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Full Length Article

The impact of auditory advanced driver distraction warning devices on the behaviour of middle-aged drivers along urban roads

A. Lioi [*], M. Bassani

Department of Environment, Land and Infrastructure Engineering (DIATI), Politecnico di Torino, Italy

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ABSTRACT

Driver distraction is one of the main causes of road crashes worldwide, with a relevant number of collisions, some fatal, especially among middle-aged drivers. In 2019, the European Regulation EU 2019/2144 mandated the installation of Advanced Driver Distraction Warning (ADDW) devices on all new vehicles by 2026. After the confirmation of its effectiveness in motorway driving, this driving simulation study evaluated the effectiveness of an auditory ADDW device in mitigating distraction on urban roads. Thirty middle-aged participants (fifteen females, aged between 25 and 35) were asked to read and respond to text messages on their cell phones, regardless of the device alert. They all drove (i) without being distracted (baseline condition), (ii) while distracted, and (iii) while distracted but supported by the ADDW device. Each participant faced three scenarios: (i) interaction with pedestrians at a mid-block crosswalk, (ii) driving in free-flow conditions on a dual-carriageway arterial, and (iii) driving behind another vehicle.

The results revealed a degradation in driving performance and worsening safety conditions. In contrast to what was demonstrated for motorway driving, the ADDW device did not produce significant improvements in driving performance along urban roads. For drivers who continue to text while driving, no positive effect of the ADDW auditory device was observed. Unlike the motorway scenario, the urban environment produces a variety of stimuli that render distracted driving dangerous irrespective of the use of an ADDW.

1. Introduction

Road traffic injuries are the main cause of death among children and young adults aged between 5 and 29 [55]. Factors contributing to these statistics include driving under the influence of alcohol and/or drugs, speeding, unsafe road infrastructures, and most importantly, distracted driving. Drivers are distracted when they divert their attention from essential driving tasks in favour of competing activities, resulting in insufficient concentration on the primary task [45].

Among the various causes of distraction, mobile phone use and texting while driving predominate. Texting while driving implies visual, physical, and cognitive distraction occurring simultaneously [56]. Although some drivers may believe in their multitasking capability [14], typing and reading messages impair driving performance and compromise safety [41,54]. It has already been established that the risk perception of drivers using a mobile phone influences their driving behaviour [17]. In the US, 8 % of fatal crashes in 2021 involved distracted drivers and 12 % of these were related to cell phone use [37]. Furthermore, the use of handheld cell phones increased among individuals aged 16 to 24 [36]. As a result, drivers who use mobile phones while driving are approximately four times more likely to be involved in a crash than those who do not use them [55].

Several studies have analysed the effects of mobile phone use on driving behaviour. Different road environments (e.g., urban, rural and motorway), road configurations (e.g., segments, intersections, and roundabouts) and lighting conditions (day and night) have been investigated [1,12]. The research involving middle-aged drivers found that using a mobile phone for social networking activities while driving in an urban environment led to longer reaction times when interacting with pedestrians and to keeping longer distances from the vehicle in front [20]. In contrast, drivers who were engaged in texting maintained a significantly shorter minimum headway from the vehicle in front [29]. Driving simulation studies also found that both young and professional drivers reduced their speed while performing a secondary task involving the use of a phone, as a kind of compensatory strategy [19].

To prevent distraction-related crashes, new on-board technologies alert drivers when they are distracted [35]. These systems consist of video-based sensors that capture the driver's eye, face, and head

* Corresponding author.
E-mail address: alessandra.lioi@polito.it (A. Lioi).

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Table 1
Factors of the experimental design.

Experimental factors	Type	Levels		
Distraction level (No.)	Within-subjects	Baseline (0)	Distraction (1)	Distraction + ADDW (2)
Gender	Between-subjects	–	Male (M)	Female (F)

movements, with image analysis algorithms detecting signs of distraction or fatigue [21,28,42,48]. With these systems, vehicles emit auditory and vibrating warnings [62] to redirect the driver's attention to their primary task. In the wake of this significant technological development, EU Regulation No. 2019/2144 of the European Parliament mandates the installation of Advanced Driver Distraction Warning (ADDW) devices on all new vehicles by 2026 [23]. Accordingly, the purpose of an ADDW device is to help drivers maintain an adequate level of attention to the traffic situation and to the road ahead, and it issues a warning when the driver is distracted. According to EU Regulation No. 2023/2590 [24], the ADDW should operate night and day when the vehicle speed is above 20 km/h. A visual, acoustic and/or haptic warning is emitted when inattention to the primary task is prolonged beyond a specific threshold. Recent studies [7] have confirmed the effectiveness of an auditory ADDW device in mitigating the negative effects on the performance of distracted drivers along motorways. However, its usefulness should also be evaluated in the urban environment, where a potentially distracted driver generates many more risky interactions with users than in a rural scenario [58].

In this driving simulation study, we aimed to evaluate the effectiveness of the ADDW device in the urban environment under three different driving scenarios: (i) interacting with a pedestrian at a mid-block crosswalk, (ii) driving in free-flow conditions, and (iii) driving behind a slow-moving vehicle. Thirty middle-aged participants completed these three scenarios while experiencing (i) no distraction, (ii) distraction, and (iii) distraction signalled with a warning emitted by an auditory ADDW device. The distraction was induced through WhatsApp messages. The hypothesis is that, although the effects of distracted driving cannot be entirely eliminated, the ADDW can mitigate the risks due to distraction.

The motivation for this study stems from the significant and troubling impact of distracted driving on road safety, especially among middle-aged people, and the need to evaluate the effectiveness of Advanced Driver Distraction Warning (ADDW) systems in urban environments, where the complexity and frequency of potential distractions are higher than in rural road environments. This study aims to contribute to the existing body of knowledge by evaluating the effectiveness of ADDW devices in urban environments in different scenarios (pedestrian interaction, free-flow conditions, car-following) for middle-aged drivers engaged in a realistic and dangerous secondary task, i.e., texting while driving.

2. Methods

2.1. Experimental design

A multi-level mixed-factor design was employed to investigate the impact of distraction and the potential effectiveness of an auditory ADDW device on driving performance along urban roads. As evident in Table 1, distraction was regarded as a within-subjects factor at three different levels: (i) no distraction (baseline, level 0), (ii) distraction (level 1), and (iii) distraction while interacting with the auditory ADDW device (level 2). This means that all participants experienced three levels of distraction, administered in random order. The gender of the test drivers is a between-subjects factor (i.e., an independent variable that is not shared by all participants) and was considered in the study by including an equal number of men and women and then analysing their documented behavioural differences [2,60].

