

VEHICLE–PEDESTRIAN INTERACTIONS INTO AND OUTSIDE OF CROSSWALKS: EFFECTS OF DRIVER ASSISTANCE SYSTEMS

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Abstract. This study aimed to analyse the driver's behaviour during the interaction with a pedestrian crossing into and outside the zebra crossing, and evaluate the effectiveness of two kinds of Advanced Driver Assistance System (ADAS) that provided to the driver an auditory alert, and a visual alert to detect the pedestrian. 42 participants joined the experiment conducted using the fixed-base driving simulator of the Department of Engineering (Roma Tre University). They experienced different crossing conditions (legal and illegal) and ADAS conditions (no ADAS, visual warning and auditory warning) in an urban scenario. The parameters Time-To-Arrive (TTA) and Speed Reduction Time (SRT) were obtained from the drivers' speed profiles in the last 150 m in advance of the conflict point with the pedestrian. Results clearly showed the criticality of illegal crossings. When the pedestrian crossed outside of the crosswalk, the highest number of collision occurred and the ANalysis Of VAriance (ANOVA) returned significant effects on both the dependent variables TTA and SRT, highlighting the higher criticality of the vehicle–pedestrian interaction and the more abrupt yielding manoeuvre. Positive effects (the vehicle–pedestrian interaction was less critical and the yielding manoeuvre was smoother) emerged for both the driver assistance systems, although not statistically significant. Besides, both the driver assistance systems positively affected the behaviour of the average cautious drivers. No significant effects of the warning systems were recorded on the aggressive drivers, which because of their behavioural characteristics ignored the warning alarm. In addition, no significant effects of the warning systems were recorded for the very cautious drivers, which adjusted their behaviour even before the alarm trigger. Finally, the outcomes of the questionnaire submitted to the participants highlighted the clear preference for the auditory warning, probably because of the different physical stimuli that are solicited by the warning signal. The results confirm that adequate pedestrian paths should be planned to avoid jaywalker conditions, which induce the driver to assume critical driving behaviour and provide useful findings of the effectiveness of driver assistance systems for pedestrian detection.

Keywords: pedestrian, driver's behaviour, driving simulator, ADAS, road safety, human factors.

Notations

ADAS – advanced driver assistance systems;
 ANOVA – analysis of variance;
 SRT – speed reduction time;
 TTA – time-to-arrive;
 TTZ – time-to-zebra.

Introduction

Accidents involving pedestrians and the relative number of pedestrian fatalities are remaining unacceptably high. As the accident data highlight, pedestrians persist among the most vulnerable road users. In the world, pedestrians comprise 23% of all road traffic deaths – approximately 310000 on 1.35 million road traffic deaths occurring every year (WHO 2018). In the US, during the 10 years

2008–2017 the number of pedestrian fatalities increased by 35%, while the number of all other traffic deaths decreased by 6% (GHSA 2018). In particular, in 2017, 5977 pedestrian lost their lives, increasing almost 9% from 2015 and representing 16% of the motor vehicle deaths. 80% of pedestrian deaths in 2016 occurred in urban areas (IIHS-HLDI 2021a, 2021b). Similar data are recorded in Europe, wherein 2015, 5320 pedestrians died in road accidents, which correspond to 21% of all road fatalities (ERSO 2018). Finally, according to the Italian accident data in 2017, 600 pedestrians lost their lives in road accidents, equal to 18% of road deaths (ISTAT 2018).

Literature indicates that vehicle–pedestrian crashes are mainly related to the lack of driver compliance towards pedestrian crossing laws (i.e., Mitman *et al.* 2010;

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Van Houten *et al.* 2013). However, unsafe pedestrian behaviours such as pedestrian crossing outside of a zebra crossing (i.e., jaywalking) may highly affect safety (Zheng *et al.* 2015).

The complex dynamic concerning the vehicle–pedestrian interaction is well identified in the “threat avoidance model” developed by Fuller (1984). According to such a model, when a vehicle–pedestrian interaction occurs, the driver can act different responses that can return in a “punishment” (e.g., a loss of time for his journey) or a “reward” (e.g., he does not suffer delay). In the first case, the driver decides to slow down and yield to the pedestrian (anticipatory avoidance response). In the second case, the driver does not slow down (no avoidance response) to communicate to the pedestrian that he/she wants to pass first; then, two possible conditions could occur: (1) the driver passes first; (2) the pedestrian assumes a “competitive behaviour” trying to pass before the driver; when this situation occurs a delayed avoidance response (e.g., a braking action) of the driver is needed to avoid the conflict.

Finally, this model suggests that the driver can experience a “no discriminative stimulus” (he does not see the pedestrian). In this case, two possible conditions could also occur: (1) the interaction with the pedestrian does not cause a risk (the pedestrian does not start to cross) or (2) a delayed avoidance response is required to avoid an accident.

Várhelyi (1998) observed that the vehicle–pedestrian interaction is highly affected by the driver’s time of arrival at the pedestrian crossing in the moment in which the pedestrian arrives at the curb. Such time, called TTZ, is obtained by calculating the distance of the vehicle from the zebra crossing divided by the vehicle’s speed when the pedestrian arrives at the curb.

The complexity of the vehicle–pedestrian interaction grows further when it occurs outside of a zebra crossing. Unlike permissible crossings at crosswalks, drivers are often caught unaware of jaywalkers, which may result in less driver reaction time and different vehicle operation dynamics (Zheng *et al.* 2015). Despite jaywalking events are particularly risky, they had received less attention. Most of the literature studies have focused on the behaviour of pedestrians during crossing (Deb *et al.* 2017; Zhuang *et al.* 2018; Zhou *et al.* 2019; Zafri *et al.* 2020; Tezcan *et al.* 2019), their crossing speed (Iryo-Asano *et al.* 2017; Zhuang, Wu 2018), the acceptance of the time gap (Petzoldt 2014; Lobjois, Cavallo 2007; Lobjois *et al.* 2013; Shaaban *et al.* 2019) or on the analysis of driver’s behaviour while approaching pedestrian crossings under different conditions of traffic calming measures (Fisher, Garay-Vega 2012; Bella, Silvestri 2015; Domenichini *et al.* 2019).

