions: 2 crosswalks (conventional vs. smart) × 2 NDRT complexity (low vs. high). (a) Mean number of answers, and (b) mean NASA Task Load Index. The green line refers to the smart crosswalk configuration, while the black one to the conventional configuration. Note that, for graphic purposes, the range of the y-axis ranges from 40 to 70, while the variables were measured in a scale from 0 to 100. Error bars represent standard errors of the mean.

4. Discussion

Driving while engaged in a secondary task is a well-known threat to road safety. The use of smart technology may help to reduce or even eliminate the negative effects associated with this driver behaviour (Angioi et al., 2023). Thus, here we carried out a driving simulation experiment to investigate the effectiveness of a mid-block smart crosswalk (Crosswalk: smart vs. conventional) on driver behaviour, performance, and subjective measures while performing a concurrent task (Task complexity: low vs. high NDRT) in night-time driving conditions.

Examining the longitudinal behaviour, our findings suggest that the maximum speed recorded in the 200 m before the crosswalk was not influenced by the type of crosswalk or engagement in a NDRT. This is a reasonable result, as the maximum speed was presumably recorded at the greatest distance from the crossing (around 200 m), and therefore, these factors did not play a key role in influencing participants' speed. This is likely because the smart crosswalk had not yet activated, and distraction had just been triggered. Concerning the speed at the moment in which drivers applied pressure to the brake pedal, the presence of the smart crosswalk did not alter longitudinal behaviour, and drivers maintained speeds similar to those at conventional crossings. However, the NDRT exerted a significant influence on the speed at the brake pedal, as the high-complexity task led drivers to adopt lower speeds. This outcome could be explained by drivers' behavioural self-regulation (risk compensation strategy), which may occur when drivers recognise the increase in the situational complexity and risk (i.e., higher complexity of maths operation). It appears that drivers adjusted to the specific overloading situation by self-regulating their behaviour by decreasing the rate at which they processed driving-related information (i.e., reducing the driving speed) (Di Stasi et al., 2023; Paire-Ficout et al., 2021; Hoogendoorn et al., 2012; Levym & Miller, 2000; Wilde, 1982). Furthermore, our results are supported by previous studies, in which driving performance still deteriorated while performing the secondary task despite the observed speed reductions (Shinar, 2017; Shinar et al., 2005; Strayer & Drew, 2004).

According to our findings, the smart crosswalk elicited a safer driver-pedestrian interaction with respect to conventional configurations. With smart crosswalks, we measured higher reaction distance and higher MTTC values for both low and high complexity tasks, providing important insights into the safety benefits of the adoption of smart crosswalks (Hussain et al., 2021; Portera & Bassani, 2023). The reaction distance significantly increased with the presence of the smart crosswalks, allowing drivers to clearly see and react earlier to pedestrians. However, as expected, the complexity of the secondary task proved detrimental to the drivers' perception (Consiglio et al., 2003) with drivers reducing the distance (from the crosswalk) at which they hit the brake pedal independently from the crosswalk configuration. Regarding the results obtained for MTTC, we observed that the smart crosswalk was instrumental in achieving conflict free interactions between drivers and pedestrians (mean MTTC above the 3 s threshold). Vice versa, with conventional crosswalks the MTTC resulted below the 3 s threshold resulting in conflict events (Tarko, 2019). It might be concluded that the presence of conventional crosswalks tends to generate more conflicts, while smart crosswalks promote relatively safer pedestrian crossings even if drivers are engaged in a NDRT. Moreover, most importantly, this result was independent of the level of cognitive difficulty associated with the secondary task, indicating that even with a high distraction level the smart crosswalk induced a safer driver-pedestrian interaction (lower MTTC). This significant finding indicates that the adoption of smart crosswalks enabled drivers to mitigate the negative impact of tasks with high cognitive demands, bringing them to levels comparable to that of low-complexity tasks. This enhancement contributes to making pedestrian crossings safer even under conditions of elevated cognitive load.