2.2. Experimental setup

The fixed-base driving simulator, equipped with SCANeR Studio™ software (AV Simulation) at the Road Safety and Driving Simulation (RSDS) laboratory of Politecnico di Torino, was used (Fig. 1). The simulator hardware includes a cockpit complete with a steering wheel, manual gearbox, and pedals. A dashboard with speedometer and rev counter is displayed on a small monitor mounted behind the steering wheel, positioned so that it remains constantly visible to the driver during the experiments. It provides a 130° horizontal × 20° vertical field of view thanks to three 32-inch full HD screens, rear and side view mirrors, and a system of speakers that reproduce the environmental sounds [7]. Previous validation studies confirmed the reliability of the simulator for longitudinal, transversal, and passing behaviour [8,16,27], and for tunnel environments [33].

An aftermarket auditory ADDW device, which uses a sensor to capture infrared images of the human face and a high-speed digital signal processor to analyse and check whether the driver is tired (eyes closed) or distracted (eyes looking away from the road ahead) was used. Using pupil identification and detection technology, the device detects changes in pupil size, blinking and head position compared to the initial calibration through real-time monitoring. In accordance with EU Regulation No. 2023/2590 [24], our ADDW device activated an audible signal when the driver's gaze was directed outside the area where his/her attention should be primarily focused, i.e., Area 1 (defined by two vertical planes obtained by rotating the longitudinal direction of the vehicle 55° to the right and left, with both planes intersecting at the driver's eye point) and Area 2 (that includes the dashboard and other vehicle controls).The device was positioned at a distance of 60 ± 5 cm from the ocular reference point, i.e., the midpoint between the centre of

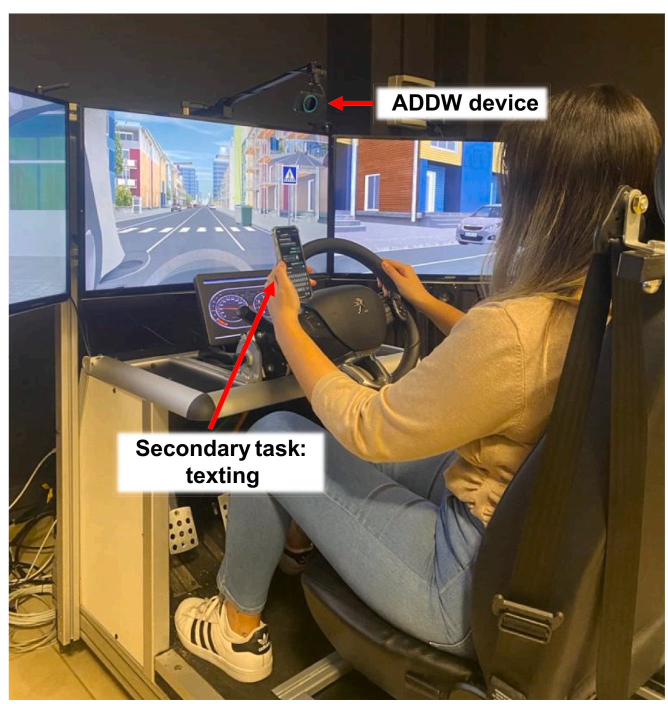

Fig. 1. Experimental apparatus: the driving simulator and the ADDW device, with a driver involved in the secondary task.

the driver's left and right eyes, as defined in UN Regulation No. 167 [51] to provide a full view of the driver's face and head, without obstructing the driver's view of the road ahead, and taking into account the driver's height when seated. To avoid any problems with facial recognition, the drivers did not wear sunglasses.

The EU Regulation No. 2023/2590 applies to vehicles in categories M ("motor vehicles designed and constructed primarily for the carriage of passengers") and N ("motor vehicles designed and constructed primarily for the carriage of goods"). Initial calibration tests of the ADDW device used in this experiment have shown that it operates in accordance with European requirements. If the device detects persistent distraction, i.e., the driver's eyes are closed or closing, or the driver is looking outside Areas 1 and 2, it emits an audible warning within 2 s. If the distraction lasts longer than 3 s, a voice message warns the driver to look at the road ahead. According to the conceptual framework described by Victor [52], this device can be considered a visual distraction alert, a preventive countermeasure (i.e., to minimize both the occurrence and the impact of distraction) active during driving, without providing any feedback to the driver. This non-intrusive and non-wearable device was found to be partially effective on motorways [7] and we want to evaluate its effectiveness on urban roads as well.

2.3. Road scenarios

The simulated scenario consisted of a 6.5 km track within a realistic urban network, where the speed limit was set at 50 km/h. The road environment included pedestrians on sidewalks, bicycles sharing the street, parked cars, and other vehicles navigating the network. The total scenario took approximately 7 min to complete. Drivers encountered three different urban road segments during the simulation. Along the first two-lane street, a pedestrian unexpectedly crossed the road at a mid-block crosswalk (Fig. 2, Section 1). After making a right turn at a T intersection, the participants drove in free-flow conditions on a two-carriageway road (Fig. 2, Section 2). When turning left at a second intersection, the participants followed a slow-moving vehicle travelling at 40 km/h (Fig. 2, Section 3). To minimize familiarity with driving