Few studies have investigated the behaviour of jaywalkers (Zhuang, Wu 2011, 2012; Shaaban *et al.* 2018), as well as the behaviour and reaction of the drivers in front of illegal crossings. These last topics were investigated only by Zheng *et al.* (2015) and Bella, Nobili (2020), using instrumented vehicles and by Obeid *et al.* (2017) and Tox-

opeus *et al.* (2018), using driving simulators.

Zheng *et al.* (2015) investigated the driver reaction to jaywalkers on the University of Florida (US) campus. Data were collected through an instrumented vehicle study and an observational study. Results showed that driver yielding decision point to jaywalkers is closer to the crossing point, and the average yield rate to jaywalkers is lower than that to pedestrians at permissible crossings. Bella and Nobili (2020), in a field study carried out using an instrumented vehicle, analysed the driver’s behaviour during the interaction with a pedestrian, who was crossing at and outside (jaywalker) of designated zebra crossings. The main results highlighted that the average yield rate to jaywalkers was lower than that to pedestrians at permissible crossings, the average deceleration rates were higher in the case of illegal crossing and driver yielding decision point to jaywalkers was closer to the conflict point.

Obeid *et al.* (2017) carried out a driving simulator experiment to study the interaction between drivers and pedestrians in a mixed-street environment. Among main findings, they highlighted that drivers’ behaviour in proximity of pedestrians tends to be statistically significantly less aggressive when their approach speed is lower and a crosswalk exists. Toxopeus *et al.* (2018), which carried out a driving simulator study too, analysed the driver’s behaviour in terms of driver response time (it was used to refer to all the different response choices including braking, swerving, accelerator release or combinations of these responses) and crash rate, when a pedestrian intruded into the path of a vehicle from the curb, in the moment in which the time to impact with the vehicle (time left for the vehicle to arrive at the collision point) was 4.35 s. They found that 8% of driver collided with the pedestrian and that there were no gender difference in terms of driver response time or crash rate.

An important aid towards the driver aimed at helping him during the crossing of a pedestrian is certainly identified in the use of ADAS. Such systems alert the driver of the pedestrian presence and therefore help to prevent or mitigate vehicle–pedestrian crashes because of the timely warning about possible collisions (Gerónimo *et al.* 2010; Spicer *et al.* 2018). Among the several types of alarms (auditory warnings, visual warnings, vibrotactile warnings, and haptic warnings), those most used concerning the auditory and the visual stimulus. The first type of alarm consists of audio signals as beep sounds, auditory icons (i.e., car horn, skidding tires) or speech message, that are sent to the driver through a vehicle on-board audio system (Gray 2011; Haas, Van Erp 2014; Yan *et al.* 2015a, 2015b), while the second type consists of a visual warning signal that appears on the vehicle dashboard (Maag *et al.* 2015; Werneke, Vollrath 2013; Hajiseyedjavadi *et al.* 2018). However, it is unclear whether more effective an audio or a visual warning is.

About this, Scott and Gray (2008) analysed the effects on drivers’ reaction time of three kind of warning modalities (tactile, auditory and visual) for a rear-end collision warning system as a function of warning timing (3 or 5 s)

by using a driving simulator. Results showed that driver reacted significantly earlier for all warning modalities compared with the no-warning condition. In addition, it was also found that the reaction time for visual warning was higher than that for the auditory warning, but the difference was not statistically significant.

Chen *et al.* (2011) analysed the driver performance at intersections of an auditory and a visual warning under different vehicle violation scenarios. They did not find statistically significant differences between visual warning and the auditory tone. However, in only one scenario (violation vehicle from right), the reaction time for the auditory tone warning was lower than that for the visual warning.

A more recent and interesting research (Wang *et al.* 2020) pointed out the necessity of an in-depth understanding of how different modalities of warning (visual and auditory warning) influence drivers' decision-making and performance when interacting with various road users. The results of this study highlighted that both visual and auditory warning improved the drivers' performance, showing different effects for the warning modality. The visual one helped drivers to drive more accurately and efficiently, whereas auditory information supports quicker responses. However, this study highlighted some important limitations (small sample, low fidelity driving simulator) and the authors suggested further studies in simulated environments developed with higher fidelity driving simulators.

The literature review shows that the body of knowledge for this topic is limited. Thus, the present study seeks to provide a contribution aimed at providing a deeper comprehension of driver's behaviour during the interaction with a pedestrian crossing into and outside the zebra crossing, and evaluate the effectiveness of two kinds of ADAS, which provided to the driver an auditory and a visual alert to detect the pedestrian. To accomplish these aims, an experiment at an advanced driving simulator, was carried out which allowed to avoid risks for participants and keep control of the boundary conditions of the experiment, ensuring the absence of confounding factors.

1. Methodology

A multi-factorial experiment was designed to analyse the effects on vehicle–pedestrian interaction of the following 2 factors:

- »» *crossing condition*: a pedestrian that crossed at the zebra crossing (legal crossing) and a pedestrian that crossed outside the zebra crossing (illegal crossing);
- »» *ADAS condition*: 3 different conditions were simulated. In one of these, the driver was not supported by the driving assistance system, while in the other two the vehicle provided to the driver an auditory alert, and a visual alert.

More specifically, a driving simulator study was conducted using the advanced driving simulator of the Department of Engineering (Roma Tre University). It is useful to highlight that several studies have showed the high

potential and reliability of the driving simulation for studying the driver–pedestrian interaction (Chai, Zhao 2016; Bella, Silvestri 2016; Obeid *et al.* 2017; Mollu *et al.* 2018; Åbele *et al.* 2019; Ryan *et al.* 2019). For this aim, driving simulators are ideal tools because allow to conduct studies whose field survey is made impossible by the implicit high risks that the experimenters would be subjected to and the difficulty of ensuring controlled experimentation conditions.

In the following sub-sections the driving simulator system used in the present study, the implemented road scenarios, the experiment procedures and the characteristics of the participants at the simulator experiment are described.

