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COMPORTAMENTO DEI PEDONI IN ATTRAVERSAMENTO: CONFRONTO TRA VEICOLI CON MOTORIZZAZIONE TRADIZIONALI ED ELETTRICA

PEDESTRIAN BEHAVIOR DURING ROAD CROSSING: COMPARISON BETWEEN VEHICLES WITH TRADITIONAL AND ELECTRIC ENGINES

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RIASSUNTO

La diffusione dei veicoli ibridi ed elettrici (HEV) nelle aree urbane rappresenta un problema per i pedoni, soprattutto se con disabilità visiva, a causa della loro bassa rumorosità. In questo studio, il comportamento dei pedoni di fase di attraversamento stradale è stato studiato mediante l'uso della realtà virtuale immersiva riproducendo diverse condizioni attraversamento. Sono state analizzate tre tipologie di veicoli: un HEV e due veicoli a combustione interna (ICEV) alimentati da motori diesel e benzina. I risultati hanno mostrato che, sebbene siano state osservate lievi differenze nei livelli sonori dei pass-by di HEV ed ICEV a benzina, i pedoni venivano investiti virtualmente con maggiore frequenza e riportavano tempi di risposta più elevati per HEV in avvicinamento. Ciò si manifestava in condizione di alto rischio e alla velocità di 30 km/h.

ABSTRACT

The increasing diffusion of hybrid and electric vehicles (HEVs) in the urban areas represents an issue for pedestrians, especially for impaired people, due to their low noise. In this study, the pedestrian behavior at road crossing has been investigated, by the immersive virtual reality, simulating different conditions of approaching vehicles. Three types of vehicles have been analyzed: an HEV and two internal combustion vehicles (ICEVs) powered by diesel and gasoline engines. Results showed that, although slight differences in pass-by sound levels were observed between HEV and gasoline ICEV, pedestrians were hit virtually more frequently and reported higher response times for approaching HEVs. This occurred in conditions of high risk at the speed 30 km/h.

Parole chiave: Veicoli elettrici, rumore stradale, sicurezza dei pedoni, virtual reality.
Keywords: Electric vehicles, road traffic noise, pedestrian safety, virtual reality.

1 Introduzione

The development of national and international policies [1] aiming to reduce urban pollution has led, in some countries, the Hybrid-Electric and all-Electric Vehicles (EV/HEVs) to be more and more diffuse within cities. According to the International Energy Agency [2], in 2020, the global electric car stock reached 10 million, with a 43% increase over 2019, representing a 1% stock share. While China has the largest fleet (4.5 million electric cars), in 2020, Europe gained the largest annual increase (3.2 million). Despite the positive effects of introducing EV/HEVs within cities [3], mainly connected to reducing air and noise pollution, some new issues have been raised. One of the most important is the consequence of the greater quietness of EV/HEVs than the Internal Combustion Engines (ICE). In fact, while the low noise emission levels of HEVs reduce the percentage of annoyed citizens by road traffic noise, on the other side, the weak auditory cues of EV/HEVs approaching the pedestrians have been significantly reduced, increasing the risk for them being hit. In a recent study of Pardo-Ferreira et al., people who came into contact with electric and hybrid vehicles during their working day considered, for the 50%, that electric vehicles pose a risk to other road users because they are more difficult to hear, and they believe it likely that other road users could be injured [4].

Comparative measurements [5] between EV/HEVs and ICEVs have shown that at speeds below the typical urban speed limit (50 km/h), HEVs' noise emissions are lower than conventional Diesel Internal Combustion Engine Vehicles (ICEVs). The lower the vehicles' speed, the greater are the differences, which can reach up to 5-7 dB(A) at 10 km/h when the tyre noise is not too significant [6].

Blind or visual-impaired people are the most vulnerable persons. Emerson showed as their ability to perceive oncoming vehicles can range significantly when the situations change, rendering them unable to determine if a sufficient gap to cross the road exists [7]. In a further article on a HEV the same author showed that greater differences are observable at speeds lower than 30 km/h. The limitation suggested that more controlled studies of vehicle characteristics impacting crossing decisions of pedestrians should be done [8]. Goodes et al. [9], investigating the risks for visual-impaired people, have observed that at about 25 km/h, the reduction of engine noise in HEVs may significantly affect the ability of blind individuals to recognize approaching vehicles. National Highway Traffic Safety Administration published reports on blind people and quiet vehicles [10,11]. Studies and activities looking for a potential countermeasure for blind pedestrians were undertaken in different countries [12-14].