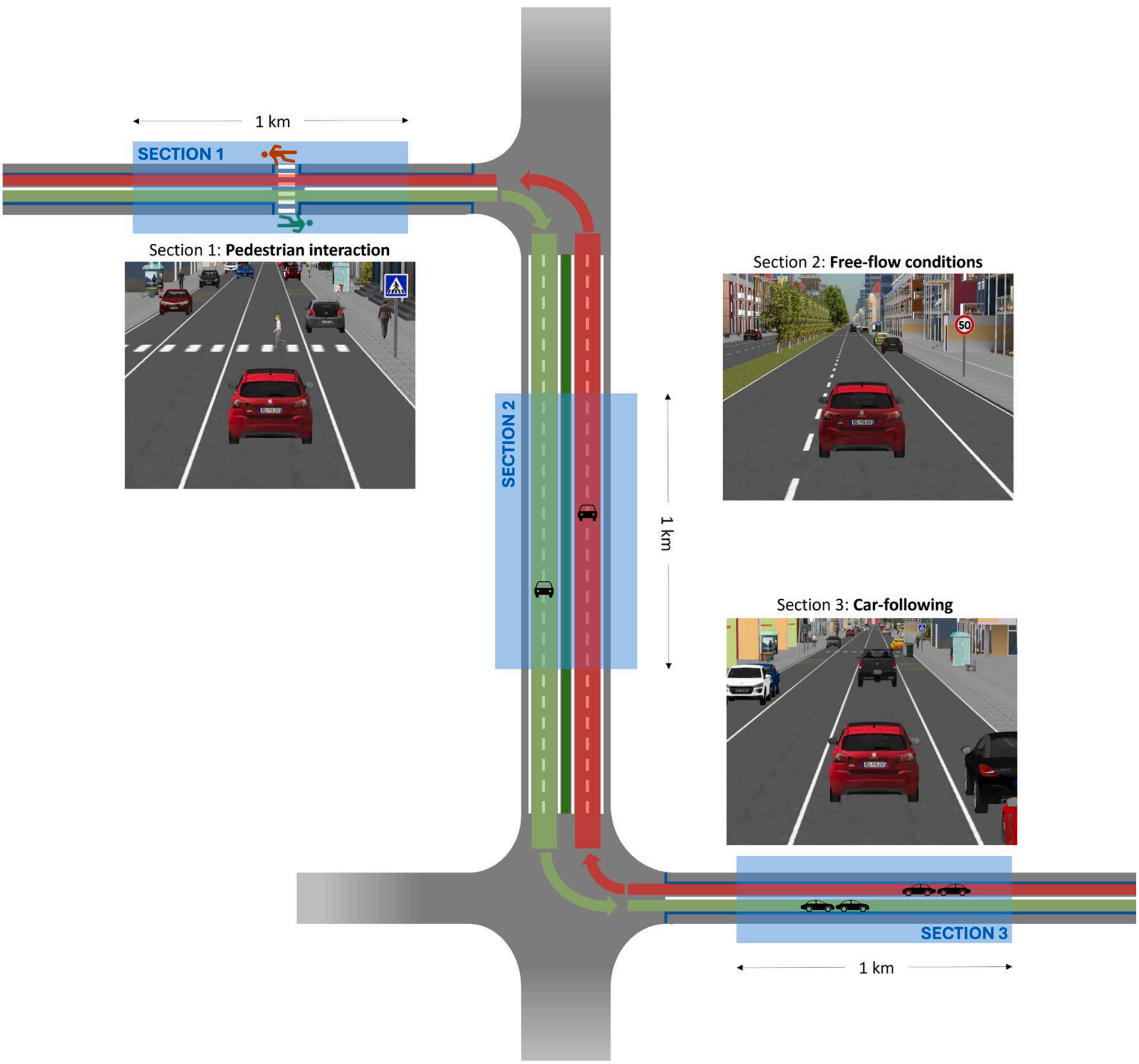

Fig. 2. General layout of the urban network with the three different events faced by participants.

Table 2
Descriptive statistics (mean and standard deviation between brackets) of participants' traits.

	No.	Age (years)	Driving experience		Crash experience (no.)
			(km/years)	(years)	
Males (M)	15	28.7 (3.2)	11,386.7 (8660.7)	10.1 (3.1)	0.4 (0.6)
Females (F)	15	28.5 (2.4)	7033.3 (5814.0)	9.7 (2.6)	0.2 (0.4)
< 28 years	12	26 (0.6)	7691.7 (5774.2)	7.3 (0.9)	0.2 (0.4)
28 – 31 years	11	28.8 (1.3)	11,590.9 (8985.6)	10.3 (1.4)	0.3 (0.5)
> 31 years	7	32.7 (1.1)	8071.4 (8085.1)	13.9 (1.1)	0.6 (0.8)
Total	30	28.6 (2.8)	9210.0 (7578.3)	9.9 (2.8)	0.3 (0.5)

conditions and mitigate over-confidence, participants completed the track three times which allowed them to experience each distraction level. The section orders (1–2–3 and 3–2–1) were randomly assigned. In addition, distinct elements such as the colour of cars and pedestrians, were modified for each distraction level, providing participants with a unique driving experience on each of the three drives.

2.4. Secondary task

Using mobile phones to text while driving was already considered a secondary task when evaluating the effects of driving distraction [14,34,38]. Alosco et al. [3] distracted drivers by asking them questions of a personal nature and to which they already knew the answer (e.g., date of birth, hometown, last name, and current day of the week). Thapa et al. [50] explored distraction with questions about the driver's personal life, job, or school commitments in the case of students. In our study, we asked questions related to personal information, tastes, and preferences (e.g., music preferences, height, favourite singer). Being the one most widely used in Italy, the instant messaging application WhatsApp was chosen here for all participants. Similarly to Drews et al. [22], the test drivers were asked in a pre-drive questionnaire whether they were able to text while driving and whether WhatsApp was already installed on their phone before they took part in the experiment. By selecting only participants who were already able to text while driving, the study aimed to assess the effects of distraction on drivers who were familiar with texting in real driving conditions. Following Choudhary and Velaga [18], participants were instructed to provide brief answers of no more than two words, and (for reasons of privacy) they were informed that their responses would not be recorded. Drivers were also directed to prioritize safe driving, thus responding to the text messages sent by the experimenter quickly but comfortably. In the trial session before starting the experiment, participants responded to five texts to ensure that they were familiar with the task of texting while using the driving simulator. During the experimental driving session, participants experienced distracted driving with and without the support of the ADDW device, reading and writing messages on their cell phones in the 1 km-long sections (see Paragraph 2.3, and Fig. 2). Participants were required to continue with the secondary task until they were notified on screen to stop.

2.5. Participants and experimental protocol

The experiment was conducted in accordance with the Code of Ethics of the World Medical Association [57]. Thirty test drivers (fifteen females) aged between 25 and 35 years participated in the experiment. Middle-aged drivers were selected to ensure familiarity with the secondary task and the use of a mobile phone [30,43,46], and also to ensure that participants had at least five years driving experience, which of course is not possible with novice drivers. Participants were recruited through email invitations, which solicited information on age, years of driving experience, average number of kilometres travelled per year, and the number of crashes they had been involved in (Table 2). Additionally, they were asked to honestly declare their ability to text while driving and whether they used WhatsApp.

Prior to commencing the driving session, drivers completed a pre-drive questionnaire to assess their health conditions, COVID-19 status, and some privacy-related issues. They then took part in a trial session in order to gain familiarity with the driving simulator and the secondary task they would be performing. All participants experienced the three distraction levels, the order of which was randomly assigned. The ADDW device was calibrated before being used in the session. At the end of the experiment, participants filled out a post-drive questionnaire on the overall experience and they also provided feedback on their use of the ADDW device. Two test drivers were excluded due to their aggressive and unrealistic speeding behaviour, as they significantly exceeded the limit of 50 km/h, and they were replaced by two other participants with similar personal traits. None of the participants suffered from simulation sickness.

2.6. Data analysis

Data were collected at a frequency of 10 Hz. Surrogate safety measures such as minimum time-to-collision (*MTTC*) and post-encroachment time (*PET*) were measured during the interaction with a pedestrian at a mid-block crosswalk (Section 1, Fig. 2). These measures are useful for predicting the potential severity of any conflict during vehicle-pedestrian interactions at crosswalks [26,49]. The maximum speed achieved in the 100 m before the crosswalk, (*MaxS*) and the distance from the crosswalk at which the maximum deceleration was recorded (*d@MaxD*) to represent the reaction distance, were also measured. Longitudinal and lateral behaviours in terms of mean speed (*S*), mean lateral position (*LP*) and their standard deviations (*SDS* and *SDLP*) were analysed when drivers operated in free-flow conditions (Section 2, Fig. 2). Finally, the standard deviation of lateral position (*SDLP*) and minimum time headway (*MinHW*) from the leading vehicle were measured in the car-following scenario (Section 3, Fig. 2). These are the variables which are most commonly analysed and studied when investigating the impact of distraction on driver performance [40,61].