1.1. Driving simulator and road scenarios

The fixed-base driving simulator of the Department of Engineering (Roma Tre University) allows representing the infrastructure scenario, traffic conditions, cross-section features, and vehicle's physical and mechanical characteristics. The hardware consists of four networked computers and three interfaces. One computer processes the motion equations while the others generate the images. The hardware interfaces (wheel, pedals and gear lever) are installed on a real vehicle in order to create a very realistic driving environment. The road scenario is projected on three projection screens (a central one and two lateral one), which form a 135° field of view (Figure 1). The resolution of the visual scene is 1024×768 pixels with a refresh rate of 30...60 Hz. The scenario is refreshed dynamically according to the travelling conditions of the vehicle, depending on the actions of the driver on the brake, the accelerator pedal, and the steering wheel. The system is also equipped with a sound system reproducing the sounds of the engine. This set-up provides a realistic view of the road and surrounding environment. During the simulation, the system records many dynamic parameters (such as the vehicle's speed, the acceleration rates, etc.), which describe the driver's behaviour.

It was previously validated (Bella 2008) and it is deemed to be a useful tool for studying the driver's behaviour (Bella, Silvestri 2017a, 2017b) as well as an ideal apparatus to carry out research activities avoiding risks for participants, ensuring a full control of the experimental conditions.

Two urban road scenarios (differentiated only for the pedestrian crossing conditions) were implemented at the driving simulator. The pedestrian crossroads along



Figure 1. Test at the driving simulator

the road scenario were designed according to the *Italian Highway Code* (MiMS 1992). The posted speed limit was 50 km/h. The cross-section of the simulated urban road was consistent with the *Italian Road Design Guidelines* (MiMS 2001), characterized by two 3.0 m wide driving lanes, 0.50 m wide shoulders and 1.50 m wide curbs. Each scenario was only 5 km long with the aim of limit the simulated drive duration and, thus, reduce the likelihood of simulator sickness.

In each scenario, 3 of the 6 pedestrian crossings of interest (obtained by the combination of the factors ADAS and crossing conditions) were included. Further interaction conditions with pedestrians were presented at drivers along the two road alignments, with only the aim of reproducing in the simulated environment similar conditions to those experimented by the participants in the real urban context.

The *first scenario* presented the following 3 pedestrian crossings:

- »» illegal crossing – without ADAS;
- »» legal crossing – visual warning;
- »» illegal crossing – audio warning.

The *second scenario* presented the other 3 pedestrian crossings of interest:

- »» legal crossing – without ADAS;
- »» illegal crossing – visual warning;
- »» legal crossing – audio warning.

The presentation order of the pedestrian crossings along with the simulated scenario and the driving sequence of the two scenarios were randomized to avoid influences due to the repetition of the same order in the experimental conditions (Section 1.2).

The pedestrian crossing from the right side of the vehicle was set to start to cross at a speed equal to 1.4 m/s, consistently with the literature, when the vehicle was at 55.6 m from the conflict point (i.e., the point of potential collision between the driver while approaching pedestrian crossing and the pedestrian who crosses the road).

The auditory signal was a speech message (“attention, pedestrian crossing”) that was reproduced into the vehicle through the audio system of the driving simulator. The visual warning consisted of an icon of a pedestrian into a white triangle. It appeared in the right corner of the central display, near the speedometer, to simulate its appearance on a device inside the vehicle and remained fixed (without flashing) from its activation to the end of the critical situation. The ADAS signals were also sent 55.6 m before the pedestrian crossing. Considering a speed equal to 50 km/h, this condition represents a time to collision at the conflict point with the pedestrian equals to 4 s (i.e., $55.6/50 \times 3.6$). However, it should be noted that this value is theoretical because depends on the actual speed adopted by the driver while approaching the conflict point with the pedestrian. In other words, if the driver reaches the triggering point located at 55.6 m from the pedestrian crossing with a higher or a lower speed of 50 km/h, the values of the time to collision will be lower or higher, re-

spectively, than 4 s. It should be noted that, taking into account the variability of the approaching speeds at the pedestrian crossing, the actual values of the time to collision in the moment in which the warning is triggered recorded during the simulated drives, are expected in the interval between 2.8 and 6.5 s (2.8 s for speed equal to 70 km/h and triggering point 55.6 m from the pedestrian crossing; 6.5 s for speed equal to 30 km/h and triggering point 55.6 m from the pedestrian crossing). Such values are fully consistent with those reported in literature (Scott, Gray 2008; Yan *et al.* 2015b; Hajiseyedjavadi *et al.* 2018; Bakhtiari *et al.* 2019). In other terms, the design of the experiment implies the simulation of ADAS in which the time to collision values are fully consistent with those suggested in literature.

1.2. Procedure and participants

The experiment was conducted with the free vehicle in its driving lane. In the other driving lane, a slight amount of traffic was distributed to induce the driver to avoid driving into that lane. The simulated vehicle was a standard medium-class car with automatic gears. The data recording system acquired all of the parameters at spatial intervals of 2 m.

The driving procedure consisted of the following steps:

- »» introducing the participants to the experiment, showing the simulator and explaining the simulation procedure; drivers were instructed to drive as they normally would in the real world;
- »» training on a specific alignment with a length of approximately 5 km, to allow the driver to become familiar with the simulator;
- »» filling in of the first section of a questionnaire in which personal data were collected;
- »» starting the experiment. Each participant drove one of the two road scenarios with a specific pedestrian crossings sequence;
- »» filling in the second section of the questionnaire. This was done to allow the participant to leave the vehicle for about 5 min in order to re-establish psychophysical conditions similar to those at the beginning of the test;
- »» driving the other road scenario with another pedestrian crossings sequence;
- »» filling in the post-test questionnaire, in which were asked about the perceived discomfort and the effectiveness of driver assistance systems. The questionnaire about the perceived discomfort was aimed to exclude data of participants, which drove in physiological discomfort and, thus, which could affect the reliability of the recorded data used for the analyses. It consisted of 4 questions, each for a kind of discomfort: nausea, giddiness, fatigue, other. Each question could be answered by a score of 1...4 in proportion to the level of discomfort experienced (null, light, medium, and high). The null or light levels for all four kinds of discomfort

was considered the acceptable condition for driving. The questionnaire about the effectiveness of driver assistance systems consisted of 3 questions: the first was related to the influence of ADASs that was perceived by driver (useful, non-useful, negative); the second (only for drivers that perceived a positive influence on their behaviour) was related to the type of influence (higher attention to driving task, speed reduction), and the third related to the preference of the type of driving assistance system (auditory warning, visual warning).