From a subjective standpoint, the technology was positively accepted by participants, and the perceived workload did not increase with respect to the conventional configuration as already stated by Portera & Bassani, (2023). This finding indicates that the introduction of smart crosswalks did not increase the perceived workload of participants, thereby allowing drivers to maintain their perception and reaction capabilities. Finally, we found a good level of technology acceptance from the drivers. On average, drivers judged the technology as useful and satisfying to use, indicating that they were receptive to its use making the potential safety benefits of a smart crosswalk more attainable (Horberry et al., 2017).

Notwithstanding the above, our results should be viewed in the context of three shortcomings. First, our testing focused exclusively on scenarios in which the ability to see pedestrians was obstructed by vehicles parked near the crosswalk. Our findings affirm the efficacy of smart technologies within these specific contexts, while recognizing that outcomes might differ under alternative circumstances. Future research should aim to assess the technology's effectiveness by comparing scenarios involving both concealed and non-concealed pedestrians.

Second, the pedestrian always adopted a deterministic (non-dynamic) behaviour. Consequently, in this experiment, they crossed without considering the actual danger of the situation, meaning it was the sole responsibility of the driver to avoid potential collisions by taking the required evasive manoeuvres. The lack of real decision-making by the virtual pedestrian introduces an element of artificiality that may not accurately reflect real-world pedestrian behaviour. To address this limitation in future research, one possible approach is to consider a co-simulation study, where drivers would engage in a driving simulation, and simultaneously, the same scenario would be replicated within a virtual reality headset for pedestrians (Deb et al., 2017).

Third, the effectiveness of the LED strip on pedestrian crosswalks was tested solely under night-time conditions. Its performance may differ in daytime scenarios due to varying perceptions of LED strip brightness during the day and night. To address this limitation, future research should consider introducing daytime testing scenarios to assess the LED strip's effectiveness under different lighting conditions. Moreover, a subjective study assessing the LED strip's ability to capture the attention of drivers could be conducted using a full-scale LED strip in a controlled environment under varying lighting conditions. Therefore, the findings should be interpreted with caution and future studies should aim to address the limitations cited by reducing the impact of confounding variables.

5. Conclusions

Our study sheds light on the efficacy of a proposed smart crosswalk in mitigating the risks associated with driver cognitive distractions (in our study replicated with mental operations) in driver-pedestrian interactions at mid-block crosswalks. The findings underscore the effectiveness of proactive measures, especially in scenarios where interventions, such as legal restrictions or educational campaigns, may prove insufficient due to the inherent nature of cognitive distractions — activities that cannot be prohibited. We offer relevant information and indications to road and transportation engineers regarding the effectiveness of an on-road visual warning system useful for promoting safer driver behaviour and, hence, safer interaction with pedestrians at crosswalks. Moreover, from a subjective viewpoint, our study reveals a significant level of technology acceptance by the drivers, which may serve to encourage (i) legislators to enable the use of these technologies through national highway codes, and (ii) local authorities to invest in these technologies as a key means of preventing or reducing the high number of fatal collisions involving pedestrians on our roads.

References

Angioi, F., & Bassani, M. (2022). The implications of situation and route familiarity for driver-pedestrian interaction at uncontrolled mid-block crosswalks. *Transportation Research Part F: Traffic Psychology and Behaviour*, *90*, 287–299. https://doi.org/10.1016/j.trf.2022.09.003

Angioi, F., Portera, A., Bassani, M., De Oña, J., & Stasi, L. L. D. (2023). Smart on-Road Technologies and Road Safety: A short overview. *Transportation Research Procedia*, *71*, 395–402. https://doi.org/10.1016/j.trpro.2023.11.100

Bassani, M., Catani, L., Hazoor, A., Hoxha, A., Lioi, A., Portera, A., & Tefa, L. (2023). Do driver monitoring technologies improve the driving behaviour of distracted drivers? A simulation study to assess the impact of an auditory driver distraction warning device on driving performance. *Transportation Research Part F: Traffic Psychology and Behaviour*, *95*, 239–250. https://doi.org/10.1016/j.trf.2023.04.013

Bassani, M., Catani, L., Ignazzi, A., & Piras, M. (2018). Validation of a Fixed-Base Driving Simulator to Assess Behavioural Effects of Road Geometrics. *Proceedings of the Driving Simulation Conference 2018 Europe VR*, 101–108.