Linear mixed-effects models (LMMs) were employed to evaluate the effect of experimental factors on dependent variables. These statistical models can deal with repeated measures within-subjects designs, ensuring more accurate estimates and greater statistical power. LMMs can include different types of variables (continuous, categorical) and their interactions to explore relationships within the data. They can handle unbalanced and missing data, and also work with correlated data and non-independent errors by including random effects to account for individual differences. The two experimental factors (distraction level and gender) were included as categorical fixed effects in the LMM calibration, while age, crash experience, and driving experience (measured by average distance travelled per year, and years holding a driving licence) were included as covariates. Random effects reported the unobserved heterogeneity related to participants' subjective characteristics, with the test driver ID as a cluster variable. The factors were selected by (i) the backward elimination technique and (ii) a comparison of model performance parameters, e.g., AIC, BIC, and likelihood. LMM were estimated with R Statistical Software version 4.3.2 [44], by using the *lme4* package [9]. Estimated marginal means were computed with the *emmeans* package [31] and the results were graphically presented

Table 3
Mean (and standard deviation) of the dependent variables considered for the pedestrian interaction. (Notes. Distraction level: 0 = baseline, 1 = distracted, 2 = distracted + ADDW; Gender: *M* = male, *F* = female).

Distraction level	Gender	*MTTC* (s)	*PET* (s)	*MaxS* (km/h)	*d@MaxD* (m)
0	M	2.52 (0.70)	5.40 (1.06)	54.8 (8.3)	31.81 (13.68)
	F	2.33 (0.85)	6.41 (2.96)	54.6 (7.1)	29.59 (8.12)
1	M	2.31 (0.90)	6.55 (2.34)	50.4 (4.5)	26.64 (7.70)
	F	2.13 (0.96)	7.15 (3.02)	50.0 (8.4)	23.53 (11.47)
2	M	1.98 (0.99)	4.91 (2.69)	49.8 (8.0)	24.25 (6.88)
	F	2.39 (1.16)	6.64 (3.68)	50.8 (8.8)	26.07 (11.36)

Table 4
Mean (and standard deviation) of the dependent variables considered for the free-flow conditions. (Notes. Distraction level: 0 = baseline, 1 = distracted, 2 = distracted + ADDW; Gender: *M* = male, *F* = female).

Distraction level	Gender	*S* (km/h)	*SDS* (km/h)	*LP* (m)	*SDLP* (m)
0	M	54.4 (4.6)	2.5 (1.6)	0.10 (0.18)	0.15 (0.06)
	F	51.7 (4.1)	2.9 (1.9)	0.09 (0.26)	0.14 (0.06)
1	M	50.8 (4.9)	2.8 (1.4)	0.16 (0.22)	0.18 (0.06)
	F	48.7 (5.5)	4.1 (1.7)	0.23 (0.33)	0.27 (0.15)
2	M	51.0 (6.1)	3.4 (1.9)	0.18 (0.15)	0.18 (0.09)
	F	48.0 (6.6)	3.9 (1.8)	0.12 (0.24)	0.22 (0.11)

Table 5
Mean (and standard deviation) of the dependent variables considered for the car-following event. (Notes. Distraction level: 0 = baseline, 1 = distracted, 2 = distracted + ADDW; Gender: *M* = male, *F* = female).

Distraction level	Gender	*MinHW* (s)	*SDLP* (m)
0	M	1.52 (0.40)	0.11 (0.03)
	F	2.33 (2.25)	0.15 (0.08)
1	M	2.21 (1.49)	0.16 (0.05)
	F	2.83 (2.33)	0.20 (0.14)
2	M	1.79 (0.70)	0.15 (0.04)
	F	2.77 (2.20)	0.21 (0.15)

with the *ggplot2* package [53]. The significance level was set at 5 %, and post-hoc tests with Holm correction were conducted for statistically significant effects and interactions.

3. RESULTS

3.1. Descriptive statistics

Table 3 provides the descriptive statistics (mean and standard deviation) for the data relating to the pedestrian interaction. An examination of the results reveals no evident differences in the *MTTC* among the three different distraction levels. It is worth noting that male drivers exhibited a lower *PET* than female ones. Additionally, *PET* increased when drivers were distracted when compared to the baseline condition (distraction level 0), while a slight improvement was noted when the ADDW device was active (distraction level 2). Speed decreased when drivers were distracted (for both distraction levels 1 and 2). The distance at which maximum deceleration occurred was lower when drivers were distracted, indicating longer reaction times.

Even under free-flow conditions (Table 4), the mean speed was lower when the secondary task was being performed. Texting caused an impairment in both longitudinal and lateral control (i.e., both *SDS* and *SDLP* increased). However, the ADDW succeeded in reducing the degree of lateral weaving by females, i.e., lower *SDLP*. The results also indicate that, when distracted, drivers tended to deviate from the lane centreline. A positive value for *LP* indicates a vehicle centre of gravity value (CoG) on the left side of the lane.

For the car-following event, Table 5 shows clear differences in the minimum time headway (*MinHW*) between males and females, with the latter driving at a greater temporal distance from the vehicle ahead than the former. As for the lateral control of the vehicle, the *SDLP* was slightly

Table 6
Significant factors and summary statistics of LMM for the pedestrian interaction (Notes: · for $p < .1$, * for $p < .05$, ** for $p < .01$, and *** for $p < .001$, symbol - means not statistically significant at a significance level of 0.05).

Variables	Effect	Estimate (*p*-value)			
		MTTC (s)	*PET* (s)	*MaxS* (km/h)	*d@MaxD* (m)
Fixed Effects *(main factors and interactions)*					
Intercept		2.326 (***)	5.904 (***)	62.471 (***)	30.699 (***)
Distraction level	1 – 0	−0.195 (-)	0.945 (·)	−4.494 (**)	−5.614 (*)
Distraction level	2 – 0	0.065 (-)	−0.127 (-)	−4.418 (**)	−5.541 (*)
Gender	M – F	0.199 (-)	–	–	–
Driving experience (y)		–	–	−0.787 (*)	–
Distraction level * Gender	(1 – 0) * (M – F)	−0.019 (-)	–	–	–
Distraction level * Gender	(2 – 0) * (M – F)	−0.610 (-)	–	–	–
Random effects					
Participant ID		(-)	(***)	(**)	(-)
Summary statistics					
AIC		258.964	428.600	603.112	668.946
BIC		278.962	441.099	618.111	681.445
Log - Likelihood		−121.482	−209.300	−295.556	−329.473
Marginal R^2		.035	0.029	0.149	.065
Conditional R^2		.139	0.460	0.462	.065
ICC for random components		.108	.444	.367	–

Table 7
Significant factors and summary statistics for LMM in free-flow conditions (Notes: · for $p < .1$, * for $p < .05$, ** for $p < .01$, and *** for $p < .001$, symbol - means not statistically significant at a significance level of 0.05).