Based on this, legislations are proposing minimum sound emission levels for HEVs, to alert other road users about the approaching vehicles, in particular at lower speeds. In Europe and in Japan guidelines for hybrid and other near-silent vehicles issued those vehicles have to be equipped with warning sounds known as *Approaching Vehicle Audible System* (AVAS) [12,13]. In US, the Federal Motor Vehicle Safety Standard (FMVSS) is setting the minimum sound level to 49 dB(A) at idle, 52 dB(A) at reverse, 55, 62 and 66 dB(A) respectively at 10, 20 and 30 km/h, recommending at the same time broadband low frequency sounds in the range 160-5000 Hz for enhancing the audibility [15]. Various studies have been conducted on HEVs equipped with exterior sounds, which allows to detect more easily the vehicles. Singh et al. [16] experimented the passing of an electric car equipped with 15 different exterior sounds. The latter may be detected faster than other vehicle sounds, although they may result in negative perceptions for the pedestrians. European Commission has funded a project in the frame of the seventh framework program, the eVADER (Electric Vehicle Alert for Detection and Emergency Response), aimed at individuating, among other, warning sounds able to improve the safety by keeping low noise levels. Possible warning sounds were assessed both in terms of characteristics of detectability and annoyance [17-19]. Nowadays, most vehicle manufacturers are moving, per legislation, toward the use of exterior sounds at cruising speeds lower than 30 km/h. The Nissan Leaf Approaching

Vehicle Sound for Pedestrians (VSP) produces a sound that stops when the vehicle speed is more than 19 mph (30 km/h) while accelerating. The sound starts when the vehicle speed is less than 16 mph (25 km/h) while decelerating [20].

Different authors carried out listening tests on the detectability of quiet vehicles. Robart & Rosenblum [21] have measured listeners' reaction times to binaural recordings of HEVs and ICEVs. They reveal that subjects (sighted and blind) could identify the ICEV's approaching direction more than HEVs. Also, the co-existent natural environmental noise reduces the perceived distance for approaching HEVs. Hong et al. [22], in two experiments, have investigated the auditory recognition distance for elderly and non-elderly's blindfolded pedestrians in public spaces, for (diesel and gasoline) ICEVs and for fully EVs and hybrid EVs, moving at 20 and 30 km/h. The first experiment showed that the probability of pedestrian crashes for EVs and HEVs increased by about 30-40% with respect to ICEs vehicles. The second is that the auditory recognition distance of a participant walking in the direction of cars was between 20 and 40 m and about 0.5 for HEVs and EVs. According to Altinsoy [23], in a condition of partial load acceleration, the sound of an HEV cruising at 20 km/h can be detected at approximately 14 meters, differently from an ICEV, which can already be perceived at a distance of approximately 36 m. Other researchers also showed that pedestrians make crossing decisions based mainly on the movement characteristics of the approaching vehicle, using visual information to estimate the safeness of crossing the road [24–26]. Then, beyond below 30 km/h HEVs approaching are less perceived than ICEVs, the change in the spectral content of HEVs may result in a possible incoherence between the audio and the visual information. The lower auditory stimulus experienced by the pedestrians may influence the perceived speed or distance suggested by the visual stimulus. In order to investigate this aspect, a laboratory audio-visual experiment was carried out in an immersive virtual environment. The authors aimed to assess the pedestrian behaviour at a road crossing under a different type of approaching vehicle, while the subjects received both visual and auditory stimuli from the surrounding environment. The subjects took their decisions and carried out the crossing task keeping a high concentration level. The possible difference in risk conditions in a sample of sighted people asked to focus their attention on the approaching vehicles has been assessed. The pedestrians' behaviour has been discussed in terms of subjects' responses and decision times.

In particular, the experiment simulated a typical residential area, where speed conditions of approaching vehicles between 30 and 50 km/h may be quite likely. Different conditions of *Approaching Time* (time required for the vehicle to reach the crossing) have also been considered.

Two different test sessions have been performed.