Catani, L., & Bassani, M. (2019). Anticipatory Distance, Curvature, and Curvature Change Rate in Compound Curve Negotiation: A Comparison between Real and Simulated Driving. *98th Annual Meeting of the Transportation Research Board, Washington, DC*.

Consiglio, W., Driscoll, P., Witte, M., & Berg, W. P. (2003). Effect of cellular telephone conversations and other potential interference on reaction time in a braking response. *Accident Analysis & Prevention*, *35*(4), 495–500. https://doi.org/10.1016/S0001-4575(02)00027-1

Deb, S., Carruth, D. W., Sween, R., Strawderman, L., & Garrison, T. M. (2017). Efficacy of virtual reality in pedestrian safety research. *Applied Ergonomics*, *65*, 449–460. https://doi.org/10.1016/j.apergo.2017.03.007

Di Stasi, L. L., Angioi, F., Fernandes, M., Cet, G. D., Caurcel, M. J., Stojmenova, K., Sodnik, J., Prat, C., & Piedra, C. D. (2023). The use of cardiac-based metrics to assess secondary task engagement during automated and manual driving: An experimental simulation study. *Application of Emerging Technologies*, *115*(115). https://doi.org/10.54941/ahfe1004334

Diaz-Piedra, C., Gomez-Milan, E., & Di Stasi, L. L. (2019). Nasal skin temperature reveals changes in arousal levels due to time on task: An experimental thermal infrared imaging study. *Applied Ergonomics*, *81*, 102870. https://doi.org/10.1016/j.apergo.2019.06.001

Dingus, T. A., Owens, J. M., Guo, F., Fang, Y., Perez, M., McClafferty, J., Buchanan-King, M., & Fitch, G. M. (2019). The prevalence of and crash risk associated with primarily cognitive secondary tasks. *Safety Science*, *119*, 98–105. https://doi.org/10.1016/j.ssci.2019.01.005

Drews, F. A., & Strayer, D. L. (2008). *Cellular Phones and Driver Distraction*. CRC Press Boca Raton, FL.

European Road Safety Observatory. (2022). *Facts and Figures – Urban areas—2022*. https://road-safety.transport.ec.europa.eu/system/files/2022-07/ff_roads_inside_urban_areas_20220707.pdf

Gianaros, P. J., Muth, E. R., Mordkoff, J. T., Levine, M. E., & Stern, R. M. (2001). A questionnaire for the assessment of the multiple dimensions of motion sickness. *Aviation, Space, and Environmental Medicine*, *72*(2), 115–119.

Harbluk, J. L., Noy, Y. I., Trbovich, P. L., & Eizenman, M. (2007). An on-road assessment of cognitive distraction: Impacts on drivers' visual behavior and braking performance. *Accident; Analysis and Prevention*, *39*(2), 372–379. https://doi.org/10.1016/j.aap.2006.08.013

Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. In P. A. Hancock & N. Meshkati (A c. Di), *Advances in Psychology* (Vol. 52, pp. 139–183). North-Holland. https://doi.org/10.1016/S0166-4115(08)62386-9

Hayward, J. (1971). *Near misses as a measure of safety at urban intersections*. Pennsylvania Transportation and Traffic Safety Center.

Hoddes, E., Zarcone, V., Smythe, H., Phillips, R., & Dement, W. C. (1973). Quantification of sleepiness: A new approach. *Psychophysiology*, *10*(4), 431–436. https://doi.org/10.1111/j.1469-8986.1973.tb00801.x

Hoogendoorn, R. G., van Arem, B., & Hoogendoorn, S. P. (2012). A Neurofuzzy Approach to Modeling Longitudinal Driving Behavior and Driving Task Complexity. *International Journal of Vehicular Technology*, *2012*, 807805. https://doi.org/10.1155/2012/807805

Horberry, T., Regan, M. A., & Stevens, A. (2017). *Driver Acceptance of New Technology: Theory, Measurement and Optimisation*. CRC Press. https://doi.org/10.1201/9781315578132