42 participants (21 males and 21 females) composed the original sample. All drivers, whose ages ranged from 25 to 60 (average 32), had full visual acuity (equal to 10/10 also through correction with glasses), absence of auditory disorders and diseases, and regular European driving licenses for at least four years. Participants were chosen from students, faculty, and staff of the University and volunteers from outside of the University. The drivers had no prior experience with the driving simulator and had an average annual driven distance on urban roads of at least 2500 km. The average number of years of driving experience was approximately 11.

2 of the 42 drivers did not complete the driving test for reasons related to an excessive level of psychophysical discomfort (simulator sickness). According to the outcomes of the questionnaire about the perceived discomfort, the remaining 40 participants experienced null or light levels of discomfort. Thus, the final sample used for the analyses consisted of 40 drivers composed of 20 males and 20 females.

2. Data processing

Based on the speed data obtained by the driving simulator, the speed profiles of drivers along the section 150 m in advance the point where the pedestrian crossed were plotted. A total of 240 speed profiles (40 participants \times 2 scenarios \times 3 conditions of pedestrian crossings), were plotted. However, in 7 cases an accident occurred: 5 out of 7 cases for the illegal pedestrian crossing, 4 out of 7 cases with no driver assistance system (Table 1).

These outcomes already seem to highlight the criticality of illegal crossing, in which the driver is less able to act an effective manoeuvre to avoid the collision with the pedestrian, and the useful support provided by driver assistance systems to safely face the pedestrian.

The following variables of the driver's behaviour in approach to the pedestrian crossing were collected from speed profiles (Figure 2):

- »» V_i – the driver's initial speed, when the driver perceives the pedestrian crossing and decreases the speed, releasing the acceleration pedal;
- »» L_{V_i} – the distance from the conflict point with the pedestrian at which V_i is registered;
- »» V_{\min} – the minimum speed registered at the end of the deceleration phase;

- »» $L_{V_{\min}}$ – the distance from the conflict point with the pedestrian where the minimum speed value is located.

From such variables the following parameters were obtained:

- »» TTA – it was obtained as L_{V_i}/V_i and represents the time left for the vehicle to arrive at the conflict point with a pedestrian at the moment he perceived the pedestrian presence. This condition represents the actual vehicle–pedestrian interaction that was recorded during simulated driving. It is based on cinematic conditions (speed and distance from the conflict point) of the driver at the moment in which he perceived the presence of the pedestrian and not at the moment in which the pedestrian started to cross. It should be noted that the theoretical vehicle – pedestrian interaction conditions were always the same: the movement of the pedestrian was always triggered when the vehicle was at 55.6 m from the conflict point; furthermore, in all the interactions the pedestrian visibility conditions were similar. This allowed avoiding the influence on driver's behaviour caused by different distances between vehicle and pedestrian when the latter starts to cross and by the different levels of visibility. In other terms, the recorded values of TTA, different from the theoretical one (4 s), depended on only the actual driver's behaviour. TTA returns a measure of the criticality of vehicle–pedestrian interaction (lower values of TTA highlight lower time left for the vehicle to arrive at the conflict point and thus greater interaction's criticality) and highlights different driver's characteristics. Drivers with low "availability" to yield (or aggressive drivers) determine low TTA because they slow down when they are close to the conflict point and/or from high initial speeds. Drivers with high "availability" to yield (or careful drivers), instead, determine high values of TTA because they reduce the speed when they are far from the conflict point and/or from low initial speeds (Bella, Silvestri 2015);
- »» SRT – it was defined as the time to pass from V_i to V_{\min} . Therefore, it returns the elapsed time between when the driver reacts to a potential conflict with a pedestrian (by reducing the speed) and when he perceives to have avoided the collision (by yielding to the pedestrian) and, thus, ends the deceleration. SRT provides indications about the gradualness of yielding manoeuvre. High values of SRT are linked to smooth yielding manoeuvres (i.e., the driver's braking behaviour is less aggressive). On the contrary, small SRTs reveal inappropriate driver's braking behaviours indicating that the driver needs to modify his speed in a short time in response to a pedestrian crossing, and therefore, he adopts abrupt manoeuvre (Haque, Washington 2015; Bella, Silvestri 2017a).

Table 1. Collisions with pedestrian for legal and illegal crossing with or without ADAS

Pedestrian crossing	ADAS	No accidents
Illegal	audio	2
Illegal	no ADAS	3
Legal	no ADAS	1
Legal	audio	1

3. Analysis and results

Two ANOVA analyses were conducted. The *first analysis* was aimed at assessing the criticality of the vehicle–pedestrian interaction (returned by TTA parameter) under the two factors “crossing condition” (legal and illegal crossings) and “ADAS condition” (no ADAS, visual warning and audio warning). The *second analysis* was aimed at evaluating how the yielding manoeuvre (returned by SRT parameter) was influenced by the two crossing conditions and three ADAS conditions.

To ensure the consistency of the performed analysis, the normality and the homogeneity of the variances between groups for the TTA and the SRT was verified. The Shapiro–Wilk test on the variable TTA showed a non significant departure from normality ($P = 0.109$); also the Levene’s test was not significant ($F_{5, 227} = 0.445$). The variable SRT was also normally distributed ($P = 0.200$), and homogeneity of variances was also confirmed ($F_{5, 227} = 0.986$).

It is worth noting that the two analyses investigate the effects of the same factors (“crossing condition” and “ADAS condition”) in two distinct phases of the vehicle–pedestrian interaction. The first analysis returns the effects in the pedestrian detection phase (effects on time left for the vehicle to arrive at the conflict point with pedestrian at the moment the driver perceives the pedestrian presence); the second analysis shows the effects on gradualness of yielding manoeuvre (effects on the elapsed time between when the driver reacts to a potential conflict with a pedestrian and when he perceives to have avoided the collision, by yielding to the pedestrian).