- First, the pedestrian behaviour at a road crossing has been analyzed for approaching HEV and diesel ICEV, under different conditions of vehicle *Speed* and *Approaching Time.* The preliminary results of the first test session have already been analyzed by the authors in previous work, but only in terms of collision occurrences [27].
- The second test session was carried out with the diesel ICEV and a gasoline ICEV, under the same conditions of vehicle *Speed* and *Approaching Time* of session n.1.

2 Methodology

2.1 Experimental Design

The experiment aimed to analyze the pedestrian behaviour at a road crossing with an approaching vehicle. Three main factors have been investigated: *Type of Vehicle,* Vehicle *Speed* and A*pproaching Time (AT).*

The *Type of Vehicle* showed three different levels: diesel ICEV, gasoline ICEV and HEV. For what concerns the vehicle *Speed*, three different levels, 30, 40 and 50 km/h, have been studied.

These values have been selected as representative of typical speeds in residential areas. The last factor was the A*pproaching Time (AT),* defined as the time required by the vehicle to reach the crossing. Three different AT levels have been hypothesized (5, 7 and 8 s) based on the Crossing Time (CT), the time that pedestrians need to complete the road crossing. This parameter can be calculated by summing the Walking Time, the ratio between the cross-section length and the walking speed, and the Decision Time, which represents the time "from the onset of a walk signal until the pedestrian steps off the curb" [28] and takes into account both the perception and reaction time. To investigate the pedestrian crossing behaviour, Knoblauch et al. [28] conducted a series of field studies on a heterogeneous pedestrians' sample. The walking speed and the decision time on pedestrians with different ages were analyzed under different conditions. They found out a 1.21 m/s 15th-percentile walking speed for younger pedestrians (14-64 years old) and 0.94 m/s for older pedestrians (over 65 years old). Regarding the decision time, they observed 3 s for the 85th-percentile of the younger pedestrians' sample and 3.75 s for the older pedestrians' sample. In line with this research, the Transportation Research Board recommends fixing a decision time of 3 s as input parameter for the design of pedestrian facilities [29].

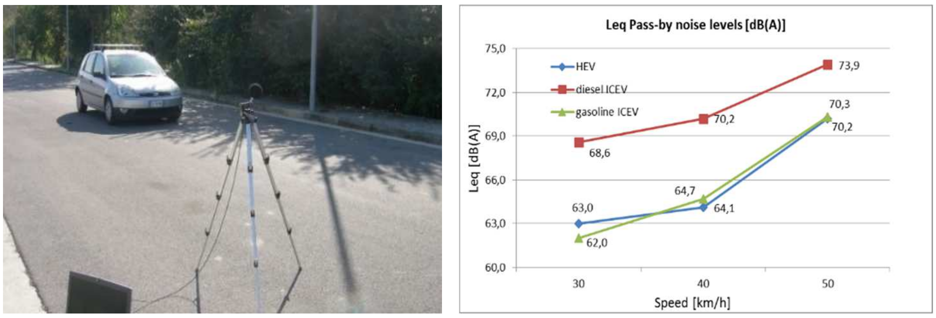
Therefore, considering a cross section length equal to 3.50 m, a walking speed of 1.21 m/s [24] and an estimated Decision time of 3 s [28-29], the default CT was calculated in 5.89 s. Based on the AT levels, three different conditions of potential risk have been considered:

I. No potential risk to be hit (AT=8 s). Pedestrians have sufficient time to decide to cross the road in safety.
II. Low potential risk to be hit (AT=7 s). Pedestrians have slightly more than the assumed CT to decide to cross the road in safety.
III. High potential risk to be hit (AT=5 s). Pedestrians have less than the assumed CT to decide to cross the road in safety.

2.2 Experimental Design

The audio signals recordings were carried out in a quiet area, characterized by low background noise levels (lower than 35.0 dB(A)). For the investigation, a Toyota Prius 1.4 Hybrid (working in full-electrical mode), a Ford Fiesta 1.2 TDI and a Renault Clio 1.2 (representative, respectively, for the HEV, the diesel ICEV, and the gasoline ICEV) have been chosen.