Hussain, Q., Alhajyaseen, W. K. M., Kharbeche, M., & Almallah, M. (2023). Safer pedestrian crossing facilities on low-speed roads: Comparison of innovative treatments. *Accident Analysis & Prevention*, *180*, 106908. https://doi.org/10.1016/j.aap.2022.106908

Hussain, Q., Alhajyaseen, W. K. M., Pirdavani, A., Brijs, K., Shaaban, K., & Brijs, T. (2021). Do detection-based warning strategies improve vehicle yielding behavior at uncontrolled midblock crosswalks? *Accident Analysis & Prevention*, *157*, 106166. https://doi.org/10.1016/j.aap.2021.106166

ISTAT. (2023). *Road Accidents for the Year 2022*. National Institute of Statistics. https://www.istat.it/it/files//2023/07/REPORT_INCIDENTI_STRADALI_2022_EN.pdf

Lantieri, C., Costa, M., Vignali, V., Acerra, E. M., Marchetti, P., & Simone, A. (2021). Flashing in-curb LEDs and beacons at unsignalized crosswalks and driver's visual attention to pedestrians during nighttime. *Ergonomics*, *64*(3), 330–341. https://doi.org/10.1080/00140139.2020.1834149

Levym, D. T., & Miller, T. (2000). Review: Risk Compensation Literature — The Theory and Evidence. *Journal of Crash Prevention and Injury Control*, *2*(1), Articolo 1. https://doi.org/10.1080/10286580008902554

Mase, J. M., Majid, S., Mesgarpour, M., Torres, M. T., Figueredo, G. P., & Chapman, P. (2020). Evaluating the impact of Heavy Goods Vehicle driver monitoring and coaching to reduce risky behaviour. *Accident Analysis & Prevention*, *146*, 105754. https://doi.org/10.1016/j.aap.2020.105754

Morales, J. M., Díaz-Piedra, C., Rieiro, H., Roca-González, J., Romero, S., Catena, A., Fuentes, L. J., & Di Stasi, L. L. (2017). Monitoring driver fatigue using a single-channel electroencephalographic device: A validation study by gaze-based, driving performance, and subjective data. *Accident Analysis & Prevention*, *109*, 62–69. https://doi.org/10.1016/j.aap.2017.09.025

National Center for Statistics and Analysis. (2023). *Distracted Driving in 2021 (Research Note. Report No. DOT HS 813 443). National Highway Traffic Safety Administration. Https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/813443*.

Paire-Ficout, L., Lafont, S., Hay, M., Coquillat, A., Fabrigoule, C., & Chavoix, C. (2021). Relationships Between Cognitive and Driving Self-awareness in Older Drivers. *The Journals of Gerontology: Series B*, *76*(6), 1077–1085. https://doi.org/10.1093/geronb/gbaa224

Patella, S. M., Sportiello, S., Carrese, S., Bella, F., & Asdrubali, F. (2020). The Effect of a LED Lighting Crosswalk on Pedestrian Safety: Some Experimental Results. *Safety*, *6*(2), 20. https://doi.org/10.3390/safety6020020

Portera, A., & Bassani, M. (2023). Red LED Strip Signalling Pedestrian Presence at Uncontrolled Mid-block Crosswalks. *Transportation Research Procedia*, *73*, 151–158. https://doi.org/10.1016/j.trpro.2023.11.903

Pravossoudovitch, K., Cury, F., Young, S. G., & Elliot, A. J. (2014). Is red the colour of danger? Testing an implicit red–danger association. *Ergonomics*, *57*(4), 503–510. https://doi.org/10.1080/00140139.2014.889220

Reagan, I. J., Cicchino, J. B., Kerfoot, L. B., & Weast, R. A. (2018). Crash avoidance and driver assistance technologies – Are they used? *Transportation Research Part F: Traffic Psychology and Behaviour*, *52*, 176–190. https://doi.org/10.1016/j.trf.2017.11.015

Shinar, D. (2017). Distraction and Inattention. In *Traffic Safety and Human Behavior* (pp. 711–795). Emerald Publishing Limited. https://doi.org/10.1108/978-1-78635-221-720162013