Variables	Effect	Estimate (*p*-value)			
		S (km/h)	*SDS* (km/h)	*LP* (m)	*SDLP* (m)
Fixed Effects *(main factors and interactions)*					
Intercept		57.260 (***)	2.673 (***)	0.094 (*)	0.142 (***)
Distraction level	1 – 0	−3.330 (**)	0.760 (*)	0.102 (*)	0.130 (***)
Distraction level	2 – 0	−3.550 (***)	0.961 (**)	0.058 (-)	0.079 (**)
Gender	M – F	–	–	–	0.010 (-)
Driving experience (y)		−0.725 (**)	–	–	–
Driving experience (km/y)		$3.220 \cdot 10^{-4}$ (**)	–	–	–
Distraction level * Gender	(1 – 0) * (M – F)	–	–	–	−0.103 (**)
Distraction level * Gender	(2 – 0) * (M – F)	–	–	–	−0.053 (-)
Random effects					
Participant ID		(***)	(***)	(***)	(***)
Summary statistics					
AIC		547.012	351.653	−8.062	−141.356
BIC		564.511	364.152	4.437	−121.358
Log - Likelihood		−266.506	−170.827	9.031	78.678
Marginal R^2		.314	0.054	0.032	.182
Conditional R^2		.581	0.435	0.524	.543
ICC for random components		.389	.403	.508	.441

higher when the secondary task was performed without the support of the ADDW device.

3.2. LMM outcomes

Tables 6, 7 and 8 summarize the LMM results for the pedestrian interaction, the free-flow conditions, and the car-following event, respectively. The distraction levels (0, 1, and 2) and gender (M and F) were included as categorical factors. Age, number of crashes, and driving experience (distance travelled per year, and years with a driving licence) were assumed as covariates, while the participant ID was regarded as a cluster variable.

3.2.1. Mid-block crosswalk pedestrian interaction

Table 6 shows the proportion of variance attributable to the fixed factors only (marginal R^2) and the proportion explained by both fixed and random effects (conditional R^2) for the dependent variables considered in the pedestrian interaction. For *MTTC*, only around 14 % of the variance in the data is explained by the model, 25 % of which is attributable to fixed effects. Around 46 % of the total variance in the models for *PET* and *MaxS* is explained, while the variance explained by the fixed factors alone is 6 % of the total for *PET* and 32 % of the total for *MaxS*, respectively. Only 6.5 % of the variance in the model for *d@MaxD* is fully explained by fixed effects (marginal R^2 = conditional R^2). LRT tests for random effects demonstrate the significance of the random component for *PET* and *MaxS*, confirmed by the values of the intraclass correlation coefficients (ICC) being greater than the cut-off value of 0.1 [6], i.e., 0.444 and 0.367 for *PET* and *MaxS*, respectively.

Although distraction level, gender and their interaction were retained in the model to enhance its performance, LMM indicates that none of the independent factors affected the *MTTC*. The distraction level was proven to slightly affect the *PET* ($PET_1 - PET_0 = 0.95$ s, $t_{58} = 1.773$, $p = .081$) from a statistical point of view. The value for *PET* was higher for distracted drivers ($M_1 = 6.85$ s, $SE_1 = 0.51$ s) than for the baseline condition ($M_0 = 5.90$ s, $SE_0 = 0.51$ s).

LMM outcomes show that the maximum speed achieved in the 100 m before the crosswalk (*MaxS*) was significantly influenced by the distraction level. The post-hoc test with Holm correction demonstrates that *MaxS* was lower when drivers were performing the secondary task than when they were operating under the baseline condition ($p = .012$), despite the support of the ADDW device ($p = .012$). No significant improvement attributable to the ADDW device is evident among distracted drivers ($p = .960$). Furthermore, *MaxS* significantly decreased as the driving experience (number of years with a driving licence) increased ($p = .040$).

The distraction level also affected the distance at which drivers started decelerating, i.e., max deceleration (*d@MaxD*). The braking manoeuvre started later, i.e., the distance of maximum deceleration was shorter among distracted drivers for levels 1 ($p = .034$) and 2 ($p = .036$) than for the baseline condition. No statistical differences were attributable to the presence of the ADDW device.

Table 8
Significant factors and summary statistics for LMM for the car-following (Notes: · for $p < .1$, * for $p < .05$, ** for $p < .01$, and *** for $p < .001$, symbol - means not statistically significant at a significance level of 0.05).

Variables	Effect	Estimate (*p*-value)	
		MinHW (s)	*SDLP* (m)
Fixed Effects *(main factors and interactions)*			
Intercept		2.163 (***)	0.131 (***)
Distraction level	1 – 0	0.595 (-)	0.051 (***)
Distraction level	2 – 0	0.357 (-)	0.047 (**)
Gender	M – F	−0.968 (*)	–
Crashes		0.818 (·)	–
Random effects			
Participant ID		(**)	(***)
Summary statistics			
AIC		351.750	−183.929
BIC		369.249	−171.430
Log - Likelihood		−168.875	96.964
Marginal R^2		.124	0.059
Conditional R^2		.407	0.682
ICC for random components		.324	.662

3.2.2. Free-flow conditions

The outcomes of the LMM for the driving performance during free-flow conditions are reported in Table 7. LMMs explain around 50 % of the variance for all the dependent variables considered. For *S*, more than half of the variance is attributable to fixed effects. As regards the other variables, 33 % of the total variance in the model for *SDLP* is explained by fixed effects. Only 12 % and 6 % of the variance in *SDS* and *LP* respectively is explained by fixed effects. The significance of random effects is confirmed by the LRT test results ($p < .001$) and the high ICC values (at least around 0.40).

As seen with the outcomes for the LMMs, longitudinal behaviour (*S* and *SDS*) was significantly affected by the distraction inherent with the performance of the secondary task. A post-hoc test with Holm correction demonstrates that distracted drivers adopted lower speeds than undistracted ones ($p = .002$). Although distracted drivers reduced their speed ($p = .001$), the support of the ADDW device did not lead to any significant differences in their speed *S* ($p = .820$). Another statistically significant factor for *S* was driving experience. Drivers who had held a licence for longer tended to reduce their speed, while those who drove more kilometres per year increased it. As anticipated before, longitudinal control was also affected by the distraction level. Compared to the baseline, texting while driving impaired the longitudinal performance, i.e., *SDS* increased for distracted drivers in both level 1 ($p = .036$) and level 2 ($p = .008$).

As far as lateral performances are concerned, the LMM for *LP* reveals that drivers tended to shift toward the left when distracted ($p = .018$). More satisfying results are obtained for the *SDLP*. The secondary task significantly influenced lateral control, both as a single factor and in interaction with gender. As a single factor, the post-hoc test with Holm correction indicates that distracted drivers impaired their lateral behaviour, i.e., *SDLP* increased compared to undistracted drivers ($p < .001$), even with the ADDW support ($p = .010$), which did not provide any benefits ($p = .165$). In interaction with gender, the post-hoc test with Holm correction indicates that texting while driving mainly affected female drivers, as evidenced by the significant increase in their *SDLP*, both for level 1 ($p < .001$) and level 2 ($p = .025$). It also highlights a slight difference in lateral control between males and females when distracted. Female drivers in level 1 had worse lateral control than their male counterparts ($p = .061$).