The audio signal recordings, as well as the measurement of the sound pressure levels, were carried out at the pass-by of different vehicles, under different speed conditions. The equipment used was composed of a ½" pre-polarized free field microphone with preamplifiers connected to a sound card NI USB-4432. The microphone was positioned at 1.50 m from the vehicle passage line and at the height of 1.60 m above the ground.



a) b)

Figure 1 - a) Pass-by di ICEV diesel; b) Livelli massimi medi del pass-by per tipo di veicolo e velocità - a) Pass-by of the diesel ICEV; b) Average max pass-by levels for each type of vehicle and pass-by speed.

In Figure 1-b the average of max pass-by levels for each Type of Vehicle and for the three pass-by Speeds are reported. The recorded sound levels have been found consistent with the values registered on measurement surveys carried out in similar conditions. The recording sessions highlighted that, although the presence of engine sounds, for the three speeds investigated the pass-by maximum levels of the gasoline ICEV were comparable with the HEV ones, whilst the difference in levels with the diesel ICEV increases as the speed decreases.

2.3 The Virtual Scenarios

The 3D model of the area around the road crossing has been created by means of a Computer Aided Design application, afterwards the objects of the scene have been textured in 3ds Max. The virtual environment recreated a road crossing in a typical residential area, consisting in a straight and flat two-lane road, with white pedestrian stripes and a traffic island in the middle. The road width was 8.50 m (two 3.50 m wide traffic lanes and a 1.50 m wide traffic island). Houses, trees, pavement, grass and a traffic light completed the scene. The participant has been exposed to the urban road with the crossroad ahead. In Figure 2, a frame of the virtual scenario proposed to the participants is shown.

Figure 2 – Immagine dello scenario di attraversamento virtuale con il veicolo in avvicinamento da sinistra - The virtual scenario with the vehicle approaching from left.

As far as the audio signals experienced by the participants, a convolution process has been carried out to provide spatialized sounds to the participants. In a Python environment, the audio signals were convolved with the Head-Related Impulse Responses of the KEMAR-MIT database. Considering the 72 azimuth orientations due to 5° horizontal increments on a xy plane, the same number of binaural audio signals was generated. Furthermore, a specific routine in Python was created for the Virtual Reality to reproduce more realistic listening conditions for the subjects. This routine was able to active the binaural audio signal corresponding to each relative angle between the subject's gaze and the car's position detected by the software.

2.4 Equipment

The experiment has been carried out in the anechoic chamber 5×5×5 m of the Department of Architecture and Industrial Design of the Università degli Studi della Campania “Luigi Vanvitelli”. The participants stood at the center of room, assuming the typical waiting position at a road crossing. They were provided of a visor through which they were able to explore the virtual environment created. The visor presented stereoscopic images, Graphics were rendered by a Intel(R) Core(TM) i7 CPU 3.07 GHz processor with a Nvidia GeForce GTX480 graphics card using the software WorldViz 4.0. Head's movement (orientation and position) were tracked using the 6 degree of freedom. motion tracking system Polhemus Patriot. The audio signals were reproduced by means of a *motherboard* ASUS N13219 and Sennheiser HD 201 headphones. The audio system was calibrated before the experiment. More precisely, the audio signals were sent to a KEMAR dummy head provided by the same headphones, to reproduce during the experiment, the same auditory conditions at the listener's ear. The test sessions were managed by an operator sitting in the room at the workstation.

3 Experiment

The experiment has been carried out into two different phases, to avoid a too long test session for the participants. The *Type of Vehicle* constituted the discriminator factor for the two test sessions. In particular, for the first test session, the diesel ICEV and the HEV have been selected, in order to investigate the variations in pedestrian behaviour when the differences in terms of noise levels are higher. Then, in the second test session, the diesel ICEV and the gasoline ICEV have been investigated. The diesel ICEV has been chosen as pivot-variable within the two test sessions, in order to keep constant, the differences in noise emission levels between the two types of vehicles in each session.

Each of the test sessions has been composed of 24 trials. For the first six trials the participants have been introduced in the virtual scenario, to train them to the test task. The remaining 18 trials resulted from the combination of factors and levels used in the plan (3x3x2) and they have been presented in a balanced sequence for each participant.

The experimental factor levels for the two sessions are resumed below.

Table 1 - Experimentals' factors and levels resume of the two sessions– Riepilogo dei fattori e livelli sperimentali per le due sessioni.