3.1. TTA

ANOVA that was carried out on the dependent variable TTA showed a statistically significant effect of the crossing condition ($F_{1, 227} = 19.386, P = 0.000$) (Figure 3a). The value of TTA for the legal crossing (3.71 s) was significantly higher than that for the illegal crossing (2.94 s, mean difference = 0.77 s; $P = 0.000$). Therefore, the vehicle–pedestrian interaction is more critical for the illegal crossing, as the driver has less TTA at the conflict point at the moment in which he begins to decrease his speed, having perceived the pedestrian.

The results showed that the effect of ADAS condition was not statistically significant ($F_{2, 227} = 0.562, P = 0.571$). However, it should be noted that TTA values for the cases in which the driver was supported by the driver assistance system with auditory warning (3.33 s) and visual warning (3.44 s) were higher than that for absence of ADAS (3.22 s)

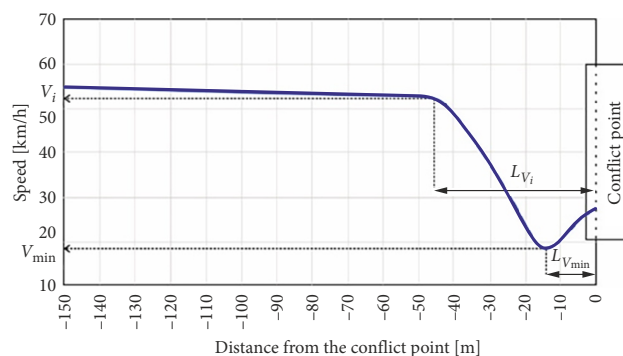


Figure 2. Dependent variables descriptive of the driver’s behaviour while approaching the conflict point with pedestrian crossing

(Figure 3b). This highlights that in presence of ADAS the vehicle–pedestrian interaction was less critical.

The interaction effect “crossing condition” × “ADAS condition” was not significant ($F_{2, 227} = 0.276, P = 0.759$).

3.2. SRT

ANOVA on the SRT dependent variable showed a statistically significant effect of the crossing condition ($F_{1, 227} = 10.442, P = 0.001$) (Figure 4a). The value of SRT for legal crossing (3.8 s) was significantly higher than that for illegal crossing (3.2 s, mean difference = 0.6 s; $P = 0.001$). This result shows that for the illegal crossing the driver completes the speed reduction manoeuvre to yield to the pedestrian in a shorter time, thus adopting a more abrupt manoeuvre.

The effects of ADAS condition was not statistically significant ($F_{2, 227} = 1.322, P = 0.269$). However also in this case, similarly to what was found for the TTA variable, it can be observed that the values of SRT for the cases in which the driver was supported by the driver assistance system with auditory warning (3.54 s) and visual warning (3.66 s) were higher than that for absence of ADAS (3.29 s) (Figure 4b). This means that in presence of ADAS the drivers adopts smoother yielding manoeuvres. Also for SRT the interaction effect was not significant $F_{2, 227} = 1.022, P = 0.326$.

3.3. Mean speed profiles

To further investigate the influence of ADAS on driver’s behaviour, an analysis was carried out on mean speed profiles for different groups of TTA values. The aim was to assess how the driver’s speed adaptation while approaching the conflict point with the pedestrian was affected by the conditions of vehicle–pedestrian interaction (and therefore implicitly by the driver’s characteristic) and how this influence occurred for ADAS conditions.

Based on the actual speeds of the drivers and their distances from the pedestrian crossings at the moment when they perceived the pedestrian, many interaction conditions of vehicle–pedestrian were recorded during the simulated drives. These interactions were classified in the following 4 groups of TTA:

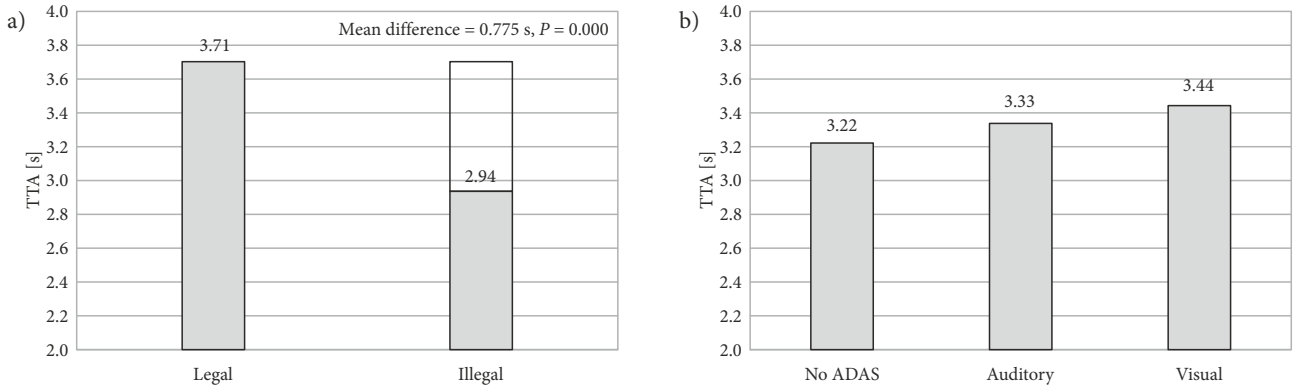


Figure 3. Effect of condition on the variable TTA: a – “crossing condition”; b – “ADAS condition”