3.2.3. Car-following

In Table 8 the outcomes for LMM in the car-following scenario are provided. For *MinHW*, approximately 40 % of the variance in the data is explained by the model, 30 % of which is attributed to fixed effects. The model for *SDLP* explains 68 % of the variance in the data, with only around 9 % attributed to fixed effects. The importance of random effects is highlighted by the statistical significance of the LRT test results and the ICC values (ranging from 0.30 to 0.70).

The LMM for *MinHW* does not reveal any statistical differences attributable to the distraction level, even when included within the model. However, *MinHW* was mainly affected by gender. Female drivers maintained a greater headway from the vehicle in front than males ($p = .047$). On the other hand, the distraction level proves to be statistically significant for the *SDLP* model. A post-hoc test with Holm correction shows that distracted drivers experienced a deterioration in their lateral behaviour, with higher *SDLP* values compared to the baseline, both in level 1 ($p = .002$) and level 2 ($p = .003$). Hence, the anti-distraction device resulted in no improvement in lateral control.

4. Discussion

This driving simulation study was designed to assess the impact of distraction on driving performance in urban road scenarios. The effectiveness of an auditory Driver Distraction Warning (ADDW) device in mitigating the negative effects of distractions was assessed. Participants drove under three conditions: (i) undistracted, (ii) distracted by engaging in texting while driving, and (iii) distracted but supported by the ADDW device. They encountered three different situations: (i) interacting with a pedestrian crossing the road, (ii) driving in free-flow conditions, and (iii) following a slow-moving vehicle.

4.1. Driver-pedestrian interaction

Contrary to expectations, the distraction level did not significantly affect the minimum time to collision (*MTTC*), indicating that drivers maintained a consistent response to a potential collision with a pedestrian, regardless of the level of distraction. Even when distracted, participants increased their level of attention in response to the risk signalled by the device, thus offsetting the negative impact of distraction on reaction times. However, distracted drivers showed a higher post-encroachment time (*PET*) than the baseline because they completed the secondary task before resuming driving. The increased *PET* also suggests a potential delay due to the cognitive demand imposed by the secondary task, diverting attention away from the immediate need to continue driving after the pedestrian crossing.

Data analysis revealed a reduction in the maximum speed adopted in the 100 m before the crosswalk (*MaxS*) when drivers were engaged in secondary tasks, even with the support of the ADDW device (Fig. 3a). As they approached the crosswalk, drivers decreased their speed to reduce the risk of collisions with pedestrians. Anttila and Luoma [5] obtained opposite results, with distracted drivers increasing their speed before the crosswalk. One possible reason for this difference lies in the behaviour of both drivers and pedestrians. While some drivers are reluctant to stop and yield priority to other road users, others increase their speed in an attempt to deter pedestrians from crossing. However, some pedestrians increase their pace to avoid any conflict and this action is not always matched by a braking action of the driver approaching the crosswalk. In contrast, in this simulation study, the simulated pedestrians maintained a constant speed of 4 km/h and crossed without stopping or accelerating, with the participants being aware of this simulated pedestrian behaviour. This difference in interaction between reality and simulation results in a different driver behavioural response which, in the case of the simulation, prompts the participant to be more cautious. Furthermore, the absence of significant effects among distracted drivers using

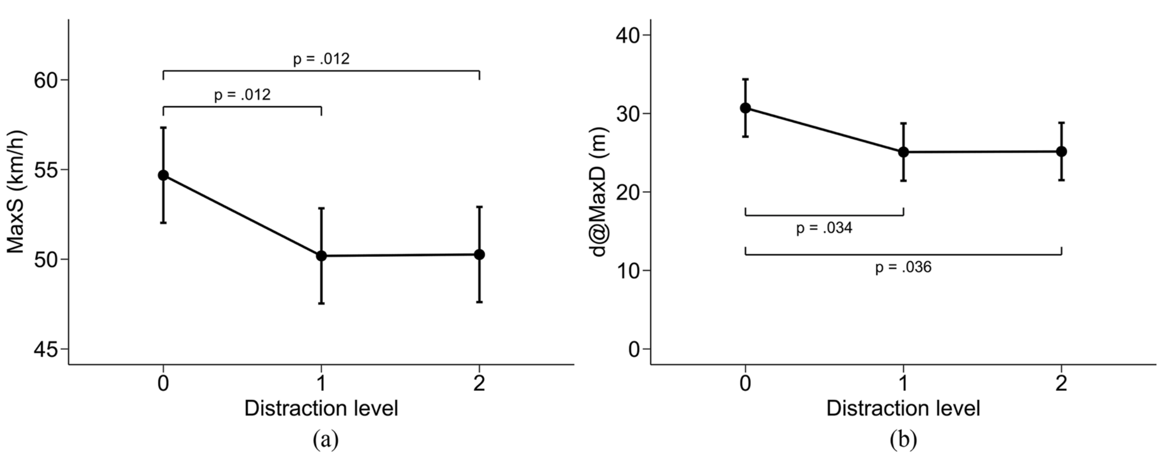

Fig. 3. Effect plots for the pedestrian interaction: (a) the maximum speed at 100 m before the crosswalk, and (b) the distance at which maximum deceleration before the crosswalk was recorded. (Notes. Distraction level: 0 = non distracted (baseline), 1 = distracted, 2 = distracted + ADDW. Error bars represent the standard error of the mean).

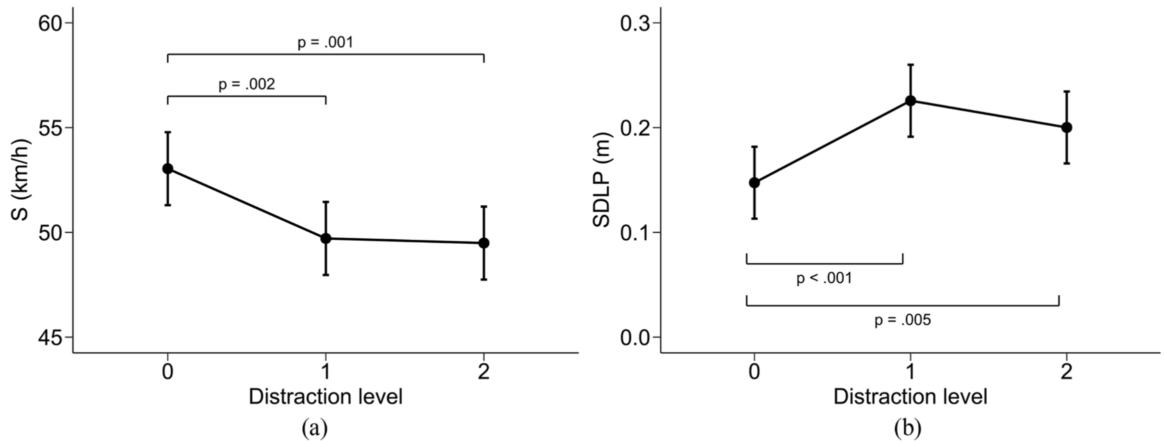

Fig. 4. Effect plots for free-flow conditions: (a) the mean speed, and (b) the standard deviation of the lateral position. (Notes. Distraction level: 0 = non distracted (baseline), 1 = distracted, 2 = distracted + ADDW. Error bars represent the standard error of the mean).

the ADDW indicates the limited effectiveness of the device. It is plausible that individual differences in distracted behaviour or the specific nature of the secondary task may limit the effectiveness of ADDWs on urban roads. It must be emphasised once again that the distraction was not voluntary but imposed by the experimental protocol.