Factors	First session	Second session
Approaching time	5, 7 and 8s	5, 7 and 8s
Vehicle speed	30, 40 and 50 km/h	30, 40 and 50 km/h
Type of Vehicle	Diesel ICEV – HEV	Diesel ICEV – Gasoline ICEV

Forty-eight subjects (23 males and 25 females), chosen among students and University staff, participated to the test. They performed both the test sessions, with a gap of one month between them. The age was between 22 and 40 years. The subjects were equipped with a 3D Visor and headphones to experience the virtual scenarios, and with a digital device to give their answers.

The participants had to decide to cross safely one traffic lane a time, moving from the curb to the traffic island when the car was approaching from left side, or from the traffic island to the curb when it was approaching from right side.

To manage the test, an indicator was introduced in the virtual scenario in front of the pedestrian position. Initially the indicator was red and the pedestrian was in a waiting position. As soon as the indicator turned green, the pedestrian had: a) to look the approaching vehicle and b) to take the decision to cross or not the road lane before the car pass-by according to the visual-audio stimuli received. For this duty a device with two buttons (yes/no) was used (Figure 3).

The pedestrian decision and the effective Decision Time were recorded in order to assess if the pedestrians were able to avoid the collision with the vehicle. The task sequence is reported below (Figure 4).

The road crossing outcome can be classified in three categories:

- No crossing: the participant did not decide to cross;
- Limit crossing: the participant decided to cross and he was able to complete the road crossing without collision, as the Crossing Time was just lower than the Approaching Time;
- Hit: the participant decided to cross and he was virtually hit by the vehicle, as the Crossing Time was higher than the *Approaching Time*.

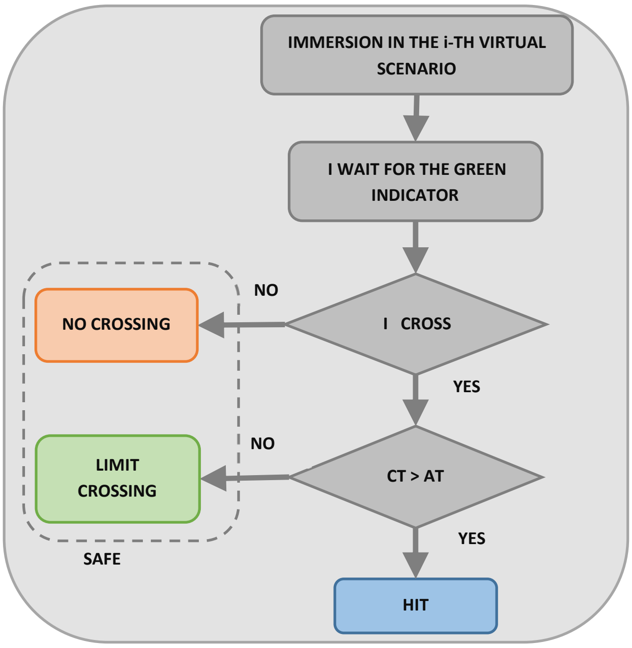


Figure 3 – Diagramma di flusso dell'esperimento - Test flow chart of the experiment.

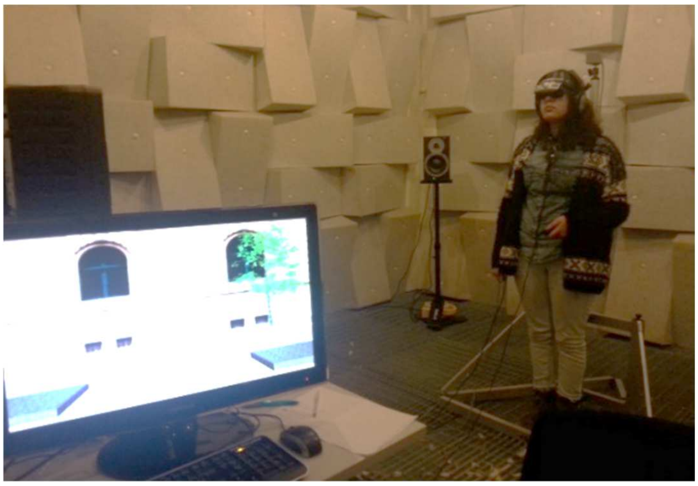


Figure 4 - Partecipante nella camera anecoica durante la sessione sperimentale - Participant in the anechoic room during the test session.