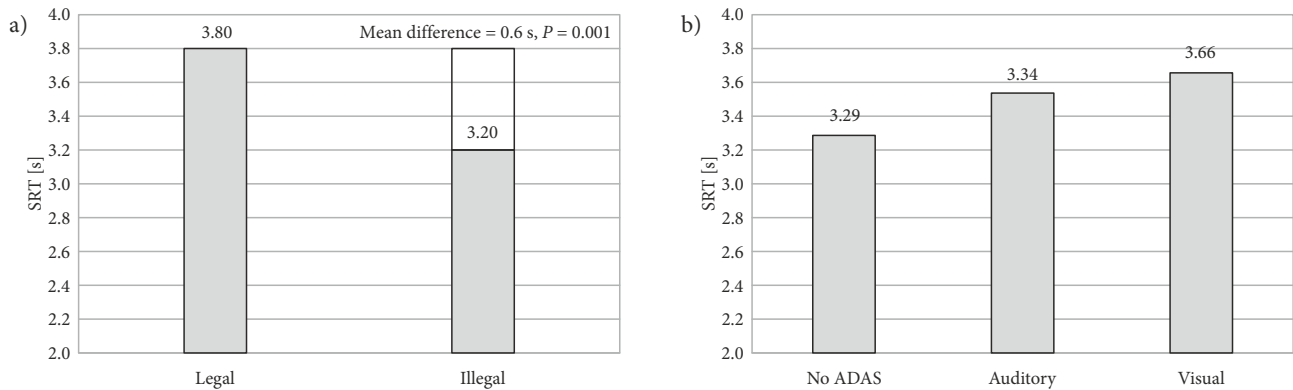


Figure 4. Effect of condition on the variable SRT: a – “crossing condition”; b – “ADAS condition”

- (1) $TTA \leq 2.5$ s;
- (2) $2.5 < TTA \leq 3.5$ s;
- (3) $3.5 < TTA \leq 4.5$ s;
- (4) $TTA > 4.5$ s.

The numerosness of each group is reported in Table 2.

The mean speed profiles differentiated for the 4 groups of TTA values were plotted for the three ADAS conditions (Figure 5). The mean speed profiles highlight that the speeds V_i and V_{min} depend only on the TTA group but they are not basically influenced by driver assistance systems.

On the contrary, differences are found in the values of L_{V_i} and $L_{V_{min}}$ distances: these variables, besides depending on the TTA group, appear to be influenced by the ADAS conditions.

For $TTA \leq 2.5$ s (aggressive drivers) the presence of ADAS does not affect the driving task. In fact, mean speed profiles show that the section where the speed reduction occurs from V_i to V_{min} has a similar length for all the ADAS conditions (35 m – for no ADAS, 40 m – for visual and 35 m for auditory warning).

For $2.5 < TTA \leq 3.5$ s and $3.5 < TTA \leq 4.5$ s (moderately cautious drivers) ADAS determines effect since it anticipates the deceleration manoeuvre, both in the case of an auditory and visual warning. For these groups, in fact, higher values of L_{V_i} were recorded compared to the value recorded for No ADAS condition (40 and 45 m for

Table 2. Collected vehicle–pedestrian interactions under different ADAS conditions

TTA	ADAS condition		
	no ADAS	auditory warning	visual warning
$TTA \leq 2.5$ s	27	19	20
$2.5 < TTA \leq 3.5$ s	26	34	33
$3.5 < TTA \leq 4.5$ s	14	13	16
$TTA > 4.5$ s	9	11	11

the 2nd and 3rd group, respectively). For both the groups, in case of ADAS with visual warning L_{V_i} was about 45 m, while for auditory warning L_{V_i} was equal to 50 m. On the contrary, the $L_{V_{min}}$ did not change (15 m in all ADAS conditions). This means that the beginning of the speed reduction manoeuvre is anticipated in the case of auditory and visual signals, thus becoming the manoeuvre less abrupt.

For $TTA > 4.5$ s (cautious drivers) for all the ADAS conditions, L_{V_i} values were higher than the trigger point at which the signals start (55.6 m). Therefore, for this group, the driver assistance systems do not contribute to improve the driving task. That because the drivers already are very cautious.

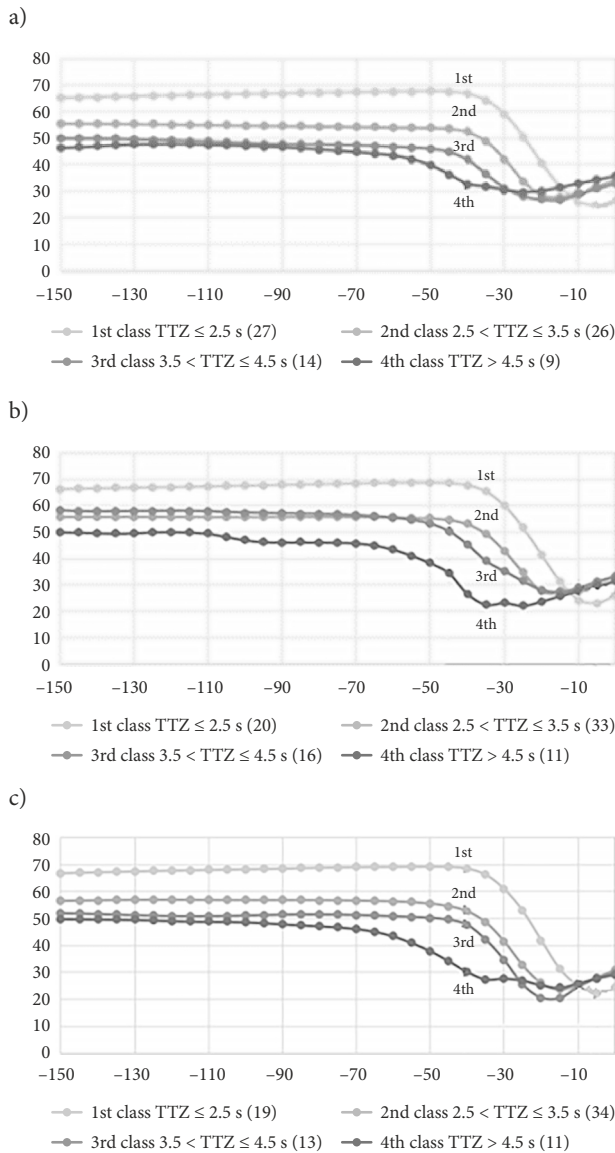


Figure 5. Mean speed profiles differentiated for “ADAS conditions”: a – no ADAS; b – visual warning; c – auditory warning

4. Questionnaire’s outcomes

A questionnaire about the perceived influence, consequence, and preference of the driving assistance systems was submitted to the drivers (40 subjects) with the aim of supplying subjective measures to support the results that were obtained recording the drivers’ behaviour at the simulator. Regarding the influence, 10% of participants considered the driving assistance systems (both auditory and visual warnings) to be an element of distraction, 28% declared that they did not affect the reaction against the pedestrian and 62% considered the driving assistance systems useful (Figure 6).