Interestingly, the findings underscored the effect of driving experience on *MaxS*. As the level of driving experience increased, the maximum speed decreased, emphasizing the impact of experience on adaptive driving behaviour. This finding suggests that experienced drivers adapt their behaviour when distracted while approaching zebra crossings due to their heightened awareness of the potential risks they face. Nevertheless, this result must be confined to the age group of middle-aged drivers (25–35).

When approaching the zebra crossing, distracted drivers were slower than non-distracted drivers to initiate a braking manoeuvre, thus having a shorter distance from the crosswalk within which to decelerate (Fig. 3b). This result highlights the impact of distraction on the braking reaction and is consistent with the findings of Calvi et al. [15]. In their driving simulation experiment, the distraction caused by texting resulted in a significant delay in the start of the deceleration manoeuvre before the pedestrian crossing. As described above, the cognitive workload associated with the secondary task delays the execution of the evasive manoeuvre. The delayed response results in increased deceleration over a shorter distance. Our result is consistent with the findings of Anttila and Luoma [5], who observed a sudden braking action when interacting with pedestrians. Texting while driving affects the allocation of attention, potentially causing a "tunnel vision" effect where drivers become more focused on the secondary task and less attentive to critical situations outside the "tunnel" [11].

4.2. *Free-flow conditions*

In free-flow conditions, distracted drivers adopted lower speeds than undistracted ones (Fig. 4a). This result is consistent with previous studies by Boets et al. [11] and Yannis et al. [58]. Additionally, Ortiz-Peregrina et al. [39] observed that participants who were texting while driving tended to drive more slowly than those who were not distracted. The secondary task itself significantly influences speed. As drivers allocate cognitive resources to non-driving-related tasks, speed reduction serves as a risk compensation mechanism [13,18], consistent with findings related to pedestrian interactions (see Section 4.1). Yannis et al. [59] confirmed that the prevalent compensatory strategy adopted during distracted driving involves reducing speed and increasing the distance from the centre of the lane. Our study also revealed that *LP* was affected by the distraction level. While these compensatory behaviours lead to lower speeds and are, therefore, beneficial in road safety terms, they may not consistently counterbalance the impairments associated with driver distraction. Prolonged reaction times and an elevated likelihood of accidents, especially during unexpected events, remain a source of concern. Our results confirm that distraction negatively influences driving performance in urban areas [10].

Interestingly, distracted drivers did not exhibit significant differences when supported by the ADDW device (Fig. 4a) which was not effective in counteracting the effects of secondary tasks on speed, as observed in the motorway environment by Bassani et al. [7]. The effectiveness of the ADDW was influenced by the fact that drivers continued to write text messages regardless of the acoustic warning. In cases of intense distraction or high mental workload, the ADDW device may fail to partly redirect attention or influence speed control [59].

As previously discussed regarding pedestrian interaction, the driving experience influences speed adjustments. Drivers who have held a licence for longer tended to reduce their speed, while those travelling for more kilometres per year increased their speed. The lower speeds exhibited by drivers with more years of holding a license can be attributed to the accumulated experience and knowledge gained over time, leading to a more cautious and safety-conscious approach. Conversely, drivers covering longer distances may prioritize efficiency and time savings, potentially resulting in higher speeds. From a safety perspective, these results underscore the impact of individual driving characteristics and experience on longitudinal behaviour, as clearly interpreted by the random effects in the LMM.

Texting while driving impairs longitudinal performance, as evidenced by an increase in *SDS* compared to the baseline. This finding aligns with Amini et al. [4], who observed higher speed variations during critical (such as pedestrian interactions) and non-critical events (such as free-flow conditions). This result diverges from the findings of Bassani et al. [7] in the context of motorway driving, where distraction was associated with a decrease in *SDS*. This discrepancy can be attributed to the more challenging nature of the urban environment where contextual stimuli are greater, compared to the relatively monotonous and stable conditions characteristic of free-flow driving on the motorway.

When distracted, drivers exhibited a reduced ability to control the vehicle lateral position, i.e., the *SDLP* values were higher than those for undistracted drivers, despite the support of the ADDW device which failed to provide any benefits (Fig. 4b). This result indicates how distraction impacts lateral control and is consistent with the findings of Rumschlag et al. [47] and Al Aufi et al. [1]. Our result confirms what Ortiz et al. [38] found, who used the same secondary task (texting using WhatsApp). The *SDLP* increment suggests a greater difficulty in maintaining a constant position within the lane for distracted drivers. Although the ADDW device was effective in motorway driving [7], no

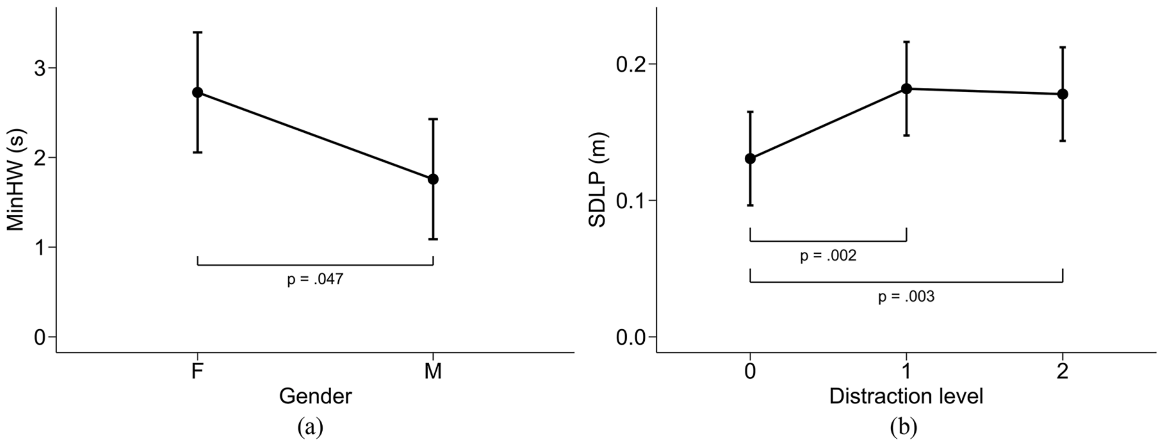

Fig. 5. Effect plots for the car-following: (a) the minimum headway from the vehicle in front, and (b) the standard deviation of the lateral position. (Notes. Distraction level: 0 = non distracted (baseline), 1 = distracted, 2 = distracted + ADDW; Gender: *M* = males, *F* = females. Error bars represent the standard error of the mean).

improvement was recorded here. The driver's engagement in the secondary task is taxing and the environment is continuously providing different stimuli, especially if the distraction intensity is high. Our result is not consistent with that of Boets et al. [11], where no differences in *SDLP* were detected when comparing texting with undistracted driving, even though the driving environment was the same (i.e., urban straight road).