Each of the 48 participants/pedestrians completed 18 trials for each of the 2 test sessions, for a total number of 1728 trials. All the collected data have been analyzed simultaneously, to facilitate the comprehension of the results.

A preliminary analysis has been performed to verify the effectiveness of the potential risk condition assumed in the experimental design. The graphic below (Figure 5) shows the number of registered hits for each Approaching Time, Type of Vehicle and Speed. Data confirm that the number of hits is relevant only for the condition "AT = 5 s" (Condition of high potential risk to be hit).

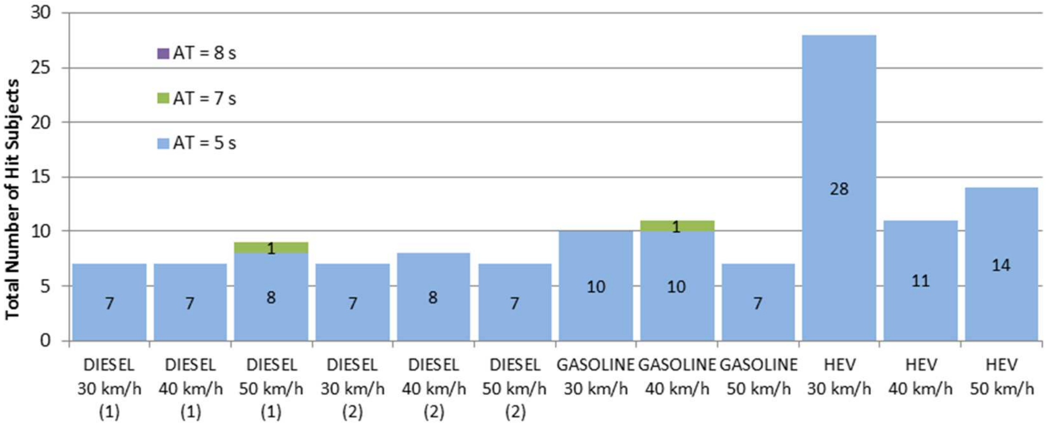


Figure 5 - Numero totale di soggetti investiti per i tre tempi di avvicinamento dei veicoli - Total number of hits for the three Approaching Times.

Based on the previous results, only the "high potential risk" condition (AT= 5 s) has been further analyzed. A mean Decision Time of 2.6 s has been registered for the 48 participants at AT= 5 s, while an 85th-percentile value of 3.1 s has been individuated. This value is only slightly higher than the estimated Decision Time value reported in [25,26]; the validity of the test design is then confirmed.

The road crossing outcome for each *Type of Vehicle* and *Speed* are reported in Figure 6. First, it can be observed that the effect in terms of "no crossing", "limit crossing" and "hit" outcomes coincides for the diesel ICEV in the two test sessions; therefore, the results confirmed that the two-test-sessions structure did not affect them. The gasoline ICEV shows similar outcomes compared with the diesel ICEV, whilst the HEV's outcomes show a different trend.

In particular, three main effects can be highlighted:

- The pedestrians show high capacity to recognize the danger condition for ICEV, independently if it was equipped with diesel or gasoline engine: the number of no crossing decisions, coherent with the situation, keeps high (corresponding to the 70% of the trials) for all speeds. For HEV the number of pedestrians taking the "no crossing" decision is slightly lower at the higher speeds while it keeps significantly lower (40%) at the lower speed of 30 km/h;
- For all the cases, there is a percentage of participants that decide to cross the road unsafely ('hit'). This percentage could be partly due to the greater risk-taking behaviour in the "safe" virtual environment, and it is more or less similar for each speed condition. More precisely, in the case of the approaching ICEVs (diesel and gasoline) this percentage is equal to 15%, while it increases for the HEV (60, 23 and 30% respectively at 30, 40 and 50 km/h). The number of virtual hits by the HEV is relevant in particular at the lowest speed (30 km/h), where the HEVs are quieter;
- Except for the HEV-30 km/h case, in each condition, there is a constant percentage of participants (15%) that decide to cross despite the potential of a collision ('limit crossing'). This condition does not represent a situation of completely safe crossing and may be related to the impulsiveness of part of the sample to give their answer. When the HEV was approaching the road crossing at 30 km/h, just one participant was able to cross the road avoiding the collision.