Shinar, D., Tractinsky, N., & Compton, R. (2005). Effects of practice, age, and task demands, on interference from a phone task while driving. *Accident Analysis & Prevention*, *37*(2), 315–326. https://doi.org/10.1016/j.aap.2004.09.007

Strayer, D. L., & Drew, F. A. (2004). Profiles in Driver Distraction: Effects of Cell Phone Conversations on Younger and Older Drivers. *Human Factors*, *46*(4), 640–649. https://doi.org/10.1518/hfes.46.4.640.56806

Verberne, F. M. F., Ham, J., & Midden, C. J. H. (2012). Trust in Smart Systems: Sharing Driving Goals and Giving Information to Increase Trustworthiness and Acceptability of Smart Systems in Cars. *Human Factors*, *54*(5), 799–810. https://doi.org/10.1177/0018720812443825

Wilde, G. J. S. (1982). The Theory of Risk Homeostasis: Implications for Safety and Health. *Risk Analysis*, *2*(4), 209–225. https://doi.org/10.1111/j.1539-6924.1982.tb01384.x

WMA. (2013). World Medical Association Declaration of Helsinki: Ethical principles for medical research involving human subjects. *JAMA*, *310*(20), 2191–2194. https://doi.org/10.1001/jama.2013.281053

Tests of Normality

Tests of Normality (Kolmogorov-Smirnov) - variables of Paper B

Combination	S @ TS	S @ CC	LP @ TS	LP @ CC	SDLP
	p-value				
Unlit_120_L	0.803	0.46	0.242	0.602	< .001
Unlit _210_L	0.901	0.642	0.908	0.319	0.591
Unlit _300_L	0.977	0.935	0.419	0.966	0.931
Unlit _440_L	0.720	0.98	0.848	0.917	0.483
Unlit _120_R	0.994	0.495	0.426	0.984	0.369
Unlit _210_R	0.839	0.903	0.595	0.846	0.823
Unlit _300_R	0.991	0.911	0.796	0.868	0.445
Unlit _440_R	0.703	0.7	0.309	0.977	0.975
White_120_L	0.800	0.654	0.685	0.974	0.015
White _210_L	0.757	0.991	0.631	0.783	0.008
White _300_L	0.891	0.958	0.289	0.515	0.021
White _440_L	0.678	0.926	0.884	0.995	0.812
White _120_R	0.576	0.762	0.961	0.315	0.249
White _210_R	0.837	0.831	0.862	0.98	0.655
White _300_R	0.664	0.983	0.814	0.942	0.303
White _440_R	0.875	0.955	0.88	0.808	0.812
Red_120_L	0.562	0.765	0.975	0.811	0.044
Red _210_L	0.951	0.731	0.945	0.471	0.052
Red _300_L	0.529	0.288	0.904	0.607	0.005
Red _440_L	0.963	0.278	0.717	0.473	0.032
Red _120_R	0.951	0.802	0.915	0.763	0.848
Red _210_R	0.850	0.213	0.9	0.735	0.825
Red _300_R	0.482	0.211	0.843	0.895	0.379
Red _440_R	0.760	0.895	0.993	0.881	0.61