Among the drivers who considered ADASs useful, 56% of them stated that such systems brought greater attention to the driving task and 44% of them stated that the driving assistance systems allowed a reduction in speed. Moreover, a clear preference for the auditory warning (80%) compared to the visual warning (8%) was recorded, while for 12% of the drivers the two driving assistance systems were equivalent (Figure 6).

5. Discussion

The effects of the factor crossing conditions (legal and illegal) clearly emerged from the analyses. The preliminary analysis of the number of accidents that were recorded during the simulated driving showed that the highest number of collisions occurred for the illegal crossing. Interestingly, it should be observed that the higher collision rate was recorded for the illegal crossing condition without ADAS (equal to 7.5%, see Table 1, i.e., 3 collisions among 40 driver–pedestrian interactions), which is consistent with the crash rate (8%) recorded by Toxopeus *et al.* (2018) in their driving simulator study.

The 2 ANOVAs on the dependent variables TTA and SRT highlighted the higher criticality of the vehicle–pedestrian interaction and the more abrupt yielding manoeuvre for the illegal crossing condition (TTA and SRT were significantly lower than those for the legal crossing).

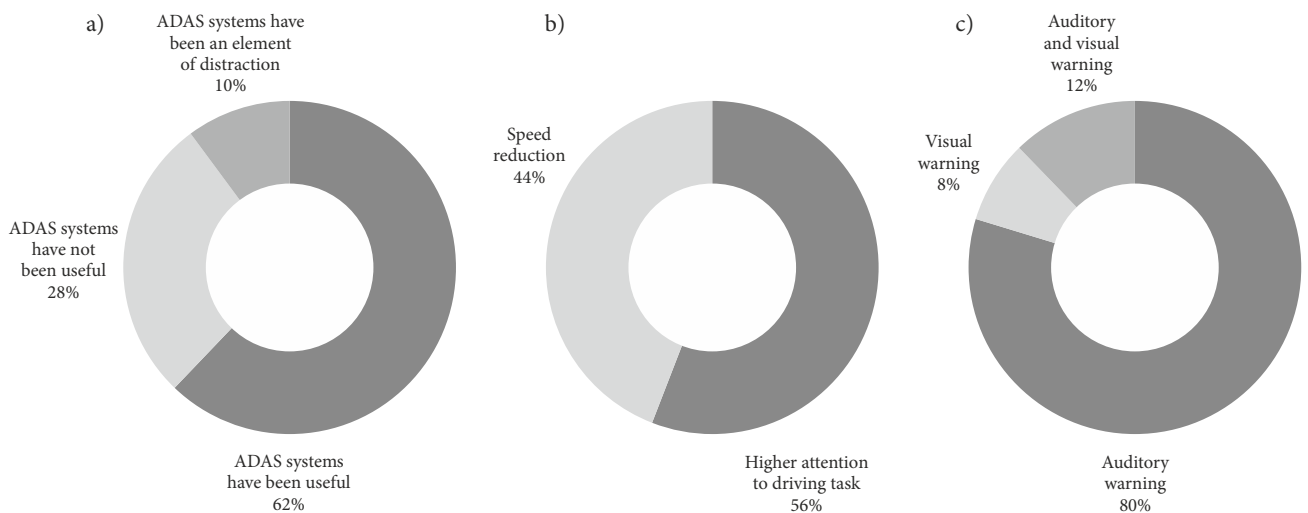


Figure 6. Outcomes of the questionnaire for the kind of ADAS: a – influence; b – consequence; c – preference

These results show that for illegal crossing the driver is caught by the “surprise” effect. The driver does not expect the occurrence of a pedestrian that crosses outside of the crosswalk and, thus, he detects the pedestrian and starts the speed reduction manoeuvre only when the TTA at the conflict point is low (i.e., high V_i and low L_{V_i}). Such delay of the speed reduction manoeuvre implies also the necessity to adopt a more abrupt yielding manoeuvre (i.e., a lower SRT). This finding confirms the results of previous studies (Lee *et al.* 2002; Zhang *et al.* 2015), in which it was found that drivers who started earlier the deceleration brake more moderately than those who started late. Moreover, the obtained outcomes are in line with the results of Zheng *et al.* (2015) and Bella, Nobili (2020), which found that, in field studies carried out using instrumented vehicles, the drivers’ yield choice to jaywalkers was clearly nearer to the conflict point. Moreover, drivers also adopted a more abrupt braking manoeuvre (higher average deceleration rates) in the case of illegal crossing.

Finally, the driving behaviour that was recorded is also fully consistent with the behavioural model of Fuller (1984); in the case of illegal crossing, the driver does not expect the pedestrian crossing (he experience a “no discriminative stimulus”) and, thus, because of the risk raised by the pedestrian behaviour, a delayed avoidance response is required to avoid an accident.

Regarding the effects of the factor “ADAS condition”, the results were less clear. Despite the preliminary investigation on the number of accidents showed that the highest number of accidents occurred for no ADAS condition, the ANOVAs on the dependent variables TTA and SRT did not highlight significant effects. However, the trend of the mean values of TTA and SRT showed that, in presence of warning system, the vehicle–pedestrian interaction was less critical and that the yielding manoeuvre was smoother (TTA and SRT values were higher for the ADAS presence), confirming the reliability of both assistance systems, as reported in literature.