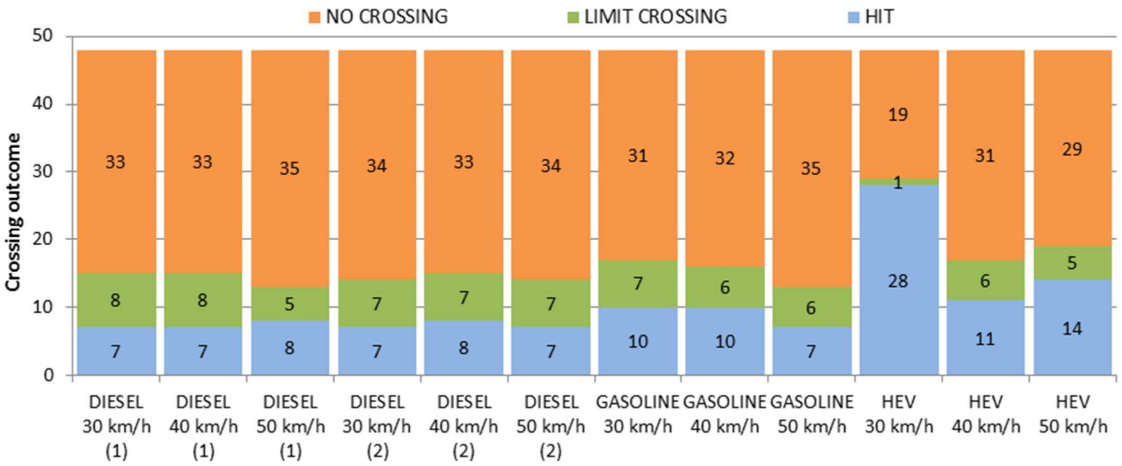


Figure 6 - Comportamento dei pedoni per AT = 5 s – Pedestrians' behaviour for AT = 5 s

To analyze the independence of the occurrences of hit pedestrians for each Speed, a χ-squared test between the four Types of Vehicles' conditions (diesel ICEV 1, diesel ICEV 2, gasoline ICEV and HEV) was performed. The results showed that for the 30 km/h condition, at the significance level of 0.05, the Type of Vehicle affects the number of hit pedestrians, $\chi^2(3,192)=35.11$, $p<0.001$. Hit pedestrians occur with higher frequency for HEV (n.28) than for diesel ICEV (n.7 for both sessions) and gasoline ICEV (n.10). For 40 km/h and 50 km/h conditions, at the level of significance of 0.05, the Type of Vehicle does not affect the number of hit pedestrians.

Based on the results achieved on the mean decision time (Table 2), it seems that, when the HEV was approaching the road crossing at 30 km/h, the low occurrence of subjects able to cross the road avoiding the collision may depend on an increase of the pedestrian decision time. It is possible to note that the mean decision time is higher than the other mean values for the condition HEV-30 km/h, where probably subjects need more time to elaborate the visual-audio information related to the approaching vehicle.

Table 2- Mean decision time (s) for each Type of Vehicle and each Speed

	Speed		
	30 km/h	40 km/h	50 km/h
Diesel ICEV (1)	2.60	2.63	2.74
Diesel ICEV (2)	2.52	2.63	2.73
Gasoline ICEV	2.50	2.59	2.72
HEV	2.90	2.69	2.72

To investigate the possible effects of the type of approaching vehicle and the approaching speed on the pedestrian response times, an ANOVA analysis has been carried out. Twelve 4 x 3 within subject ANOVAs, treating the Type of Vehicle (diesel ICEV 1, diesel ICEV 2, gasoline ICEV and HEV) as 4-level within-subject factors and the Speed (30, 40 and 50 km/h) as 3-level within-subject factors, have been performed. To analyze post-hoc effects, the Bonferroni correction has been used.

The ANOVA results show that, at 30 km/h, the response time was affected by the *Type of Vehicle*, $F(3,45) = 6.964$, $p < 0.001$, while not significant effects could be observed at the other speeds. For what concerns the *Speed*, the factor never affects the response time.