Tests of Normality (Kolmogorov-Smirnov) - variables of Paper C

Combination	S @ TS	S @ CC	LP @ TS	LP @ CC	SDLP
	p-value				
Unlit_120_L	0.986	0.884	0.475	0.701	0.023
Unlit_120_R	0.993	0.848	0.747	0.872	0.352
Unlit_210_L	0.388	0.48	0.973	0.989	0.683
Unlit_210_R	0.928	0.253	0.931	0.861	0.264
Unlit_300_L	0.768	0.569	0.846	0.846	0.295
Unlit_300_R	0.765	0.811	0.881	0.57	0.073
Unlit_440_L	0.896	0.891	0.577	0.443	0.345
Unlit_440_R	0.607	0.756	0.794	0.966	0.757
Edge_120_L	0.891	0.684	0.946	0.568	0.806
Edge_120_R	0.48	0.964	0.68	0.959	0.484
Edge_210_L	0.651	0.475	0.967	0.519	0.756
Edge_210_R	0.886	0.998	0.386	0.99	0.324
Edge_300_L	0.918	0.79	0.614	0.945	0.33
Edge_300_R	0.701	0.963	0.963	0.939	0.55
Edge_440_L	0.971	0.894	0.421	0.3	0.751
Edge_440_R	0.791	0.692	0.523	0.991	0.28
Center_120_L	0.866	0.594	0.966	0.487	0.655
Center_120_R	0.925	0.878	0.981	0.991	0.189
Center_210_L	0.468	0.77	0.781	0.675	0.814
Center_210_R	0.452	0.849	0.808	0.305	0.327
Center_300_L	0.226	0.144	0.445	0.996	0.213
Center_300_R	0.576	0.719	0.422	0.748	0.806
Center_440_L	0.944	0.994	0.788	0.511	0.548
Center_440_R	0.455	0.796	0.919	0.972	0.034
EdgeCenter_120_L	0.532	0.811	0.339	0.734	0.806
EdgeCenter_120_R	0.906	0.8	0.803	0.849	0.493
EdgeCenter_210_L	0.756	0.997	0.943	0.617	0.284
EdgeCenter_210_R	0.826	0.848	0.989	0.332	0.293
EdgeCenter_300_L	0.489	0.902	0.548	0.951	0.519
EdgeCenter_300_R	0.839	0.388	0.923	0.694	0.954
EdgeCenter_440_L	0.328	0.467	0.483	0.959	0.686
EdgeCenter_440_R	0.515	0.678	0.865	0.966	0.076
Lane_120_L	0.958	0.976	0.854	0.615	0.841
Lane_120_R	0.748	0.967	0.996	0.486	0.44
Lane_210_L	0.294	0.835	0.941	0.949	0.469
Lane_210_R	0.771	0.826	0.148	0.595	0.226
Lane_300_L	0.412	0.574	0.903	0.801	0.711
Lane_300_R	0.685	0.369	0.998	0.776	0.286
Lane_440_L	0.55	0.762	0.877	0.841	0.07
Lane_440_R	0.224	0.541	0.627	0.948	0.563

Tests of Normality (Kolmogorov-Smirnov) - variables of Paper D

Combination	**Speed**	**React Dist**	**MTTC**	**PET**
	p-value			
4 sec - 1 lane – Unlit	0.987	0.572	0.277	0.036
6 sec - 1 lane – Unlit	0.957	0.954	0.995	0.299
8 sec - 1 lane – Unlit	0.942	0.38	0.567	0.579
4 sec - 2 lanes – Unlit	0.922	0.221	0.122	0.122
6 sec - 2 lanes – Unlit	0.873	0.245	0.97	0.271
8 sec - 2 lanes – Unlit	0.912	0.735	0.938	0.567
4 sec - 1 lane – Fixed	0.778	0.402	0.111	0.061
6 sec - 1 lane – Fixed	0.971	0.964	0.862	0.874
8 sec - 1 lane – Fixed	0.818	0.757	0.849	0.72
4 sec - 2 lanes – Fixed	0.165	0.473	0.287	0.398
6 sec - 2 lanes – Fixed	0.183	0.878	0.832	0.725
8 sec - 2 lanes – Fixed	0.281	0.819	0.634	0.482
4 sec - 1 lane - Flashing	0.865	0.21	0.15	0.071
6 sec - 1 lane – Flashing	0.54	0.834	0.918	0.37
8 sec - 1 lane – Flashing	0.824	0.517	0.972	0.132
4 sec - 2 lanes - Flashing	0.584	0.094	0.575	0.925
6 sec - 2 lanes – Flashing	0.959	0.445	0.797	0.702
8 sec - 2 lanes - Flashing	0.596	0.952	0.813	0.268

Tests of Normality (Kolmogorov-Smirnov) variables of Paper E

Combination	**Max Speed**	**Speed @ brake**	**React Dist**	**MTTC**
	p-value			
No LED - Low complexity	0.923	0.794	0.659	0.839
No LED - High complexity	0.479	0.67	0.491	0.444
LED - Low complexity	0.474	0.957	0.907	0.733
LED - High complexity	0.69	0.906	0.983	0.985