Gender differences were observed through the significant increment in *SDLP* in females for both levels of distraction. This result is in line with the findings of Irwin et al. [25], who observed that distracted females make more lateral errors than males while driving. Even when the *SDLP* is reduced by the ADDW device (distraction level 2) with respect to level 1, the improvement is not statistically significant.

When considering the data on speed and *SDLP* as a whole, this study confirms that distraction leads to a deterioration in lateral control, which is partly counterbalanced by a contemporaneous reduction in speed. Furthermore, the intervention of the ADDW device did not result in any discernible change in the driving behaviour of users who remained distracted despite being alerted by the device, compared to those who were simply distracted by using their mobile phone.

4.3. Car-following

Maintaining an adequate headway from the car in front is crucial for collision avoidance. No effects attributable to the distraction level were identified in our experiment, while Peng et al. [41], as well as Lansdown [29] and Drews et al. [22] stated that texting while driving has a negative impact on the mean and the standard deviation of headway. Nevertheless, female drivers consistently maintained a greater headway from the vehicle in front than their male counterparts (Fig. 5a). Females adopted a cautious behaviour, in line with existing literature highlighting differences in risk perception and driving styles between genders [2,7,25].

In the car-following situation, there was also a deterioration in the lateral control of distracted drivers irrespective of the presence or otherwise of the ADDW device, as evidenced by the significant increase in SDLP values compared to those for undistracted drivers (Fig. 5b). This increase in SDLP values when engaged in the performance of a secondary task during critical events, i.e., car-following, was also observed in Amini et al. [4]. Similarly to free-flow conditions, the ADDW device did not improve the lateral control of participants.

4.4. Limitations and future research

It is important to highlight the limitations of this study in order to identify areas that should be addressed in future studies. Firstly, the drivers were asked to ignore the ADDW warnings and continue sending text messages while driving, thus precluding the positive effect that might have resulted from the driver choosing to stop texting and concentrate on the primary task. Secondly, the real urban environment presents events that were not reproduced in the simulation, and which may condition the perception of risk and the level of attention the driver dedicates to primary and secondary tasks. Thirdly, the drivers were selected from a narrow age range of middle-aged drivers who declared they had already engaged in texting while driving. This ability may have influenced the results since some drivers used their mobile phone by placing it to the side or on the steering wheel, and others texted without looking at the screen, effectively bypassing the warnings from the ADDW device. It has been demonstrated that the positioning of the phone in close proximity to the steering wheel can affect the outcomes [32]. The freedom to manage the phone introduced some noise into the data. The intentional lack of control adopted during the experiments may have reduced the statistical difference between the two levels of distraction (levels 1 and 2) involving the secondary task.

Future studies should explore the effectiveness of alternative ADDW devices with different features and functionalities. These alternatives may provide solutions which prove to be more effective in countering the distraction of those drivers who persist in using their phones while driving. Additionally, the possibility that older drivers could benefit from the ADDW device should not be ruled out, so future research should be carried out to develop more targeted and age-appropriate usage guidelines for the ADDW device. By considering a larger and more diverse sample of drivers, we can extend the external validity of our results and address additional aspects.

5. Conclusions

Driver distraction represents a significant challenge for road safety, necessitating a comprehensive understanding of its implications. In this driving simulation study, we contributed to current knowledge by analysing the effectiveness of a driver distraction warning device (ADDW) in counteracting the negative effects of driver engagement in secondary non-driving-related tasks while driving on urban roads.

Data analysis and model calibration revealed critical insights that highlight the need for enhanced road safety measures. Distracted driving exacerbates unsafe driving behaviours, as evidenced by delayed braking manoeuvres and reduced attention to critical elements such as crosswalks. The increased mental effort required to simultaneously perform primary and secondary tasks, both with and without an alert from the ADDW, compromises the performance of drivers when they are interacting with pedestrians, driving behind another vehicle, and driving in free-flow conditions. Distracted drivers adopted compensation mechanisms that led them to prolong post-encroachment times and reduce speeds both near pedestrian crosswalks and in free-flow conditions.

The effectiveness of the ADDW device in mitigating the negative effects on driving performance attributable to drivers who persist with texting appears negligible. While it does have a positive impact on lateral control in free-flow conditions (albeit not statistically significant), it fails to significantly improve other aspects of driving behaviour, including longitudinal control and headway with vehicles in front. In conclusion, the ADDW device did not significantly improve the driving performance of drivers while they were engaged in performing a secondary task on urban roads. This finding was in contrast to the positive effects previously demonstrated for motorway driving [7].

More experienced middle-aged drivers tended to adopt lower speeds when approaching a crosswalk while those who cover longer distances during the year tended to increase their speed while travelling in free-flow conditions. Furthermore, females maintained a greater headway from the vehicle in front than males did. Recognizing these influences is crucial for the development of targeted interventions to enhance road safety.

The findings underscore the perilous nature of distracted driving and reveal the limited efficacy of the technology currently employed to enhance driver behaviour on urban roads. The limited effectiveness of the ADDW device in urban driving contexts suggests that the current theoretical literature needs to consider the influence of these devices in different driving environments (e.g., urban vs. rural).

It is imperative to seek more comprehensive strategies for improving road safety and mitigating the impact of driver distraction. From a practical point of view, the study suggests that ADDW devices may need to have additional features to render them more effective in urban driving conditions. For example, the integration of visual or haptic feedback, rather than just an audible warning, could improve their effectiveness. The limited effectiveness of ADDW devices suggests that technology alone may not be sufficient to reduce distracted driving. Policy makers may need to consider additional measures to address the distraction caused by the use of mobile phones while driving. Some countries have banned the practice, while many road authorities have disseminated awareness campaigns that have helped to highlight the risks associated with distracted driving and to improve situational awareness in this area, i.e., the importance of reaction time near pedestrian crossings. However, the persistence of this risky behaviour necessitates a cultural shift towards responsible driving practices. Road safety engineers could consider designing roads and intersections to naturally reduce the likelihood of distraction-related incidents, for example by adding more visible crossings or implementing traffic calming measures.

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CRediT authorship contribution statement

A. Lioi: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M. Bassani:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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