Conclusioni

Attraverso l'utilizzo di un ambiente virtuale, è stato analizzato il comportamento di pedoni in fase di attraversamento con diversi tipi di veicoli e condizioni di avvicinamento. Sono state confrontate le decisioni prese dai pedoni ed i tempi di risposta dei pedoni. La registrazione dei pass-by ha evidenziato che, per le tre velocità indagate (30, 40 e 50 km/h), i veicoli diesel ha mostrato livelli massimi di pass-by superiori alle altre due tipologie di veicoli, mentre i livelli massimi del pass-by di quelli a benzina erano paragonabili a quelli HEV.

I risultati sperimentali hanno mostrato che per i veicoli diesel e benzina il comportamento del pedone rimane sostanzialmente lo stesso, mentre per HEVs in avvicinamento i soggetti possono tendono a prendere decisioni sbagliate. Più precisamente, in condizione di alto rischio potenziale (corrispondente al caso in cui il tempo di avvicinamento del veicolo è paragonabile a quello di attraversamento), i pedoni presentavano una scarsa capacità di riconoscere il pericolo per HEV in avvicinamento. Questa condizione si è verificata con maggiore frequenza a 30 km/h con una possibilità di essere virtualmente investito superiore di quella rilevata con veicoli diesel e benzina.

Analizzando i tempi di risposta dei pedoni registrati durante l'esperimento, è stato osservato che a 30 km/h il tempo di decisione era significativamente più alto per HEV in avvicinamento rispetto a quelli diesel e benzina. Questo risultato può giustificare l'elevata frequenza di collisioni nella condizione di HEV-30 km/h e, in particolare, il numero esiguo di "attraversamento limite". In effetti, questi pedoni potrebbero aver bisogno di più tempo per elaborare le informazioni audio-visive relative al veicolo in avvicinamento e trasformare la loro rapidità di risposta in un errore.

Infine, i risultati sperimentali evidenziano che bassi livelli di pressione sonora dei veicoli in transito non sono necessariamente una condizione di pericolo per i pedoni. Altre caratteristiche sonore, come la differenza spettrale tra il suono HEV e ICEV o il diverso aumento del rumore legato alla prossimità, dovrebbero essere prese in considerazione nell'analisi del riconoscimento del pericolo. Tuttavia, la differenza nel comportamento dei pedoni è possibile sia anche influenzata dalla scarsa familiarità dei pedoni con il suono dei veicoli elettrici.

Conclusions

A virtual reality simulation has been used to test the pedestrian behaviour during the road crossing with different type of approaching's vehicles and conditions. The pedestrians' decisions and response times were compared. The pass-by recordings showed that, for the three speeds investigated (30, 40 and 50 km/h), diesel ICEV showed having maximum pass-by levels higher than the other two types of vehicles. At the same time, the pass-by peaks of gasoline ICEV resulted comparable to HEVs.

The experimental results have shown that for the diesel and the gasoline ICEV the pedestrian behaviour keeps substantially the same, while with an approaching HEV the subjects could take wrong decisions. More precisely, under conditions of high potential risk (corresponding to the case of vehicle Approaching Time comparable to Crossing Time), pedestrians presented a low capacity to recognize the danger for an approaching HEV. This condition was maximum at 30 km/h, with a higher number of virtual hits than in the case of the ICEV diesel and gasoline. Analyzing the pedestrian response times, it has been observed that at 30 km/h the decision time was significantly higher for the approaching HEV compared to the diesel and gasoline ICEV. This result can justify the high occurrence of virtual hits in the HEV-30 km/h condition and, in particular, the exiguous number of 'limit crossing'. Indeed, these pedestrians may need more time to elaborate the audio-visual information related to the approaching vehicle and transform their quickness of response in an error.

Finally, the experimental results highlight that low pass-by sound pressure levels are not necessary an hazard condition for pedestrians. Other sound characteristics, like the spectral difference between the HEV and the ICEV sound or the different increase in noise related to the proximity, should be taken into account in the analysis of danger recognition. However, the difference in pedestrian behaviour may be also affected by the pedestrian unfamiliarity with the HEV sound.

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