The results obtained by the simulated tests did not allow to identify which, between the two kinds of ADAS (visual and auditory warning) was more effective. However, the outcomes of the questionnaire highlighted a clear preference for the auditory warning. This result is consistent with some previous studies (Chen *et al.* 2011; Wickens *et al.* 2012) and is probably due to the different physical stimuli that are solicited by the warning signal. An auditory warning stimulates the sense of hearing, which is much less busy during the driving task. Conversely, a visual signal can overload the already demanding visual task needed for the driving activity and, therefore, the driver could less tolerate this kind of alarm.

An interesting result was observed in the analysis of the mean speed profiles differentiated for group of TTA and ADAS conditions. For aggressive and very cautious drivers ($TTA \leq 2.5$ s and $TTA > 4.5$, respectively), the presence of ADAS (both in the case of auditory and visual warning) did not determine significant differences com-

pared to the condition of ADAS absence. On the contrary, for the average cautious drivers ($2.5 < TTA \leq 3.5$ s and $3.5 < TTA \leq 4.5$ s) the presence of ADAS (both in the case of auditory and visual warning) determined an advanced beginning of the speed reduction manoeuvre, thus becoming the manoeuvre less abrupt.

Such a result shows that ADAS does not affect the driving behaviour of the very cautious drivers, because they adapt their behaviour (by reducing the speed) even before the warning trigger. On the other hand, it highlights that ADAS has not effects also on aggressive drivers, which, due to their behavioural characteristic, ignore the warning and does not adapt their behaviour. This outcome supports some recent needs raised from recent research papers – Butakov, Ioannou (2015); Martinez *et al.* (2018) – aimed at developing personalized advanced driver assistance systems (i.e., ADAS that takes into account the characteristics of each individual driver). The reason behind this new design principle aims at avoiding that an ADAS designed for an average driver may be found to be too conservative and annoying towards more aggressive drivers and too aggressive towards more passive drivers.

Conclusions

The present study aimed to investigate the driver’s behaviour during the interaction with a pedestrian crossing into and outside the zebra crossing and evaluate the effectiveness of two kinds of ADAS, which provided to the driver a visual and auditory warning.

42 participants drove a simulated urban scenario in which legal and illegal crossing conditions were presented and different ADAS conditions (no ADAS, visual warning and auditory warning) helped the driver in the pedestrian’s perception.

Two ANOVA analyses were performed on the two dependent variables that were obtained from the speed profile of each drive approaching the pedestrian crossings: TTA (time left for the vehicle to arrive at the conflict point with pedestrian at the moment he perceived the pedestrian presence) and SRT (elapsed time between when the driver reacts to the conflict with a pedestrian and when he perceives to have avoided the collision). A further analysis was based on the speed profiles of drivers.

The first analysis was aimed at assessing the criticality of the vehicle–pedestrian interaction (returned by TTA parameter) under the two factors “crossing condition” (legal and illegal crossings) and “ADAS condition” (no ADAS, visual warning and audio warning). The second analysis was aimed at evaluating how the yielding manoeuvre (returned by SRT parameter) was influenced by the two crossing conditions and three ADAS conditions.

The study provided several findings. The effects of the crossing conditions were clear and highlighted the criticality of illegal crossings. When the pedestrian crossed outside of the crosswalk, the higher number of collisions occurred and the ANOVAs returned significant effects on

both the dependent variables TTA and SRT, highlighting the higher criticality of the vehicle–pedestrian interaction and the more abrupt yielding manoeuvre.

As for the driver assistance systems, the ADAS utility emerged from the study, although not statistically significant. The trends of the mean values of TTA and SRT showed that the vehicle–pedestrian interaction was less critical and the yielding manoeuvre was smoother in presence of the warning systems.

The analysis of the mean speed profiles differentiated for group of TTA and ADAS condition highlighted that the two warning systems positively affected the behaviour of the average cautious drivers, while no effects were observed for the aggressive and the very cautious driver. The aggressive drivers, because of their behavioural characteristics, ignored the alarm, while the very cautious drivers adapted their behaviour even before the alarm trigger.

Finally, the outcomes of the questionnaire highlighted the clear preference for the auditory warning, probably because of the different physical stimuli that are solicited by the warning signals.

It is useful to highlight some novelty elements of the research.

The main novelty of the study concerns the analysis of the driver's behaviour with respect of the two phases of interaction with the pedestrian: in the detection phase of pedestrian (through the parameter TTA) and the speed reduction manoeuvre to yield to the pedestrian (through the parameter SRT). This analysis goes beyond the limits of the few research papers that provide indications only with respect of the first phase of interaction (i.e., driver response time), providing more extended findings of the driver's behaviour during the whole interaction with the pedestrian (from the detection of the pedestrian to the moment in which the conflict ends).

Another novelty element is represented by the analysis of the drivers' behaviour with respect of their low or high "availability" to yield (aggressive and caution drivers, respectively) which allowed to confirm the recent research needs in literature aimed to personalize the driving assistance systems taking into account the characteristics of each individual driver.

On the other hand, despite driving simulators are useful tools widely used for driver behaviour analysis, the driver's performance observed in driving simulation could be different from that in the real world (absolute validity). However, for the aim of the current study, only the relative validity, which refers to the correspondence between the effects of different variations in the driving situation, is required (Törnros 1998).

The advanced features of the driving simulator used in this study and the consistent results obtained in previous similar driving simulator studies using the same apparatus and procedure (i.e., Bella, Silvestri, 2015, 2016) ensure the reliability of the findings provided by the present research in terms of relative effects induced by legal and illegal pedestrian crossings and by different kinds of ADAS on the driver's behaviour.

In conclusion, the results of the present study confirm that adequate pedestrian paths should be planned to avoid jaywalking conditions, that being unexpected events induce the driver to assume critical driving behaviour, and provide useful findings of the effectiveness of driver assistance systems for pedestrian detection.

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Author contributions

Francesco Bella conceived the study and was responsible for the design and development of the data analysis.

Francesco Bella and *Manuel Silvestri* were responsible for data collection and analysis.

Francesco Bella was responsible for data interpretation.

Francesco Bella and *Manuel Silvestri* wrote the first draft of the paper.

Francesco Bella and *Manuel Silvestri* read and approved the final paper.

Disclosure statement

The authors declare that they have no competing financial, professional, or personal interests from other parties.

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